

Chapter 7 — Ditches and Channels

TABLE OF CONTENTS

CHAPTER 7 — DITCHES AND CHANNELS	1
7.1 Introduction	1
7.2 Design Policy.....	2
7.2.1 Federal Policy.....	2
7.2.2 Commonwealth of Virginia Policy	2
7.2.2.1 Adequate Receiving Channels	2
7.2.3 VDOT Policy.....	2
7.3 Design Criteria.....	4
7.3.1 Roadside Ditches and Channel Classifications.....	4
7.3.1.1 Minor Channels (Roadside Ditches).....	4
7.3.1.2 Major Channels (Drainage Channels)	4
7.3.1.3 Natural Channels	4
7.3.2 Adequate Receiving Channels	4
7.3.3 Minor Channels (Roadside Ditches)	5
7.3.4 Major Channels	7
7.3.5 Natural Channels.....	7
7.4 Design Concepts.....	9
7.4.1 Minor Channels (Roadside Ditches)	9
7.4.1.1 General	9
7.4.1.2 Design Considerations.....	9
7.4.2 Major Channels	10
7.4.2.1 General	10
7.4.2.2 Flow Classifications	10
7.4.3 Natural Channels.....	11
7.4.3.1 Stream Morphology	11
7.4.3.1.1 Introduction.....	11
7.4.4 Channel Analysis.....	11
7.4.4.1 General	11
7.4.4.2 Equations.....	12
7.4.4.2.1 Specific Energy	12
7.4.4.2.2 Velocity Distribution Coefficient.....	13
7.4.4.2.3 Total Energy Head	14
7.4.4.2.4 Froude Number	14
7.4.4.2.5 Critical Flow.....	15
7.4.4.2.6 Subcritical Flow	15
7.4.4.2.7 Supercritical Flow	15
7.4.4.2.8 Continuity Equation	15
7.4.4.2.9 Manning's Equation.....	16
7.4.4.2.10 Conveyance	16
7.4.4.2.11 Energy Equation.....	17
7.4.4.3 Hydraulic Representation of Channels.....	18
7.4.4.3.1 Cross Sections	18
7.4.4.3.2 Manning's n-Value Selection.....	19
7.4.4.3.3 Calibration	20
7.4.4.3.4 Switchback Phenomenon.....	20

7.4.4.4	Single-Section Analysis	20
7.4.4.5	Water Surface Profile Analysis	21
7.4.4.5.1	Water Surface Profile Methodology	21
7.4.4.5.2	Classifications of Backwater Profiles	23
7.4.4.5.3	Water Surface Profile Computations.....	26
7.4.5	Water and Sediment Routing.....	26
7.4.6	Ditch and Channel Protection.....	26
7.4.6.1	Permissible Velocity.....	27
7.4.6.2	Tractive Force (Permissible Shear)	27
7.4.6.2.1	Shear Stress in Bends	29
7.4.6.3	Geotextile Channel Linings.....	30
7.4.6.3.1	Design Criteria, Geotextile Linings.....	30
7.4.6.3.2	Paved Flumes	34
7.4.6.4	Riprap	34
7.4.6.4.1	Riprap Dimensions and Weights.....	35
7.4.6.4.2	Soils Survey	35
7.4.6.4.3	Riprap Bedding	36
7.4.6.4.4	Major Channels	36
7.4.6.4.5	Minor Channels	36
7.5	Design Procedures and Sample Problems	37
7.5.1	Documentation Requirements.....	37
7.5.2	Roadside Ditches and Minor Channels	37
7.5.2.1	Roadside Ditch and Minor Channel Design Procedure.....	37
7.5.2.2	VDOT Method for Design of Roadside Ditch Linings using Tractive Force Method.....	40
7.5.2.2.1	Design Procedure for Roadside Ditch Linings Using VDOT Method using the Tractive Force Method	40
7.5.2.2.2	Caveats to General Design Procedures for Roadside Ditch Linings	41
7.5.2.2.3	Roadside Ditch Lining Sample Problem (Tractive Force Method)	42
7.5.2.3	VDOT Method for Design of Roadside Ditch Linings (Permissible Velocity Method)	43
7.5.2.3.1	Design Procedure for Roadside Ditch Linings Using VDOT Method	44
7.5.2.3.2	Caveats to General Design Procedures for Roadside Ditch Linings	45
7.5.2.3.3	Roadside Ditch Lining Sample Problem	45
7.5.3	Major Channels	47
7.5.3.1	Single-Section Stage-Discharge Curve Procedure	47
7.5.3.2	Water Surface Profile Procedure.....	47
7.5.3.2.1	Water Surface Profile Sample Problem	50
7.5.4	Natural Channels.....	51
7.5.4.1	General.....	51
7.5.4.2	Natural Channels Design Procedure	51
7.5.4.3	Natural Channels Design Reporting and Documentation.....	54
7.5.4.4	Natural Channels Design Plan Requirements.....	57
7.5.4.5	Natural Channels Design Plan Submittal and Review	58
7.5.5	Riprap Channel Lining Design Procedure.....	59
7.5.5.1	Riprap Lining Design Method for Major Channels (HEC-11)	59
7.5.5.1.1	Riprap Lining Design for Major Channels (HEC-11) Sample Problem.....	61
7.5.5.2	Riprap Lining Design Method for Minor Channels (HEC-15)	62

7.5.5.2.1	Channel Stability Sample Problem - Tractive Force Calculation.....	63
7.5.5.2.2	Riprap Lining Design for Minor Channels (HEC-15) Sample Problem.....	65
7.6	References.....	67

List of Figures and Tables

Figure 7-1.	Sample Roadside Ditch Plan and Profile	6
Figure 7-2.	Specific Energy Diagram for Rectangular Channels	13
Figure 7-3.	Terms in the Energy Equation	18
Figure 7-4.	Hypothetical Cross Section Showing Reaches, Segments, and Subsections Used in Assigning n-Values.....	19
Figure 7-5.	Example of Switchback Phenomenon	20
Figure 7-6.	Energy Slope between Two Channel Sections	23
Figure 7-7.	Notation for Classifying Water Surface Profiles	24
Figure 7-8.	Types of Backwater Profiles	25
Table 7-1.	Allowable Velocity and Shear Stress Values for Lined Ditches	32
Table 7-2A.	Recommended Manning's n-Values for Lined Ditches	33
Figure 7-9.	Roadside Ditch Protection Sample Problem, Plan and Section	42
Figure 7-10.	Worksheet (LD-268) for Calculation of Roadside Ditch Protection, Sample Problem.....	43
Figure 7-11.	Roadside Ditch Protection Sample Problem, Plan and Section.....	46
Figure 7-12.	Worksheet (LD-268) for Calculation of Roadside Ditch Protection , Sample Problem.....	46
Figure 7-13.	Water Surface Profile Sample Problem	50
Figure 7-14.	Worksheet for Calculation of Non-Uniform Flow in Open Channels, Sample Problem.....	51
Table 7-3.	Manning's n-Values for Depth Ranges	62

List of Appendices

Appendix 7B-1 LD-268V Roadside and Median Ditch Design Form – Permissible Velocity

LD-268S Roadside and Median Ditch Design Form – Tractive Force
(Permissible Shear)

Appendix 7B-2 Water Surface Profile Calculation Form

Appendix 7B-3 Channel Stability Work Sheet

Appendix 7B-4 Riprap Design Work Sheet for Standard VDOT Riprap Sizes Only

Appendix 7B-5 Riprap Design Work Sheet for Other Than VDOT Standard Riprap Sizes

Appendix 7B-6 Natural Channel Design Project Summary Sheet

Appendix 7C-1 Nomograph for Solution of Manning's Equation

Appendix 7C-2 Trapezoidal Channel Capacity Chart

Appendix 7C-3 Nomograph for Solution of Normal Depth

Appendix 7C-4 Side Ditch Flow Chart (Side Slopes = 6:1, 1.5:1)

Appendix 7C-5 Side Ditch Flow Chart (Side Slopes = 4:1, 1:1)

Appendix 7C-6 Side Ditch Flow Chart (Side Slopes = 4:1, 1.5:1)

Appendix 7C-7 Side Ditch Flow Chart (Side Slopes = 3:1, 2:1)

Appendix 7C-8 Side Ditch Flow Chart (Side Slopes = 3:1, 1.5:1)

Appendix 7C-9 Side Ditch Flow Chart (Side Slopes = 3:1, 2:1)

Appendix 7C-10 Side Ditch Flow Chart (Side Slopes = 6:1, 2:1)

Appendix 7C-11 Side Ditch Flow Chart (Side Slopes = 6:1, 4:1)

Appendix 7C-12 Triangular Median Ditch Flow Chart (Side Slopes = 6:1, 6:1)

Appendix 7C-13 Triangular Median Ditch Flow Chart (Side Slopes = 4:1, 4:1)

Appendix 7C-14 Triangular Median Ditch Flow Chart (Side Slopes = 2:1, 2:1)

Appendix 7C-15 Toe Ditch Flow Chart (Side Slopes = 1.5:1, 1.5:1)

Appendix 7C-16 Standard PG-4 Flow Chart

Appendix 7C-17 Trapezoidal Ditch Flow Chart (B=1', Side Slopes = 1.5:1)

Appendix 7C-18 Trapezoidal Channel Flow Chart (B=2', Side Slopes = 2:1)

Appendix 7C-19 Trapezoidal Channel Flow Chart (B=3', Side Slopes = 2:1)

Appendix 7C-20 Trapezoidal Channel Flow Chart (B=4', Side Slopes = 2:1)

Appendix 7C-21 Trapezoidal Channel Flow Chart (B=5', Side Slopes = 2:1)

Appendix 7C-22 Trapezoidal Channel Flow Chart (B=6', Side Slopes = 2:1)

Appendix 7C-23 Trapezoidal Channel Flow Chart (B=7', Side Slopes = 2:1)

Appendix 7C-24 Trapezoidal Channel Flow Chart (B=8', Side Slopes = 2:1)
Appendix 7C-25 Trapezoidal Channel Flow Chart (B=9', Side Slopes = 2:1)
Appendix 7C-26 Trapezoidal Channel Flow Chart (B=10', Side Slopes = 2:1)
Appendix 7C-27 Trapezoidal Channel Flow Chart (B=12', Side Slopes = 2:1)
Appendix 7C-28 Trapezoidal Channel Flow Chart (B=14', Side Slopes = 2:1)
Appendix 7C-29 Trapezoidal Channel Flow Chart (B=16', Side Slopes = 2:1)
Appendix 7C-30 Trapezoidal Channel Flow Chart (B=18', Side Slopes = 2:1)
Appendix 7C-31 Trapezoidal Channel Flow Chart (B=20', Side Slopes = 2:1)
Appendix 7D-1 Values of Roughness Coefficient n (Uniform Flow)
Appendix 7D-2 Recommended Maximum Water Velocities and Manning's n as a
Function of Soil Type and Flow Depth
Appendix 7D-3 Standard VDOT Riprap Classifications, Weights, and Blanket Thickness
Appendix 7D-4 Approximate Rock Dimensions and Equivalent Weights for Riprap
Appendix 7D-5 Selection of Stability Factors
Appendix 7D-6 Permissible Velocities for Erodible Linings
Appendix 7E-1 Angle of Repose of Riprap in Terms of Mean Size and Shape of Stone
Appendix 7E-2 Permissible Shear Stress for Non-Cohesive Soils
Appendix 7E-3 Permissible Shear Stress for Cohesive Soils
Appendix 7E-4 Bank Angle Correction Factor (K_1) Nomograph
Appendix 7E-5 Correction Factor for Riprap Size
Appendix 7E-6 Riprap Size Relationship
Appendix 7E-7 Channel Side Shear Stress to Bottom Shear Stress Ratio
Appendix 7E-8 Tractive Force Ratio (K_2)
Appendix 7E-9 Determination of the Mean Spherical Diameter

Chapter 7 — Ditches and Channels

7.1 Introduction

The **function*** of ditches and open channels is to convey stormwater runoff from, though, or around roadway rights-of-way without damage to the highway, to the open channel, to other components of the highway system, or to adjacent property. Culverts and storm drains can be used for the same purposes. Open channels may be natural or constructed. In either case, the water surface is exposed to the atmosphere, and the gravity force component in the direction of motion is the driving force. Open channels are free to overflow their banks, and cannot develop pressure flow, as can closed conduits such as circular pipes. However, closed conduits flow as open channels when the water surface is below the crown of the conduit, and the design concepts of this chapter apply to closed conduits flowing partly full.

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7.2 Design Policy

Following are Federal, Commonwealth of Virginia, and Virginia Department of Transportation (VDOT) design policies related to channel design.

7.2.1 Federal Policy

Channel designs and/or designs of highway facilities that impact channels should satisfy the policies of the Federal Highway Administration applicable to floodplain management. Federal Emergency Management Agency (FEMA) floodway regulations and Corps of Engineers (COE) wetland restrictions for permits should also be satisfied.

7.2.2 Commonwealth of Virginia Policy

7.2.2.1 Adequate Receiving Channels

The Virginia Erosion and Sediment Control Regulations, Minimum Standard 19 (VESCR MS-19 <<http://www.deq.virginia.gov/>>*) requires that properties and waterways, downstream from new development sites, shall be protected from sediment deposition, erosion, and damage due to increases in the volume, velocity, and peak flow rate of stormwater runoff for the stated frequency storm of 24-hour duration. Design criteria for adequate channels are summarized in Section 7.3.2.

7.2.3 VDOT Policy

The following statements represent VDOT goals for ditch and channel design:

- Coordination with other Federal, State and local agencies concerned with water resources planning has high priority in the planning of highway facilities
- Safety of the general public is an important consideration in the selection of the cross-sectional geometries of artificial drainage channels
- The design of artificial drainage channels or other facilities should consider the frequency and type of maintenance expected and make allowance for maintenance access
- Stability is the goal for all channels that are located on highway right-of-way or that impact highway facilities
- Environmental impacts of channel modifications, including disturbance of fish habitat, wetlands and channel stability, should be assessed

*Rev. 7/16

- The range of design channel discharges should be selected by the designer based on class of roadway, consequences of traffic interruption, flood hazard risks, economics, and local site conditions
- Wherever possible, encroachment into streams should be avoided and encroachment onto flood plains should be minimized to the fullest extent practical
- Whenever natural channels must be relocated or otherwise modified, the extent of channel reach and degree of modification should be the minimum necessary to provide compatibility of the channel and roadway, and will incorporate any necessary natural channel design and/or stream restoration
- Roadside ditches and channels should have adequate gradient to outfall the roadway for the design discharge. “Grade to Drain” shall not be notated on the plans, as it truly does not prove that adequate discharge persists with the design^{*}

A thorough analysis of the stream’s morphology and environment shall be conducted and documented in addition to the economic and engineering alternatives available for the particular location.

^{*}Rev. 7/16

7.3 Design Criteria

7.3.1 Roadside Ditches and Channel Classifications

In this chapter, ditches and channels are classified as:

7.3.1.1 Minor Channels (Roadside Ditches)

Minor channels collect sheet flow from the highway pavement or right-of-way and convey that flow to collection points in larger channels or pipes. Flows are generally 50 cfs or less in minor channels. Minor channels usually parallel the highway embankment and are within the highway R/W. See Section 7.3.3 for minor channel criteria.

7.3.1.2 Major Channels (Drainage Channels)

Major channels collect drainage from minor channels, pipe systems, and offsite areas, and convey that flow to an adequate discharge point on- or offsite. Flows are generally greater than 50 cfs in major channels. See Section 7.3.4 for major channel criteria.

7.3.1.3 Natural Channels

Natural channels are formed through geomorphologic activity, including erosion and sedimentation. Generally meandering and irregular in cross-section, natural channels may convey any flow rate. See Section 7.3.5 for natural channel criteria.

7.3.2 Adequate Receiving Channels

Minimum Standard 19 (*Virginia Erosion and Sediment Control Handbook*) for adequate receiving channels establishes the following design criteria for all channels.

Concentrated stormwater runoff leaving a development site must be discharged directly into an adequate* well-defined, natural or man-made offsite receiving channel, pipe, or storm sewer system. If there is no adequate offsite receiving channel or pipe, one must be constructed to convey stormwater to the nearest adequate channel. Newly constructed channels shall be designed as adequate channels.

An adequate channel is defined as follows: (1) A natural channel, which is capable of conveying the runoff from a 2-yr storm without overtopping its banks or eroding after development of the site in question, (2) A previously constructed man-made channel shall be capable of conveying the runoff from a 10-yr storm without overtopping its banks, and bed or bank erosion shall not occur due to a 2-yr storm, (3) Pipes and storm sewer systems shall contain the 10-yr storm.

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A receiving channel may also be considered adequate at any point where the total contributing drainage area is at least 100 times greater than the drainage area of the development site in question; or, if it can be shown that the peak rate of runoff from the site during a 2-yr storm will not be increased after development.

Runoff rate and channel adequacy must be verified with acceptable engineering calculations. Refer to Chapter 6, Hydrology, for peak discharge methods.

If an existing offsite receiving channel is not an adequate channel, the applicant must choose one of the following options:

- Obtain permission from downstream property owners to improve the receiving channel to an adequate condition. Such improvements should extend downstream until an adequate channel section is reached.
- Develop a site design that will not cause the pre-development peak runoff rate from a 2-yr storm to increase when outfall is into a natural channel, or will not cause the pre-development rate from a 10-yr storm to increase when outfall is to a man-made channel. Such a design may be accomplished by enhancing the infiltration capability of the site or by providing on-site stormwater detention measures. The pre-development and post-development peak runoff rates must be verified by engineering calculations.
- Provide a combination of channel improvement, stormwater detention, or other measures which are satisfactory to prevent downstream channel erosion.

All channel improvements or modifications must comply with all applicable laws and regulations.

Increased volumes of unconcentrated sheet flows which may cause erosion or sedimentation of adjacent property must be diverted to an adequate outlet or detention facility.

Outfall from a detention facility shall be discharged to an adequate channel. Outlet protection and/or energy dissipation should be placed at the discharge point as necessary.

7.3.3 Minor Channels (Roadside Ditches)

Minor channels are normally V-shaped and sometimes trapezoidal in cross section and lined with grass or a protective lining. They are usually designed to convey the 10-yr discharge, and to resist erosion from the 2-yr discharge. Higher design discharges may be necessary when the channel intercepts offsite drainage.

Special design ditches are designed for storm frequencies appropriate to the functional classification of the roadway and the risk involved when the design capacity is exceeded.

A secondary function of a roadside ditch is to drain subsurface water from the base of the roadway to prevent saturation and loss of support for the pavement or to provide a positive outlet for subsurface drainage systems such as pipe underdrains.

The alignment, cross-section, and grade of roadside ditches are usually constrained largely by the geometric and safety standards applicable to the project. These ditches should accommodate the design runoff in a manner that assures the safety of motorists and minimizes future maintenance, damage to adjacent properties, and adverse environmental, or aesthetic effects. A sample roadside ditch plan and profile is shown in Figure 7-1. The VDOT Method for Design of Roadside Ditch Linings (Section 7.5.2.2) is recommended for use on minor channels.

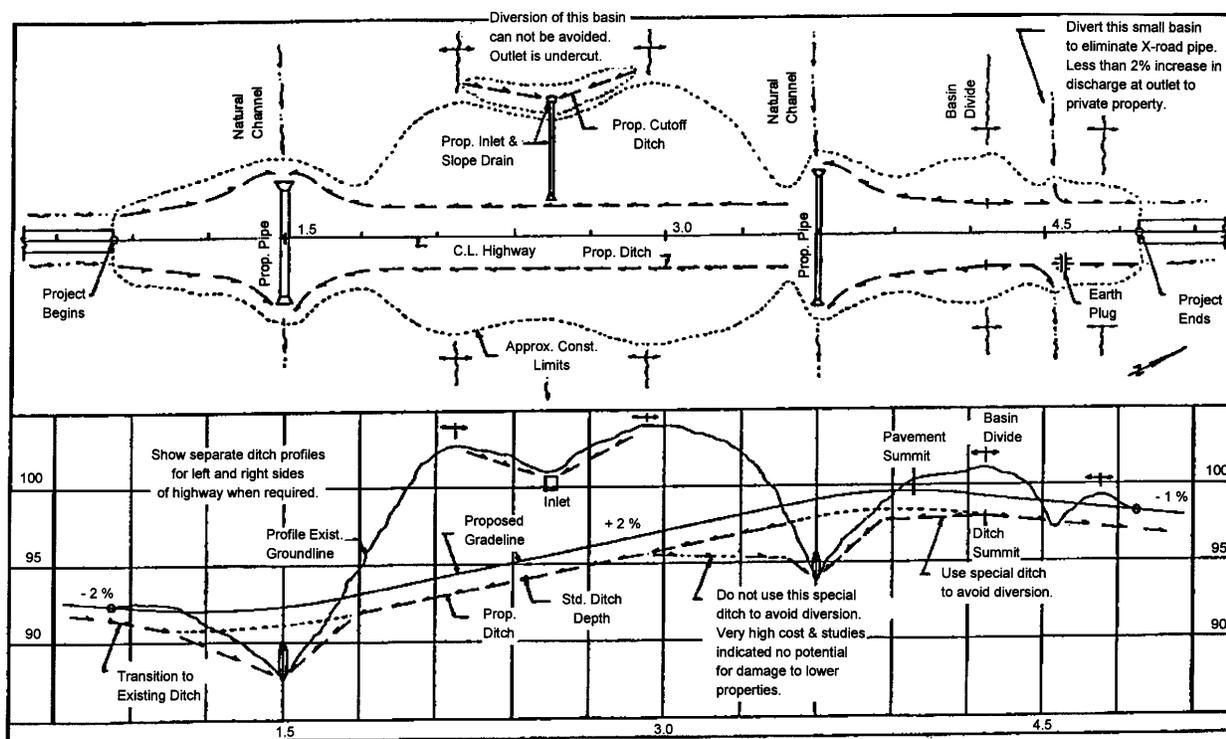


Figure 7-1 Sample Roadside Ditch Plan and Profile

*It is not recommended to specify non-standard or atypical roadside ditches for highway projects, due to safety and economical concerns. If the designer chooses to specify an atypical ditch section, the designer should minimize its use to the greatest extent possible. Where the volume, flow, or other considerations dictate enlarging or deepening the roadside ditch or otherwise deviating from the standard designs, careful consideration must be given to the following:

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- Using an enclosed drainage system, where economically feasible, in order to eliminate the need for the non-standard or a typical roadside ditch or channel
- Minimizing the size and depth of the proposed non-standard or atypical roadside ditch or channel
- Flattening the front slope (the slope adjacent to the highway shoulder) of the non-standard or atypical roadside ditch or channel. Where right of way is available, or can reasonably be obtained, the front slope of the non-standard or atypical roadside ditch or channel should be no steeper than the front slope of the standard roadside ditch for the specific roadway classification involved
- Locating necessary non-standard or atypical roadside ditches or channels as far from the proposed highway shoulder as the existing or proposed right of way will reasonably allow

7.3.4 Major Channels

Major channels may be within or outside the highway right-of-way. The same design criteria apply as for minor channels. Conveyance is usually based on the 10-yr storm but may be greater based upon risk. Erosive protection is based on the 2-yr storm. Major channels are usually trapezoidal in cross section. One foot or more of freeboard is recommended for larger channels where the consequences of overtopping are significant. The consequences of failure are usually more severe for major channels; therefore, a higher level of engineering analysis and design is usually justified for major channels.

7.3.5 Natural Channels

The hydraulic effects of floodplain encroachments should be evaluated over a full range of frequency-based peak discharges from the 2-yr through the 500-yr recurrence intervals on any major highway facility, as deemed necessary by the Department. The hydrologic and hydraulic analysis procedure and required documentation for such situations are more fully described in Chapter 12, Bridge, Structure and Riverine* Hydraulics. If the floodplain encroachment is located in a FEMA or other officially delineated floodplain, no increase in the established natural 100-yr flood level will be permitted either up or downstream. It should be noted that the Department's criteria is more stringent than FEMA's in this instance. In situations where no FEMA or other officially delineated floodplain exists, it will be acceptable to increase the level of the 100-yr flood event not to exceed one foot up or downstream, provided such increase does not adversely impact adjacent properties, buildings, etc. If an increase in the 100-yr flood level will cause such adverse impact then no increase shall be permitted. The Department's State Hydraulics Engineer must approve exceptions to either of the above criteria.

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If relocation of a stream channel is unavoidable, the cross-sectional shape, meander, pattern, roughness, sediment transport, and slope should conform to the existing conditions as far as practical. Some means of energy dissipation may be necessary when existing conditions cannot be duplicated.

Streambank stabilization should be provided when appropriate, because of any stream disturbance such as encroachment and should include both upstream and downstream banks as well as the local site.

Relocation of major streams is complex, and special expertise in river mechanics engineering and appropriate natural channel and/or stream restoration design may be necessary.

*Natural channel design principles will be used, to the extent practicable, in all stream restoration and relocation projects.

Natural channel design principles are encouraged as a means of effectively addressing localized bank erosion.

VDOT recognizes the value and importance of peer review and Quality Assurance/Quality Control (QA/QC) processes in delivering quality products within established and accepted time frames. An interdisciplinary QA/QC team managed by the Central Office Environmental Division, Natural Resources Section, will administer this process for all natural channel design projects.

All in-stream activities require coordination with district environmental staff to ensure that water quality permits are obtained and environmental commitments adhered to, as required. The project manager is responsible for ensuring that coordination is conducted.

*Rev. 7/16

Design Concepts

7.4.1 Minor Channels (Roadside Ditches)

7.4.1.1 General

Design discharges (peak flows) should be determined by the Rational Method as defined in Chapter 6, Hydrology.

Velocity should be based on normal depth computed using Manning's equation. Manning's equation requires information on the ditch geometry, such as side slopes, the longitudinal grade, and the appropriate Manning's n-value.

Ditch side slopes should not exceed the angle of repose of the soil and/or lining and should have a maximum slope of 2H:1V or flatter. See Section 7.4.6 for further discussion on channel linings.

Figure 7-1 shows a sample plan and profile for a roadside ditch.

7.4.1.2 Design Considerations

Roadside ditch design involves both capacity and erosion resistance. A trial-and-error process may be necessary to obtain the optimum design. More information on roadside ditch design procedures is contained in Section 7.5.

The VDOT method for design of roadside ditch linings is recommended for use on minor channels. Consideration should be given to ditch bends, steep slopes, and composite linings, which are further defined in Section 7.4.6, HEC-11, and HEC-15. The riprap design procedures described in HEC-15 are for minor channels having a design discharge of 50 cfs or less. When the design discharge exceeds 50 cfs, the design procedures presented in HEC-11 should be followed for riprap-lined channels. HEC-15 may be used for design of larger channels with linings other than riprap.

Except where severe right-of-way limitations exist, a minimum of 5' is to be provided between the end of the cut slope round-off and the front slope of a berm ditch. Severe right-of-way limitations may include, but are not limited to, adverse environmental impacts, significant distance to tie to existing grade, and property damage. * Additional right-of-way is to be obtained for construction and maintenance of the berm ditch.

Except where severe right-of-way limitations exist, a minimum of 5' is to be provided between the toe of the fill slope and the front slope of a toe ditch. Severe right-of-way limitations may include, but are not limited to, adverse environmental impacts, significant distance to tie to existing grade, and property damage. Additional right of way is to be obtained for construction and maintenance of the ditch.

*Rev. 7/19

7.4.2 Major Channels

7.4.2.1 General

Design analysis of both natural and artificial channels proceeds according to the basic principles of open channel flow (see Chow, 1959; Henderson, 1966). The basic principles of fluid mechanics, continuity, momentum, and energy can be applied to open channel flow with the additional complication that the position of the free surface is usually one of the unknown variables. The determination of this unknown is one of the principal problems of open channel flow analysis and it depends on quantification of the flow resistance. Natural channels display a much wider range of roughness values than do artificial channels.

7.4.2.2 Flow Classifications

The classifications of open channel flow are summarized as follows:

Steady Flow (Rate of flow remains constant with time)

1. Uniform Flow (Velocity and depth of flow remain constant over length)
2. Non-uniform Flow (Velocity and depth of flow vary over length)
 - Gradually Varied Flow
 - Rapidly Varied Flow

Unsteady Flow (Rate of flow varies with time)

1. Unsteady Uniform Flow (rare)
2. Unsteady Non-uniform Flow
 - Gradually Varied Unsteady Flow
 - Rapidly Varied Unsteady Flow

The steady uniform flow class and the steady non-uniform flow class are the most common types of flow treated in highway engineering hydraulics. However, uniform flow is rare in natural channels.

*Rev. 9/09

7.4.3 Natural Channels

7.4.3.1 Stream Morphology

7.4.3.1.1 Introduction

The form assumed by a natural stream, which includes its cross-sectional geometry as well as its plan-form, is a function of many variables for which cause-and-effect relationships are difficult to establish. The stream may be graded or in equilibrium with respect to long time periods, which means that on the average it discharges the same amount of sediment that it receives, although there may be short-term adjustments in its bed-forms in response to flood flows. On the other hand, the stream reach of interest may be aggrading or degrading as a result of deposition or scour in the reach, respectively. The plan-form of the stream may be straight, braided, or meandering. These complexities of stream morphology can be assessed by inspecting aerial photographs and topographic maps for changes in slope, width, depth, meander form and bank erosion with time.

A qualitative assessment of the river response to proposed highway facilities is possible through a thorough knowledge of river mechanics and accumulation of engineering experience. The FHWA publications "Stream Stability at Highway Structures" (HEC-20) and "River Engineering for Highway Encroachments" (HDS-6) provide additional and more detailed information on making such assessments. Both publications can be accessed and/or downloaded from the FHWA's Internet web site at http://www.fhwa.dot.gov/engineering/hydraulics/library_listing.cfm.

7.4.4 Channel Analysis

7.4.4.1 General

The hydraulic analysis of a channel determines the depth and velocity at which a given discharge will flow in a channel of known geometry, roughness and slope. The depth and velocity of flow are necessary for the design or analysis of channel linings and highway drainage structures.

Two methods are commonly used in hydraulic analysis of open channels. The single-section method is a simple application of Manning's equation to determine tailwater rating curves for culverts or to analyze other situations in which uniform or nearly uniform flow conditions can be assumed.

The step-backwater method is used to compute the complete water surface profile in a stream reach to evaluate the unrestricted water surface elevations for bridge hydraulic design or to analyze other gradually varied flow problems in streams.

*Rev. 9/09

- A. Where the 100-yr discharge for a particular site is less than 500 cfs, the site is generally considered to be a minor drainage installation. A single cross section analysis, using nomographs and charts, usually provides an acceptable level of hydraulic analysis. Documentation requirements are satisfied by supplying all requested information on VDOT standard hydraulic computation forms.
- B. Where the 100-yr discharge for a particular site is 500 cfs or more, the site is generally considered to be a major drainage installation. The method of hydraulic analysis and the level of documentation must conform to hydrology analysis (H&HA) outline provided in Chapter 12, Bridge and Structure Hydraulics. This type of analysis often requires water surface profile calculations such as those provided by the HEC-2, HEC-RAS, or WSPRO computer models. However, other methods of analysis, which provide the necessary data for proper documentation, may be approved for use.

The single-section method will generally yield less reliable results than the step-backwater method because it requires more judgment and assumptions. In many situations, however, the single-section method is all that is justified. In minor drainage channels such as roadside ditches, the single section method is adequate, except in the case of special design channels or critical locations.

The step-backwater method should be used for important major channels, where an accurate definition of the water surface profile is needed. The basic principles of open channel hydraulics are applicable to all drainage channels, as well as culverts and storm drains. The variable is the level of detail required in design, which depends on the risks of damage or loss of life caused by a failure of the facility.

7.4.4.2 Equations

The following equations are those most commonly used to analyze open channel flow. The detailed use of these equations in analyzing open channel hydraulics is discussed in Section 7.5.

7.4.4.2.1 Specific Energy

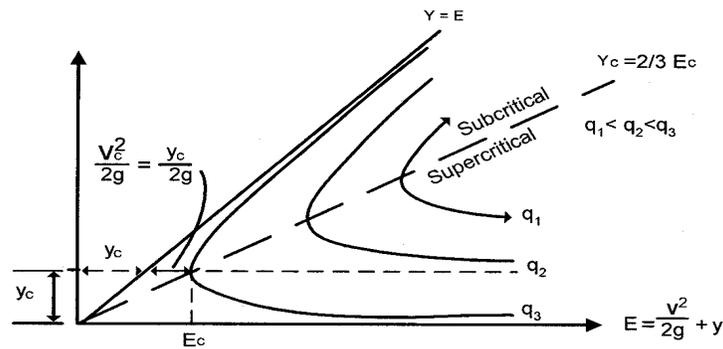
Specific energy (E) is defined as the energy head relative to the channel bottom. If the channel slope is less than 10% and the streamlines are nearly straight and parallel (so that the hydrostatic assumption holds), the specific energy (E) becomes the sum of the depth and velocity head:

$$E = d + \alpha \frac{V^2}{2g} \tag{7.1}$$

Where:

- d = Depth of flow, ft
- α = Velocity distribution coefficient (see Equation 7.2)
- v = Mean velocity, fps
- g = Gravitational acceleration, 32.2 ft/s²

When specific energy is plotted against depth of flow, a curve with a minimum specific energy results, as shown in Figure 7-2. At the minimum specific energy, the depth is called critical depth. Depths above critical depth are subcritical, and below critical depth are supercritical. The velocity distribution coefficient is usually assumed to have a value of one for turbulent flow in prismatic channels but may be significantly different than one in natural channels.



Note: $y = d$ in Equation 7.1

Figure 7-2 Specific Energy Diagram for Rectangular Channels

7.4.4.2.2 Velocity Distribution Coefficient

Due to the presence of a free surface and due to friction along the channel boundary, the velocities in a channel are not uniformly distributed across the channel cross section. Because of non-uniform distribution of velocities in a channel section, the velocity head of an open channel is usually greater than the average velocity head computed as $(Q/A_t)^2/2g$. A weighted average value of the velocity head is obtained by multiplying the average velocity head, above, by a velocity distribution coefficient (α) defined as:

$$\alpha = \frac{\sum_{i=1}^n \frac{K_i^3}{A_i^2}}{\frac{K_t^3}{A_t^2}} \quad (7.2)$$

Where:

- K_i = Conveyance in subsection (see Equation 7.8)
- K_t = Total conveyance in section (see Equation 7.8)
- A_i = Cross-sectional area of subsection, ft²
- A_t = Total cross-sectional area of section, ft²
- n = Number of subsections

7.4.4.2.3 Total Energy Head

The total energy head is the specific energy head plus the elevation of the channel bottom with respect to some datum. A plot of the energy head from one cross section to the next defines the energy grade line.

7.4.4.2.4 Froude Number

The Froude number (F_r) is an important dimensionless parameter in open channel flow. It represents the ratio of inertial forces to gravitational forces and is defined as:

$$F_r = \frac{V}{\sqrt{\frac{gH_D}{\alpha}}} \quad (7.3)$$

Where:

- α = Velocity distribution coefficient
- V = Mean velocity = Q/A , fps
- g = Gravitational acceleration, 32.2 ft/s²

$$H_D = \text{Hydraulic depth} = \left(\frac{A}{T} \right), \text{ ft}$$

(For rectangular channels the hydraulic depth is equal to the flow depth.)

- A = Cross-sectional area of flow, ft²
- T = Channel top width at the water surface, ft
- Q = Discharge, cfs

This expression for Froude number applies to channel flow at any cross section. The Froude number is useful in determining the flow regime for water surface profiles.

- $F_r < 1$, Subcritical Flow
- $F_r = 1$, Critical Flow
- $F_r > 1$, Supercritical Flow

*Rev. 9/09

7.4.4.2.5 Critical Flow

Critical flow occurs when the specific energy is a minimum for a given flow rate (see Figure 7-2). The variation of specific energy with depth at a constant discharge shows a minimum in the specific energy at a depth called critical depth at which the Froude number has a value of one. Critical depth is the depth of maximum discharge when the specific energy is held constant. During critical flow the velocity head is equal to one-half of the hydraulic depth. The general expression for flow at critical depth is:

$$\frac{\alpha Q^2}{g} = \frac{A^3}{T} \quad (7.4)$$

Where:

- α = Velocity distribution coefficient
- Q = Discharge, cfs
- g = Gravitational acceleration, 32.2 ft/s²
- A = Cross-sectional area of flow, ft²
- T = Channel top width at the water surface, ft

When flow is at critical depth, Equation 7.4 must be satisfied, regardless of the shape of the channel.

7.4.4.2.6 Subcritical Flow

Depths greater than critical occur in subcritical flow. The Froude number is less than one for subcritical flow. In this state of flow, small water surface disturbances can travel both upstream and downstream, and the control is always located downstream.

7.4.4.2.7 Supercritical Flow

Depths less than critical depth occur in supercritical flow. The Froude number is greater than one. Small water surface disturbances are always swept downstream in supercritical flow, and the location of the flow control is always upstream.

7.4.4.2.8 Continuity Equation

The continuity equation is the statement of conservation of mass in fluid mechanics. For the special case of one-dimensional, steady flow of an incompressible fluid, it assumes the simple form:

$$Q = A_1 \cdot V_1 = A_2 \cdot V_2 \quad (7.5)$$

Where:

- Q = Discharge, cfs

*Rev. 9/09

- A = Cross-sectional area of flow, ft²
- V = Mean cross-sectional velocity, fps (which is perpendicular to the cross section)

Subscripts 1 and 2 refer to successive cross sections along the flow path.

7.4.4.2.9 Manning's Equation

For a given depth of flow in an open channel with a steady, uniform flow, the mean velocity (V) can be computed using Manning's equation:

$$V = \frac{1.486}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \quad (7.6)$$

Where:

- V = Velocity, fps
- n = Manning's roughness coefficient
- R = Hydraulic radius = A/P, ft
- A = Flow area, ft²
- P = Wetted perimeter, ft
- S = Slope of the energy grade line, ft/ft

The selection of Manning's n is generally based on observation; however, considerable experience is essential in selecting appropriate n-values. The selection of Manning's n is discussed in Section 7.4.4.3.2. The range of n-values for various types of channels and floodplains is given in Appendix 7D-1 and 7D-2.

The continuity equation can be combined with Manning's equation to obtain the steady, uniform flow discharge as:

$$Q = \frac{1.486}{n} A R^{\frac{2}{3}} S^{\frac{1}{2}} \quad (7.7)$$

For a given channel geometry, slope, roughness, and a specified discharge (Q), a unique value of depth occurs in steady, uniform flow. It is called normal depth. At normal depth, the slope of the energy grade line, the hydraulic grade line, and the channel slope are the same. Normal depth is computed from Equation 7.7 by expressing the area and hydraulic radius in terms of depth. The resulting equation may require a trial-and-error solution. See Section 7.5 for a more detailed discussion of the computation of normal depth.

If normal depth is greater than critical depth, the channel slope is classified as a mild slope. On a steep slope, the normal depth is less than the critical depth. Thus, uniform flow is subcritical on a mild slope and supercritical on a steep slope.

7.4.4.2.10 Conveyance

In channel analysis, it is often convenient to group the channel properties in a single term called the channel conveyance (K):

$$K = \frac{1.486}{n} AR^{\frac{2}{3}} \quad (7.8)$$

Then Equation 7.7 can be written as:

$$Q = KS^{\frac{1}{2}} \quad (7.9)$$

The conveyance represents the carrying capacity of a stream cross-section based upon its geometry and roughness characteristics alone and is independent of the streambed slope.

The concept of channel conveyance is useful when computing the distribution of overbank flood flows in the stream cross-section and the flow distribution through the opening in a proposed stream crossing. It is also used to determine the velocity distribution coefficient (α).

7.4.4.2.11 Energy Equation

The energy equation (Bernoulli's Equation) expresses conservation of energy in open channel flow defined as energy per unit weight of fluid, which has dimensions of length, and is called energy head. The energy head is composed of potential energy head (elevation head), pressure head, and kinetic energy head (velocity head). These energy heads are scalar quantities, the sum of which gives the total energy head at any cross section. Written between an upstream open channel cross section designated "1" and a downstream cross section designated "2", the energy equation is:

$$h_1 + \alpha_1 \frac{V_1^2}{2g} = h_2 + \alpha_2 \frac{V_2^2}{2g} + h_L \quad (7.10)$$

Where:

- h_1 = Upstream water surface elevation, ft.
- h_2 = Downstream water surface elevation, ft.
- α = Velocity distribution coefficient
- V = Mean velocity, fps
- h_L = Head loss due to local cross-sectional changes (minor loss) plus friction loss, ft

The stage (h), is the sum of the elevation head (z) at the channel bed and the pressure head, or depth of flow (y); i.e., $h = z+y$. The terms in the energy equation are illustrated graphically in Figure 7-3. The energy equation states that the total energy head at an upstream cross section is equal to the energy head at a downstream section plus energy head losses between two consecutive sections. The energy equation can only be applied between two cross sections at which the streamlines are nearly straight and parallel so that vertical acceleration can be neglected.

*Rev. 7/16

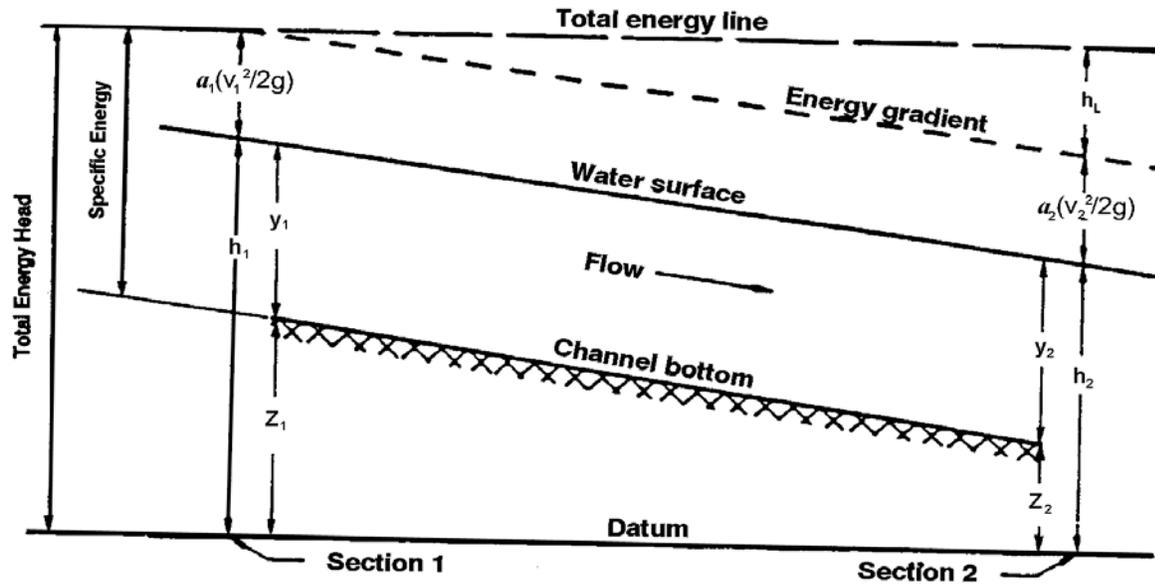


Figure 7-3 Terms in the Energy Equation

7.4.4.3 Hydraulic Representation of Channels

The following sections describe the data needed to apply Manning's equation to the analysis of open channels.

7.4.4.3.1 Cross Sections

The cross-sectional geometry of streams is defined by coordinates of lateral distance and ground elevation, which locate individual ground points. Individual cross sections are taken normal to the flow direction along a single straight line where possible, but in wide floodplains or bends it may be necessary to use intersecting straight lines to form a section; i.e., a "dog-leg" section. It is especially important to make a plot of the cross section to reveal any inconsistencies or errors.

Cross sections should be located to be representative of the sub-reaches between them. Stream locations with major breaks in bed profile, abrupt changes in roughness or shape, control sections such as free overfalls, bends and contractions, or other abrupt changes in channel slope or conveyance will require cross sections taken at shorter intervals in order to better model the changes in conveyance.

Cross sections should be subdivided with vertical boundaries where there are abrupt lateral changes in geometry and/or roughness as in the case of overbank flows. The conveyances of each subsection are computed separately to determine the flow distribution and α , and are then added to determine the total flow conveyance. The subsection divisions must be chosen carefully so that the distribution of flow or conveyance is nearly uniform in each subsection (Davidian, 1984). Selection of cross sections and vertical subdivision of a cross section are shown in Figure 7-4.

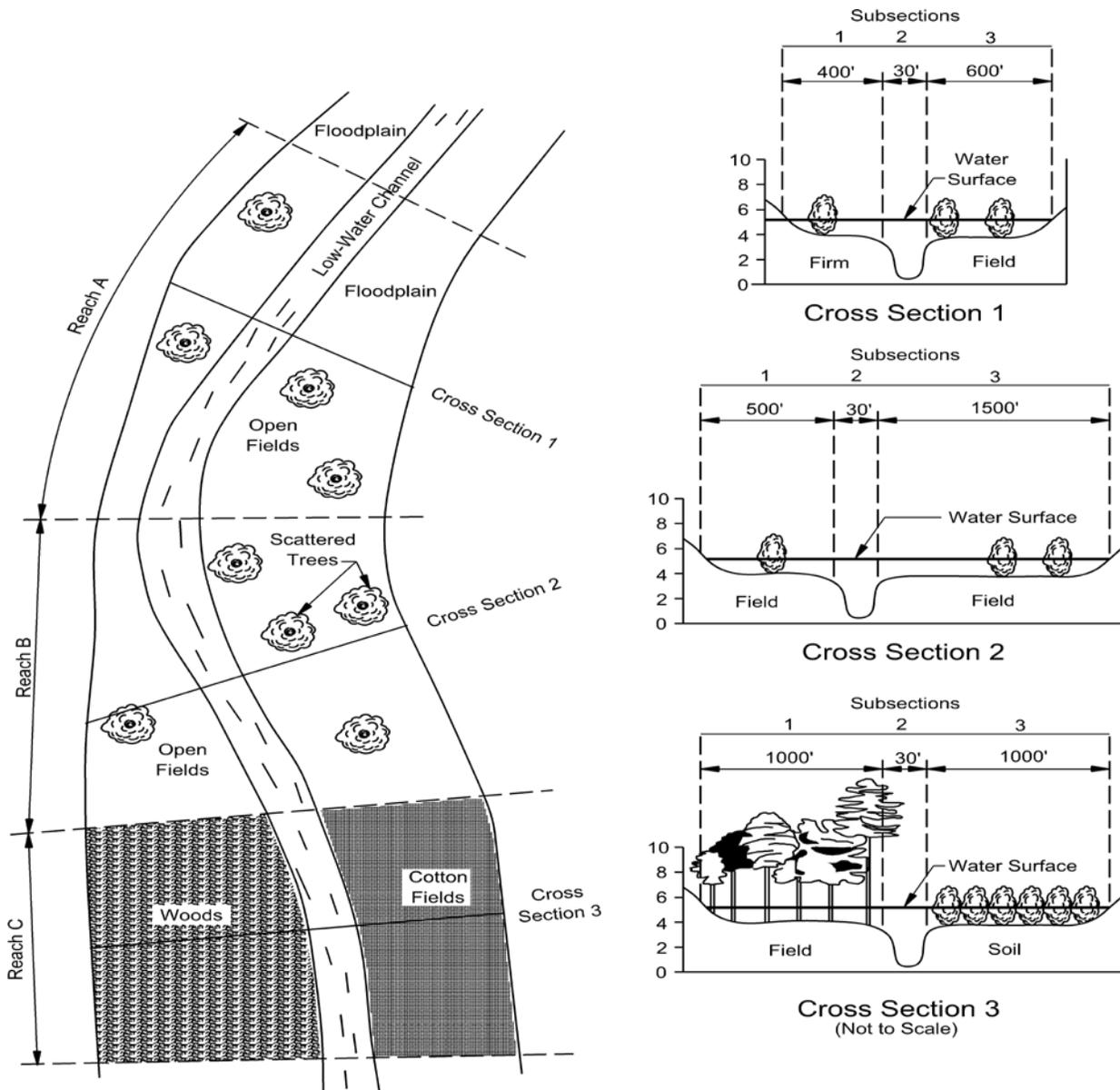


Figure 7-4 Hypothetical Cross Section Showing Reaches, Segments, and Subsections Used in Assigning n-Values

7.4.4.3.2 Manning's n-Value Selection

Manning's n is affected by many factors and its selection, especially in natural channels depends heavily on engineering experience. Photographs of channels and flood plains, for which the discharge has been measured, and Manning's n has been calculated, are very useful (see Arcement and Schneider, 1984; Barnes, 1978). For situations lying outside the engineer's experience, a more regimented approach is presented (Arcement and Schneider, 1984). Once the Manning's n -values have been selected, it is highly recommended that they be verified or calibrated with historical highwater marks and/or gaged stream flow data.

Manning's n-values for artificial channels are more easily obtained than for natural stream channels. Refer to Appendix 7D-1 and 7D-2 for typical n-values for both man-made and natural stream channels.

7.4.4.3.3 Calibration

For major channel analyses in existing channels, the equations should be calibrated with historical highwater marks and/or gaged stream flow data to ensure that they accurately represent local channel conditions. The following parameters, in order of preference, should be used for calibration: Manning's n, slope, discharge, and cross section. Proper calibration is essential if accurate results are to be obtained.

7.4.4.3.4 Switchback Phenomenon

If the cross section is improperly subdivided, the mathematics of Manning's equation causes a switchback. A switchback results when the calculated discharge decreases with an associated increase in elevation. This occurs when, with a minor increase in water depth, there is a large increase of wetted perimeter. Simultaneously, there is a corresponding small increase in cross-sectional area, which causes a net decrease in the hydraulic radius from the value computed for a lesser water depth. With the combination of the lower hydraulic radius and the slightly larger cross-sectional area, a discharge is computed which is lower than the discharge based upon the lower water depth. More subdivisions within such cross sections should be used, and the divisions should be based on both vegetation and geometry, in order to avoid the switchback error. Figure 7-5 depicts an example of the switchback phenomenon.

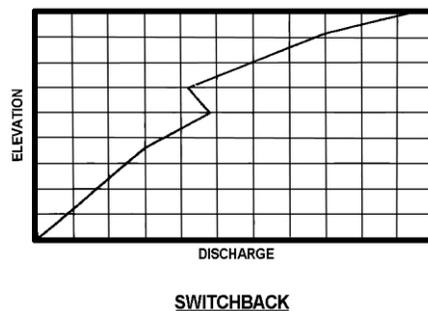


Figure 7-5 Example of Switchback Phenomenon

7.4.4.4 Single-Section Analysis

The single-section analysis method (slope-area method) is simply a solution of Manning's equation for the normal depth of flow, given the discharge and channel cross section properties including geometry, slope and roughness. It implicitly assumes the existence of steady, uniform flow; however, uniform flow rarely exists in either man-made or natural channels. Nevertheless, the single-section method is often used to design man-made channels for uniform flow as a first approximation, and to develop a stage-discharge rating curve in a natural channel for tailwater determination at a culvert or storm drain outlet. The single-section analysis method is used in the VDOT method for design of roadside ditch linings.

A stage-discharge rating curve is a graphical relationship of stream flow depth or elevation versus discharge at a specific point on a channel. This relationship should cover a range of discharges up to at least the base (100-yr) flood. The stage-discharge curve procedure is discussed in Section 7.5.3.1.

Alternatively, a graphical technique such as those given in the appendices can be used for trapezoidal and prismatic channels. The best approach, especially in the case of natural channels, is to use a computer program such as FEMA's "Quick-2" software package.

In natural channels, the transverse variation of velocity in any cross section is a function of subsection geometry and roughness and may vary considerably from one stage and discharge to another. It is important to know this variation for purposes of designing erosion control measures and locating relief openings such as in highway fills. The single-section method can be used by dividing the cross section into subsections of relatively uniform roughness and geometry. It is assumed that the energy grade line slope is the same across the cross section so that the total conveyance (K_t) of the cross section is the sum of the subsection conveyances. The total discharge is then $K_t S^{1/2}$ and the discharge in each subsection is proportional to its conveyance. The velocity in each subsection is obtained from the continuity equation, $V = Q/A$.

7.4.4.5 Water Surface Profile Analysis

The step-backwater analysis is useful for determining unrestricted water surface profiles where a highway crossing or encroachment is planned, and for analyzing how far upstream the water surface elevations would be affected. Because the calculations involved in this analysis are tedious and repetitive, it is recommended that a computer program such as the Corps of Engineers HEC-RAS model be used.

7.4.4.5.1 Water Surface Profile Methodology

When uniform flow cannot be reasonably assumed and, therefore, a single cross section cannot represent the channel segment, then an energy balance method must be used to compute the water surface profile (elevation). The energy equation is used in computing the water surface profile.

The method requires definition of the geometry and roughness of each cross section as discussed previously. Manning's n values can vary both horizontally and vertically across the section. Expansion and contraction head loss coefficients, variable main channel and overbank flow lengths and the method of averaging the slope of the energy grade line can all be specified.

The energy equation is derived from Equation 7.10 in Section 7.4.4.2.11.

$$d_1 + \alpha_1 \frac{V_1^2}{2g} + z_1 = d_2 + \alpha_2 \frac{V_2^2}{2g} + z_2 + h_L \quad (7.11)$$

Where:

- d = Depth of flow, ft
- V = Mean velocity, fps
- z = Elevation of flow line, ft
- h_L = Total head loss, ft
- α = Velocity distribution coefficient*

Equation 7.11 shows that the total head at Section 1 is equal to the total head at Section 2 and the energy (head) losses. Total energy losses include friction and minor losses.

$$h_L = h_f + h_o \quad (7.12)$$

Where:

- h_L = Total head losses, ft.
- h_f = Friction loss, ft.
- h_o = Summation of minor losses, ft.

In most simple water surface profile calculations, minor losses are ignored; therefore, h_L is assumed to be equal to h_f .

$$h_f = LS_A \quad (7.13)$$

Where:

- L = Length of channel segment, ft.
- S_A = Average energy slope of channel segment, ft./ft.

$$S_A = \frac{S_1 + S_2}{2} \quad (7.14)$$

*Rev. 9/09

Where:

S_1 = Energy slope at Section 1, ft./ft.

S_2 = Energy slope at Section 2, ft./ft.

The energy slope at a given cross section is computed using Equation 7.15 and is shown graphically in Figure 7-6.

$$S = \frac{Q^2 n^2}{2.25 R^{\frac{4}{3}} A^2} \quad (7.15)$$

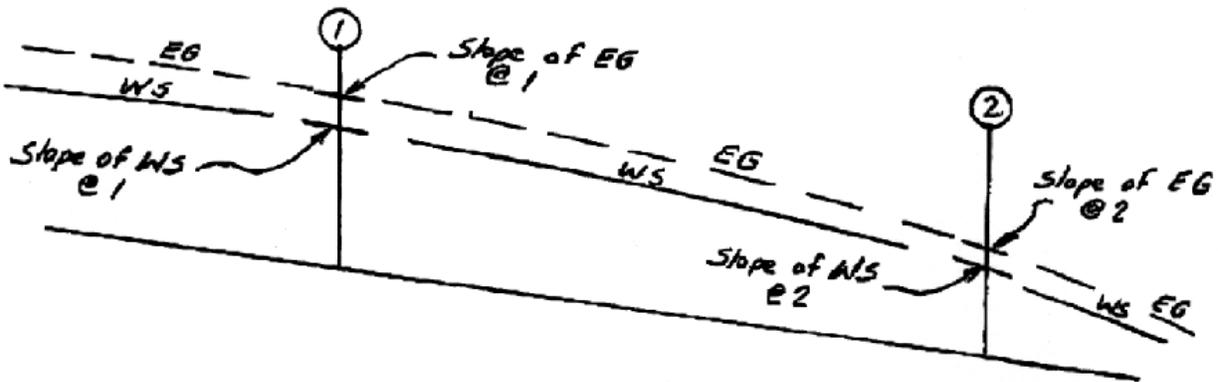


Figure 7-6 Energy Slope between Two Channel Sections

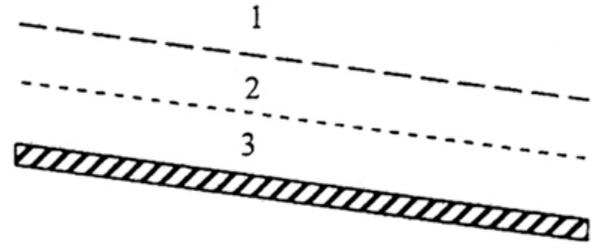
7.4.4.5.2 Classifications of Backwater Profiles

Figure 7-7 shows the notation for classifying water surface profiles and Figure 7-8 shows the types of possible flow profiles. Figure 7-7 and Figure 7-8 are from the USACE's Gary Brunner.

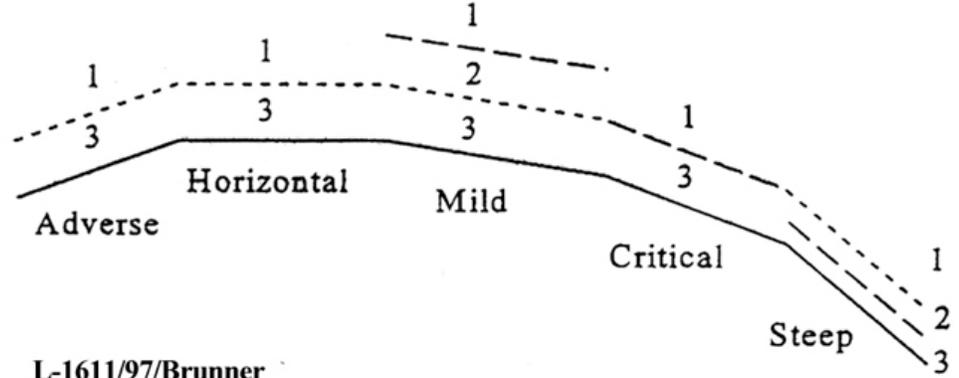
DEPTHS

Actual Depth	—————
Normal Depth	- - - - -
Critical Depth	- · - · -

REGIONS



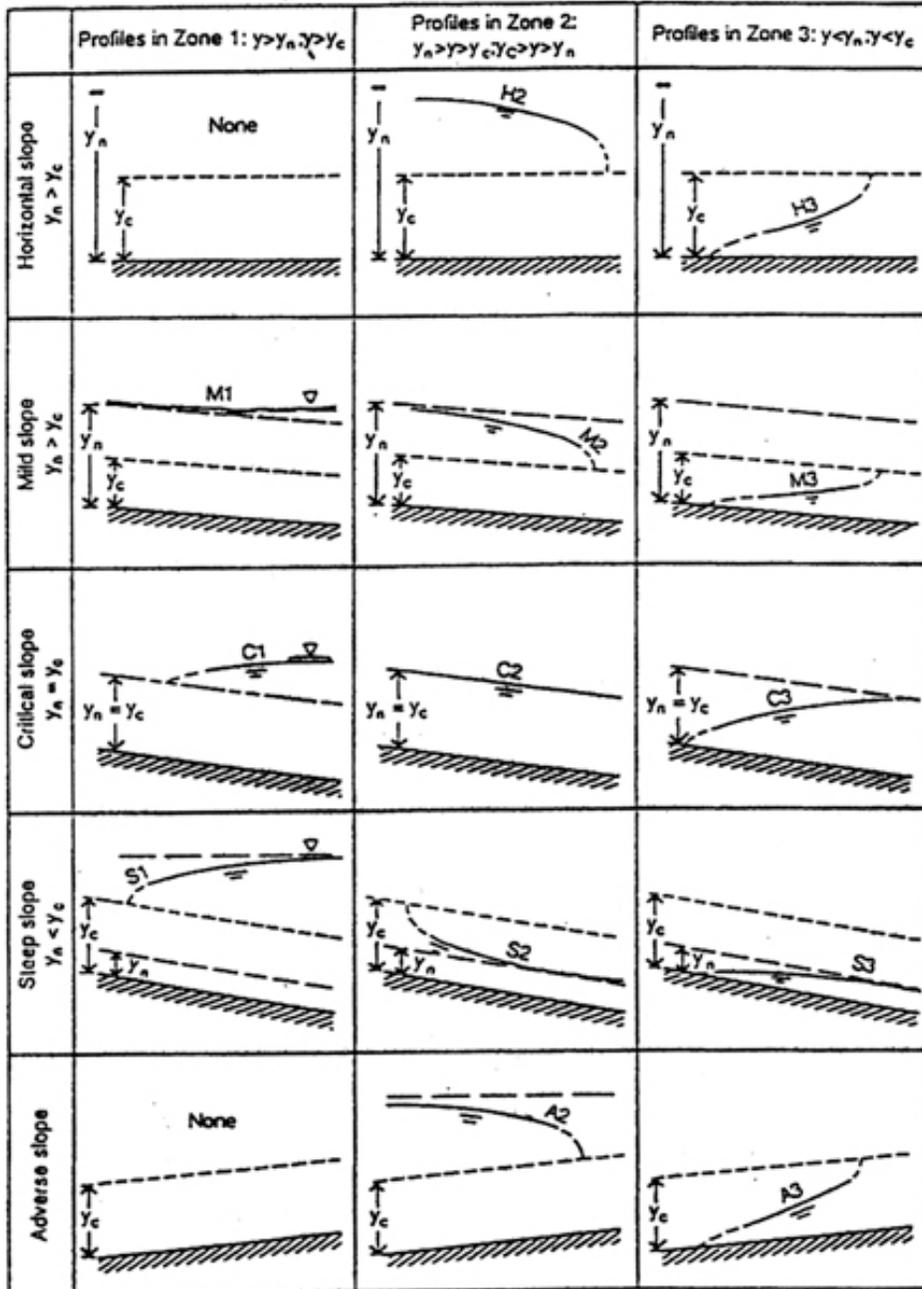
SLOPES



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Figure 7-7 Notation for Classifying Water Surface Profiles

GRADUALLY VARIED FLOW



L-1611/97/Brunner

Figure 7-8 Types of Backwater Profiles

7.4.4.5.3 Water Surface Profile Computations

The references (Davidian, 1984 and USACE, 1986) are valuable sources of guidance on the practical application of the step-backwater method to roadway drainage problems involving open channels. These references contain guidance on cross section determination, location and spacing, and stream reach determination. The reference (USACE, 1986) investigates the accuracy and reliability of water surface profiles related to n-value determination and the survey or mapping technology used to determine the cross section coordinate geometry.

7.4.5 Water and Sediment Routing

Water and sediment routing is a complex phenomenon, and a detailed discussion is beyond the scope of this manual. Information may be found in documentation of the BRI-STARS (Bridge Stream Tube Model for Alluvial River Simulation) Computer Model, (Molinas, 2000). The model is semi-two dimensional, and both energy and momentum functions are incorporated so that the water surface profile computation can be carried out through combinations of subcritical and supercritical flows without interruption. Another computer model for sediment routing is the Corps of Engineers HEC-6, "Scour and Deposition in Rivers and Reservoirs." (legacy software)

7.4.6 Ditch and Channel Protection

A significant means of reducing erosion associated with roadways is through the use of properly designed ditches and ditch lining. Linings may be flexible such as vegetation, synthetic material; or riprap or linings may be rigid such as concrete. Erosion resistant vegetation should be used whenever possible and may in some locations require the use of either a temporary Rolled Erosion Control Product (RECP) (VDOT Standard EC-2) or a permanent Rolled Erosion Control Product (RECP) (VDOT Standard EC-3). Flexible linings are generally less expensive than rigid linings and permit infiltration and filtering of pollutants. Flexible linings provide a lower flow capacity for a given cross-sectional area when compared to rigid linings. They also have correspondingly lower velocities than rigid linings.

Rigid linings are **traditionally*** used on steep grades due to high velocities and shear stresses and may be used for areas where channel width is restricted and the higher flow capacity is needed. Rigid channels require channel protection or energy dissipation at the termination point to prevent scour due to the high outlet velocities. Rigid linings can be damaged or destroyed due to flow undercutting the lining at bends, joints or intersecting ditches where the flow is not contained within the lining. The design of channels with rigid lining **shall** provide any design details that are needed to protect the undercutting of the lining and preserve **its** integrity.

*Rev. 5/17

Two methods are commonly applied to determine whether a channel is stable from an erosion standpoint: Permissible Velocity and Tractive Force (Permissible Shear) Methods. These methods are described **more in detail** in the following sections.

7.4.6.1 Permissible Velocity

Using the permissible velocity approach, the channel is assumed to be stable if the mean velocity is lower than the maximum permissible velocity. The application of the permissible velocity method is quite simple. The Manning's equation is used to compute the flow velocity in the channel for the design storm. The flow velocity is then compared with the maximum permissible velocity for the channel bed and bank soils and the lining material.

If the computed velocity is less than the maximum permissible velocity, the channel should be **considered as** stable. Corrections to the maximum permissible velocity may be applied based on flow depth and channel sinuosity.

The maximum permissible velocity (MPV) in a channel varies with the channel bed material and with the material being transported by the water. Clear water is the most erosive, and therefore its MPVs are the lowest for a given bed material (see Appendix 7D-6). When the water is transporting fine silts, the MPV is up to 100% higher than **that** for clear water. For this reason, clear water being released from a settling facility such as a detention pond is often called "hungry water."

For water carrying a courser material such as sand and gravel, the MPV may be higher or lower than for clear water. For this situation, refer to Appendix 7D-6 to obtain the MPV for the given channel bed material.

While the permissible velocity method **has been** widely used, the tractive force (permissible shear) method provides a more **physical-based** and realistic model for particle detachment and erosion processes (FHWA's HEC-15, "Design of Roadside Channels with Flexible Linings"). **The designer shall apply** the tractive force method be used for roadside ditches and major channel analyses.

7.4.6.2 Tractive Force (Permissible Shear)

The Permissible Tractive Force (Permissible Shear) Method provides a physical-based and realistic model for particle detachment and erosion processes (FHWA's HEC-15, "Design of Roadside Channels with Flexible Linings").

The Tractive Force (Permissible Shear) Method takes into account the physical factors of bed material, channel geometry, depth, and velocity of flow. The method is applicable to non-cohesive materials for which the permissible tractive force is related to particle size and shape and the sediment load in the water.

*Rev. 5/17

Particle diameters are based on the equivalent spherical volume and assume 75% of the mass is smaller by weight (D_{75}). In the absence of a gradation curve, it may be assumed that the D_{75} stone size is equal to 1.96 times the D_{50} stone size.

The average tractive force formula is: *

$$\tau_o = 62.4RS_o \quad (7.16)$$

Where:

$$\begin{aligned} \tau_o &= \text{Average tractive force, lbs/ft}^2 \\ R &= \text{Hydraulic radius, ft.} \\ S_o &= \text{Channel slope, ft/ft.} \end{aligned}$$

In channels whose width (B) to depth (d) ratio is 10 or more, the depth of flow (d) may be substituted for R, thus obtaining the maximum tractive force on the channel bed.

$$\tau_{\max} = 62.4dS_o \quad (7.17)$$

Where:

$$d = \text{Depth of flow, ft}$$

The material on the side slope may establish the limiting condition for permissible tractive force, rather than the material on the bed. The resistance to movement of the material on the side slope is reduced by the downward sliding force due to gravity. The ratio of critical shear on the side slope to critical shear on the bottom is expressed as factor K_1 .

Note: K_1 in HEC-11 is the same variable as K_2 in HEC-15.

$$K_1 = \sqrt{1 - \frac{\sin^2 \theta}{\sin^2 \phi}} \quad (7.18)$$

Where:

$$\begin{aligned} \theta &= \text{Side slope angle (measured from the horizontal), degrees} \\ \phi &= \text{Natural angle of repose of material under consideration (measured from the horizontal), deg.} \end{aligned}$$

Note: The descriptions for θ and ϕ (above) are reversed in Appendix 7E-8.
(shown one way in HEC-11 and the other way in HEC-15)

*Rev. 7/16

The angles of repose for various sizes of non-cohesive materials can be determined from Appendix 7E-1.

The permissible tractive force for various non-cohesive soils is obtained from Appendix 7E-2. Appendix 7E-3 can be used to estimate the permissible tractive force for cohesive soils.

7.4.6.2.1 Shear Stress in Bends*

Flow around a bend can impose higher shear stresses on the channel bottom and sides as compared to a straight channel. The following equation gives the maximum shear stress in a bend:

$$\tau_b = K_b \tau_{\max} \quad (7.19)$$

Where:

τ_b = Maximum bend shear stress, lb/ft²

K_b = Ratio of channel bend to bottom shear stress

τ_{\max} = Shear stress in straight channel at maximum depth, lb/ft²

The ratio of channel bend to bottom shear stress (K_b) is a function of the ratio of channel curvature to the top (water surface) width, R_c/T . K_b can be determined from the following equation:

$$\begin{aligned} K_b &= 2.00 & R_c/T &\leq 2 \\ K_b &= 2.38 - 0.206(R_c/T) + 0.0073(R_c/T)^2 & 2 < R_c/T < 10 & \quad (7.20) \\ K_b &= 1.05 & 10 &\leq R_c/T \end{aligned}$$

Where:

R_c = radius of curvature of the Centerline of the bend, ft

T = channel top (water surface) width, ft

*Rev. 7/16

7.4.6.3 Geotextile Channel Linings

Geotextile materials designated as Standard EC-3 RECP (Permanent) are used for protective linings in ditches. Standard EC-3 RECP (Permanent) is intended to be used as a protective ditch lining material to be applied when the design velocity or tractive force exceeds the allowable velocity or tractive force for Standard EC-2 RECP (Temporary).

When the design velocity or tractive force exceeds the allowable velocity or tractive force for Standard EC-3, a paved (or riprap) lining is required.

The Standard EC-3 RECP (Permanent) may be used as a protective slope lining for dry cut or fill slopes and wet cut slopes to stabilize the slope on which vegetation is being established. (See VDOT Road and Bridge Standards)

7.4.6.3.1 Design Criteria, Geotextile Linings

Under the Permissible Velocity method, differing types of EC-2 or EC-3 linings will be selected due to the following criteria, while using the Manning's n-values shown in Table 7-2A:*

- EC-2 Types 1, 2, 3, or 4 when the 2-yr design velocity in the ditch does not exceed 4 feet per second (fps)
- EC-3 Type 1, when the 2-yr design velocity is between 4-7 fps
- EC-3 Type 2, when the 2-yr design velocity is between 7-10 fps
- If the 2-yr design velocity is greater than 10 fps, the use of a flexible lining shall be avoided, and a rigid lining shall be specified.

Under the Tractive Force method, differing types of EC-2 or EC-3 linings will be selected due to the following criteria, while using the Manning's n-values in Table 7-2A.

- EC-2 Type 1, when the 2-yr design tractive force does not exceed 1.5 lb/ft²
- EC-2 Type 2, when the 2-yr design tractive force is between 1.5 – 1.75 lb/ft²
- EC-2 Type 3, when the 2-yr design tractive force is between 1.75 - 2.0 lb/ft²
- EC-2 Type 4, when the 2-yr design tractive force is between 2.0 - 2.25 lb/ft²
- EC-3 Type 1, when the 2-yr design tractive force is between 2.25 - 6 lb/ft²

*Rev. 5/17

- EC-3 Type 2, when the 2-yr design tractive force is between 6 - 8 lb/ft²
- EC-3 Type 3, when the 2-yr design tractive force is between 8 – 10 lb/ft²
- If the 2-yr design tractive force exceeds 20 lb/ft², the use of a flexible lining shall be avoided, and a rigid lining shall be specified.*

Manufacturers have developed a variety of rolled erosion control products (RECPs) for erosion protection of ditches and channels. The AASHTO National Transportation Product Evaluation Program (NTPEP) has identified the test procedures applicable to RECPs. These test results shall be submitted to VDOT for acceptance before use. The test results shall include a table of “Standard n value versus Applied Shear” as shown in Table 5.4, Chapter 5 of the HEC-15 manual. The upper allowable shear stress should equal or exceed the calculated design tractive force. The upper and lower allowable shear stress values must equal twice and one-half of the middle value, respectively.

It is understood that computing ditch/channel capacities is an iterative procedure through the design process. Ultimately in terms of completed calculations, it is encouraged that the designer compute the Manning’s n-value of that type of EC-2/EC-3 that he/she specified in the material quantities. It is understood that most manufacturers demark a range Manning’s n-value for each type of VDOT EC-2/3 classification. The designer shall use the mid-range value of the range of such Manning’s n-value that the manufacturer provides.

*Rev. 5/17

Table 7-1 Allowable Velocity and Shear Stress Values for Lined Ditches*

Type of Lining	Maximum Allowable Velocity (fps)	Maximum Allowable Shear Stress (lb/ft ²)
Bare Earth (See Appx 7D-2)	Varies	Varies
VDOT EC-2 Type-1	4.0	1.5
VDOT EC-2 Type-2	4.0	1.75
VDOT EC-2 Type-3	4.0	2.0
VDOT EC-2 Type-4	4.0	2.25
VDOT EC-3 Type 1	7.0	6.0
VDOT EC-3 Type 2	10.0	8.0
VDOT EC-3 Type-3	N/A	10.0
Concrete	NA	NA
VDOT Riprap	Based on Shear Stress	Varies

*Rev. 5/17

Table 7-2A Recommended Manning's n-Values for Lined Ditches

Lining Category	Lining Type	Manning's n		
		Maximum	Typical	Minimum
Unlined	Bare Soil	0.025	0.020	0.16
	Rock Cut	0.045	0.035	0.025
Temporary RECP/EC-2 ¹	Type 1	0.045	0.045 – 0.028	0.028
	Type 2	0.045	0.045 – 0.028	0.028
	Type 3	0.045	0.045 – 0.028	0.028
	Type 4	0.022	0.022 – 0.014	0.014
Permanent RECP/EC-3 Type 1 thru Type 3 ¹	Unvegetated	0.036	0.036 – 0.024	0.024
Riprap ^{2,3}	Class A1	0.124	0.072	0.038
	Class I	0.153	0.086	0.041
	Class II	0.181	0.095	0.042
Rigid	Concrete	0.015	0.013	0.013

¹ General values based on approved product list
Consult with individual manufactures for more specific information

² Values interpolated from data provided in HEC-15

³ In general, $n=0.0395(d_{50})^{0.167}$, where d_{50} =median stone diameter

7.4.6.3.2 Paved Flumes

Due to the substantial number of failures and continual maintenance problems associated with PG-4 flumes on fill slopes, flumes shall* not be used on fill slopes.

In lieu of paved flumes, the appropriate type of drop inlet and pipe be used in all possible situations. For design considerations of pipe on steep slopes see Section 9.4.8.7 of the Drainage Manual.

To a lesser degree, similar problems and concerns have been noted with paved flumes in cut sections. The alternatives for paved flumes in cut sections are usually very limited unless the cut is of a shallow depth.

When design situations involve the apparent need for paved flumes, the Drainage Designer shall explore all feasible alternatives to develop a design that will address both constructability and future maintenance concerns; however a flume shall not be lined with riprap.

7.4.6.4 Riprap

Riprap is defined as a blanket of well-graded stone used to counteract the effects of erosion or scouring on channels, ditches, embankments, jetties, shorelines, and bridge substructure members such as abutments and piers. Riprap is usually described in terms of the size and/or weight of the stone whose volume makes up approximately 50% of the total mass. The size of the 50% stone is measured in terms of its equivalent mean spherical diameter (MSD) and is referred to as the stone's D_{50} . The weight of the 50% stone is referred to by its W_{50} . The Department has six standard riprap classifications whose 50% stone size and weights and recommended blanket thickness (T) are tabulated in Appendix 7D-3.

Additional information on VDOT standard riprap may be found in the Department's Road and Bridge Specifications.

The designer shall specify on the plans the type of Riprap and the dimensions (length, width and depth) for placement. The quantity shall be computed using two (2) tons/cy (148 lbs/ft³) for plan estimating purposes, unless otherwise specified by the District Administrator.

*Rev. 5/17

The following general note is to be copied on the plans when riprap is specified.

“The proposed riprap may be omitted by the Engineer if the slope upon which the plans designate riprap to be placed is found to meet the following criteria: The slope designated for placement of riprap is comprised of solid rock or closely consolidated boulders with soundness, size and weight equal to or exceed the specifications for the proposed riprap. If the slope is found to be comprised of material, which is coarser than the bedding aggregate filter blanket specified on the plans, the aggregate filter blanket may be deleted by the Engineer.”

7.4.6.4.1 Riprap Dimensions and Weights

Appendix 7D-4 may be used as a guide to match certain rock dimensions to equivalent weights. This table is not to be used for acceptance or rejection of riprap material.

The approximate percentage of voids for all VDOT standard riprap classes is 25% for the estimation of quantities.

7.4.6.4.2 Soils Survey

A soil survey is to be conducted through areas where a channel change is proposed and through embankment areas where riprap may be required. The plans or profile rolls for the regular soil survey will show the location of channel changes and the location where riprap will be required on the fill section.

Borings along the proposed channel change are to be taken at sufficient intervals to determine the type of material encountered along the slopes and in the bottom of the channel.

The borings made in the cut sections or in the borrow pits for construction of the fills are adequate to determine the type of material used in the fills. The test results on the material used in embankments or along channel changes where riprap is required should include the plastic and liquid limits of the minus No. 40 sieve and the grading or particle size of the total sample. This information should be submitted in the regular soil survey report.

The Project Inspector will visually examine the slope upon which the plans designate riprap to be placed. If the slope material appears coarser than the bedding aggregate specified the Project Inspector is to notify the District Material Engineer, through normal channels, for a more detailed investigation to determine the actual need for the bedding. If the slope is comprised of solid rock or closely consolidated boulders with soundness, size and weight equal to or exceeding the specifications for the proposed riprap, then the riprap may be deleted by the District Construction Engineer.

The quantities will be field adjusted, using the supplier's stone weight and the applicable percent of voids for the type or class of material used, to obtain the actual quantity.

7.4.6.4.3 Riprap Bedding

Riprap shall be placed over an appropriate bedding material consisting of a geotextile and aggregate cushion layer in accordance with the following guidelines

- In the case of Class A1, I, and II riprap, the aggregate cushion is not required.
- In the case of Class III, Type I, and Type II riprap, an intermediate aggregate cushion layer will be required which consists of a material of a size, gradation, and thickness as recommended by the Materials Division.

The geotextile may only be omitted under the conditions discussed above or with the approval of the District Materials Engineer or District Drainage Engineer.

7.4.6.4.4 Major Channels

Riprap is often used as slope protection for natural or man-made stream channels. The need for such slope protection is predicated on the fact that the native soil material or fill material may be displaced by design flows in the channel. The first step in the design process is to determine whether or not the fill or native material will be displaced. The tractive force method is usually employed to make this determination.

7.4.6.4.5 Minor Channels

VDOT normally does not permit the use of standard riprap for linings in standard roadside or median ditches due to its size and normal blanket thickness reducing the ditch cross section. In addition, hand placement, as opposed to end dumping, would probably be necessary in small channels. There are, however, situations in which the smaller riprap sizes such as Class A1 and I may be used to good advantage where special design small trapezoidal ditches such as those connecting culvert cross drains, outfalls, or the discharge point of standard design ditches, are required. In such situations, the Department requires that the riprap be sized in accordance with procedures presented in HEC-15. When riprap is used to line minor channels, the design for the channel cross section should allow for the thickness of the riprap and bedding layers without reducing the available flow section.

*Rev. 9/09

Design Procedures and Sample Problems

The following design procedures and examples pertain to minor channels, major channels, and natural channels. The procedures are similar, but become more detailed for the larger channel projects.

7.4.1 Documentation Requirements

These items establish a minimum requirement for all channels except roadside ditches. Also, see Chapter 3, Documentation.* The following items used in the design or analysis should be included in the documentation file:

- Hydrology and stage discharge curves for the design, check floods and any historical water surface elevation(s)
- Cross section(s) used in the design water surface determinations and their locations
- Roughness coefficient assignments (n-values)
- Information on the method used for design water surface determinations
- Observed highwater, dates and discharges
- Channel velocity measurements or estimates and locations
- Water surface profiles through the reach for the design, check floods and any historical floods
- Design or analysis of materials proposed for the channel bed and banks;
- Energy dissipation calculations and designs
- Copies of all computer analyses.

7.4.2 Roadside Ditches and Minor Channels

7.4.2.1 Roadside Ditch and Minor Channel Design Procedure

The following six basic design steps are normally applicable to minor channel design projects:

Step 1: Establish a roadside plan

- A. Collect available site data
- B. Obtain or prepare existing and proposed plan-profile layout including highway, culverts, bridges, etc.
- C. Determine and plot on the plan the locations of natural basin divides and roadside ditch outlets and perform the layout of the proposed roadside ditches to minimize diversion flow lengths

An example of a roadside ditch plan/profile is shown in Figure 7-1.

*Rev. 9/09

Step 2: Obtain or establish cross section and data

- A. Provide ditch depth adequate to drain the subbase and minimize freeze-thaw effects using the standard underdrain outfall requirements that are appropriate for the project
- B. Choose ditch side slopes based on geometric design criteria including safety, economics, soil, aesthetics and access
- C. Establish bottom width of trapezoidal ditch
- D. Identify features which may restrict cross section design:
 - Right-of-way limits
 - Trees or other environmentally-sensitive areas
 - Utilities
 - Existing drainage facilities

Step 3: Determine initial ditch grades

- A. Plot initial grades on plan-profile layout. (The roadside ditch grade in cut is usually controlled by the grade of the highway.)
- B. Provide desirable minimum grade of 0.5%
- C. Consider influence of type of lining on grade
- D. Where possible, avoid features which may influence or restrict grade, such as utility locations

Step 4: Check flow capacities and adjust as necessary

- A. Compute the design discharge at the downstream end of a ditch segment (See Chapter 6, Hydrology)
- B. Set preliminary values of ditch size, roughness coefficient, and slope
- C. Determine maximum allowable depth of ditch, including freeboard
- D. Check flow capacity using Manning's equation and the single-section analysis

- E. If ditch capacity is inadequate, possible adjustments are as follow:
- Increase bottom width
 - Make channel side slopes flatter
 - Make channel slope steeper
 - Provide smoother channel lining
 - Install drop inlets and a parallel storm drain pipe beneath the channel to supplement channel capacity
- F. Provide smooth transitions at changes in channel cross sections
- G. Provide extra channel storage where needed to replace floodplain storage and/or to reduce peak discharge

Step 5: Determine ditch lining/protection needed

- A. Use the VDOT Method – Roadside Ditch Linings (Preferred Method - Section 7.5.2.2 Tractive Force (HEC-15)), or
- B. Use the method of Permissible Velocity

Step 6: Analyze outlet points and downstream effects

- A. Identify any adverse impacts such as increased flooding or erosion to downstream properties which may result from one of the following at the channel outlet:
- Increase or decrease in discharge
 - Increase in velocity of flow
 - Concentration of sheet flow
 - Change in outlet water quality
 - Diversion of flow from another watershed
- B. Mitigate any adverse impacts identified in Step 6A. Possibilities include:
- Enlarge outlet channel and/or install control structures to provide detention of increased runoff in channel
 - Install velocity control structures (energy dissipaters)
 - Increase capacity and/or improve lining of downstream channel
 - Install sedimentation/infiltration basins
 - Install sophisticated weirs or other outlet devices to redistribute concentrated ditch flow
 - Eliminate diversions which result in downstream damage and which cannot be mitigated in a less expensive fashion.

7.4.2.2 VDOT Method for Design of Roadside Ditch Linings using Tractive Force Method

The following computational procedure to determine the need for roadside ditch linings is recommended for use on roadside ditches and minor channels. Before the computational analysis can be performed, a soils report from the **USDA NRCS Published Soil Surveys for Virginia** is needed which specifies the type of soil that is found in the area of the ditch. The soil classification is then used with Appendix 7D-2 to determine the maximum allowable velocity for the native soil. Native soil is assumed for new ditches and for ditches with vegetation established for less than two years. When the maximum allowable velocity is exceeded, some type of ditch lining is needed.

Step 1: Determine the section of each ditch where the following exist:

- Steepest grade
- Highest flow or drainage area

Step 2: Determine the longitudinal grade, discharge, and tractive force for these sections, assuming no lining

If the **tractive force** is greater than the allowable **tractive force** for the appropriate soil type, a ditch lining is needed and the following “General Design Procedure for Roadside Ditch Linings” should be used. If the **tractive force** is less than the allowable tractive force, no ditch lining is needed for this section of ditch. The same type of analysis should be used for the remainder of the ditches on the project.

7.4.2.2.1 Design Procedure for Roadside Ditch Linings Using VDOT Method using the Tractive Force Method

Roadside ditch computations may be done using the format presented as Appendix 7B-1.

Step 1: The ditch under investigation is divided into convenient segments of length. Usually 100' stations are used. The drainage area and runoff coefficient(s) for use in the Rational Method are determined for the first or most upstream segment of the ditch to be analyzed.

Step 2: Determine the time of concentration to the downstream end of the first segment of ditch. Using 2-yr frequency rainfall intensity, determine the 2-yr discharge by the Rational Method.

Step 3: Determine the average longitudinal grade for the ditch segment under consideration.

*Rev. 7/16

Step 4: Find the tractive force for the 10-yr frequency design discharge. (Note: Permanent roadside ditch linings should be designed to protect the channel and remain stable during passage of a 10-yr peak flood discharge and temporary channel linings should be designed for a 2-yr peak discharge.)*

Step 5: If the tractive force is less than the maximum allowable tractive force, no ditch lining is needed. If the tractive force is more than the allowable tractive force, ditch lining should be required. The usual progression of types of ditch lining used as tractive forces increase would begin with Grass lining, VDOT Standard EC-2, then EC-3 Type A, EC-3 Type B and lastly concrete lining (Standard PG-2A). Change the ditch lining and repeat Steps 4 and 5 until a stable channel section is obtained.

Step 6: Determine the depth of flow for the 10-yr frequency discharge to insure that the hydraulic capacity has not been exceeded.

Step 7: Repeat the above steps for the next downstream segment of ditch. To calculate the discharge, add or accumulate the Rational Method CA values for each segment of the ditch contributing to the point of study. For rainfall intensity, the time of concentration for second and subsequent ditch sections are done as follows: Flow time = T_c of previous section + (Section length / Design Velocity of previous section / 60). The 2-yr, 10-yr, 50-yr and 100-yr flood events are computed from the rainfall Intensity Duration-Frequency (IDF) curve based on the B, D and E values for the particular County/City. The corresponding discharges are computed using the VDOT Modified Rational Method.

If the computed Q value for any segment of ditch is found to be less than the preceding upstream segment, the Q should be held at the higher value of Q until a higher Q is calculated for a downstream segment.

7.4.2.2 Caveats to General Design Procedures for Roadside Ditch Linings

The designer should be cautious in using this computational procedure to ensure that the factors for runoff coefficients, times of concentration, and drainage areas properly reflect the actual conditions.

The velocity and depth of flow calculated by this method is based upon uniform flow conditions. Abrupt changes in alignment or grade may cause significant deviations from uniform flow conditions and should be carefully evaluated. Design details must be provided that provide for erosion protection of the ditch in critical areas.

*Rev. 7/16

7.4.2.2.3 Roadside Ditch Lining Sample Problem (Tractive Force Method)

Given:

LOCATION: Spotsylvania Area*

DITCH SLOPE:

STATION	SLOPE
218+00 – 218+25	4.1%
218+25 - 218+50	4.3%
218+50 – 218+75	4.4%
218+75 – 219+00	3.9%
219+00 – 219+25	3.4%

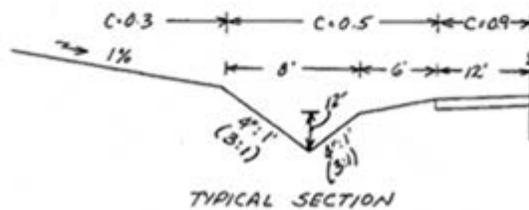
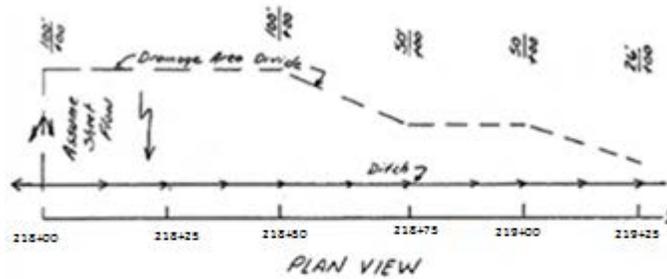


Figure 7-9 Roadside Ditch Protection Sample Problem, Plan and Section

*Rev. 7/16

LD-268

Rte 620W LANE
Left SIDE

ADD NEW ROW

PROJECT 51845 Harrison Road
SHEET 1 of 3
LOCATION Spotsylvania
DESIGNED BY / DATE
CHECKED BY / DATE

Calculate Protective Lining

STA. TO STA.	FLOW LENGTH (ft)	0.9		0.5		0.3		CA		T c (min)	I2	Q2 (cfs)	TYP. SECTION	Slope (Ft/Ft)	Radius of Bend (ft)	Protective Covering							REMARKS		
		A (ac)	CA	A (ac)	CA	A (ac)	CA	INCR	ACC.							Type	Manjls *	Allow Shear	Calculated Shear	VEL (ft/sec)	I10	Q10 (cfs)		DEP (ft)	
218+00	218+25	25	0.19	0.17	0.38	0.19		0	0.36	0.36	7.4	4.66	1.63	1	0.041		EC-2 Type 1	0.040	1.50	1.08	2.59	6.20	2.212	0.47	
218+25	218+50	25	0.04	0.04	0.01	0.01	0.05	0.02	0.06	0.42	7.6	4.63	1.88	1	0.043		EC-2 Type 1	0.040	1.50	1.18	2.74	6.16	2.563	0.50	
218+50	218+75	25	0.04	0.04	0.01	0.01	0.05	0.02	0.06	0.48	7.7	4.50	2.14	1	0.044		EC-2 Type 1	0.040	1.50	1.27	2.86	6.12	2.911	0.52	
218+75	219+00	25	0.04	0.04	0.01	0.01	0.05	0.02	0.06	0.53	7.9	4.48	2.39	1	0.039		EC-2 Type 1	0.040	1.50	1.20	2.80	6.09	3.255	0.55	
219+00	219+25	25	0.04	0.04	0.01	0.01	0.05	0.02	0.06	0.59	8.0	4.46	2.64	1	0.034		EC-2 Type 1	0.040	1.50	1.13	2.75	6.05	3.594	0.59	
219+25	219+50	25	0.04	0.04	0.01	0.01	0.05	0.02	0.06	0.65	8.2	4.42	2.89	1	0.031		EC-2 Type 1	0.040	1.50	1.06	2.70	6.01	3.929	0.62	
219+50	219+75	25	0.04	0.04	0.01	0.01	0.05	0.02	0.06	0.71	8.3	4.39	3.13	1	0.027		EC-2 Type 1	0.040	1.50	0.98	2.61	5.98	4.26	0.66	
219+75	220+00	25	0.04	0.04	0.01	0.01	0.05	0.02	0.06	0.77	8.5	4.36	3.37	1	0.023		EC-2 Type 1	0.040	1.50	0.88	2.50	5.94	4.586	0.70	
220+00	220+25	25	0.04	0.04	0.01	0.01	0.05	0.02	0.06	0.83	8.6	4.33	3.6	1	0.019		EC-2 Type 1	0.040	1.50	0.79	2.39	5.90	4.906	0.74	
220+25	220+50	25	0.04	0.04	0.01	0.01	0.05	0.02	0.06	0.89	8.8	4.30	3.84	1	0.015		EC-2 Type 1	0.040	1.50	0.67	2.22	5.86	5.221	0.79	
220+50	220+75	25	0.04	0.04	0.01	0.01	0.05	0.02	0.06	0.95	9.0	4.27	4.06	1	0.011		EC-2 Type 1	0.040	1.50	0.53	2.01	5.82	5.529	0.85	
220+75	221+00	25	0.04	0.04	0.01	0.01	0.05	0.02	0.06	1.01	9.2	4.24	4.28	1	0.008		EC-2 Type 1	0.040	1.50	0.40	1.76	5.77	5.828	0.94	
221+00	221+25	25	0.04	0.04	0.01	0.01	0.05	0.02	0.06	1.07	9.4	4.20	4.49	1	0.004	250	EC-2 Type 1	0.040	1.50	0.38	1.35	5.72	6.116	1.10	
221+25	221+50	25	0.04	0.04	0.01	0.01	0.05	0.02	0.06	1.13	9.8	4.15	4.68	1	0.108	200	EC-3 Type 1	0.030	6.00	4.45	6.05	5.65	6.381	0.53	
221+50	221+75	25	0.04	0.04	0.01	0.01	0.05	0.02	0.06	1.19	9.8	4.14	4.92	2	0.076		EC-2 Type 1	0.040	1.50	0.68	2.72	5.64	6.7	0.17	
221+75	222+00	25	0.04	0.04	0.01	0.01	0.05	0.02	0.06	1.25	10.0	4.11	5.13	2	0.076		EC-2 Type 1	0.040	1.50	0.70	2.76	5.61	6.996	0.18	
222+00	222+25	25	0.04	0.04	0.01	0.01	0.05	0.02	0.06	1.31	10.1	4.09	5.35	2	0.038		EC-2 Type 1	0.040	1.50	0.44	2.26	5.58	7.288	0.22	

Figure 7-10 Worksheet (LD-268) for Calculation of Roadside Ditch Protection, Sample Problem *

7.4.2.3 VDOT Method for Design of Roadside Ditch Linings (Permissible Velocity Method)

The following computational procedure to determine the need for roadside ditch linings is recommended for use on roadside ditches and minor channels. It was developed by VDOT and has been used for many years.

Before the computational analysis can be performed, a soils report from USDA NRCS Published Soil Surveys for Virginia is needed which specifies the type of soil that is found in the area of the ditch. The soil classification is then used with Appendix 7D-2 to determine the maximum allowable velocity for the native soil.

* Rev. 7/16

Native soil is assumed for new ditches and for ditches with vegetation established for less than two years. When the maximum allowable velocity is exceeded, some type of ditch lining is needed.

Step 1: Determine the section of each ditch where the following exist:

- Steepest grade
- Highest flow or drainage area

Step 2: Determine the longitudinal grade, discharge, and velocity for these sections, assuming no lining

If the velocity is greater than the allowable velocity for the appropriate soil type, a ditch lining is needed and the following “General Design Procedure for Roadside Ditch Linings” should be used. If the velocity is less than the allowable velocity, no ditch lining is needed for this section of ditch. The same type of analysis should be used for the remainder of the ditches on the project.

7.4.2.3.1 Design Procedure for Roadside Ditch Linings Using VDOT Method*

Roadside ditch computations may be done using the format presented as Appendix 7B-1.

Step 1: The ditch under investigation is divided into convenient segments of length. Usually 100-foot stations are used. The drainage area and runoff coefficient(s) for use in the Rational Method are determined for the first or most upstream segment of the ditch to be analyzed.

Step 2: Determine the time of concentration to the downstream end of the first segment of ditch. Using 2-year frequency rainfall intensity, determine the 2-year discharge by the Rational Method.

Step 3: Determine the average longitudinal grade for the ditch segment under consideration.

Step 4: Find the velocity for the 2-year frequency design discharge.

Step 5: If the velocity is less than the maximum allowable velocity, no ditch lining is needed. If the velocity is more than the allowable velocity, ditch lining should be required. The usual progression of types of ditch lining used as velocities increase would begin with VDOT Standard EC-2, then EC-3 Type A, EC-3 Type B and lastly concrete lining (Standard PG-2A).

Step 6: Determine the depth of flow for the 10-year frequency discharge to insure that the hydraulic capacity has not been exceeded.

*Rev. 7/16

Step 7: Repeat the above steps for the next downstream segment of ditch. To calculate the discharge, add or accumulate the Rational Method CA values for each segment of the ditch contributing to the point of study. For rainfall intensity, use the rainfall intensity value from the previous segment minus 0.1 inch. This is a simplifying assumption or approximation of the actual time of concentration that is used for computational efficiency. If the computed Q value for any segment of ditch is found to be less than the preceding upstream segment, the Q should be held at the higher value of Q until a higher Q is calculated for a downstream segment.

7.4.2.3.2 Caveats to General Design Procedures for Roadside Ditch Linings*

The designer should be cautious in using this computational procedure to ensure that the factors for runoff coefficients, times of concentration, and drainage areas properly reflect the actual conditions.

The velocity and depth of flow calculated by this method is based upon uniform flow conditions. Abrupt changes in alignment or grade may cause significant deviations from uniform flow conditions and should be carefully evaluated. Design details must be provided that provide for erosion protection of the ditch in critical areas.

7.4.2.3.3 Roadside Ditch Lining Sample Problem

Given:

- LOCATION: Lynchburg Area
- ALLOWABLE VELOCITY: 2.0 fps (Bare Earth)
- DITCH SLOPE:

STATION	SLOPE
1-2	0.5%
2-3	2.0%
3-4	3.0%
4-5	4.0%
5-6	4.0%

*Rev. 7/16

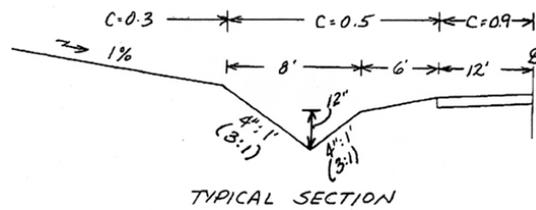
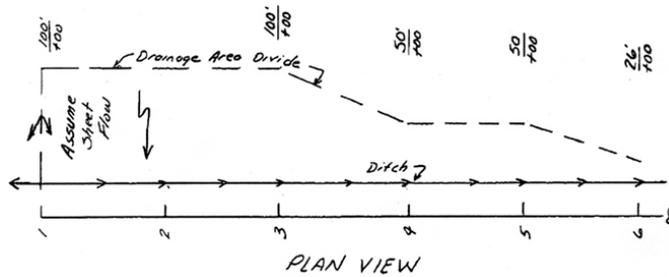


Figure 7-11 Roadside Ditch Protection Sample Problem, Plan and Section

LD-268

LANE SIDE

CUT

MED.

FILL

PROJECT DITCH PROTECTION
 BY EXAMPLE PROBLEM
 DATE _____
 SHEET _____ of _____

STA. TO STA.	FLOW	CA			INCR.	ACC.	Tc	I ₂	Q ₂	C or F	Slope Ft/Ft	ALLOW VEL.	Protective Lining					REMARKS					
		0.9	0.5	0.3									n=.03	n=.05		n=.015			I ₁₀	Q ₁₀	DEP		
		WS/CA	WS/CA	WS/CA									VEL	Q ₁₀	VEL	DEP	Q ₁₀	DEP					
1	2	12 .025	14 .016	74 .05	.09	.09	15	3.5	0.32	C	.005	2	1.2						4.8	.43	4	OK	
2	3	12 .025	14 .016	74 .05	.09	.18		3.4	0.61	C	.02	2	2.3										EC-2 REQ'D START STA Z+00
3	4	12 .025	14 .016	49 .017	.075	.26		3.3	0.85	C	.03	4		1.7	4.5				4.6	1.2	5	EC-2 REQ'D	
4	5	12 .025	14 .016	24 .017	.058	.32		3.2	1.02	C	.04	4		2.4	4.5				4.5	1.4	5	EC-2 REQ'D	
5	6	12 .025	16 .016	12 .008	.049	.37		3.1	1.15	C	.04	4		2.5	5				4.4	1.6	5.5	EC-2 REQ'D D=12"	

Figure 7-12 Worksheet (LD-268) for Calculation of Roadside Ditch Protection, Sample Problem

*Rev. 7/16

7.4.3 Major Channels

The following procedures are used to analyze flow in major channels.

7.4.3.1 Single-Section Stage-Discharge Curve Procedure

The stage-discharge curve procedure is basically a single section analyses. The following steps outline the development of a stage-discharge curve:

- Step 1: Select the typical cross section at or near the location where the stage-discharge curve is needed*
- Step 2: Subdivide cross section and assign n-values to subsections as described in Section 7.4.4.3.*
- Step 3: Estimate water-surface slope. Since uniform flow is assumed, the average slope of the streambed is normally used.*
- Step 4: Apply a range of incremental water surface elevations to the cross section.*
- Step 5: Calculate each incremental elevation. Total discharge at each elevation is the sum of the discharges from each subsection at that elevation. In determining hydraulic radius, the wetted perimeter should be measured only along the solid boundary of the cross section and not along the vertical water interface between subsections.*
- Step 6: After the discharge has been calculated at several incremental elevations, a plot of stage versus discharge should be made. This plot is the stage-discharge curve and it can be used to determine the water-surface elevations corresponding to the design discharge or other discharges of interest.*

7.4.3.2 Water Surface Profile Procedure

The water surface profile computations must be started at a point of a known or an assumed water surface elevation. This starting water surface elevation can be derived in one of three ways.

- Critical Depth (d_c) - When changes in flow conditions or channel characteristics cause a transition from subcritical to supercritical flow, or supercritical to subcritical flow, the flow must, at some point, pass through critical depth. When the transition in flow is caused by a change in the slope of the channel bed, then critical depth can be assumed to occur at the change of grade point. Critical depth d_c can then be used to generate a starting elevation.

- **Known Water Surface Elevation** - When controls within the channel section dictate a certain stage (elevation)-discharge relationship, then the elevation generated by that control for the targeted discharge can be used as a starting elevation. Examples of controls within the channel section are a culvert under an embankment across the channel, a dam across the channel section, etc.
- **Slope/Area (Normal Depth - d_n)** - Water Surface Profile computations can be started at a point in the channel where uniform flow can be assumed and, therefore, normal depth (d_n) can be used in order to generate a starting elevation.

The following VDOT procedure for developing water surface profiles is recommended. A convenient design form can be found in Appendix 7B-2.

Step 1: Determine flow type - subcritical or supercritical

- A. If flow is supercritical, computations will proceed in a downstream direction from some known starting point.
- B. If flow is subcritical, computations will proceed in an upstream direction.

Step 2: Starting point based on:

- A. Critical depth (d_c)
- B. Known water surface elevation
- C. Slope/Area method (d_n)

Step 3: On computation sheet, let subscript 1 reflect the values at the known cross section and subscript 2 reflect the values at the unknown cross section

Step 4: After determining the starting point and its water surface elevation, compute the Total Head for the starting cross section

$$h_1 = d_1 + \frac{V_1^2}{2g} + z_1$$

Step 5: For the channel segment between the starting point and the next cross section

- A. Determine the Target Head, which is equal to the Total Head of the known cross section (starting point) (from step 4).
- B. Assume a depth (d_2) at the unknown cross section.
- C. Compute area (A_2), wetted perimeter (P_2), hydraulic radius (R_2) and velocity (V_2) for the unknown cross section based on the assumed depth (d_2).

D. Compute velocity head for unknown cross section ($V_2^2/2g$). Determine z_2 (elevation) at unknown cross section and length (L) between known and unknown cross section.

E. Compute energy slope (S_1) at the known cross section

$$S_1 = \frac{Q^2 n^2}{2.25 R_1^{\frac{4}{3}} A_1^2}$$

F. Compute energy slope (S_2) at the unknown cross section

$$S_2 = \frac{Q^2 n^2}{2.25 R_2^{\frac{4}{3}} A_2^2}$$

G. Compute average energy slope (S_A) between cross section

$$S_A = \frac{S_1 + S_2}{2}$$

H. Compute total head loss (h_L) between cross sections

$$h_L = L S_A$$

I. Compute total head (h_2) at the unknown cross section

$$h_2 = d_2 + \frac{V_2^2}{2g} + z_2$$

J. Solve equation:

Total Head at the upstream cross section = Total Head at the downstream cross section + head loss (h_f or h_L).

Use trial and error method until the two sides of the equation balance within the permissible tolerance.

K. Once the equation has been satisfied and the depth (d_2) established (Step 5j), then the previous unknown cross section becomes the known cross section for the next segment. Assume a depth (d_2) for the new unknown cross section, compute properties (A_2 , P_2 , R_2 , V_2) and repeat the procedure.

7.4.3.2.1 Water Surface Profile Sample Problem

GIVEN: $Q = 100$ cfs

$n = 0.15$

Cross section shown in Figure 7-13

REQUIRED: Compute Water Surface Profile (WSP) between sections 1 and 3 with a tolerance of 0.2'.

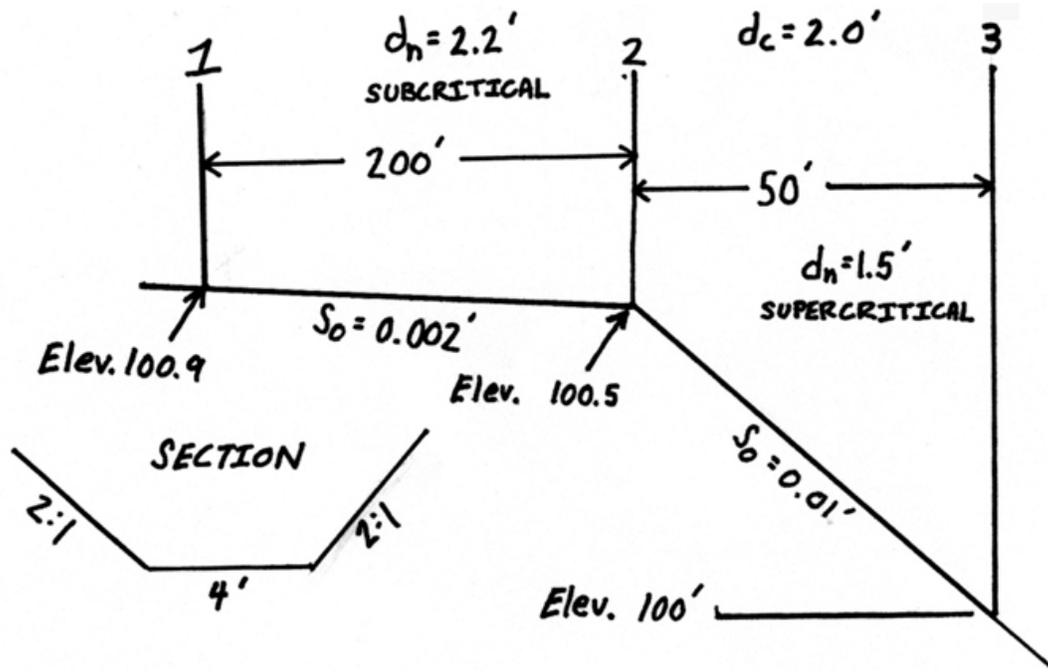


Figure 7-13* Water Surface Profile Sample Problem

- (1) Compute values for d_n and d_c at each section (use the nomographs in Appendix 7C). Determine elevation at each section. Determine subcritical or supercritical flow at each section.
- (2) Determine starting point and direction of computations.

Starting point = # 2 (d_c)

Compute from # 2 to # 3 (supercritical flow)

Compute from # 2 to # 1 (subcritical flow)

*Rev. 7/16



Worksheet For Non-Uniform Flow In Open Channels

STA.	H_1	d_2	A_2	P_2	R_2	V_2	$\frac{V^2}{2g}$	Z_2	L	S_1	S_2	S_A	h_1	H_2	$H_{up} = H_{down} + h_1$
2	103.11	$\frac{2}{4}$	$\frac{A_1}{16}$	$\frac{P_1}{12.99}$	$\frac{R_1}{1.24}$	$\frac{V_1}{6.25}$	$\frac{V_1^2}{0.67}$	$\frac{Z_1}{100.5}$	-	.00293					ASSUME WSP STARTS @ SEC. 2 WITH d_c 2' \therefore WSE 100.5 + 2 = 102.5'
3 \rightarrow	103.11	$\frac{1.5}{d_n}$	10.5	10.71	0.98	9.52	1.41	100	50	.00293	.00932	.00612	0.31	102.91	$103.11 + 102.91 + 0.31 =$ 103.22 OK \therefore WSE = 100 + 1.5 = 101.5'
\leftarrow	103.11	$\frac{2.2}{d_n}$	18.48	13.84	1.34	5.41	0.45	100.9	200	.00293	.00198	.00246	0.49	103.55	$103.55 = 103.11 + 0.49 =$ 103.6 OK \therefore WSE = 100.9 + 2.2 = 103.1'

Figure 7-14* Worksheet for Calculation of Non-Uniform Flow in Open Channels, Sample Problem

7.4.4 Natural Channels

7.4.4.1 General

The analysis procedure for all types of channels has some common elements as well as some substantial differences. This section will outline a process for assessing a natural stream channel.

7.4.4.2 Natural Channels Design Procedure

Usually the analysis of a natural channel is in conjunction with the design of a highway hydraulic structure such as a culvert or bridge or a longitudinal encroachment such as a highway embankment. In general, the objective is to convey the water along or under the highway in such a manner that does not cause damage to the highway, stream, or adjacent property. An assessment of the existing channel is usually necessary to determine the potential for problems that might result from a proposed action. The level of detail of the studies necessary should be commensurate with the risk associated with the action, and with the environmental sensitivity of the stream and adjoining floodplain.

*Rev. 7/16

Although the following step-by-step procedure may not be appropriate for all possible applications, it does outline a process that will usually apply to natural channel design.

Step 1: Assemble site data and project file

A. Data Collection

- Topographic, site and location maps
- Roadway profile
- Photographs
- Field reviews
- Design data at nearby structures
- Gaging records
- Historic flood data and local knowledge
- Utilities, including existing drainage

B. Studies by other agencies

- Flood insurance studies
- Floodplain studies
- Watershed studies

C. Environmental constraints

- Floodplain encroachment
- Floodway designation
- Fish and wildlife habitat
- Commitments in review documents

D. Design criteria

Step 2: Determine the project scope

A. Determine level of assessment

- Stability of existing channel
- Potential for damage
- Sensitivity of the stream

B. Determine type of hydraulic analysis

- Single-section analysis
- Step-backwater analysis

C. Determine survey information needed

- Extent of streambed profiles
- Locations of cross-sections
- Elevations of flood-prone property
- Details of existing structures
- Properties of bed and bank materials

Step 3: Evaluate hydrologic variables

- A. Compute discharges for selected frequencies.
- B. Consult Chapter 6, Hydrology

Step 4: Perform hydraulic analysis

- A. Single-section analysis (7.4.4.4, 7.5.3.1)
- Select representative cross section
 - Select appropriate n-values (Appendix 7D-1 and 7D-2)
 - Compute stage-discharge relationship
- B. Step-backwater analysis (7.5.3.2)
- C. Calibrate with known high water

Step 5: Perform stability analysis

- A. Geomorphic factors
- B. Hydraulic factors.
- C. Stream response to change

Step 6: Design countermeasures

- A. Criteria for selection
- Erosion mechanism
 - Stream characteristics
 - Construction and maintenance requirements
 - Cost

B. Types of countermeasures

- Meander migration countermeasures
- Bank stabilization
- Bend control countermeasures
- Channel braiding countermeasures
- Degradation countermeasures
- Aggradation countermeasures

C. For additional information

- HEC-20 Stream Stability
- Highways in the River Environment
- References

Step 7: Documentation (Section 7.5.1)

- Prepare report and file with background information

7.4.4.3 Natural Channels Design Reporting and Documentation*

Reporting and documentation detail is dependent upon several factors including:

- FEMA Floodplain Designation
- Project Permit and Compensatory Mitigation Requirements
- Project Scope

FEMA Floodplain Designation

- All projects within a FEMA Flood Insurance Rate Map-designated 100-year floodplain require review and approval by a River Mechanics Engineer regarding the level of analysis necessary for the project.

Project Permit and Compensatory Mitigation Requirements

*Rev. 7/16

- Project permit and compensatory mitigation requirements may vary from project to project and can determine the degree to which natural channel design components are required. Consideration of and adherence to permit requirements should be evaluated at the earliest possible time in the project development process.

Project Scope: Projects are separated into several categories: 1. local instream structures, 2. associated structures, and 3. relocation and restoration. Generally, instream and associated structures are defined as those structures directly associated with roadway drainage structure installation, repair or replacement, or bank protection (e.g., erosion protection). Relocation and restoration involve use of natural channel design principles to relocate existing channels, create new channels or restore degraded channels and are not always associated with roadway drainage structures. The project scope, along with the remaining items listed above, will determine the degree to which documentation and QA/QC review is required. *

- Local instream structures include individual structures or groups of structures (weirs, rock vanes, log vanes and other similar structures) intended to protect, or improve the function of, existing roadway drainage structures or address discrete erosion concerns. Some minor channel modification may be required to relocate the thalweg, remove sediment deposits, or reshape the local cross-section. In many cases, these projects may require limited data collection or design and may serve to retrofit existing structures.

Applicability:

- No channel modifications required other than minor modifications necessary for proper installation and function of the structure(s) itself
- The structure is intended to provide scour protection, redirect thalweg alignment, reduce bank erosion or restore channel geometry (i.e., bankfull width and depth) in the vicinity of an existing structure (culvert or bridge) or to a localized area
- Structure placement is not part of a larger natural channel design project

Requirements:

- The project manager must complete and submit an Abbreviated Plan, as described in the Plan Requirements Section.
- Structure design, with respect to natural channel design features, must be performed under the supervision of, or reviewed and approved by, a Hydraulic Engineer and an Environmental Stream Team member.
- Permit application must be coordinated with the District Environmental Section.

*Rev. 7/16

- Associated Structures includes any individual roadway structure designed in accordance with natural channel design principles. Examples of these structures include, but are not limited to, placement of floodplain culverts to carry the 10-year (Q_{10}) and greater design floods, base flow culverts designed to carry the 2-year (Q_2) discharges, and box culverts or bridge spans properly sized to accommodate floodplain deposition.*

Applicability:

- Channel modifications may be required to improve functionality and are limited to the minimum extent necessary upstream and downstream of the structure. All modifications must be in compliance with current permit regulations and must include natural channel design features.
- Associated Structures are not part of a larger natural channel design project.

Requirements:

- The project manager must complete and submit an Abbreviated Plan as described in the Plan Requirements Section.
- Structure design, with respect to natural channel design principles, must be performed under the supervision of, or reviewed and approved by, a Hydraulic Engineer and an Environmental Stream Team member.
- Permit application must be coordinated with the District Environmental Section.

- Restoration and Relocation may include relocation of sections of existing channels to restore stable channel geometry, channel relocation associated with road crossings, installation of instream structures, bank stabilization and other natural channel design features included as part of a compensatory stream mitigation proposal. Restoration restores flow control and habitat features to a degraded or unstable stream reach and is often part of a compensatory stream mitigation proposal. Relocation includes movement of channel sections to accommodate structure or roadway design requirements. Channel work at either end of an Associated Structure is not included in this category. Channel relocation that employs natural channel design principles is typically considered as compensation for channel impacts on a 1:1 basis. Restoration and Relocation projects can be subdivided into small and large scale projects and have different reporting and documentation requirements, as described in the Plan Requirements Section.

Applicability:

- All channels
- All projects

Requirements:

- The project manager must provide the information listed under Plan Requirements, as required, below.

*Rev. 7/16

- Conceptual and Final Design plans must be submitted to the Central Office Natural Resources Section for Quality Assurance/Quality Control review by a multidisciplinary team.

7.4.4.4 Natural Channels Design Plan Requirements

The degree to which documentation is required for plan assemblies for projects employing natural channel design principles is dependent upon project scope, as described below.*

Hydraulic data must be provided with the summary sheet for all projects, unless otherwise approved by the Hydraulic Engineer.

Additional information may be required by permit agencies. The project manager is responsible for coordinating with district environmental staff prior to finalizing plans to determine if any additional information may be required.

Abbreviated Plan

- For Instream Structures and Associated Structures, the Project Manager will complete and submit a Natural Channel Design Project Summary Sheet to the District Environmental Manager and the Natural Resources Section Manager (Central Office, Environmental Division) for review. A copy should be placed in the project file.
- Plan view, profile and cross section drawings will be attached to document each structure.

Small-Scale Projects

- For projects less than 300 feet long, plans should include the following:

Conceptual Plan

- Site Location Map
- Reference reach measurements (bank full width and depth, valley slope, channel slope, bed material characterization)
- Existing site conditions (including survey data)
- Conceptual plan view of channel design
- Buffer width, if applicable
- R/W requirements, as applicable

*Rev. 7/16

Final Plan

- Project Summary Sheet
- Design storm discharges ($Q_{1.5}$, Q_2 and Q_{10} discharges, at a minimum)
- Proposed typical channel cross section(s) and plan view showing thalweg and bank full features
- Grading Plan - Proposed Design with Profile (including alignment data)
- Gradient control structures and locations
- Structure Details
- Summary Sheet with approximate quantities for stream channel
- General notes for Grading, E&S control, and Incidentals (See IIM-LD-110)
- Sequence of Construction
- Planting Plan
- Quantities of plants, seed, fertilizer, and other incidental items required for the compensation site.
- Erosion and Sediment Control Plan
- Transport or other applicable construction estimate
- Applicable Special Provisions and Copied Notes for construction

Large-Scale Projects*

- For projects exceeding 300 feet in length, in addition to the items above, Final Plan documentation shall also include:
 - Natural Channel Design supporting data and analyses
 - Written summary – Project history and design considerations
 - Plant schedule with planting season
 - Monitoring plan and Success Criteria

NOTE: Some projects in small, intermittent or first order perennial watersheds that exceed the length thresholds above may be appropriately addressed with the information required for a *Small-Scale Project* (excluding required items such as the monitoring plan and success criteria). Individual exceptions must be reviewed and approved by the Central Office, Environmental Division Stream Restoration Specialist and the Location and Design Division River Mechanics Engineer, or their designees.

7.4.4.5 Natural Channels Design Plan Submittal and Review

The Natural Resource Section, Central Office Environmental Division, will serve as a central clearing house and contact point for QA/QC review of natural channel design projects. Reviews will be conducted by an interdisciplinary team.

Individual or associated structures do not require QA/QC review, however, submittal of the Abbreviated Plan is required.

*Rev. 7/16

Individual stream restoration plans will require submittal and review according to the QA/QC process timelines.*

7.4.5 Riprap Channel Lining Design Procedure

In riprap lining design, it is first necessary to determine whether a lining is needed based upon the most appropriate method.

7.4.5.1 Riprap Lining Design Method for Major Channels (HEC-11)

If it is determined that riprap lining protection is required for a major stream channel, the design procedures employed by the department are predicated directly on the FHWA publication, "Design of Riprap Revetment" (HEC-11). This publication can be accessed and/or downloaded from the FHWA's Internet web site at <http://isddc.dot.gov/OLPFiles/FHWA/009881.pdf>.

The riprap design procedure presented in HEC-11 is based on the equation:

$$D_{50} = C \left[\frac{0.001V_a^3}{K_1^{1.5} \sqrt{d_{avg}}} \right] \quad (7.22)$$

Where:

- D_{50} = Median riprap particle size, ft
- C = Stone size correction factor
- V_a = Average velocity in the main channel, fps
- d_{avg} = Average flow depth in the main flow channel, ft

The equation for K_1 is from HEC-11:

$$K_1 = \sqrt{1 - \frac{\sin^2 \theta}{\sin^2 \phi}} \quad (7.23)$$

*Rev. 7/16

Where:

- θ = Side slope angle (measured from the horizontal), deg.
- ϕ = Natural angle of repose of material under consideration (measured from the horizontal), deg.

$$C = C_{sg} C_{SF} \quad (7.24)$$

Where:

C_{sg} = Adjustment factor for specific gravity of stone

C_{SF} = Adjustment factor for stability

$$C_{sg} = \frac{2.12}{(S_g - 1)^{1.5}}$$

Where:

S_g = Specific gravity of the rock riprap (Assume 2.65 for all VDOT standard riprap sizes.)

$$C_{SF} = \left(\frac{SF}{1.2} \right)^{1.5} \quad (7.25)$$

Where:

SF = Stability Factor, See Appendix 7D-5, (Usually 1.2)

Notes:

1. Nomographs for the solutions of ϕ , K_1 , C , and D_{50} are found in Appendix 7E.
2. K_1 in HEC-11 is the same variable as K_2 in HEC-15.

Convenient forms that can be used for manually performing these computations are Appendices 7B-4 for standard VDOT riprap sizes and 7B-5 for non-standard VDOT riprap sizes.

7.4.5.1.1 Riprap Lining Design for Major Channels (HEC-11) Sample Problem

Given: Channel is in a relatively straight section of stream. Curve radius/channel width (RW) > 30 with uniform flow. Wave action and floating debris are not a consideration. The average velocity is 5.4 fps. The average depth is 2'. The side slope ratios are 2:1 (26.57°). The angle of repose for the riprap is 42°. The specific gravity of the riprap is 2.65.

Determine:

Size of required riprap slope protection and appropriate VDOT standard riprap.

Solution:

Step 1: Determine the stability factor (SF)

From Appendix 7D-5, select a stability factor (SF) of 1.2.

$$\text{Step 2: } C_{SF} = \left(\frac{SF}{1.2}\right)^{1.5} = \left(\frac{1.2}{1.2}\right)^{1.5} = 1$$

$$\text{Step 3: } C_{sg} = \frac{2.12}{(S_g - 1)^{1.5}} = \frac{2.12}{(2.65 - 1)^{1.5}} = 1$$

$$\text{Step 4: } C = C_{sg} C_{SF} = 1(1) = 1$$

$$\text{Step 5: } K_1 = \sqrt{1 - \frac{\sin^2 \theta}{\sin^2 \phi}} = \sqrt{1 - \frac{\sin^2 (26.57)}{\sin^2 (42)}} = 0.74$$

$$\text{Step 6: } D_{50} = C \left[\frac{0.001V_a^3}{K_1^{1.5} \sqrt{d_{avg}}} \right] = 1 \left[\frac{0.001(5.4)^3}{(0.74)^{1.5} \sqrt{2}} \right] = 0.17 \text{ ft.}$$

Step 7: Closest standard VDOT riprap size = Class AI ($D_{50} = 0.8$ ft).

7.4.5.2 Riprap Lining Design Method for Minor Channels (HEC-15)

The following design procedures employed by the department are predicated directly on the FHWA publication, "Design of Roadside Channels With Flexible Linings" (HEC-15). This publication can be accessed and/or downloaded from the FHWA's Internet web site at <http://www.fhwa.dot.gov/engineering/hydraulics/pubs/05114/05114.pdf>.[†] Once it has been determined that the natural or backfill material is unstable, using either (1) the Tractive Force procedure, (2) a table of allowable velocities for specific soil types such as Appendix 7D-2 and 7D-6, or (3) engineering judgment, select a trial riprap size and proceed as follows:

Step 1: Determine the permissible shear stress (τ_p) for the riprap size selected

Use 3.2 lbs/ft² for Class AI Riprap and 4.4 lbs/ft² for Class I Riprap.

Step 2: Select a trial flow depth range for the ditch configuration using the following table from HEC-15:

Table 7-3 Manning's n-Values for Depth Ranges

Riprap Size	0-0.5'	0.5-2.0'	>2.0'
Class AI	0.104	0.069	0.035
Class I	--	0.078	0.040

Step 3: Using the n-value for the selected trial flow depth range, calculate the actual depth of flow for the ditch configuration using the actual design discharge and ditch slope using an appropriate method such as Appendix 7C-3. If the calculated depth is within the trial depth range selected, proceed to the next step. If it is not, select another trial depth range and try again.

Step 4: Calculate the actual shear stress (τ_o):

$$\tau_o = \gamma d S_o \quad (7.26)$$

Where:

- γ = Unit weight of water (62.4 lbs/ft³)
- d = Depth of flow, ft.
- S = Average ditch flowline slope, ft/ft

*Rev. 9/09

If $\tau_o > \tau_p$, the selected riprap size is too small. Choose the next larger size and try again.

If the ditch side slopes are steeper than 3:1, it is necessary to perform the additional calculations shown below:

Step 5: Determine the angle of repose for the riprap size determined above.

It should be noted that all VDOT standard riprap sizes are assumed to have angles of repose of 42° .

Step 6: Determine the ratio of maximum side shear to maximum bottom shear (K_1) using Appendix 7E-7.

Step 7: Determine tractive force ratio (K_2) from Appendix 7E-8.

Step 8: Calculate required D_{50} for side slopes ($D_{50 \text{ side}}$)

$$D_{50 \text{ side}} = \frac{K_1}{K_2} D_{50 \text{ bottom}}$$

From a practical standpoint, whatever riprap size is indicated for the ditch side slope should be used on the bottom as well.

7.4.5.2.1 Channel Stability Sample Problem - Tractive Force Calculation

Check the stability of channel's native material using tractive force calculation. Note that the "RIPRAP" computer program referenced in section 7.4.6.4.4 could be employed to perform this computation.

Given: A natural channel with a bed and banks of native materials composed of cobbles and pebbles. Mean diameter is 1.25" for the D_{75} size stone. The channel bottom width (B) is 10'. The longitudinal slope is 0.008 ft/ft. Its side slope is 2(h):1(v). The flow (Q) is 150 cfs at a depth (d) of 2'.

Determine whether the channel is stable for the indicated condition.

Solution:

Step 1: Determine the permissible shear stress (τ_p)

From Appendix 7E-2, for a D_{75} particle diameter of 1.25", read a permissible tractive force (τ_p) on the channel bottom of 0.5 lbs/ft².

Step 2: For a side slope ratio of 2:1, the sine of the slope angle ($\theta = 26.6^\circ$) is 0.5

*Rev. 9/09

Step 3: From Appendix 7E-1, for a particle diameter of 1.25", read an angle of repose (ϕ) of 40°

The sine of $40^\circ = 0.643$

$$\text{Step 4: } K_1 = \sqrt{1 - \frac{\sin^2 \theta}{\sin^2 \phi}} = \sqrt{1 - \frac{0.447^2}{0.643^2}} = 0.72$$

Step 5: Permissible tractive force on the side slopes (τ_s)

$$\tau_s = K_1 \tau_p = 0.72(0.05) = 0.36 \text{ lbs/ft.}^2$$

Step 6: Compute the width to depth ratio

$$\frac{B}{d} = \frac{10}{2} = 5, \text{ which is less than 10, therefore use } \tau_o = 62.4RS_o$$

Step 7: Flow cross-sectional area

$$\begin{aligned} A &= Bd + zd^2 \\ &= 10(2) + 2(2)^2 \\ &= 28 \text{ ft.}^2 \end{aligned}$$

Step 8: Wetted perimeter

$$\begin{aligned} P &= B + 2d\sqrt{1 + z^2} \\ &= 10 + 2(2)\sqrt{1 + 2^2} \\ &= 18.94 \text{ ft.} \end{aligned}$$

Step 9: Hydraulic radius

$$R = \frac{A}{P} = \frac{28}{18.94} = 1.48 \text{ ft.}$$

Step 10: Compute the average tractive force

$$\begin{aligned} \tau_o &= 62.4RS_o \\ &= 62.4(1.48)(0.008) \\ &= 0.74 \text{ lbs/ft.}^2 \end{aligned}$$

Step 11: Compare the average tractive force of the channel to the allowable tractive force of the channel sides and bottom

$$\tau_o \text{ of } 0.74 > \tau_p \text{ (bottom) of } 0.5 \text{ lbs/ft}^2 \text{ or } \tau_s \text{ (side slope) of } 0.36 \text{ lbs/ft}^2$$

Native material is unstable. Channel protection is required.

7.4.5.2.2 Riprap Lining Design for Minor Channels (HEC-15) Sample Problem

Given: It has been determined that a special design ditch connected to culvert cross drain pipes will need a riprap lining. The ditch has a bottom width (B) of 2', 2:1 side slopes ($z = 2$), and a slope along the ditch line (S) of 0.005 ft/ft. The design discharge is 20 cfs.

Determine what size VDOT standard riprap will be required?

Step 1: Try Class A1 standard riprap, $D_{50} = 0.8'$

$$\tau_p = 3.2 \text{ lb/ft}^2$$

Step 2: Assume a depth range of from 0.5-2.0 ft. with an n-value of 0.069

Step 3: Using Appendix 7E-3 for $S = 0.005 \text{ ft/ft}$, $B = 2 \text{ ft}$, $z = 2$, $Qn = 20 (0.069) = 1.38$,

$$\text{Read } d/B = 0.78. \quad d = 0.78 (2) = 1.56 \text{ ft.} \quad 0.5 < 1.56 < 2.0,$$

Therefore, the assumed n-value of 0.069 is acceptable.

Step 4: Determine the maximum shear stress

$$\tau_{\max} = \gamma d S_o = 62.4(1.56)(0.005) = 0.49 \text{ lb/ft}^2$$

Step 5: Evaluate the maximum shear stress with the permissible shear stress

$$\tau_{\max} < \tau_p,$$

$$0.49 < 3.2$$

Therefore, Class A1 riprap is acceptable for the ditch bottom and side slopes of 3:1 or flatter. However, since the side slopes are 2:1, proceed with checking the side slope stability

Step 6: Determine the angle of repose for Class A1 riprap

$$\phi = 42^\circ$$

Step 7: Determine K_1

From Appendix 7E-7, for $B/d = 2 / 1.56 = 1.28$ and $z = 2$, read $K_1 = 0.9$

Step 8: Determine K_2

From Appendix 7E-8 for $z = 2$ and angle of repose = 42° , read $K_2 = 0.73$.

Step 9: Determine the D_{50} for the side slopes

$$D_{50 \text{ side}} = \frac{K_1}{K_2} D_{50 \text{ bottom}} = \frac{0.90}{0.73} (0.8) = 0.98 \text{ ft.}$$

Therefore, it would probably be best to use Standard Class I riprap ($D_{50} \approx 1.1'$) for both the channel bottom and side slopes in lieu of the originally proposed Class AI ($D_{50} = 0.8'$).

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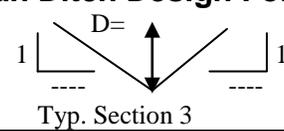
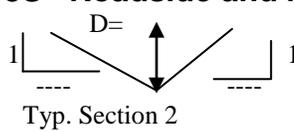
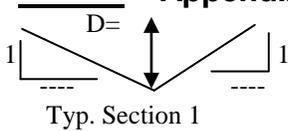
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*Rev. 9/09

LD-268S
(5-16)
LANE
SIDE

Appendix 7B-1 LD-268S Roadside and Median Ditch Design Form – Permissible Shear



PROJECT _____
BY _____
DATE _____
SHEET _____ of _____.

STA. TO STA.	FLOW	0.9	0.5	0.3	CA		Tc	I ₂	Q ₂	C or F	Slope Ft/Ft	ALLOW VEL.	Earth		Protective Lining			I ₁₀	Q ₁₀	DEP	REMARKS			
		WS/ CA	WS/ CA	WS/ CA	INCR	ACC.							n=.03	n=.05		n=.015								
													VEL.	Qn	VEL	DEP	Qn	DEP						

Appendix 7B-3

CHANNEL STABILITY WORK SHEET

CHANNEL DATA

$Q =$ _____ (cfs) $P =$ _____ (ft.) Native Material
 $S_o =$ _____ (ft/ft) $R =$ _____ (ft.) $D_{50} =$ _____
 $d_n =$ _____ (ft.) $V_n =$ _____ (fps) $D_{75} =$ _____
 $A =$ _____ (ft²) Side Slope = _____ :1 $n =$ _____

STABILITY OF NATIVE MATERIAL

$\tau_o = 62.4 \cdot R \cdot S_o = 62.4 \cdot$ _____ \cdot _____ $=$ _____

τ_p Bed = _____ (Appendix 7E-2 or 3)

For $D_{50} =$ _____ $\phi =$ _____ ° (Appendix 7E-1)

For $D_{75} =$ _____ $\phi =$ _____ ° (Appendix 7E-9)

Side Slope = _____ :1 $\theta =$ _____ °

$K_1 = [1 - (\sin^2 \theta / \sin^2 \phi)]^{0.5}$

$K_1 = [1 - (\sin^2$ _____ ° $/ \sin^2$ _____ ° $)]^{0.5} =$ _____

τ_s Side Slope (SS) = τ_p Bed $\cdot K =$ _____ \cdot _____ $=$ _____

τ_p Bed (_____) (<) (=) (>) τ_o (_____)

∴ Native Material on Bed is (stable) (unstable)

τ_s SS (_____) (<) (=) (>) τ_o (_____)

∴ Native Material on Side Slope is (stable) (unstable)

Source: VDOT

Appendix 7B-4

RIPRAP DESIGN WORK SHEET
FOR STANDARD VDOT RIPRAP SIZES ONLY

CHANNEL DATA

Q = _____(cfs) P = _____(ft.) n = _____

S_o = _____(ft/ft) R = _____(ft.)

d_n = _____(ft.) V_n = _____(fps)

A = _____(ft.²) Side Slope = _____ :1

DETERMINE RIPRAP SIZE

φ = 42° Side Slope = _____ :1 θ = _____°

$K_1 = [1 - (\sin^2 \theta / \sin^2 \phi)]^{0.5}$

$K_1 = [1 - (\sin^2 \text{_____}^\circ / \sin^2 42^\circ)]^{0.5} = \text{_____}$

For Specific Gravity = 2.65 and Stability Factor = 1.2

$D_{50} = 0.001 \cdot V_a^3 / (d_{avg}^{0.5} \cdot K_1^{1.5})$

$D_{50} = 0.001 \cdot \text{_____}^3 / (\text{_____}^{0.5} \cdot \text{_____}^{1.5})$

D₅₀ Computed = _____

Note: All VDOT standard riprap (Class AI through Type II) is assumed to have a φ of approximately 42° and a Specific Gravity of 2.65. Therefore, the Computed D₅₀ should be adjusted by the Stability Correction Factor (C_{SF}) (if any) to derive a Final D₅₀. The VDOT standard class of riprap with the next higher D₅₀ should be specified.

Correction Factor For Stability Factor (SF) other than 1.2 (Default = 1.0)

$C_{SF} = (SF / 1.2)^{1.5} = (\text{_____} / 1.2)^{1.5} = \text{_____}$

Final D₅₀ = C_{SF} • Computed D₅₀ = _____ • _____ = _____

RIPRAP RECOMMENDATION: VDOT (Class) (Type) _____

Thickness (T) = _____" (2 • D₅₀ MSD minimum)

Source: VDOT

Appendix 7B-5

RIPRAP DESIGN WORK SHEET
FOR OTHER THAN VDOT STANDARD RIPRAP SIZES

CHANNEL DATA

Q = _____(cfs) P = _____(ft.) n = _____

S₀ = _____(ft/ft) R = _____(ft.)

d_n = _____(ft.) V_n = _____(fps)

A = _____(ft²) Side Slope = _____ :1

ASSUMED RIPRAP SIZE - D₅₀ = _____

VERIFY ASSUMED RIPRAP SIZE

φ = _____° (Appendix 7E-1)

Side Slope = _____ : 1 θ = _____°

K₁ = [1 - (sin² θ / sin² φ)]^{0.5}

K₁ = [1 - (sin² _____° / sin² _____°)]^{0.5} = _____

For Specific Gravity = 2.65 and Stability Factor = 1.2

D₅₀ = 0.001 • V_a³ / (d_{avg}^{0.5} • K₁^{1.5})

D₅₀ = 0.001 • _____³ / (_____^{0.5} • _____^{1.5}) = _____

D₅₀ Computed (_____) (<) (=) (>) D₅₀ Assumed (_____)

Assumed D₅₀ is (correct) (incorrect)

Note: The above process of assuming a D₅₀ size, determining the natural angle of repose (φ) and computing a D₅₀ size should be repeated until the Assumed D₅₀ size equals the Computed D₅₀ size. Once the D₅₀ size determination has been made, it should be adjusted for the Specific Gravity Correction Factor C_{sg} (if any) and the Stability Correction Factor (C_{SF}) (if any) to derive a Final D₅₀.

Correction Factor For Riprap Specific Gravity (S_s) other than 2.65 (Default = 1.0)

C_{sg} = 2.12 / (S_s - 1)^{1.5} = 2.12 / (_____ - 1)^{1.5} = _____

Correction Factor For Stability Factor (SF) other than 1.2 (Default = 1.0)

C_{SF} = (SF / 1.2)^{1.5} = (_____ / 1.2)^{1.5} = _____

Final Correction Factor = C = C_{sg} • C_{SF} = _____ • _____ = _____

Final D₅₀ = C • Computed D₅₀ = _____ • _____ = _____

RIPRAP RECOMMENDATION: _____

Thickness (T) = _____" (2 • D₅₀ MSD minimum)

Source: VDOT

Appendix 7B-06 Natural Channel Design Project Summary Sheet

NATURAL CHANNEL DESIGN
PROJECT SUMMARY SHEET

Project Number: _____ Permit Number: _____ Project Name: _____
 PPMS / UPC / CSC Number: _____ HUC: _____ City or County: _____
 _____ District: _____
 Latitude: _____ FEMA Floodplain: Yes No Residency: _____
 _____ Date: _____

 Longitude: _____

 USGS Quad. (Attach): _____
 Site Location: _____

Site Description (include goals and objectives)

Type: (check ONE box only)

<input type="checkbox"/> Instream Structure *	<input type="checkbox"/> Channel Relocation	Intermittent I.f.	Perennial I.f.
<input type="checkbox"/> Associated Structure *	<input type="checkbox"/> Channel Restoration	_____	_____

* For instream structures and associated structures, attach plan and profile view drawings

Geomorphic Description:

Bankfull width _____ Floodprone width _____ Channel slope _____
 Bankfull depth _____ Bankfull cross sectional area _____ Valley slope _____
 Bankfull Q _____

Bed Material

Bedrock Boulder Cobble Gravel Sand Silt/clay

Rosgen Class: _____
 Valley Type: _____

Hydraulic Analysis Complete:

Based on the scope of the project, additional hydraulic analysis is not required. (Attach documentation.)

This project has been reviewed and provides a hydraulically equivalent replacement structure that does not require additional coordination or review. See attached LD-1095A.

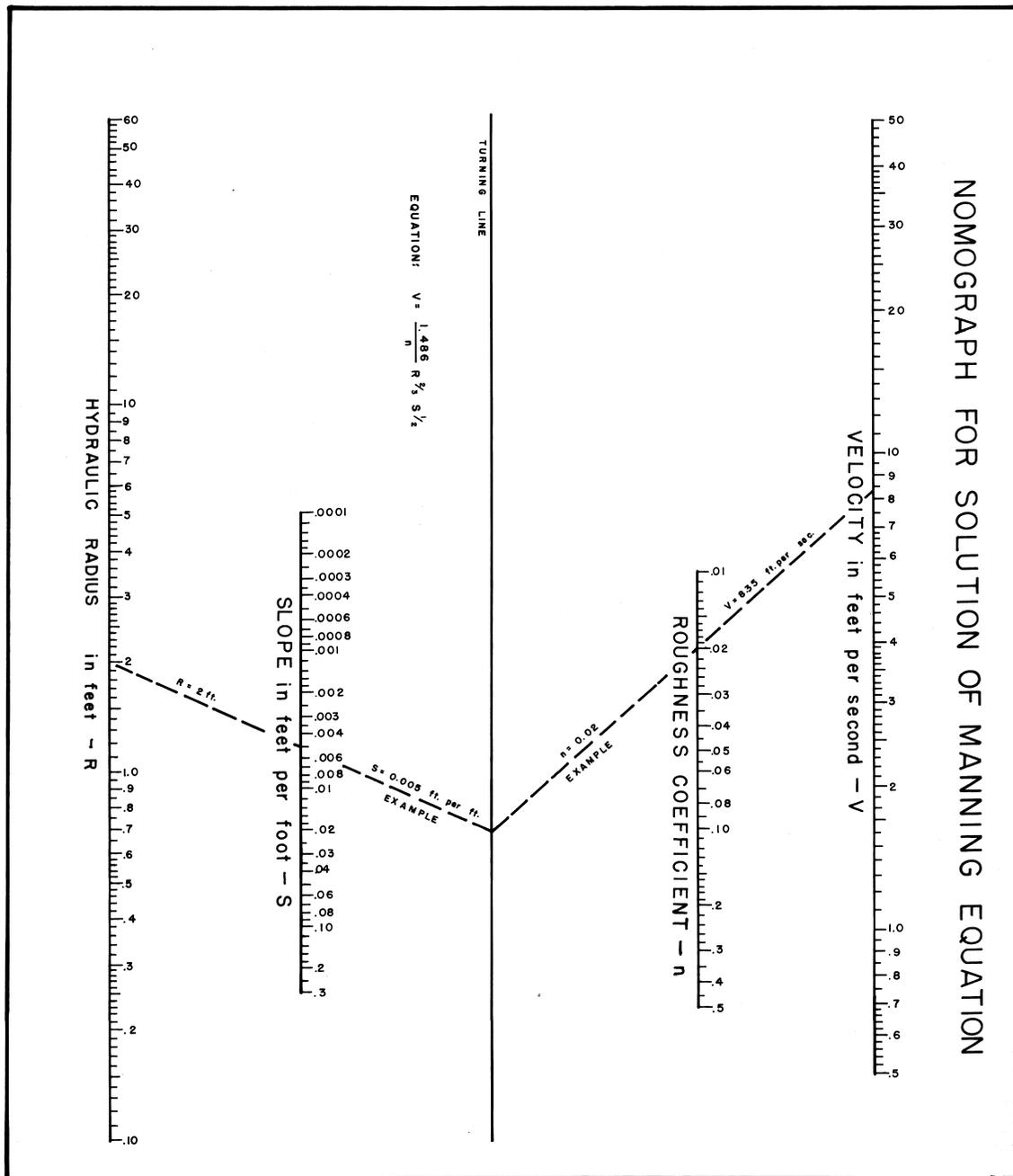
Design storm data provided by a Hydraulic Engineer:

Design Storm	cfs	Design Storm	cfs
Q _{1.5} Discharge:	_____	Q ₁₀ Discharge	_____

Place one copy of the completed form in the project file and provide one copy of this form to:
 C.O. Environmental Division
 Natural Resources Program Manager
 1201 East Broad Street
 Richmond, VA 23219

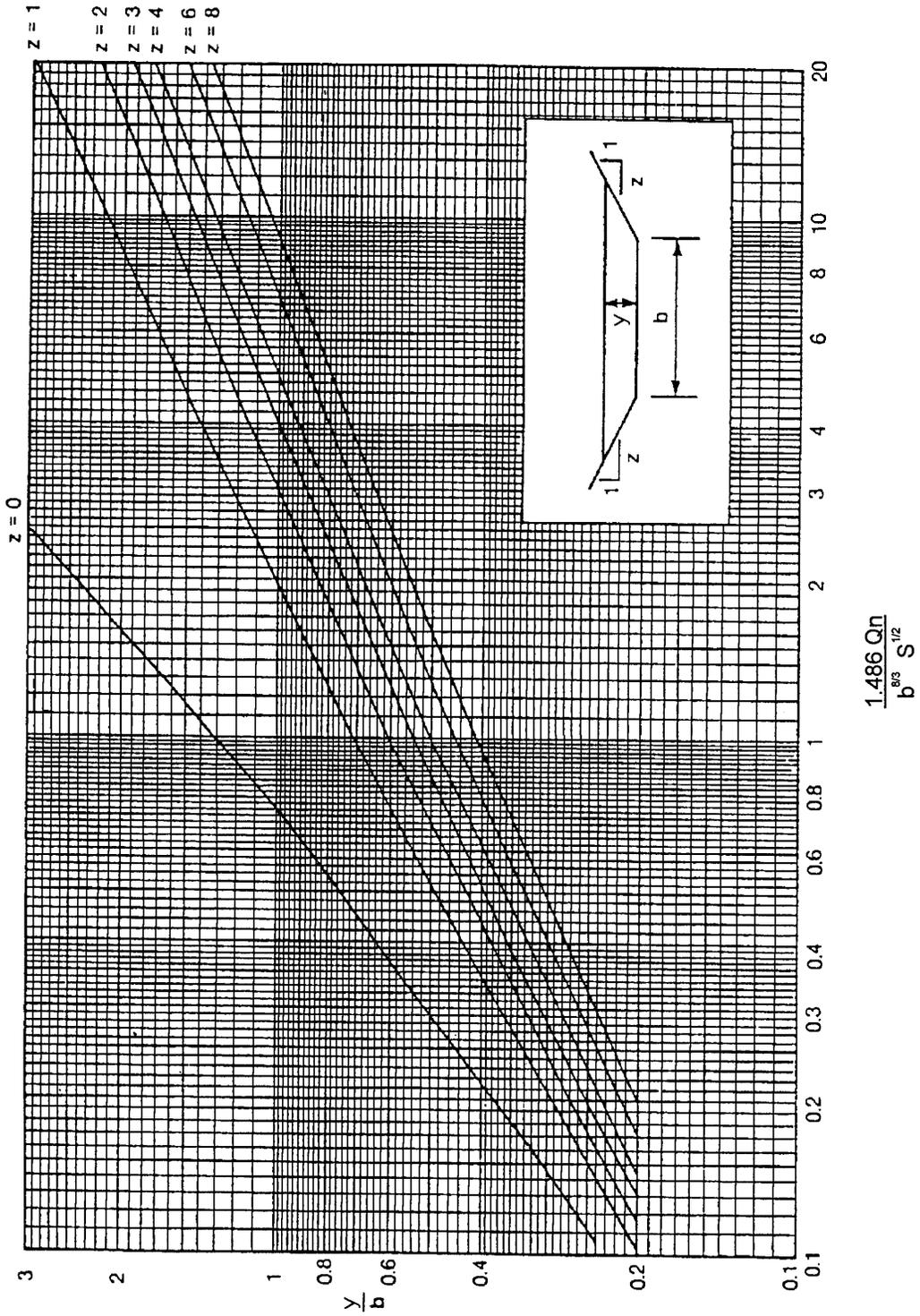
Appendix 7C-1

Nomograph for Solution of Manning's Equation



Source: VDOT

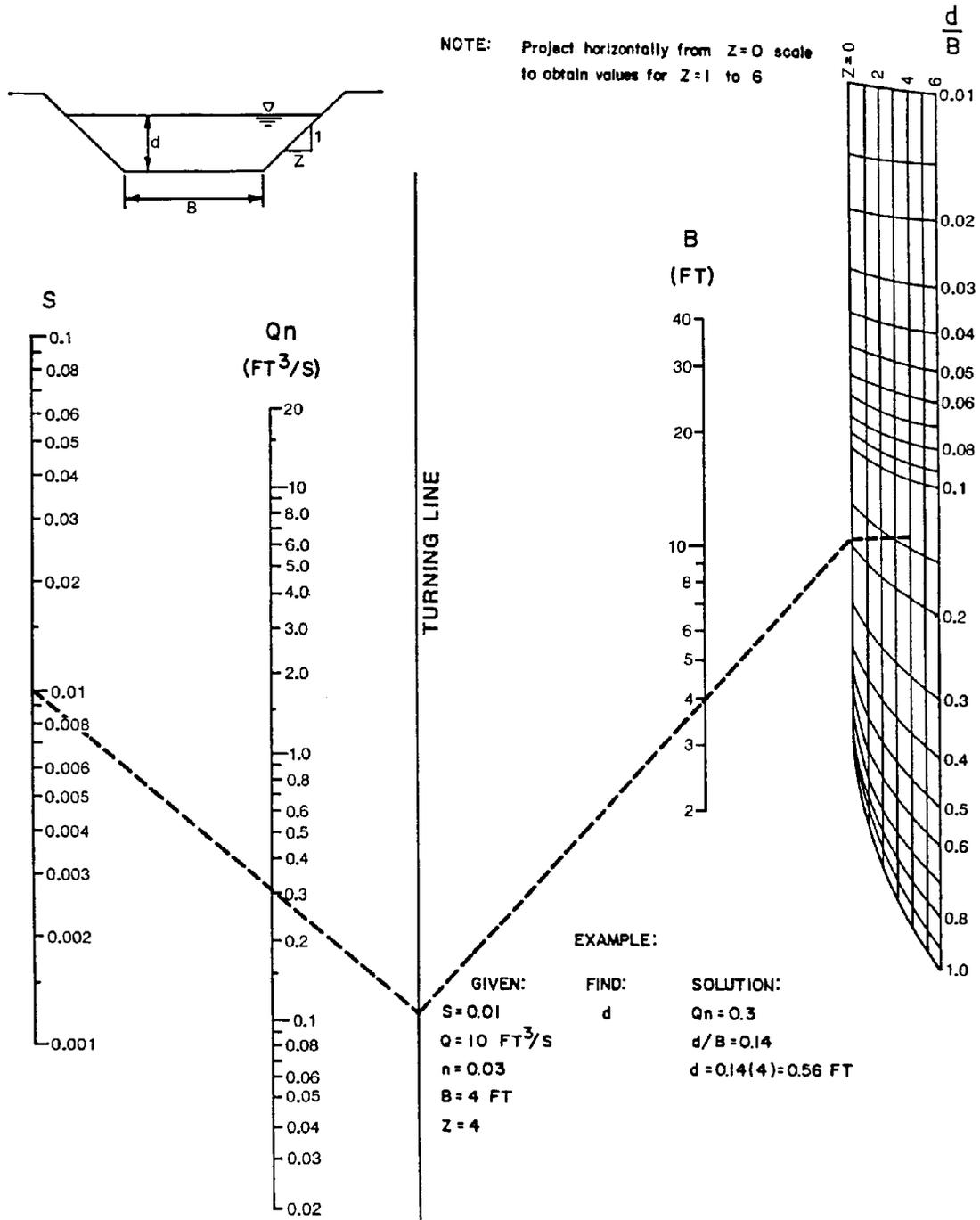
Appendix 7C-2 Trapezoidal Channel Capacity Chart



Source:

Appendix 7C-3

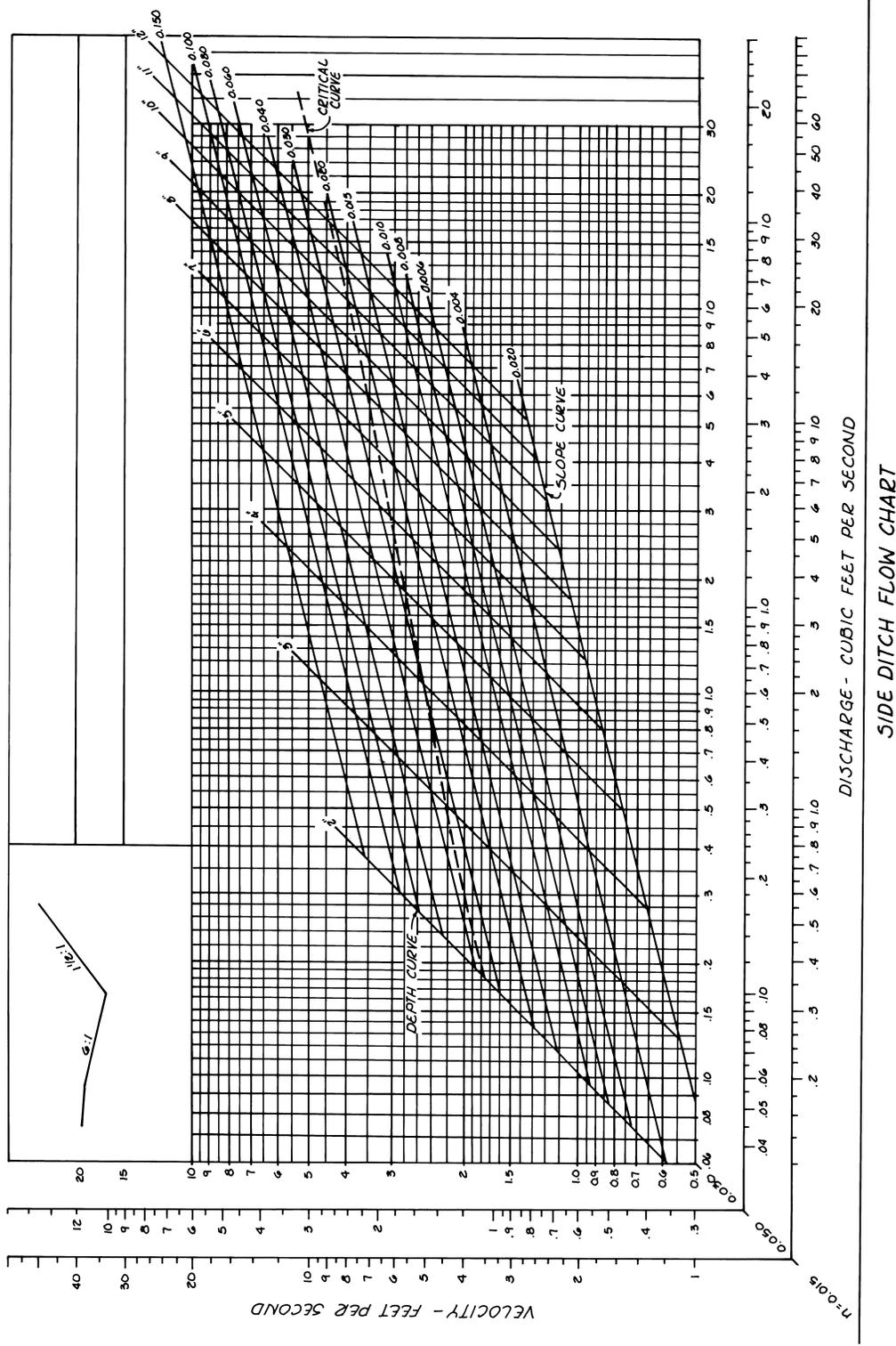
Nomograph for Solution of Normal Depth



Source: HEC-15 (Archived) 1988

Appendix 7C-4

Side Ditch Flow Chart
(Side Slopes = 6:1, 1.5:1)

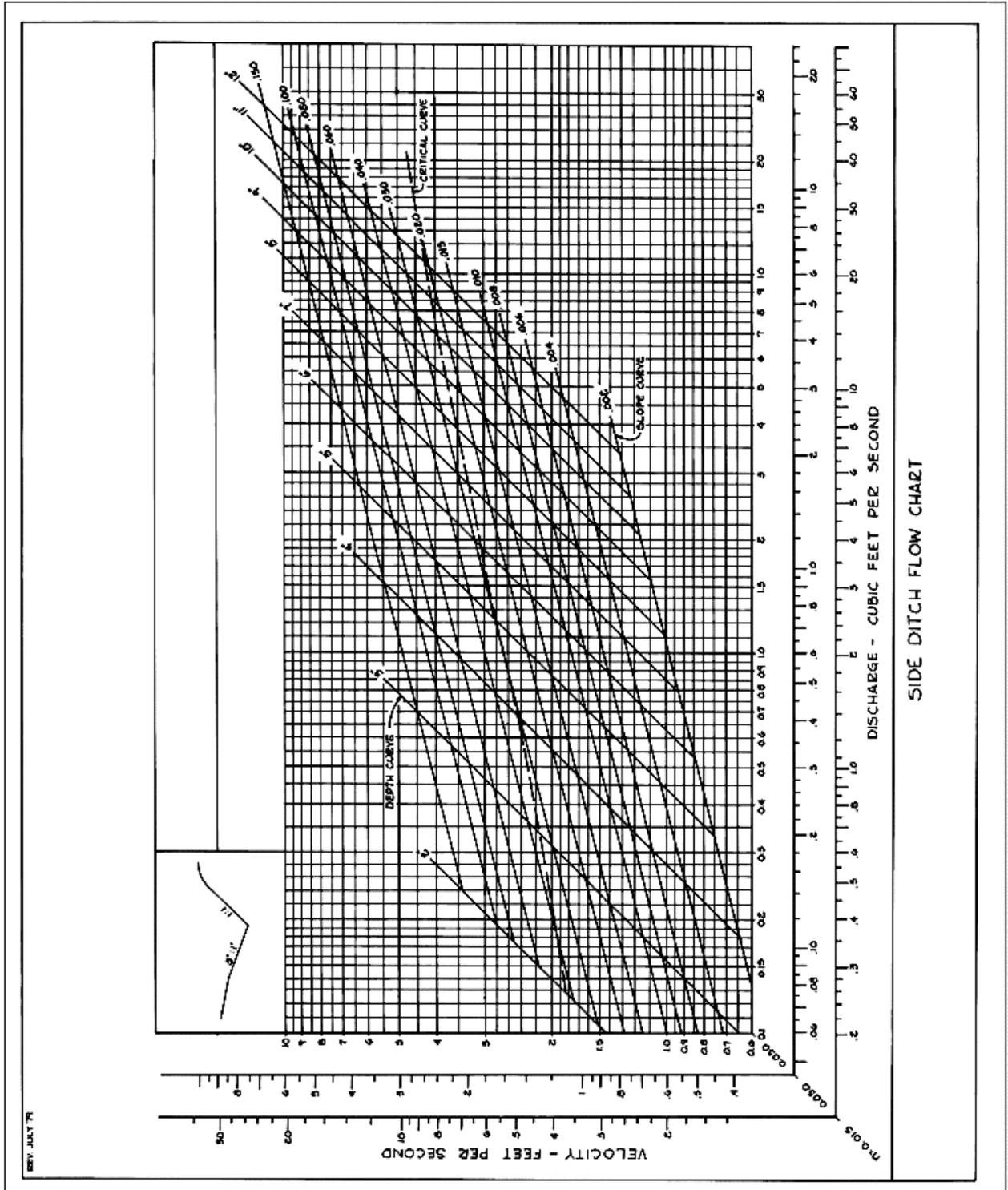


Source: VDOT

Appendix 7C-5

Side Ditch Flow Chart
(Side Slopes = 4:1, 1:1)

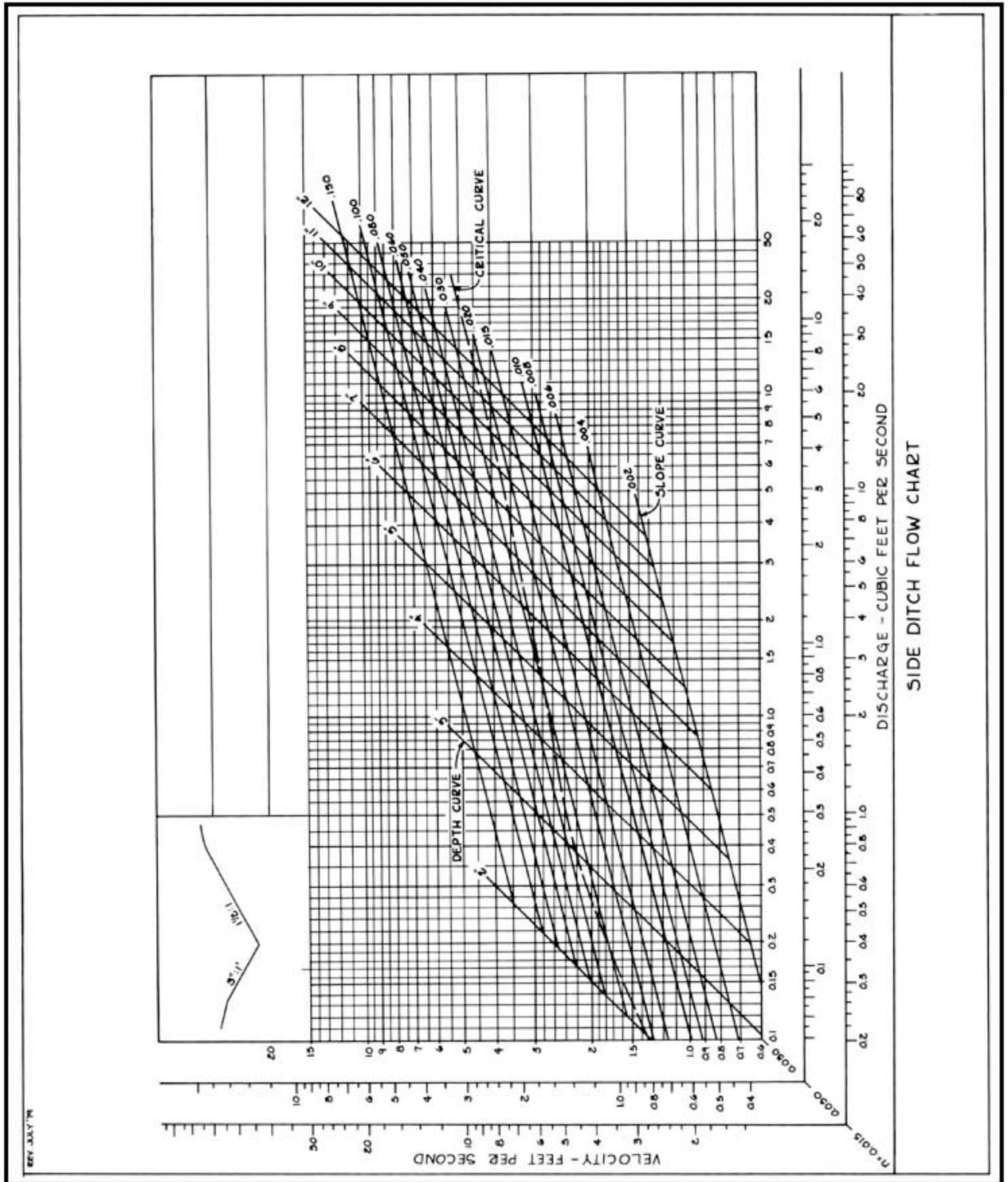
2-05



Source: VDOT

Appendix 7C-6

Side Ditch Flow Chart
(Side Slopes = 4:1, 1.5:1)

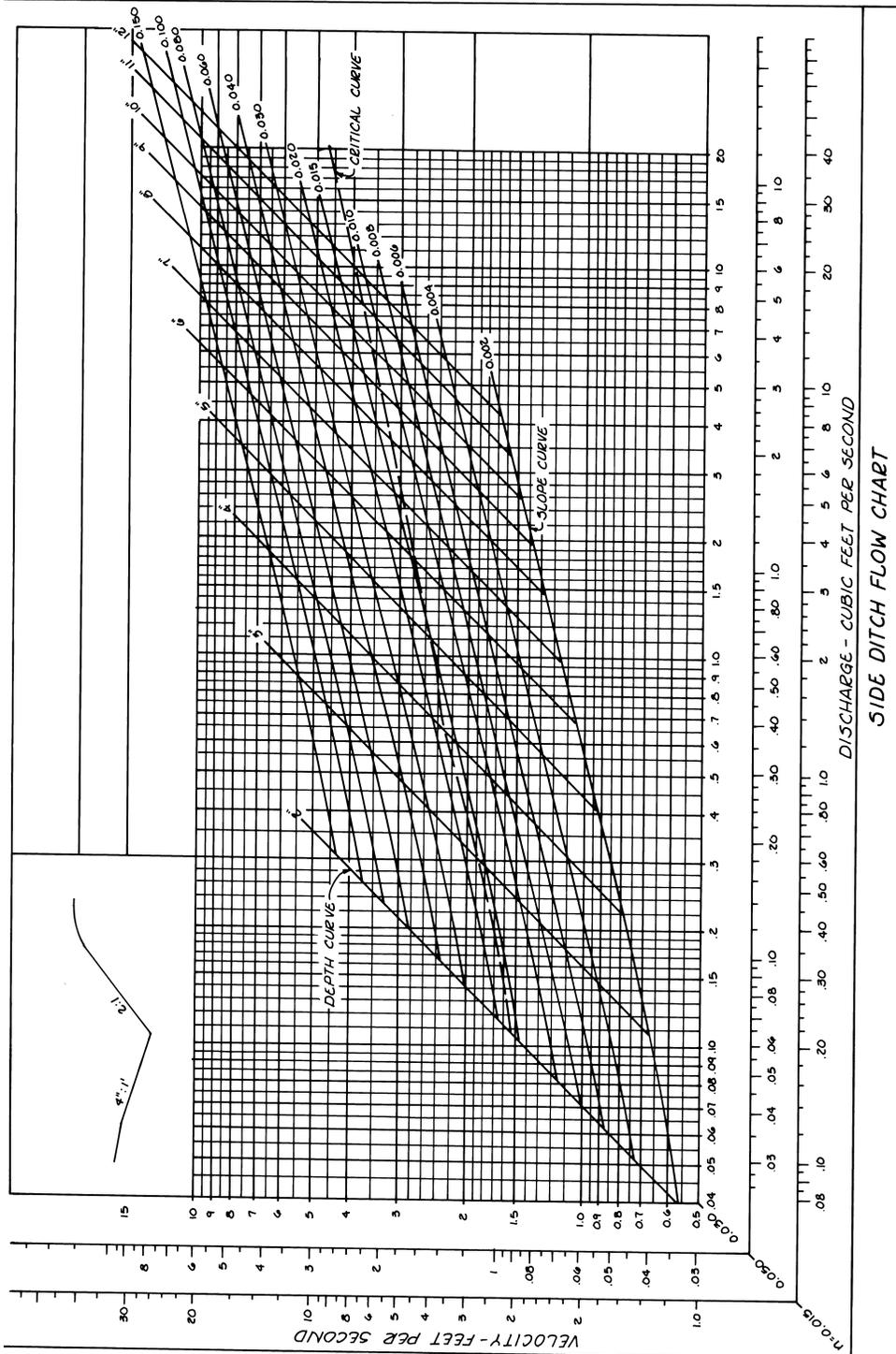


SP-3

Source: VDOT

Appendix 7C-7

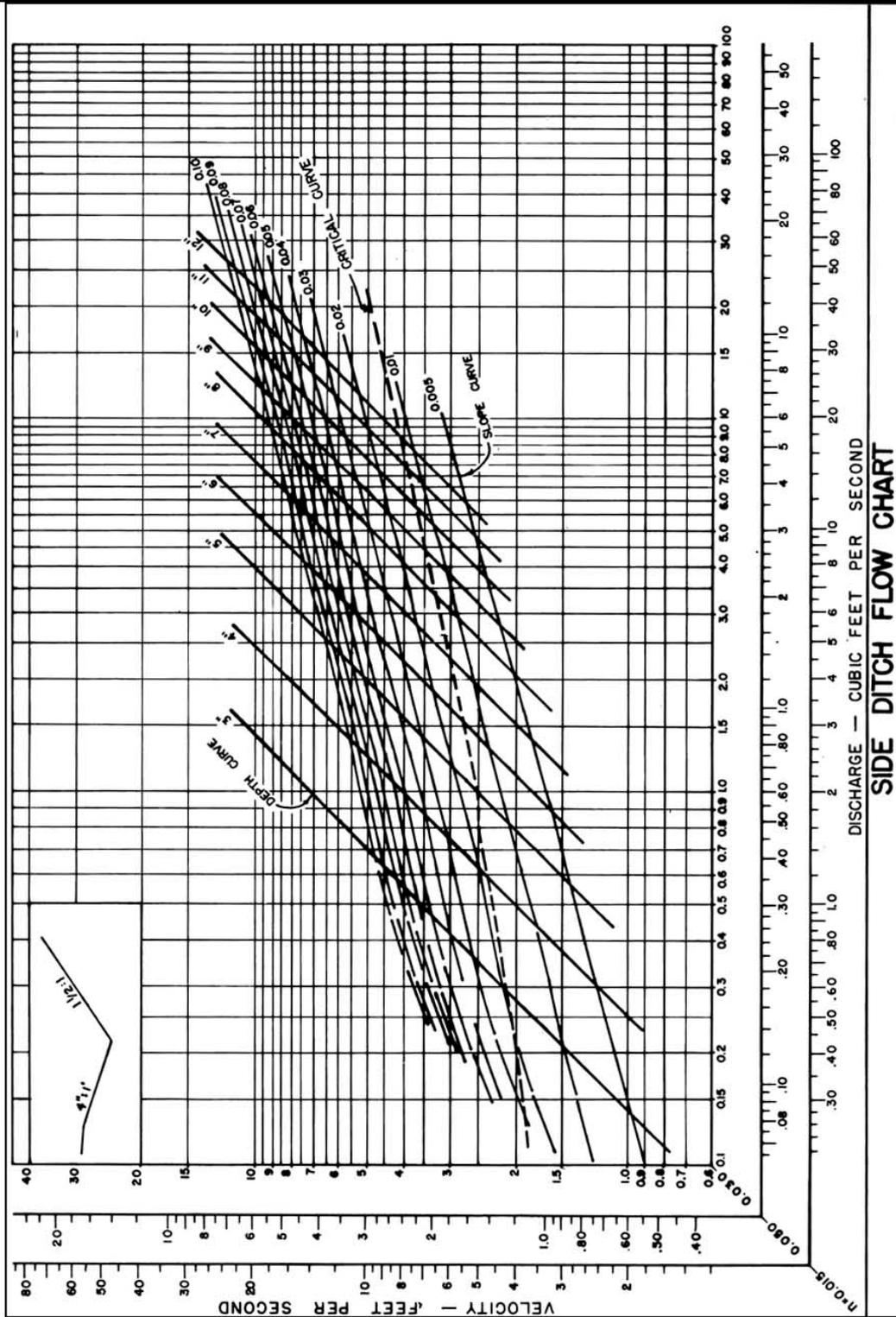
Side Ditch Flow Chart (Side Slopes = 3:1, 2:1)



Source:

Appendix 7C-8

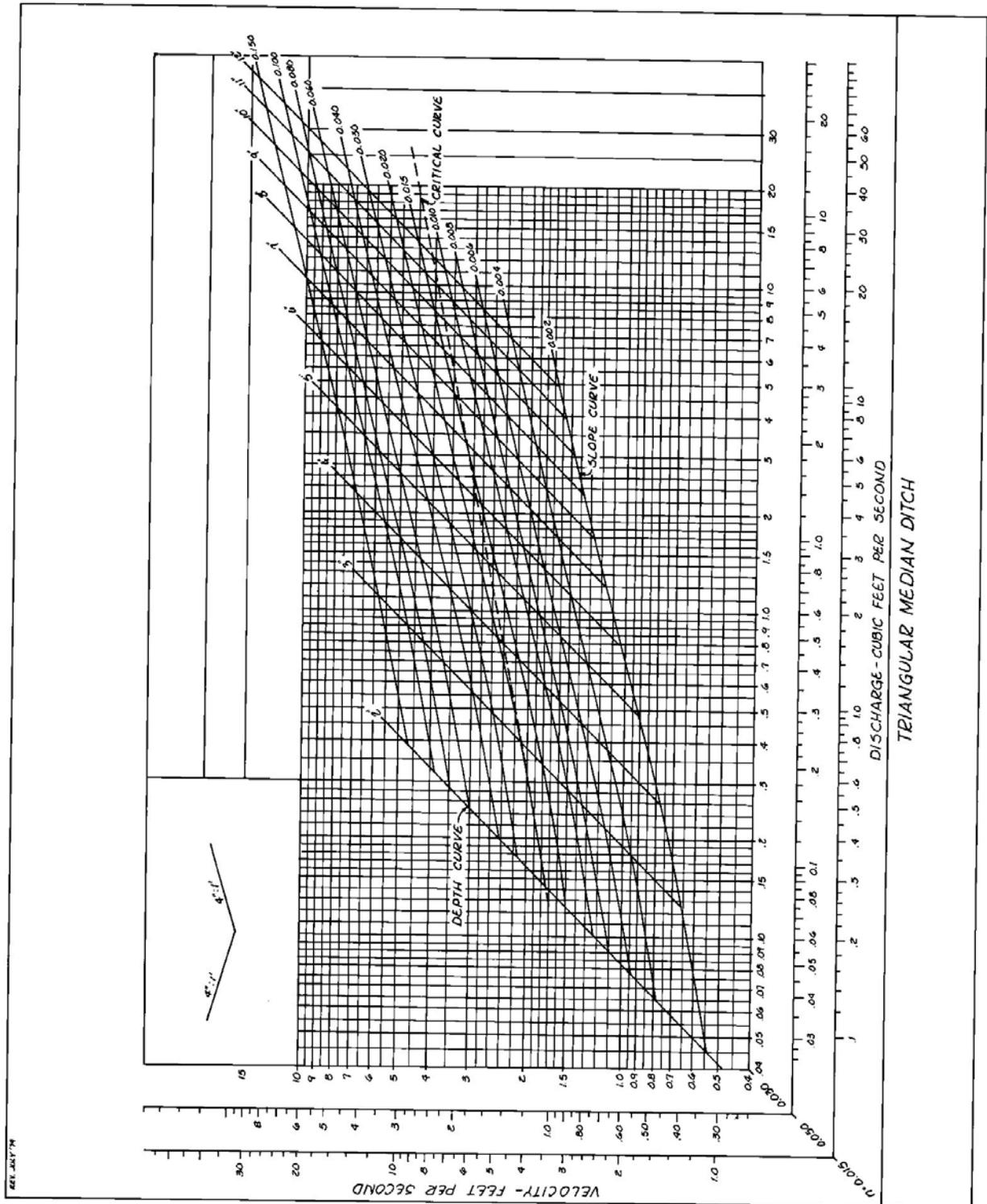
Side Ditch Flow Chart
(Side Slopes = 3:1, 1.5:1)



Source: VDOT

Appendix 7C-9

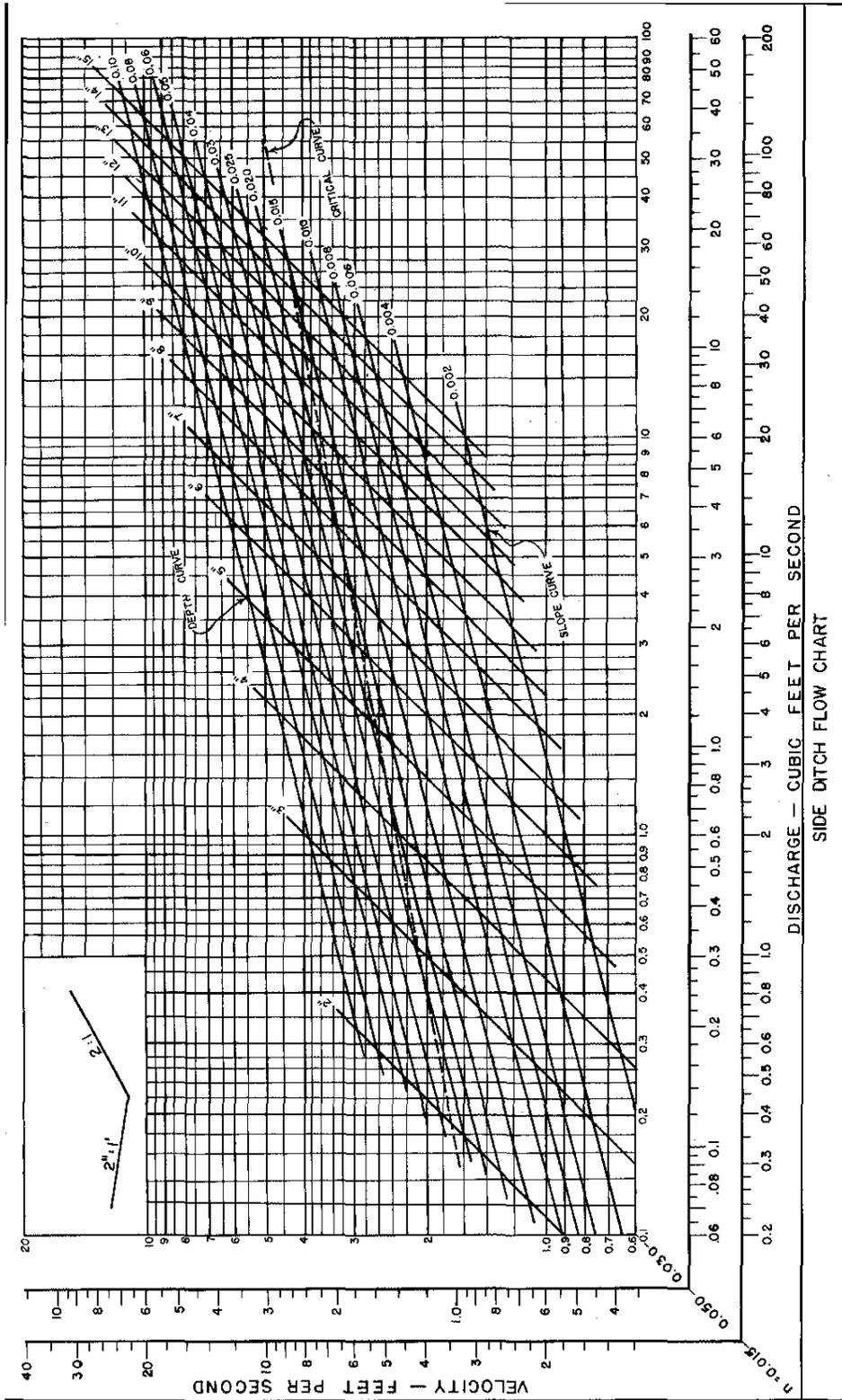
Side Ditch Flow Chart
(Side Slopes = 3:1, 3:1)



Source: VDOT

Appendix 7C-10

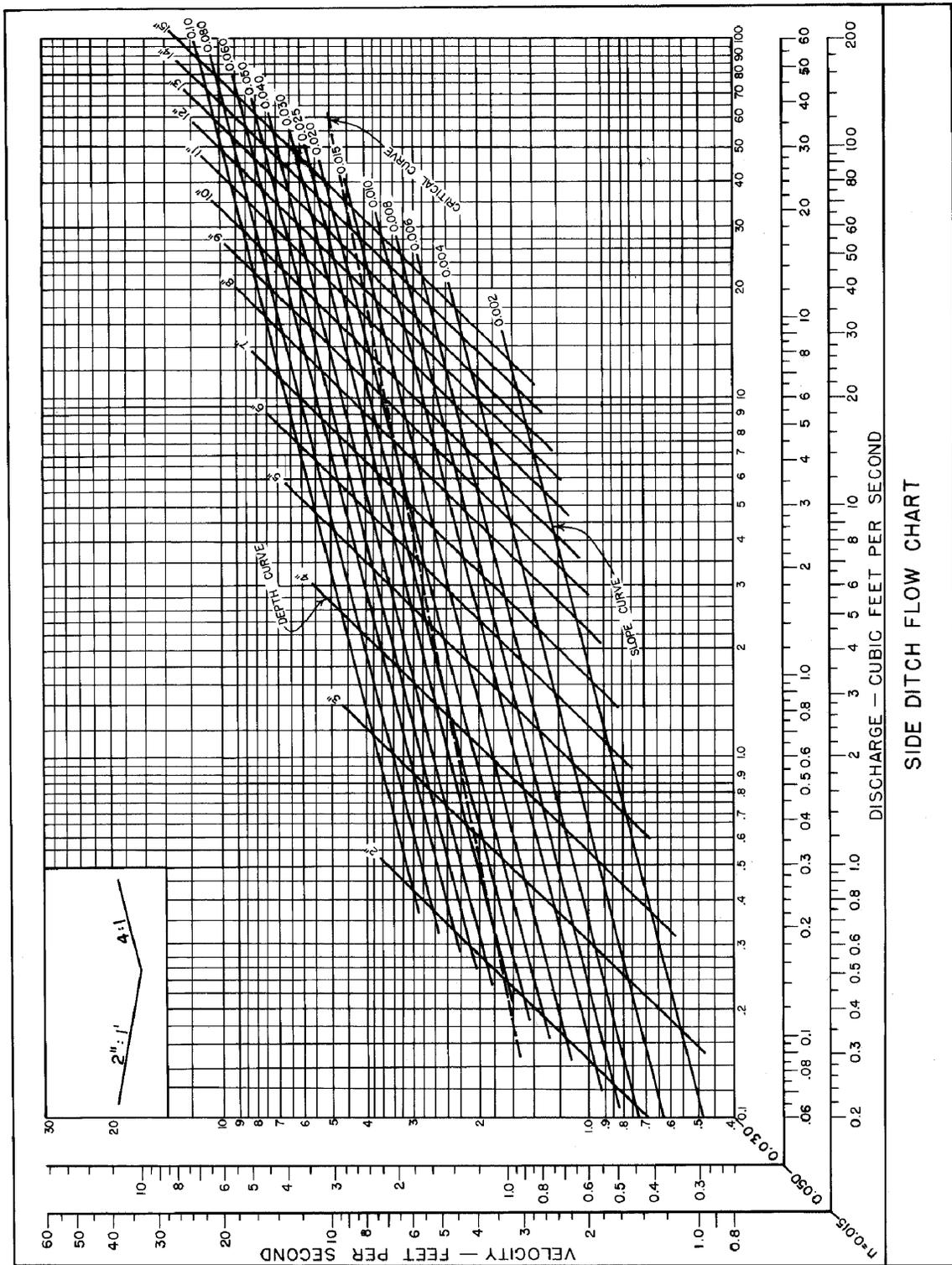
Side Ditch Flow chart
(Side Slopes = 6:1, 2:1)



Source: VDOT

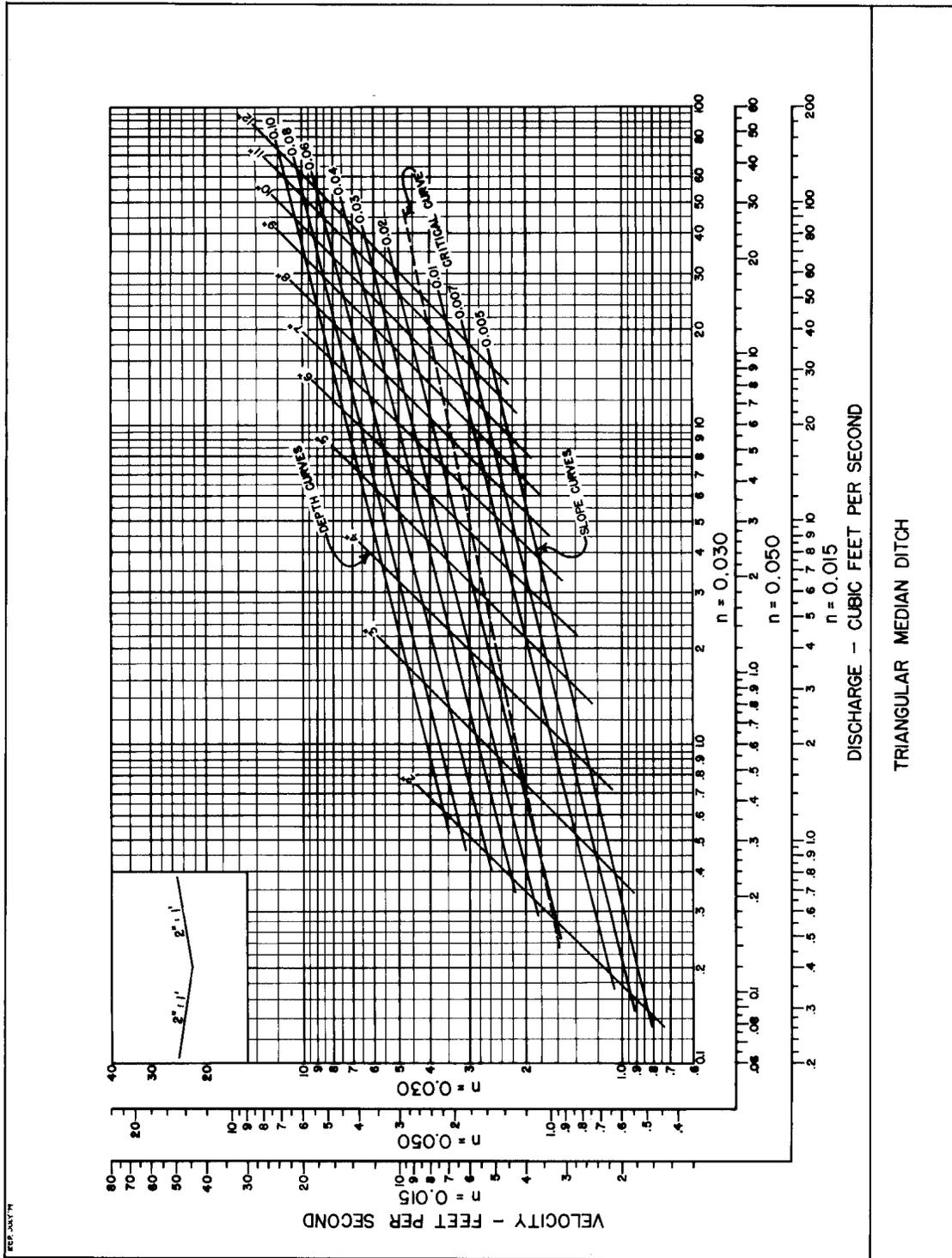
Appendix 7C-11

Side Ditch Flow Chart
(Side Slopes = 6:1, 4:1)



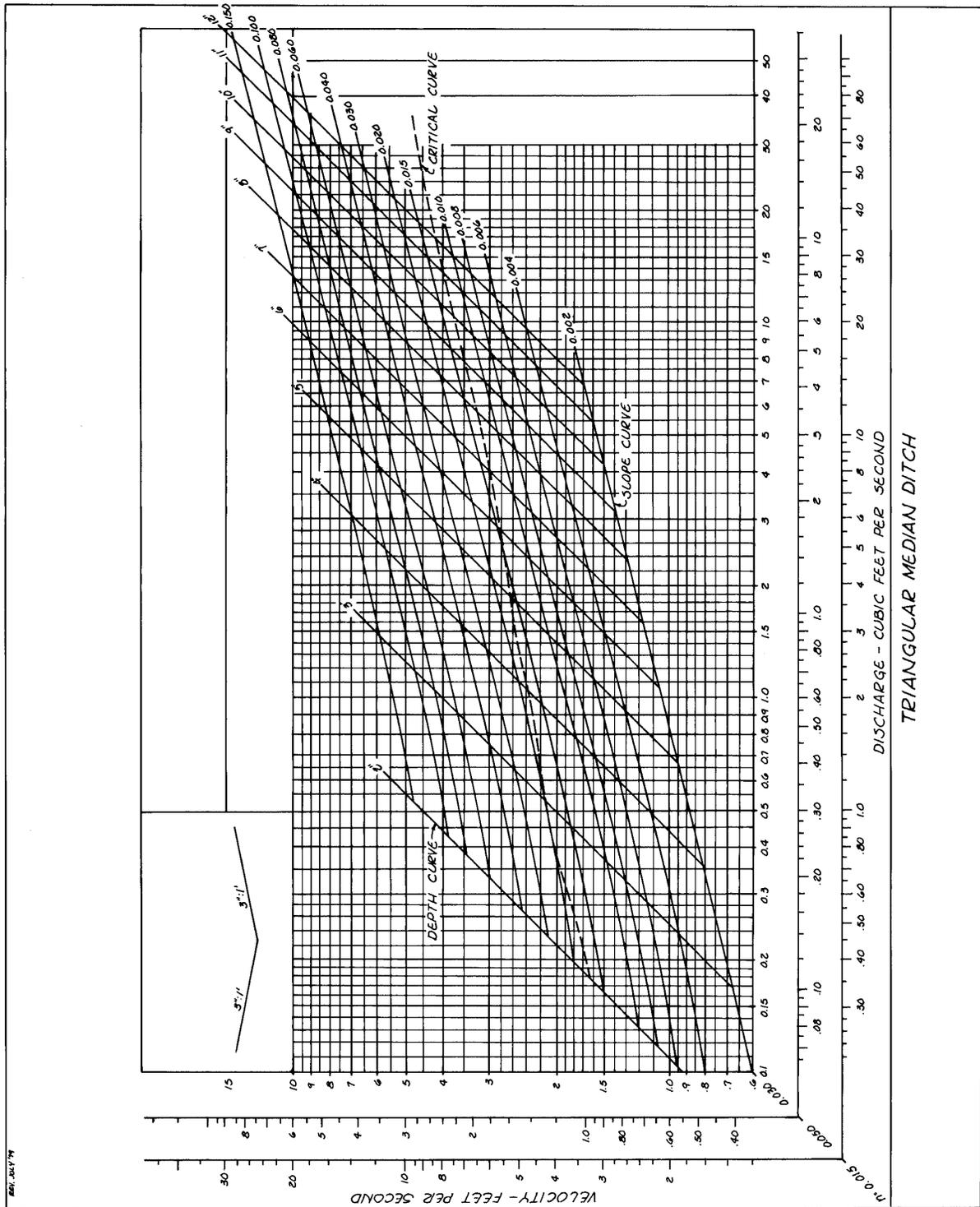
Source: VDOT

Appendix 7C-12 Triangular Median Ditch Flow Chart
(Side Slopes = 6:1, 6:1)



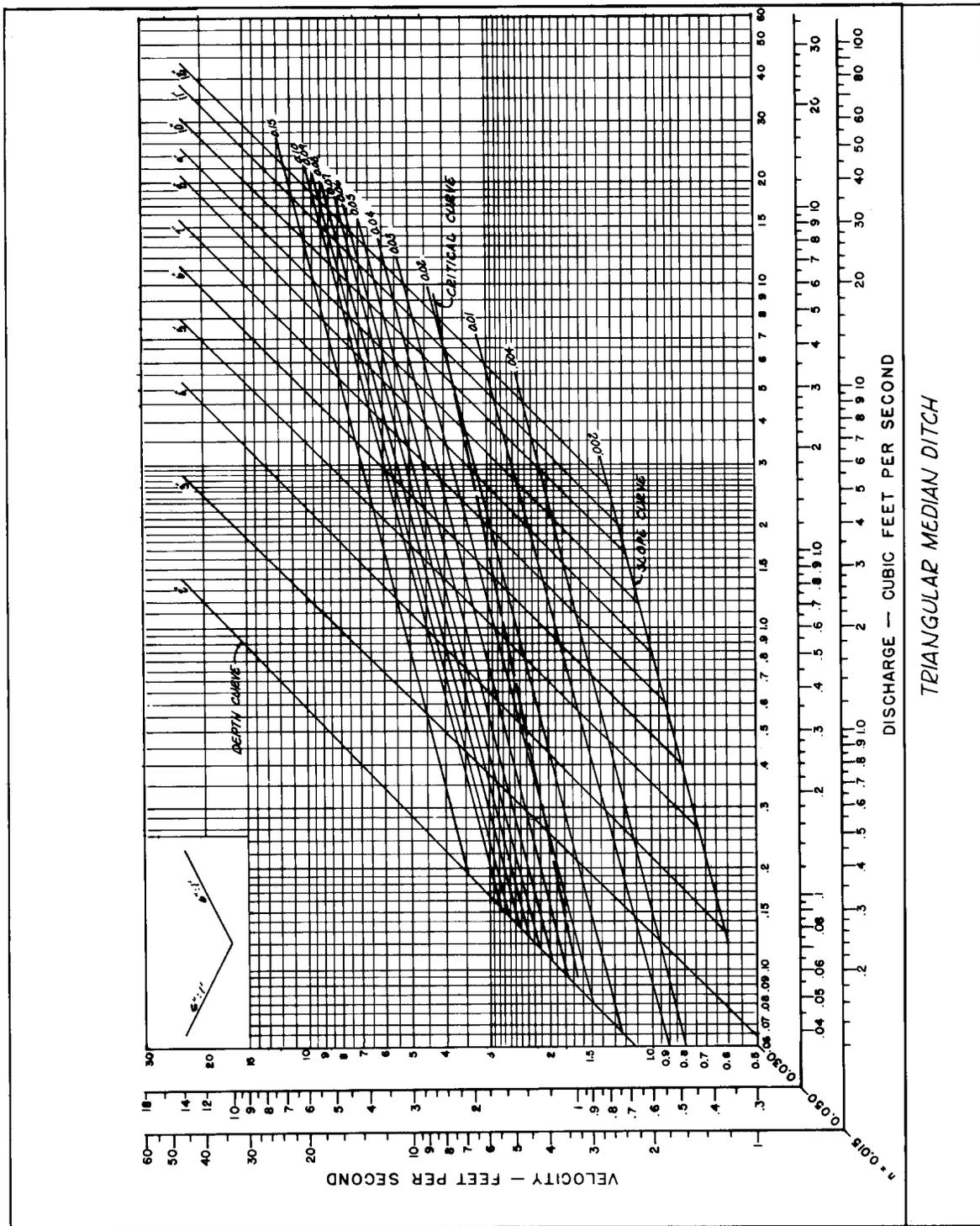
Source: VDOT

Appendix 7C-13 Triangular Median Ditch Flow Chart
(Side Slopes = 4:1, 4:1)



Source: VDOT

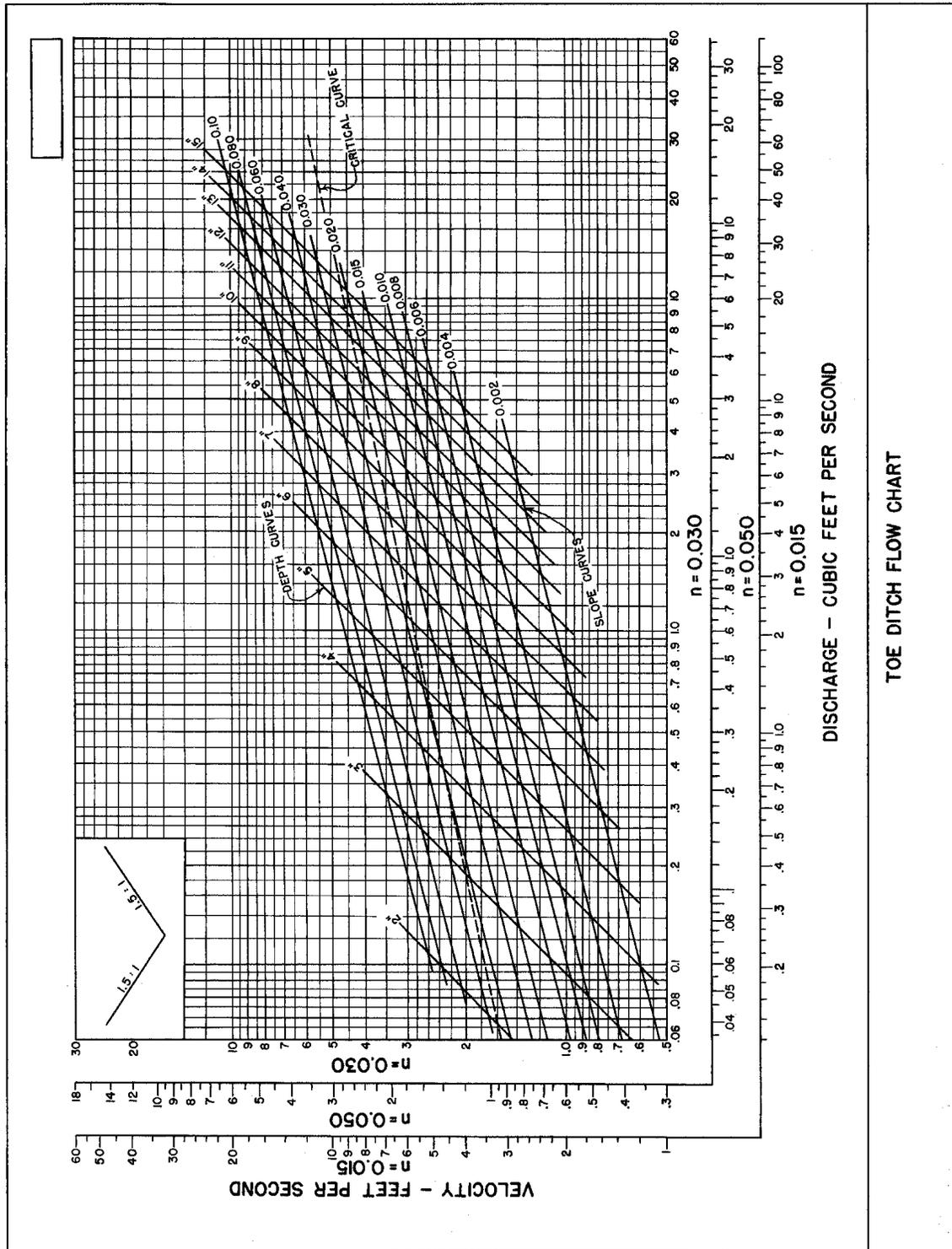
Appendix 7C-14 Triangular Median Ditch Flow Chart
(Side Slopes = 2:1, 2:1)



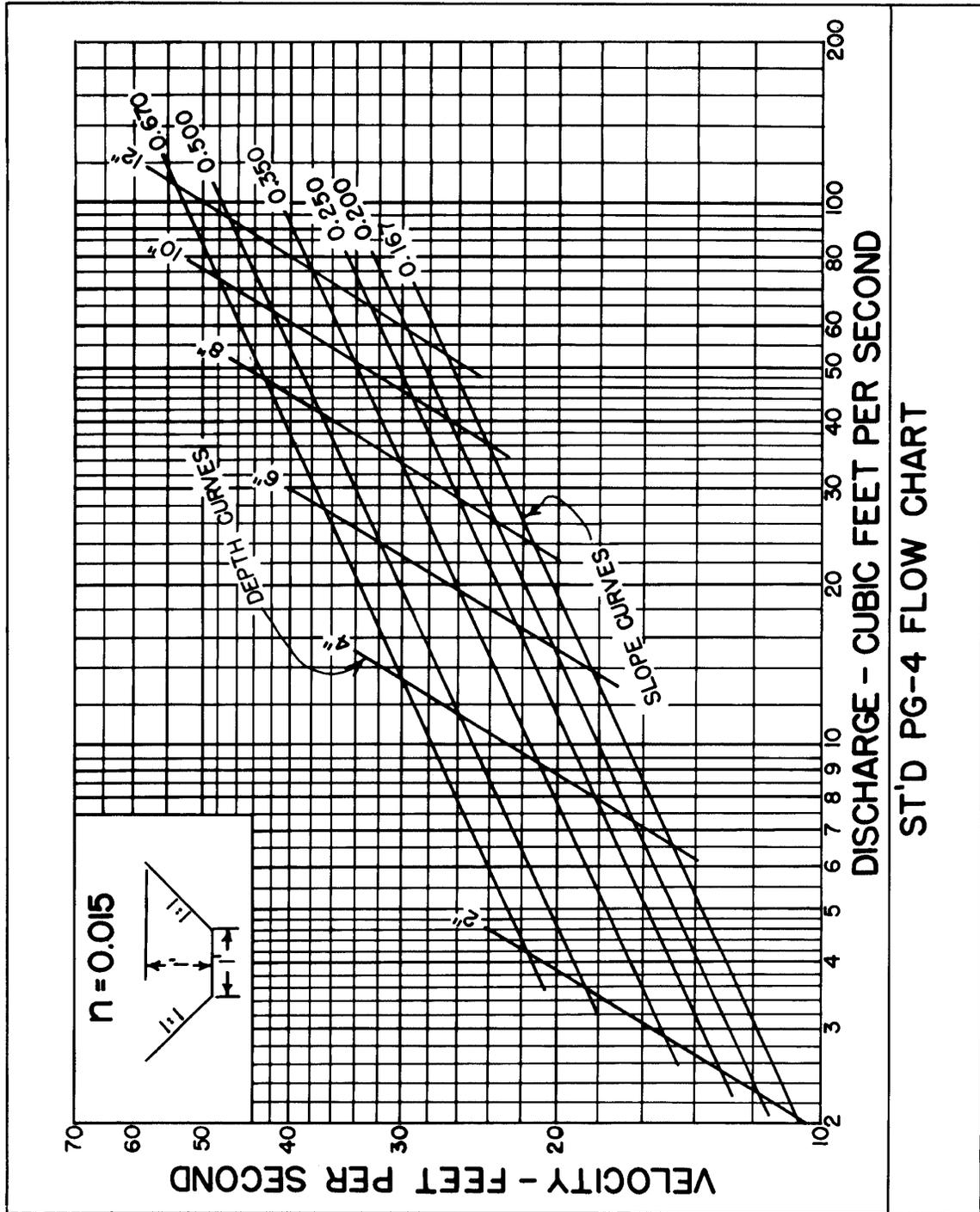
Source: VDOT

Appendix 7C-15

Toe Ditch Flow Chart
(Side Slopes = 1.5:1, 1.5:1)



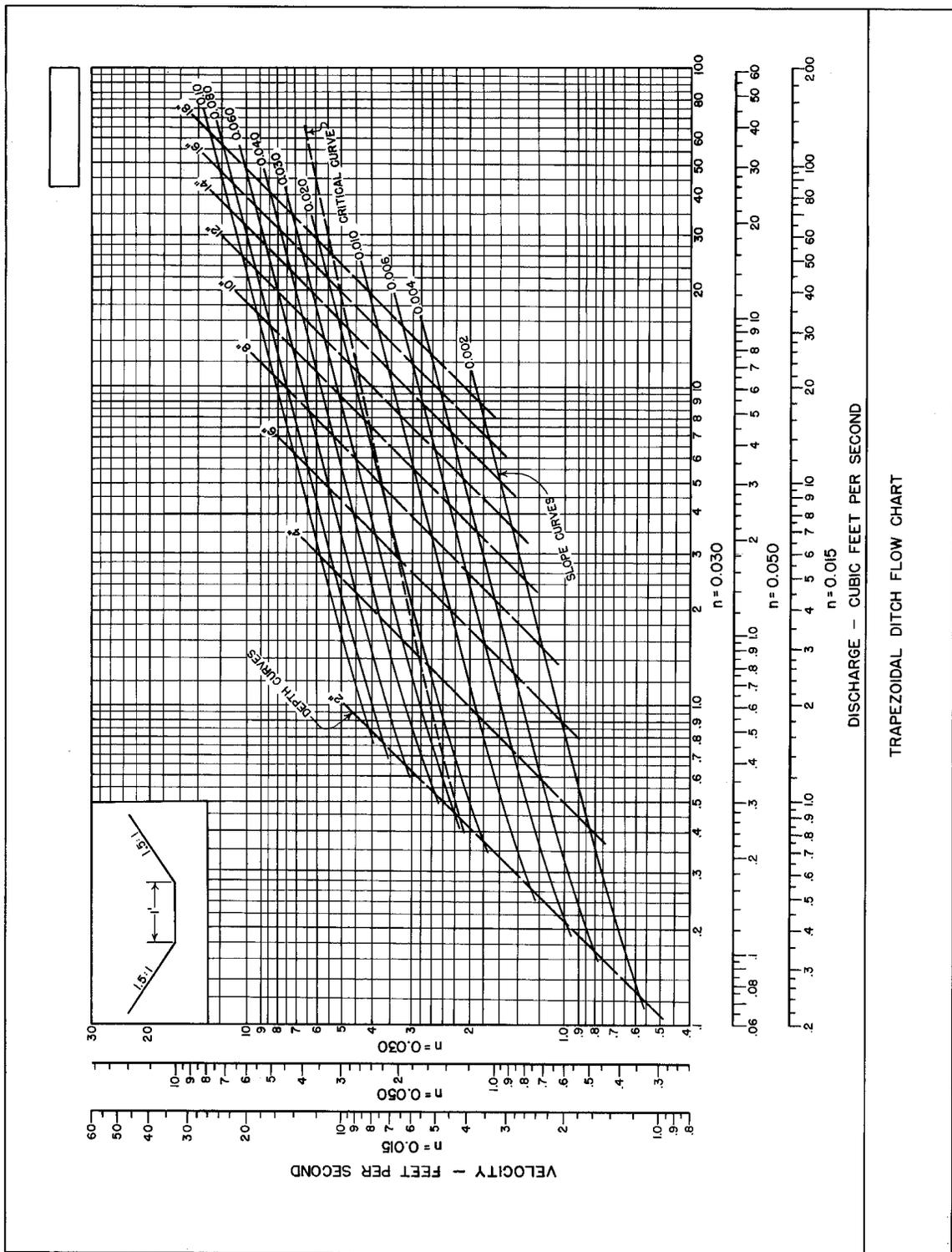
Source: VDOT



Source: VDOT

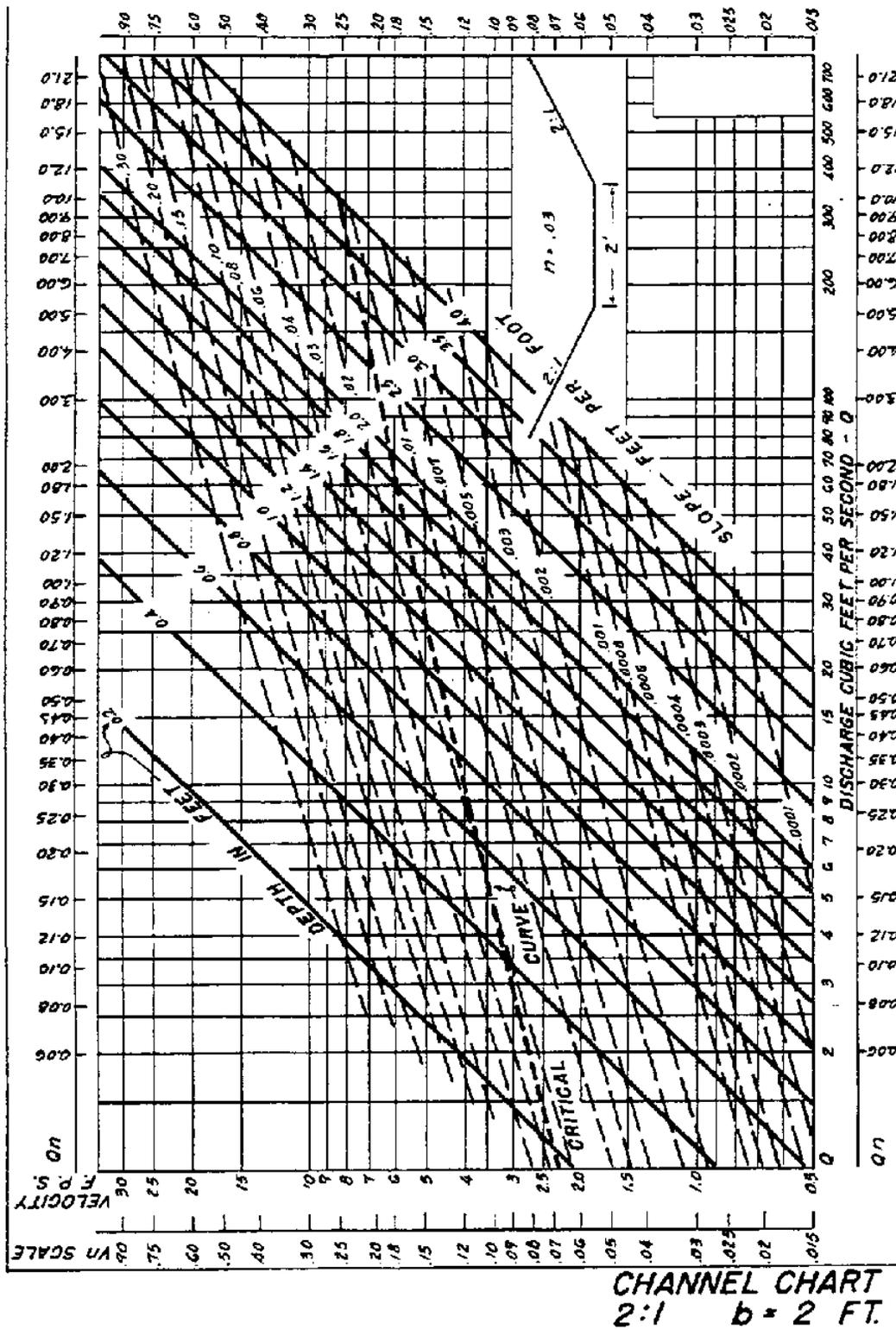
Appendix 7C-17

Trapezoidal Ditch Flow Chart
(B=1', Side Slopes = 1.5:1)



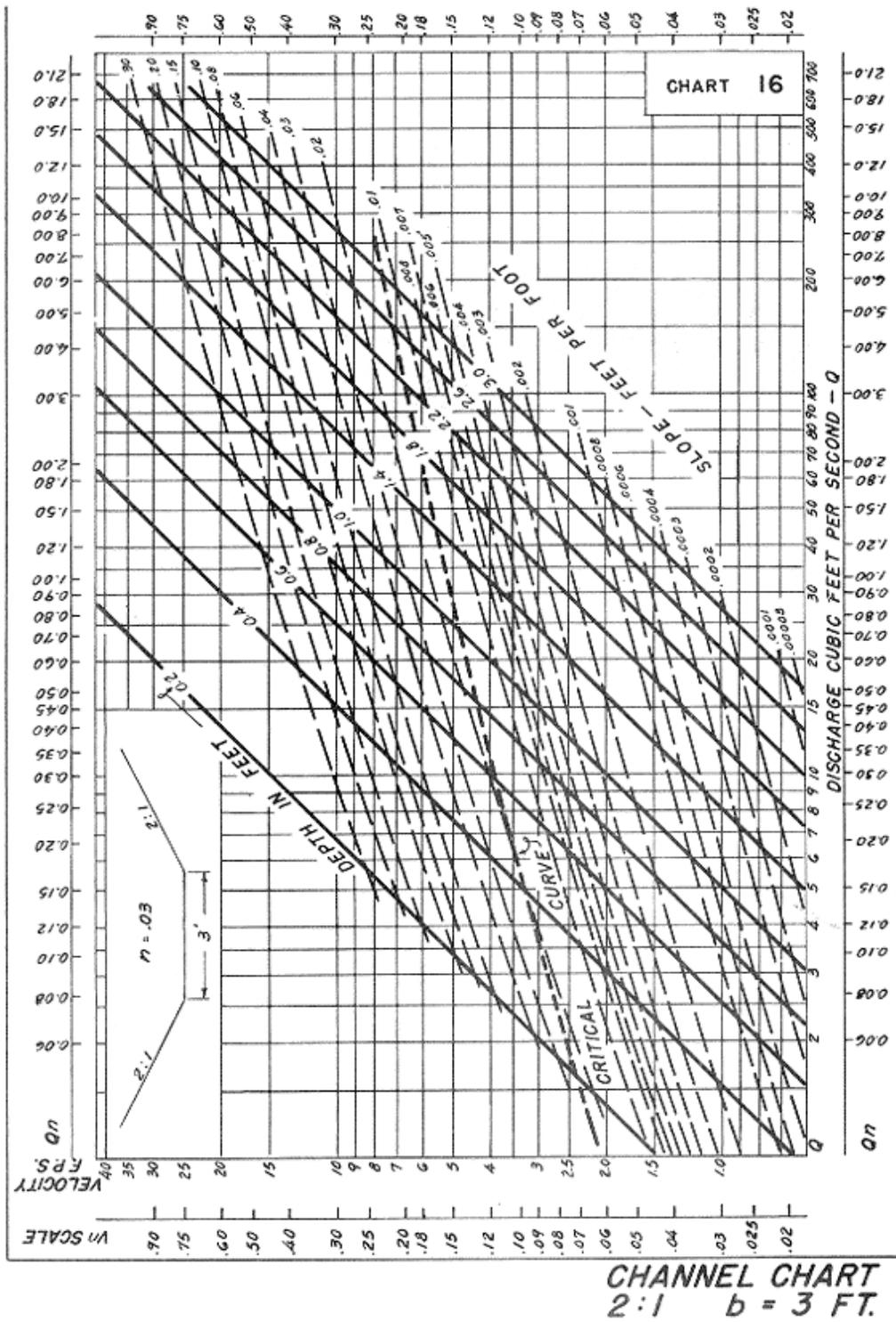
Source: HDS-3

Appendix 7C-18 Trapezoidal Channel Flow Chart
(B=2', Side Slopes = 2:1)



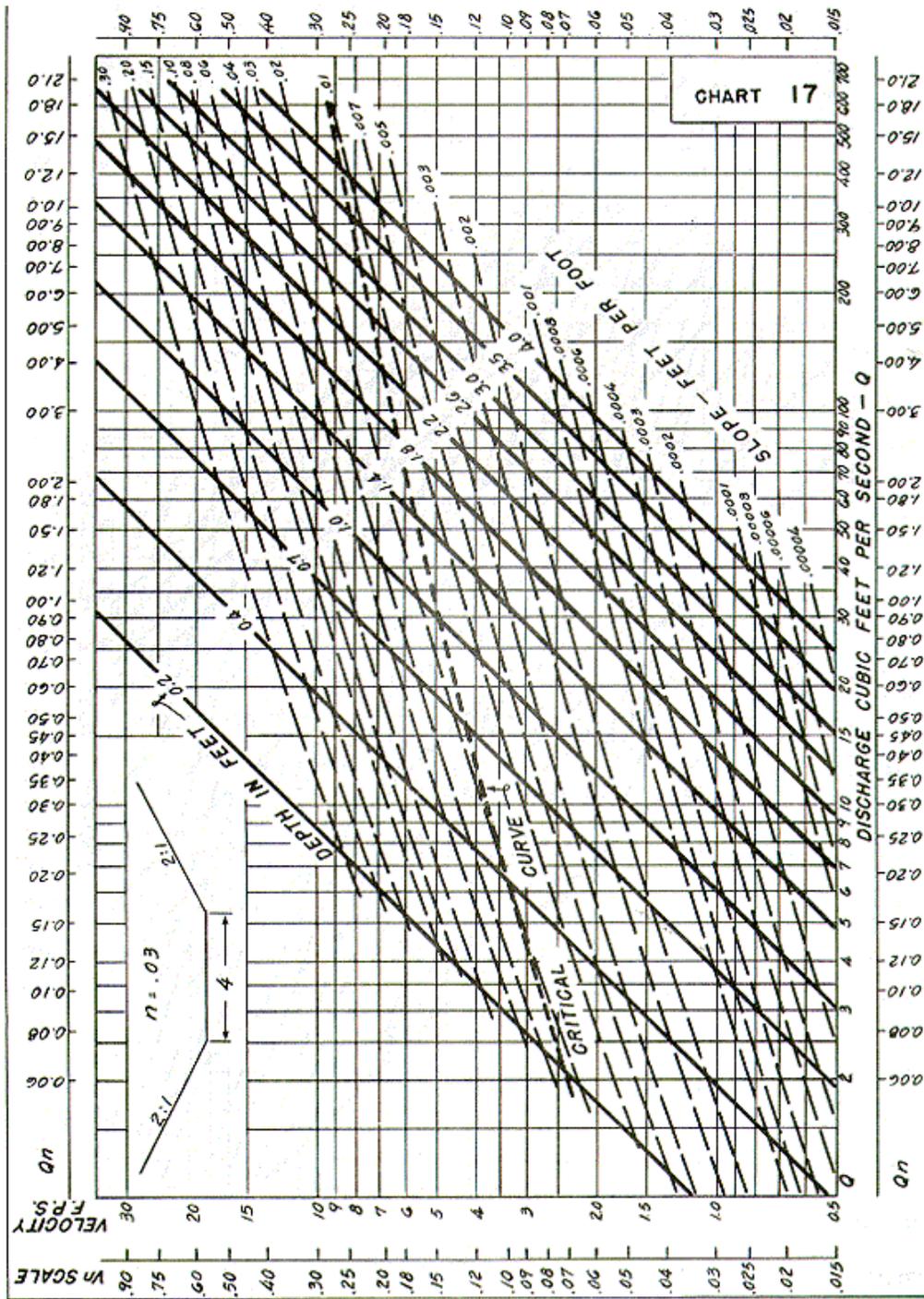
Source: HDS-3

Appendix 7C-19 Trapezoidal Channel Flow Chart
(B=3', Side Slopes = 2:1)



Source: HDS-3

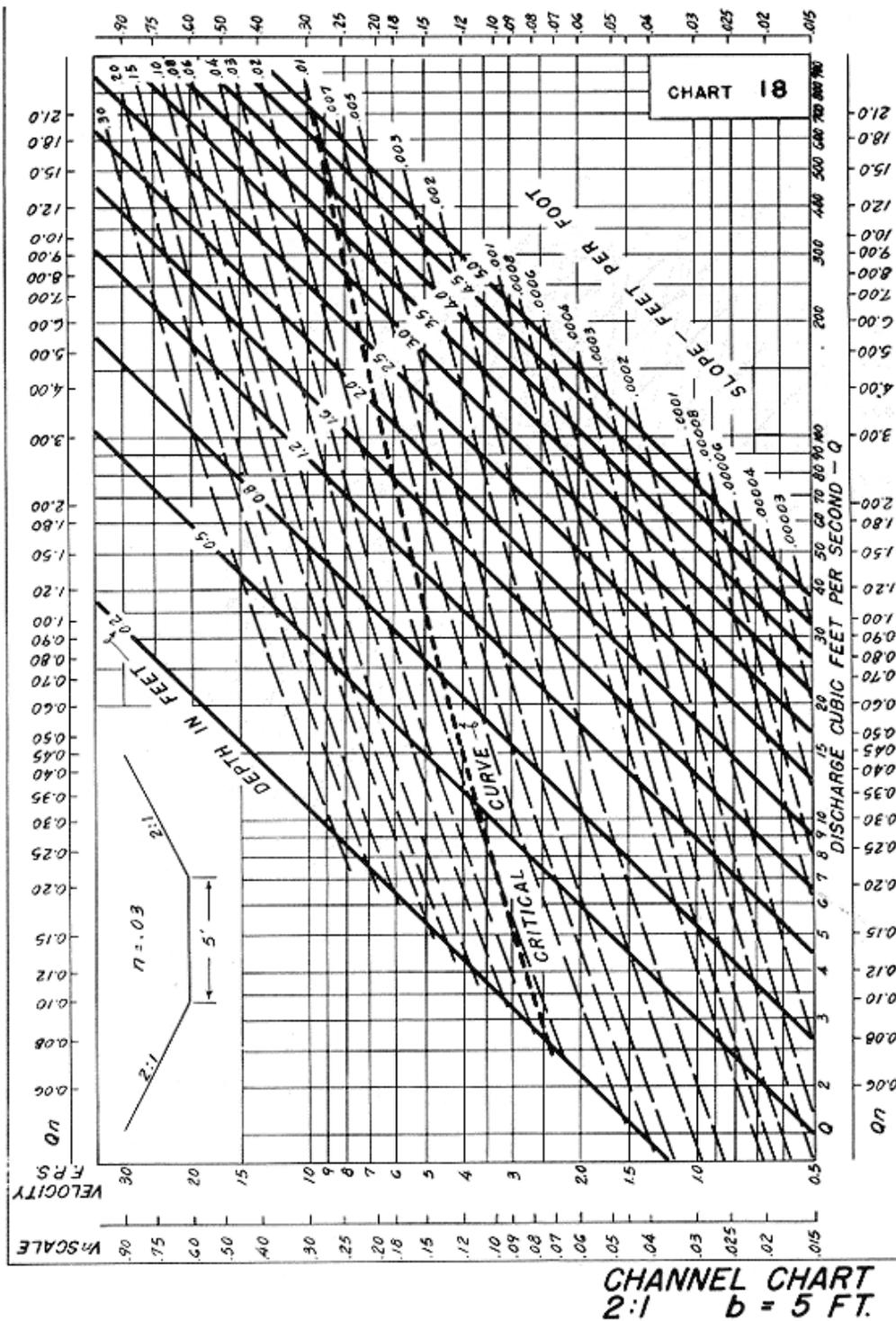
Appendix 7C-20 Trapezoidal Channel Flow Chart
(B=4', Side Slopes = 2:1)



CHANNEL CHART
2:1 b = 4 FT.

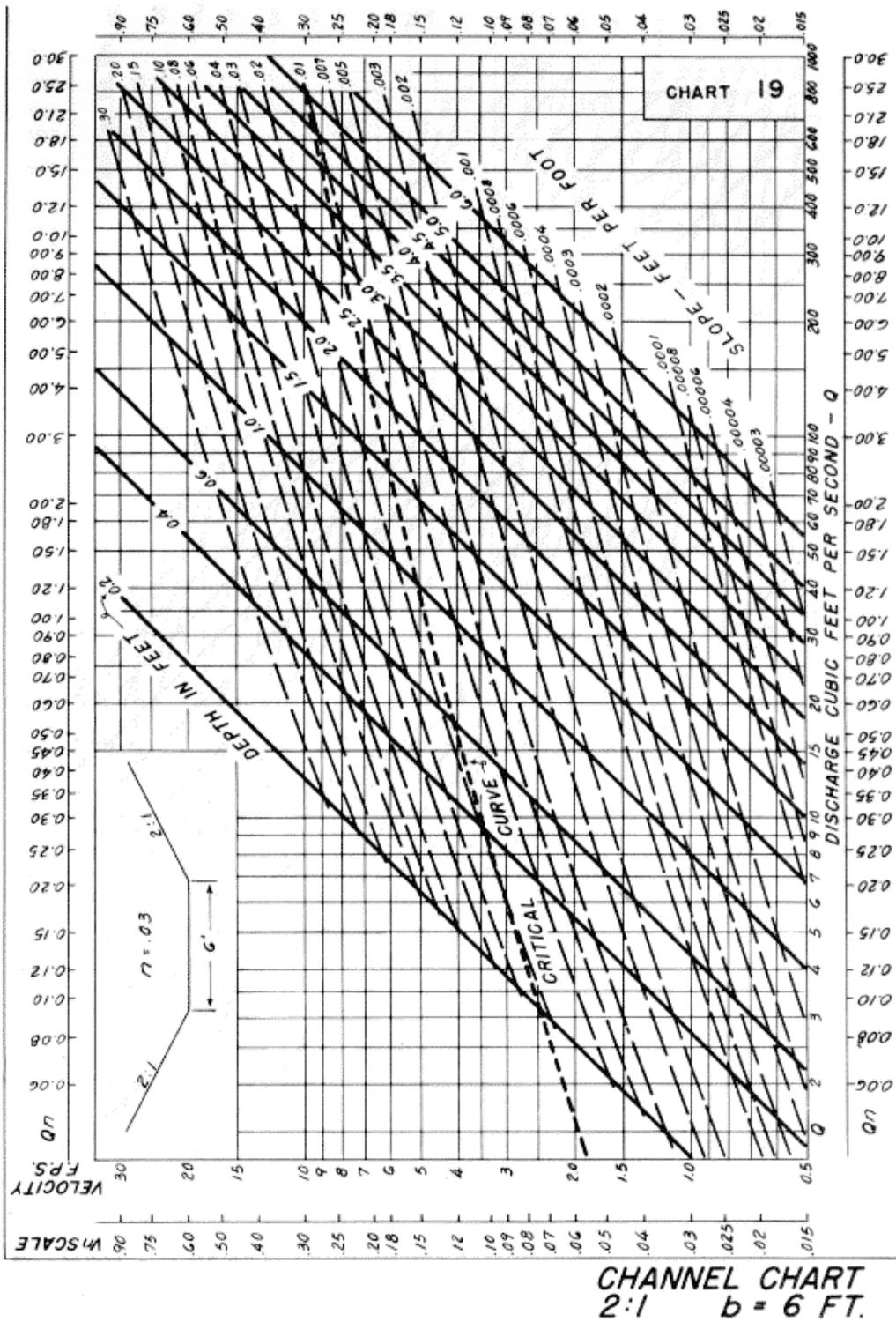
Source: HDS-3

Appendix 7C-21 Trapezoidal Channel Flow Chart
(B = 5', Side Slopes = 2:1)



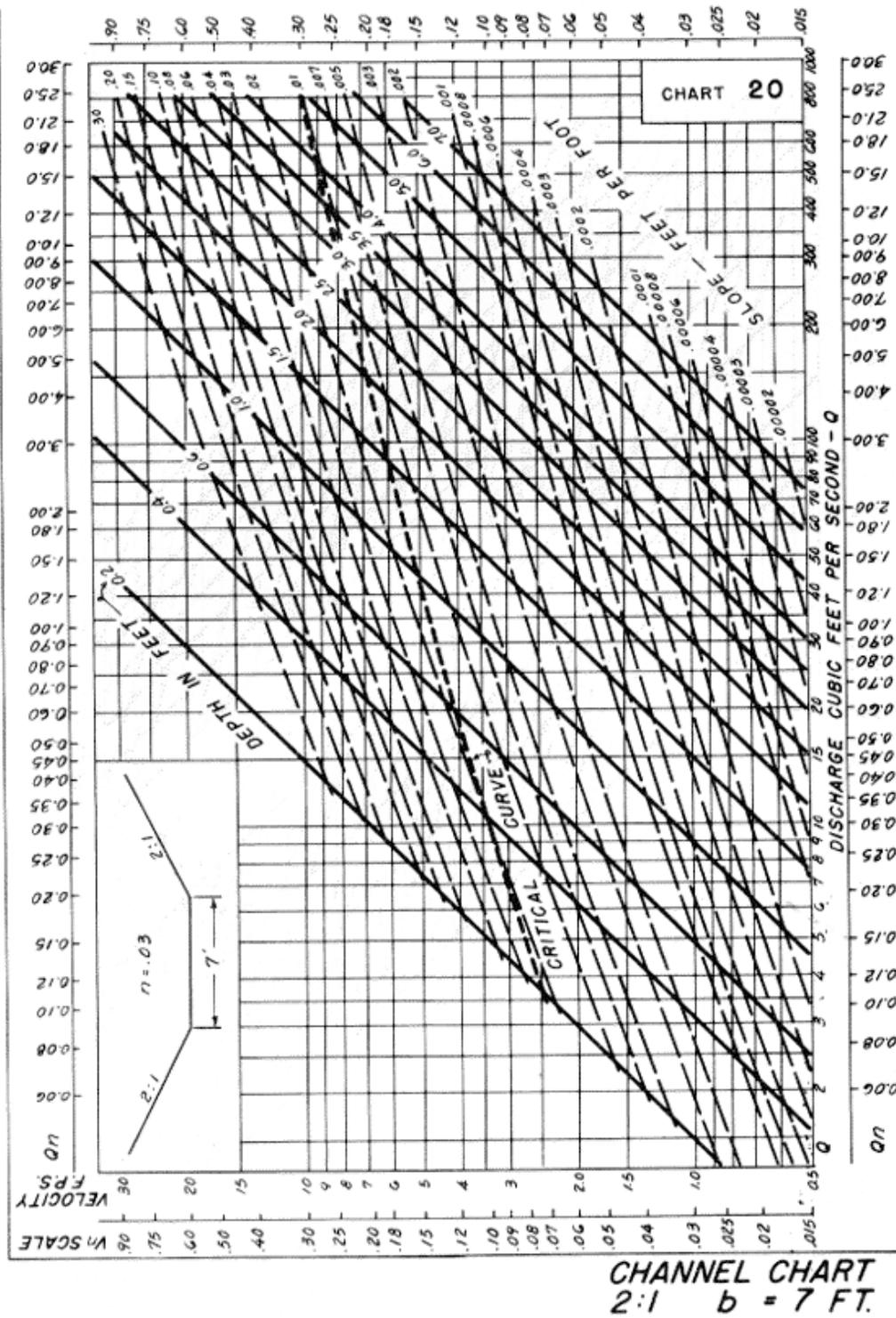
Source: HDS-3

Appendix 7C-22 Trapezoidal Channel Flow Chart
(B = 6', Side Slopes 2:1)



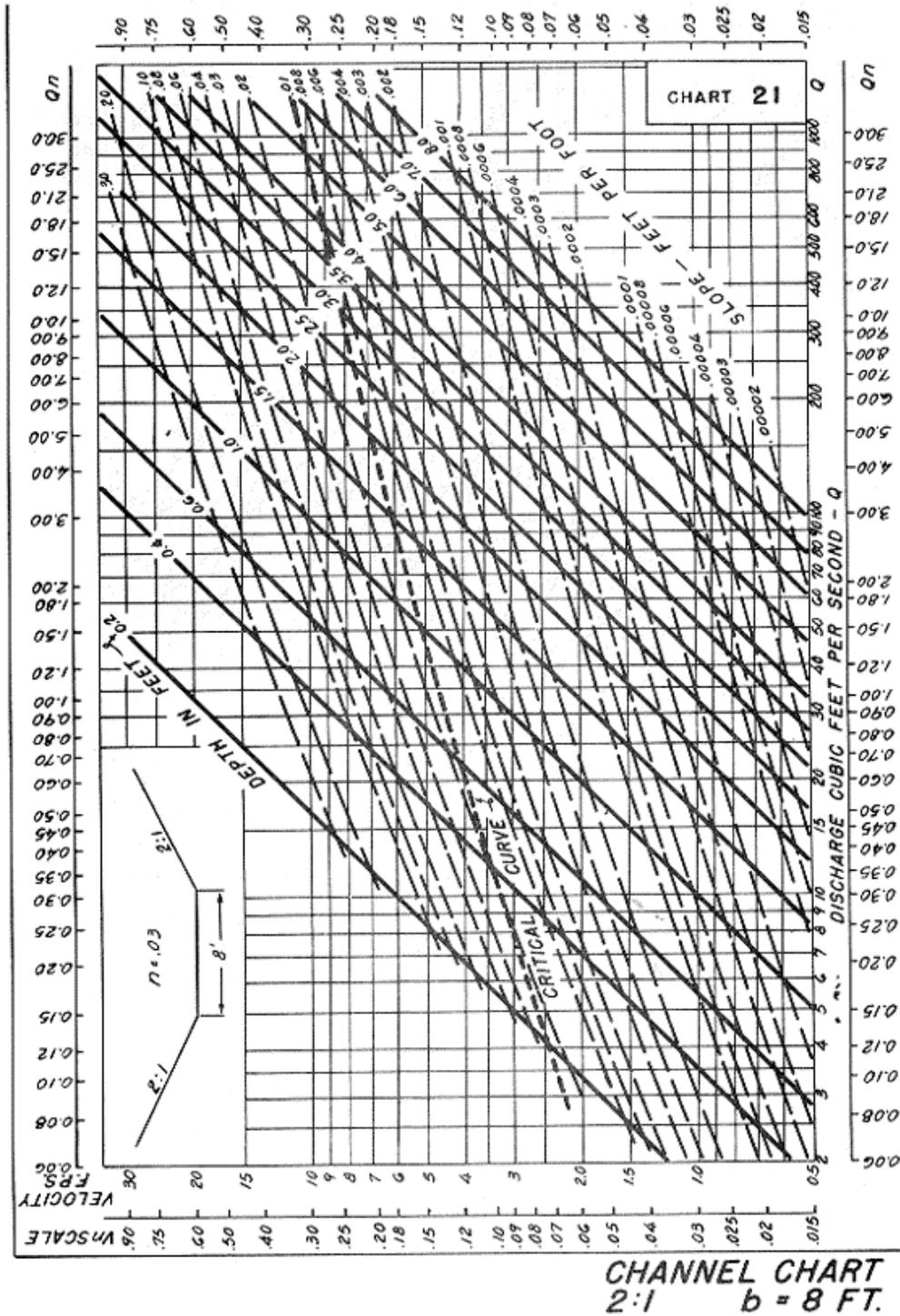
Source: HDS-3

Appendix 7C-23 Trapezoidal Channel Flow Chart
(B = 7', Side Slopes = 2:1)



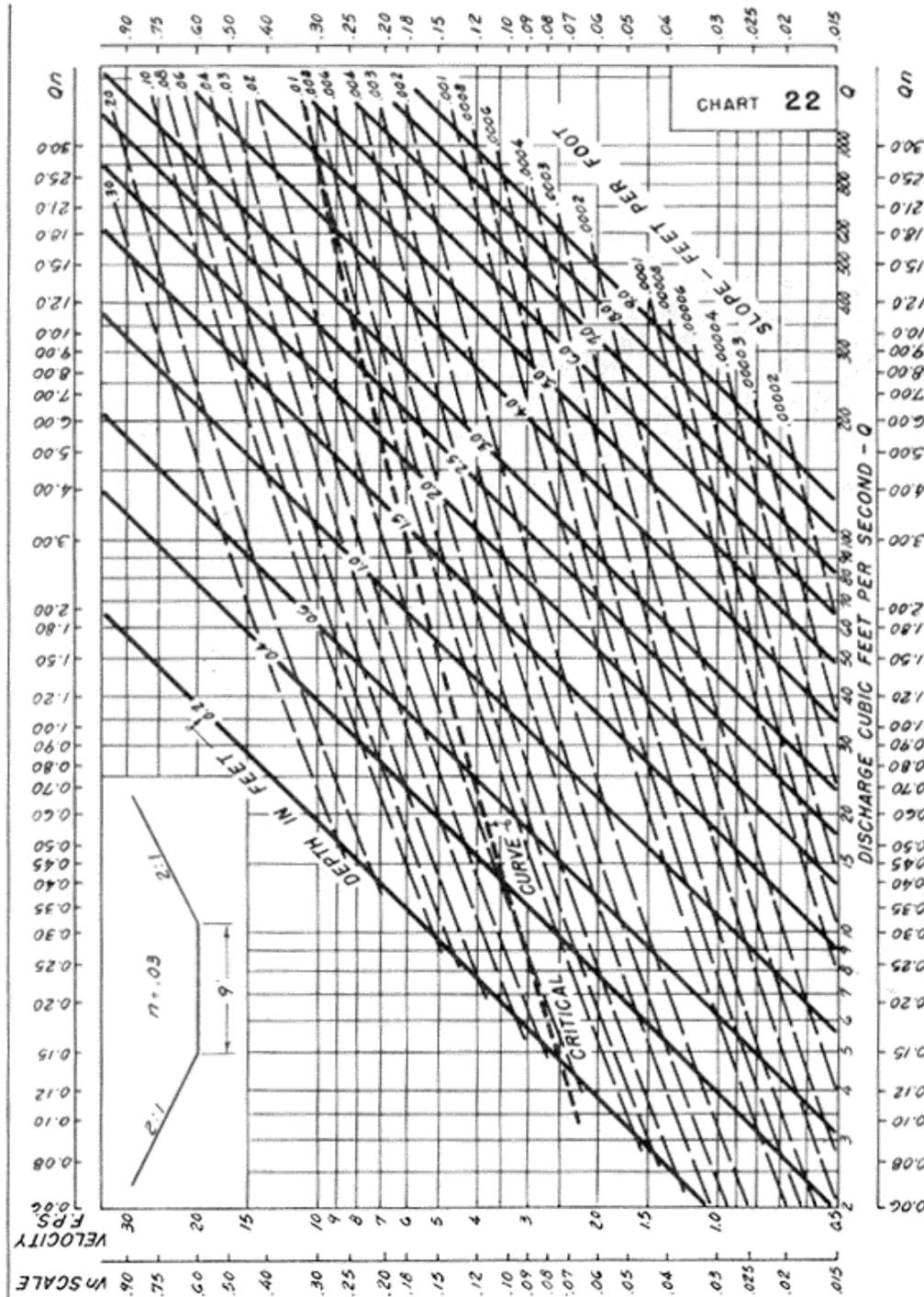
Source: HDS-3

Appendix 7C-24 Trapezoidal Channel Flow Chart
(B = 8', Side Slopes = 2:1)



Source: HDS-3

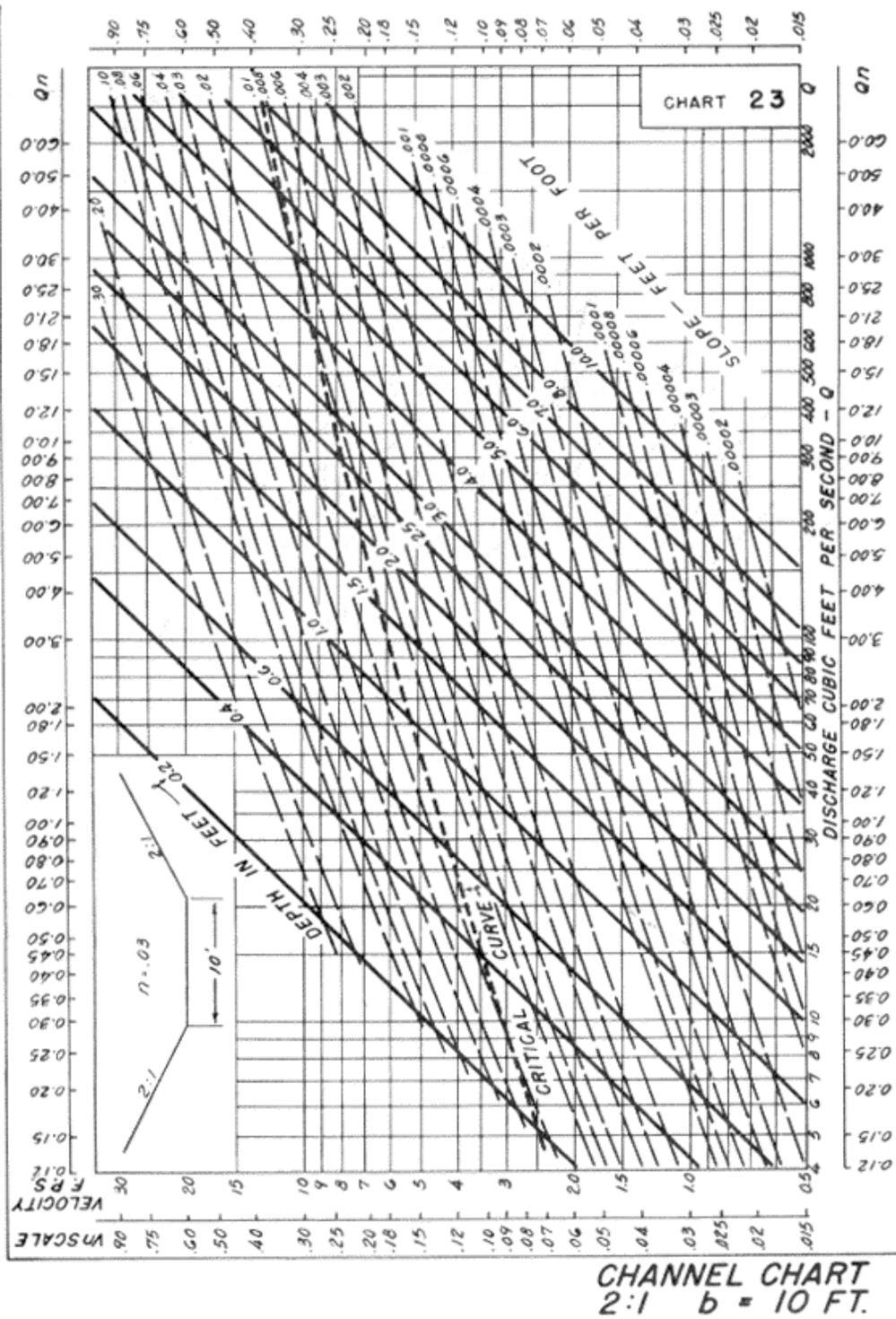
Appendix 7C-25 Trapezoidal Channel Flow Chart
(B = 9', Side Slopes = 2:1)



CHANNEL CHART
2:1 b = 9 FT.

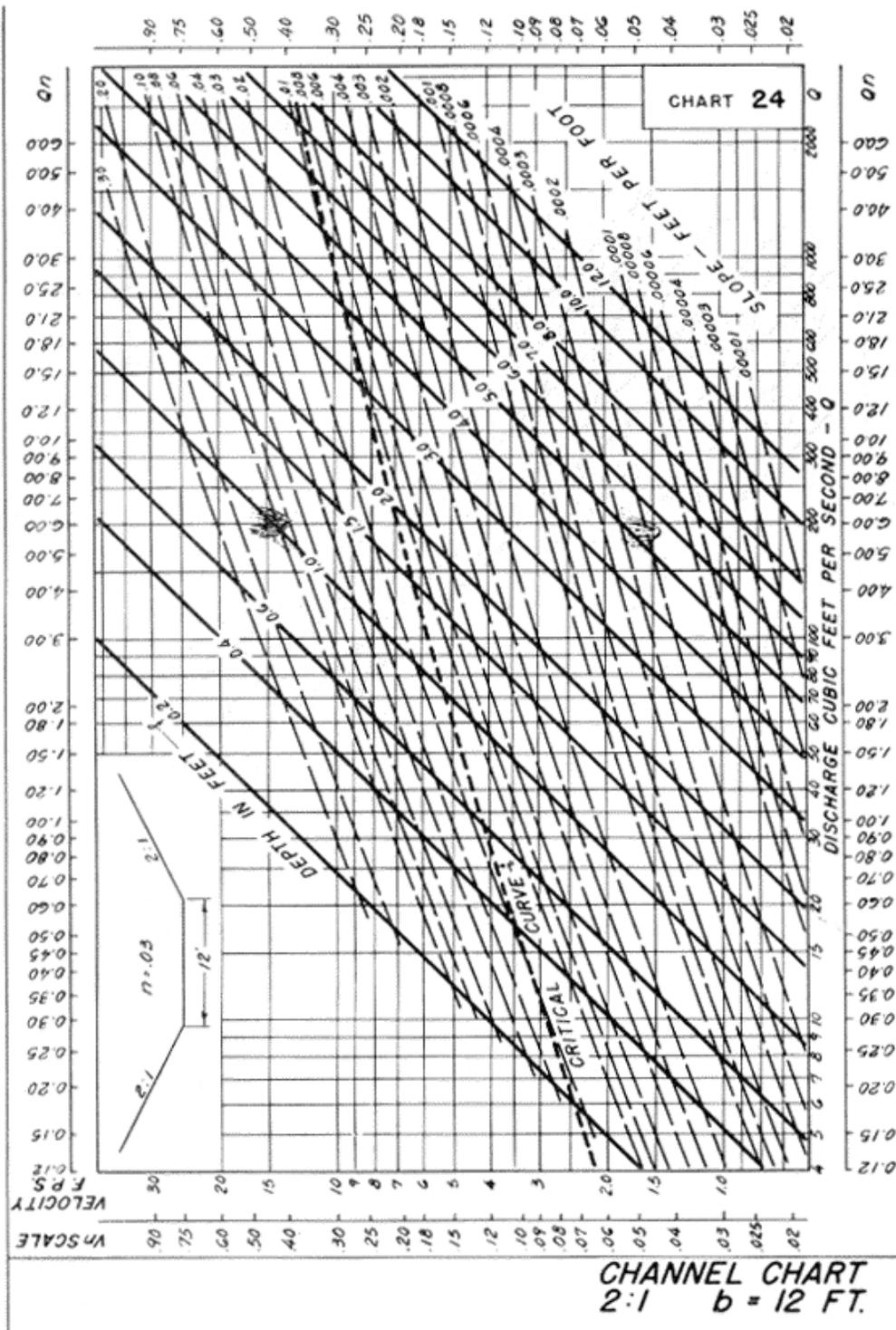
Source: HDS-3

Appendix 7C-26 Trapezoidal Channel Flow Chart
(B = 10', Side Slopes = 2:1)



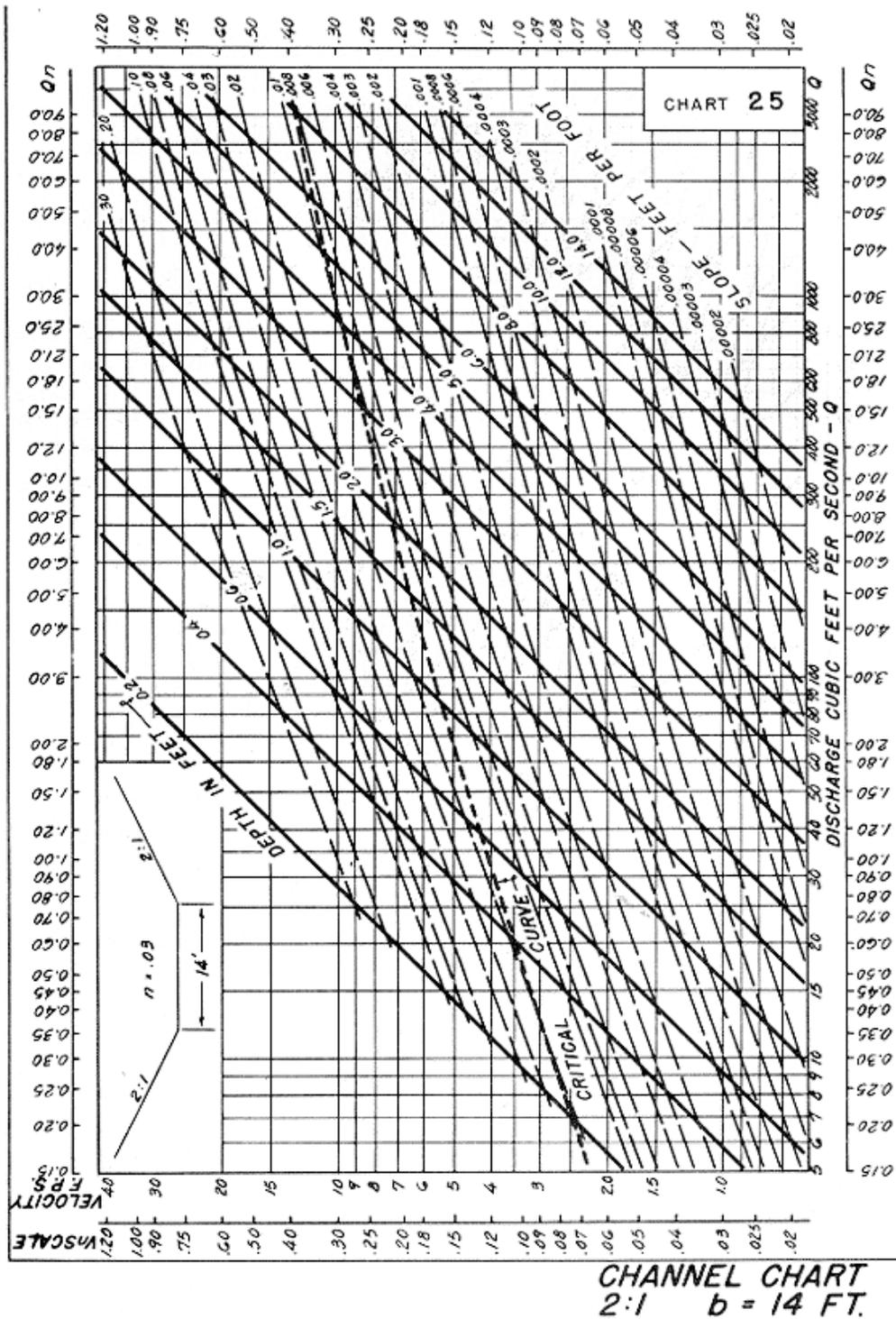
Source: HDS-3

Appendix 7C-27 Trapezoidal Channel Flow Chart
(B = 12', Side Slopes = 2:1)



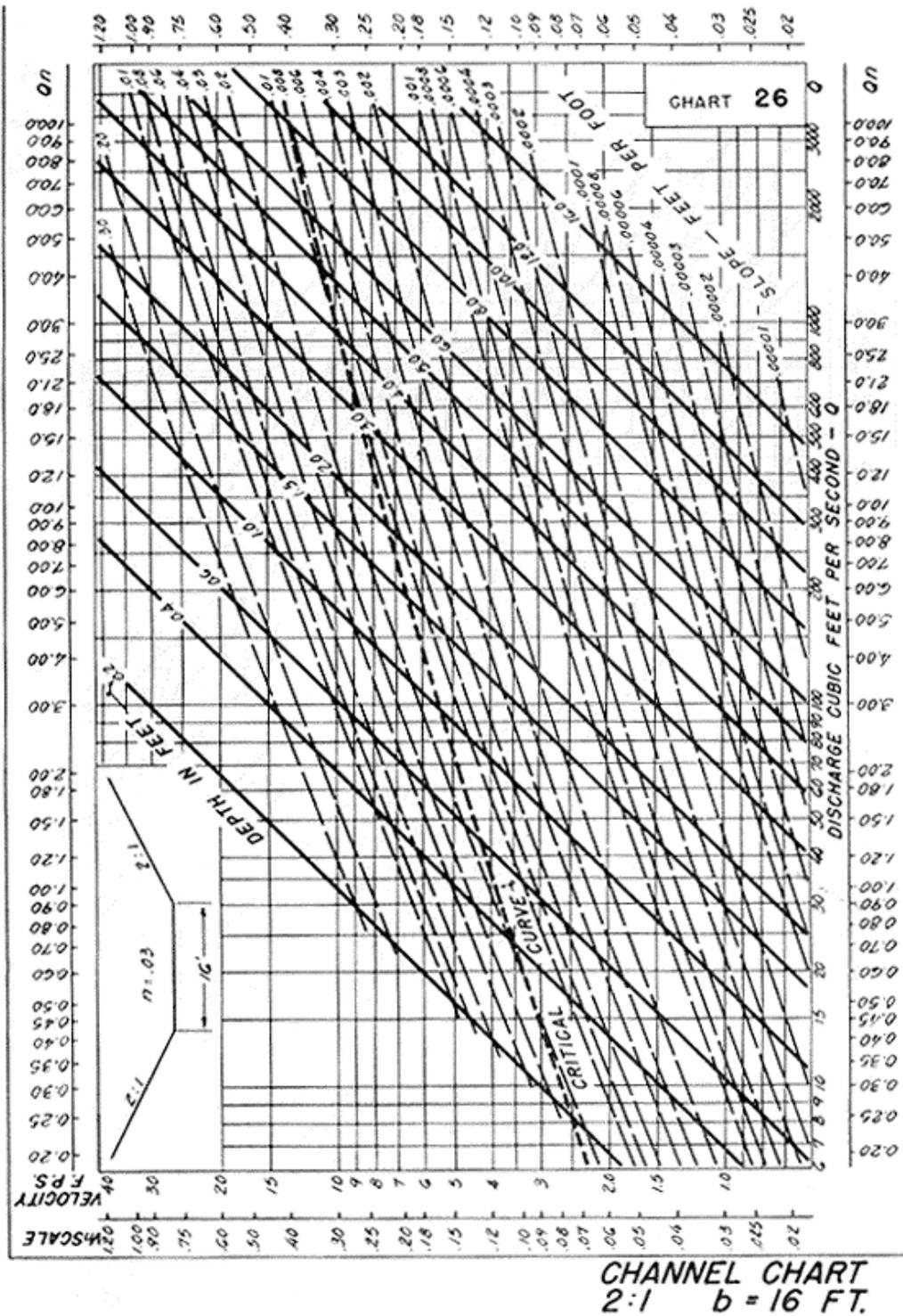
Source: HDS-3

Appendix 7C-28 Trapezoidal Channel Flow Chart
(B = 14', Side Slopes = 2:1)



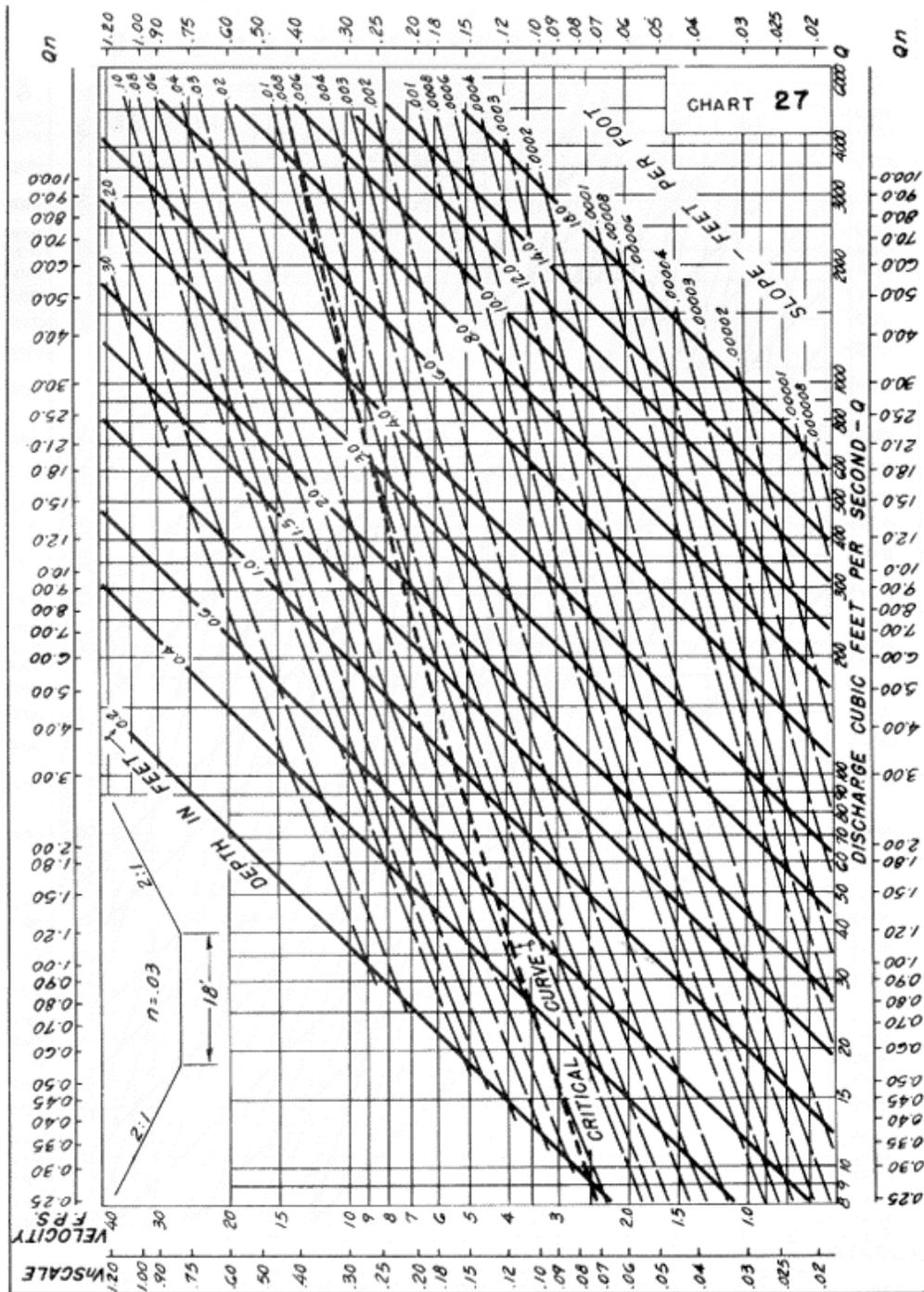
Source: HDS-3

Appendix 7C-29 Trapezoidal Channel Flow Chart
(B = 16', Side Slopes = 2:1)



Source: HDS-3

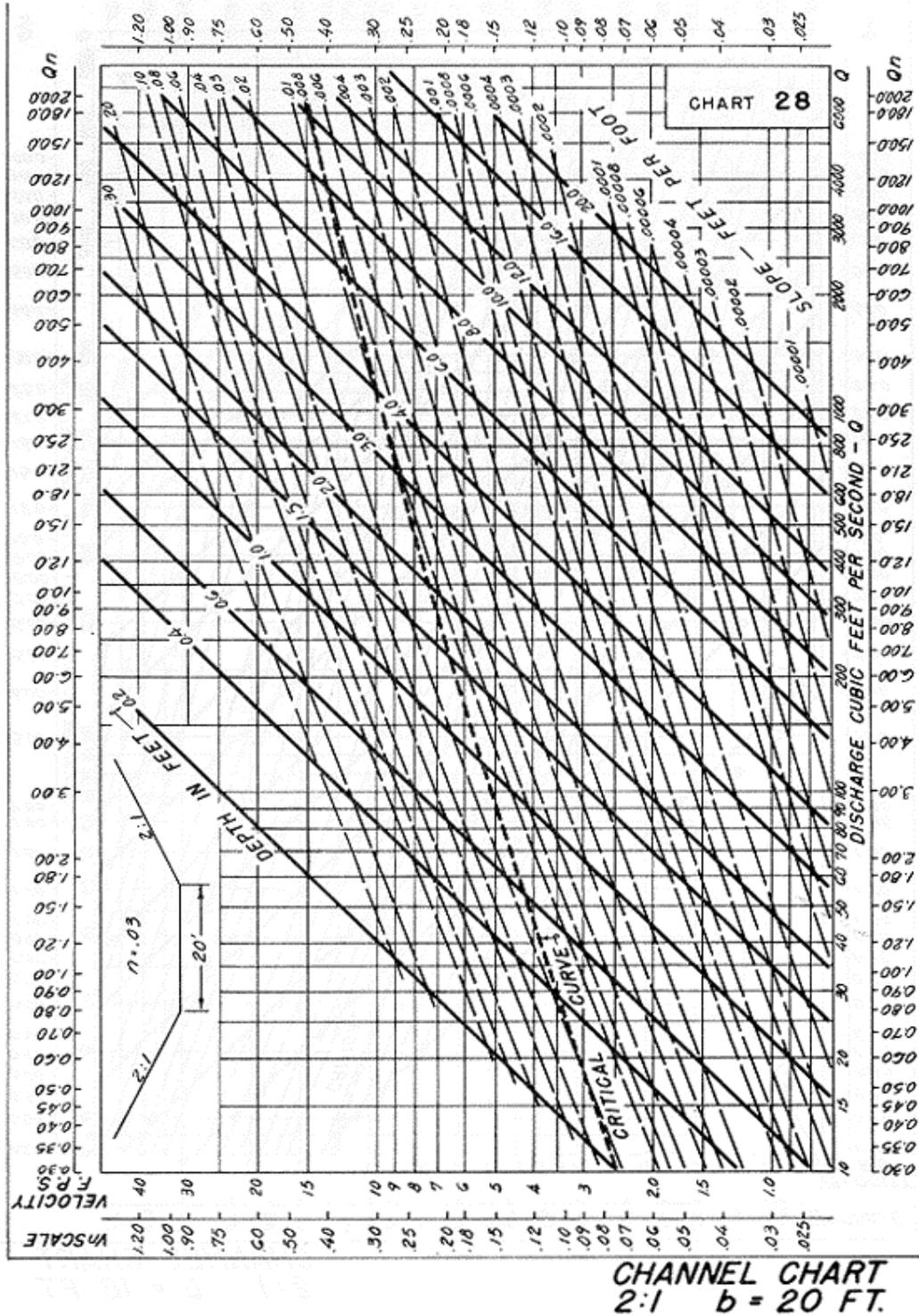
Appendix 7C-30 Trapezoidal Channel Flow Chart
(B = 18', Side Slopes = 2:1)



CHANNEL CHART
2:1 b = 18 FT.

Source: HDS-3

Appendix 7C- 31 Trapezoidal Channel Flow Chart
(B = 20', Side Slopes = 2:1)



Source: HDS-3

Chapter 7 – Ditches and Channels

Appendix 7D-1

**Values of Roughness
Coefficient n (Uniform Flow)**

Type of Channel and Description	Minimum	Normal	Maximum
LINED CHANNELS (Selected linings)			
a. Concrete			
1. Trowel finish	0.011	0.013	0.015
2. Float finish	0.013	0.015	0.016
3. Gunite, good section	0.016	0.019	0.023
b. Asphalt			
1. Smooth	0.013	0.013	-
2. Rough	0.016	0.016	-
c. Riprap (st'd VDOT sizes)			
1. Class 1A	0.033	0.038	-
2. Class 1	0.035	0.040	-
3. Class 2	0.037	0.042	-
4. Class 3	0.039	0.045	-
5. Type I	0.041	0.047	-
6. Type II	0.044	0.050	-
EXCAVATED OR DREDGED			
a. Earth, straight and uniform			
1. Clean, recently completed	0.016	0.018	0.020
2. Clean, after weathering	0.018	0.022	0.025
3. Gravel, uniform section, clean	0.022	0.025	0.030
4. With short grass, few weeds	0.022	0.027	0.033
b. Earth, winding and sluggish			
1. No vegetation	0.023	0.025	0.030
2. Grass, some weeds	0.025	0.030	0.033
3. Dense weeds or aquatic plants in deep channels	0.030	0.035	0.040
4. Earth bottom and rubble sides	0.025	0.030	0.035
5. Stony bottom and weedy sides	0.025	0.035	0.045
6. Cobble bottom and clean sides	0.030	0.040	0.050
c. Dragline excavated or dredged			
1. No vegetation	0.025	0.028	0.033
2. Light brush on banks	0.035	0.050	0.060
d. Rock cuts			
1. Smooth and uniform	0.025	0.035	0.040
2. Jagged and irregular	0.035	0.040	0.050
e. Channels not maintained, weeds and brush uncut			
1. Dense weeds, high as flow depth	0.050	0.080	0.120
2. Clean bottom, brush on sides	0.040	0.050	0.080
3. Same, highest stage of flow	0.045	0.070	0.110
4. Dense brush, high stage	0.080	0.100	0.140
NATURAL STREAMS			
1. Minor streams (top width at flood stage <100 ft)			
a. Streams on Plain			
1. Clean, straight, full stage, no rifts or deep pools	0.025	0.030	0.033
2. Same as above, but more stones/weeds	0.030	0.035	0.040
3. Clean, winding, some pools/shoals	0.033	0.040	0.045
4. Same as above, but some weeds/stones	0.035	0.045	0.050
5. Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
6. Same as 4, but more stones	0.045	0.050	0.060
7. Sluggish reaches, weedy, deep pools	0.050	0.070	0.080

* Rev 7/09

Appendix 7D-1 Values of Roughness Coefficient n (Uniform Flow)

Type of Channel and Description	Minimum	Normal	Maximum
8. Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
b. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
1. Bottom: gravels, cobbles and few boulders	0.030	0.040	0.050
2. Bottom: cobbles with large boulders	0.040	0.050	0.070
2. Floodplains			
a. Pasture, no brush			
1. Short grass	0.025	0.030	0.035
2. High grass	0.030	0.035	0.050
b. Cultivated area			
1. No crop	0.020	0.030	0.040
2. Mature row crops	0.025	0.035	0.045
3. Mature field crops	0.030	0.040	0.050
c. Brush			
1. Scattered brush, heavy weeds	0.035	0.050	0.070
2. Light brush and trees, in winter	0.035	0.050	0.060
3. Light brush and trees, in summer	0.040	0.060	0.080
4. Medium to dense brush, in winter	0.045	0.070	0.110
5. Medium to dense brush, in summer	0.070	0.100	0.160
d. Trees			
1. Dense Willows, summer, straight	0.110	0.150	0.200
2. Cleared land with tree stumps, no sprouts	0.030	0.040	0.050
3. Same as above, but with heavy growth of sprouts	0.050	0.060	0.080
4. Heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.080	0.100	0.120
5. Same as above, but with flood stage reaching branches	0.100	0.120	0.160
3. Major Streams (top width at flood stage > 100 ft)			
The n-value is less than that for minor streams of similar description, because banks offer less effective resistance.			
a. Regular section with no boulders or brush	0.025	-	0.060
b. Irregular and rough section	0.035	-	0.100

Source: Chow, V.T., FHWA's HDS-6 publication

* For bare earth linings when the soil classifications in accordance with either AASHTO or USCS designations are known, use the Manning's "n" values recommended in the appropriate table from Appendix 7D-2

* Rev 7/09

Appendix 7D-2 Recommended Maximum Water Velocities and Manning's n as a Function of Soil Type and Flow Depth

ASSHTO Classification	ASSHTO Soil Description	Fortier and Scobey Soil Description	Maximum Water Velocity (ft/s)	Manning's n -Flow Depth 0.5-2.0 ft
	BROKEN ROCK and COBBLES	Cobbles and Shingles	5.5	0.030
A-1-a	Stone fragments or GRAVEL , with or without well-graded ¹ binder ²	Coarse gravel, non-colloidal	4.5	0.025
same	same	Fine gravel	3.5	0.020
A-1-b	Coarse SAND , with or without well-graded ¹ binder ²	Graded loam to cobbles when non-colloidal	4.0	0.030
A-2 (A-2-4, A-2-5, A-2-6, A-2-7)	Mixture of GRAVEL and SAND , with silty or clay fines ³ , or nonplastic silt fines	Graded silts to cobbles when colloidal	4.5	0.030
same	same	Sandy loam, non-colloidal	2.0	0.020
A-3	Fine SAND , without silty clay fines; e.g. beach sand or stream-deposited fine sand	Fine Sand, non-colloidal	1.5	0.020
same	same	Silt loam, non-colloidal	2.3	0.020
A-4	Non- to moderately plastic ⁴ SILT ; mixtures of silt, sand, and/or gravel, with a minimum silt content of 36%	Alluvial silts, non-colloidal	2.3	0.020
A-5	Moderately to highly plastic ⁴ SILT . Soil; mixtures of silt, sand, and/or gravel, with a minimum fines ³ content of 36%	Ordinary firm loam	2.5	0.020
A-6	Plastic ⁴ CLAY soil; mixtures of clay, sand, and/or gravel, with a minimum fines ³ content of 36%	Alluvial silts, colloidal	3.5	0.025
A-7	Moderately to highly plastic, CLAY ; mixtures of clay, sand, and/or gravel, with a minimum clay content of 36%	Stiff clay, very colloidal	4.0	0.025

- 1) Well-graded-containing a broad range of particle sizes with no intermediate sizes missing.
- 1) Binder - soil particles consisting of fine sand, silt, and clay.
- 2) Fines - particle sizes finer than 0.074 mm (e.g., silt and clay particles).
- 3) Plasticity - ability of a soil mass to deform at constant volume without cracking or crumbling.
- + Relationship between AASHTO classification and Fortier and Scobey description is loosely correlated.

Chapter 7 – Ditches and Channels

USCS Classification	USCS Soil Description	Fortier and Scobey Soil Description	Maximum Water Velocity (ft/s)	Manning's n -Flow Depth 0.5-2.0 ft
	BROKEN ROCK and COBBLES	Cobbles and Shingles	5.5	0.030
GP, GW, SW, SP	Poorly graded gravel, well graded gravel, well graded sand, poorly graded sand	Coarse gravel, non-colloidal	4.5	0.025
		Fine gravel	3.5	0.020
SW	Well graded sand	Graded loam to cobbles when non-colloidal	4.0	0.030
GC, SC	Clayey gravel, clayey sand	Graded silts to cobbles when colloidal	4.5	0.030
SM	Silty sand	Sandy loam, non-colloidal	2.0	0.020
SP, SW	Poorly graded sand, well graded sand	Fine Sand, non-colloidal	1.5	0.020
ML	Silt	Silt loam, non-colloidal	2.3	0.020
CL	Lean clay	Alluvial silts, non-colloidal	2.3	0.020
ML, CL	Silt, lean clay	Ordinary firm loam	2.5	0.020
CL	Lean clay	Alluvial silts, colloidal	3.5	0.025
CH	Fat clay	Stiff clay, very colloidal	4.0	0.025

Note: Relationship between Unified Soil Classification System (USCS) classification and Fortier and Scobey description is loosely correlated.

**Appendix 7D-3 Standard VDOT Riprap Classifications,
Weights, and Blanket Thickness**

Classification	D₅₀ (ft)	W₅₀ (lbs)	T (in)
Class A1	0.8	50	20
Class I	1.1	100	26
Class II	1.6	300	38
Class III	2.2	1000	53
Type I	2.8	2000	60
Type II	4.5	8000	97

Appendix 7D-4 Approximate Rock Dimensions and Equivalent Weights for Riprap

WEIGHT	MEAN SPHERICAL DIAMETER	RECTANGULAR SHAPE	
		LENGTH	HT./WIDTH
25 lbs.	0.7'	1.1'	0.4'
50 lbs.	0.8'	1.4'	0.5'
75 lbs.	1.0'	1.6'	0.5'
100 lbs.	1.1'	1.75'	0.6'
150 lbs.	1.3'	2.0'	0.67'
300 lbs.	1.6'	2.6'	0.9'
500 lbs.	1.9'	3.0'	1.0'
1000 lbs.	2.2'	3.7'	1.25'
1500 lbs.	2.6'	4.7'	1.5'
2000 lbs.	2.75'	5.4'	1.8'
2 tons	3.6'	6.0'	2.0'
3 tons	4.0'	6.9'	2.3'
4 tons	4.5'	7.6'	2.5'
10 tons	6.1'	10.0'	3.3'

Appendix 7D-5 Selection of Stability Factors

CONDITION	STABILITY FACTOR RANGE
Uniform flow; straight or mildly curving reach (curve radius/channel width >30); impact from wave action and floating debris is minimal; little or no uncertainty in design parameters.	1.0 - 1.2
Gradually varying flow; moderate bend curvature ($30 > \text{curve radius/channel width} > 10$); impact from waves or floating debris is moderate.	1.3 - 1.6
Approaching rapidly varying flow; sharp bend curvature ($30 > \text{curve radius/channel width} > 10$); significant impact potential from floating debris and/or ice; significant wind and/or bore generated waves (1-2 ft); high flow turbulence; mixing flow at bridge abutments; significant uncertainty in design parameters.	1.6 - 2.0
Channel bends when ratio of curve radius to channel width (R/W) > 30.	1.2
Channel bends when $30 > R/W > 10$.	1.3 - 1.6
Channel bends when $R/W < 10$.	1.7

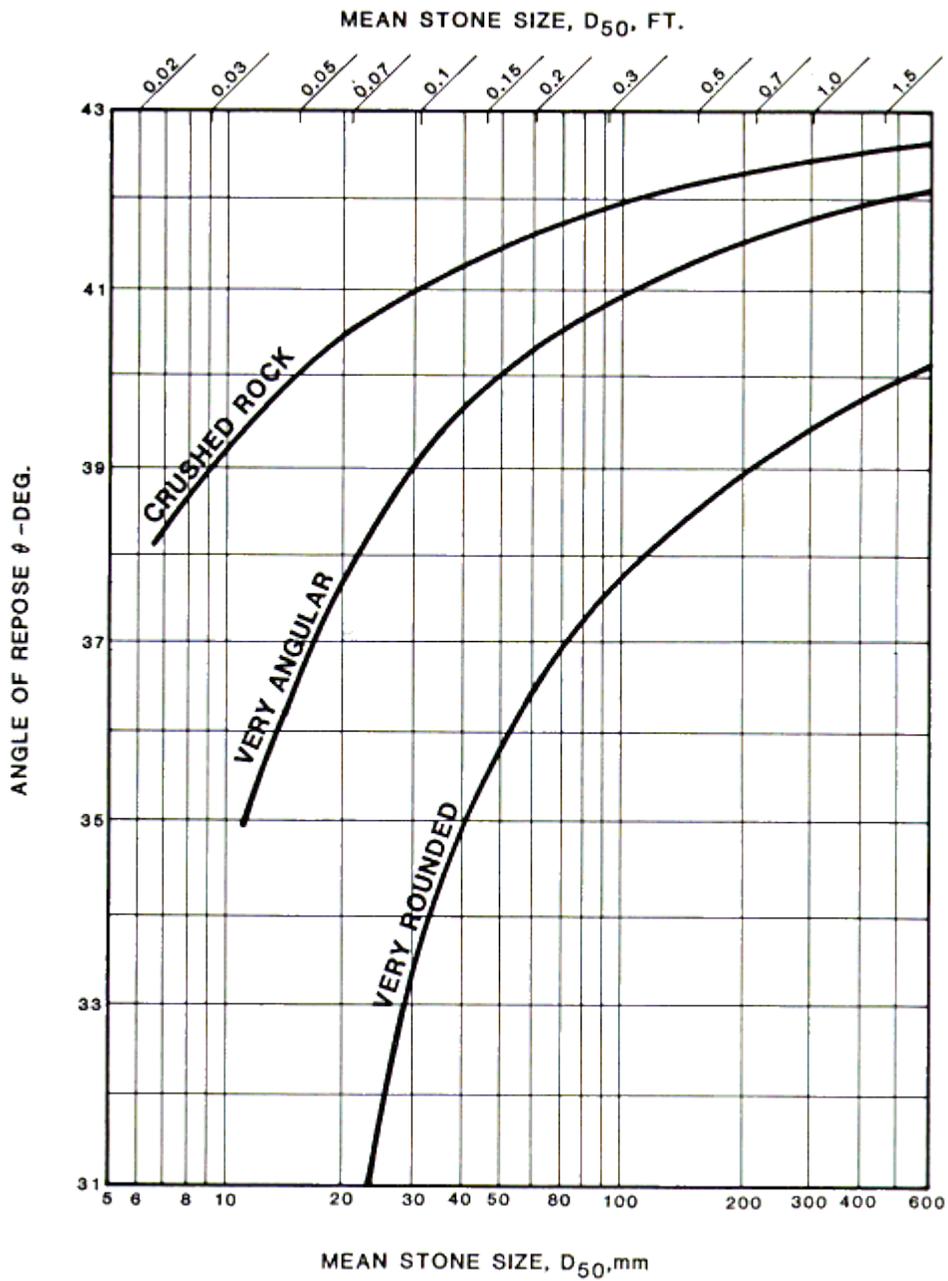
**Appendix 7D-6 Permissible Velocities
for Erodible Linings**

Permissible velocities for channels with erodible linings, based on uniform flow in continuously wet, aged channels¹:

Soil type or lining (earth; no vegetation)	Maximum permissible velocities for		
	Clear water	Water carrying fine silts	Water carrying sand and gravel
	<i>F.p.s.</i>	<i>F.p.s.</i>	<i>F.p.s.</i>
Fine sand (noncolloidal)	1.5	2.5	1.5
Sandy loam (noncolloidal)	1.7	2.5	2.0
Silt loam (noncolloidal)	2.0	3.0	2.0
Ordinary firm loam	2.5	3.5	2.2
Volcanic ash	2.5	3.5	2.7
Fine gravel	2.5	5.0	3.7
Stiff clay (very colloidal)	3.7	5.0	3.0
Graded, loam to cobbles (noncolloidal)	3.7	5.0	5.0
Graded, silt to cobbles (colloidal)	4.0	5.5	5.0
Alluvial silts (noncolloidal)	2.0	3.5	2.0
Alluvial silts (colloidal)	3.7	5.0	3.0
Coarse gravel (noncolloidal)	4.0	6.0	6.5
Cobbles and shingles	5.0	5.5	6.5
Shales and hard pans	6.0	6.0	5.0

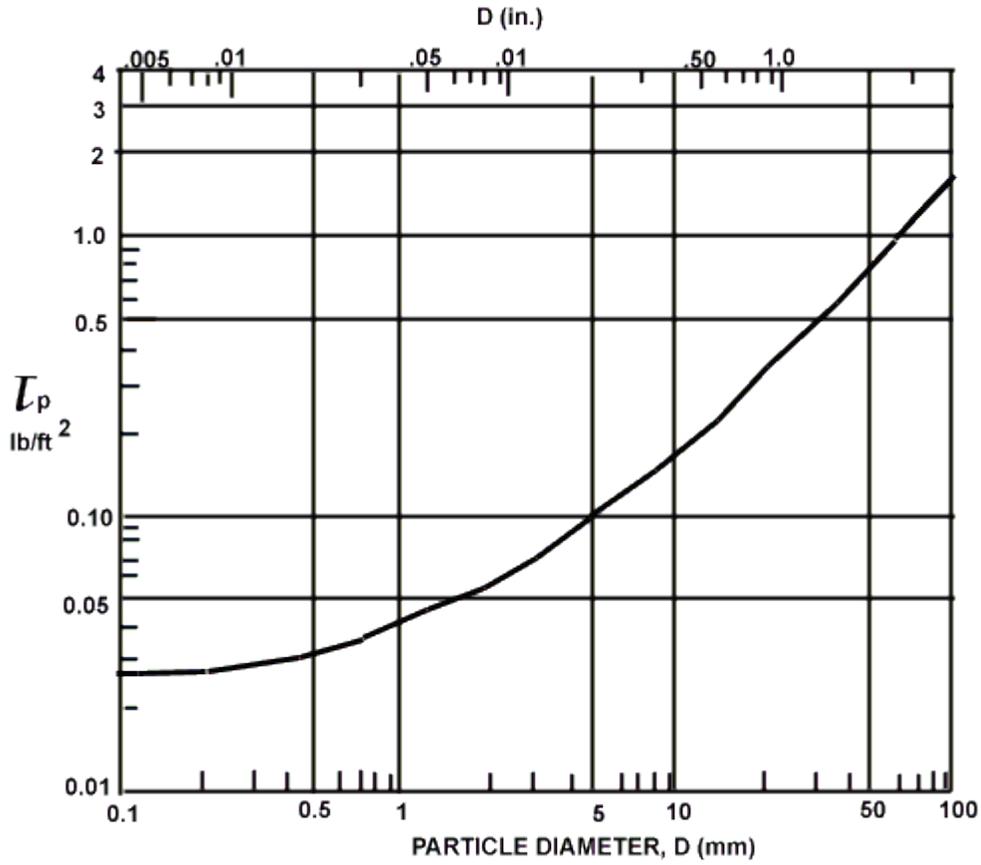
Source: ¹As recommended by Special Committee on Irrigation Research, American Society of Civil Engineers, 1926.

Appendix 7E-1 Angle of Repose of Riprap in Terms of Mean Size and Shape of Stone



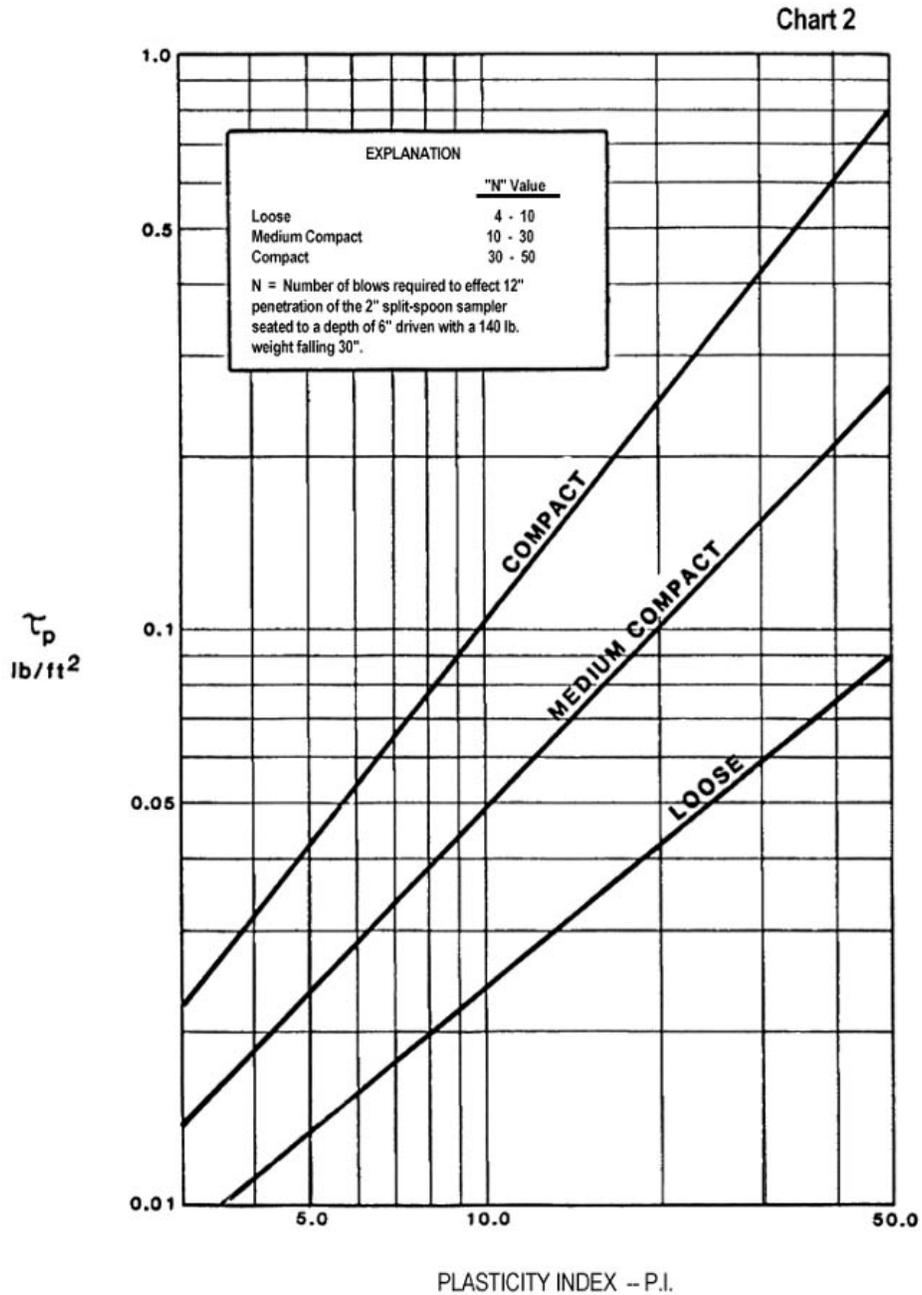
Source: HEC-15 (2005)

Appendix 7E-2 Permissible Shear Stress for Non-Cohesive Soils



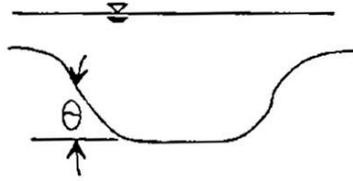
Source: HEC-15 (Archived) 1988

Appendix 7E-3 Permissible Shear Stress for Cohesive Soils



Source: HEC-15 (Archived) 1988

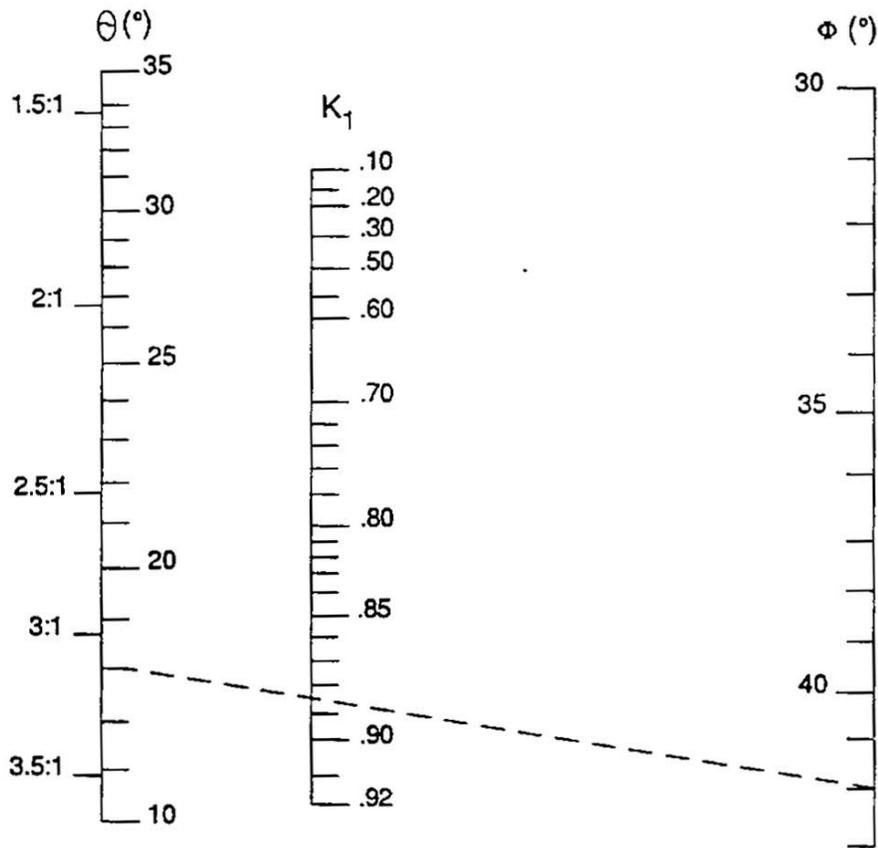
Appendix 7E-4 Bank Angle Correction Factor (K_1) Nomograph



$$K_1 = \left[1 - \frac{\sin^2 \theta}{\sin^2 \phi} \right]^{0.5}$$

θ = Bank angle with horizontal

ϕ = Material angle of repose
(See chart 4)



Example

Given:
 $\theta = 18^\circ$
Very Angular
 $D_{50} = 1.5$ ft.

Find:
 K_1

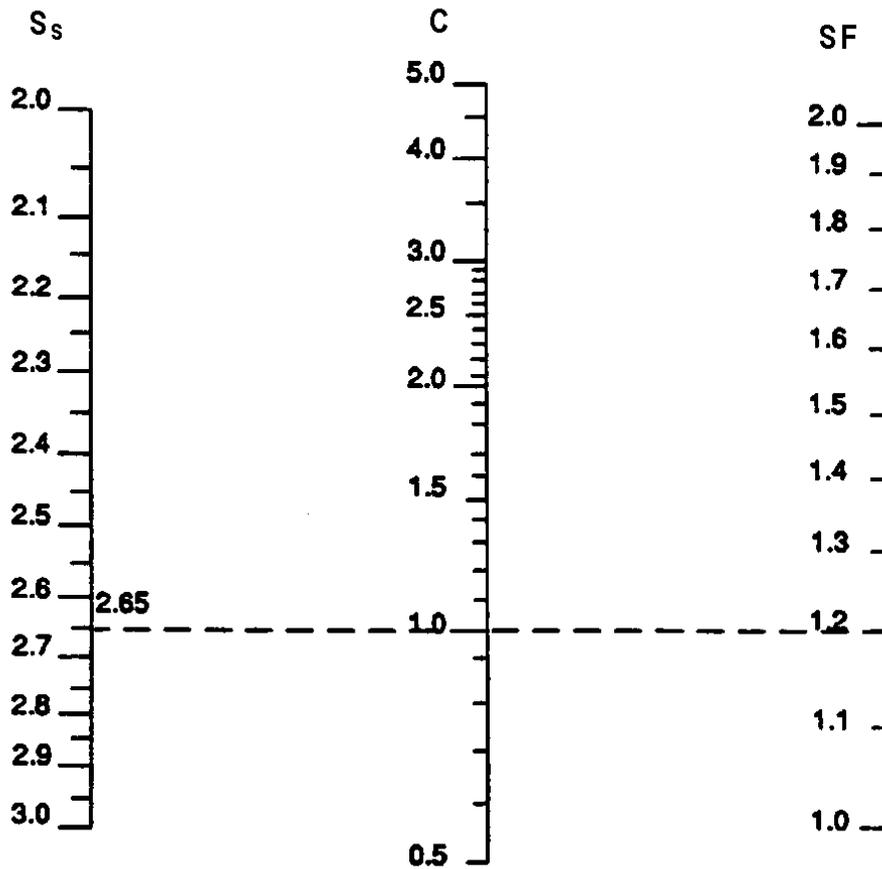
Solution:
 $\phi = 42^\circ$
 $K_1 = 0.885$

Source: HEC-11

Appendix 7E-5 Correction Factor for Riprap Size

$$C = 1.61 SF^{1.5} / (S_s - 1)^{1.5}$$

C = D₅₀ CORRECTION FACTOR
 SF = STABILITY FACTOR
 S_s = SPECIFIC GRAVITY OF ROCK



Example:

Given:
 S_s = 2.65
 SF = 1.2

Solution:
 C = 1.0

Source: HEC-11
 Comment: S_s=S_g(text)

Appendix 7E-6

Riprap Size Relationship

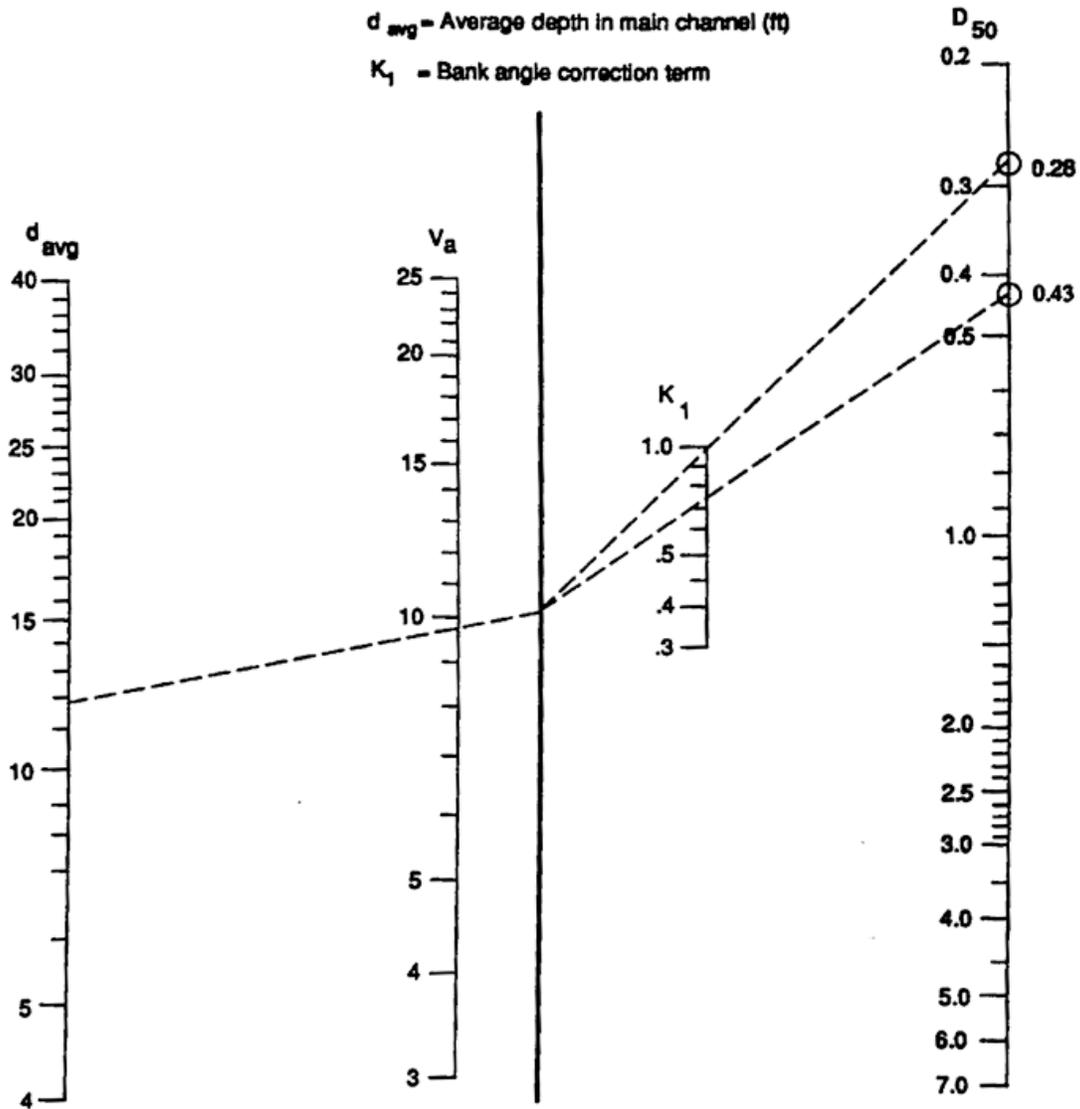
$$D_{50} = 0.001 V_a^3 / (d_{avg}^{1/2} K_1^{3/2})$$

D_{50} = Median Riprap Size (ft.)

V_a = Average velocity in main channel (ft/sec)

d_{avg} = Average depth in main channel (ft)

K_1 = Bank angle correction term



Example

Given:

$V_a = 9.7$

$d_{avg} = 11.8$ ft.

$K_1 = 0.73$

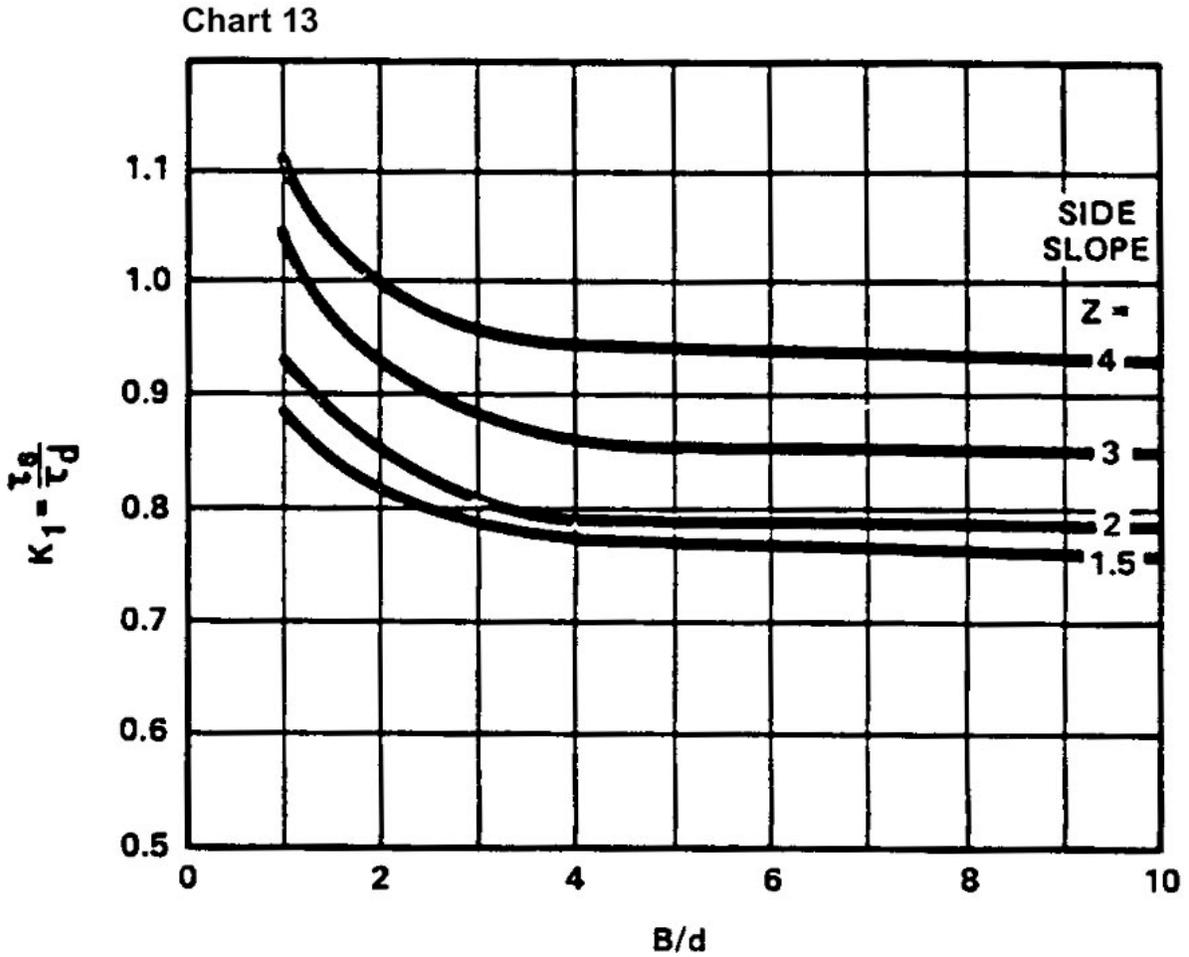
Find:

D_{50}

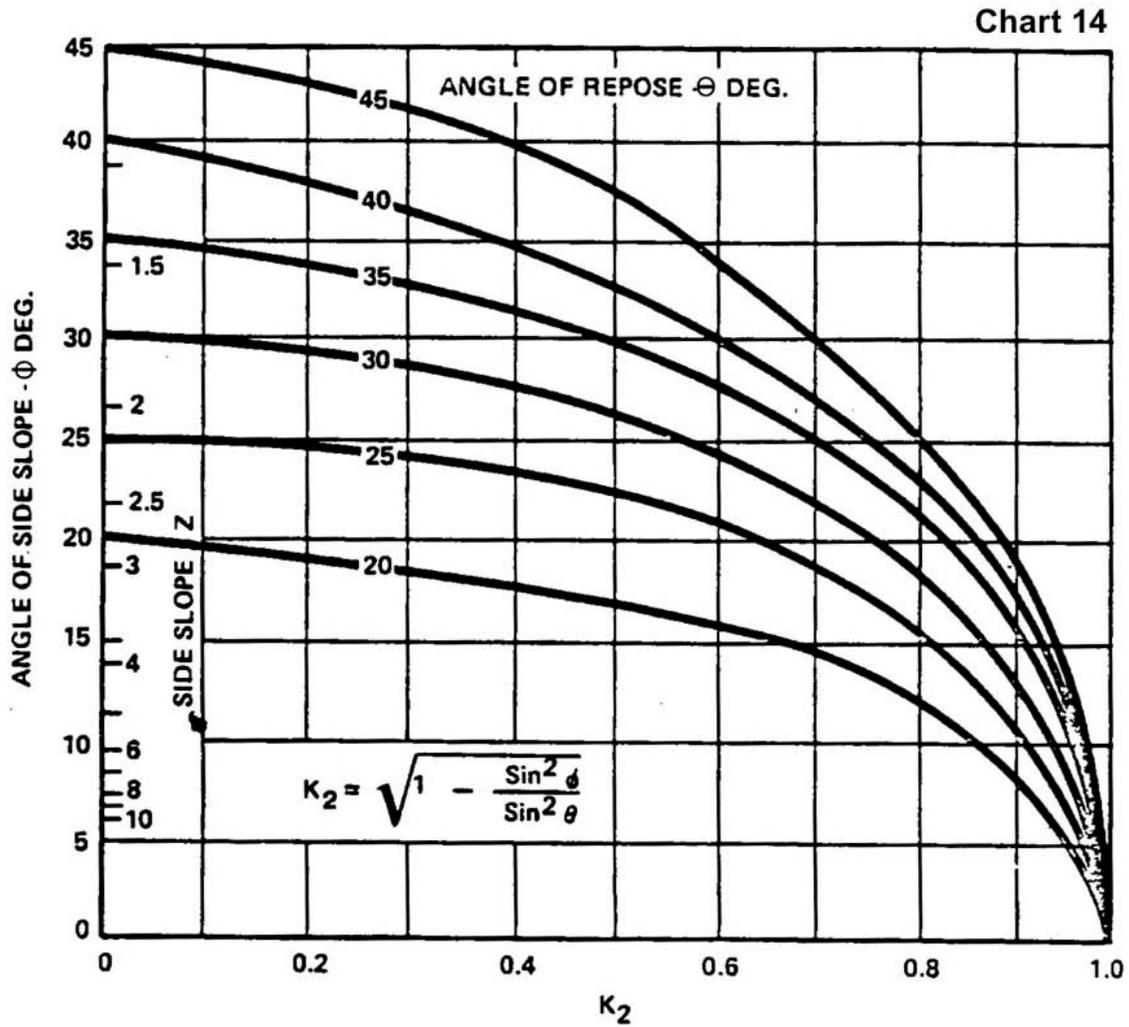
Solution:

$D_{50} = 0.43$

Source: HEC-11



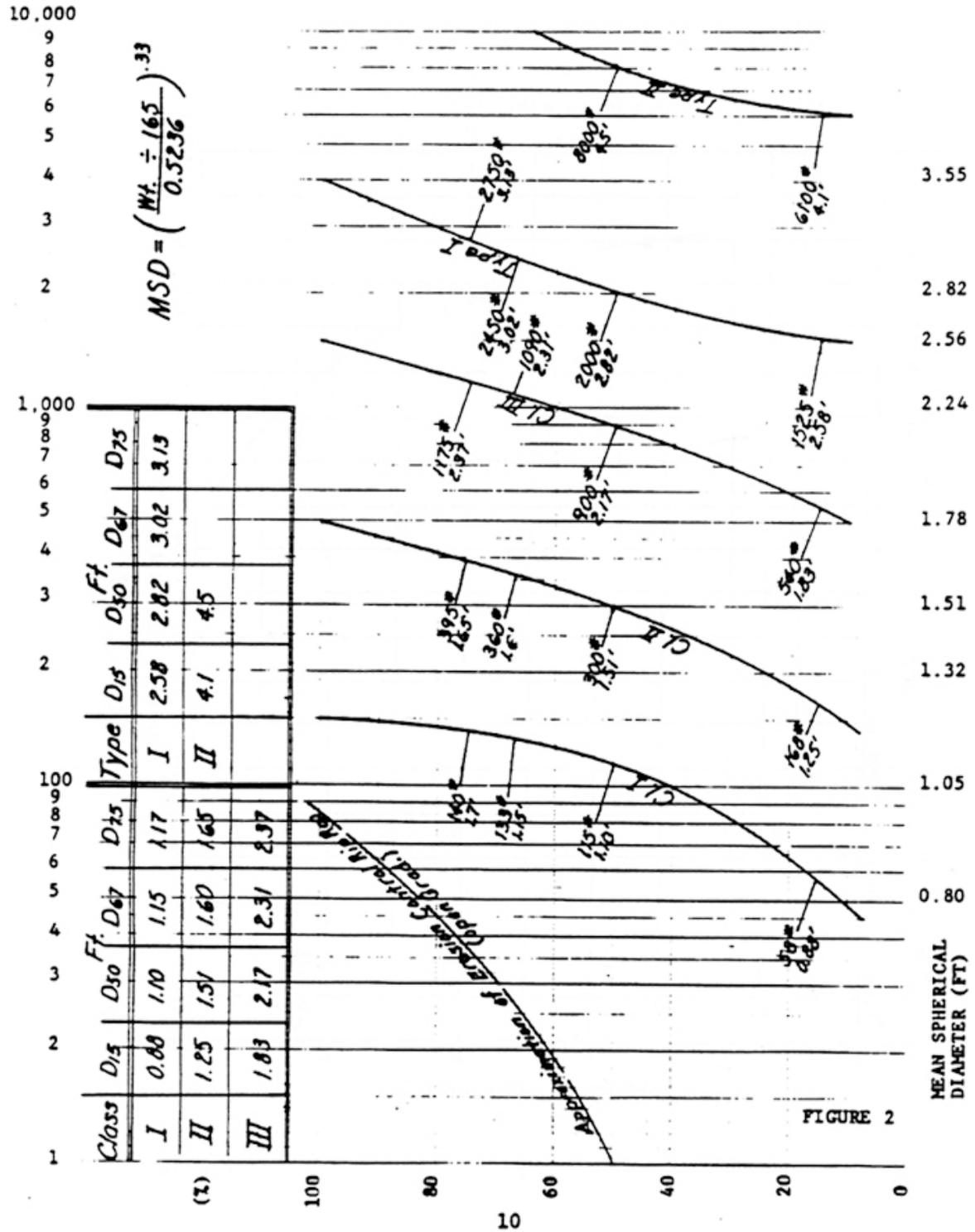
Source: HEC-15 (Archived 1988)



Source: HEC-15 (Archived 1988)

Comment: The symbols of ϕ and θ are reversed from Appendix 7E-4.

Appendix 7E-9 Determination of Mean Spherical Diameter



Source: VDOT
 Comment: Use this chart to obtain D₇₅ information for the Channel Stability Worksheet (Appendix 7B-3).