

**CHAPTER 6. OPEN CHANNEL FLOW DESIGN****CONTENTS**

	Section	Page
	OC-	
<b>EXECUTIVE SUMMARY</b> .....	<b>1</b>	
Purpose of the Chapter.....	1	
Chapter Summary.....	1	
City Open Channel Flow Requirements .....	1	
Summary of Critical Design Criteria .....	2	
<b>1. INTRODUCTION</b> .....	<b>11</b>	
1.1. General.....	11	
1.2. Types of Major Open Channels .....	11	
1.3. Overview of Chapter.....	12	
1.4. Issues in Open Channel Planning and Engineering.....	13	
1.5. Fluvial Geomorphology.....	13	
1.5.1. Effects of Urbanization on Existing Stream Channels .....	14	
1.5.2. Stable Channel Balance .....	14	
<b>2. OPEN CHANNEL DESIGN PRINCIPLES</b> .....	<b>15</b>	
2.1. General Open Channel Flow Hydraulics .....	15	
2.1.1. Types of Flow in Open Channels.....	15	
2.1.2. Roughness Coefficients.....	17	
2.1.3. Specific Energy of Channel Flow.....	18	
2.1.4. Flow Regime.....	19	
2.1.4.1. Critical Flow.....	20	
2.1.4.2. Subcritical Flow .....	21	
2.1.4.3. Supercritical Flow .....	22	
2.2. Preliminary Design Criteria.....	23	
2.2.1. Design Velocity .....	23	
2.2.2. Design Depths .....	23	
2.2.3. Design Slopes.....	23	
2.2.3.1. Channel Slope.....	23	
2.2.3.2. Side Slopes .....	24	
2.2.4. Curvature and Transitions .....	24	
2.2.5. Design Discharge Freeboard.....	25	
2.2.6. Erosion Control.....	25	
2.2.7. Utility Proximity .....	25	
2.3. Choice of Channel Type and Alignment .....	26	
2.3.1. Types of Channels for Major Drainageways.....	26	
2.3.2. Factors to Consider in Selection of Channel Type and Alignment.....	27	
2.3.3. Environmental Permitting Issues .....	28	
2.3.4. Maintenance .....	31	
2.4. Design Flows.....	31	
2.5. Maintenance Classification – Primary Channels, Secondary Channels, and Tertiary Channels.....	32	
<b>3. OPEN-CHANNEL DESIGN CRITERIA</b> .....	<b>33</b>	
3.1. Grass-Lined Channels.....	34	
3.1.1. Design Criteria.....	34	
3.1.1.1. Design Velocity and Froude number .....	34	
3.1.1.2. Design Depths.....	34	
3.1.1.3. Design Slopes .....	34	
3.1.1.4. Curvature .....	34	
3.1.1.5. Design Discharge Freeboard .....	35	

OPEN CHANNEL FLOW

- 3.1.2. Channel Cross Sections .....35
  - 3.1.2.1. Bottom Width.....35
  - 3.1.2.2. Trickle and Low-Flow Channels .....35
  - 3.1.2.3. Outfalls Into Channel.....36
- 3.1.3. Roughness Coefficients.....36
- 3.1.4. Trickle and Low-Flow Channels.....37
- 3.1.5. Erosion Control.....41
  - 3.1.5.1. Erosion at Bends.....42
  - 3.1.5.2. Riprap Lining of Grass-lined Channels .....42
- 3.1.6. Water Surface Profile.....42
- 3.1.7. Maintenance .....43
- 3.1.8. Calculation Tool .....43
- 3.2. Composite Channels .....43**
  - 3.2.1. Design Criteria .....44
  - 3.2.2. Design Procedure .....44
  - 3.2.3. Water Surface Profile.....46
  - 3.2.4. Life Expectancy and Maintenance.....47
  - 3.2.5. Calculation Tool .....48
- 3.3. Concrete-Lined Channels .....48**
  - 3.3.1. Design Criteria .....48
    - 3.3.1.1. Design Velocity and Froude Number .....48
    - 3.3.1.2. Design Depths.....49
    - 3.3.1.3. Curvature .....49
    - 3.3.1.4. Design Discharge Freeboard .....49
  - 3.3.2. Concrete Lining Specifications .....50
    - 3.3.2.1. Concrete Lining Section .....50
    - 3.3.2.2. Concrete Joints and Reinforcement.....50
    - 3.3.2.3. Concrete Finish .....50
    - 3.3.2.4. Weep Holes.....51
  - 3.3.3. Channel Cross Section .....51
    - 3.3.3.1. Side Slopes .....51
    - 3.3.3.2. Depth.....51
    - 3.3.3.3. Bottom Width.....51
    - 3.3.3.4. Trickle and Low-Flow Channels .....51
    - 3.3.3.5. Outfalls Into Channel.....51
  - 3.3.4. Safety Requirements .....51
  - 3.3.5. Calculation Tools.....52
  - 3.3.6. Maintenance .....52
- 3.4. Riprap-Lined Channels .....53**
  - 3.4.1. Types of Riprap.....54
    - 3.4.1.1. Riprap and Soil Riprap .....54
    - 3.4.1.2. Grouted Boulders .....55
    - 3.4.1.3. Wire-Enclosed Rock (Gabions).....57
    - 3.4.1.4. Alternatives to Riprap Lining/Structures.....58
  - 3.4.2. Design Criteria .....58
    - 3.4.2.1. Design Velocity.....58
    - 3.4.2.2. Design Depths.....58
    - 3.4.2.3. Riprap Sizing.....58
    - 3.4.2.4. Riprap Toes .....59
    - 3.4.2.5. Curves and Bends.....60
    - 3.4.2.6. Transitions.....60
    - 3.4.2.7. Design Discharge Freeboard .....60
  - 3.4.3. Roughness Coefficient.....60
  - 3.4.4. Bedding Requirements .....61
    - 3.4.4.1. Granular Bedding .....61
    - 3.4.4.2. Filter Fabric .....62
  - 3.4.5. Channel Cross Section.....63
    - 3.4.5.1. Side Slopes .....63
    - 3.4.5.2. Depth.....63
    - 3.4.5.3. Bottom Width.....63
    - 3.4.5.4. Outfalls Into Channel.....63

DRAINAGE CRITERIA MANUAL

3.4.6.	Erosion Control .....	63
3.4.7.	Maintenance .....	64
<b>3.5.</b>	<b>Bioengineered Channels.....</b>	<b>68</b>
3.5.1.	Components .....	68
3.5.2.	Applications .....	69
3.5.3.	Bioengineering Resources .....	69
3.5.4.	Characteristics of Bioengineered Channels .....	69
3.5.5.	Advantages of Bioengineered Channels .....	71
3.5.6.	Technical Constraints.....	71
3.5.7.	Design Guidelines.....	73
<b>3.6.</b>	<b>Natural Channels .....</b>	<b>73</b>
<b>4.</b>	<b>REFERENCES .....</b>	<b>79</b>

**TABLES**

Table OC-6 – Acceptable/Preferred Open Channel Types .....  
12

Table OC-7 – Manning’s n Roughness Coefficients for Channel Design (After Chow 1959) .....  
17

Table OC-7a – Open Channel Maintenance Classification Physical Criteria<sup>5</sup> .....  
33

Table OC-8 – Values for Manning’s n in Grass-lined Overflow Bank Areas in Composite Channel  
(Guo 2006) .....  
46

Table OC-9 – Manning’s n Roughness Coefficients for Concrete-Lined Channels (UDFCD  
USDCM 2002) .....  
48

Table OC-10 – Classification and Gradation of Riprap .....  
54

Table OC-11 – Classification of Boulders (UDFCD USDCM 2002) .....  
55

Table OC-12 – Specifications and Placement Instructions for Grout in Grouted Riprap and  
Grouted Boulders (UDFCD USDCM 2002) .....  
56

Table OC-13 – Riprap Requirements for Channel Linings \* (UDFCD USDCM 2002 [modified for  
City of Rogers]) .....  
59

Table OC-14 – Gradation for Granular Bedding .....  
61

Table OC-15 – Granular Bedding Thickness Requirements (UDFCD USDCM 2002) .....  
62

Table OC-16 – Guidelines for Use of Various Types of Channels (UDFCD USDCM 2002) .....  
73

**FIGURES**

Figure OC-1 – Specific Energy Diagram for Rectangular Channels (Bedient and Huber 2002) .....  
19

Figure OC-2 – Flow Chart for Selecting Channel Type and Assessing Need for 404 Permit  
(UDFCD USDCM 2002) .....  
30

Figure OC-3 – Manning’s n vs. VR for Two Retardances in Grass-Lined Channels (taken from  
SCS-TP-61 Rev. 1954) .....  
37

Figure OC-5 – Composite Grass-lined Channel with a Low-Flow Channel, including a Wetland  
Bottom Low-Flow Channel (UDFCD USDCM 2002) .....  
40

Figure OC-6 – Grass-lined Channel with a Trickle Channel (UDFCD USDCM 2002) .....  
41

Figure OC-7 – Composite Channel At Bridge or Culvert Crossing (UDFCD USDCM 2002) .....  
46

Figure OC-8 – Concrete Lined Channel (Trapezoidal) .....  
52

Figure OC-10 – Filter Fabric Details (UDFCD USDCM 2002) .....  
66

Figure OC-11 – Detail – Boulder Edged Low-Flow Channel (UDFCD USDCM 2002) .....  
67

Figure OC-12 – Live Willow Staking for Bare Ground and Joint Installation (UDFCD USDCM  
2002) .....  
76

Figure OC-13 – Fascine in Conjunction With Jute Mesh Mat (UDFCD USDCM 2002) .....  
77

DRAINAGE CRITERIA MANUAL

Figure OC-14 – Fiber Roll (UDFCD USDCM 2002) .....

78

## EXECUTIVE SUMMARY

### Purpose of the Chapter

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

### Chapter Summary

Once stormwater runoff has been collected in a storm drainage system it continues to combine with other sections of the storm drainage system until, typically, culminating into open channels. Except for roadside ditches and swales, open channels are nearly always a component of the major drainage system. There are a number of factors which must be considered in determining whether to specify an open drainageway as opposed to an underground storm drain: material and installation cost, maintenance costs and problems, acceptability to the developer or home buyer, public safety, water quality, appearance, etc. Effective planning and design of open drainageways can significantly reduce the cost of storm drainage facilities, while enhancing the quality of the development.

In planning a development, the designer should begin by determining the location and the width of existing drainageways. Streets and lots should be laid out in a manner to preserve the existing drainage system to the greatest degree practical. Constructed channels should be used only when it is not practical or feasible to utilize existing drainageways.

This section covers the evaluation of capacity and stability of natural drainage channels, and design of constructed drainage channels.

### City Open Channel Flow Requirements

To comply with the City requirements for open channel flows, channels must be planned and designed to address the applicable criteria outlined below:

- **Layout and Structure**
  - Safety of the general public and preventing damage to private property are the most important considerations in the selection of the cross-sectional geometry and type of open channel. Channel shape, type, and alignment should be selected to ensure that velocities and depths do not exceed those specified in [Section 2.0](#) and [Section 3.0](#) of this

## DRAINAGE CRITERIA MANUAL

chapter. The range of design channel discharges should be selected by the designer based on flood hazard risks and local site conditions.

- Channels must be designed with long-term stability in mind. Following the guidelines and design criteria presented in this chapter for designing open channels provides reasonable parameters that when met provide adequate channel stability. Regular channel maintenance will be a necessary part of maintaining channel stability as well. The design of open channels must consider the frequency and types of maintenance expected and make allowance for maintenance access along and within the channel.

### ▪ **Environmental and Regulatory**

- Environmental and regulatory criteria as mentioned herein are not discussed in detail in this *Manual*. Local, state, and federal regulations must be reviewed and addressed for the appropriate agency having jurisdiction over impacted areas.
- Environmental impacts of channel modifications, including disturbance of fish habitat, wetlands and channel stability, should be assessed and if needed remediation planned within the overall drainage design for such impacted areas.
- Channel designs that impact existing open channels shall satisfy the policies of the Federal Emergency Management Agency (FEMA) applicable to floodplain management and regulation. Wherever possible, disturbance of natural channels/streams shall be avoided and encroachment onto flood plains shall be minimized to the fullest extent practical.
- Coordination with other Federal, State and local agencies (US Army Corp of Engineers, US Fish and Wildlife Service, Arkansas Department of Energy & Environment Division of Environmental Quality, Arkansas Historic Preservation Program, etc.) concerned with water resources planning must be carried out as part of the design of open channels to ensure all laws and regulations are adhered to in a design.

## **Summary of Critical Design Criteria**

The summary below outlines some of the most critical design criteria essential to design engineers for proper drainage design of open channels according to City of Rogers' requirements. The information below contains exact numerical criteria as well as general guidelines that must be adhered to during the design process. This section is meant to be a summary of critical design criteria for this section; however, the engineer is responsible for all information in this chapter. It should be noted that any design engineer who is not familiar with Rogers' Drainage Criteria Manual and its accepted design techniques and methodology should review the entirety of this chapter.

<b>Maintenance Classifications – Primary Channels, Secondary Channels, and Tertiary Channels</b>
--

Primary Channels	<ul style="list-style-type: none"> <li>▪ major open channel that serves as a primary waterway to conduct runoff generated in a large composite area (typically <math>\geq 30</math>-acres).</li> <li>▪ a channel that has a flood zone (floodway, floodplain, etc.) as determined/studied by the City and/or FEMA.</li> <li>▪ to be maintained by the owner and/or City and shall be placed in a drainage and recreation easement.</li> <li>▪ 100-year design storm with <math>\geq 2</math>-foot of freeboard.</li> <li>▪ Designate extent of 100-year water surface elevation on grading plan and as a drainage easement.</li> </ul>
Secondary Channels	<ul style="list-style-type: none"> <li>▪ a medium open channel that collects runoff from storm sewer systems, tertiary and other secondary channels, and feeds the runoff into primary or other secondary channels.</li> <li>▪ drainage areas for secondary channels typically range from <math>&gt; 2</math>-acres and <math>&lt; 30</math>-acres.</li> <li>▪ to be maintained by a POA, developer of the subdivision, or other responsible entity for a development and shall be placed in a drainage and recreation easement.</li> <li>▪ 100-year design storm with <math>\geq 1</math>-foot of freeboard.</li> <li>▪ Designate extent of 100-year water surface elevation on grading plan and as a drainage easement.</li> </ul>
Tertiary Channels	<ul style="list-style-type: none"> <li>▪ a small minor channel that serves as a conduit to channel runoff (typically <math>\leq 2</math>-acres).</li> <li>▪ These types of channels are to be maintained by the owners of the property which the channel serves.</li> <li>▪ 10-year design storm. Convey 100-year between structures.</li> </ul>

More detailed information can be found in [Section 2.5](#) and [Table OC-7a](#)

Refer to the City of Rogers' GIS site for Streambank Inventory-BEHI (Bank Erosion Hazard Index) for areas of special design considerations (<http://www.rogersgis.com/>).

In addition to the design criteria outlined in the following tables in this chapter, primary channels will also need to incorporate natural channel design elements, unless otherwise approved by the Director of Community Development and the City Engineer. Natural channel design elements would include riparian zones, floodplains, alluvial landscapes, natural weirs and vanes, toe wood along channel banks, etc.

DRAINAGE CRITERIA MANUAL

<b>Table OC-1 – Grass-Lined Open Channel Design</b>	
Use of channel type subject to City approval	No
Maximum Normal Depth Velocity	≤ 5-fps for 100-year design
Manning's <i>n</i> – Used to check channel depth	0.040 (or see <a href="#">Section 3.1.3, Figure OC-3</a> Retardance Class C)
Manning's <i>n</i> – Used to check maximum (channel stability)	0.030 (or see <a href="#">Section 3.1.3, Figure OC-3</a> Retardance Class B)
Froude Number <sup>3</sup>	< 0.8

<b>Table OC-1 – Grass-Lined Open Channel Design Criteria</b>	
Longitudinal Channel Slope <sup>1</sup>	≥ 0.75% ≥ 1.00% if no trickle channel is present
Side Slopes (max.)	3H:1V
Channel Bottom Width (trapezoidal)	≥ 5-ft
Channel Bottom Cross-slope	1% to 2%
Centerline Curve Radius (feet) (subcritical)	≥ 2x the top width of the 100-year design storm
Centerline Curve Radius (supercritical)	Supercritical Flow <b>NOT ALLOWED</b>
Channel Bend Protection	See <a href="#">Section 3.1.5.1</a>
Outfall Height Above Channel Invert	≥ 1-ft (with properly designed outlet protection)
Normal Depth outside of the trickle/low flow channel	≤ 5-ft at 100-year design peak flow for fully developed watershed
<i>Secondary Channels</i> Freeboard <sup>2</sup>	≥ 1-ft
<i>Primary Channels</i> Freeboard <sup>2</sup>	≥ 2-ft
Trickle Channel (if any) sized for ...	2.0% of 100-year design peak flow for fully developed watershed
Trickle Channel (if any) Bottom Width	≥ 5-ft
Low-flow Channel sized for ...	5-year design peak flow for fully developed watershed
Low-flow Channel Bottom Width	≥ 5-ft
Low-flow Channel Depth	≥ 3.0-ft and ≤ 5.0-ft
Maintenance Access Road for <i>Primary Channels</i>	10-ft (min) stable surface with 12-ft (min) clear width, 20-ft at deep structures
Maintenance access locations from city drainage easements...	Locations to be determined during the review process.

Drop downstream of each culvert or bridge	See <a href="#">Section 3.2.3</a>
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Use of channel type subject to City approval?	No
Maximum Normal Depth Velocity	≤ 5-fps for 100-year design
Manning's <i>n</i> – Used to check channel capacity (flow depth)	0.040 (or see <a href="#">Section 3.1.3</a> , <a href="#">Figure OC-3</a> Retardance Curve C)
Manning's <i>n</i> – Used to check maximum velocity (channel stability)	0.030 (or see <a href="#">Section 3.1.3</a> , <a href="#">Figure OC-3</a> Retardance Curve D)
<i>Secondary Channels</i> water surface profile computed for...	1-, 2-, 5-, 10-, 25-, 50- and 100-year storm events
<i>Primary Channels</i> water surface profile computed for...	1-, 2-, 5-, 10-, 25-, 50-, and 100-year storm events
Utility location and depth near channel	No utilities are allowed between the top of banks except for crossings which must be ≥ 3-ft deep.

- 1 – Maximum channel slope controlled by maximum channel velocity.
- 2 – Superelevation must be added in curves/bends – See [Section 2.2.4](#).
- 3 – Flows at Froude numbers between 0.8 and 1.2 are unstable and unpredictable and must be avoided.

Use of channel type subject to City approval?	No
Maximum Normal Depth Velocity (ft/s)	≤ 5-fps for 100-year design
Manning's <i>n</i> – Used to check maximum velocity (channel stability)	See <a href="#">Section 3.2.1</a> , <a href="#">Figure OC-3</a> (Retardance Curve D), <a href="#">Table OC-3</a>
Manning's <i>n</i> – Used to check channel capacity (flow depth)	See <a href="#">Section 3.2.1</a> , <a href="#">Figure OC-3</a> (Retardance Curve C), <a href="#">Table OC-3</a>
Composite Manning's <i>n</i> calculated for use in hydraulic computations	See <a href="#">Section 3.2.2</a> , <a href="#">Equation OC-11</a>
Froude Number <sup>3</sup>	< 0.8
Longitudinal Channel Slope <sup>1</sup>	Base on “new channel” roughness condition. See <a href="#">Section 2.2.4</a>
Side Slopes (max.) in low-flow channel	2.5H:1V [TRM (preferred) or soil riprap (requires approval)]
Side Slopes (max.) above low-flow channel	3H:1V (grass-lined)
Channel Bottom Width <sup>4</sup>	≥ 5-ft
Channel Bottom Cross-slope <sup>4</sup>	“Flat bottom”
Centerline Curve Radius (feet) (subcritical)	≥ 2x the top width of the 100-year design storm

# DRAINAGE CRITERIA MANUAL

<b>Table OC-2 – Composite Open Channel Design Criteria</b>		
Use of channel type subject to City approval?	No	
Maximum Normal Depth Velocity (ft/sec)	≤ 5-fps for 100-year design	
Manning's <i>n</i> – Used to check maximum velocity (channel stability)	See <a href="#">Section 3.2.1</a> , <a href="#">Figure OC-3</a> (Retardance Curve D), <a href="#">Table OC-3</a>	
Manning's <i>n</i> – Used to check channel capacity (flow depth)	See <a href="#">Section 3.2.1</a> , <a href="#">Figure OC-3</a> (Retardance Curve C), <a href="#">Table OC-3</a>	
Centerline Curve Radius (supercritical)	Supercritical Flow <b>NOT ALLOWED</b>	
Channel Bend Protection	See <a href="#">Section 3.1.5.1</a>	
Outfall Height Above Channel Invert	≥ 2-ft	
Normal Depth outside of the trickle/low flow	≤ 5-ft at 100-year design peak flow for fully developed watershed	
<i>Secondary Channel</i> Freeboard <sup>2, 4</sup>	≥ 1-ft	
<i>Primary Channel</i> Freeboard <sup>2, 4</sup>	≥ 2-ft	
Low-flow Channel sized for ...	5-year design peak flow for fully developed watershed	
Low-flow Channel depth	≥ 3.0-ft and ≤ 5.0-ft	
Maintenance Access Road <sup>4</sup>	10-ft (min) stable surface with 12-ft (min) clear width, 20-ft at drop structures	
	Maintenance access locations from drainage easements...	Locations to be determined during the review process.
Drop downstream of each culvert or structure	See <a href="#">Section 3.2.3</a>	
	<i>Secondary Channels</i> water surface profile computed for...	1-, 10-, 25-, and 100-year storm events
	<i>Primary Channels</i> water surface profile computed for...	1-, 2-, 5-, 10-, 25-, 50- and 100-year storm events
<b>Table OC-2 – Composite Open Channel Design Criteria</b>		
	Utility location and depth near channels	No utilities are allowed between the top of banks except for crossings which must be ≥ 3-ft deep. No utilities are allowed between

- 1 – Maximum channel slope controlled by maximum channel velocity.
- 2 – Superelevation must be added in curves/bends – See [Section 2.2.4](#).
- 3 – Flows at Froude numbers between 0.8 and 1.2 are unstable and unpredictable and must be avoided.
- 4 – See Figure OC-5

<b>Table OC-3 – Concrete-Lined Open Channel Design</b>		
Use of channel type subject to City approval	Yes	
Maximum Normal Depth Velocity	≤ 18-fps for 100-year design	
Manning's <i>n</i> – Used to check maximum Froude Number ≤ 0.7	0.011	
Manning's <i>n</i> – Used to check channel Froude Number ≥ 1.4	0.013	
Froude Number <sup>5</sup>	≤ 0.7 <sup>3</sup> and ≥ 1.4 <sup>4</sup> under both Manning's <i>n</i>	
Longitudinal Channel Slope <sup>1</sup>	≤ 1.00%	
Side Slopes (max.)	1.5H:1V (unless structurally designed for steeper slope)	
Channel Bottom Width	≥ 5-ft	
Centerline Curve Radius (subcritical flow)	≥ 2x the top width for the 100-year design storm	
Centerline Curve Radius (supercritical flow)	No curvature permitted	
Concrete channel lining thickness	≥ 5-in when $F_r \leq 0.7$ <sup>3</sup> ; ≥ 8-in when $F_r > 1.4$ <sup>4</sup>	
Outfall Height Above Channel Invert	≥ 1-ft	
	<i>Secondary Channels</i> Freeboard <sup>2</sup>	≥ 1-ft See <a href="#">Section 3.3.1.4</a>
	<i>Primary Channels</i> Freeboard <sup>2</sup>	≥ 2-ft See <a href="#">Section 3.3.1.4</a>
Maintenance Access Road	10-ft (min) stable surface with 12-ft (min) clear width, 20-ft at drop structures	
	Maintenance access locations from city drainage easements...	Locations to be determined during the review process.
	<i>Secondary Channels</i> water surface profile computed for...	1-, 10-, 25-, and 100-year storm events
<b>Table OC-3 – Concrete-Lined Open Channel Design Criteria</b>		
	<i>Primary Channels</i> water surface profile computed for...	1-, 2-, 5-, 10-, 25-, 50- and 100-year storm events
Safety Requirements	6-ft chain link or approved equivalent fence/barrier required in areas where channel depth is ≥ 2-ft	
Utility location and depth near channels	No utilities are allowed between the top of banks except for crossings which must be ≥ 3-ft deep. No utilities are allowed between	

1 – Minimum channel slope controlled by minimum channel cleaning velocity (3-fps) during low-flows.  
2 – Superelevation must be added in curves/bends – See [Section 2.2.4](#).  
3 – Requires free draining granular bedding under channel cover at 6-inch minimum thickness.  
4 – Requires free draining granular bedding under channel cover at 9-inch minimum thickness.  
5 – Flows at Froude numbers between 0.8 and 1.2 are unstable and unpredictable and must be avoided.

# DRAINAGE CRITERIA MANUAL

<b>Table OC-4 – Riprap-Lined Open Channel Design</b>	
Use of channel type subject to City approval	Yes
Maximum Normal Depth Velocity (ft/s)	$\leq 12$ -fps
Manning's $n$ – Used to check maximum velocity (channel stability)	0.030
Manning's $n$ – Used to check channel depth (flow depth)	0.041
Froude Number <sup>1</sup>	$\leq 0.8$
Side Slopes (max.)	2.5H:1V
Use of soil riprap ...	<a href="#">Section 3.1.5.2</a> ; <a href="#">Figure OC-5</a> ; <a href="#">Section 3.4.1.1</a>
Rock specific gravity and other rock properties	$\geq 2.50$ and see <a href="#">Section 3.4.1.1</a>
Riprap rock size / gradation	Sizing – <a href="#">Equation OC-13</a> and <a href="#">Table OC-13</a> Gradation – <a href="#">Table OC-13</a>
Riprap blanket thickness	$\geq 2x d_{50}$ in normal channel $\geq 3x d_{50}$ for at least 3-ft at upstream and downstream ends of lining
Toe protection provided according to	<a href="#">Section 3.4.2.4</a> & <a href="#">Figure OC-9</a>
Centerline Curve Radius (subcritical)	$\geq 2x$ the top width of the 100-year design storm
Centerline Curve Radius (supercritical)	Supercritical Flow <u>NOT ALLOWED</u>
<b>Table OC-4 – Riprap-Lined Open Channel Design Criteria</b>	
Channel Bend Protection – Riprap sizing	Size riprap in bends according to <a href="#">Section 3.4.2.5</a> . Use <a href="#">Equation OC-13</a> and <a href="#">Table OC-13</a> based on the adjusted velocity ( $V_a$ ) from
Channel Bend Protection – Riprap extent	Extend downstream of bend $\geq 2x$ the top width of the 100-year design storm
Outfall Height Above Channel Invert	$\geq 1$ -ft
<i>Secondary Channels</i> Freeboard <sup>2</sup>	$\geq 1$ -ft See <a href="#">Section 3.3.1.4</a>
<i>Primary Channels</i> Freeboard <sup>2</sup>	$\geq 2$ -ft See <a href="#">Section 3.3.1.4</a>
Riprap at transitions – Riprap sizing	Use <a href="#">Table OC-13</a> by using $\geq 1.25x$ maximum velocity in transition
Riprap at transition – Riprap extents	Extend upstream by 5-ft and downstream by $\geq 5x$ design flow depth
Granular bedding – Gradation...	See <a href="#">Section 3.4.4.1</a> ; <a href="#">Table OC-14</a>

Table OC-4 – Riprap-Lined Open Channel Design Criteria		
Use of channel type subject to City approval?	Yes	
Maximum Normal Depth Velocity (ft/sec)	≤ 12-fps	
Manning's <i>n</i> – Used to check maximum velocity (channel stability)	0.030	
Manning's <i>n</i> – Used to check channel capacity (flow depth)	0.041	
Granular bedding – Thickness...	See <a href="#">Section 3.4.4.1</a> ; <a href="#">Table OC-15</a>	
Maintenance Access Road	10-ft (min) stable surface with 12-ft (min) clear width, 20-ft at drop structures	
	Maintenance access locations from drainage easements...	Locations to be determined during the review process.
<i>Secondary Channels</i> water surface computed for...	1-, 2-, 5-, 10-, 25-, 50- and 100-year storm events	
<i>Primary Channels</i> water surface profile computed for...	1-, 2-, 5-, 10-, 25-, 50- and 100-year storm events	
Utility location and depth near channels	No utilities are allowed between the top of banks except for crossings which must be ≥ 3-ft deep. No utilities are allowed between	

- 1 – Flows at Froude numbers between 0.8 and 1.2 are unstable and unpredictable and must be avoided.  
 2 – Superelevation must be added in curves/bends – See [Section 2.2.4](#).

Table OC-5 – Bioengineered Open Channel Design Criteria	
Use of channel type subject to City approval?	Yes
Maximum Normal Depth Velocity	≤ 2-fps for 5-year design ≤ 4-fps for 100-year design
Froude Number <sup>2</sup>	0.3 for 5-year design 0.3 for 100-year design

## DRAINAGE CRITERIA MANUAL

Longitudinal Channel Slope <sup>1</sup>	≤ 0.20%
	Centerline Curve Radius (feet) (subcritical) ≥ 2x the top width of the 100-year design storm
	Centerline Curve Radius (supercritical) Supercritical Flow <u>NOT ALLOWED</u>
Design guidelines	See <a href="#">Section 3.5.7</a>
Utility location and depth near channel	No utilities are allowed between the top of banks except for crossings which must be ≥ 3-ft deep. No utilities are allowed between maintenance road stable surface

### Water surface profiles

1 – Maximum channel slope controlled by maximum channel velocity.

2 – Flows at Froude numbers between 0.8 and 1.2 are unstable and unpredictable and must be avoided. Maintenance roads and access easements.

# 1.

## INTRODUCTION

### 1.1. General

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

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

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

Secondary and primary open channels shall be placed in Drainage and Recreation Easements.

### 1.2. Types of Major Open Channels

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

# DRAINAGE CRITERIA MANUAL

**Table OC-6 – Acceptable/Preferred Open Channel Types**

<b>Channel Type</b>	<b>Preference Rating <sup>1</sup> 1 – most preferred 4 – least preferred</b>	<b>City approval required prior to implementation <sup>2</sup></b>
Natural	1	No
Grass-lined	2	No
Composite	2	No
Concrete-lined	3	Yes
Riprap-lined	4	Yes
Bioengineered	2	No <sup>3</sup>

- 1: Even though the City prefers to see specific channel types over others, the final channel type selected must be based on preference as well as applicability to the hydraulic conditions.
- 2: Channel types listed as requiring City approval means the design engineer will have to address in the drainage report why the certain type of channel had to be used (i.e. R.O.W. constraints, hydraulic requirements, etc.) in lieu of the City's most preferred channel types (1 and 2). Additionally, written authorization from the City will be required prior to implementing a "lesser preferred" channel type (3 and 4) into a final design.
- 3: Design of channel must be carried out by a designer considered to be an authority in the design of such channels. Credentials of the engineer of record shall be provided with the plan submittal for City review.

As discussed in the rest of this chapter, the selection of the channel type for any given reach of a major drainageway is a complex function of hydraulic, hydrologic, structural, financial, environmental, sociological, public safety, and maintenance considerations and constraints. [Table OC-6](#) merely provides preferences the design engineer should keep in mind when selecting an open channel type for a project.

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

### **1.3. Overview of Chapter**

This chapter addresses the major topics related to the design of open channels, beginning with essential background on the issues of open channel planning and engineering ([Section 1.4](#)) and fluvial geomorphology ([Section 1.5](#)). General open channel hydraulics and preliminary design criteria are presented in [Section 2.0](#). It is the responsibility of the designer to be knowledgeable of open channel

hydraulics, and, therefore, the key principles and equations are reviewed without extensive background of the subject matter, theoretical considerations, etc. [Section 3.0](#) contains specific design criteria for a variety of channel types and includes example calculations, typical cross sections, and other representative design details.

#### **1.4. Issues in Open Channel Planning and Engineering**

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

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

Open channels for transporting major storm runoff are the most desirable type of major drainageway because they offer many opportunities for creation of multiple use benefits such as incorporation of parks and greenbelts along the channel and other aesthetic and recreational uses that closed-conveyance drainageway designs preclude. Open channels are also usually less costly and they provide a higher degree of flood routing storage. Where opportunities are presented for establishing primary or secondary channels, or enhancing the functionality of already existing open channels, deviating from utilizing an open channel would first need to be approved by the City Engineer.

The choice of the type of open channel is a critical decision in planning and design of major drainageways. The preferred channel is a stable natural one carved by nature over a long period of time that can remain stable after urbanization. Generally, the closer an artificial channel's character can be made to that of a natural channel, the more functional and attractive the artificial channel will be. In an urban area, however, it is rarely feasible to leave a natural channel untouched since urbanization alters the hydrology of the watershed. Consequently, some level of stabilization is usually necessary to prevent the channel from degrading and eroding. Channel type evaluation should be done in ascending order as shown in [Table OC-6](#).

#### **1.5. Fluvial Geomorphology**

A drainage system within a watershed involves flowing water or movement of water, thus the term *fluvial*. When flowing water develops a drainage pattern or surface forms, the process is identified as *fluvial geomorphology*. Surface form characteristics represented by open channels (natural and manmade) behave in a complex manner dependent on watershed factors such as geology, soils, ground cover, land

## DRAINAGE CRITERIA MANUAL

use, topography, and hydrologic conditions. These same watershed factors contribute to the sediment eroded from the watershed and transported by the stream channel. The sediments moved by the flowing water also influence channel hydraulic characteristics. The natural-like channel and stabilization systems recommended in this *Manual* are based on fluvial geomorphology principles. The remainder of this section will provide the reader with a basic understanding of the workings and evolution of open channels within an urban watershed.

### 1.5.1. Effects of Urbanization on Existing Stream Channels

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

### 1.5.2. Stable Channel Balance

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

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

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

in which:

$Q_w$  = water discharge (cfs)

$S$  = channel slope (ft/ft)

$Q_s$  = bed material load (tons/day)

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

For a stable channel, these four parameters are balanced, and, when one or more of the parameters changes, the others adjust to restore the state of equilibrium. For example, if the stream flow increased

with no change in channel slope, there would be an adjustment on the sediment side of the balance, with an increase in either bed material size or sediment load, or both. It is this principle on which the remaining open channel design equations and criteria are based in this chapter.

## **2. OPEN CHANNEL DESIGN PRINCIPLES**

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

### **2.1. General Open Channel Flow Hydraulics**

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

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

#### **2.1.1. Types of Flow in Open Channels**

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

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

## DRAINAGE CRITERIA MANUAL

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

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

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

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

in which:

$Q$  = discharge (cfs)

$n$  = roughness coefficient

$A$  = area of channel cross section (ft<sup>2</sup>)

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

$P$  = wetted perimeter (ft)

$S$  = channel bottom slope (ft/ft)

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

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

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

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

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

Solution of [Equation OC-2](#) for depth is iterative. To help in quickly obtaining a solution without having to perform iterations the **RDM-Channels** spreadsheet is provided as a supplementary tool to this *Manual*. It can be used to perform normal flow calculations for trapezoidal channels and can help with the design of such channels.

### 2.1.2. Roughness Coefficients

When applying Manning's Equation, the choice of the roughness coefficient,  $n$ , is the most subjective parameter. Manning's  $n$  is affected by many factors and its selection, especially in natural channels depends heavily on engineering experience. [Table OC-7](#) provides guidance on values of roughness coefficients  $n$  to use for channel design. **Both** maximum and minimum roughness coefficients shall be used for channel design to check for sufficient hydraulic capacity and channel lining stability, respectively.

When using the retardance curves for grass-lined channels and swales ([Figure OC-3](#)), use Retardance C for finding Manning's  $n$  for determining channel capacity (depth) in a mature channel and Retardance D for checking the stability (velocity) in a newly constructed channel.

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

**Table OC-7 – Manning's  $n$  Roughness Coefficients for Channel Design (After Chow 1959)**

Channel Type	Roughness Coefficient ( $n$ )		
	Minimum	Typical	Maximum

## DRAINAGE CRITERIA MANUAL

I. Excavated or Dredged			
1. Earth, straight and uniform	0.022	0.025	0.030
a. Gravel, uniform section, clean	0.022	0.027	0.033
b. With short grass, few weeds			
2. Earth, winding and sluggish	0.025	0.030	0.033
a. Grass, some weeds	0.030	0.035	0.040
b. Dense weeds or aquatic plants	0.028	0.030	0.035
c. Earthy bottom and rubble/riprap sides			
3. Channels not maintained, weeds and brush uncut	0.050	0.080	0.120
a. Dense weeds, high as flow depth	0.040	0.050	0.080
b. Clean bottom, brush on sides			
II. Natural streams (top width at flood stage ≥ 100 ft)			
1. Streams on plain			
a. Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
b. Clean, winding, some pools and shoals, some weeds and stones	0.035	0.045	0.050
c. Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
III. Lined or Built-Up Channels			
1. Gravel bottom with sides of:			
a. Formed concrete	0.017	0.020	0.025
b. Random stone in mortar	0.020	0.023	0.026
c. Dry rubble or riprap	0.023	0.033	0.036
2. Concrete Lined Channels and Swales	See <a href="#">Table OC-9</a>		
3. Composite (Wetland Bottom) Channels and Swales	See <a href="#">Section 3.2.1 Equation OC-11</a> , <a href="#">Table OC-8</a>		
4. Grass-Lined Channels and Swales	0.040 (capacity check); 0.030 (velocity check) or see <a href="#">Section 3.1.3</a> , <a href="#">Figure OC-3</a>		

### 2.1.3. Specific Energy of Channel Flow

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

$$E = y + \frac{V^2}{2 * g} = y + \frac{Q}{2 * g * A^2}$$

(Equation OC-6)

Where:

$y$  = Depth of flow (ft)

$V$  = Mean flow velocity (ft/sec)

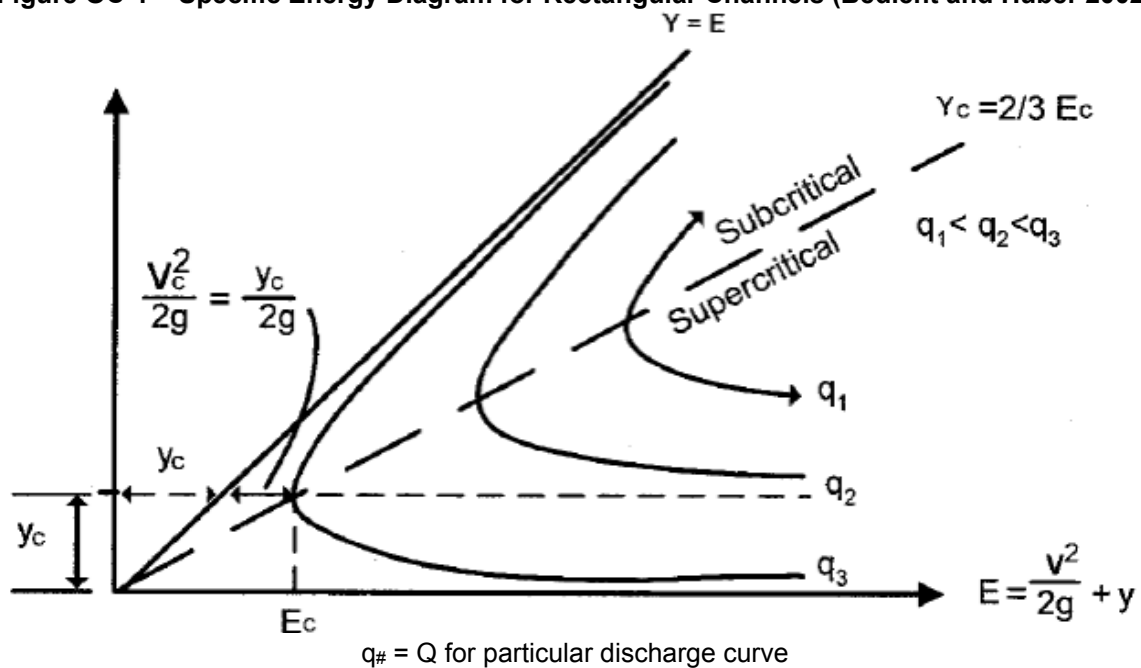
$g$  = Gravitational acceleration (32.2 ft/sec<sup>2</sup>)

$Q$  = Discharge (ft<sup>3</sup>/sec)

$A$  = Cross-sectional area of flow (ft<sup>2</sup>)

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

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



#### 2.1.4. Flow Regime

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

$$F_r = \frac{V}{\sqrt{g^* d}}$$

(Equation OC-7)

in which:

## DRAINAGE CRITERIA MANUAL

$V$  = Mean flow velocity (ft/sec)

$g$  = Gravitational acceleration (32.2 ft/sec<sup>2</sup>)

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

[Equation OC-7](#) applies to channel flow at any cross section. When:

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

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

For all subcritical channels, check the Froude number using the *minimum* value of  $n$  for the relevant channel type from [Table OC-7](#). When performing hydraulic computations for grassed channels, the  $n$  values for the 0.1-foot to 1.5-foot flow depth range ([Table OC-8](#)) are generally suitable for calculating the wetted channel portion for the initial storm runoff. For major runoff computations, however, the greater than 3.0-foot depth  $n$  values ([Table OC-8](#)) are more appropriate since flows will tend to lay the grass down to form a smoother bottom surface.

### 2.1.4.1. Critical Flow

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

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

If the critical state of flow exists throughout an entire reach, the channel flow is critical flow, and the channel slope is at critical slope,  $S_{cr}$ . A slope less than  $S_{cr}$  will cause subcritical flow, and a slope greater than  $S_{cr}$  will cause supercritical flow. Critical depth is the depth of maximum discharge when the specific energy is held constant. A flow at or near the critical state is not stable and as such flows at Froude

numbers between 0.8 and 1.2 shall be avoided. In design, if the depth is found to be at or near critical, the shape or slope shall be changed to achieve greater hydraulic stability.

The general expression for flow at critical depth is:

$$\frac{Q^2}{g} = \frac{A^3}{T} \quad \text{(Equation OC-8)}$$

Where:

$Q$  = Discharge (cfs)

$g$  = Gravitation acceleration (32.2 ft/sec<sup>2</sup>)

$A$  = Cross-sectional area of flow (ft<sup>2</sup>)

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

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

#### **2.1.4.2. Subcritical Flow**

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

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

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

A concrete-lined channel shall not be used for subcritical flows except in unusual circumstances where a narrow right-of-way exists. A stabilized natural channel, a wide grass-lined channel, or a channel with a wetland bottom are most preferred in the City storm drainage system. Do not design a subcritical channel

## DRAINAGE CRITERIA MANUAL

for a Froude number greater than 0.8 using the velocity and depth calculated with the lowest recommended range for Manning's  $n$  ([Table OC-7](#)). When designing a concrete-lined channel for subcritical flow, use a Manning's  $n = 0.013$  for capacity calculations and 0.011 to check whether the flow could go supercritical. If significant sediment deposition or sediment transport is likely, a Manning's  $n$  greater than 0.013 may be necessary for capacity calculations.

### 2.1.4.3. Supercritical Flow

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

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

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

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

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

## **2.2. Preliminary Design Criteria**

### **2.2.1. Design Velocity**

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

The flow velocity during the major design storm (i.e., 100-year) must recognize the scour potential of the channel, whether natural, grassed, bioengineered, riprapped or concrete-lined. Average velocities need to be determined using backwater calculations, which account for water drawdowns at drops, expansions, contractions and other structural controls. Velocities must be kept sufficiently low to prevent excessive erosion in the channel. As preliminary design criteria, flow velocities shall not exceed velocities and Froude numbers given in [Table OC-1](#) and [Table OC-2](#) for non-reinforced channel linings and, in general, shall not exceed 18 ft/sec for reinforced channel linings. Channel-specific velocity criteria depend greatly on the channel lining and slope and are presented in more detail in [Section 3.0](#) of this chapter for various types of open channels.

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

### **2.2.2. Design Depths**

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

### **2.2.3. Design Slopes**

#### **2.2.3.1. Channel Slope**

The slope of a channel affects flow velocity, depth, and regime and can have a significant impact on erosion and channel stability. Channel slope criteria vary based on the type of channel; however, the slope of a channel shall not be so steep as to result in a Froude number greater than 0.5 or 0.8, depending on soil erodibility characteristics (see [Table OC-1](#) through [Table OC-5](#)), for the 100-year event. For steep-gradient drainageways, drop structures are necessary to meet slope criteria. For purposes of

## DRAINAGE CRITERIA MANUAL

this *Manual*, design of drop structures is not specifically addressed. Instead the design engineer is directed to FHWA's *Hydraulic Engineering Circular No. 14, 3<sup>rd</sup> Edition (HEC-14 2006)*, *Hydraulic Design of Energy Dissipators for Culverts and Channels*. An important consideration in channel slope is sinuosity of the channel—straightening of a natural channel inevitably results in an increase in slope. Conversely, for a constructed channel, a design incorporating meanders can be used to satisfy slope criteria, potentially reducing the number of drop structures required.

### 2.2.3.2. Side Slopes

The flatter the side slopes, the more stable channel banks remain. For grassed channels, channels with wetland bottoms, and bioengineered channels, side slopes shall not be steeper than 3H:1V. Channels that require minimal slope maintenance such as concrete channels may have side slopes as steep as 1.5H:1V, although public safety issues must be taken into account. For riprap-lined channels, side slopes shall not be steeper than 2.5H:1V (riprap lined channels shall only be used upon approval by the City).

### 2.2.4. Curvature and Transitions

Generally, the gentler the curves, the better the channel will function. Channel alignments should not be selected to maximize land-use opportunities for lot layout; instead, lot layouts should be selected based on channel alignment. The centerline curvature of the channel shall have a radius of at least two-times (2x) the top width of the 100-year flow channel. The exception to this curvature requirement is for concrete channels that may experience *supercritical* flow conditions. From a practical standpoint, it is not advisable to have any curvature in a channel conveying *supercritical* flow, since minor perturbations can be amplified as they move downstream.

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

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

in which:

$\Delta y$  = Increase in water surface elevation above average elevation due to superelevation (ft)

$V$  = Mean flow velocity (ft/sec)

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

$g$  = Gravitational constant (32.2 ft/sec<sup>2</sup>)

$r_c$  = Radius of curvature (ft)

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

### **2.2.5. Design Discharge Freeboard**

Residual discharge freeboard is necessary to ensure that a design developed using idealized equations will perform as desired under actual conditions. The amount of residual freeboard that must be allowed depends on the type of channel and the location and elevation of structures adjacent to the channel. Preserving existing floodplains maximizes “natural” freeboard. Freeboard requirements are addressed for specific channel types in [Section 3.0](#) of this chapter.

### **2.2.6. Erosion Control**

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

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

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

### **2.2.7. Utility Proximity**

It is important to consider the location and depth of utilities near open channels. Utilities that are too close linearly and too shallow when crossing a channel pose future maintenance problems along with future planning issues. Keeping utilities out of the general operating plane of open channels allows the entity maintaining and operating the channel more flexibility when it comes to dredging, repairing,

## DRAINAGE CRITERIA MANUAL

widening, or other improvements/maintenance. For this reason, in all channels within the City no utilities are allowed between the top of banks except for crossings which must be a minimum of 3-feet deep. Furthermore, no utilities are allowed between the maintenance road's stable surface and top of bank. By implementing these proximity requirements between open channels and utilities the City hopes to prevent costly conflicts between open channels and utilities in the future.

### 2.3. Choice of Channel Type and Alignment

#### 2.3.1. Types of Channels for Major Drainageways

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

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

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

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

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

Riprap-Lined Channels (and use of TRMs)—Riprap-lined channels offer a compromise between grass-lined channels and concrete-lined channels. Riprap-lined channels can somewhat reduce right-of-way needs relative to grass-lined channels and can handle higher velocities and greater depths than grass-lined channels. Relative to concrete-lined channels, velocities in riprap-lined channels are generally not

as high. Riprap-lined channels are more difficult to keep clean and maintain than other types of channels and are recommended for consideration only in retrofit situations where existing urban flooding problems are being addressed. The use of this channel type is discouraged and subject to City approval. A more desirable alternative to the use of riprap would be substituting turf reinforcement mats (TRMs) in place of riprap. This method is encouraged by the City when the use of such TRMs would adhere to the manufacturers recommended application. Refer to the EPA's *Storm Water Technology Fact Sheet – Turf Reinforcement Mats* document (<http://www.epa.gov/> – EPA 832-F-99-002) for more information concerning the employment of TRMs.

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

### **2.3.2. Factors to Consider in Selection of Channel Type and Alignment**

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

#### Hydraulic Considerations

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

#### Structural Considerations

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

#### Environmental Considerations

- Neighborhood character
- Neighborhood aesthetic requirements
- Street and traffic patterns
- Municipal or county policies
- Need for new green areas
- Wetland mitigation

## DRAINAGE CRITERIA MANUAL

- Character of existing channel
- Wildlife habitat
- Water quality enhancement

### Sociological Considerations

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

### Maintenance Considerations

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

### **2.3.3. Environmental Permitting Issues**

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

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

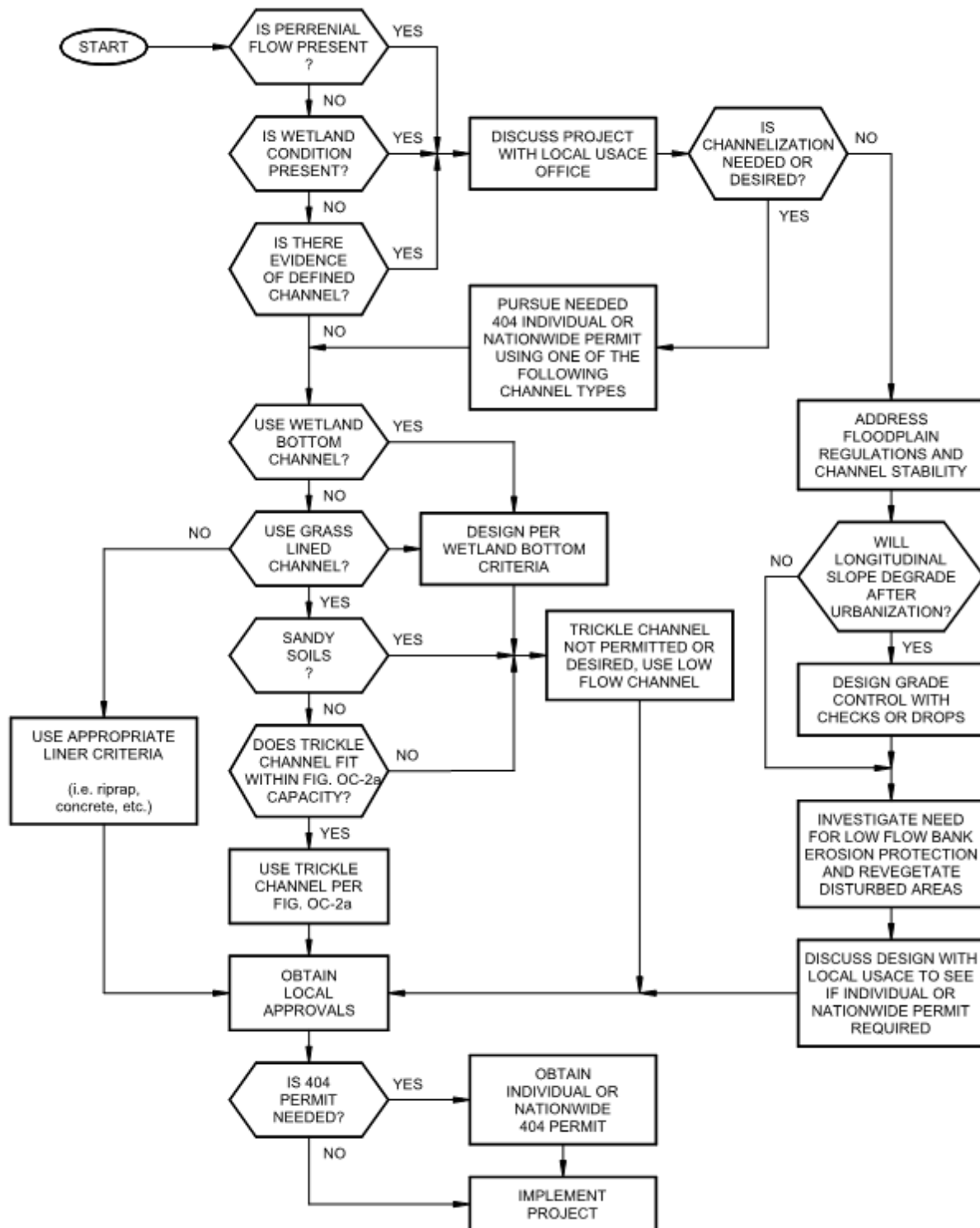
If the decision is to neither channelize nor re-channelize an existing drainageway, investigate the stability of the natural drainageway and its banks, design measures to stabilize the longitudinal grade and banks, if needed in selected areas, and obtain, if necessary, Section 404 permits and other approvals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

If the decision is to channelize, then determine whether the existing natural drainageway has a perennial flow, evidence of wetland vegetation, or is a well-established intermittent channel. This will often require

the assistance of a biologist with wetland training. If any of these conditions exist, then the project is likely to be subject to individual or nationwide Section 404 permitting requirements. Regardless, it is suggested the designer check with the local USACE office early to determine which permit will be needed. Keep in mind that it is the responsibility of the proponent to comply with all applicable federal and state laws and regulations. Approvals by the local authorities do not supersede or waive compliance with these federal laws.

# DRAINAGE CRITERIA MANUAL

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



#### **2.3.4. Maintenance**

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

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

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

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

### **2.4. Design Flows**

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

- Primary Channel – 100-year design storm with  $\geq 2$ -foot of freeboard
- Secondary Channel – 100-year design storm with  $\geq 1$ -foot of freeboard
- Tertiary Channel – 10-year design storm and pass 100-year design storm between structures

Furthermore, open channels, including residual floodplain, must be able to convey the flow from a fully urbanized watershed, assuming no upstream detention, for the event with a 100-year recurrence interval without significant damage to the system. In addition to the capacity consideration of the 100-year event, the designer must also consider events of lesser magnitudes. For the low-flow channel in any type, 5-year

## DRAINAGE CRITERIA MANUAL

storm peak discharge for fully developed conditions, assuming no upstream detention, is to be used for its design. Base flow must also be assessed, especially for grassed channels, channels with wetland bottoms, and bioengineered channels. Base flows are best estimated by examining already-urbanized watersheds that are similar to the planned urban area in terms of imperviousness, land use, and hydrology.

### **2.5. Maintenance Classification – Primary Channels, Secondary Channels, and Tertiary Channels**

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

Being that open channels provide a benefit to a number of different users the City has established certain physical and operational criteria that designate channels within the city limits as either primary, secondary, or tertiary. The definitions below along with [Table OC-7a](#) describe the use, maintenance/repair responsibilities, and designation criteria of each of the channels.

- Primary Channel – a major open channel that serves as a primary waterway to conduct runoff generated in a large composite area (typically  $\geq 30$ -acres). More so, any channel that has a flood zone (floodway, floodplain, etc.) as determined/studied by the City and/or FEMA is to be considered a primary channel. Runoff conducted by primary channels is collected in the channel from discharges of a watershed, closed storm sewer systems, secondary and tertiary channels, and from the convergence of other primary channels. These types of channels are to be maintained by the City, POA, developer of the subdivision or other responsible entity for a development and shall be placed in a Drainage and Recreation Easement. Designate extent of 100-year water surface elevation on grading plan and as a Drainage and Recreation Easement.
- Secondary Channel – a moderate open channel that collects runoff from storm sewer systems, tertiary and other secondary channels, and feeds the runoff into primary channels. Drainage areas for secondary channels typically range from  $\geq 2$ -acres and  $\leq 30$ -acres. These types of channels are to be maintained by a POA, developer of the subdivision, or other responsible entity for a development and shall be placed in a Drainage and Recreation Easement. Designate extents of 100-year water surface elevation on grading plan and as a Drainage and Recreation Easement.
- Tertiary Channel – a small minor channel that serves as a conduit to channel runoff (typically  $\leq 2$ -acres). These types of channels are to be maintained by the owners of the property which the channel serves. Maintenance responsibilities for the property owner end at the furthest point

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

**Table OC-7a – Open Channel Maintenance Classification Physical Criteria<sup>5</sup>**

<b>Channel Designation</b>	<b>Maintenance/Repair Responsibility Assigned to ...</b>	<b>Channel Criteria for Design Event</b>
Primary	City, POA, developer	≥ 2-foot flow depth <sup>1</sup> & ≥ 10-foot bottom width <sup>1</sup>
Secondary	POA, developer	≥ 1-foot flow depth <sup>2</sup> & ≥ 5-foot bottom width <sup>2</sup> or ≥ 1.5-foot flow depth <sup>3</sup> & ≥ 10-foot top width of flow <sup>3</sup>
Tertiary	Property owner / homeowner	≤ 1-foot flow depth <sup>4</sup> or ≤ 10-foot top width of flow <sup>4</sup>

- 1 – Channel criteria based on a trapezoidal ditch, 3:1 side slopes, 10-foot bottom width, 0.50% longitudinal slope,  $n=0.040$ , 10-min  $T_c$  with intensity from 10-yr. design storm, 30-acre drainage area.
- 2 – Channel criteria based on a trapezoidal ditch, 3:1 side slopes, 5-foot bottom width, 0.50% longitudinal slope,  $n=0.040$ , 10-min  $T_c$  with intensity from 10-yr. design storm, 4-acre drainage area.
- 3 – Channel criteria based on a typical v-bottom ditch, 3:1 side slopes, 0.50% longitudinal slope,  $n=0.040$ , 10-min  $T_c$  with intensity from 10-yr. design storm, 4-acre drainage area.
- 4 – Channel criteria based on a typical v-bottom ditch, 5:1 side slopes, 0.50% longitudinal slope,  $n=0.040$ , 10-min  $T_c$  with intensity from 10-yr. design storm, 4-acre drainage area.
- 5 – The criterion presented in [Table OC-7a](#) does not address every kind of channel type possible within the City. Instead the listed criteria provide an approximate basis from which to evaluate the maintenance classification of a channel that is either under design or already in use. The City will make the final determination of channel classification.

Backwater analysis computer modeling software, such as HEC-RAS, shall be used to design/analyze primary channels while channel design spreadsheets associated with this *Manual* shall be used in the design of tertiary and secondary channels, though the city may require a backwater analysis for some secondary channels.

### **3. OPEN-CHANNEL DESIGN CRITERIA**

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

## DRAINAGE CRITERIA MANUAL

### 3.1. Grass-Lined Channels

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

#### 3.1.1. Design Criteria

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

##### 3.1.1.1. Design Velocity and Froude number

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

##### 3.1.1.2. Design Depths

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

##### 3.1.1.3. Design Slopes

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

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

##### 3.1.1.4. Curvature

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

### 3.1.1.5. Design Discharge Freeboard

Bridge deck bottoms and sanitary sewers (culvert tops, etc.) often control the freeboard along the channel in urban areas. Where such constraints do not control the freeboard, the allowance for freeboard shall be determined by the conditions adjacent to the channel. For instance, localized overflow in certain areas may be acceptable and may provide flow storage benefits. In general, a minimum freeboard of 1-foot (or 2-foot if directed by the City) shall be allowed between the water surface and top of bank. Along major streams such as Osage Creek, Turtle Creek, Prairie Creek, Blossom Way Creek, and others where potential for downed trees and other debris exists during a flood, a 2-foot freeboard is required for the 100-year design flow.

For curves in the channel, superelevation shall be evaluated using [Equation OC-9](#) in [Section 2.2.4](#) and shall be included in addition to freeboard.

### 3.1.2. Channel Cross Sections

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

#### 3.1.2.1. Bottom Width

The bottom width should be designed to satisfy the hydraulic capacity of the cross section recognizing the limitations on velocity, depth, and Froude number. For a given discharge, the bottom width can be calculated using the depth, velocity, and Froude number constraints in [Section 3.1.1.1](#) and [Section 3.1.1.2](#) using [Equation OC-2](#) from [Section 2.1.1](#) of this chapter. In no case shall the bottom of the channel be any less than 5-feet wide.

#### 3.1.2.2. Trickle and Low-Flow Channels

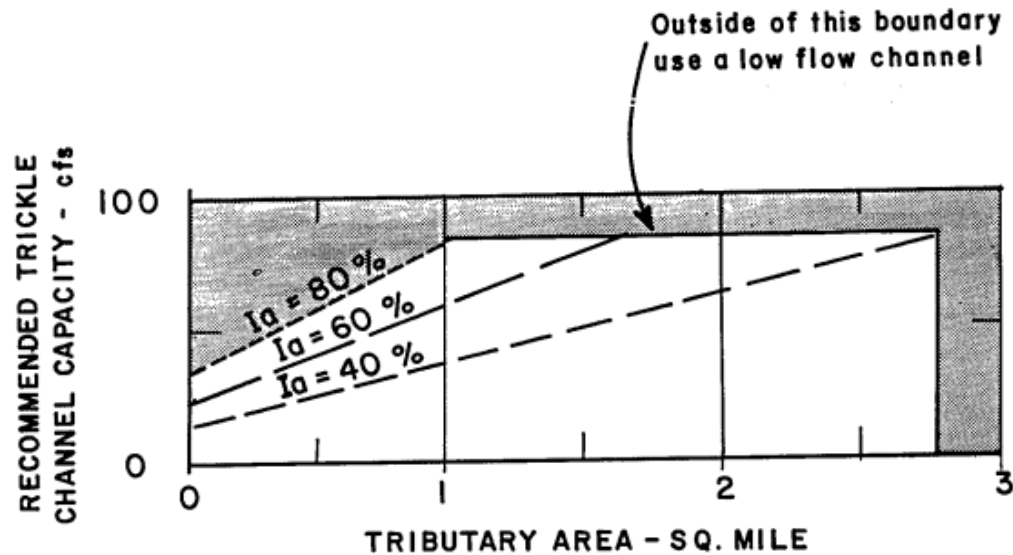
When base flow is present or is anticipated as the drainage area develops, a trickle or low-flow channel is required. Steady base flow will affect the growth of grass in the bottom of the channel, create maintenance needs, and can cause erosion. The purpose of a trickle channel is to convey very small perennial flows in a localized section of the overall channel to prevent adverse maintenance and erosion conditions. A trickle channel is a defined (typically narrow) longitudinal channel located at the thalweg of the overall prime channel and is used to transport steady base flows, typically  $\leq 1$ -ft. Steady base flows that would be typical of a trickle channel to convey would be runoff from lawn irrigation, groundwater inflow into the channel, etc. [Figure OC-2a](#) should be used to estimate the required capacity of a trickle channel based on the percent of impervious area,  $I_a$ .

A low-flow channel on the other hand serves two essential purposes. One purpose of a low-flow channel would be that of a trickle channel just on a larger scale. Should a channel have a steady base flow that exceeds the limits set forth in [Figure OC-2a](#) for channel capacity for a specific impervious area,  $I_a$ , a low-flow channel having stabilized banks must be used in place of a trickle channel. Secondly, a low-flow

## DRAINAGE CRITERIA MANUAL

channel is designed to carry stormwater runoff conveyed in the channel during smaller and more common design storm events. A low-flow channel is designed to flow full at a depth  $\leq 5$ -ft. More specific sizing and design criteria for low-flow/trickle channels are presented in [Section 3.1.4](#) of this chapter.

Figure OC-2a – Minimum Capacity Requirements for Trickle Channel (UDFCD USDCM 2002)



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

### 3.1.2.3. Outfalls Into Channel

Outfalls into grass-lined, major channels shall be at least 1-foot above the channel invert with adequate erosion protection provided at the outlet.

### 3.1.3. Roughness Coefficients

Designers shall use 0.040 and 0.030 for Manning's roughness coefficients,  $n$ , for grass-lined channels when checking design channel capacity (flow depth) and design maximum velocity (channel stability), respectively. In addition to these two set Manning's  $n$ , the designer is allowed to determine project specific roughness coefficients for grass-lined channels. Project specific roughness coefficients for grass-lined channels shall be determined based upon the product of the velocity and the hydraulic radius for different vegetative retardance classes (see [Figure OC-3](#)). When using the retardance curves for grass-lined channels, use Retardance C for finding Manning's  $n$  for determining channel capacity (depth) in a mature channel and Retardance D for finding the controlling velocity in a newly constructed channel to determine stability. The designer is referenced to *SCS Technical Paper No. 61 – Handbook of Channel Design for Soil and Water Conservation* and FHWA's *Hydraulic Engineering Circular No. 15, 3<sup>rd</sup> Edition (HEC-15 2005)* for additional information concerning the background and development of the retardance curves in [Figure OC-3](#).

### 3.1.4. Trickle and Low-Flow Channels

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

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

Steady base and/or low flows must be carried in a trickle channel or a low-flow channel. Trickle channels are to be used to pass constant base flows from groundwater or the return flow from irrigation or other constant sources of water runoff. The capacity of a trickle channel shall be 2.0% of the major (100-year storm) design flow for the fully developed condition assuming no upstream detention. Low-flow channels shall be used for larger major drainageways, streams, and rivers and for channels located on sandy soils. A low-flow channel shall have a minimum capacity of passing the 5-year storm peak flow under the fully developed watershed conditions, assuming no upstream detention. To the extent practicable, a low-flow channel shall be gently sloped and shallow to promote flow through the channel's vegetation. See [Figure OC-5](#) and [Figure OC-6](#) for typical details of grass-lined channels with trickle and low-flow channels.

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

**Figure OC-3 – Manning's  $n$  vs.  $V/R$  for Two Retardances in Grass-Lined Channels (taken from SCS-TP-61 Rev. 1954)**

DRAINAGE CRITERIA MANUAL

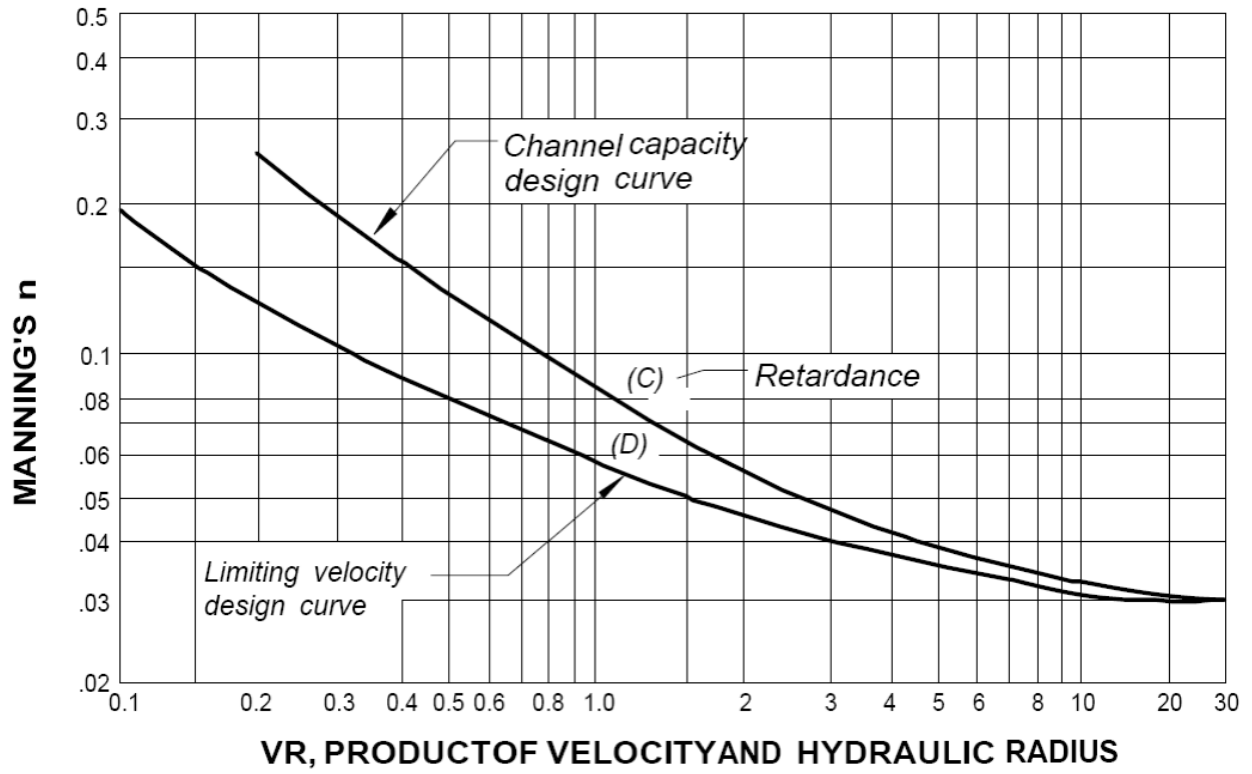
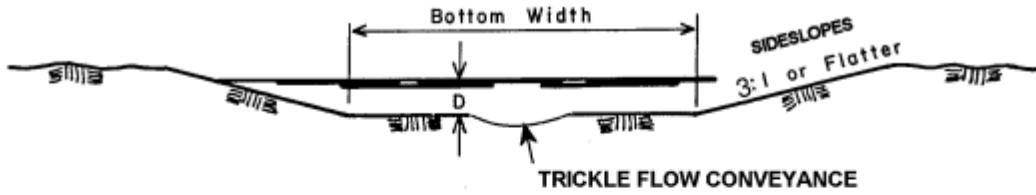
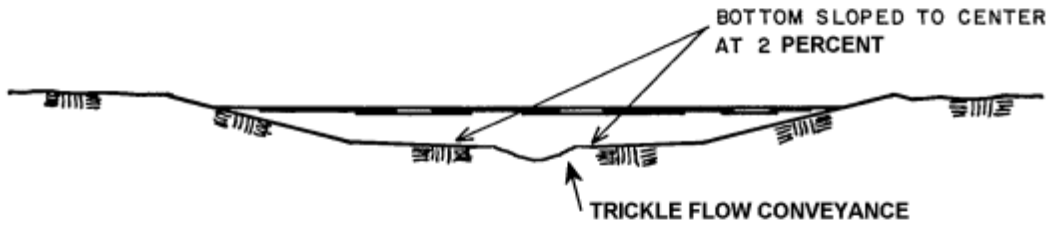


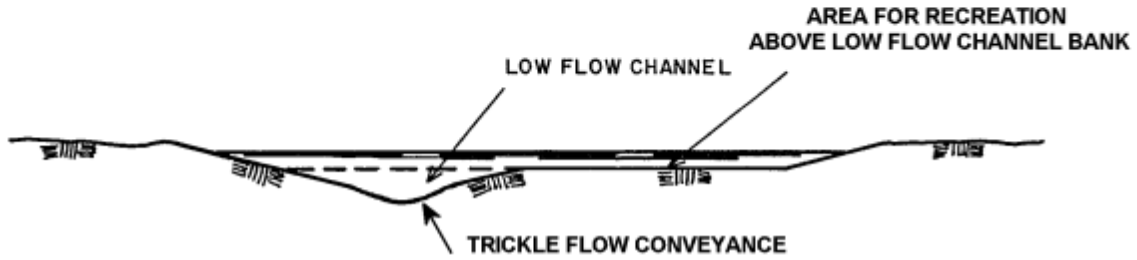
Figure OC-4 – Typical Grassed Channels (IDFCD USDCM 2002)



CROSS SECTION WITH OVAL OR SLOPED BOTTOM WITH TRICKLE CHANNEL



CROSS SECTION WITH OVAL OR SLOPED BOTTOM WITH TRICKLE CHANNEL



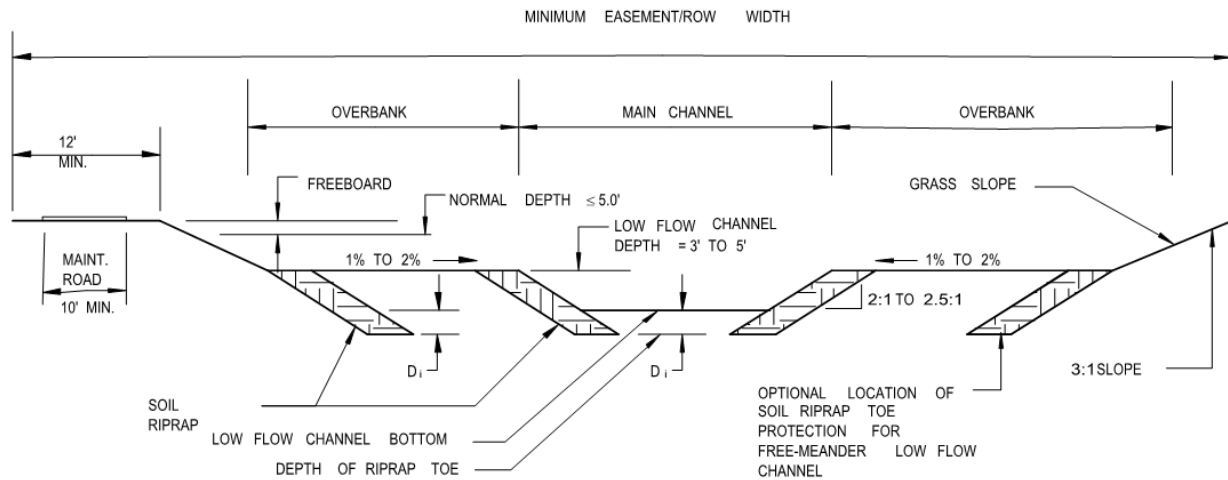
CROSS SECTION WITH LOW FLOW CHANNEL WITH TRICKLE CHANNEL  
AREA FOR MAJOR DRAINAGE RUNOFF



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

# DRAINAGE CRITERIA MANUAL

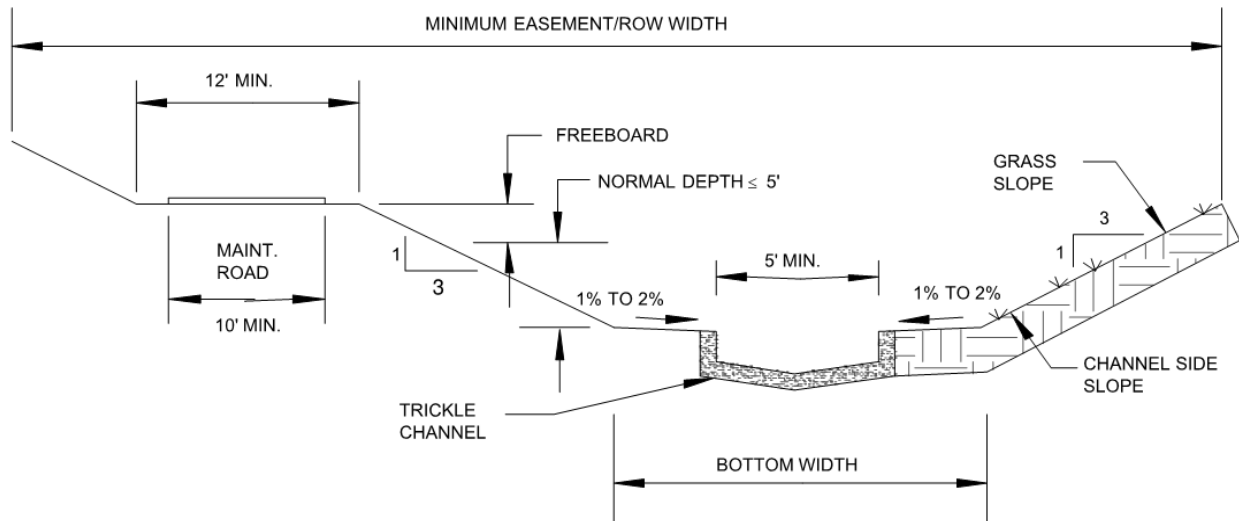
**Figure OC-5 – Composite Grass-lined Channel with a Low-Flow Channel, including a Wetland Bottom Low-Flow Channel (UDFCD USDCM 2002)**



## NOTE:

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

**Figure OC-6 – Grass-lined Channel with a Trickle Channel (UDFCD USDCM 2002)**



**NOTE:**

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

**3.1.5. Erosion Control**

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

## DRAINAGE CRITERIA MANUAL

### 3.1.5.1. Erosion at Bends

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

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

(Equation OC-10)

in which:

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

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

$r_c$  = channel centerline radius (ft)

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

TRMs or riprap shall be applied to the outside  $\frac{1}{4}$  of the channel bottom and to the channel side slope for the entire length of the bend plus a distance of  $1 \cdot T$  upstream and  $2 \cdot T$  downstream of the bend. When using riprap, as an alternative to lining the channel bottom, extend the riprap liner at the channel side slope to 5-feet below the channel's bottom.

### 3.1.5.2. Riprap Lining of Grass-lined Channels

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

### 3.1.6. Water Surface Profile

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

ensure against errors. Worksheets (**D-Step** and **S-Step**) are available in the **RDM-Channels** spreadsheet for calculating water surface profiles in channels using Direct Step and Standard Step Methods.

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

### **3.1.7. Maintenance**

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

### **3.1.8. Calculation Tool**

Calculations for sizing of a grass-lined channel using hydraulic equations from [Section 2.0](#) and criteria from [Section 3.1](#) can be performed using the **Channel Design** and/or **SCS Retardance** worksheet of the **RDM-Channels** spreadsheet. The **Composite Design** worksheet of the **RDM-Channels** spreadsheet can be used for the design of a grass-lined channel with a low-flow channel.

## **3.2. Composite Channels**

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

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

## DRAINAGE CRITERIA MANUAL

### 3.2.1. Design Criteria

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

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

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

### 3.2.2. Design Procedure

If a composite channel is to be used, the designer shall utilize the **Composite Design** worksheet of the **RDM-Channels** spreadsheet. The following steps outline the specific design procedures necessary:

1. Design Discharge – Determine the 2-year peak flow rate in the wetland channel without reducing it for any upstream ponding or flood routing effects.
2. Channel Geometry – Define the newly-built channel's geometry to pass the design 2-year flow rate at  $\leq 4$ -ft/sec with a channel depth between 2- to 4-feet. The channel cross section should be trapezoidal with side slopes of 3:1 (H/V) or flatter. Bottom width shall be  $\geq 5$ -feet.
3. Longitudinal Slope – Set the longitudinal slope using Manning's equation and a Manning's roughness coefficient of  $n=0.035$ , for the 2-year flow rate but no flatter than 0.0025 ft/ft. If the

desired longitudinal slope cannot be satisfied with existing terrain, grade control checks or small drop structures must be incorporated to provide desired slope.

4. Low-flow Channel Capacity – Calculate the mature channel capacity during a 2-year flood using a Manning’s roughness coefficient of  $n=0.065$  and the same geometry and slope used when initially designing the channel with  $n=0.035$ .
5. Full-width Channel Capacity – After the low-flow channel has been designed to pass the 2-year storm peak discharge, complete the composite channel design by providing additional channel capacity through design/analysis of channel overbank areas. The final Manning’s  $n$  for the composite channel shall be determined using [Equation OC-11](#). Use [Table OC-7](#) for Manning’s  $n$  values for the middle area (low-flow), left overbank, and right overbank areas of a composite channel.

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

In which:

$n_C$  = Manning’s  $n$  for the composite channel

$n_L$  = Manning’s  $n$  for the left overbank (...if grass-lined see [Table OC-8](#))

$n_R$  = Manning’s  $n$  for the right overbank (...if grass-lined see [Table OC-8](#))

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

when,  $2\text{-ft} \leq y_0 < 5\text{-ft}$ ,  $n_M = 0.0018 * y_0^2 - 0.0206 * y_0 + 0.099$  **(Equation OC-11a)**

or  $5\text{-ft} \leq y_0 < 10\text{-ft}$ ,  $n_M = 0.0001 * y_0^2 - 0.0025 * y_0 + 0.050$  **(Equation OC-11b)**  
 where,  $y_0$  = depth of flow

$P_L$  = Wetted perimeter of the left overbank (ft)

$P_R$  = Wetted perimeter of the right overbank (ft)

$P_M$  = Wetted perimeter of the middle area (ft)

$R_L$  = Hydraulic radius of the left overbank (ft)

## DRAINAGE CRITERIA MANUAL

$R$  = Hydraulic radius of the right overbank (ft)

$R_M$  = Hydraulic radius of the middle area (ft)

**Table OC-8 – Values for Manning's  $n$  in Grass-lined Overflow Bank Areas in Composite Channel (Guo 2006)**

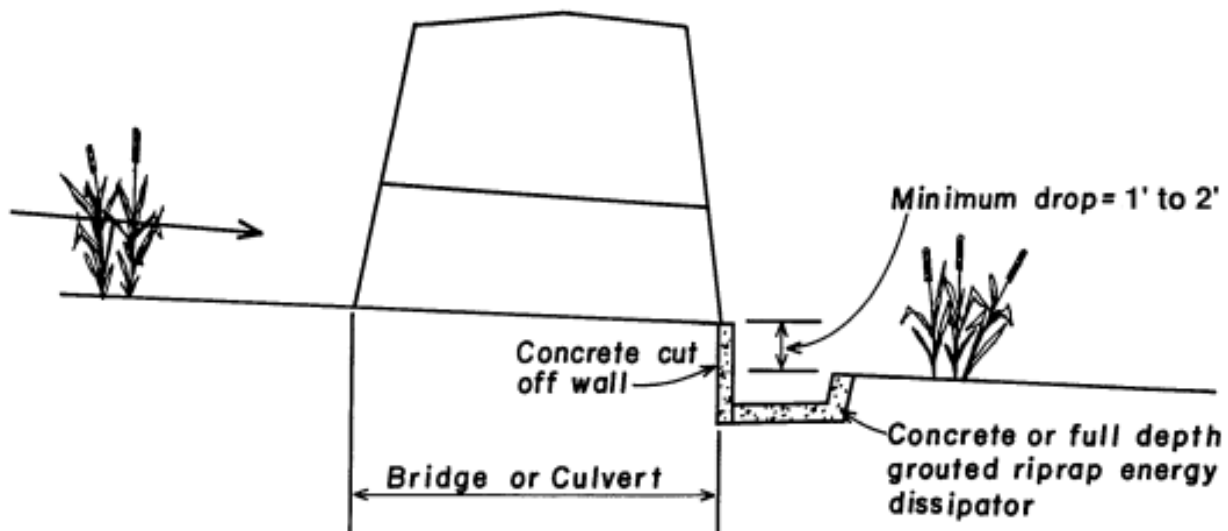
Grass Type	Grass Length	0.1 ft <Depth<1.5 ft	Depth>3.0 ft
		For Minor Runoff	For Major Runoff
Bermuda	2-inch	0.0350	0.0300
	4-inch	0.0400	0.0300
Kentucky	2-inch	0.0350	0.0300
	4-inch	0.0400	0.0300
Grass (Good Stand)	12-inch	0.0700	0.0350
	24-inch	0.1000	0.0350
Grass (Fair Stand)	12-inch	0.0600	0.0350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

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

### 3.2.3. Water Surface Profile

Whenever a composite bottom channel is crossed by a road, railroad, or a trail requiring a culvert or a bridge, a drop structure shall be provided immediately downstream of such a crossing. This will help reduce sediment deposition in the crossing. A minimum 1-foot to 2-foot drop is required (a larger drop may be preferred in larger systems) on the downstream side of each culvert and crossing of a wetland bottom channel (see [Figure OC-7](#)).

**Figure OC-7 – Composite Channel At Bridge or Culvert Crossing (UDFCD USDCM 2002)**



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

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

### 3.2.4. Life Expectancy and Maintenance

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

## DRAINAGE CRITERIA MANUAL

### 3.2.5. Calculation Tool

Calculations for sizing of a composite channel using hydraulic equations from [Section 2.0](#) and criteria from [Section 3.2](#) can be performed using the **Composite Design** worksheet of the **RDM-Channels** spreadsheet.

### 3.3. Concrete-Lined Channels

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

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

#### 3.3.1. Design Criteria

##### 3.3.1.1. Design Velocity and Froude Number

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

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

**Table OC-9 – Manning's  $n$  Roughness Coefficients for Concrete-Lined Channels (UDFCD USDCM 2002)**

Type of Concrete Finish	Roughness Coefficient ( $n$ )		
	Minimum	Typical	Maximum

<u>Concrete</u>			
Trowel finish*	0.011	0.013	0.015
Float finish*	0.013	0.015	0.016
Finished, with gravel on bottom*	0.015	0.017	0.020
Unfinished*	0.014	0.017	0.020
Shotcrete, trowelled, not wavy	0.016	0.018	0.023
Shotcrete, trowelled, wavy	0.018	0.020	0.025
Shotcrete, unfinished	0.020	0.022	0.027
On good excavated rock	0.017	0.020	0.023
On irregular excavated rock	0.022	0.027	0.030

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

### 3.3.1.2. Design Depths

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

### 3.3.1.3. Curvature

Curvature is not allowed for channels with supercritical flow regimes. For concrete-lined channels with subcritical flow regimes, the centerline radius of curvature shall be at least two-times (2x) the top width, and superelevation shall be evaluated for all bends using [Equation OC-9](#) in [Section 2.2.4](#) and included in determining freeboard.

### 3.3.1.4. Design Discharge Freeboard

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

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

in which:

$H_{fb}$  = Freeboard height (ft)

$V$  = Velocity of flow (ft/sec)

$y_o$  = Depth of flow (ft)

$\Delta y$  = Increase in water surface elevation due to superelevation at bends (see [Equation OC-9](#)) (no bends allowed in supercritical channels)

In addition to  $H_{fb}$ , add height of estimated standing roll waves and/or other water surface disturbances to calculate the total freeboard. In all cases, the freeboard shall be no less than 2 feet and the concrete lining shall be extended above the flow depth to provide the required freeboard. The **Steep Channel** worksheet of the **RDM-Channels** spreadsheet can be used to calculate standing roll wave heights.

## DRAINAGE CRITERIA MANUAL

### 3.3.2. Concrete Lining Specifications

#### 3.3.2.1. Concrete Lining Section

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

#### 3.3.2.2. Concrete Joints and Reinforcement

Concrete joints must satisfy the following criteria:

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

#### 3.3.2.3. Concrete Finish

The surface of the concrete lining may be finished in any of the finishes listed in [Table OC-9](#), provided an appropriate finishing technique is used.

#### **3.3.2.4. Weep Holes**

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

#### **3.3.3. Channel Cross Section**

##### **3.3.3.1. Side Slopes**

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

##### **3.3.3.2. Depth**

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

##### **3.3.3.3. Bottom Width**

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

##### **3.3.3.4. Trickle and Low-Flow Channels**

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

##### **3.3.3.5. Outfalls Into Channel**

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

#### **3.3.4. Safety Requirements**

A 6-foot-high chain-link or comparable fence or handrail shall be installed to prevent access wherever the 100-year channel concrete section depth exceeds 3 feet. Appropriate numbers of gates, with top latch, shall be placed and staggered where a fence is required on both sides of the channel to permit good maintenance access.

## DRAINAGE CRITERIA MANUAL

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

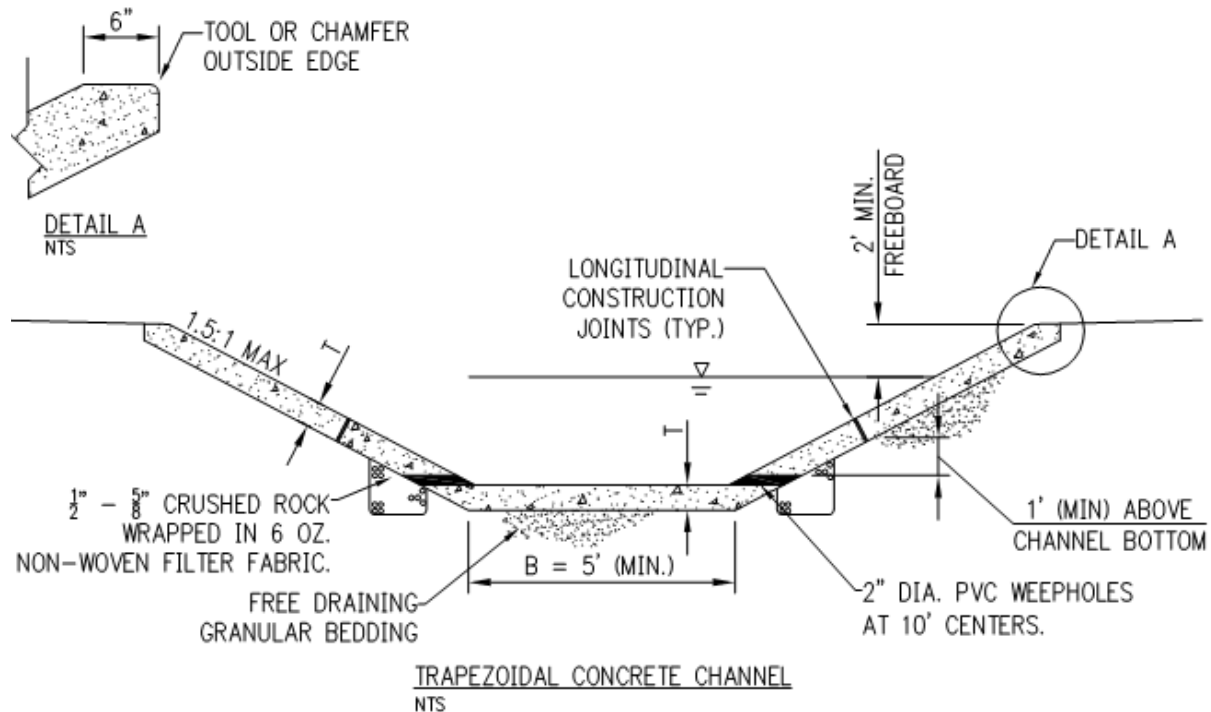
### 3.3.5. Calculation Tools

Calculations for sizing of a concrete-lined channel using hydraulic equations from [Section 2.0](#) and criteria from [Section 3.3](#) can be performed using the **Basics** worksheet of *RDM-Channels* spreadsheet.

### 3.3.6. Maintenance

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

**Figure OC-8 – Concrete Lined Channel (Trapezoidal)**



**NOTES:**

1.  $Fr \leq 0.7$ ,  $T = 5"$  REINFORCE WITH 6X6-8/8 WWM INSTALLED 2" FROM THE BOTTOM OF THE SLAB; AND PROVIDE 6-INCH (MIN.) FREE DRAINING GRANULAR BEDDING UNDER CONCRETE SECTION.
  
- $Fr \geq 14$ ,  $T = 8"$  REINFORCE WITH #4'S @ 12" TRANSVERSE INSTALLED 2" FROM THE BOTTOM OF THE SLAB, #4'S @ 18" LONGITUDINAL; AND PROVIDE 9-INCH (MIN) FREE DRAINING GRANULAR BEDDING UNDER CONCRETE SECTION.
  
2. CONCRETE WORK SHALL CONFORM TO THE REQUIREMENTS OF THE CITY OF ROGERS TECHNICAL SPECIFICATIONS FOR PUBLIC WORKS CONSTRUCTION.
  
3. INSTALL EXPANSION JOINTS AT 50' (MIN.) SPACING NOT TO EXCEED 75' (MAX) AND SAW JOINTS AT 10' SPACING MAXIMUM ON ALL DITCH SECTIONS. ALL SAW JOINTS ARE TO HAVE BACKER ROD & CAULKING PROPERLY INSTALLED PER MANUFACTURE'S SPECIFICATIONS.

### 3.4. Riprap-Lined Channels

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

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

## DRAINAGE CRITERIA MANUAL

4. Where rapid changes in channel geometry occur such as channel bends and transitions.

Design criteria applicable to these situations are presented in this section. Riprap-lined channels shall only be used for subcritical flow conditions where the Froude number is 0.8 or less. Loose stones serving as a protective blanket will not be accepted for riprap lining. Instead riprap shall either receive a full grout matrix or be partially grouted. The type of grouting, full or partial, a riprap lining is to receive will be as directed by the City. The grout for riprap receiving a full grout matrix shall adhere to the methods and specifications outlined in [Table OC-12](#) of this *Manual*. Furthermore, requirements for riprap that is grouted that aren't covered in this *Manual* shall adhere to ARDOT's *Standard Specification for Highway Construction – Section 816 – Filter Blanket and Riprap for Dumped Riprap (Grouted)*. Partially grouted riprap shall be designed, specified, and constructed according to the criteria presented in FHWA's [HEC 23](#) (2001) and other trusted sources on the subject. Furthermore, when used, it is required that all riprap outside frequent flow zones have the voids filled with soil, the top of the rock covered with topsoil, and the surface revegetated with native grasses. This combination of riprap, soil, and vegetation is considered *soil riprap*.

### 3.4.1. Types of Riprap

#### 3.4.1.1. Riprap and Soil Riprap

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

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

Classification and gradation for riprap and boulders are given in [Table OC-10](#) and [Table OC-11](#) and are based on a minimum specific gravity of 2.50 for the rock. Because of its relatively small size and weight, riprap Types 1 and 2 must be used in soil riprap applications only. Type 3 riprap shall be used for all other riprap lining needs. This practice also protects the rock from vandalism.

Soil Riprap consists of 35% by volume of native soil, taken from the banks of the channel, that is mixed in with 65% by volume of riprap on-site, before placement as channel liner. A typical section for soil riprap installation is illustrated in [Figure OC-10](#).

**Table OC-10 – Classification and Gradation of Riprap**

Riprap Designation	$d_{50}$ (inches)*	Maximum Rock Size (inches)	...a gradation such that no more than 15% will be less than ____ (inches)
--------------------	--------------------	----------------------------	---

Type 1	6**	10	3
Type 2	12**	20	4
Type 3	18	28	6

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

\*\* Mix Type 1 and Type 2 riprap with 35% topsoil (by volume) and bury it with 4 inches of topsoil, all vibration compacted, and revegetate.

Note: Bedding material must be used under riprap. Bedding material shall consist of granular bedding as shown in [Table OC-14](#).

Basic requirements for riprap stone are as follows:

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

### 3.4.1.2. Grouted Boulders

[Table OC-11](#) provides the classification and size requirements for boulders. When grouted boulders are used, they provide a relatively impervious channel lining which is less subject to vandalism than riprap. Grouted boulders require less routine maintenance by reducing silt and trash accumulation and are particularly useful for lining low-flow channels and steep banks. The appearance of grouted boulders is enhanced by exposing the tops of individual stones and by cleaning the projecting rocks with a wet broom right after the grouting operation. In addition, it is required that grouted boulders on channel banks and outside of frequent flow areas be buried with topsoil and revegetated with native grasses, with or without shrubs depending on the local setting. Boulders used for grouting shall meet all the properties of rock for riprap, and rock of uniform size shall be used. The boulder sizes are categorized in [Table OC-8](#).

**Table OC-11 – Classification of Boulders (UDFCD USDCM 2002)**

Boulder Classification	Nominal Size and [Range in Smallest Dimension of Individual Rock Boulders] (inches)	Maximum Ratio of Largest to Smallest Rock Dimension of Individual Boulders
Type B18	18 [17 – 20]	2.5
Type B24	24 [22 – 26]	2.0

## DRAINAGE CRITERIA MANUAL

Type B30	30 [28 – 32]	2.0
Type B36	36 [34 – 38]	1.75
Type B42	42 [40 – 44]	1.65
Type B48	48 [45 – 51]	1.50

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

Two types of grout, Type A and Type B, are to be selected from for filling the voids for the grouted boulders. The technical specifications for two types of structural grout mix are given in [Table OC-12](#). Type A can be injected using a low-pressure grout pump and can be used for the majority of applications. Type B has been designed for use in streams and rivers with significant perennial flows where scouring of Type A grout is a concern. It requires a concrete pump for injection.

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

**Table OC-12 – Specifications and Placement Instructions for Grout in Grouted Riprap and Grouted Boulders (UDFCD USDCM 2002)**

<a href="#">Material Specifications</a>	<a href="#">Placement Specifications</a>
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<ol style="list-style-type: none"> <li>1. All grout shall have a minimum 28-day compressive strength equal to 3200 psi.</li> <li>2. One cubic yard of grout shall have a minimum of six (6) sacks of Type II Portland cement.</li> <li>3. A maximum of 25% Type F Fly Ash may be substituted for the Portland cement.</li> <li>4. For Type A grout, the aggregate shall be comprised of 70% natural sand (fines) and 30% 3/8-inch rock (coarse).</li> <li>5. For Type B grout, the aggregate shall be comprised of 3/4-inch maximum gravel structural concrete aggregate.</li> <li>6. Type B grout shall be used in streams with significant perennial flows.</li> <li>7. The grout slump shall be 4-inches to 6-inches.</li> <li>8. Air entrainment shall be 5.5%-7.5%.</li> <li>9. To control shrinkage and cracking, 1.5 pounds of Fibermesh, or equivalent, shall be used per cubic yard of grout.</li> <li>10. Color additive in required amounts shall be used when so specified by contract.</li> </ol>	<ol style="list-style-type: none"> <li>1. All Type A grout shall be delivered by means of a low pressure (less than 10 psi) grout pump using a 2-inch diameter nozzle.</li> <li>2. All Type B grout shall be delivered by means of a low pressure (less than 10 psi) concrete pump using a 3-inch diameter nozzle.</li> <li>3. Full depth penetration of the grout into the riprap/boulder voids shall be achieved by injecting grout starting with the nozzle near the bottom and raising it as grout fills, while vibrating grout into place using a pencil vibrator.</li> <li>4. After grout placement, exposed riprap/boulder faces shall be cleaned with a wet broom.</li> <li>5. All grout between riprap/boulders shall be treated with a broom finish.</li> <li>6. All finished grout surfaces shall be sprayed with a clear liquid membrane curing compound as specified in ASTM C-309.</li> <li>7. Special procedures shall be required for grout placement when the air temperatures are less than 40°F or greater than 90°F. Contractor shall obtain prior approval from the design engineer of the procedures to be used for protecting the grout.</li> <li>8. Clean Riprap/Boulders by brushing and washing before grouting.</li> </ol>
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**3.4.1.3. Wire-Enclosed Rock (Gabions)**

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

## DRAINAGE CRITERIA MANUAL

### 3.4.1.4. Alternatives to Riprap Lining/Structures

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

### 3.4.2. Design Criteria

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

#### 3.4.2.1. Design Velocity

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

#### 3.4.2.2. Design Depths

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

#### 3.4.2.3. Riprap Sizing

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

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

(Equation OC-13)

in which:

$V$  = Mean channel velocity (ft/sec)

$S$  = Longitudinal channel slope (ft/ft)

$d_{50}$  = Mean rock size (ft)

$G_s$  = Specific gravity of stone (minimum = 2.50, Preferred = 2.65)

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

[Table OC-13](#) shall be used to determine the minimum size of rock type required. Note that rock types for riprap, including gradation, are presented in [Table OC-10](#).

**Table OC-13 – Riprap Requirements for Channel Linings \* (UDFCD  
USDCM 2002 [modified for City of Rogers])**

$\frac{V * S^{0.17}}{(G_s - 1)^{0.66} **}$	Rock Type
< 3.3	Type 1** ( $d_{50} = \frac{1}{2}$ foot)
$\geq 3.3$ to < 4.6	Type 2 ( $d_{50} = 1$ foot)
$\geq 4.6$ to 5.6	Type 3 ( $d_{50} = 1\frac{1}{2}$ foot)

\* Applicable only for a Froude number of < 0.8 and side slopes no steeper than 2.5H:1V.

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

[Table OC-13](#) provides riprap requirements for all channel side slopes up to and including 2.5H:1V. Rock-lined side slopes steeper than 2.5H:1V are unacceptable under any circumstances because of stability, safety, and maintenance considerations. Proper bedding is required both along the side slopes and the channel bottom for a stable lining. The riprap blanket thickness shall be at a minimum two-times (2x)  $d_{50}$  and shall extend up the side slopes at least 1-foot above the design water surface. At the upstream and downstream termination of a riprap lining, the thickness shall be increased 50% for at least 3-feet to prevent undercutting.

Where the required riprap size from [Equation OC-13](#) exceeds those as defined in [Table OC-10](#) the design engineer shall look at adjusting the channels geometry and/or slope in order to satisfy the requirements of [Equation OC-13](#), review alternate channel linings, etc.

#### **3.4.2.4. Riprap Toes**

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

## DRAINAGE CRITERIA MANUAL

### 3.4.2.5. Curves and Bends

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

The minimum allowable radius for a riprap-lined bend is two-times (2x) the top width of the design flow water surface. The riprap protection shall be placed along the outside of the bank and shall be extended upstream and downstream from the bend a distance of not less than one-times (1x) and two-times (2x) the top width of the channel, respectively. Whenever an outside bend in a grass-lined channel needs protection, soil riprap, TRMs (e.g. ScourStop, ShoreMax, etc.), or other alternative shall be used, then covered with native topsoil and revegetated to provide a grassed-line channel appearance.

Where the mean channel velocity exceeds the allowable non-eroding velocity so that riprap protection is required for straight channel sections, increase the rock size using the adjusted flow velocity found using [Equation OC-10](#). Use the adjusted velocity in [Table OC-13](#) to select appropriate riprap size.

### 3.4.2.6. Transitions

Scour potential is amplified by turbulent eddies near rapid changes in channel geometry such as transitions and at structures (culverts, bridges, etc.). [Table OC-13](#) may be used for selecting riprap protection for subcritical transitions (Froude numbers 0.8 or less) by using the maximum velocity in the transition and then increasing the velocity by 25%.

Protection must extend upstream from the transition entrance at least 5 feet and downstream from the transition exit for a distance equal to at least five-times (5x) the design flow depth. This is not intended as culvert outlet protection, refer to Chapter 5 – Storm Sewer System Design.

### 3.4.2.7. Design Discharge Freeboard

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

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

### 3.4.3. Roughness Coefficient

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

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

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

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

### 3.4.4. Bedding Requirements

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

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

#### 3.4.4.1. Granular Bedding

The acceptable method for establishing gradation requirements for granular bedding for riprap consists of a single- or two-layer bedding that uses what are defined as Type I and Type II gradations. These gradations are shown in [Table OC-14](#).

**Table OC-14 – Gradation for Granular Bedding**

U.S. Standard Sieve Size	Percent Weight by Passing Square-Mesh Sieves	
	Type I ARDOT Sect. 501.02 Materials (b) Fine Aggregate	Type II ARDOT Sect. 303 Aggregate Base Course, Class 3
3 inches	----	90-100
1½ inches	----	----
¾ inches	----	60-90
⅜ inches	100	40-80
#4	95-100	30-60
#8	70-95	----
#10	----	20-45
#16	45-85	----
#30	20-65	----
#40	----	10-35
#50	5-30	----
#100	0-5	----
#200	----	3-12

## DRAINAGE CRITERIA MANUAL

The Type I bedding in [Table OC-14](#) is designed to be the lower layer in a two-layer filter for protecting fine-grained soils and has a gradation identical to ARDOT concrete fine aggregate specification AASHTO T 27 (ARDOT Section 501.02 (b)). Type II bedding, the upper layer in the two-layer filter, is equivalent to ARDOT's Class 3 aggregate base course specification AASHTO T 11 and T 27 (ARDOT Section 303). When the channel is excavated in coarse sand and gravel (50% or more of coarse sand and gravel retained on the #40 sieve by weight), only the Type II filter is required. Otherwise, a two-layer bedding (Type I topped by Type II) is required. Alternatively, a single 12-inch layer of Type II bedding can be used, except at drop structures. For required bedding thickness, see [Table OC-15](#).

**Table OC-15 – Granular Bedding Thickness Requirements (UDFCD USDCM 2002)**

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

- \* May substitute one 12-inch layer of Type II bedding. The substitution of one layer of Type II bedding shall not be permitted at drop structures. The use of a combination of filter fabric and Type II bedding at drop structures is acceptable.
- \*\* Fifty percent or more by weight retained on the # 40 sieve.

### 3.4.4.2. Filter Fabric

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

At drop structures and sloped channel drops, where seepage forces may run parallel to the fabric and cause piping along the bottom surface of the fabric, special care is required in the use of filter fabric. Seepage parallel with the fabric must be reduced by folding the edge of the fabric vertically downward about 2 feet (similar to a cutoff wall) at 12-foot intervals along the installation, particularly at the entrance

and exit of the channel reach. Filter fabric has to be lapped a minimum of 12 inches at roll edges, with upstream fabric being placed on top of downstream fabric at the lap.

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

### **3.4.5. Channel Cross Section**

#### **3.4.5.1. Side Slopes**

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

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

#### **3.4.5.2. Depth**

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

#### **3.4.5.3. Bottom Width**

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

#### **3.4.5.4. Outfalls Into Channel**

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

### **3.4.6. Erosion Control**

For a properly bedded and lined riprap channel section, in-channel erosion should not generally be a problem. As with concrete channels, the primary concern with erosion is control of erosion in the watershed tributary leading up to the channel. Good erosion control practices in the watershed will reduce

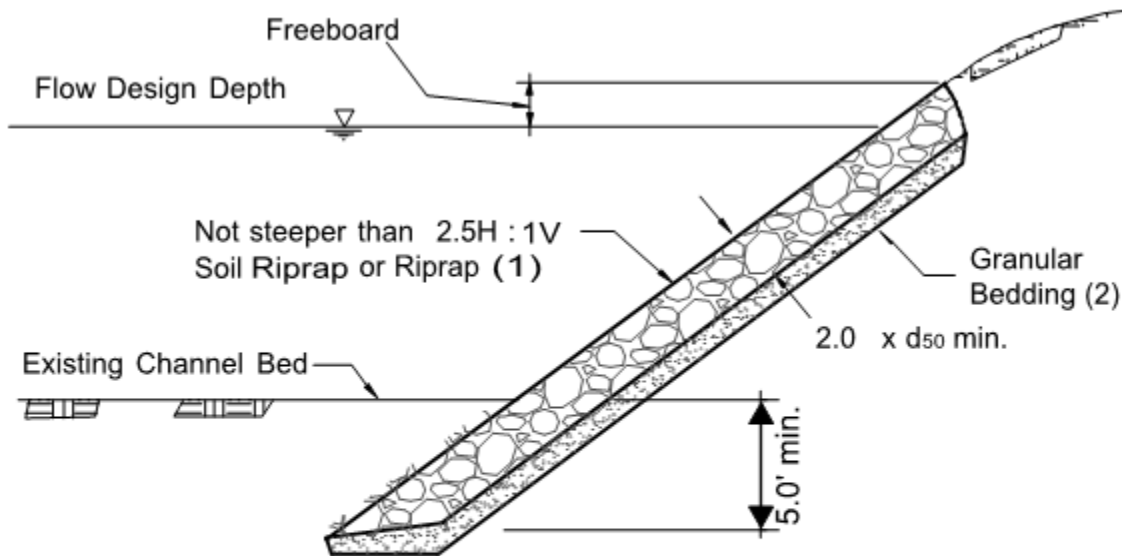
## DRAINAGE CRITERIA MANUAL

channel maintenance. In addition, accumulation of debris in the channel, especially after a large event, may be of concern due to the potential for movement of riprap and damming.

### **3.4.7. Maintenance**

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

Figure OC-9 – Riprap Channel Bank Lining, Including Toe Protection (UDFCD USDCM 2002)

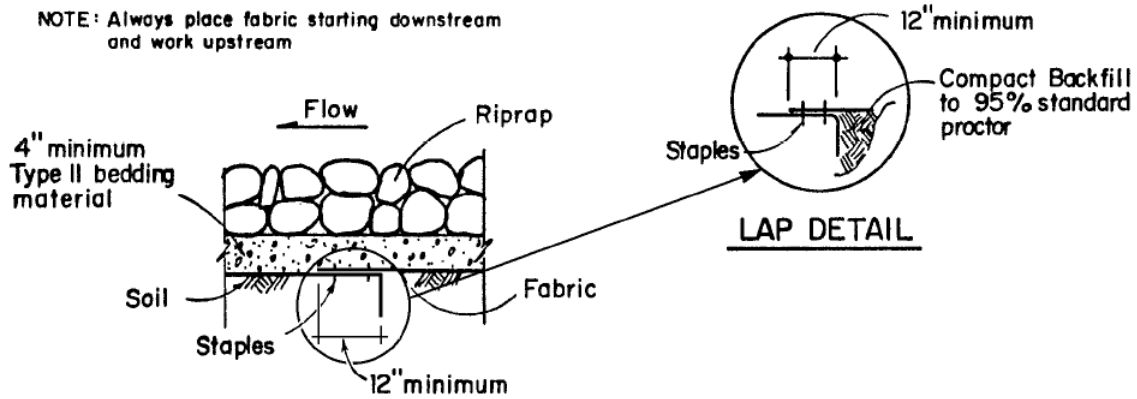


- (1) Use Soil Riprap when  $d_{50}$  is less than or equal to Type 1.  
(Suggest use of Soil Riprap for larger riprap sizes as well)
- (2) Eliminate granular bedding when soil-riprap is used.

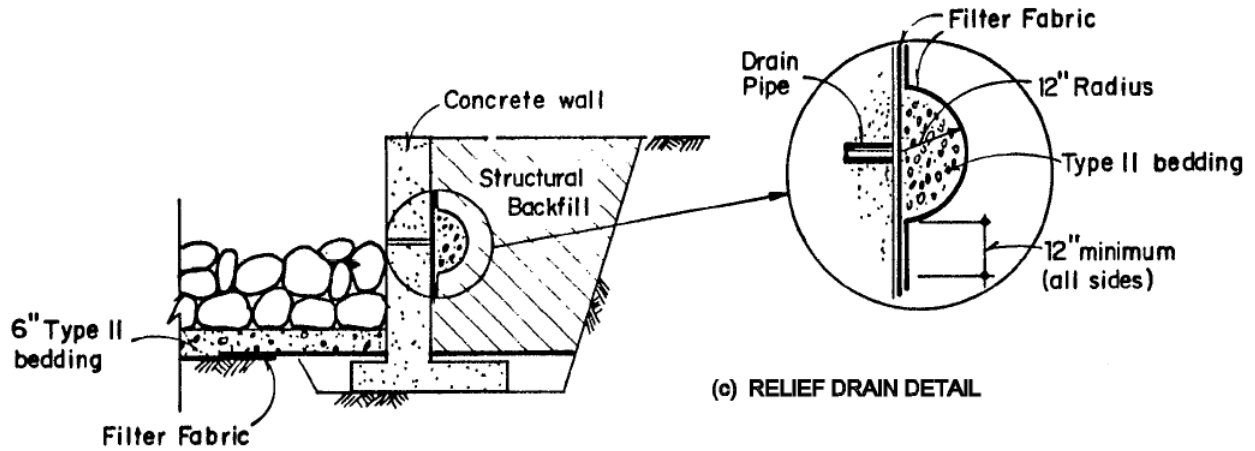
# DRAINAGE CRITERIA MANUAL

## Figure OC-10 – Filter Fabric Details (UDFCD USDCM 2002)

NOTE: Always place fabric starting downstream and work upstream

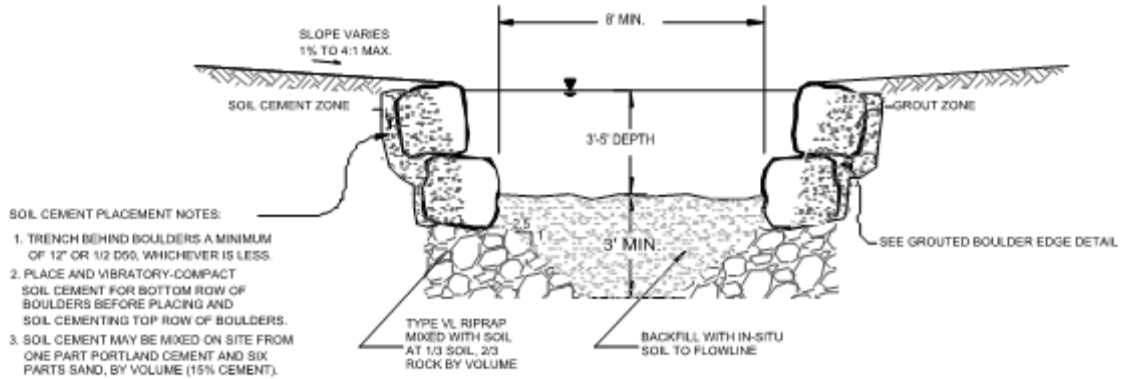


(a) TYPICAL LAP DETAIL AND FILTER FABRIC PLACEMENT

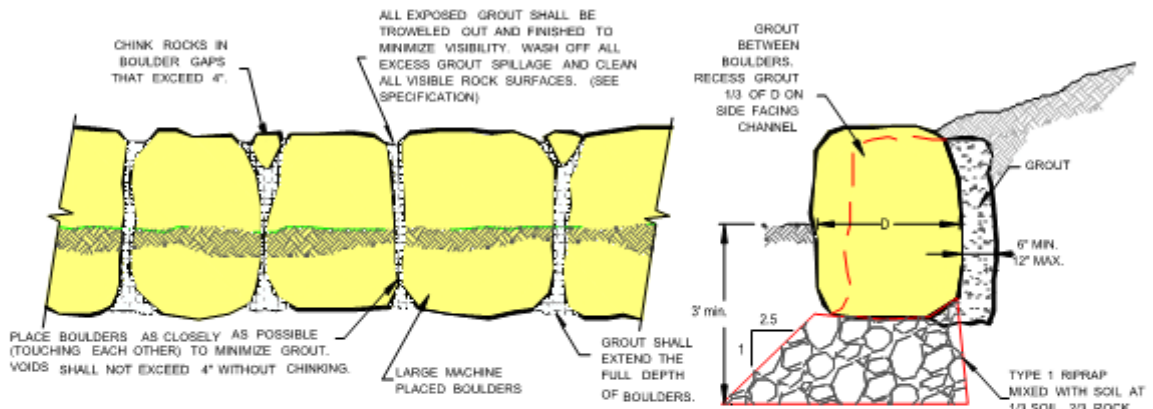


(c) RELIEF DRAIN DETAIL

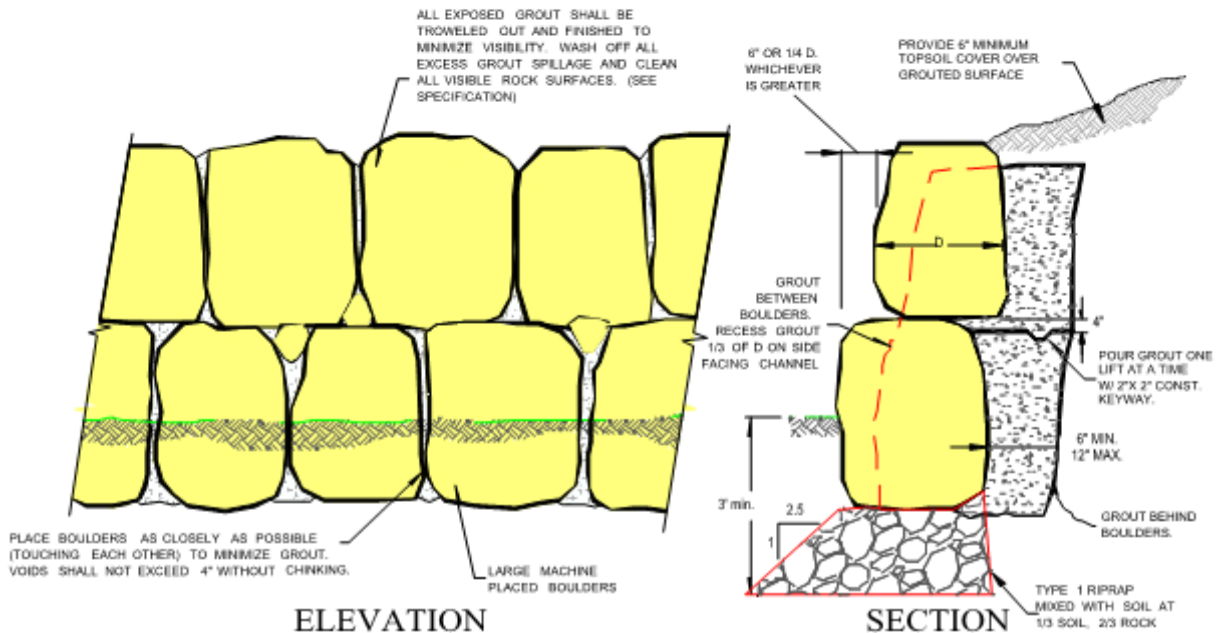
Figure OC-11 – Detail – Boulder Edged Low-Flow Channel (UDFCD USDCM 2002)



**BOULDER EDGED LOW FLOW CHANNEL CROSS-SECTION**



**GRouted BOULDER EDGE DETAIL**



**GRouted BOULDER STACKED WALL EDGE**

## DRAINAGE CRITERIA MANUAL

### 3.5. Bioengineered Channels

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

#### 3.5.1. Components

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

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

1. Planted riprap
2. Planted, grouted boulders
3. Turf reinforcement mats
4. Brush layering
5. Fiber rolls
6. Fascines

7. Live willow stakes (with and without joint plantings in soil filled rock)
8. Live plantings in conjunction with geotextile mats
9. Wide ranges of planting of wetland and upland vegetation
10. Wrapped soil lifts for slope stability

See Figure OC-11 through Figure OC-14 for more guidance.

### **3.5.2. Applications**

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

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

### **3.5.3. Bioengineering Resources**

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

### **3.5.4. Characteristics of Bioengineered Channels**

The following characteristics are generally associated with bioengineered channels:

1. Their design must address the hydrologic changes associated with urbanization (increased peak discharges, increased runoff volume, increased base flow, and increased bank-full frequency). These changes typically necessitate the use of grade control structures. In the absence of grade control structures purely bioengineered channels will normally be subject to bed and bank erosion, channel instability, and degradation.

## DRAINAGE CRITERIA MANUAL

2. In addition to grade controls, most bioengineered channels require some structural methods to assist the vegetation with maintaining channel stability. Examples include buried riprap at channel toes and at outer channel banks (see [Figure OC-12](#), [Figure OC-13](#) and [Figure OC-14](#)).
3. The designer must ensure that there will be sufficient flow in the channel (or from other sources, such as locally high groundwater) to support the vegetation. A complicating factor is that, in newly developing areas, base flows will *not* be present; whereas, if the tributary drainage area is large enough, base flows will often materialize after substantial urbanization has occurred. Therefore, it is important to match the channel stabilization technique to the water available at the time of construction, whether naturally or from supplemental water sources.
4. The extent to which vegetative techniques for channel stabilization will need to be supplemented with structural measures is a function of several factors:
  - a) Slope
  - b) Maximum velocity during 5-year event
  - c) Maximum velocity during 100-year event
  - d) Froude number during 5-year event
  - e) Froude number during 100-year event
  - f) Tractive force
  - g) Sinuosity
  - h) Timing of period of construction relative to the growing season
  - i) Other site-specific factors

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

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

[Figure OC-11](#) shows examples of details for boulder toe protection (grouted and ungrouted, for one- and two-boulder high toe walls) that can be used to define a hardened, low-flow channel within which base flows and small storm flows can freely meander. Boulders shall be placed on a Type 1 riprap foundation, and boulders shall be aligned so that they are wider than they are tall. Boulders shall be placed so that the top of the toe protection wall is flat. If stacking is stable, grouting may not be necessary. In areas where the channel is easily accessible to the public, the top row of boulders may be grouted in place so that vandals cannot remove them.

### **3.5.5. Advantages of Bioengineered Channels**

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

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

### **3.5.6. Technical Constraints**

The following constraints are associated with bioengineered channels:

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

## DRAINAGE CRITERIA MANUAL

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

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

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

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

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

### 3.5.7. Design Guidelines

To provide the designer with guidelines for the applicability of bioengineered channels, a comparison of hydraulic characteristics is provided in [Table OC-16](#) for four types of channels, ranging from a fully bioengineered channel to a structural channel. To allow for growth of vegetation and accumulation of sediment, outfalls into bioengineered channels shall be 2 feet above the channel invert.

**Table OC-16 – Guidelines for Use of Various Types of Channels  
(UDFCD USDCM 2002)**

*(Note: All channel types typically require grade control structures.)*

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

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

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

### 3.6. Natural Channels

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

## DRAINAGE CRITERIA MANUAL

In the Rogers area, most natural waterways will need drops and/or erosion cutoff check structures to maintain a mild channel slope and to control channel erosion. Typically, these grade control structures are spaced to limit channel degradation to what is expected to be the final stable longitudinal slope after full urbanization of the tributary watershed. In the Rogers area, this slope, depending on watershed size and channel soils, has been observed to range from 0.30% to 1.5%, with the Illinois River itself approaching a slope of 0.06% to 0.10% within Benton County. Whenever feasible, natural channels shall be kept in as near a natural condition as possible by limiting modifications to those necessary to protect against the destabilizing hydrologic forces caused by urbanization.

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

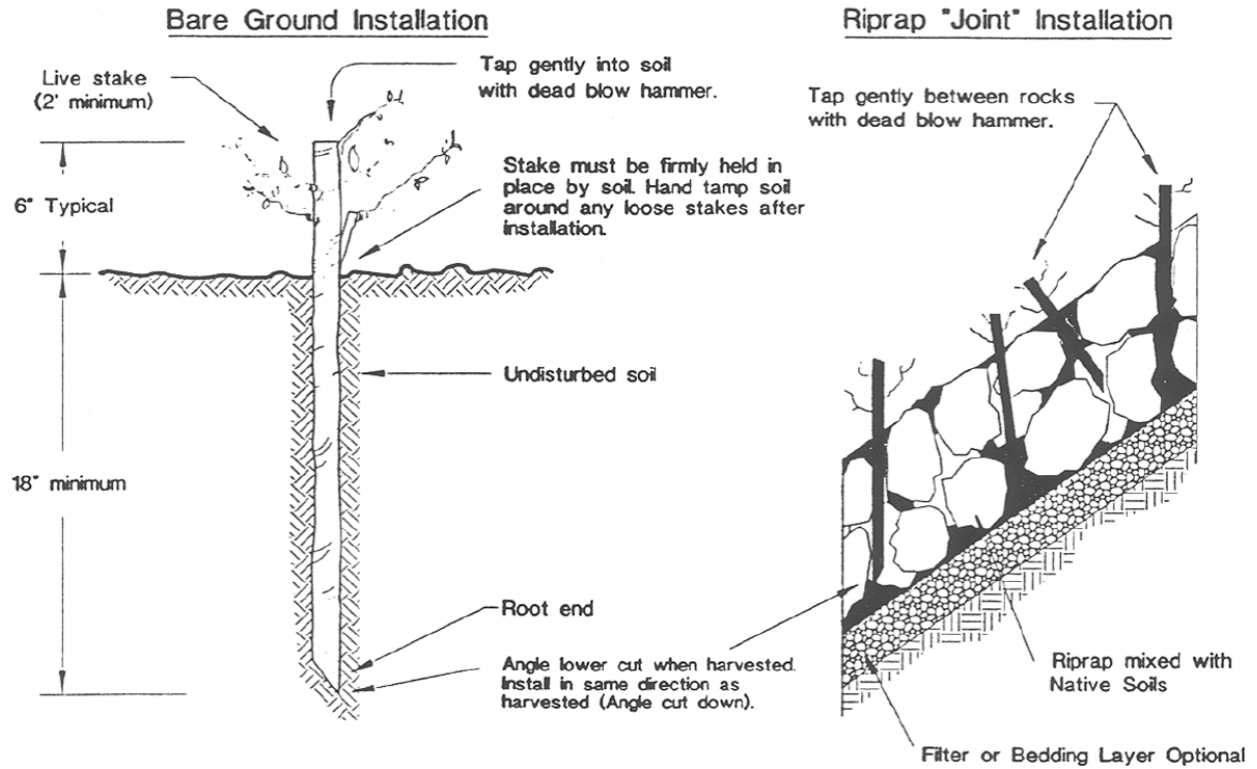
The following design criteria are required when evaluating natural channels:

1. The channel and overbank floodplain shall have adequate capacity for the 100-year flood.
2. A water surface profile shall be defined in order to identify the 100-year floodplain, to control earthwork, and to build structures in a manner consistent with Roger's floodplain regulations and ordinances.
3. Use roughness factors ( $n$ ) representative of un-maintained channel conditions for analysis of water surface profiles. Roughness factors for a variety of natural channel types are presented in [Table OC-7](#).

4. Use roughness factors ( $n$ ) representative of maintained channel conditions to analyze effects of velocities on channel stability. Roughness factors for a variety of natural channel types are presented in [Table OC-7](#).
5. Prepare plan and profile drawings of the channel and floodplain.
6. Provide erosion-control structures, such as drop structures or grade-control checks, to control channel erosion and/or degradation as the tributary watershed urbanizes.
7. Outfalls into natural channels shall be 2 feet above the channel invert to account for vegetation and sediment accumulation. The engineer should visit the site of any outfalls into natural drainageways to examine the actual ground surface condition.

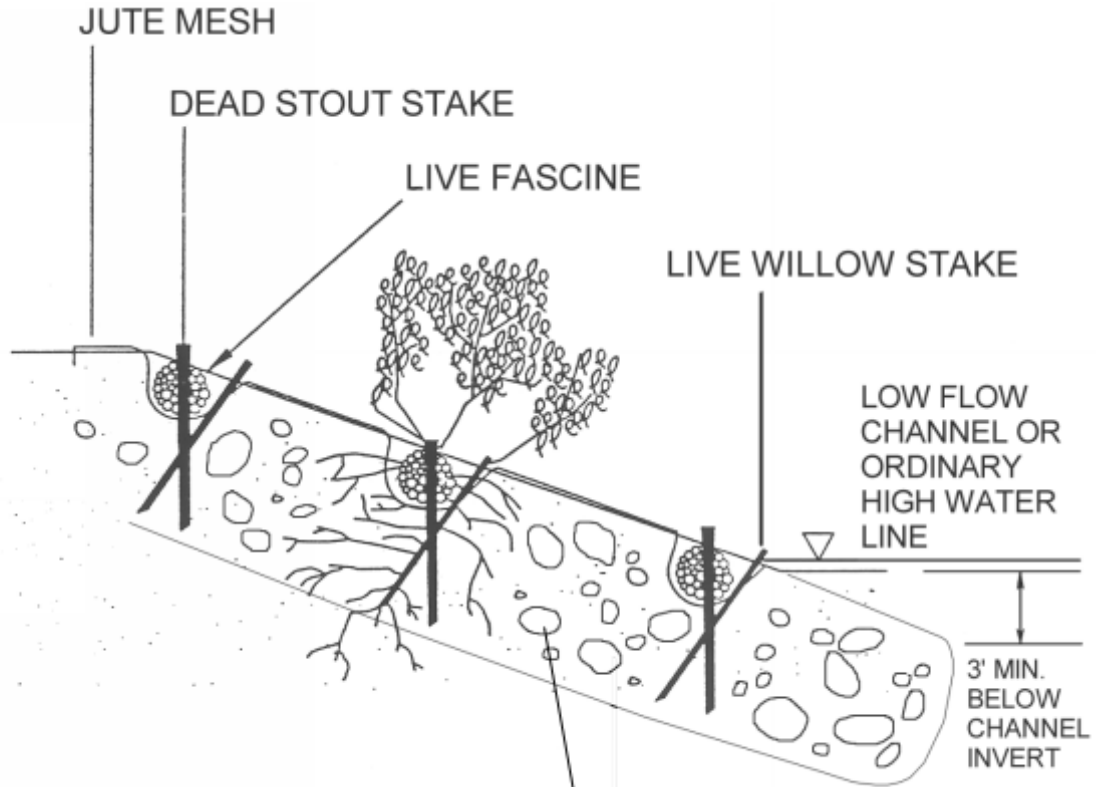
# DRAINAGE CRITERIA MANUAL

## Figure OC-12 – Live Willow Staking for Bare Ground and Joint Installation (UDFCD USDCM 2002)



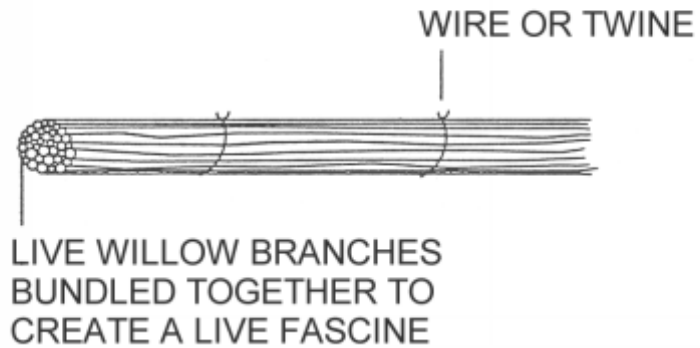
**Single Willow Stake Detail**  
For use in granular soils with available ground water

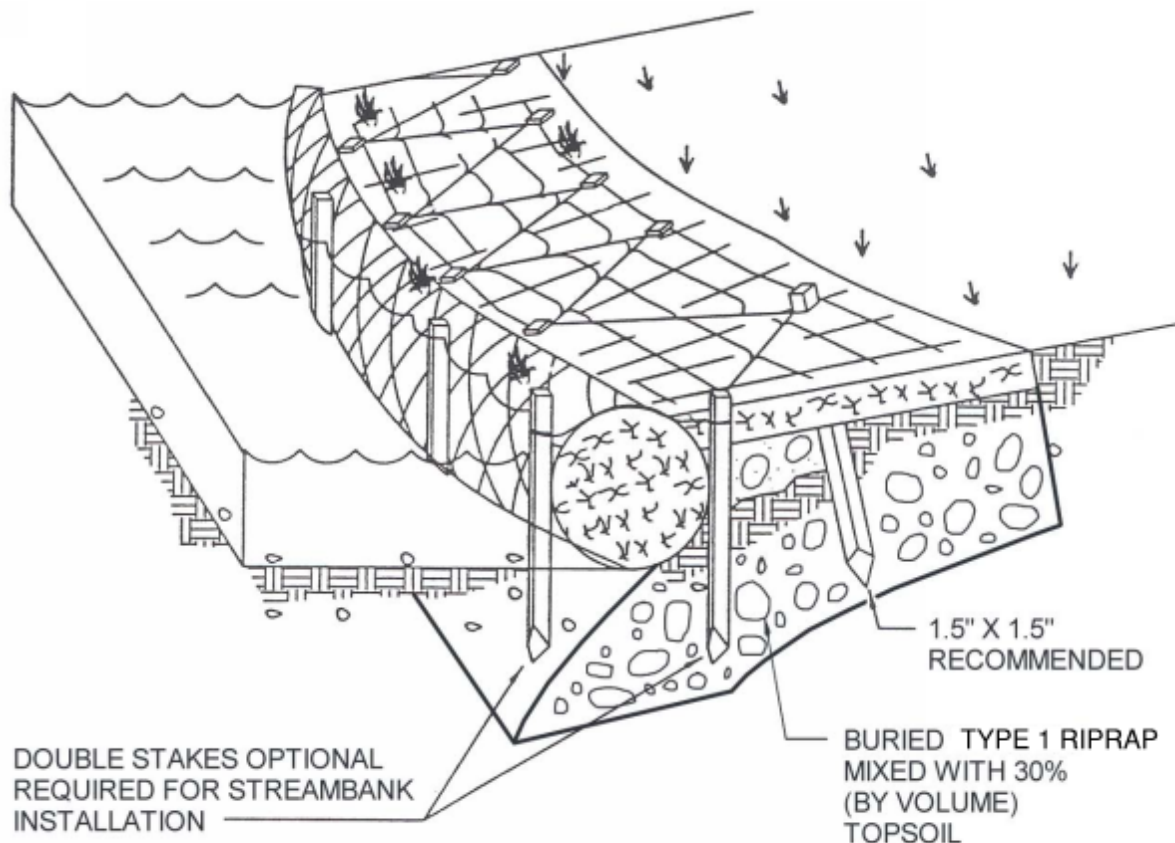
Figure OC-13 – Fascine in Conjunction With Jute Mesh Mat (UDFCD USDCM 2002)



NOTES:

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





NOTES:

1. LENGTH OF STAKE DETERMINED BY THE SUBSTRATE.
2. REFER TO CONTRACT DOCUMENTS FOR FURTHER DETAILS.

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#### 4.

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