TDOT DESIGN DIVISION

DRAINAGE MANUAL

CHAPTER V
ROADSIDE DITCHES & STREAMS

CHAPTER 5 – ROADSIDE DITCHES AND STREAMS

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SECTION 5.01 – INTRODUCTION

This chapter will cover criteria and methods for the design of roadside ditches and minor stream modifications for TDOT highway projects. Stream relocations that require natural stream design methods should follow the guidance provided in Chapter 11. In general, stormwater runoff from the highway right-of-way should not discharge onto adjacent property except at an appropriate outlet point. Thus, the purpose of roadside ditches and stream channels is to convey stormwater runoff from, through, or around TDOT roadway facilities without damage to the highway or adjacent property.

The guidelines provided in this chapter are divided into two broad categories: roadside ditches and streams. Because different criteria are applied to these two categories, the designer should have a clear understanding of the definition of each category. In general:

Roadside Ditches are constructed ditches either on the sides or in the median of the roadway. The primary purpose of these waterways is to convey runoff from the roadway to acceptable outlet points; however, they may also carry a small amount of off-site flow. Roadside ditches are generally man-made and are usually provided with some type of engineered lining, such as sod, riprap or other materials.

Streams may include any watercourses that have natural stream characteristics as determined by the Environmental Division. Any natural or dredged watercourse which conveys significant flows in addition to runoff from the roadway would usually be considered a stream. However, situations may exist where a roadside ditch would also be considered a stream. Thus, the designer should exercise appropriate judgment in determining whether a waterway adjacent to the roadway should be considered a ditch or a stream. Where it is unclear whether a roadside ditch would be considered a ditch or a stream, the determination should be coordinated with the Environmental Division.

A stream cross section will often include both a channel and overbanks. The channel is the portion of the cross section that conveys low flows and most often will not have sufficient capacity to convey flood flows. Flows in excess of the channel capacity will be carried on the stream overbanks. The vegetation and other physical characteristics of the overbanks will generally be different than those in the channel and this adds some complexity to the criteria provided in this chapter for stream modifications. When reviewing these criteria, the designer should carefully note whether a specific guideline should be applied to the stream cross section as a whole or only to the channel.

This chapter provides criteria for the geometric and hydraulic design of roadside ditches and stream modifications, as well as guidance on providing them with linings that will serve to minimize erosion and promote channel stability. To properly utilize the information in this chapter, the designer should be familiar with the behavior of water in open-channels, and understand the basic concepts related to analyzing tractive and other hydraulic forces exerted by the flow of water. The designer should have a firm understanding of the basic hydraulics of open channel flow.

SECTION 5.02 – DOCUMENTATION PROCEDURES

The designer will be responsible for the documentation of the hydraulic design analysis of all roadside ditches and stream modifications on the project. As a general principle, the documentation maintained should not be excessive. Rather, the documentation should be sufficient to answer any reasonable question that may arise in the future regarding the proposed ditch or stream modification.

The documentation should be stored in a project folder and should be organized by roadway stationing from the beginning to the end of the project. It should include a discussion of any unusual features or conditions within the project and all of the assumptions and design decisions made to accommodate these special conditions. Further, any assumption made during the design of a roadside ditch or stream modification should be clearly and concisely documented. Where the drainage facility is designed by other than normal or generally accepted engineering procedures, or if the design of the facility is governed by factors other than hydrologic or hydraulic factors, a narrative summary detailing the design basis should be included. Additionally, any environmental or other special considerations which may have influenced the design of the ditch or stream modification should be discussed.

In general, the items listed in the following paragraphs should be in the project documentation file. The intent is not to limit the information provided, but instead, to provide a guide to the minimum documentation requirements consistent with the guidelines presented in this chapter.

It may be useful to place a summary sheet at the beginning of the project folder. This sheet should include an entry for each design item documented in the folder, along with an index of the computer programs, hand computations, and other methods that were employed.

The designer should provide adequate information on all hand calculation sheets to accurately identify the project design. In general, the information to be provided in the project file should include, but is not limited to, a project description, project location, a description of the type of calculation, project specific location (station and offset), project designer, and the date of the computations. All hand calculations shall be prepared and assembled in a neat, legible and orderly manner.

The documentation for roadside ditches should contain an indication of how the drainage area was determined. Where it is practical, this should be in the form of a drainage area map; although other types of information would be acceptable. The documentation should also include the discharge computations, as well as the computations for the hydraulic design and channel lining analysis. Reference should be made to any nomographs, charts, tables, or graphs that were used; however, copies of these items need not be included.

The documentation requirements for stream modifications are similar to those for roadside ditches, but may necessitate additional information as follows:

- hydrology and stage-discharge curves
- cross sections and locations used for water surface determinations
- Manning’s roughness coefficient assignments
- method used for determining water surface elevations
- observed high water elevations, with dates and discharge if available

- water surface profiles through the study reach
- analysis of any proposed linings for channel bends and banks
- energy dissipation design information, if needed (see Chapter 9)

Input and output files from computer analysis should be clearly identified with a project description, type of calculation, roadway station, name of designer, and date of computation. The following items should be included in the documentation file when computer calculations are performed:

- printout of input data and program output, or a computer disk containing the input and output files. When the output file is only a few pages, both may be included.
- file names and dates
- software used for analysis
- written description of any methods used in spreadsheet computations, if necessary

SECTION 5.03 – OPEN CHANNEL HYDRAULICS

To provide an effective design for a roadway side ditch or stream modification, the designer should have a clear understanding of the principles of open channel hydraulics. Thus, this section presents the basic concepts and equations required for hydraulic analysis.

A variety of reference materials are available to assist the designer in gaining a more complete understanding of open channel hydraulics. On-line sources include the *HEC-RAS Hydraulic Reference Guide* available from the web site of the U.S. Army Corps of Engineers, Hydraulic Engineering Center, and *HDS-3, Design Charts for Open-Channel Flow* (FHWA # EPD-86-102) which may be found at the hydraulics page of the Federal Highway Administration web site. Text books and other resources for this topic are listed in the references section of the Appendix.

5.03.1 OPEN CHANNEL FLOW

Open channel flow occurs when the water surface is exposed to the atmosphere and the force driving the flow is gravity. Flow in open channels may be classified as follows:

- ***Steady vs. Unsteady Flow:*** Steady flow occurs when the flow rate is constant, that is, where it does not vary with time. In contrast, unsteady flow occurs in situations where discharge varies with time.
- ***Uniform vs. Non-Uniform Flow:*** Steady flows are further classified according to the configuration of the water surface profile. Uniform steady flow occurs where the channel cross section, roughness, and slope are constant. In this situation, the water surface and energy grade line are parallel to the flow line of the channel. If the channel properties vary along the ditch alignment, the water surface will no longer be parallel to the flow line and the flow is classified as non-uniform or varied flow.
- ***Gradually vs. Rapidly Varied Flow:*** Varied flow may be classified as gradually or rapidly varied flow depending on the rate of change in the flow rate, velocity, area, or slope. Rapidly varied flows usually involve highly turbulent flow conditions, such as flows over spillways or hydraulic jumps.

Generally, the design of roadside ditches will be based on assuming steady uniform flow at the design discharge. Stream modifications are usually designed assuming a steady, non-uniform flow condition.

Open channel flow may be classified into three regimes, subcritical, critical, or supercritical, based on the velocity of the flow. In the subcritical flow regime, gravitational forces acting on the water outweigh the inertial forces; thus, the effect of a downstream obstruction can be transmitted upstream. In other words, a change to the channel will have an effect on the upstream water surface profile. Conversely, inertial forces are dominant in the supercritical flow regime. As a result, an obstruction or channel change will have no effect on the upstream water surface profile. Where the gravitational and inertial forces are equally balanced, the flow is in the critical state. In each of these three regimes, the flow may be steady or unsteady. It is important to note that the depth for critical flow is dependent only upon the flow rate and the shape of the channel. Critical depth is independent of slope and roughness of the channel.

5.03.2 OPEN CHANNEL FLOW EQUATIONS

This section describes the most common equations that will be used in the design and analysis of roadside ditches and stream channels. The basic principles of fluid mechanics can be applied to open channel flow analysis (i.e. continuity, momentum, and energy).

5.03.2.1 SPECIFIC ENERGY

The energy head relative to the channel bottom is defined as the specific energy, E. It is the sum of the pressure head (or depth, d) and the velocity head ($V^2/2g$). If the channel is not too steep (generally slopes less than 10 percent) and the streamlines are straight and parallel, the specific energy is expressed as:

$$E = d + \frac{V^2}{2g} \qquad (5\text{-}1)$$

Where: d = depth of flow, (ft)
V = mean cross sectional velocity, (ft/s)
g = acceleration due to gravity, (32.2 ft/sec^2)

At critical flow, the specific energy is a minimum for a constant discharge. Figures 5-1 and 5-2 plot specific energy vs. depth of flow and discharge vs. specific energy, respectively, and illustrate important properties of critical flow.

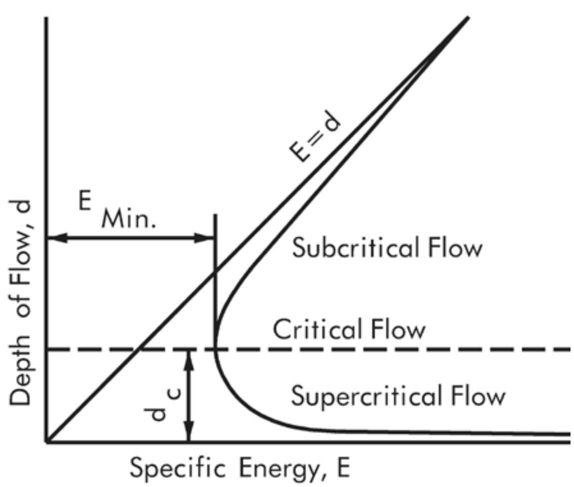


Figure 5-1
Specific Energy vs. Depth of Flow

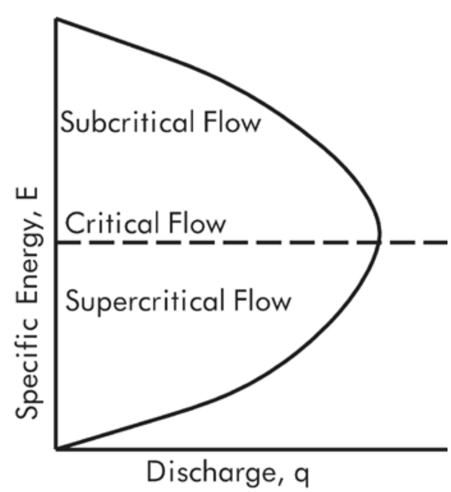


Figure 5-2
Specific Energy vs. Discharge

5.03.2.2 FROUDE NUMBER

The Froude Number is a dimensionless number representing the ratio of the inertial forces to gravitational forces. It is defined as:

$$Fr = \frac{V}{(gD)^{0.5}} \tag{5-2}$$

Where: Fr = Froude Number
V = mean cross sectional velocity, (ft/s)
g = acceleration due to gravity, (32.2 ft/sec^2)
D = hydraulic depth*, (ft), ($D = A/T$)
A = cross sectional area of flow, (ft^2)
T = channel top width at the water surface, (ft)

* For rectangular channels, hydraulic depth equals depth of flow

The Froude Number can be used to determine if the flow regime is subcritical or supercritical, and can be applied to channel flow at any cross section. When the Froude Number is less than one, the flow is considered subcritical. The flow is supercritical where the Froude Number is greater than one. The Froude Number for flow in the exact critical state is equal to one.

5.03.2.3 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 water, the continuity equations is expressed as follows:

$$Q = A \times V \tag{5-3}$$

Where: Q = discharge, (ft^3/s)
A = cross sectional area of flow, (ft^2)
V = mean cross sectional velocity, (ft/s)

The continuity equation can be used to compute the unknown variable if the other two variables are known.

5.03.2.4 MANNING'S EQUATION

Manning's equation is used to compute the mean velocity in an open channel with steady uniform flow as follows:

$$V = \left(\frac{1.486}{n}\right) R^{0.667} S^{0.5} \tag{5-4}$$

Where: V = mean cross sectional velocity, (ft/s)

n = Manning's coefficient of channel roughness, (dimensionless)
A = cross sectional area of flow, (ft^2)
P = wetted perimeter (the length of the cross section touched by water), (ft)
R = hydraulic radius, (ft), ($R = A/P$)
S = energy grade line slope, (ft/ft)

The selection of the Manning's roughness coefficient, n, is generally based on observation. Methods for selecting roughness coefficients are discussed in Section 5.03.3. For simplicity, once the geometric properties of the channel are known, Manning's equation may also be solved using nomographs. For a solution to Manning's equation using nomographs, see Figures 5A-2 and 5A-3 in the chapter Appendix.

Manning's equation can be combined with the Continuity equation to compute the flow rate. This form of the equation is as follows:

$$Q = \left(\frac{1.486}{n}\right) AR^{0.667} S^{0.5} \quad (5\text{-}5)$$

Where: Q = flow rate, (ft^3/s)
n = Manning's coefficient of channel roughness, (dimensionless)
A = cross sectional area of flow, (ft^2)
R = hydraulic radius, (ft), ($R = A/P$)
S = energy grade line slope, (ft/ft)

During the hydraulic design and analysis of channels it is sometimes convenient to group the channel properties into one term called conveyance. Thus:

$$K = \left(\frac{1.486}{n}\right) AR^{0.667} \quad (5\text{-}6)$$

Where: K = conveyance, (dimensionless)
n = Manning's coefficient of channel roughness, (dimensionless)
A = cross sectional area of flow, (ft^2)
R = hydraulic radius, (ft), ($R = A/P$)

Conveyance is independent of the streambed slope. The conveyance represents the carrying capacity of a given stream cross section and is based on the sections geometry and roughness characteristics. Conveyance may be used in a variety of situations, including determining the distribution of flows between the flood plain and stream channel.

5.03.2.5 ENERGY EQUATION

The Energy equation (also known as Bernoulli's equation) expresses the conservation of energy in open channel flow. The Energy equation is written as follows:

$$h_1 + \left(\frac{V_1^2}{2g}\right) = h_2 + \left(\frac{V_2^2}{2g}\right) + h_L \tag{5-7}$$

Where: h_1 = upstream water surface elevation, (ft)
h_2 = downstream water surface elevation, (ft)
V_1 = mean velocity upstream, (ft/s)
V_2 = mean velocity downstream, (ft/s)
h_L = head loss due to local cross sectional changes and friction loss, (ft)
g = acceleration due to gravity, (32.2 ft/sec^2)

Figure 5-3 illustrates the terms in the Energy equation. The equation states that the total energy head at the upstream location of a channel is equal to the sum of the energy head at the next downstream location plus the energy head losses between the two consecutive sections. To apply the energy equation, streamlines must be approximately straight and parallel so that vertical acceleration can be neglected.

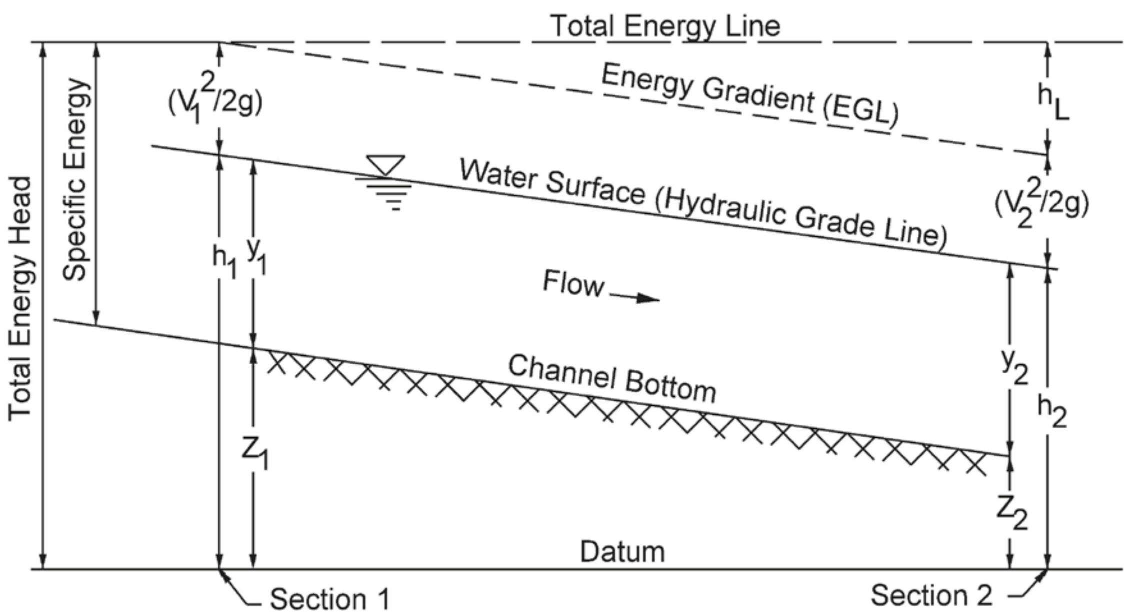


Figure 5-3
Total Energy in Open Channel Flow

5.03.3 MANNING'S CHANNEL ROUGHNESS COEFFICIENTS

Manning's equation is an empirical relationship in which the roughness coefficient, n, is used to quantitatively express the degree of retardation of flow. The selection of a Manning's channel roughness coefficient is usually based on consideration of many factors, including the depth of flow, the season, the height of any obstructions, and the types of vegetation. Further, the selection of a coefficient for a natural stream channel is more dependent on engineering experience than for a man-made channel. USGS Water Supply Paper 1849, *Roughness Characteristics of Natural Channels,* contains photographs of channels with varying n-values and may serve a guide to the designer. This report is available on the internet by accessing the archived documents available on the hydraulics page of the FHWA website. In addition, Table 5A-1 lists typical ranges of Manning's channel roughness coefficients for man-made and natural stream channels.

Manning's roughness coefficient reflects not only the roughness of the sides and bottom of the channel, but other irregularities of the channel and profile. The effect of these irregularities can be estimated for natural channels using the Cowan method. This method accounts for several primary factors in the selection of the roughness coefficients including the degree of irregularity in the channel shape and size, the types of bed materials involved, other obstructions, vegetation, and the degree of channel meandering. The method is considered reliable for cross sections with a hydraulic radius of 15 feet or less.

Cowan's equation for estimating Manning's roughness coefficients is as follows:

$$n = \left(n_0 + n_1 + n_2 + n_3 + n_4\right) m_5 \qquad (5\text{-}8)$$

Where: n = Manning's channel roughness coefficient for a natural or excavated channel
n_0 = base n-value for the natural bed material
n_1 = coefficient for the degree of channel irregularity
n_2 = coefficient for variations in the channel cross section
n_3 = coefficient for relative effect of channel obstructions
n_4 = coefficient for channel vegetation
m_5 = correction factor for the degree of meandering

Table 5A-2 lists the values for use in the Cowan's equation, along with a brief description of the criteria used to select values. A more complete description of Cowan's method and Manning's channel roughness coefficients is available in Ven Te Chow's *Open Channel Hydraulics*.

5.03.4 CHANNEL ANALYSIS METHODS

Depth and velocity of flow in the channel are necessary elements in the analysis and design of roadside ditches and stream modifications. For a channel of known geometry, roughness, and slope, the depth and velocity of flow can be computed for a given discharge using hydraulic analysis methods. The two most commonly used methods are:

- Slope Conveyance Method (Normal Depth)
- Standard Step Backwater Method

The slope conveyance method will generally be used for roadside ditch design and analysis. The standard step backwater method will be used for the more complex analyses of proposed realignments of natural streams.

5.03.4.1 SLOPE CONVEYANCE METHOD

The underlying assumption in the slope conveyance method is that uniform flow conditions exist. For the design of roadside ditches, which tend to have a constant slope and a uniform cross section, this assumption is acceptable. The slope conveyance method may also be used for simple natural stream realignments and to determine tailwater rating curves at culvert crossings or storm sewer outlets. The method should be used with caution at locations where the channel cross section or bottom slope varies significantly over short distances.

The data required for the slope conveyance method is the channel slope, the channel cross section, channel roughness, and design flow rate. While the method requires the hydraulic grade line slope, the channel bottom slope is used as an approximation of the hydraulic grade line slope which under uniform flow conditions will often correspond to the average channel slope. The channel cross section should be taken perpendicular to the direction of flow.

There are two ways to apply the slope conveyance method to the design of roadside ditches. One is to compute a stage-discharge rating curve that includes the design flows. The second is to iteratively compute the stage for the design flow rates. Either method is acceptable.

5.03.4.2 STANDARD STEP BACKWATER METHOD

The standard step backwater method uses the energy equation to determine the water surface profile along a roadside ditch or stream channel. The manual calculation process for the standard step backwater method is cumbersome and tedious for channels of any length or with numerous variations in cross section shape, roughness, slope, or discharge within the area of interest. Thus, HEC-RAS or another acceptable computer program should be used to calculate water surface profiles when this method is required (see Section 5.07).

The standard step backwater method should be used where:

- the channel cross section, slope, roughness, or flow is highly irregular
- a structure (culvert, bridge, weir, gate, etc.) affects the water surface profile
- stream or channel confluences affect the water surface profile
- the slope conveyance method is either not applicable or not sufficiently accurate

A detailed description of the standard step backwater method may be found in the HEC-RAS Hydraulic Reference Guide.

SECTION 5.04 – GUIDELINES AND CRITERIA FOR ROADSIDE DITCHES

Roadside ditches can include any constructed ditch adjacent to the roadway, including both side and median ditches. These ditches usually have a consistent cross section with an engineered lining and serve to convey runoff from the roadway to appropriate outlet points. Where a roadside ditch includes features that might be associated with a natural stream, it may be considered a stream by the Tennessee Department of Environment and Conservation. In that situation, the designer should refer to Section 5.05 for the criteria which would govern the design of stream realignments and/or Chapter 11 for the criteria which would govern the design of stream relocations.

Roadway geometric safety standards, as provided in the Standard Drawings, normally control the alignment, cross section, and grade of roadside ditches. These ditches should be designed to accommodate the design discharge in a manner that does not endanger motorists. In designing a roadside ditch, the designer should also consider maintenance needs, preventing damage to adjacent property, and any possible environmental impacts.

This section presents criteria for the general design of roadside ditches as well as criteria for hydraulic analysis and lining design.

5.04.1 ROADSIDE DITCH GEOMETRIC CRITERIA

Geometric design criteria for roadside ditches within the clear zone are presented in the TDOT Standard Roadway Drawings. These criteria are based on achieving a balance between construction cost, maintenance needs, damage to adjacent property, environmental considerations, and the expected level of service for the roadway. In general:

- The foreslope of ditches adjacent to freeways, arterials and divided multi-lane collectors should be no steeper than 6H:1V.
- The foreslope of ditches adjacent to undivided collectors should normally be no steeper than 6H:1V. However, where the current ADT is less than 400 and the design speed is less than 50 mph, a foreslope of 4H:1V may be permitted.
- The foreslope of ditches adjacent to local streets and roads should normally be no steeper than 4H:1V. However, for a design speed of less than 40 mph or where the ADT is less than 400, a foreslope of 2H:1V may be permitted.
- The flow line of a roadside ditch should be rounded as shown in the Standard Roadway Drawings to provide a more traversable cross section.
- Where a multi-lane roadway has a depressed median, the side slopes of the median ditch should be no steeper than 6H:1V. The flow line of the median ditch should be rounded as shown in the Standard Roadway Drawings.
- Roadside ditch backslopes should be determined as described in the RD01-S series of Standard Roadway Drawings.
- The flow line of a template ditch in a cut sections will be 2 to 3 feet below the edge of the shoulder, as shown in the RD01-TS series of standard drawings.

Guardrail or some other type of safety appurtenance should be employed where these criteria cannot be met within the clear zone.

The designer should identify the required ditch cross section based on the proposed ditch plan, ditch grade, and design discharges. The side slopes of the proposed cross section should be equal to or flatter than those required by the roadway geometric safety standards presented above. As shown in the TDOT Standard Roadway Drawings, the typical ditch cross section will normally have a rounded bottom to provide a traversable section and minimize the shock of impact for errant vehicles. Trapezoidal ditch sections should only be used when the typical rounded ditch section will not provide adequate conveyance capacity for the design discharge.

The designer should keep in mind that a 3H:1V side slope is the steepest that may be easily maintained by mowing equipment. Further, the designer should verify that the proposed side slope will be stable for local soil conditions.

5.04.2 ESTABLISHING THE DITCH PLAN

The first step in establishing the ditch plan should be to identify the location and flow direction of:

- the proposed drainage structures (culverts, bridges, etc.) for the project
- any existing streams
- all discharge points along the proposed roadway

Based on this information, the designer should identify where roadside ditches are necessary to convey stormwater runoff from the highway to the appropriate discharge points. As much as possible, existing drainage patterns should be preserved in the proposed plan.

The designer should give careful consideration to the selection of outlet points for median ditches. Often, the continuous flow of median ditches will be interrupted by the presence of median crossovers, bridge piers or other structures in the median. Where this occurs, the designer should decide whether to convey flows through or around the obstruction in the median or to provide an outlet from the median to the side of the roadway. This decision should be based on consideration of a number of factors, including:

- the depth of flow in the median ditch
- whether a feasible means exists to convey flows through or around the median obstruction
- the size of outlet pipe required to convey flows from the median to the side
- cover available for the outlet pipe
- the elevation of the side ditch

When providing an outlet for a median ditch, the designer should also consider the location of the actual low point in the median ditch profile. Where there are no structures in the median, the low point in the ditch profile will most often be at the same location as the low point in the roadway profile grade. However, the location and grade of a median ditch may be affected by the presence of any structure, such as guardrail or a left turn lane, which would alter the typical ditch side slope. In such cases, the actual location of the low point in the ditch profile would be shifted upstream.

Side ditches may be classified as either normal or special ditches. In many cases, the grade of the side ditch will follow the profile grade of the roadway. Where this is the case, the depth of the ditch and the distance of the ditch flow line from the edge of pavement will usually not vary along the course of the roadway, and these ditches are termed *template ditches*.

Usually, template ditches will be used where a cut is needed to establish the ditch profile. The grades of *special ditches* are independent of the roadway profile grade. Thus, the depth of special ditches and the distance between the flow line and the edge of pavement will vary along the course of the roadway. An example of a special ditch would be a ditch at the toe of a roadway fill slope. The design of these ditches should be evaluated in terms of any additional right-of-way which may be required.

5.04.3 DITCH GRADE

The designer should determine the approximate grade of each ditch based on topography, flow line elevations for any existing structures and streams, and the roadway profile. The minimum depth of the ditch invert should be set below the bottom of the subgrade as specified in the Standard Roadway Drawings. This will allow subsurface water in the roadway base course to drain freely to the roadside ditch. The ditch invert should also be set so that the underdrains will have a positive outlet to the ditch.

Ditch grade slopes should be 0.5% or steeper to minimize the amount of ponding and siltation that may occur. Also, ditches with slopes flatter than 0.5% are more likely to have maintenance problems due to the growth of unwanted vegetation. Occasionally, to properly convey the design flow, it may be necessary to provide a ditch that is wider than the ditch described in the Standard Roadway Drawings. When these ditches must be at a flat slope, they may be subject to erosion due to the meandering of low flows across the ditch bottom.

In areas where the topography does not allow roadside ditches to be at the minimum grade, the designer should provide measures to reduce the likelihood of maintenance problems. These measures may include a riprap lining on a geotextile to discourage the growth of vegetation. A concrete lining could be used for this purpose in a median ditch where runoff from the site can be controlled and where its use would not raise environmental concerns. Ditches which are widened to provide additional hydraulic capacity may be provided with a “V”-shaped bottom to minimize the amount of channel meandering that may occur.

5.04.3.1 STEEP DITCH GRADES

As a general rule, the designer should attempt to avoid placing ditches on slopes greater than 10%. Where the topography may require the use of steep ditches, the designer should consider ditch checks or other structures to minimize the ditch grade. Where such structures are not practical, the ditch should be provided with a lining sufficient to control the erosion of the channel invert as described in Section 5.04.7.

5.04.4 DITCH OUTLETS

The discharge points for the roadside ditches should be evaluated for potential impacts on the receiving stream, including changes in the velocity and flow rate.

The designer should design the outlets of roadside ditches to minimize erosion in the downstream outlet channel. If possible, the ditch outlet should be aligned to minimize the approach angle to the outlet channel. Where the ditch outlet is perpendicular to the outlet channel, the ditch outlet and the channel should be lined with appropriate materials to reduce the amount of erosion that will occur due to turbulence of flow at the discharge point.

Occasionally, a previously stable channel will begin to erode due to increased velocities at the outlet of a roadside ditch. To prevent this maintenance problem, the flow velocity in the proposed roadside ditch should be compared with the velocity of existing flows at the outlet point. If the proposed outlet velocity is greater than the existing velocity in the channel, the designer should modify the proposed roadside ditch design to decrease the proposed velocity. This may be done by increasing cross sectional area, reducing the ditch slope, increasing the roughness of the roadside ditch lining, or decreasing the discharge.

Another potential problem is increased flow rates at the outlet due to drainage areas being diverted as a result of a new roadway alignment, or increased runoff from the roadway itself. The designer should evaluate whether any such increased discharge rate will have an impact on the outlet channel or adjacent property. When necessary, the designer should investigate whether a practical method may be found to return the flow rate to an acceptable level.

A possible impact of new roadway construction is concentrating existing sheet flow to a point flow at the outlet of a cross drain or side ditch. Such concentrated flows may result in undesirable erosion to property adjacent to the roadway. Where this may occur, the designer should provide a means to convey these flows to an acceptable outlet point. Where this is not possible, methods to spread the concentrated flow back to a sheet flow condition should be considered. Possible methods may include riprap splash pads placed in a “fan” configuration or specialized grading to transition from the ditch configuration to the natural ground configuration. These options should be considered carefully as they may require additional right of way or permanent drainage easements.

5.04.5 DITCH DESIGN STORM FREQUENCIES

Table 4-1 in Chapter 4 of this Manual provides design storm frequencies for roadside ditches. Ditch design should be based on the 50-year storm for interstate systems and arterials with full access control, while the ditch design for other facilities should be based on the 10-year storm. As described in Section 5.04.6, the ditch should be provided with sufficient capacity that the design high water elevation will be below the bottom of the subgrade. In situations where the ditches may drain slowly or high water depths may be sustained for several hours, the designer may wish to use a higher design storm frequency to provide additional protection for the subgrade of the roadway.

Temporary ditches used for erosion prevention and sediment control should be designed for the 2-year storm event.

5.04.6 DITCH CAPACITY

In general, the design of a roadside or median ditch should be as described in the Standard Drawings. However, the designer should also check the hydraulic capacity of the ditch to insure that the high water elevation at the design flow will be below the bottom of the subgrade. Where the roadway is elevated with respect to natural grades, the designer should check whether flows from the ditch would impact adjacent property. The designer should insure that the flow line depth is such that the subgrade will have positive drainage to the ditch. The following sections provide guidance for determining the hydraulic roughness of vegetated and riprap channel linings. Table 5A-1 provides information for the selection of Manning’s n-values for other types of materials.

5.04.6.1 HYDRAULIC CAPACITY OF DITCHES WITH VEGETATED LININGS

The resistance to flow in a vegetated channel will vary depending on the depth of the water compared to the height of the grass. However, a determination of this relative height is complicated by the fact that the grass will bend in the flow, changing both the height and the character of the roughness. Further, different varieties of grasses vary in stiffness and would thus present differing amounts of resistance to the same flow. In general, taller and stiffer grasses present a higher resistance to flow, while short flexible grasses offer less resistance. Thus, it is not possible to use a single Manning's n-value to describe the roughness of all grass lined ditches. The hydraulic roughness of ditches lined with sod or other types of grasses should be based on determining the vegetal retardance class of the lining.

As described in the NRCS publication *TP-61*, sod or grass-lined ditches may be grouped into five retardance classes, from A to E, depending on the length of the grass and whether a good stand of grass has been established. In this system, retardance class A presents the highest resistance to flow while Class E presents the lowest resistance to flow.

Table 5A-4 provides guidance for determining the retardance class of a lining based on the length of the vegetation. In practice, the principal factor for determining the length of the vegetation will be the ditch maintenance schedule, which is generally unknown at the time of design. Therefore, the hydraulic roughness of a grass or sod lining should typically be determined based on a retardance class of C.

The hydraulic capacity of a vegetated ditch is normally evaluated by assuming a trial depth and determining an equivalent n-value for the proposed ditch lining. The flow rate is then computed using Manning's equation (see Section 5.03.2.4) and is compared to the design discharge rate. A detailed procedure for these computations is provided in Section 5.06.1.

5.04.6.2 HYDRAULIC CAPACITY OF DITCHES WITH RIPRAP LININGS

The hydraulic roughness of a riprap-lined ditch will vary depending on the class of riprap specified and the depth of water. When the depth at the design flow is relatively small, the determination of the ditch capacity may require a trial-and-error solution. Manning's n-values for riprap lined ditches are provided in Table 5A-6 in the Appendix, and a procedure for determining ditch capacity is provided in Section 5.06.1.3.

5.04.6.3 HYDRAULIC CAPACITY OF DITCHES WITH GEOTEXTILE LININGS

Geotextile linings may be either erosion control blankets, as described in Section 5.04.7.1.1.2 or turf reinforcement mats, as described in Section 5.04.7.1.1.3. These types of linings protect the ditch cross section while the grasses comprising the final lining are being established. The final value for the hydraulic roughness of these linings should be based on the vegetal retardance of the grass without any other type of lining. However, before the grass is established, the hydraulic roughness of the ditch should be evaluated based on the resistance of the geotextile blanket by itself. This is primarily a function of the roughness of the blanket surface. Thus, when evaluating the hydraulic performance of a ditch lined with erosion control blanket or turf reinforcement mat, it should be possible to select an appropriate n-value for the lining from Table 5A-6. Because the effective n-value of the lining will vary with depth, the hydraulic analysis may involve a small amount of trial and error, as described for Section 5.06.1.3.2.

5.04.6.4 HYDRAULIC CAPACITY OF DITCHES WITH COMPOSITE LININGS

Composite ditch linings usually consist of some type of hard lining on the bottom of the ditch combined with a vegetated lining on the sides. Because these two materials normally have differing hydraulic roughness, computation of flow conditions for a composite lining should be based on an effective Manning's n-value for the entire cross section. Since the foreslope and backslope of a roadside ditch may be at different slopes, the effective n-value may be computed from:

$$n_{eff} = \left\{ \frac{\left[P_L \left(n_L^{1.5} \right) + P_M \left(n_M^{1.5} \right) + P_R \left(n_R^{1.5} \right) \right]}{P} \right\}^{0.667} \qquad (5\text{-}9)$$

Where: n_{eff} = effective Manning's n-value
P_L = wetted perimeter of the vegetated portion of the left ditch side slope, (ft)
n_L = Manning's n-value of the vegetated portion of the left ditch side slope
P_M = wetted perimeter of the hard lining on the bottom of the ditch, (ft)
n_M = Manning's n-value of the hard lining on the bottom of the ditch
P_R = wetted perimeter of the vegetated portion of the right ditch side slope, (ft)
n_R = Manning's n-value of the vegetated portion of the right ditch side slope
P = wetted perimeter of the entire ditch cross section, (ft)

As described in Section 5.04.6.1, the Manning's n-value of a vegetated lining is dependent on the hydraulic radius of the cross section. It should be noted that the hydraulic radius used in this determination is that of the entire cross section, not that of the individual ditch segment.

5.04.7 ROADSIDE DITCH LINING DESIGN

Channel linings are used to protect roadside ditches when the design velocity is high enough to cause erosion in an unprotected channel. This section provides descriptions of the materials available for ditch linings. Section 5.04.7.2 provides design guidance for the selection of permanent ditch linings.

5.04.7.1 DITCH LINING MATERIALS

Linings for roadside ditches may be classified as either flexible or rigid. The primary difference between rigid and flexible channel linings from an erosion control standpoint is their response to changing channel shape. Flexible linings are able to conform to changes in the channel shape while rigid linings will not. Flexible linings can accommodate some change in channel shape while maintaining their overall integrity. Rigid linings tend to fail if a portion of the lining is damaged by forces such as undermining or slumping. Thus, where flexible linings are capable of withstanding the design velocity, they are preferred over rigid linings. Flexible linings usually will consist of the following materials:

- sod or seeded grasses
- erosion control blankets or turf reinforcement mats

- machined riprap
- wire-enclosed rock (such as gabions or mattresses)

Rigid linings may consist of either cast-in-place concrete or grouted riprap. As a general rule, the use of rigid linings should be avoided.

Roadside ditches for all TDOT road projects will typically be provided with a sodded lining which is generally sufficient for ditches with slopes of 1 percent or less. Ditches with slopes greater than 1 percent, or which drain an area greater than 5 acres, should be examined to determine whether another lining type will be required.

The following sections provide descriptions of the materials used as linings for TDOT roadside ditches. The use of any other material should be approved by the Design Manager.

5.04.7.1.1 VEGETATATION

As described in the Standard Drawings the most common form of vegetative lining is sod. However, ditches may also be lined with seeded grasses which are usually protected by some type of temporary erosion control blanket. Ditches subject to highly erosive flows may be lined with permanent turf reinforcement mats.

Vegetative linings are suited to hydraulic conditions where uniform flow exists and shear stresses are moderate. However, they may not be suitable in areas that experience long periods of submergence or sustained flows which may cause the grass to drown, thus destroying the lining. Other means of erosion protection should be provided in these areas.

Many vegetated ditches are provided with erosion control blankets or are simply provided with seeding and mulch at the time of construction. The designer should verify that any such temporary ditch linings will be capable of resisting erosion until the permanent vegetation is established. This will normally require that the adequacy of the lining be evaluated for both the temporary and permanent condition.

5.04.7.1.1.1 SOD

The Standard Specifications require that sod consist of live, dense and well-rooted grasses at the time of delivery to a project site. Unlike seeded grasses, sod provides a good stand of grass from the time it is installed. Thus, it may be assumed that sod provides its full protection against erosion from the time it is installed; whereas other linings will require a grow-in period. In general, sod lined ditches should be assigned a vegetal retardance class C.

Sod should be placed parallel to the direction of flow and should be secured in place with pins or staples.

5.04.7.1.1.2 EROSION CONTROL BLANKETS

Seeded grasses require a grow-in period to achieve their full level of erosion protection; while other types of lining, including sod, are considered to offer their full level of erosion protection at the time of installation. Erosion control blankets usually combine a photodegradable geotextile grid with organic fibers. These ditch linings help to insure soil stability in the ditch cross section until the permanent vegetation is fully established. In addition, erosion control blankets aid in holding seed and fertilizer in place when flow occurs in the ditch. This section discusses the application of erosion control blankets as ditch liners. Chapter 10 of this Manual provides additional information on the use of these materials.

Erosion control blankets usually consist of organic fibers sewn onto one or more layers of plastic mesh, also referred to above, as a geotextile lining. The plastic grid and organic fibers in an erosion control blanket are designed to decompose over a specified time period, ranging from a few months to as long as two years. During this time, the permanent vegetation would become fully established and should provide the needed erosion protection on its own.

The Standard Specifications provide for four types of erosion control blanket:

- **Type I blankets** may utilize processed degradable natural or polymer fibers mechanically bound together by a single degradable synthetic or natural fiber netting to form a continuous matrix or an open weave textile composed of processed degradable natural or polymer yarns or twines woven into a continuous matrix. Type I blankets should provide protection for at least 12 months.
- **Type II blankets** may utilize processed degradable natural and/or polymer fibers mechanically bound together between two degradable, synthetic or natural fiber nettings. Type II blankets typically provide protection for at least 12 months.
- **Type III blankets** may be composed of processed slow degrading natural or polymer fibers mechanically bound together between two slow degrading synthetic or natural fiber nettings to form a continuous matrix or an open weave textile composed of processed slow degrading natural or polymer yarns or twines woven into a continuous matrix. Type III blankets typically provide protection for at least 24 months.
- **Type IV blankets** utilize processed slow degrading natural or polymer fibers mechanically bound together between two slow degrading synthetic or natural fiber nettings to form a continuous matrix or an open weave textile composed of processed slow degrading natural or polymer yarns or twines woven into a continuous matrix. Type IV blankets typically provide protection for at least 36 months.

Erosion control blankets are usually supplied in 4-foot wide rolls which are secured with either staples or stakes. They should be seamed according to the Erosion Control Standard Drawings. When specifying an erosion control blanket, the designer should ensure that the design life of the blanket is longer than the expected time required for the permanent vegetation to establish. That is, the permanent vegetation should be well established before the degradable portions of the blanket have degraded to a point that they no longer offer any resistance to erosion.

Erosion control blankets require proper preparation of the subgrade prior to installation. The areas to be protected should be free of rocks or other irregularities which would tend to cause poor contact between the blanket and the face of the ditch. Experience has shown that good contact is necessary to encourage the germination and growth of the grass seed.

5.04.7.1.1.3 TURF REINFORCEMENT MATS (TRM)

A turf reinforcement mat is a type of geotextile lining used to protect the bottom and sides of a newly constructed ditch while vegetation is being established. In addition, the mat serves to hold seed and fertilizer in place when flow occurs in the ditch. Turf reinforcement mats differ from erosion control blankets in that the plastic grid in a TRM is composed of UV stabilized materials which are designed to resist degradation and maintain a specified percentage of their original tensile strength. The grid will remain in place even after vegetation is fully established and will contribute to the overall erosion resistance of the ditch lining.

TRM's generally consist of two or more plastic grids which contain a matrix of large fibers. These fibers may consist of straw, coconut fibers, polypropylene or even recycled materials. Detailed specifications for materials, placement and performance are typically available from the manufacturers and may be available on their internet sites. Turf reinforcement mats should be secured in place with either staples or stakes. In addition, turf reinforcement mats should be seamed according to the Erosion Control Standard. As with erosion control blankets, proper preparation of the subgrade is critical to the success of the TRM. Additional information on the use and installation of TRM's may be found in Chapter 10 of this Manual.

Turf reinforcement mats are divided into three classes based on the shear strength of the material **after** the grass has established in the ditch. A description of the various products available may be found in the Qualified Products Lists. The vegetated shear strengths of these materials, by Class, are provided in Table 5A-7.

5.04.7.1.1.4 PERMISSIBLE SHEAR STRESSES FOR GEOTEXTILE LININGS

General guidance on the permissible shear stress for various types of geotextile linings (including both erosion control blankets and turf reinforcement mats) is provided on Table 5A-7. Many vendors of erosion control products have conducted hydraulic testing of their products and found that they are capable of withstanding greater shear stresses than those listed in the Appendix. Although the results of these tests may be allowable for the design of temporary ditch linings, the designer should note that these results are usually obtained in laboratories with linings installed in strict conformance with vendor specifications. In selecting allowable shear stresses for use on a roadway project, the designer should make allowances for uncertainties in the actual construction due to varying field conditions.

Although permanent turf reinforcement mats can resist high shear stresses, they provide far less erosion resistance prior to the establishment of the vegetation. Thus, the designer should check the erosion resistance of the liner in the unvegetated state to ensure the stability of the channel during the grow-in phase. However, since the liner should achieve its full strength in one to two growing seasons, the unvegetated adequacy of the liner need only be checked using the 2-year storm event. Where the shear developed by the 2-year flow exceeds the unvegetated strength of the TRM, the bottom of the ditch should be lined with appropriately-sized riprap to form a composite lining. This process is described further in Section 5.04.7.2.

5.04.7.1.1.5 SEEDED GRASSES

The Standard Specifications provide a variety of seed groups which may be utilized for seeding at different times of the year. Typically, the seed will be placed with fertilizer and will be mulched. Mulch is usually held in place by tackifier sprayed over the seeded area.

When seeding with mulch is specified as a ditch lining, the designer should check the ability of the ditch to withstand erosion before the permanent grass lining is established. This analysis should be based on the allowable shear stresses for bare soil listed in HEC-15. In general, a well established grassed ditch lining would be designed using a vegetal retardance class of C. However, the designer may assume a different retardance class, based on Table 5A-4 in the Appendix, depending on the type of grass used and any assumptions made regarding future maintenance practices in the project area.

5.04.7.1.2 RIPRAP

Riprap consists of crushed rock placed on geotextile fabric on a prepared surface. The individual stones are typically angular in shape and well-graded so that they will interlock. This interlocking property combines with the weight of the stone to form a solid mass which will resist erosion.

Due to environmental concerns, the use of riprap as a ditch lining should be minimized. Turf reinforcement mats are often an effective substitute. In general, riprap should be used where perennial flows or frequent ponding would drown a vegetated lining or where the shear stress on an unvegetated permanent turf reinforcement mat during the 2-year storm event exceeds the shear strength of the lining. The selection of riprap class is based on the computed velocity in the ditch. However, if the slope of the proposed ditch is 10 percent or greater, special criteria apply. Where this is the case, the selection of riprap should be based on the criteria provided in Section 5.04.7.1.2.1.

The classes of machined riprap which are generally used for channel linings are described below. It should be noted that the D_{50} values listed below are ***approximate*** and intended ***only*** to aid the designer in evaluating the hydraulic performance of the various classes of machined riprap.

Machined Riprap (Class A-1) may be used for flow velocities up to 5 feet per second. The median stone size (D_{50}) for this class of riprap is approximately 9 inches and it is placed to a minimum depth of 18 inches. Machined riprap Class A-2 consists of the same basic material as Class A-1 riprap; however, it is hand-placed to a depth of 12 inches. Because of the difficulty in ensuring the integrity of hand placement, machined riprap Class A-2 is not recommended for ditch linings. Class A-3 is also not recommended due to the small size of the stone.

Machined Riprap (Class B) may be used for flow velocities greater than 5 feet per second, up to 10 feet per second. The D_{50} of this material is approximately 15 inches.

Machined Riprap (Class C) may be used for flow velocities greater than 10 feet per second, up to12 feet per second. The D_{50} of this material is approximately 20 inches.

Classes of riprap other than those listed above should not be used without the approval of the Design Manager. Specific requirements for the gradation of each of these materials are given in Section 709 of the Standard Specifications.

If riprap is to be placed on a ditch side slope steeper then 3H:1V, the designer should consult Chapter 4 of the FHWA publication HEC-15 to insure that the riprap on the side slopes will be stable.

5.04.7.1.2.1 RIPRAP LININGS ON STEEP SLOPES

In general, riprap stability on a ditch side slope depends on the forces acting on the individual stones in the riprap layer. These forces include the weight of a stone, the lift, and drag forces induced on it by the ditch flow. On a steep slope, the weight of a stone has a significant component in the direction of flow. Because of this, a stone within the riprap will tend to be moved by the flow more easily than the same stone on a mild gradient. Hence, for a given discharge, ditches on steep slopes require larger stones to compensate for the greater shear forces in the flow direction.

Stone size is less critical for wire enclosed riprap (gabions) on steep slopes because the stones are bound by a wire mesh which allows the material to act as a single unit. However, the stability of wire enclosed riprap depends on the integrity of the wire mesh. In ditches carrying high concentrations of sediment or rocks, the wire mesh may be abraded and could potentially fail. Thus, the use of these structures should be avoided where such conditions exist.

The actual vector analysis of riprap stability on steep slopes can be very complex and involves a number of assumptions. Tables 5A-22 through 5A-25 are provided in the Appendix as a guide for selecting riprap for ditches on steep gradients. For a given ditch slope and cross section, these tables specify the greatest design discharge allowed for different classes of riprap linings. It should be noted that the tables are based on a safety factor of 1.5. A detailed procedure for the use of these tables is presented in Section 5.06.1.3.6.

To the extent possible, steep ditches should be on straight alignments. Freeboard should be equal to the average depth of flow, since the wave heights in the flow may reach approximately twice the mean depth. In addition, an energy dissipation structure such as a riprap basin may be required where the steep ditch transitions to a mild gradient ditch. More information on the use and design of these structures may be obtained in Chapter 9 of this Manual.

5.04.7.1.3 GROUTED RIPRAP

This material consists of hand-placed rubble-stone riprap with grout poured into the voids to form a rigid lining. The principal advantage of this material is that it can withstand velocities up to 15 feet per second without the need to transport large stones to the construction site with the resulting wear and tear on equipment.

However, before recommending the use of grouted riprap, the designer should be aware of its limitations. First, construction of grouted riprap is labor-intensive. The higher construction cost may offset the cost of transporting larger sized riprap to the project site. Second, even though the material is rigid, it is fairly weak structurally. Thus, it may fail if large gaps form in the underlying material. The designer should make an effort to check whether undermining may occur before recommending grouted riprap at a site.

5.04.7.1.4 CAST-IN-PLACE CONCRETE

A concrete paved side or median ditch may be used where it would be more economical than a riprap-lined ditch or where flow velocities exceed 12 feet per second. Where the use of a concrete-lined ditch is not preferable, it may be possible to line the ditch with riprap and use rock check dams to control the velocity. However, these situations tend to occur where the slope of the ditch is steep, and the designer should refer to Section 5.04.7.1.2.1 for criteria to be applied to riprap ditches at slopes of 10 percent or greater.

Because concrete lining is rigid, it is subject to failure from undermining or from any other change in grade that may occur in the underlying materials. Thus, the design of a paved ditch should include considerations to minimize the potential for failure. Concrete-lined ditches should be anchored to the subgrade by cut-off walls (or lugs) at the intervals specified in the TDOT Standard Drawings. These cut-off walls anchor the ditch into the subgrade, help to minimize erosion beneath the lining and defend against erosion at the ditch outlet.

Paved ditches should be provided with a minimum freeboard of 1 foot for the design flow. This will allow for splashing and bulking effects from air entrainment due to high flow velocities. Typically, above the paved section, sod will be used on the ditch slopes to provide additional protection.

The effect of high velocity flows at the channel exit must be considered and some provision should be made to dissipate the excess energy; otherwise, erosion at the outlet likely will result in undermining, and potentially, a progressive failure of the upstream paved ditch sections. Design of stilling basins and energy dissipators is discussed in Chapter 9 of this Manual.

5.04.7.1.5 WIRE-ENCLOSED STONE (GABIONS)

Wire-enclosed stone refers to rectangular containers made of galvanized woven (twisted) steel wire mesh or welded steel wire mesh in a uniform pattern which are filled with stone. Typically, wire-enclosed stone, or gabions, will be either rectangular boxes or thin mattresses. The individual stone-filled units are tied together and anchored to the ditch side slope. Because of their flexibility, gabion structures can yield to earth movement and remain structurally sound while maintaining their intended purpose. Gabions absorb energy contained in a storm discharge by forcing water to pass through the void spaces in the structure; whereby reducing velocity in the ditch or channel. Because this material is permeable, it should be placed on a geotextile fabric to prevent any piping of the underlying materials.

Gabions may be used where machined riprap is either not available, impractical, or not economical. Mattress units may be placed on a geotextile on standard ditch side slopes. In addition, gabions may be stacked to stabilize extremely steep slopes. Thus, they may be used where machined riprap would not provide sufficient slope stability. The use of wire-enclosed stone should be avoided where flows may carry high quantities of abrasive materials such as sand, gravel, or a heavy debris load. The coating, which protects the wire from rust, can be worn off, resulting in the potential failure of the structure. Due to safety considerations, gabions should not be used within the clear zone of any roadway.

5.04.7.1.6 COMPOSITE DITCH LININGS

As shown in the Standard Roadway Drawings, the bottom of a roadside ditch may be lined with concrete, riprap or other material while the sides adjacent to the bottom are provided with a vegetated strip of sod or erosion control blanket. The vegetated strip should be at least two feet wide. This type of composite lining is useful in situations where frequent low flows or sustained flows could drown the grass in a sodded ditch lining.

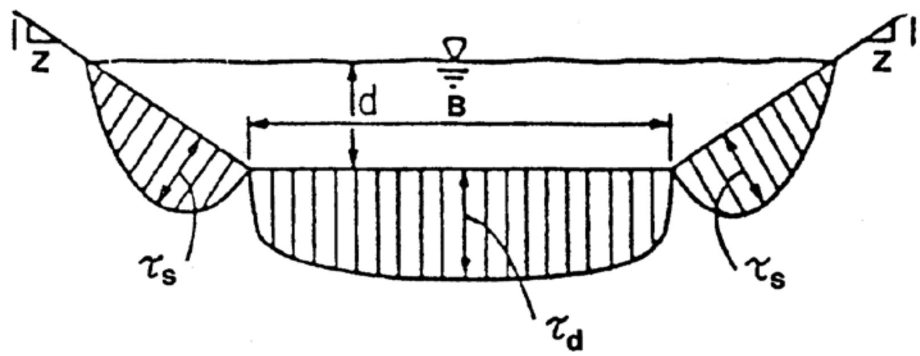


Figure 5-4
Typical Shear Stress Distribution in a Trapezoidal Channel
Reference: USDOT, FHWA, HEC-15 (1988)

The erosion resistance of a composite lining should be based on the permissible stress for the vegetated lining on the sides of the ditch. Where the side slope of a ditch is 3H:1V or steeper, the maximum shear stress experienced on the side slope may be less than the shear experienced on the ditch bottom. In this situation, the designer should refer to the FHWA publication HEC-15 for more information. For most practical design problems, the maximum shear experienced on the sides of the ditch will be approximately equal to the maximum shear in the cross section as defined by Equation 5-10.

As indicated in Figure 5-4, the point on the side slope of a ditch where the maximum shear is experienced is approximately equal to one third of the depth. In addition, the shear stress on the sides of the ditch reduces significantly above approximately two-thirds of the depth. Based on sound engineering judgment, the designer may allow lining materials with a somewhat lower erosion resistance in the upper third of the depth at the design discharge, provided that the ditch is on a straight alignment. Hydraulic analysis of composite ditch linings is discussed in Section 5.04.6.4.

5.04.7.2 LINER SELECTION AND DESIGN

In general, a vegetated lining is the preferred lining type. The use of riprap should be minimized and the use of hard armor such as concrete should be avoided where possible. The following criteria provide a general guide for selecting a roadside ditch lining:

1. Roadside ditches should be sodded unless the slope is greater than 1 percent or the drainage area is greater than 5 acres. In such cases, hydraulic and tractive force analyses should be conducted to determine whether the flow will exceed the allowable tractive force for the vegetative lining.

2. Where the ditch slope or drainage area are greater than specified above, sod or seeded grasses with erosion control blanket may be used where the computed shear at the design flow rate is equal to or less than 2 lb/sf.

3. Where the computed shear on a vegetated lining exceeds 2 lb/sf, a turf reinforcement mat should be provided. The heaviest classes of these materials are able to withstand a shear stress of up to 10 lb/sf after vegetation has established in the ditch.

4. Where permanent turf reinforcement mats are used, they should be checked to ensure that the shear stress imposed by the 2-year storm event will not exceed the strength of the unvegetated lining. Where this is exceeded, it is likely that high flows in the ditch will cause damage to the lining before its fully vegetated shear strength can be developed. In this case, riprap should be used on the bottom of the channel up to a height equal to the depth of flow in the 2-year storm event on the class of riprap selected. Permanent turf reinforcement mat may then be placed above the riprap. It should be noted that the class of riprap and turf reinforcement mat should be selected based on the design flow rate.

5. Riprap should also be used where perennial flows or frequent ponding could drown the grass in a vegetated lining. In this case, the height of the riprap above the channel bottom only needs to be sufficient to accommodate the low flows. Permanent turf reinforcement mat, sod, or seeded grasses with erosion control blanket may be placed above the riprap, depending upon the shear stress imposed by the design discharge. It should be noted that this riprap may not be required where a ditch has a rock bottom.

6. Hard armor, such a concrete lining or grouted riprap may be used where the shear stress imposed by the design flow exceeds 10 lb/sf. However, in these cases the designer should consider the use of ditch checks or other means of reducing the velocity of the flow.

7. When the slope of the proposed ditch is 10 percent or greater, the designer should refer to Section 5.04.7.1.2.1 for special criteria regarding the use of riprap ditches on steep slopes.

Table 5A-13 through 5A-18 in the Appendix can serve as guide to selecting a lining material.

5.04.7.2.1 TRACTIVE FORCE ANALYSIS

The hydrodynamic force of water flowing in a channel is known as the tractive force. The ditch will be stable when the flow-induced tractive force does not exceed the permissible shear stress of the lining materials. In a uniform flow, the tractive force is equal to the effective component of the gravitational force acting on the body of water, parallel to the channel bottom. Thus, the maximum shear stress for a straight channel occurs on the ditch bottom and is less than or equal to the shear stress at maximum depth. This is expressed as:

$$\tau_{max} = \gamma d S \qquad (5\text{-}10)$$

Where:
τ_{max} = maximum shear stress, (lb/ft^2)
γ = unit weight of water, (62.4 lb/ft^3)
d = maximum depth of flow, (ft)
S= average bed slope or energy slope, expressed as a decimal, (ft/ft)

Table 5A-7 lists the permissible shear stress for a variety of materials. For unlined channels, permissible shear stress for the bed material can be obtained from Figure 5A-5 or 5A-6. Shear stress is not uniformly distributed along the wetted perimeter of the ditch and the maximum shear stress in a trapezoidal channel is usually experienced at the center line of the bed. However, in order to provide a conservative analysis, it is assumed that the maximum stress may be experienced at any point in the cross section of the ditch.

5.04.7.2.2 REQUIRED ANALYSIS LOCATIONS

In areas where the ditch slope is less than 1 percent and the drainage area is less than 5 acres, a sodded lining or seeded grass with erosion control blanket may generally be considered adequate, and, tractive force analysis would not be necessary in these areas.

A list of specific points where a detailed ditch design should be performed is provided in Section 5.06.1.1. Based on sound engineering judgment, the designer should perform a detailed ditch design or analysis at any other point where it appears to be necessary.

SECTION 5.05 – GUIDELINES AND CRITERIA FOR STREAM REALIGNMENTS

To the extent possible, modifications to an existing natural stream channel should be avoided. Occasionally, however, it will be necessary to realign a stream channel to provide the most cost-effective roadway design. The design objectives for stream realignment will usually be different than those for a roadside ditch. Usually, the design objective for a roadside ditch is primarily to prevent erosion damage. However, stream realignments usually represents a change to a complex hydraulic situation and often results in a curved channel alignment. This change can have results that extend both upstream and downstream of the actual stream realignment. Thus, the designer should bear in mind that designing a stream realignment is often a complex process involving a number of competing factors. The criteria presented in this section are aimed at achieving a balance between environmental impact, construction cost, maintenance needs, and damage to adjacent property. A detailed procedure for the design of stream realignments is provided in Section 5.06.2. Streams relocations that require natural stream design methods should follow the guidance provided in Chapter 11.

The design criteria presented in this section apply to streams which convey a design discharge less than 500 cfs. Streams where this criteria is exceeded should be referred to the Hydraulics Section of the Structures Division.

5.05.1 ESTABLISHING THE REALIGNMENT PLAN

The designer should clearly identify on the plan sheet the existing and proposed alignments of a stream to be realigned. The plan should identify the length and location of each channel transition, the location of any low flow channel and the materials used to prevent channel erosion. In addition, the roadway cross sections should be extended as necessary to provide cross sectional data on the existing and proposed stream channels.

5.05.2 STORM FREQUENCIES FOR STREAM REALIGNMENT DESIGN

Typically, the design storm frequency for stream realignments will be the 50-year storm event. This frequency should be used to design any required revetments for stream stability and to evaluate the freeboard on the roadway. As described in Section 5.05.5, the hydraulic capacity of the relocated stream should be checked for the 100-year flood.

A natural stream will usually consist of a channel section which conveys low flows and overbanks which will convey flows when the stream is at flood stage. Where this situation exists, the designer should not attempt to provide a channel which will convey the entire design discharge. Rather, an effort should be made to maintain the existing stream cross section to the greatest extent possible.

5.05.3 DATA REQUIREMENTS

To provide a complete design for stream channel realignment, the designer should gather the data necessary to:

- complete an hydraulic analysis of the existing and proposed stream channels
- design revetments to insure the stability of the realigned channel
- coordinate the realignment design with the Environmental Division

Much of the needed data will already be contained in the project plans and site survey. As the realignment plan is developed, it may become apparent that supplemental survey activities on the existing stream channel may be required. Other data may be obtained by site inspection, when feasible, or from examination of aerial photography.

The following sections deal with many of the specific types of data that should be available before designing a stream realignment.

5.05.3.1 EXISTING CHANNEL CROSS SECTIONS

Cross sectional data on the existing stream will be used in the hydraulic analysis of the stream realignment. Additionally, it will be used as a guide in determining the cross section of realigned channel. In some cases, it may be possible to supplement the surveyed cross-sectional data with other existing topographic mapping to construct a complete valley cross section. It is important that the existing cross sectional data be representative of the overall shape of the stream channel and overbanks. Finally, if it appears that downstream conditions may create a high tailwater condition, additional cross sections may be necessary to evaluate downstream flow elevations.

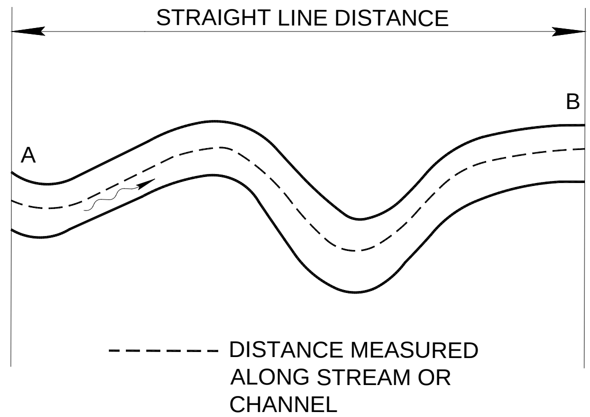
5.05.3.2 SLOPE, LENGTH, AND SINUOSITY

The longitudinal slope of the existing channel downstream of the proposed realignment should be determined to provide a proper starting condition for the hydraulic analysis. It will sometimes be necessary to obtain additional cross sectional data downstream of the reach being realigned. For calculating the stream slope, the lowest streambed elevations should be used with the distance between the cross sections.

The stream slope determined from the surveyed cross sections should be carefully evaluated before it is applied in the hydraulic analysis of the stream. This slope should be examined for consistency with the overall valley slope as determined from topographic mapping for the stream. If the local slope determined from the cross sections is significantly different than the slope determined from the mapping, the generalized slope from the mapping may yield a more accurate hydraulic analysis.

It should always be kept in mind that the energy slope of the flow may not always be equal to the slope of the channel. Extra stream cross sections downstream of the proposed realigned reach will allow the hydraulic model to stabilize prior to the start of the project and will provide a more accurate assessment of the water surface elevations in the project area.

As shown in Figure 5-5, sinuosity is the ratio of the length of channel measured along its centerline to the length measured along a straight line connecting the ends of the reach to be realigned. When the valley itself is curved, it may be preferable to measure along the valley centerline. Straight stream reaches have a sinuosity of one, and the maximum value of sinuosity for natural streams is about four. A procedure for determining sinuosity is provided in Step 3 of Section 5.06.2.1.



$$\text{SINUOSITY RATIO} = \frac{\text{DISTANCE FROM 'A' TO 'B' ALONG STREAM}}{\text{STRAIGHT LINE DISTANCE FROM 'A' TO 'B'}}$$

Figure 5-5
Channel or Stream Sinuosity Ratio Illustrated

5.05.3.3 TAILWATER CONDITIONS

Usually, the tailwater elevations experienced at the beginning of the realigned reach will be determined by the hydraulic conveyance and downstream slope of the stream. However, tailwater elevations can often be significantly increased by downstream conditions including impoundments, obstructions, channel constrictions, and junctions with other watercourses. Therefore, conditions which might promote high tailwater elevations during flood events should be investigated and carefully evaluated before any hydraulic analysis of the stream is conducted. The presence of such conditions can often be determined from field observations or topographic maps.

When a high tailwater condition results from the existence of a stream junction near the project site, the designer should carefully evaluate whether flood elevations on the receiving water body should be considered. In general, if flood discharges on the two streams are likely to peak at about the same time, it would be acceptable to consider the higher tailwater in the analysis of the stream realignment. However, if the peak discharge times are likely to be significantly different, the realignment could be designed based on the hydraulic capacity of the channel.

5.05.3.4 CHANNEL STABILITY

It is important to carefully evaluate the stability of the existing stream and to consider the effect of the proposed realignment on stream morphology. Features to be examined include the occurrence or possibility of streambed degradation (head cutting) resulting from downstream dredging or other channel modifications. Signs of bank slippage and erosion should be noted, as well as buildings or other structures which appear to be located relatively close to the bank. The presence of trees growing at odd angles from the bank, exposed tree roots, and trees that have fallen into the stream should also be noted. The composition of channel bed materials should be considered as well as the location and likely direction of any lateral migration. These factors should be carefully considered to insure that changes to flow patterns due to the channel realignment will not result in unintended consequences to the morphology of the stream and to insure that the realigned channel will be stable.

5.05.3.5 EXISTING RIPARIAN VEGETATION

Because specific concerns regarding revegetation of the proposed channel will likely be addressed by the Environmental Division, the designer will most likely not be required to conduct a detailed survey of the existing vegetation. However, the designer should coordinate with the Environmental Division with regards to the types of vegetation to be provided along the limits of the realigned stream.

5.05.3.6 HYDRAULIC ROUGHNESS

The hydraulic roughness of the existing stream cross section may be determined by an assessment of the stream morphology, vegetation and the composition of the materials in the stream bed. Specific guidance on determining Manning's n-values for the existing stream is contained in Section 5.03.2.4.

5.05.4 SAFETY AND MAINTENANCE CONSIDERATIONS

The side slopes of a realigned stream are not subject to the criteria that govern the side slopes of roadside ditches. In general, the side slopes of the realigned channel will match the side slopes of the existing stream as much as possible. In addition, the designer should verify that the proposed side slope will be stable for the local soil conditions.

Where there is sufficient right-of-way, realigned streams should be located outside of the clear zone. Where this is not possible, it may be necessary to provide appropriate safety measures adjacent to the stream channel.

5.05.5 HYDRAULIC CONSIDERATIONS

Often, properties adjacent to the right-of-way will lie within the floodplain of a stream being realigned. The designer should carefully evaluate the effect of proposed stream realignments on any property outside of any TDOT right-of-way or drainage easements. In general, the proposed realignment should not increase the 100-year flood elevation or increase the flooded area on these properties. However, this policy should not be applied where the realigned stream includes a cross drain since Section 4.03.1 of this Manual allows some increase in water surface elevation for culverts. In this situation, the designer should verify that the water surface elevation upstream of the cross drain will comply with the criteria provided in Chapter 6 of this Manual.

The hydraulic capacity of the realigned stream should be checked by means of water surface profile computations using the standard step method as described in Section 5.03.4.2. At least two profiles will be needed for the 100-year event, one for the existing stream and one for the proposed relocation. The study reach should begin downstream of the channel realignment as far as is practical, and should include a minimum of three stream cross sections. The study reach should extend far enough above the stream realignment to show that the profile of the realigned stream is converging with the existing profile.

5.05.5.1 CURVED CHANNEL ALIGNMENTS

Flow conditions in a channel bend are complicated by the distortion of flow patterns which occurs in the vicinity of the bend. In long, relatively straight channels, the flow conditions are uniform, and symmetrical about the center line of the channel. However, in channel bends, centrifugal forces and secondary currents lead to non-uniform and non-symmetrical flow conditions.

Under ideal conditions with subcritical flows, the general flow pattern through a curvilinear section of channel will resemble a spiral vortex. Laboratory investigations have shown that the strength of this vortex is related to the ratio of radius of curvature, R_C, of the bend to the bottom width of the channel, B. As the radius of curvature decreases with respect to the channel width (that is, at the ratio R_C / B decreases in value), the strength of the vortex increases moderately. However, the strength of the vortex increases more sharply where the value of the ratio becomes less than 3. Thus, a value of 3 for R_C / B represents an ideal balance between the need to minimize the right-of-way take for the channel realignment and the need to minimize the adverse impacts that would result from flows around a sharp bend.

Two aspects of flow in channel bends affect the design of revetments for a realigned stream. First, flows around a bend impose higher shear stresses on the channel sides and bottom compared to a straight reach, as shown in Figure 5-6. At the beginning of the bend, the maximum shear stress is near the inside and moves toward the outside as the flow leaves the bend. This increased shear stress persists downstream of the bend for a distance termed L_P. The maximum shear stress in a bend is a function of the ratio of the radius of the curve, R_C, to the channel bottom width, B. As R_C / B decreases, that is, as the bend becomes sharper, the maximum shear stress in the bend tends to increase. To determine the shear stress in the bend, τ_{bend}, the maximum shear for a straight alignment is first computed from Equation 5-10. This value is then multiplied by a dimensionless factor, K_b, which accounts for the increased stress:

$$\tau_{bend} = K_b(\tau_{max}) \quad (5\text{-}11)$$

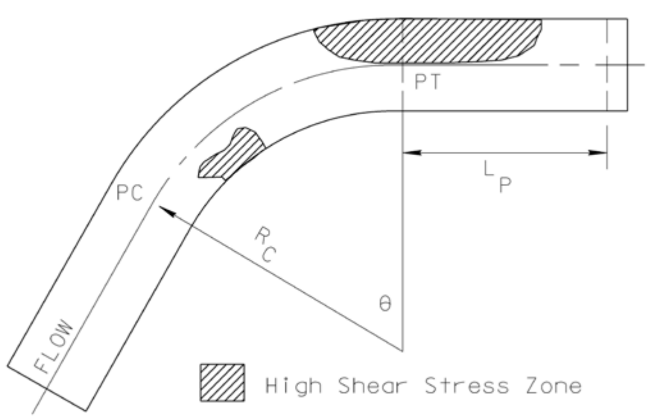


Figure 5-6
Shear Stresses in Channel Bend
Reference: USDOT, FHWA, HEC-15 (1988)

Values of K_b may be determined from the relationship:

$$K_b = 2.36e^{-0.082(R_c/B)} \quad (5\text{-}12)$$

Superelevation of flow in channel bends is a second consideration in the design of revetments for stream realignments. It should be noted that superelevations in subcritical flows are driven by different mechanisms than superelevations in supercritical flows. Sub-critical flows around bends tend to establish spiral vortices which result in increased water surface elevations around the outside of the bend. On the other hand, superelevations in supercritical flows are usually due to conflicting cross waves established in the curvilinear flows. In addition, hydraulic jumps can occur in very severe bends.

The magnitude of superelevation is relatively small in subcritical flows, but can be significant for supercritical flows. When considering freeboard for revetments on bends, the designer should allow for at least 1 foot of superelevation in subcritical flows. Where flows are supercritical, the magnitude of the superelevation may be estimated flow by the following equation:

$$Z = C\left[\frac{V_a^{2} \times T}{g \times R_c}\right] \quad (5\text{-}13)$$

Where:
- Z = superelevation of the water surface, (ft)
- C = coefficient that ranges between 0.5 and 3.0, with an average of 1.5
- V_a = mean channel velocity, (ft/s)
- T = water-surface width at the section, (ft)
- g = acceleration due to gravity, (32.2 ft/sec^2)
- R_c = the mean radius of the channel centerline at the bend, (ft)

5.05.5.2 CHANNEL TRANSITIONS

Ideally, the cross section of the realigned stream will be similar, if not identical to, the cross section of the existing stream. Where this is not possible, adequate transitions should be provided between the unaffected portions of the existing stream and the realigned portion of the stream. The length of these transitions may be determined as follows: The top width of the flow at the design discharge in the existing stream should be compared with the top width of the flow in the proposed stream and the width of the existing channel bottom should be compared with the width of any low flow channel which may be provided in the realigned stream. The length of the transition will be equal to the greater of the two differences. In other words, the transition should be based on an expansion or contraction ratio of 2:1.

The centerline of the realigned channel should be continuous with the centerline of the existing channel. Further, if a curved alignment is necessary at either end of the realigned stream, the transitions should be placed outside of these curved areas. That is, the transition to the realigned stream cross section should be complete before the beginning of the curved alignment.

5.05.6 ENVIRONMENTAL CONSIDERATIONS

To the extent possible, stream realignments, relocations, and modifications should be avoided. If modifications are necessary because of the physical constraints of the highway facility, terrain, or land use, the environmental impacts of the modifications should be minimized. The modifications should be evaluated for their long and short-term impacts to the stream system. In general, the designer should pay particular attention to the mitigation plan which is usually provided by the TDOT Environmental Division.

The realignment, relocation, or modification of an existing stream has the potential to cause stream instability problems upstream and downstream of the roadway. The designer should also take care to minimize any potential impacts to the stream system due to these modifications. The designer should attempt to keep the riparian functions of the existing stream in the new channel. Typical riparian functions are to provide habitat for aquatic life, shading of the stream by vegetation to moderate stream temperature fluctuations, bank vegetation that prevents erosion and promotes bank stability, and habitat corridors for aquatic and terrestrial fauna and flora. The following criteria describe the steps to be followed by the designer to minimize any environmental impacts.

Where a proposed project requires the realignment of a stream channel, the following guidelines should be met:

- Abrupt changes in channel alignment should be avoided and adequate transitions should be provided at both ends of the project.
- Concrete lined channels and riprap lined channels are not acceptable for channel changes on streams except as needed to prevent erosion.
- For streams with enough flow to support aquatic life, a low flow channel as shown in Figure 5-7 within a channel change should be considered if flood plain hydraulics dictate that a channel larger than the natural channel is required. The normal flow keyway should have approximately the same width, X, and height, Y, as the existing normal flow channel.
- Meanders should be included in stream relocations to maintain the natural stream length and slope.

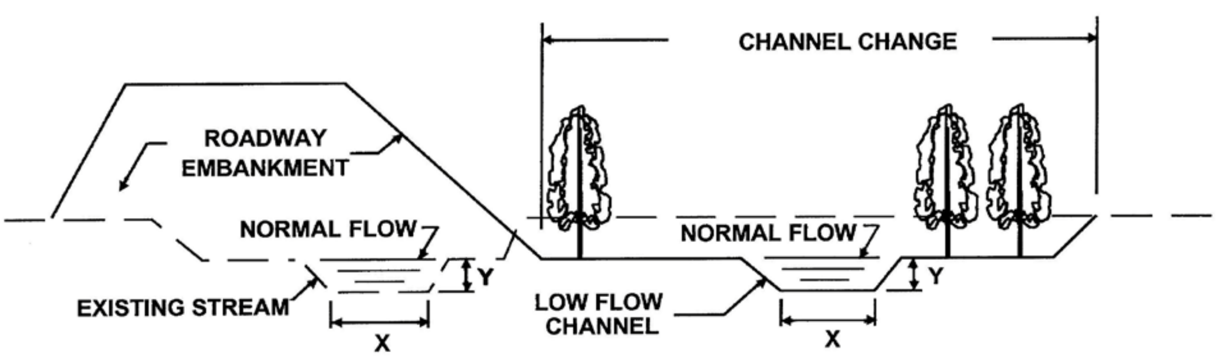


Figure 5-7
Low Flow Channel for Stream Realignments

In general, the designer should maintain the following stream properties as much as possible, unless directed otherwise by the Environmental Division:

- Stream length
- Stream slope
- Cross section shape
- Stream sinuosity
- Existing riparian vegetation
- Lining Material

When a stream realignment has an identified environmental impact, such as endangered species or adjacent wetlands, the designer should contact and work with the Environmental Division to ensure that the proposed design any special requirements established for the project. In addition, the designer should make every effort to comply with any other recommendations from the Environmental Division.

5.05.7 REVETMENTS FOR STREAM REALIGNMENTS

As stated in Section 5.05.6, modifications to an existing natural stream channel should be avoided as much as possible. Because of the complexity of the flows that occur in a curved stream alignment, the realignment of a stream can sometimes result in unintended erosion or deposition of sediments which may result in damage to the roadway or adjacent property. Thus, hard revetments may be placed in the realigned channel to stabilize the alignment.. However, because hard revetments can sometimes be undesirable from an environmental standpoint, the objective of the design will be to stabilize the stream alignment using a minimum of these materials.

This section provides guidance on the selection and design of stream revetments.

5.05.7.1 REVETMENT TYPES FOR CURVED ALIGNMENTS

This section provides descriptions of the materials to be used as revetments for channel realignments for TDOT projects. The use of any material other than those listed in this section should be approved by the Design Manager.

5.05.7.1.1 VEGETATION

Although vegetation cannot be considered an actual type of revetment, it is the preferred method of providing stabilized channel banks. Section 5.05.3.5 indicates that the riparian vegetation in the existing steam channel should be replaced in the realigned stream channel as much as possible. Thus, the designer should investigate the allowable shear stress for the existing riparian vegetation. If the tractive force of the flows around the bend will be greater than the allowable shear stress, the designer may investigate at least three options:

- modify the vegetation proposed for the realigned stream banks to include more erosion resistant species
- increase the radius of the bend to reduce the tractive force that would be experienced on the outside of the bend
- turf reinforcement mats
- use some form of hard revetment as described in the following sections

The determination of the best course of action should reflect a balance between the hydraulic conditions, economic considerations, and the availability of right-of-way. The choice should also be coordinated with the Environmental Division.

5.05.7.1.2 RIPRAP

Detailed descriptions of the various classes of riprap available for use as revetments are provided in Section 5.04.7.1.2. Although it is extremely difficult to predict the maximum velocity that will occur along the outside of a curved section of channel, the velocity criteria provided for riprap in Section 5.04.7.1.2 reflect an allowance for this uncertainty. Thus, the selection of riprap will be based on the average flow velocity as follows:

- Machined Riprap (Class A-1) should be used for average flow velocities up to 5 feet per second
- Machined Riprap (Class B) should be used for average flow velocities up to 10 feet per second
- Machined Riprap (Class C) should be used for average flow velocities greater than 10 feet per second up to 12 feet per second

Situations where the average flow velocity is greater than 12 feet per second may be supercritical and present an extremely complex design problem. The designer should make every reasonable effort to avoid curved alignments in areas of such high velocity.

5.05.7.1.3 PRECAST CONCRETE FORMS

Precast concrete forms can consist of “jacks” or of concrete blocks which are tied together with steel cables. “Jacks” differ from concrete block riprap or stacked sand-cement bags in that they usually provide an arm or other type of structure that protrudes into the flow field. These structures act by creating additional flow resistance to reduce velocities in areas where turbulent flows might create erosion. These structures are usually placed in a tight pattern on filter fabric. In many installations, these structures reduce velocities sufficiently that sediments will be deposited in the voids between the individual precast units. This in turn can encourage the growth of vegetation which may serve to enhance the erosion resistance of the revetment. Cable-tied blocks are also placed on filter fabric and may be used in areas of high velocity flows where machined riprap may not otherwise be stable.

At this time, no standard design exists for these structures and a variety of forms are available from various manufacturers. Specific design guidance for these structures usually can be obtained from the manufacturers. However, this design data is often based upon laboratory studies and the prudent designer will seek to obtain information on the performance of any given structure in an actual field installation. Before specifying these structures, the designer should check the Qualified Products List. Request to use any structure not on the Qualified Products List must be made to, and subsequently approved by, the Design Manager.

Precast concrete forms are typically shipped in pieces and assembled on-site. The designer should consider labor costs in determining whether some form of these units should be used at a specific site.

5.05.7.1.4 REVETMENT TYPES TO BE AVOIDED

The following revetment types should be avoided on channel bends for stream realignments:

- **Wire Enclosed Stone:** The flow velocities experienced at the outside of a channel bend can be relatively high, even in situations where the average steam velocity is moderate. Thus, granular sediments carried by the flows in these areas can quickly abrade the coating on the wire used to enclose the stone. The resulting rust can cause the wire to break, resulting in the premature failure of the structure.
- **Concrete Block Riprap:** This type of revetment normally provides erosion protection by providing a smooth continuous wall. However, it is particularly vulnerable to failure due to undermining. Further, the displacement of a few blocks, often at the upstream edge of the wall, can lead to increased erosion behind the wall and the progressive failure of more blocks. Providing an interlocking form of concrete block does not seem to significantly improve the performance of the wall.
- **Concrete Pavement:** Concrete slope walls tend to increase the overall velocity of flow in the channel. This can lead to increased erosion downstream as well as other unintended geomorphic consequences. In addition, the increased flow velocities that would occur in a concrete-lined channel may significantly reduce the flow time in certain situations. This may tend to increase the peak flow rate or have other unintended consequences on the receiving stream.

5.05.7.2 REVETMENT SELECTION AND DESIGN

Where feasible, vegetation will be the preferred method of stabilizing channel banks for stream realignments. Thus, the designer should make every reasonable effort to provide vegetated erosion protection as described in Section 5.04.7.1.1. Where vegetation is not feasible, the designer may specify hard revetments based upon coordination with the Environmental Division. While it may be possible to specify machined riprap as described in Section 5.05.7.1.2, a variety of other options exist. A number of resources to aid in these designs are available on the internet, including the NRCS Watershed Technology Electronic Catalog (WTEC) site and the FHWA publication *Highways in the River Environment (HIRE)*, available from the archived publications list on the FHWA Hydraulics website. Chapter 5 of *HIRE* is of particular interest in the design of streambank revetments.

One of the principal objectives of a channel realignment design should be to stabilize the channel banks using the minimum necessary amount of hard revetment. The following sections provide guidance on the extent of the placement of revetments, both laterally along the stream and vertically.

5.05.7.2.1 LONGITUDINAL EXTENT OF REVETMENT

The longitudinal extent of protection required for a particular revetment installation is highly dependent on local site conditions. In general, the revetment should be continuous for a distance greater than the length that is impacted by channel-flow forces severe enough to cause erosion.

The following general rules will provide a starting point for the determination of the longitudinal extent of the revetment:

Where the ratio of the radius of channel curvature to the width of the channel is 3 or greater (RC / B ≥ 3), the revetment should extend upstream from the curve a minimum distance approximately equal to the channel width, and downstream from the curve a distance equal to at least 1.5 channel widths, as shown in Figure 5-8. Where RC / B is less than 3, these lengths should be extended using Figure 5A-7 as a guide.

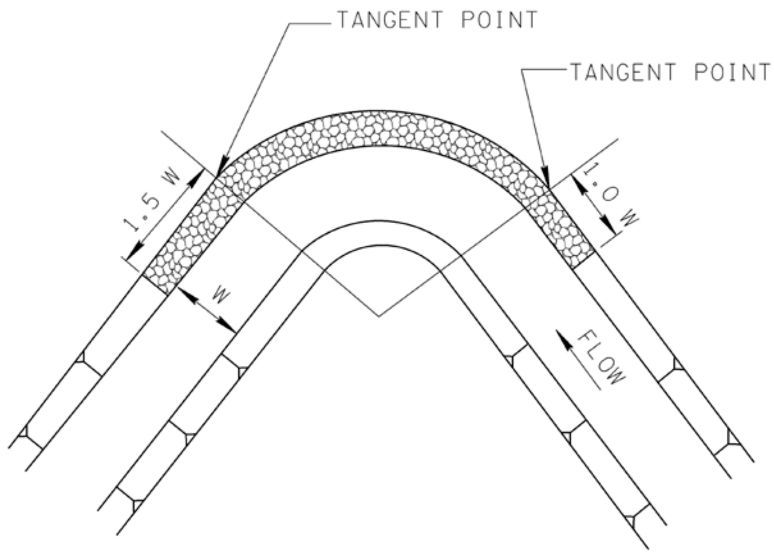


Figure 5-8
Longitudinal Extent of Revetment at a Channel Bend
Reference: USDOT, FHWA, HEC-11 (1989)

The designer may find the above criterion difficult to apply on mildly curving bends or on irregular, non-symmetric channels. In such cases, average values for the radius of curvature and width of the channel should be determined as well as possible based on engineering judgment. It should be noted that this criterion is based on laboratory analysis of symmetric channel bends. Real-world conditions are rarely as simplistic. In actuality, many site-specific factors have a bearing on the actual length of bank that should be protected. The designer may find field reconnaissance to be a useful tool for the evaluation of the longitudinal extent of protection to be provided, particularly if the existing channel is actively eroding.

5.05.7.2.2 VERTICAL EXTENT OF REVETMENT

Vertically, a hard revetment should extend from a height that provides adequate freeboard above the design flow elevation to a depth below the channel bottom sufficient to provide toe protection.

The design freeboard is provided to account for factors such as superelevation in channel bends, hydraulic jumps and flow irregularities due to transitions, and flow junctions. In addition, unforeseen slope settlement, the accumulation of debris in the channel, and the growth of vegetation should be considered when setting freeboard heights.

Although the amount of freeboard cannot be fixed by a single, widely applicable formula, the guidance provided in Section 5.05.5.1 will be considered to be generally adequate. However, the designer may adjust the required freeboard estimate based on any of the factors listed in the previous paragraph.

Undermining of the revetment toe protection can be one of the primary mechanisms of revetment failure. Thus, the toe of the revetment should be keyed into the streambed to a depth sufficient to prevent undermining. Where riprap is being used as revetment, the toe depth should equal to be at least the minimum layer thickness for that class of riprap. Machined Riprap Class B should be keyed to a depth of at least 2.5 feet while Machined Riprap Class C should be keyed to a depth of at least 3.5 feet.

In a stream realignment that has been provided with a low-flow channel as shown in Figure 5-7, it should be assumed that the low-flow channel could meander on the bottom of the realigned stream cross section and eventually reach the toe of the protected slope. Thus, the depth of the keyed slope revetment should be based on the flow line of the keyway.

SECTION 5.06 – DESIGN PROCEDURES

This section provides detailed procedures for the design of roadway side and median ditches as well as general guidance for the design of stream realignments. Because the design of a stream realignment involves a variety of interrelated and complex factors, it is not possible to provide a detailed step-by-step procedure for these designs. The design of roadway side ditches or stream realignments normally begins with some overall system planning to establish a generalized design framework. Once this has been accomplished, hydrologic computations can be performed to determine design flow rates at the required points. The design then proceeds to ensuring that the proposed ditches will have sufficient hydraulic capacity and the selection of channel linings to control erosion in the ditch or stream.

The designer should possess an understanding of open channel hydraulics before undertaking the procedures outlined in this section. The application of these procedures without that understanding could result in a design that is inadequate, unsafe or unduly costly.

5.06.1 ROADSIDE AND MEDIAN DITCH DESIGN PROCEDURES

Once the ditch plan has been determined, as described in Section 5.04.2, the design of roadway side and median ditches will usually consist of two parts: ensuring that the ditch will have adequate hydraulic capacity and providing a ditch lining that will resist the erosive forces exerted by the design flow. This section provides a general framework for this two-part design process. The subsequent sections provide expanded detail for specific items in the general framework.

5.06.1.1 DITCH ANALYSIS LOCATIONS

As provided in Section 5.04.7.2.2, detailed ditch design should generally be needed only in areas were the ditch slope exceeds 1 percent or the drainage area is greater than 5 acres. To insure an adequate ditch design, the capacity and lining of the ditches for a project should be spot-checked at the following points:

- points just upstream and just downstream of any grade break in the ditch profile
- at the approximate midpoint of any curved portion of the alignment where the ratio of the radius of curvature, R_c, to the bottom width of the ditch, B, is 3 or less, as described in Section 5.05.5.1
- just downstream of any point where a significant amount of flow is added to the ditch, such as culvert or other drainage structure outlets (but usually not including underdrain outlets)
- just upstream of any culvert inlet or any other structure that would receive flows from the ditch
- just upstream of any ditch outlet

The designer should exercise sound engineering judgment in determining any additional analysis locations.

5.06.1.1.1 OTHER FACTORS AFFECTING DEPTH IN A DITCH

In most locations, the capacity of median or other ditches will be evaluated by determining the depth necessary to convey the design discharge at normal depth. However, the depth in a ditch will frequently be affected by features associated with the ditch such as:

- inlets placed in the ditch flow line
- culvert inlets
- outlets to a receiving stream

The depth due to these features should be compared to the normal depth of flow in the ditch. The greater depth should be used to evaluate the capacity of the ditch.

5.06.1.2 GENERAL DITCH DESIGN AND ANALYSIS PROCEDURE

In general, the design computations for a specific location in a ditch should initially assume that the cross section is a rounded “V” with a vegetated lining as described in the TDOT Standard Roadway Drawings. As shown in the flow chart provided in Figure 5A-1, the ditch cross section may be expanded to a trapezoidal shape or the lining type may be changed when the computations show that the initial assumption would not provide an adequate design. Thus, the following steps may be taken to evaluate the adequacy of the ditches proposed for a project:

Step 1: Determine the design discharge and the 2-year flow rate for each point on the ditch where it will be necessary to check the ditch design. Methods for determining these discharges are contained in Chapter 4 of this Manual.

Step 2: Assume that the ditch cross section will be a rounded “V” and determine the side slopes based on the criteria provided in Section 5.04.1.

Step 3: Assume that the ditch will be provided with a vegetated lining in vegetal retardance class C. This assumption should be made regardless of the type of vegetated lining. Although sod, seeded grasses and turf reinforcement mats offer differing levels of erosion resistance, the hydraulic roughness of all three linings is based on the presence of grass. As discussed in Section 5.04.7.1.1.5, vegetated linings are generally assigned to retardance class C based upon normal long-term maintenance practices. Another retardance class may be used where the ultimate length of the established grass can be determined with confidence. In such cases, the retardance class may be determined based on the expected length of the grass using Table 5A-4.

Where a ditch is subject to perennial flows or frequent ponding, it may be necessary to provide a composite lining using riprap to protect areas where grasses would otherwise drown.

Step 4: Compute the depth of flow in the ditch for the design discharge. Where a vegetated ditch lining is proposed, the depth of flow should be determined using the procedure provided in Section 5.06.1.3.1. Where a non-vegetated lining is proposed, Manning’s equation may be used as described in Section 5.06.1.3.3.

Step 5: The computed depth of ditch flow should be evaluated based on the criteria provided in Section 5.04.6. If it is found that the depth of flow is acceptable, the designer may proceed to Step 6. Otherwise, one of the following actions should be taken to increase the ditch capacity:

- increase the slope of the ditch
- increase the depth of the ditch (which may also have an effect on the ditch slope)
- use flatter side slopes
- assume a trapezoidal cross section

Once the slope or the cross section of the ditch has been revised, the designer should return to Step 4.

Step 6: Compute the maximum tractive force and flow velocity for the depth determined in Step 5. Tractive force may be computed by using Equation 5-10 and the procedure provided in Section 5.04.7.2.1. Often, flow velocity will be obtained as a part of finding the depth in Step 5. However, where this is not the case, velocity may be computed from the Continuity equation as described in Section 5.03.2.3.

Where the proposed ditch follows a curved alignment, it may be necessary to increase the computed shear stress using the procedure described in Section 5.05.5.1.

Step 7: Check the computed tractive force and flow velocity to determine whether they are less than the allowable limits for the proposed lining. Table 5A-7 may be used to evaluate the tractive force and Table 5A-3 may be used to evaluate the maximum allowable flow velocity. In general, vegetated linings should be checked for shear while riprap linings should be checked for velocity. If the computed values for these parameters are less than the permissible, the designer may proceed to Step 9. Otherwise, the designer should evaluate the situation as described in Step 8.

Step 8: Where either the computed shear stress for flow velocity are greater than allowable for the proposed lining, the designer should make a judgment as to whether changing the ditch cross section or slope would reduce the shear stress or flow velocity to acceptable levels. If so, the designer should take one of the actions described in Step 5 and then return to Step 4.

Where it does not appear that shear stress or velocity can be sufficiently reduced by modifying the cross section or slope, or where such modifications are not feasible, another type of lining should be selected. In general, a vegetated lining is preferred over a hard lining such as riprap. Thus, the order of preference for lining selection is as follows:

- vegetation (sod or seeded grasses)
- turf reinforcement mats, as described in Section 5.04.7.1.1.3
- machined riprap
- concrete pavement

Once a new lining has been selected, the designer should return to Step 4.

Step 9: Ditch linings such as seeded grasses or turf reinforcement mats require a “grow-in” period to achieve their full erosion resistance. Thus, the designer should take steps to reduce the risk of possible erosion during this time. For other lining types, including sod, the designer may proceed to Step 10.

Seeded grass ditch linings should be considered to offer no erosion resistance, even when the seed has been “tacked” into place with a tackifier and should be protected by an erosion control blanket, as described in Section 5.04.7.1.1.2. As shown in Table 5A-7, these blankets offer a higher permissible shear than does a class C vegetated lining. Thus, they should offer adequate protection where a class C lining is assumed. Where longer grasses are to be used to provide greater permanent erosion resistance, the erosion control blanket may be selected as follows:

- Select a trial blanket for the site. Information on the several types of blankets is provided in Section 5.04.7.1.1.2; however, the designer should also refer to the Standard Specifications for information on any other types of blankets which may be available.
- Based on the guidelines provided in Section 5.04.6.3, select a Manning’s n-value for the proposed temporary blanket and compute depth, flow velocity and maximum shear for the 2-year discharge.
- If the computed depth, velocity and shear stress are less than the permissible, the designer may proceed to Step 10. Otherwise, this procedure should be repeated for another type of temporary erosion control blanket.

Turf reinforcement mats usually offer significantly reduced erosion protection before the grassed portion of the lining has been established. However, since vegetation can generally be established in one or two seasons, the 2-year storm should be used to evaluate whether the unvegetated mat will offer adequate protection. In situations where the shear imposed by the 2-year flow rate exceeds the shear strength of the unvegetated lining, it is recommended that riprap be used to form a composite lining. The procedure for evaluating an unvegetated turf reinforcement mat is as follows:

- Determine the 2-year flow rate at the site, and use Table 5A-7 to determine the permissible shear stress on the unvegetated lining.
- Determine the depth of flow and shear on the unvegetated turf reinforcement mat as described in Section 5.06.1.3.2.
- If the computed shear exceeds the permissible shear for the unvegetated lining, the designer should provide a riprap lining on the bottom of the ditch. Since the hydraulic roughness of the riprap will be different than the roughness of the mat, the height of the riprap lining should be equal to the 2-year flow depth on the stone, not on the unvegetated turf reinforcement mat. Section 5.06.1.3.3 provides a procedure for determining the depth of flow on riprap.
- Turf reinforcement mat may be used on the sides of the ditch, above the riprap.

Table 5A-19 through 5A-21 can provide assistance in evaluating the adequacy of an unvegetated turf reinforcement mat.

Step 10: The final step of the lining design process would be to determine the vertical and horizontal extents of the lining. The height of the lining should be determined based on the required freeboard above the depth at the design discharge as discussed in Section 5.05.7.2.2.

Due to varying conditions along the course of a roadway project, different types of lining may be required at various locations in the ditches for the project. This is particularly true where the ditch must follow a sharply curved alignment, where a different type of lining may be required to accommodate the increased shear stresses. Along gently curving or tangent sections of roadway, the designer should determine the extent of any given type lining based upon breaks in ditch grade, points where significant amounts of flow are added, and the overall consistency of the design. The longitudinal extent of lining types selected for erosion protection in sharply curving alignments may be determined using the guidelines provided in Section 5.05.7.2.1.

Once it has been shown that the proposed ditch will offer sufficient capacity and that the lining will be adequate for both the design shear stress and flow velocity, the design may be considered complete.

5.06.1.3 DETAILED COMPUTATION PROCEDURES FOR DITCH DESIGN

The general design procedure described in the previous section includes a number of detailed procedures that may vary depending on the type of lining being analyzed. The following sections provide specific procedures that may be used for specific lining types at various points in the ditch design process.

5.06.1.3.1 CAPACITY COMPUTATIONS FOR DITCHES WITH VEGETATED LININGS

As described in Section 5.04.6.1, the effective resistance to flow in a ditch with a vegetated channel lining will vary with depth. Thus, when applying Manning’s equation to analyze the flow in the ditch, the term “n” is not constant.

When the depth, ditch cross section and slope are known, it is possible to compute a value for Manning’s n from:

$$n = \frac{R^{1/6}}{C_{rf} + 19.97 \log\left(R^{1.4} S^{0.4}\right)} \qquad (5\text{-}14)$$

Where: n = Manning’s n-value, (dimensionless)
R = hydraulic radius, (ft)
C_{rf} = retardance factor coefficient, selected from Table 5-1
S = slope of the ditch, expressed as a decimal, (ft/ft)

Values for “n” may also be determined from Tables 5A-8 through 5A-12 in the Appendix, which provide solutions to Equation 5-14 for given values of hydraulic radius and ditch slope. The value of C_{rf} will be determined based on the retardance class determined for the proposed ditch lining as shown in Table 5-1. Table 5A-4 in the Appendix provides guidance on selecting the vegetal retardance class of a grassed lining, based on the expected length of the grass.

When evaluating the capacity of a ditch, the designer will typically know the design discharge, retardance class of the proposed lining, the slope of the ditch and the ditch cross section. With this information, the procedure would be as follows:

Step 1: Assume a trial flow depth and compute the hydraulic radius corresponding to that depth.

Retardance Class	C_{rf}
A	15.8
B	23.0
C	30.2
D	34.6
E	37.7

Table 5-1
Retardance Factor Coefficients

Step 2: Using the hydraulic radius computed in Step 1, determine a value for Manning's n from either Equation 5-14 or from Tables 5A-8 through 5A-12 in the Appendix.

Step 3: Compute the flow rate in the ditch using Manning's equation (Equation 5-5), based on the trial depth assumed in Step 1 and the Manning's n-value determined in Step 2.

Step 4: Compare the flow rate computed in Step 3 with the actual design discharge at that location on the ditch. If the computed flow rate does not match the design flow rate, the designer should assume a different trial depth and return to Step 1. Generally, if the computed flow rate is greater than the design flow rate, a lower trial depth should be assumed. Conversely, if the computed flow rate is too low, a greater depth should be assumed. The assumed depth should be adjusted until the computed flow rate is reasonably close to the design discharge. Usually, the elevation can be determined to within 0.01 feet with only a few trials. This level of precision should be more than adequate.

5.06.1.3.2 CAPACITY COMPUTATIONS FOR DITCHES WITH GEOTEXTILE LININGS

The method used to determine the hydraulic capacity of ditches lined with erosion control blankets or turf reinforcement mats will usually depend on whether or not the vegetation has been fully established. Where the grass lining has been well established, the capacity of the ditch should be determined based on a vegetated lining, as described in Section 5.06.1.3.1. On the other hand, while the lining is still in the "unvegetated" state (that is, little or no grass has grown), the capacity would typically be determined based on the slope-conveyance method described in Section 5.06.1.3.4.

The slope conveyance method is based on the use of Manning's equation with the assumption that the roughness coefficient "n" is constant. However, when evaluating the resistance of a geotextile lining, it is generally assumed that the value of "n" can vary with depth. Generally, a relatively large n-value should be used for depths up to 0.5 feet, and a lower value should be used for depths greater than 2 feet. Between the two depths, the effective n-value may be assumed to vary linearly with depth. Table 5A-6 provides n-values that may be used to evaluate the roughness of unvegetated turf reinforcement mats for depth of 0.5 to 2 feet.

Where the design discharge, slope and cross section of the ditch are known, the depth may be determined as follows:

Step 1: Assume a trial flow depth and compute the flow area, hydraulic radius and effective n-value for that depth. When the depth is less than 0.5 feet, the n-value will equal to the higher value recommended for the proposed lining in Table 5A-6. Similarly, where the depth is greater than 2 feet, the effective n-value would be the lower value. Between these two depths, the effective n-value may be determined by linear interpolation.

Step 2: Compute a trial discharge value from Manning's equation (see Section 5.03.2.4) based on the parameters computed in Step 1.

Step 3: Compare the trial discharge to the design discharge. If the trial discharge is less than the design discharge, increase the assumed depth and return to Step 1. Similarly, if the trial discharge is greater than the design discharge, decrease the assumed depth and return to Step 1.

The flow depth should be varied until the trial discharge is in reasonable agreement with the design discharge. Usually, the elevation can be determined to within 0.01 feet with only a few trials. This level of precision will be more than adequate.

5.06.1.3.3 CAPACITY COMPUTATIONS FOR DITCHES WITH NON-VEGETATED LININGS

Capacity computations for ditches with non-vegetative linings typically utilize the slope-conveyance method described in the following section. This method is based on the use of Manning's equation with the assumption that the roughness coefficient "n" is constant. However, it has been demonstrated that the value of "n" can vary with depth, particularly when the channel lining is composed of relatively large elements, as is the case with riprap. In general, as the depth of flow increases, the effective n-value decreases.

Table 5A-6 provides Manning's n-values for a variety of man-made channel linings for various ranges of depth. Inspection of this table will reveal that, for many types of materials, the variation in n-value with depth is quite small and may be neglected. Thus, it will normally be sufficient to use the n-values provided for depths between 0.5 feet and 2 feet for unlined ditches or for ditches with rigid linings.

In riprap lined ditches, the variation of n-value with depth may be too great to be neglected for flows at shallow depths. Thus, when applying Manning's equation to a riprap-lined ditch, the following procedure should be used:

Step 1: Assume that the depth for the design flow will be between 0.5 and 2 feet and determine the corresponding n-value for the proposed riprap lining from Table 5A-6.

Step 2: Compute the depth for the design flow using the n-value determined in Step 1 with the slope-conveyance method.

Step 3: Evaluate the computed depth against the assumption made in Step 1. If the computed depth is between 0.5 and 2 feet, the result should be accepted and used to proceed with the ditch design. The result may also be accepted if the computed depth is slightly greater than 2 feet, or if it is slightly less than 0.5 feet. Otherwise, the result should be rejected and the designer should proceed to Step 4.

Step 4: Select a new n-value for the proposed lining based on the depth obtained in Step 2 and re-compute the depth using the slope-conveyance method.

Step 5: Evaluate the depth determined in Step 4 against the assumed n-value. Generally, if the depth agrees with the assumption in selecting the n-value, the result may be used to proceed with the design. That is, if the n-value for depths less than 0.5 feet yields a depth less than 0.5 feet, the result may be accepted. Similarly, if the n-value for depths greater than 2 feet yields a depth greater than 2 feet, the result may be accepted. Otherwise, the depth determined in Step 2 should be used for design.

Based on sound engineering judgment, this process may also be applied to coarse ditch lining materials other than riprap.

5.06.1.3.4 SLOPE-CONVEYANCE COMPUTATIONS

The purpose of slope-conveyance computations is to determine the depth of flow in a channel based on the use of Manning's equation with a constant n-value. A description of Manning's equation is provided in Section 5.03.2.4 and criteria for the application of the slope-conveyance method are provided in Section 5.03.4.1.

Manning's equation relates depth to discharge by means of the flow area and hydraulic radius, both of which are functions of depth. However, these functions can frequently be quite complicated, particularly where the channel cross section is irregular. Thus, it is usually not possible to rearrange Manning's equation for a direct solution of depth. Depth may be found by one of the two following approaches.

The **first** approach to determining depth involves constructing a rating curve as follows:

Step 1: Estimate the greatest flow depth that may reasonably occur in the channel and divide this depth into a series of equal increments beginning from the flow line. The number of increments may be based on engineering judgment; however, 10 increments are often sufficient.

Step 2: For each incremental depth, determine the flow area, wetted perimeter and hydraulic radius. Based on these parameters, determine the conveyance, K, at each increment of depth using Equation 5-15. This provides a rating curve of conveyance versus depth for the channel. The computation of conveyance is recommended because it is a function of only the channel cross section and roughness. Should subsequent changes to the ditch plan alter the slope of the ditch, it will not be necessary to re-compute the rating curve.

Step 3: Compute the conveyance required to pass the design discharge as:

$$K = \frac{Q}{S^{0.5}} \qquad (5\text{-}15)$$

Where: K = required conveyance, (dimensionless)
Q = design discharge, (ft^3/s)
S = channel slope, expressed as a decimal, (ft/ft)

Step 4: The depth of flow may then be determined by interpolating the required conveyance on the conveyance rating curve determined in Step 2.

The **second** method of applying the slope-conveyance method involves trial and error as follows:

Step 1: Assume a trial depth of flow and compute the flow area, wetted perimeter and hydraulic radius at that depth. From these, compute the flow rate using Manning's equation.

Step 2: If the computed discharge is greater than the design discharge, Step 1 should be carried out again with a somewhat lower depth. Conversely, if the computed discharge is less than the design discharge, a higher trial depth should be selected.

The principal advantage of this method is that it can be less computationally intensive than the rating curve method, provided that the trial depths are judiciously selected.

5.06.1.3.5 TRACTIVE FORCE COMPUTATIONS

Criteria for tractive force analysis and equations for its application are provided in Sections 5.04.7.2.1 and 5.05.5.1. The procedure for tractive force computations should be as follows:

Step 1: Using the flow depth determined in the ditch capacity analysis, determine the maximum tractive force exerted by the flow from Equation 5-10. Note that the maximum tractive force is computed instead of the average tractive force, as it is assumed that the maximum force may occur anywhere in the cross section.

Step 2: If the proposed ditch will follow a curved alignment, determine whether the correction factor for curvature, K_b, should be applied. Where the ditch consists of a standard rounded "V" ditch, this factor should be required only where the radius of curvature, R_c, is less than 40 feet.

Step 3: If the correction for curvature is to be applied, determine the ratio R_c/B (where B is the bottom width of the channel) and compute K_b from Equation 5-12. It will be necessary to apply sound engineering judgment in determining the term "B" for standard side and median ditches. It is recommended that the bottom width be assumed to be equal to the width of the rounded portion of the ditch as depicted on the TDOT Standard Roadway Drawings.

Step 4: Compute the maximum tractive force in the curved section of ditch from Equation 5-11.

5.06.1.3.6 SIDE SLOPE STABILITY FOR DITCHES ON STEEP GRADES

As discussed in Section 5.04.3.1, special criteria apply when the grade of a side or median ditch is 10% or greater. Unless a ditch is to be constructed in durable rock, some type of lining will normally be required on steep gradients to prevent erosion. Occasionally, it may be possible to line the ditch with a turf reinforcement mat. The designer should investigate this lining prior to specifying riprap. Machined riprap may be used where a turf reinforcement mat would not be feasible, although gabion mattresses or paved ditches may also be considered for use.

Where a steep ditch is lined with riprap, stability will depend on the relative balance of the forces acting on each individual stone in the lining, including the weight of the stone and the lift and drag forces induced by the flow. On a steep slope, the weight of a stone has a significant component in the direction of flow. Thus it will tend to be moved by the flow more easily than the same size stone on a mild gradient. Hence, the velocity criteria for the selection of the class of riprap may not be sufficient for riprap lining design on a steep gradient.

This section provides a design procedure for selecting the class of riprap to be used for channel linings on gradients of 10% or greater. This procedure uses Tables 5A-22 through 5A-25 in the Appendix, which have been developed based on the riprap stability equations provided in Appendix C of the FHWA publication HEC-15. These tables provide a value for the maximum allowable design flow rate that should be allowed in a ditch that has a given cross section, gradient and lining. It should be noted that these tables have been developed for a safety factor of 1.5.

The procedure for riprap lining selection for ditches on a steep gradient should be as follows:

Step 1: Determine the design discharge based on the criteria and procedures provided in Chapter 4 of this Manual.

Step 2: Determine the proposed ditch cross section based on the criteria provided in Section 5.04.1.

Step 3: From Tables 5A-22 through 5A-25, select the table which corresponds to the proposed ditch gradient. Values may be interpolated where the proposed ditch grade falls between the gradients covered by the tables.

Step 4: Locate the entries on the selected table for the proposed ditch bottom width and side slope. In cases where the ditch is to be provided with a rounded bottom, the bottom width of the ditch may be assumed to be equal to the rounded width.

Step 5: For a given bottom width and side slope, the table will provide a maximum allowable discharge for machined riprap Class A-1, Class B, and Class C. The selection of riprap class will be a matter of comparing the design discharge to the maximum allowable discharges for each class of lining.

Step 6: If the design discharge is greater than the allowable discharge for machined riprap Class C, the designer should modify the design. Possible courses of action may include:

- modifying the proposed ditch gradient
- providing flatter side slopes
- providing a wider ditch bottom width
- selecting either a wire-enclosed rock or paved lining

The choice of a course of action will depend upon economics and the available right-of-way. Design guidance for wire-enclosed rock linings may be found in Chapter V of the FHWA publication HEC-15.

Step 7: The depth and velocity of flow may then be computed as needed to complete the design using Manning's equation and the guidance provided in this chapter for riprap ditches on mild gradients.

5.06.2 STREAM CHANNEL REALIGNMENT DESIGN PROCEDURES

Although general TDOT policy is to avoid modifications to an existing natural stream channel as much as possible, it will occasionally be necessary to realign a stream channel to accommodate the most cost-effective design for a new culvert or some other aspect of the roadway project. The design of a stream channel modification is often a complex process that requires finding a balance between a number of competing factors including environmental impact, construction cost, and maintenance needs. In addition, there will usually be a need to coordinate the proposed realignment with the Environmental Division. Stream relocations that require natural stream design methods should follow the guidance provided in Chapter 11.

Because of the complexities often involved in designing stream channel realignments, it is not possible to provide a single step-by-step design procedure that may be applied in all cases. Thus, the following recommended procedure represents a broad outline that may be varied as necessary to fit the specific circumstances of a particular project.

Step 1: **Collect data on the existing stream:** As much as possible, the designer should collect the information listed below to achieve an effective design and to support any coordination that may be necessary with the Environmental Division. Much of the needed data will already be provided in the project plans and survey; however, site visits or supplemental surveys may also be required.

The data to be collected may include:

- flow rates for both the design storm (usually the 50-year event) and the 100-year storm, as determined by the procedures provided in Chapter 4 of this Manual
- topographic data on the existing stream, including channel and valley cross sections, length, flow line elevations, and sinuosity
- the presence of any downstream features that may contribute to a high tailwater condition
- where they are needed, flood elevations or profiles that may be available from the Hydraulics Section in the Structures Division

Additional guidance on useful data may be found in Section 5.05.3.

Step 2: **Evaluate the existing stream hydraulics:** Most often, this will consist of using one of the computer programs listed in Section 5.07 to determine the water surface profiles for both the design discharge and the 100-year discharge. These profiles will provide a baseline for determining the impact of the realignment on flood elevations, and may provide information that would be useful in assessing the stability of the existing stream channel. Features that may prove to be useful include velocity distribution computations at sensitive points in the study reach or the computation of shear stresses.

One of the important issues in modeling stream flows in the subcritical flow regime is that of determining the starting water surface elevation (sometimes called the boundary condition). In general, the guidance provided in Section 6.03.1 of this Manual should be sufficient for assessing the tailwater conditions at the site. When using a computer program to compute water surface profiles through the study reach, the designer will normally input the slope of the water surface that has been determined for the downstream end of the study reach. The computer program will then determine the starting water surface elevation using the slope-conveyance method as described in Section 5.03.4.1. Additional information on determining the starting water surface elevation is provided in Section 5.05.5.

Another important issue in modeling stream flows is the selection of Manning's roughness coefficients, n, to be applied at each cross section. Because Manning's equation underlies most step-backwater computations, the n-value is a primary factor in determining the energy loss between valley cross sections. Changes in n-value may have a significant impact on the water surface elevations computed at each cross section. Thus, the designer should carefully consider the n-values selected at each cross section, and the information used in the selection process should be well-documented, as described in Section 5.02. Table 5A-1 in the Appendix provides a guide for selecting n-values for man-made channels and natural streams. As an alternative to this table, the designer may choose to use Cowan's Method as described in Section 5.03.3.

Most hydraulic modeling software packages allow the designer to separately specify n-values for the channel and flood plains. Where the entire flow will be contained within the channel, a single n-value may be applied to the entire cross section. However, in areas where the design flow exceeds the channel capacity and spills out onto the adjacent flood plain, separate n-values should be defined for the channel and flood plain. This is true even where the flood plain and channel may be assigned the same n-value. In other words, the channel and flood plains should be assigned separate n-values even when those n-values are all equal.

The hydraulic model of the existing stream should begin at a point downstream of the area to be affected by the proposed stream realignment. Specific guidance on the determination of the extents of the study reach is provided in Section 5.05.5.

Step 3: **Develop the Realignment Plan:** As described in Section 5.05.1, the realignment plan should provide information on the locations of the existing and proposed channel alignments as well as the location of other important existing and proposed features of the stream. It may be necessary to add detail sheets to the relocation plan to fully describe the proposed placement of hard revetments or other means of controlling erosion in the proposed relocated stream. Items in the relocation plan should include:

- location of the existing stream including the alignment of the flow line
- locations of important features of the existing stream, including areas where trees have fallen into the creek, point bars, erosion on the channel banks, etc…
- flow line elevations at the upstream and downstream limits of the reach to be realigned *and, if necessary, a table showing the length, slope and sinuosity of the existing and proposed stream alignments*
- locations and lengths of the transitions between the realigned stream channel and the unaffected portions of the stream
- location of any low flow channel that may be required in the proposed steam cross section (note that a cross section of the proposed stream with the low flow channel should be provided either on the realignment plan or on a detail sheet)
- locations of all hard revetments and vegetation that will be used to control erosion in the realigned stream

Initially, the realignment plan would be used to provide a framework for the hydraulic model of the proposed realignment as well as for the selection of the materials used to line the relocated stream. The stream cross section, alignment and channel lining materials would be placed onto the plan based on the best estimate of the designer. The plan would then be adjusted as needed as the hydraulic and channel stability analyses progress.

Step 4: **Evaluate the proposed stream hydraulics:** The hydraulic model of the proposed stream alignment would be based on the initial relocation plan. The proposed conditions hydraulic model should employ the same software package and cover the same model reach as the model for the existing stream. Any cross sections beyond the limits of the proposed relocation should be in the same location and have the same topographic and roughness data in both the existing and proposed models. As with the existing stream profiles, the proposed stream profiles should be computed for both the design discharge and the 100-year discharge.

Manning's n-values used in the hydraulic model of the proposed stream should be based on an "aged" condition. Often, the hydraulic characteristics of a relocated stream will change within a few years of construction due to the growth of additional vegetation or the effects of sediment transport. The designer should make an attempt to take these conditions into account when selecting n-values for the proposed conditions hydraulic model. In general, proposed conditions n-values should not be significantly lower than the existing conditions n-values.

The hydraulic model of the design discharge on the proposed alignment will provide the information needed to specify a stable lining for the relocated stream. Special features of the software such as velocity distribution and stable channel lining computations may prove to be useful for this purpose.

The capacity of the relocated stream should be checked for the 100-year flood discharge. As noted in Section 5.05.5, the potential for increasing flood elevations should be checked at any point where flood waters could exceed the right-of-way or dedicated drainage easement. The proposed cross section of the relocated stream may have to be adjusted if it is found that higher flood elevations on adjacent properties could create the potential for increased flood hazards.

Step 5: **Design a stable channel lining:** The selection of a lining for a realigned stream will require a considerable amount of engineering judgment and possibly a small amount of trial and error. As stated in Section 5.05.7, the preferred means of providing channel stability would be to duplicate the existing vegetation in the realigned channel. However, the existing vegetation may not provide sufficient protection, especially where the existing stream is already unstable. Further, the shear stresses that may exist in curved portions of the proposed alignment will likely be higher than those in the straight portions. It is likely that one type of lining will not be adequate for all portions of the realigned reach of the stream. Rather, different types of lining may be specified for different portions of the realigned channel, depending on the needs of each area. Often, the use of riprap is less desirable from an environmental point of view. Thus, it is preferable to use a turf reinforcement mat or more erosion resistant vegetation in place of riprap where feasible.

The general process for designing erosion protection in the realigned stream would be as follows:

A. To start the process, the designer should assume that the realigned stream will be lined with some sort of vegetation. Based upon a consideration of the stability of the existing vegetation and any information provided by the Environmental Division, the vegetation may consist of the species found in the existing stream or of a more erosion resistant species.

B. Manning's n-values for the selected lining would then be determined based on the procedures found in Section 5.06.2 and the hydraulic parameters (depth and hydraulic radius) determined in the analysis of the existing stream. These n-values would then be placed into the hydraulic model for the proposed alignment.

C. Based on the results of the hydraulic model of the proposed alignment, a value for maximum shear stress would be determined at each cross section, based on Equation 5-10. The designer should carefully evaluate any shear stress computations performed by the hydraulic software to insure that the result is not based on the average shear stress.

The shear stress values computed by Equation 5-10 or by the computer represent the shear that would occur in a straight section of channel. Thus, it is necessary to evaluate any increased shear stress that may be due to the curved alignment using Equation 5-11. Note that the shear stress must be evaluated at each bend in the proposed alignment regardless of whether a cross section in the hydraulic model is located at that point. If it becomes necessary to evaluate shear stress for a curved section which does not have a cross section in the hydraulic model, it should be possible to extrapolate shear stresses from the adjacent upstream and downstream cross sections and then adjust for curvature.

D. Most likely, the shear stress analysis conducted in Step C will indicate that the selected lining will be adequate in some areas of the proposed realignment, but not in others. In areas where the initial lining will not provide adequate protection against the computed shear stress, the designer may either alter the proposed alignment to increase the radius of the bends or specify a type of lining for those areas that would be adequate for the computed shear.

The longitudinal extent and freeboard of areas of "harder" lining should be determined in accordance with the criteria provided in Sections 5.05.5 and 5.05.7. The first step in determining the amount of freeboard that should be allowed is to determine whether the flow is in the subcritical or supercritical flow regime. A procedure for this determination is provided in Section 5.05.5.1.

The hydraulic roughness of the proposed stream alignment will be altered in areas where a "harder" channel lining is specified. Thus, once the design for the proposed "harder" lining areas has been determined, the process would return to Step B so that the hydraulic performance of the realigned stream can be checked. This process would continue until the selected lining materials will provide adequate protection in all portions of the realigned stream.

5.06.2.1 ROUGHNESS COEFFICIENT DETERMINATION BY COWAN'S METHOD

When selecting Manning's n-values to be used in the hydraulic analysis of a stream channel, the designer has the option of estimating the value from Table 5A-1 or applying Cowan's equation (Equation 5-8), described in Section 5.03.3. Cowan's equation may prove useful, especially where the selection of n-value is not straightforward, based on an examination of Table 5A-1. The equation may be applied to any channel where the hydraulic radius is equal to 15 feet or less in the following manner:

Step 1: Select the base n-value, n_o, from Table 5A-2 in the Appendix. This value represents the effective Manning's n-value for the material comprising the channel bed, and would be the value used for a perfectly straight, smooth channel free of obstructions or vegetation.

Step 2: Determine values for n_1, n_2, n_3 and n_4 from Table 5A-2. For each factor, match the description provided under the "Criteria" column to the conditions in the stream being analyzed. A more complete description of each of these criteria is provided in Ven T. Chow's *Open Channel Hydraulics*, pages 106 through 108. It should be remembered that these factors are additive; that is, each value represents an additional amount to be added to the base n-value. Due care should be exercised to not "double count" any of the factors when selecting these values. For example, severe sloughing of the channel banks considered in selecting a value due to irregularity should not be considered as representing a variation in the channel cross section.

Step 3: Compute a value for the sinuosity (see Figure 5-5) of the stream through the study reach for the hydraulic model. This may be accomplished using either topographic mapping or aerial photography. First, trace a line along the centerline of the stream valley from the beginning of the study reach to the end and measuring its length, L_v. If the overall valley (as opposed to the channel) follows a curved alignment, L_v should be based on a line that follows the valley curvature. Then measure the length of the channel, L_{chan}, between the same two points following any meanders that may exist. Where the channel follows a meandering path through the valley, the value of L_{chan} will be greater than L_v. Sinuosity is then equal to:

$$Sin = \frac{L_{chan}}{L_v} \qquad (5\text{-}16)$$

Step 4: Based on the computed value for sinuosity, select a value for m_5 from Table 5A-2 and compute a value for Manning's n-value from Equation 5-8.

SECTION 5.07 – ACCEPTABLE SOFTWARE

Table 5-2 lists software packages acceptable for use on TDOT projects for channel design and the type of task that is appropriate for each software package. This software should be used unless special circumstances on the project or in the watershed require the use of another software package. The TDOT design manager should approve the use of any software other than what is listed in this section. Each acceptable software package is described in the following sections.

Approved Software	Uses
GEOPAK	Roadside Ditch Design
HEC-RAS	Small Stream Design and Stable Channel Lining Design

Table 5-2
Acceptable Computer Software

5.07.1 GEOPAK

GEOPAK may be used for the hydraulic design of roadside ditches. A GEOPAK Drainage project may contain multiple drainage networks, each comprised of any number of topologically connected drainage areas, inlets, pipes, and ditches. Ditches can be many different shapes including:

- regular shapes such as trapezoidal, rectangular, or triangular
- irregular with shapes based on user input
- geometry extracted from DTM's
- side slope control
- bottom width control
- ditch depth control
- maximum and minimum velocity control

Other computational features include:

- multiple pipe-to-ditch outlets in a single network
- ditch design and analysis
- ability to design or analyze trapezoidal ditches anywhere within a storm drain network
- backwater curve computations for ditch hydraulics
- junction loss options for pipe hydraulic computations

However, GEOPAK does not include stable channel lining analysis. This analysis would have to be evaluated using either one of the software packages listed below or hand computation methods.

5.07.2 HEC-RAS

HEC-RAS was developed by the U.S. Army Corps of Engineers for performing one-dimensional steady or unsteady flow analysis of open channel flow. The software also incorporates the analysis of bridge and culvert crossings. Beginning with version 3.1.1, HEC-RAS incorporates the ability to analyze and design stable channel sections. HEC-RAS should be used for the analysis of natural stream channels impacted by the highway alignment.

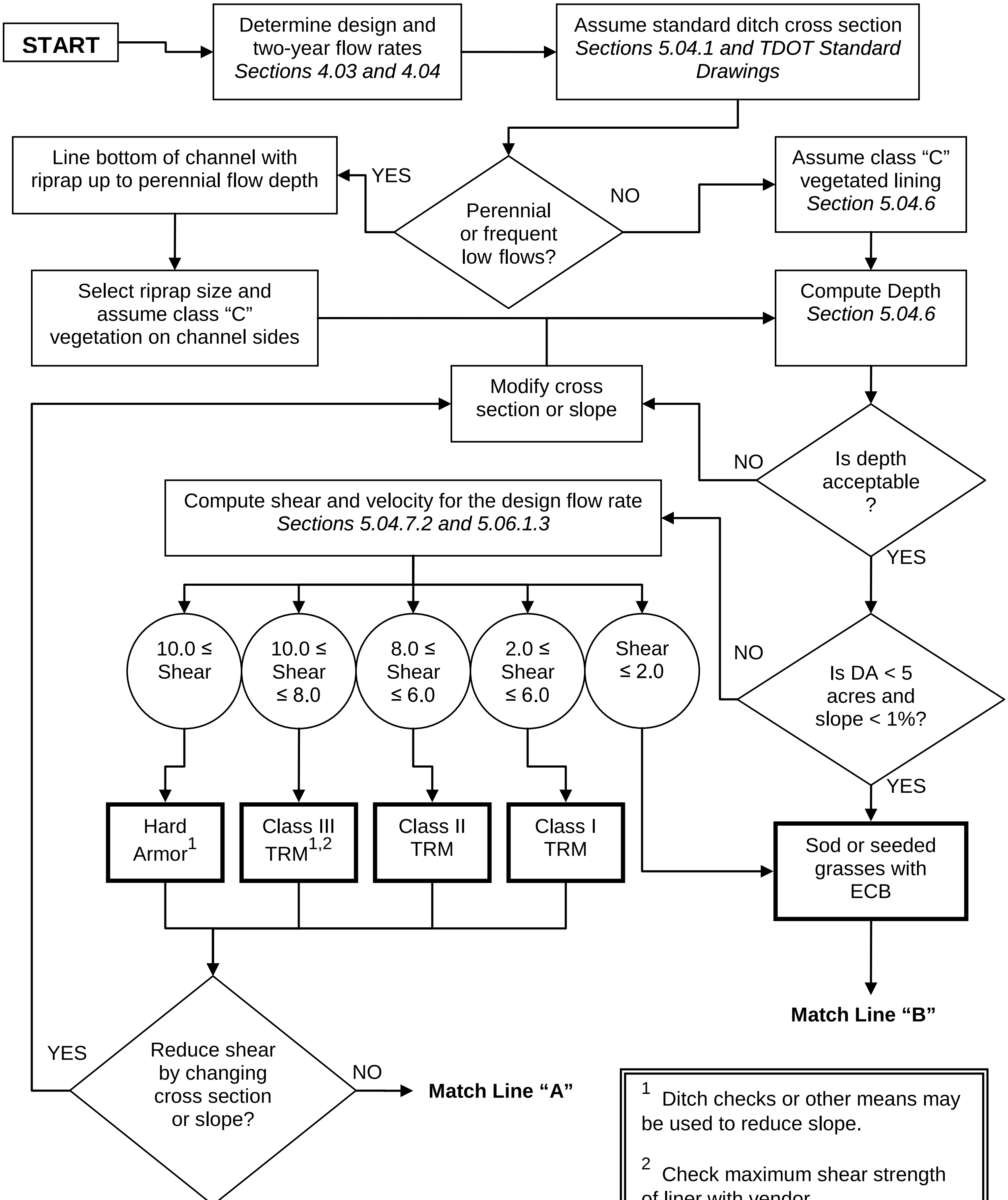
TDOT DESIGN DIVISION

DRAINAGE MANUAL

CHAPTER V
APPENDIX 5A

SECTION 5.08 - APPENDIX

5.08.1 FIGURES AND TABLES



[1] Ditch checks or other means may be used to reduce slope.

[2] Check maximum shear strength of liner with vendor.

Figure 5A-1
Ditch Design Flow Chart

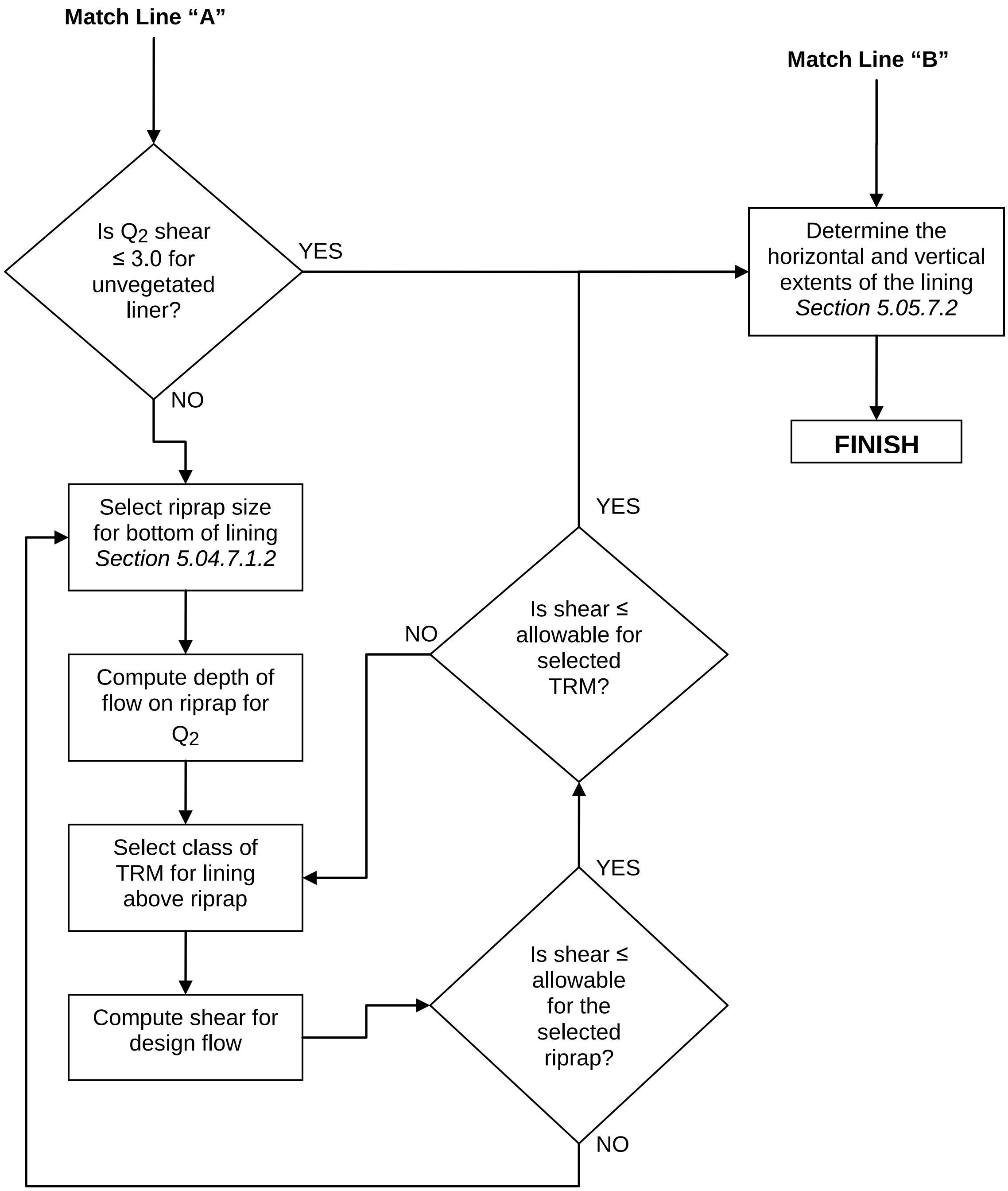


Figure 5A-1 (continued)
Ditch Design Flow Chart

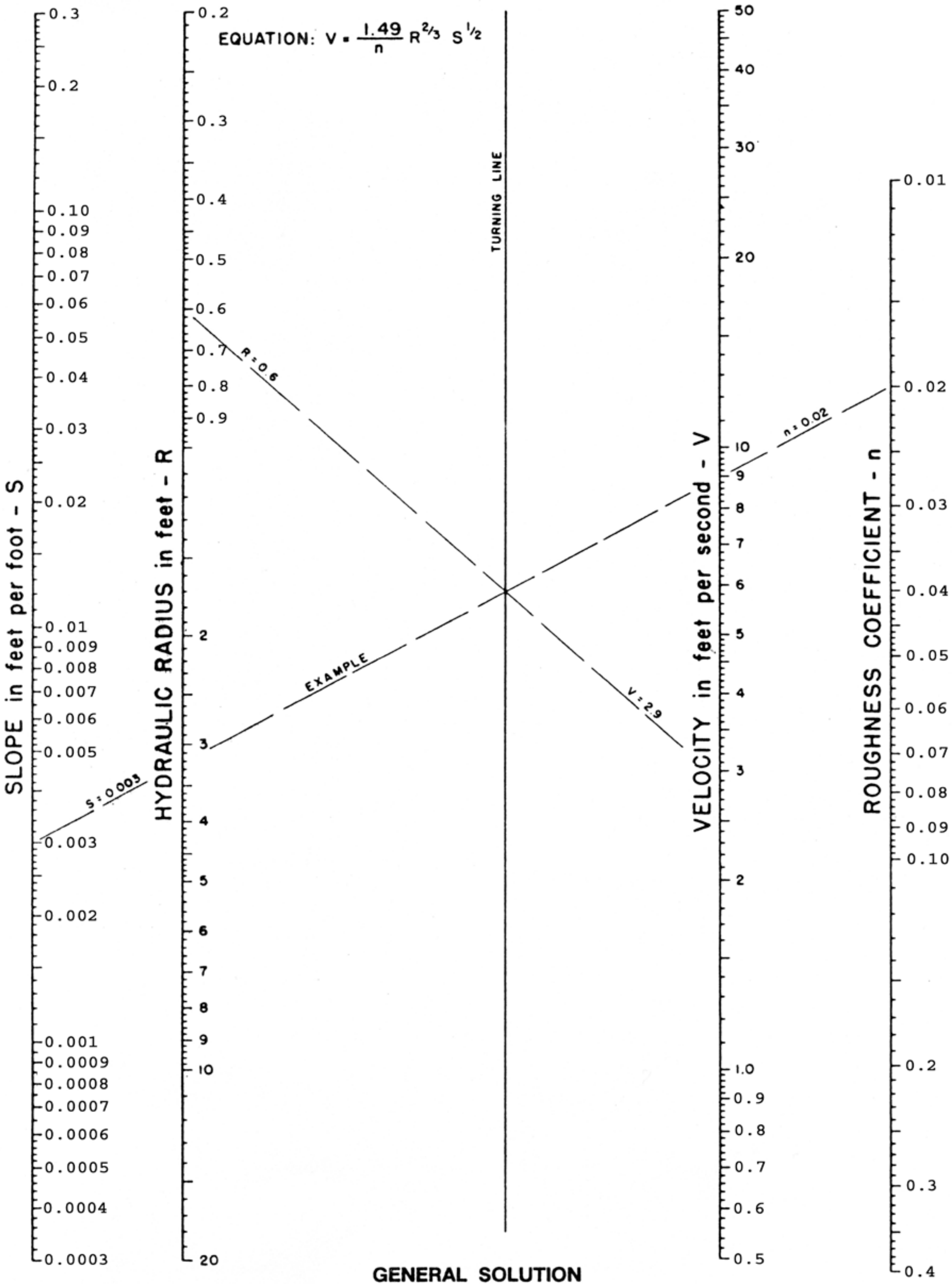


Figure 5A-2
Nomograph for the Solution of Manning's Equation
Reference: USDOT, FHWA, HDS-3 (1961)

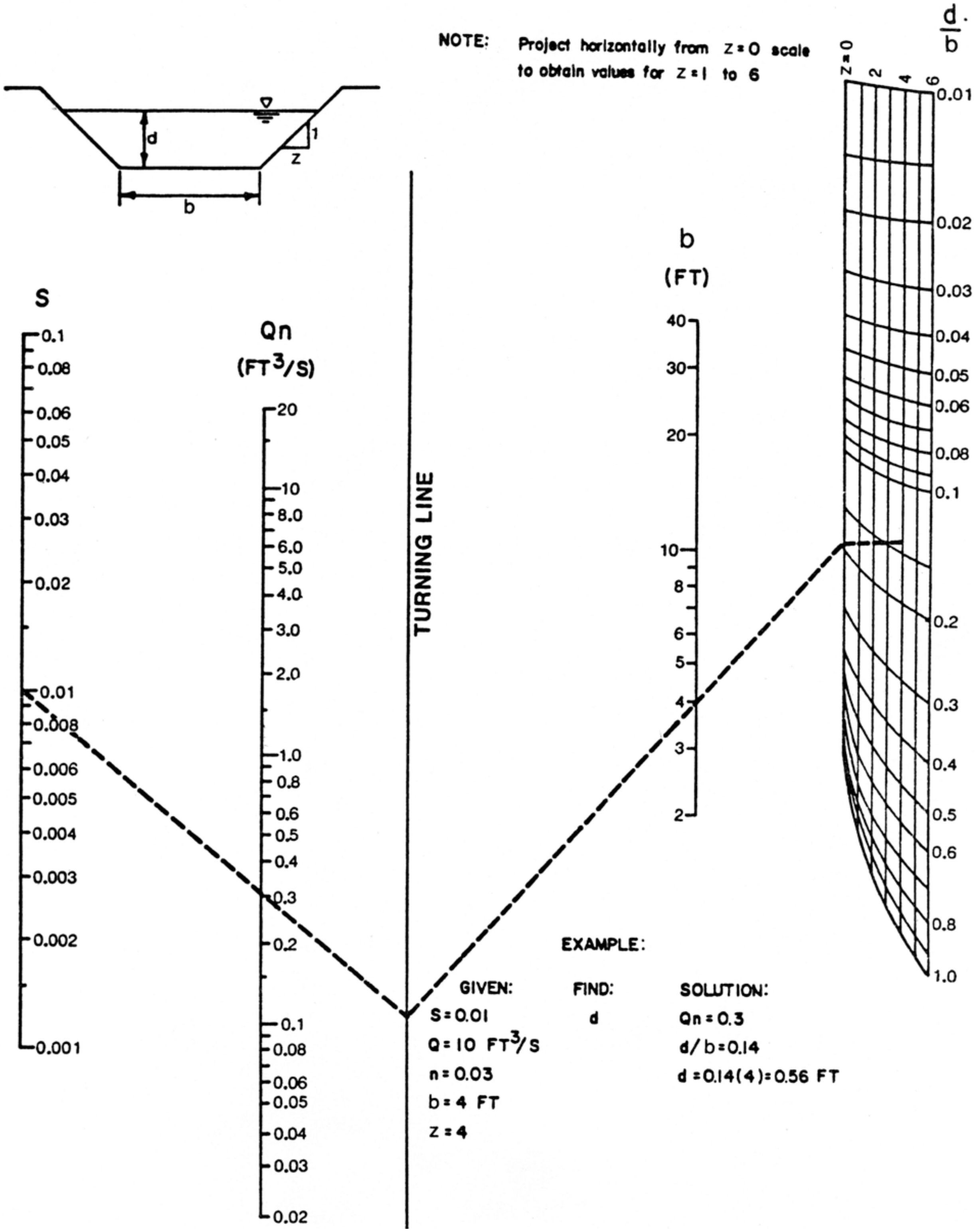


Figure 5A-3
Solution of Manning's Equation for Trapezoidal Channels
Reference: USDOT, FHWA, HEC-15 (1986)

Section	Area A	Wetted Perimeter P	Hydraulic Radius R	Top Width T	Critical Depth Factor, Z
Trapezoid	$bd+zd^2$	$b+2d\sqrt{z^2+1}$	$\frac{bd+zd^2}{b+2d\sqrt{z^2+1}}$	$b+2zd$	$\frac{[(b+zd)d]^{1.5}}{\sqrt{b+2zd}}$
Rectangle	bd	$b+2d$	$\frac{bd}{b+2d}$	b	$bd^{1.5}$
Triangle	zd^2	$2d\sqrt{z^2+1}$	$\frac{zd}{2\sqrt{z^2+1}}$	$2zd$	$\frac{\sqrt{2}}{2}\,zd^{2.5}$
Parabola	$\frac{2}{3}dT$	$T+\frac{8d^2}{3T}$ [1]	$\frac{2dT^2}{3T^2+8d^2}$ [1]	$\frac{3a}{2d}$	$\frac{2}{9}\sqrt{6}\,Td^{1.5}$
Circle - < ½ full [2]	$\frac{D^2}{8}\left(\frac{\pi\theta}{180}-\sin\theta\right)$	$\frac{\pi D\theta}{360}$	$\frac{45D}{\pi\theta}\left(\frac{\pi\theta}{180}-\sin\theta\right)$	$D\sin\frac{\theta}{2}$ or $2\sqrt{d(D-d)}$	$a\sqrt{\frac{a}{D\sin\frac{\theta}{2}}}$
Circle - > ½ full [3]	$\frac{D^2}{8}\left(2\pi-\frac{\pi\theta}{180}+\sin\theta\right)$	$\frac{\pi D(360-\theta)}{360}$	$\frac{45D}{\pi(360-\theta)}\left(2\pi-\frac{\pi\theta}{180}+\sin\theta\right)$	$D\sin\frac{\theta}{2}$ or $2\sqrt{d(D-d)}$	$a\sqrt{\frac{a}{D\sin\frac{\theta}{2}}}$

[1] Satisfactory approximation for the interval $0 < \frac{d}{T} \leq 0.25$
When $d/T > 0.25$, use $p = \frac{1}{2}\sqrt{16d^2+T^2} + \frac{T^2}{8d}\sinh^{-1}\frac{4d}{T}$

[2] $\theta = 4\sin^{-1}\sqrt{d/D}$
[3] $\theta = 4\cos^{-1}\sqrt{d/D}$
Insert θ in degrees in above equations

Note: Small z = Side Slope Horizontal Distance
Large Z = Critical Depth Section Factor

Figure 5A-4
Open Channel Geometric Relationships for Various Cross Sections
Reference: USDA, SCS, NEH-5 (1956)

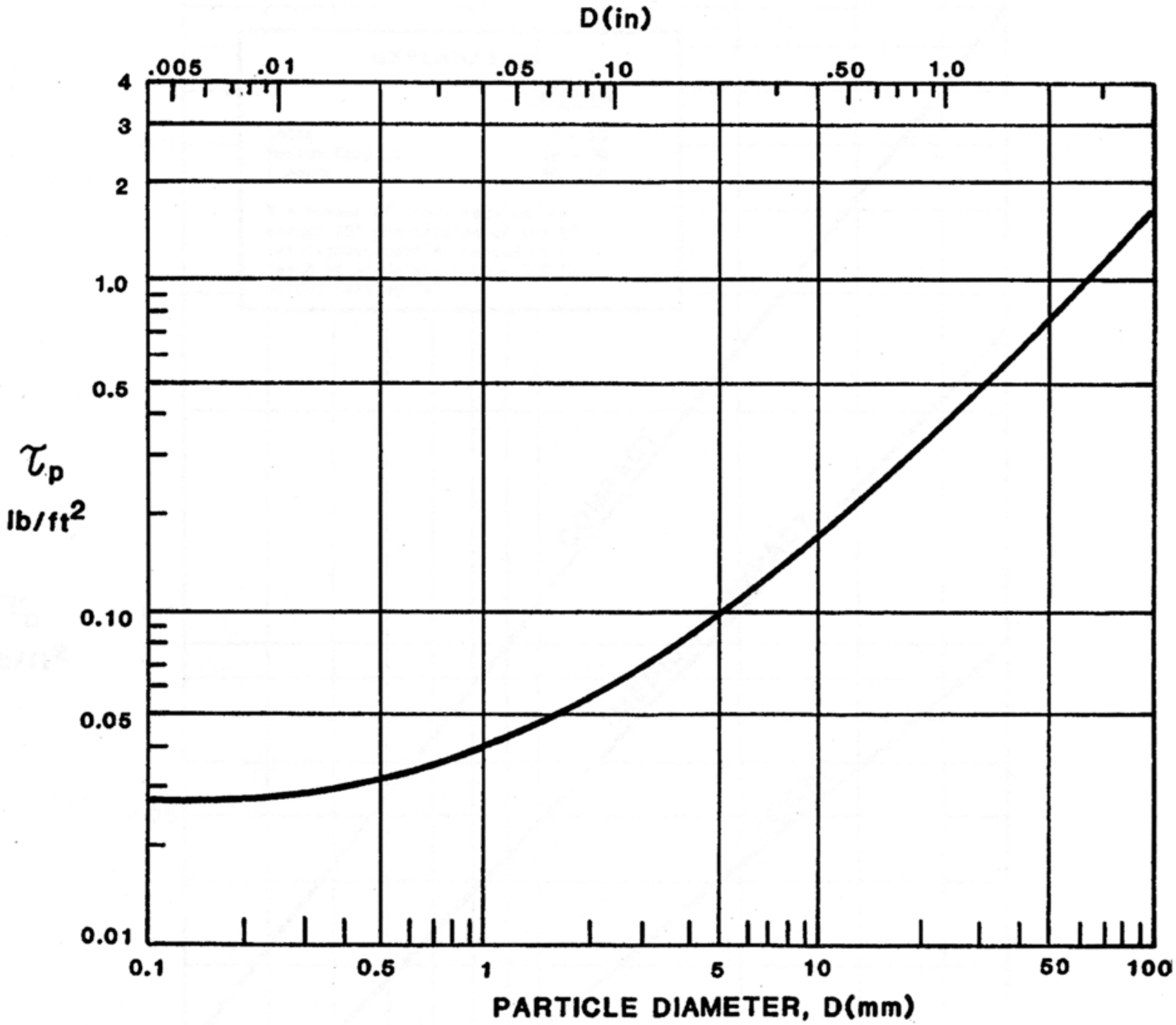


Figure 5A-5
Permissible Shear Stress for Non-cohesive Soils
Reference: USDOT, FHWA, HEC-15 (1988)

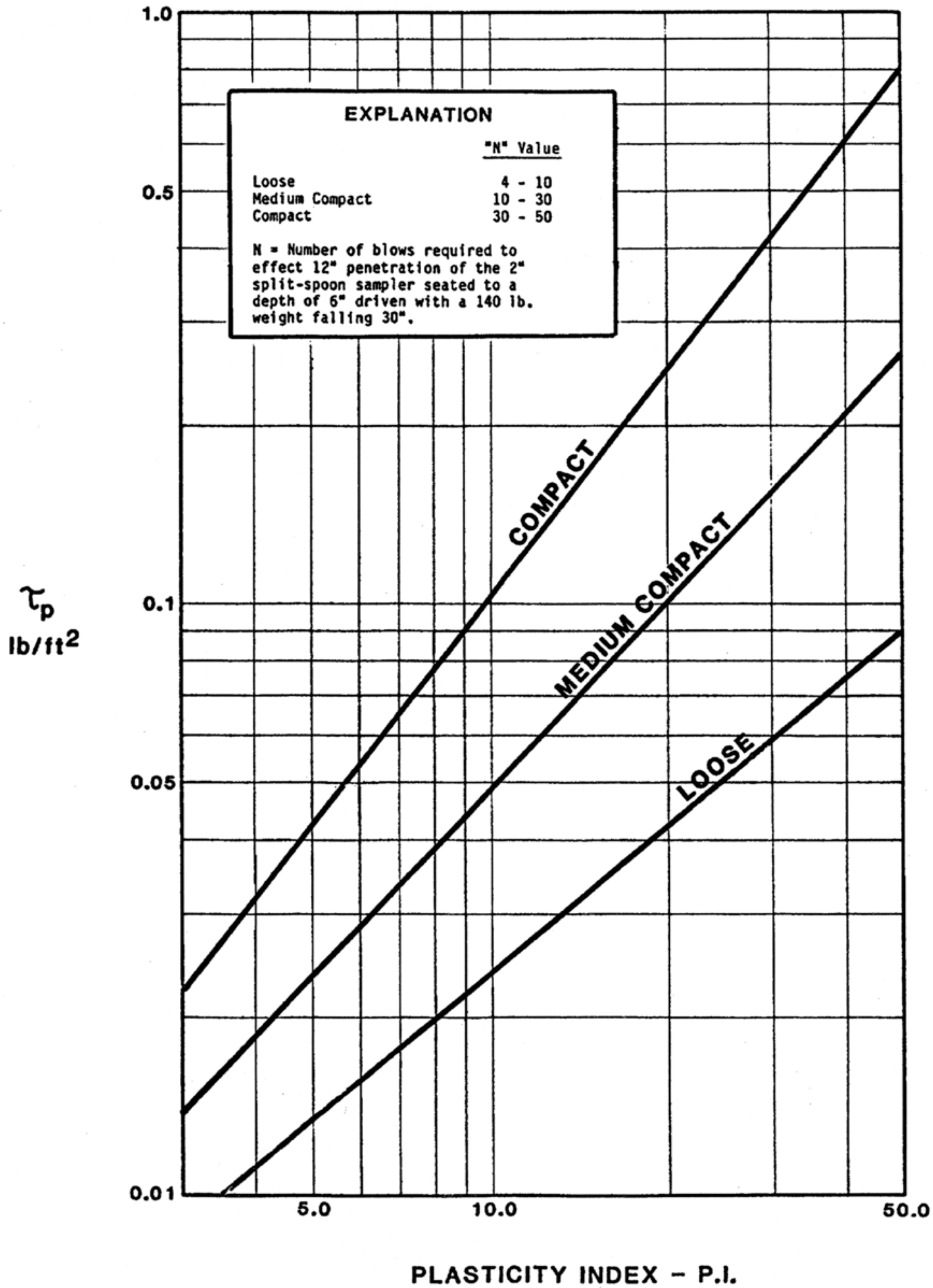


Figure 5A-6
Permissible Shear Stress for Cohesive Soils
Reference: USDOT, FHWA, HEC-15 (1988)

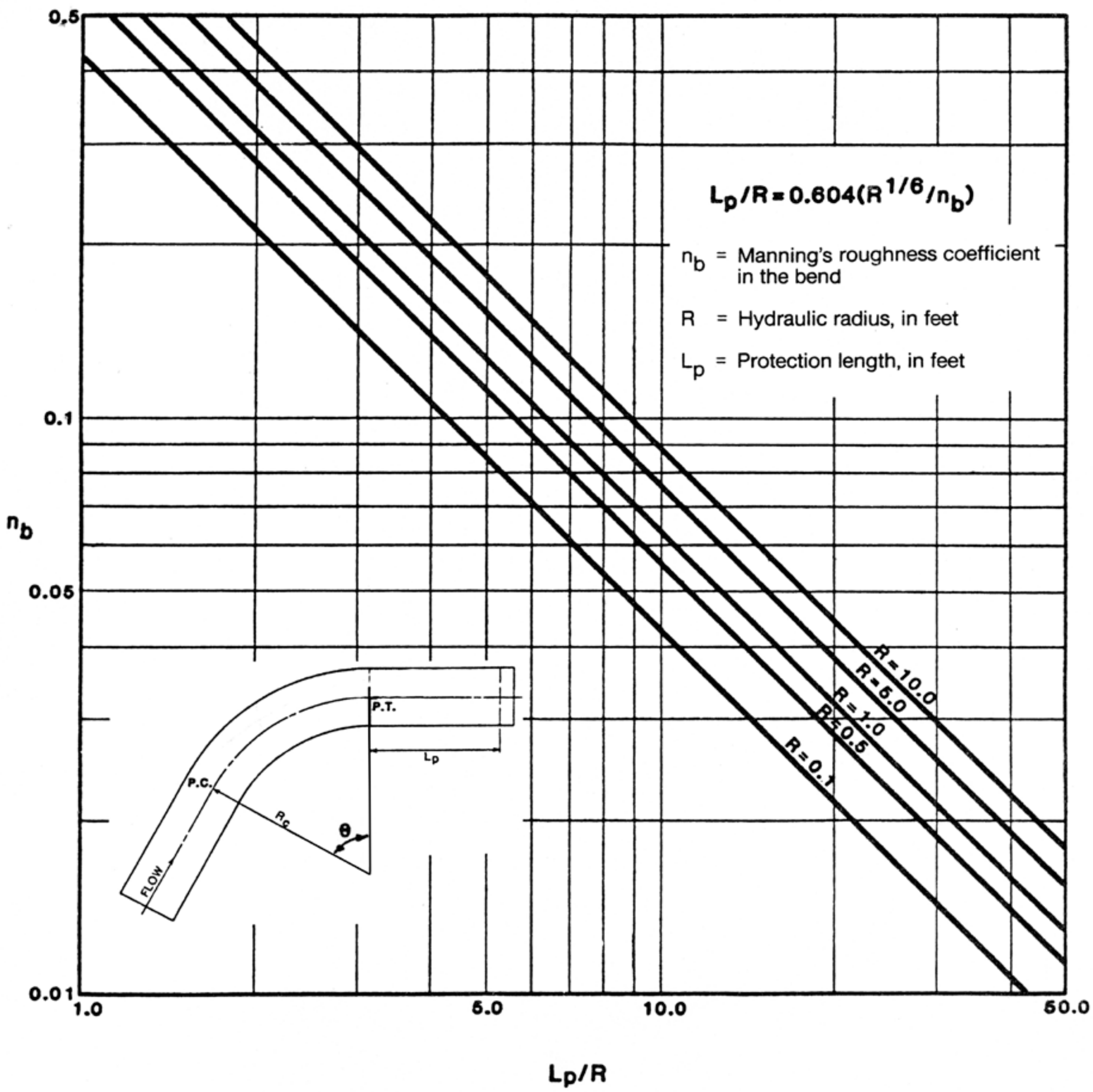


Figure 5A-7
Protection Length, L_p, Downstream of Channel Bend
Reference: USDOT, FHWA, HEC-15 (1988)

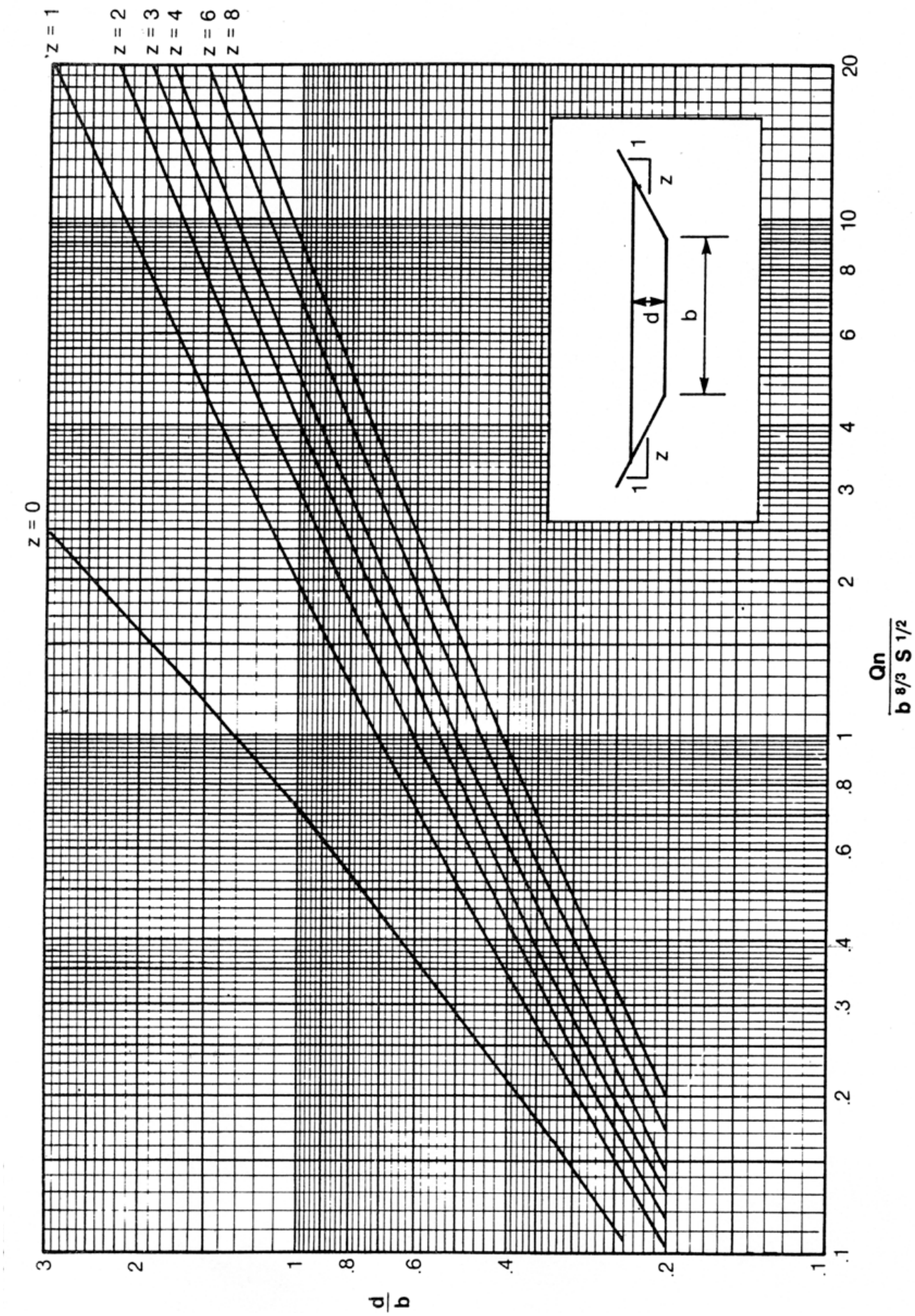


Figure 5A-8
Trapezoidal Channel Capacity Chart
Reference: USDOT, FHWA, HEC-15 (1988)

Type of Channel and Description	Minimum	Normal	Maximum
LINED CHANNELS (Selected Linings)			
a. Concrete			
Trowel Finish	0.011	0.013	0.015
Float Finish	0.013	0.015	0.016
Gunite, good section	0.016	0.019	0.023
b. Asphalt			
Smooth	0.013	0.013	-
Rough	0.016	0.016	-
EXCAVATED OR DREDGED			
a. Earth, straight and uniform			
Clean, recently completed	0.016	0.018	0.020
Clean, after weathering	0.018	0.022	0.025
Gravel, uniform section, clean	0.022	0.025	0.030
With short grass, few weeds	0.022	0.027	0.033
b. Earth, winding and sluggish			
No vegetation	0.023	0.025	0.030
Grass, some weeds	0.025	0.030	0.033
Dense weeds or aquatic plants in deep channels	0.030	0.035	0.040
Earth bottom and rubble sides	0.025	0.030	0.035
Stony bottom and weedy sides	0.025	0.035	0.045
Cobble bottom and clean sides	0.030	0.040	0.050
c. Dragline excavated or dredged			
No vegetation	0.025	0.028	0.033
Light brush on banks	0.035	0.050	0.060
d. Rock Cuts			
Smooth and uniform	0.025	0.035	0.040
Jagged and irregular	0.035	0.040	0.050
e. Channels not maintained, uncut weeds and brush			
Dense weeds as high as flow depth	0.050	0.080	0.120
Clean bottom, brush on sides	0.040	0.050	0.080
Same, highest stage of flow	0.045	0.070	0.110
Dense brush, high stage	0.800	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 and weeds	0.030	0.035	0.040
3. Clean, winding, some pools and shoals	0.033	0.040	0.045
4. Same as above, but some weeds and stones	0.035	0.045	0.050
5. Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055

Table 5A-1
Values of Roughness
Coefficient ‘n’ (Uniform Flow)
Reference: Chow, Ven T., *Open Channel Hydraulics* (1959)

Continue on following page

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
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
b. 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 2, 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 4, 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

Table 5A-1 (continued)
Values of Roughness
Coefficient ‘n’ (Uniform Flow)
Reference: Chow, Ven T., *Open Channel Hydraulics* (1959)

Description		Condition	Criteria	Value
n_o	Material Involved	Earth		0.020
		Rock Cut		0.025
		Fine Gravel		0.024
		Coarse Gravel		0.028
n_1	Degree of Irregularity	Smooth	Dredged, no erosion	0.000
		Minor	Dredge, slightly eroded	0.005
		Moderate	Moderately eroded and natural streams	0.010
		Severe	Badly eroded or sloughed sides	0.020
n_2	Variation in Channel Cross Section	Gradual	Gradual change, channel centered	0.000
		Occasional	Main flow occasionally changes from small to large sections	0.005
		Frequent	Main flow frequently changes in cross-sectional shape	0.010 – 0.015
n_3	Effect of Obstructions	Negligible	Few to no snags or debris	0.000
		Minor	Smooth obstructions, channel slightly encroached	0.010 – 0.015
		Appreciable	Woody debris, channel significantly encroached	0.020 – 0.030
		Severe	Channel entirely blocked with woody and other debris	0.040 – 0.060
n_4	Vegetation	Low	Long, flexible grasses, few small willows	0.005 – 0.010
		Medium	Stemmy or tall grasses, moderate brush	0.010 – 0.025
		High	Tall grasses equal to depth, mature willows with brush	0.025 – 0.050
		Very High	Tall grasses above depth, trees and brush, cattails	0.050 – 0.100
m_5	Degree of Sinuosity	Minor	Sinuosity < 1.2	1.000
		Appreciable	Sinuosity 1.2 to 1.5	1.150
		Severe	Sinuosity > 1.5	1.300

Table 5A-2
Coefficients for Computing Manning's n-Values
for Natural or Excavated Channels Using Cowan's Equation
Reference: Chow, Ven T., *Open Channel Hydraulics* (1959), Table 5-5, p. 109

Material	Maximum Velocity (feet/second)
Bare Soil	
Silt or fine sand	1.5
Sandy loam	1.75
Silt loam	2
Stiff clay	3.75
Ordinary firm loam	2.5
Fine gravel	2.5
Graded, loam to cobbles (noncolloidal)	3.7
Graded, silt to cobbles (colloidal)	4
Alluvial Silts (noncolloidal)	2
Alluvial Silts (colloidal)	3.7
Coarse gravel (noncolloidal)	4
Cobbles and shingles	5
Shales and hard pans	6
Sod	4
Lapped Sod	5.5
Vegetation	See Table 5A-5
Rigid	10

Table 5A-3
Maximum Velocities for Comparing Lining Materials
Reference: USDOT, FHWA, HDS-3 (1961) &
USDA, SCS, TP-61 (March, 1947)

Quality of Stand	**Average Length of Vegetation**	**Retardance Class**
Good	Longer than 30 inches	A
	11 to 24 inches	B
	6 to 10 inches	C
	2 to 6 inches	D
	Less than 2 inches	E
Fair	Longer than 30 inches	B
	11 to 24 inches	C
	6 to 10 inches	D
	2 to 6 inches	D
	Less than 2 inches	E

Table 5A-4
Guide to Selection of Vegetal Retardance
Reference: USDA, SCS, TP-61 (March, 1947)

Vegetation Type	Exit Channel Slope Range (%)	Maximum Velocity [1] (feet/second)
Bermudagrass	0 – 5	6
	5 – 10	5
	over 10	4
Kentucky Bluegrass, Buffalo grass, Smooth Brome	0 – 5	5
	5 – 10	4
	over 10	3
Grass Mixture	0 – 5	4
	5 – 10	3
Lespedeza Sericea, Kudzu, Alfalfa, Crabgrass	0 – 5	2.5
Common Lespedeza [2,3] Sudangrass	0 - 5	2.5

[1] Based on erosive soils

[2] Annuals used on mild slopes or as temporary protection until permanent cover is established

[3] Use on slopes steeper than 5 percent is not recommended

Table 5A-5
Maximum Velocities for Vegetative Channel Linings
Reference: USDA, SCS, TP-61 (March, 1947)

		Depth Ranges [a]		
Lining Category	**Lining Type**	**0 - 0.5 ft**	**0.5 - 2.0 ft**	**> 2.0 ft**
Rigid	Concrete (Broom or Float Finish)	0.015	0.013	0.013
	Gunite	0.022	0.02	0.02
	Grouted Riprap	0.04	0.03	0.028
	Stone Masonry	0.042	0.032	0.03
	Soil Cement	0.025	0.022	0.02
	Asphalt	0.018	0.016	0.016
Unlined	Bare Soil	0.023	0.02	0.02
	Rock Cut	0.035	0.035	0.025
Erosion Control Blankets [b]	Type I	0.055	0.055 - 0.021	0.021
	Type II	0.055	0.055 - 0.021	0.021
	Type III	0.055	0.055 - 0.021	0.021
	Type IV	0.022	0.022 - 0.014	0.014
Turf Reinforcement Mats [b]	Unvegetated	0.04	0.04 - 0.015	0.015
Machined Riprap [c,d]	Class A1	0.124	0.072	0.038
	Class B	0.153	0.086	0.041
	Class C	0.181	0.095	0.042

[a] Values listed are representative values for the respective depth ranges. Manning's roughness coefficients vary with the flow depth

[b] General values based on vendor information. Consult with individual vendors for more specific information

[c] Values interpolated from data provided in HEC-15

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

Table 5A-6
Recommended Manning's n-Values for Artificial Channels
References: USDOT, FHWA, HEC-15 (1988) &
North American Green, Evansville, Indiana

		Permissible Unit Shear Stress	
Lining Category	**Lining Type**	**(lb/ft^2)**	**(Pa)**
Erosion Control Blanket [a]	Type I	1.5	72
	Type II	1.75	84
	Type III	2.00	96
	Type IV	2.25	108
Turf Reinforcement Mat [a]	Unvegetated	3.0	143.6
	Class I	6.0	288
	Class II	8.0	384
	Class III	10.0	480
Grass [b]	Class A	3.70	177.2
	Class B	2.10	100.5
	Class C	1.00	47.9
	Class D	0.60	28.7
	Class E	0.35	16.8
Rock Riprap	Class A1	3.00	143.6
	Class B	5.00	239.4
	Class C	6.70	320.8
Bare Soil	Non-cohesive	(See Hydraulic Engineering Circular No. 15)	
	Cohesive		

[a] General values based on vendor information, assuming a vegetated condition. Maximum permissible shear stress for an unvegetated mat is 3.0 lb/ft^2)
Consult with individual vendors for more specific information.

[b] Grassed linings are classified into 5 vegetal retardance classifications
See Section 5.04.6.1 and Table 5A-4

Table 5A-7
Permissible Shear Stresses for Lining Materials
Reference: USDOT, FHWA, HDS-4 (2001) &
Erosion Control Technology Council, St. Paul, Minnesota

Hydraulic Radius (feet)	Ditch Slope (Decimal) Note Minimum allowable slope is 0.004										
	0.001	**0.002**	**0.004**	**0.006**	**0.008**	**0.01**	**0.02**	**0.04**	**0.06**	**0.08**	**0.10**
0.6											0.571
0.8								0.501	0.289	0.223	0.189
1.0							0.449	0.216	0.166	0.142	0.128
1.5			0.682	0.360	0.269	0.225	0.150	0.112	0.098	0.089	0.084
2.0		0.422	0.222	0.174	0.150	0.136	0.105	0.086	0.078	0.073	O.069
2.5	0.393	0.217	0.150	0.127	0.114	0.106	0.087	0.074	0.068	0.064	0.062
3.0	0.232	0.158	0.120	0.105	0.097	0.091	0.077	0.067	0.062	0.059	0.057
3.5	0.175	0.130	0.104	0.093	0.086	0.082	0.071	0.062	0.058	0.055	0.054
4.0	0.145	0.114	0.093	0.085	0.079	0.076	0.066	0.059	0.055	0.053	0.051
4.5	0.127	0.103	0.086	0.079	0.074	0.071	0.063	0.056	0.053	0.051	0.049
5.0	0.115	0.095	0.081	0.074	0.070	0.068	0.060	0.054	0.051	0.049	0.048
6.0	0.099	0.084	0.073	0.068	0.065	0.062	0.056	0.051	0.048	0.047	0.046
7.0	0.089	0.077	0.068	0.064	0.061	0.059	0.053	0.049	0.047	0.045	0.044
8.0	0.083	0.073	0.065	0.061	0.058	0.056	0.051	0.047	0.045	0.044	0.043
9.0	0.078	0.069	0.062	0.058	0.056	0.054	0.050	0.046	0.044	0.043	0.042
10.0	0.074	0.066	0.060	0.056	0.054	0.053	0.049	0.045	0.043	0.042	0.041

Table 5A-8
Solutions of Equation 5-14 for n-Values in Ditches with Vegetative Linings
Retardance Class "A" $C_{rf} = 15.8$

Hydraulic Radius (feet)	Ditch Slope (Decimal) Note Minimum allowable slope is 0.004										
	0.001	0.002	0.004	0.006	0.008	0.01	0.02	0.04	0.06	0.08	0.10
0.4									0.406	0.276	0.221
0.6							0.285	0.163	0.131	0.114	0.104
0.8			0.848	0.379	0.272	0.223	0.143	0.106	0.091	0.084	0.078
1.0		0.694	0.260	0.190	0.160	0.142	0.106	0.085	0.076	0.070	0.067
1.5	0.270	0.168	0.122	0.105	0.096	0.090	0.075	0.064	0.059	0.056	0.054
2.0	0.151	0.114	0.092	0.082	0.077	0.073	0.063	0.055	0.052	0.050	0.048
2.5	0.115	0.093	0.078	0.071	0.067	0.064	0.057	0.051	0.048	0.046	0.045
3.0	0.097	0.081	0.070	0.065	0.061	0.059	0.053	0.048	0.045	0.044	0.042
3.5	0.086	0.074	0.065	0.060	0.057	0.055	0.050	0.046	0.043	0.042	0.041
4.0	0.079	0.069	0.061	0.057	0.055	0.053	0.048	0.044	0.042	0.041	0.040
4.5	0.074	0.065	0.058	0.055	0.052	0.051	0.046	0.043	0.041	0.040	0.039
5.0	0.070	0.062	0.056	0.053	0.051	0.049	0.045	0.042	0.040	0.039	0.038
6.0	0.065	0.058	0.053	0.050	0.048	0.047	0.043	0.040	0.039	0.037	0.037
7.0	0.061	0.055	0.050	0.048	0.046	0.045	0.042	0.039	0.038	0.037	0.036
8.0	0.058	0.053	0.049	0.046	0.045	0.044	0.041	0.038	0.037	0.036	0.035
9.0	0.056	0.051	0.047	0.045	0.044	0.043	0.040	0.037	0.036	0.035	0.035
10.0	0.054	0.050	0.046	0.044	0.043	0.042	0.039	0.037	0.036	0.035	0.034

Table 5A-9
Solutions of Equation 5-14 for n-Values in Ditches with Vegetative Linings
Retardance Class “B” $C_{rf} = 23.0$

Hydraulic Radius (feet)	Ditch Slope (Decimal) Note Minimum allowable slope is 0.004										
	0.001	0.002	0.004	0.006	0.008	0.01	0.02	0.04	0.06	0.08	0.10
0.2									0.852	0.403	0.286
0.4				0.647	0.369	0.277	0.156	0.109	0.092	0.083	0.077
0.6		0.377	0.190	0.147	0.127	0.114	0.088	0.072	0.065	0.060	0.057
0.8	0.273	0.162	0.116	0.099	0.090	0.084	0.069	0.059	0.054	0.051	0.049
1.0	0.160	0.116	0.091	0.080	0.074	0.070	0.060	0.053	0.049	0.047	0.045
1.5	0.096	0.079	0.067	0.062	0.058	0.056	0.050	0.045	0.042	0.041	0.039
2.0	0.077	0.066	0.058	0.054	0.051	0.050	0.045	0.041	0.039	0.038	0.037
2.5	0.067	0.059	0.053	0.049	0.047	0.046	0.042	0.039	0.037	0.036	0.035
3.0	0.061	0.055	0.049	0.047	0.045	0.044	0.040	0.037	0.036	0.035	0.034
3.5	0.057	0.052	0.047	0.045	0.043	0.042	0.039	0.036	0.035	0.034	0.033
4.0	0.055	0.049	0.045	0.043	0.042	0.041	0.038	0.035	0.034	0.033	0.032
4.5	0.052	0.048	0.044	0.042	0.041	0.040	0.037	0.034	0.033	0.032	0.032
5.0	0.051	0.046	0.043	0.041	0.040	0.039	0.036	0.034	0.033	0.032	0.031
6.0	0.048	0.044	0.041	0.039	0.038	0.037	0.035	0.033	0.032	0.031	0.031
7.0	0.046	0.043	0.040	0.038	0.037	0.037	0.034	0.032	0.031	0.031	0.030
8.0	0.045	0.042	0.039	0.038	0.037	0.036	0.034	0.032	0.031	0.030	0.030
9.0	0.044	0.041	0.038	0.037	0.036	0.035	0.033	0.032	0.031	0.030	0.029
10.0	0.043	0.040	0.038	0.036	0.035	0.035	0.033	0.031	0.030	0.030	0.029

Table 5A-10
Solutions of Equation 5-14 for n-Values in Ditches with Vegetative Linings
Retardance Class “C” C_{rf} = 30.2

Hydraulic Radius (feet)	Ditch Slope (Decimal) Note Minimum allowable slope is 0.004										
	0.001	0.002	0.004	0.006	0.008	0.01	0.02	0.04	0.06	0.08	0.10
0.2							0.514	0.197	0.144	0.121	0.108
0.4		0.448	0.199	0.150	0.128	0.114	0.087	0.070	0.063	0.058	0.055
0.6	0.207	0.134	0.099	0.086	0.079	0.074	0.062	0.053	0.049	0.047	0.045
0.8	0.122	0.093	0.076	0.068	0.064	0.061	0.053	0.046	0.044	0.042	0.040
1.0	0.094	0.077	0.065	0.059	0.056	0.054	0.048	o.043	0.040	0.039	0.038
1.5	0.069	0.060	0.053	0.049	0.047	0.045	0.041	0.038	0.036	0.035	0.034
2.0	0.059	0.052	0.047	0.044	0.043	0.042	0.038	0.035	0.034	0.033	0.032
2.5	0.054	0.048	0.044	0.042	0.040	0.039	0.036	0.034	0.032	0.032	0.031
3.0	0.050	0.046	0.042	0.040	0.039	0.038	0.035	0.033	0.031	0.031	0.030
3.5	0.048	0.044	0.040	0.038	0.037	0.036	0.034	0.032	0.031	0.030	0.029
4.0	0.046	0.042	0.039	0.037	0.036	0.036	0.033	0.031	0.030	0.030	0.029
4.5	0.044	0.041	0.038	0.037	0.036	0.035	0.033	0.031	0.030	0.029	0.029
5.0	0.043	0.040	0.037	0.036	0.035	0.034	0.032	0.030	0.029	0.029	0.028
6.0	0.042	0.039	0.036	0.035	0.034	0.033	0.032	0.030	0.029	0.028	0.028
7.0	0.040	0.038	0.035	0.034	0.033	0.033	0.031	0.029	0.029	0.028	0.028
8.0	0.039	0.037	0.035	0.034	0.033	0.032	0.031	0.029	0.028	0.028	0.027
9.0	0.039	0.036	0.034	0.033	0.032	0.032	0.030	0.029	0.028	0.027	0.027
10.0	0.038	0.036	0.034	0.033	0.032	0.032	0.030	0.029	0.028	0.027	0.027

Table 5A-11
Solutions of Equation 5-14 for n-Values in Ditches with Vegetative Linings
Retardance Class “D” $C_{rf} = 34.6$

Hydraulic Radius (feet)	Ditch Slope (Decimal) Note Minimum allowable slope is 0.004										
	0.001	0.002	0.004	0.006	0.008	0.01	0.02	0.04	0.06	0.08	0.10
0.1										0.695	0.388
0.2					0.543	0.350	0.167	0.109	0.091	0.081	0.075
0.4	0.329	0.171	0.116	0.097	0.087	0.081	0.066	0.056	0.051	0.048	0.046
0.6	0.122	0.092	0.074	0.067	0.062	0.059	0.051	0.045	0.042	0.040	0.039
0.8	0.087	0.072	0.061	0.056	0.053	0.051	0.045	0.040	0.038	0.037	0.036
1.0	0.073	0.062	0.054	0.050	0.048	0.046	0.041	0.038	0.036	0.035	0.034
1.5	0.057	0.051	0.046	0.043	0.041	0.040	0.037	0.034	0.033	0.032	0.031
2.0	0.051	0.046	0.042	0.040	0.038	0.037	0.034	0.032	0.031	0.030	0.029
2.5	0.047	0.043	0.039	0.037	0.036	0.035	0.033	0.031	0.030	0.029	0.029
3.0	0.044	0.041	0.038	0.036	0.035	0.034	0.032	0.030	0.029	0.028	0.028
3.5	0.043	0.039	0.037	0.035	0.034	0.033	0.031	0.030	0.029	0.028	0.027
4.0	0.041	0.038	0.036	0.034	0.033	0.033	0.031	0.029	0.028	0.028	0.027
4.5	0.040	0.037	0.035	0.034	0.033	0.032	0.030	0.029	0.028	0.027	0.027
5.0	0.039	0.037	0.034	0.033	0.032	0.032	0.030	0.028	0.028	0.027	0.027
6.0	0.038	0.036	0.033	0.032	0.032	0.031	0.029	0.028	0.027	0.027	0.026
7.0	0.037	0.035	0.033	0.032	0.031	0.030	0.029	0.028	0.027	0.026	0.026
8.0	0.036	0.034	0.032	0.031	0.031	0.030	0.029	0.027	0.027	0.026	0.026
9.0	0.036	0.034	0.032	0.031	0.030	0.030	0.028	0.027	0.026	0.026	0.026
10	0.035	0.033	0.032	0.031	0.030	0.030	0.028	0.027	0.026	0.026	0.025

Table 5A-12
Solutions of Equation 5-14 for n-Values in Ditches with Vegetative Linings
Retardance Class "E" C_{rf} = 37.7

Flow (cfs)	Increasing Ditch Slope (ft/ft) →									
	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10
5	SOD	SOD	SOD	SOD	SOD	I	I	I	I	I
6	SOD	SOD	SOD	SOD	I	I	I	I	I	I
8	SOD	SOD	SOD	I	I	I	I	I	I	I
10	SOD	SOD	SOD	I	I	I	I	I	I	I
15	SOD	SOD	I	I	I	I	I	I	I	I
20	SOD	SOD	I	I	I	I	I	I	I	I
25	SOD	SOD	I	I	I	I	I	I	I	I
30	SOD	SOD	I	I	I	I	I	I	I	II
40	SOD	I	I	I	I	I	I	I	II	II
50	SOD	I	I	I	I	I	I	II	II	II
60	SOD	I	I	I	I	I	II	II	II	III
70	SOD	I	I	I	I	I	II	II	III	III
80	SOD	I	I	I	I	II	II	II	III	III
90	SOD	I	I	I	I	II	II	III	III	III
100	SOD	I	I	I	I	II	II	III	III	III
120	SOD	I	I	I	II	II	III	III	III	HARD
140	SOD	I	I	I	II	II	III	III	HARD	HARD
160	I	I	I	I	II	III	III	III	HARD	HARD
180	I	I	I	II	II	III	III	HARD	HARD	HARD
200	I	I	I	II	II	III	III	HARD	HARD	HARD
250	I	I	I	II	III	III	HARD	HARD	HARD	HARD
300	I	I	I	II	III	HARD	HARD	HARD	HARD	HARD
350	I	I	II	II	III	HARD	HARD	HARD	HARD	HARD
400	I	I	II	III	III	HARD	HARD	HARD	HARD	HARD
450	I	I	II	III	HARD	HARD	HARD	HARD	HARD	HARD
500	I	I	II	III	HARD	HARD	HARD	HARD	HARD	HARD

Notes:

[1] A "vee" ditch with a rounded bottom my be considered a trapezoidal ditch with bottom width equal to the width of the rounding. Side slopes are assumed to be 3:1. The recommendations provided by this table may be relaxed for flatter side slopes.

[2] The following codes designate the recommended type of ditch liner:

"Sod" = Sod or seeded liner with erosion control blanket
"I" = Class I Turf Reinforcement Mat
"II" = Class II Turf Reinforcement Mat
"III" = Class III Turf Reinforcement Mat
"Hard" = Hard armoring with riprap or concrete[3]

[3] The designer should consider using ditch checks or other means to reduce the ditch slope.

Table 5A-13
Vegetated Liner Selection for a Trapezoidal[1] Ditch with a Bottom Width of 2 Feet

Flow	Increasing Ditch Slope (ft/ft) →									
(cfs)	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10
5	SOD	SOD	SOD	SOD	SOD	SOD	I	I	I	I
6	SOD	SOD	SOD	SOD	SOD	SOD	I	I	I	I
8	SOD	SOD	SOD	SOD	SOD	I	I	I	I	I
10	SOD	SOD	SOD	SOD	I	I	I	I	I	I
15	SOD	SOD	SOD	I	I	I	I	I	I	I
20	SOD	SOD	SOD	I	I	I	I	I	I	I
25	SOD	SOD	I	I	I	I	I	I	I	I
30	SOD	SOD	I	I	I	I	I	I	I	I
40	SOD	SOD	I	I	I	I	I	I	I	I
50	SOD	I	I	I	I	I	I	I	I	II
60	SOD	I	I	I	I	I	I	I	II	II
70	SOD	I	I	I	I	I	I	II	II	II
80	SOD	I	I	I	I	I	I	II	II	II
90	SOD	I	I	I	I	I	II	II	II	III
100	SOD	I	I	I	I	I	II	II	II	III
120	SOD	I	I	I	I	II	II	II	III	III
140	SOD	I	I	I	I	II	II	III	III	III
160	SOD	I	I	I	II	II	II	III	III	HARD
180	SOD	I	I	I	II	II	III	III	HARD	HARD
200	I	I	I	I	II	II	III	III	HARD	HARD
250	I	I	I	II	II	III	III	HARD	HARD	HARD
300	I	I	I	II	III	III	HARD	HARD	HARD	HARD
350	I	I	I	II	III	III	HARD	HARD	HARD	HARD
400	I	I	II	II	III	HARD	HARD	HARD	HARD	HARD
450	I	I	II	II	III	HARD	HARD	HARD	HARD	HARD
500	I	I	II	III	III	HARD	HARD	HARD	HARD	HARD

Notes:

[1] A "vee" ditch with a rounded bottom my be considered a trapezoidal ditch with bottom width equal to the width of the rounding. Side slopes are assumed to be 3:1. The recommendations provided by this table may be relaxed for flatter side slopes.

[2] The following codes designate the recommended type of ditch liner:

- "Sod" = Sod or seeded liner with erosion control blanket
- "I" = Class I Turf Reinforcement Mat
- "II" = Class II Turf Reinforcement Mat
- "III" = Class III Turf Reinforcement Mat
- "Hard" = Hard armoring with riprap or concrete[3]

[3] The designer should consider using ditch checks or other means to reduce the ditch slope.

Table 5A-14
Vegetated Liner Selection for a Trapezoidal[1] Ditch with a Bottom Width of 4 Feet

Flow	Increasing Ditch Slope (ft/ft) →									
(cfs)	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10
5	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	I	I
6	SOD	SOD	SOD	SOD	SOD	SOD	SOD	I	I	I
8	SOD	SOD	SOD	SOD	SOD	SOD	I	I	I	I
10	SOD	SOD	SOD	SOD	SOD	SOD	I	I	I	I
15	SOD	SOD	SOD	SOD	I	I	I	I	I	I
20	SOD	SOD	SOD	SOD	I	I	I	I	I	I
25	SOD	SOD	SOD	I	I	I	I	I	I	I
30	SOD	SOD	SOD	I	I	I	I	I	I	I
40	SOD	SOD	I	I	I	I	I	I	I	I
50	SOD	SOD	I	I	I	I	I	I	I	I
60	SOD	SOD	I	I	I	I	I	I	I	I
70	SOD	I	I	I	I	I	I	I	I	II
80	SOD	I	I	I	I	I	I	I	II	II
90	SOD	I	I	I	I	I	I	II	II	II
100	SOD	I	I	I	I	I	I	II	II	II
120	SOD	I	I	I	I	I	II	II	II	III
140	SOD	I	I	I	I	I	II	II	III	III
160	SOD	I	I	I	I	II	II	II	III	III
180	SOD	I	I	I	I	II	II	III	III	III
200	SOD	I	I	I	II	II	II	III	III	HARD
250	I	I	I	I	II	II	III	III	HARD	HARD
300	I	I	I	II	II	III	III	HARD	HARD	HARD
350	I	I	I	II	II	III	III	HARD	HARD	HARD
400	I	I	I	II	III	III	HARD	HARD	HARD	HARD
450	I	I	I	II	III	III	HARD	HARD	HARD	HARD
500	I	I	II	II	III	HARD	HARD	HARD	HARD	HARD

Notes:

[1] A "vee" ditch with a rounded bottom my be considered a trapezoidal ditch with bottom width equal to the width of the rounding. Side slopes are assumed to be 3:1. The recommendations provided by this table may be relaxed for flatter side slopes.

[2] The following codes designate the recommended type of ditch liner:

"Sod" = Sod or seeded liner with erosion control blanket
"I" = Class I Turf Reinforcement Mat
"II" = Class II Turf Reinforcement Mat
"III" = Class III Turf Reinforcement Mat
"Hard" = Hard armoring with riprap or concrete[3]

[3] The designer should consider using ditch checks or other means to reduce the ditch slope.

Table 5A-15
Vegetated Liner Selection for a Trapezoidal[1] Ditch with a Bottom Width of 6 Feet

Flow (cfs)	Increasing Ditch Slope (ft/ft) →									
	0.01	**0.02**	**0.03**	**0.04**	**0.05**	**0.06**	**0.07**	**0.08**	**0.09**	**0.10**
5	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD
6	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	I
8	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	I	I
10	SOD	SOD	SOD	SOD	SOD	SOD	SOD	I	I	I
15	SOD	SOD	SOD	SOD	SOD	I	I	I	I	I
20	SOD	SOD	SOD	SOD	I	I	I	I	I	I
25	SOD	SOD	SOD	SOD	I	I	I	I	I	I
30	SOD	SOD	SOD	I	I	I	I	I	I	I
40	SOD	SOD	SOD	I	I	I	I	I	I	I
50	SOD	SOD	I	I	I	I	I	I	I	I
60	SOD	SOD	I	I	I	I	I	I	I	I
70	SOD	SOD	I	I	I	I	I	I	I	I
80	SOD	SOD	I	I	I	I	I	I	I	II
90	SOD	I	I	I	I	I	I	I	I	II
100	SOD	I	I	I	I	I	I	I	II	II
120	SOD	I	I	I	I	I	I	II	II	II
140	SOD	I	I	I	I	I	II	II	II	II
160	SOD	I	I	I	I	I	II	II	II	III
180	SOD	I	I	I	I	II	II	II	III	III
200	SOD	I	I	I	I	II	II	II	III	III
250	SOD	I	I	I	II	II	II	III	III	HARD
300	I	I	I	I	II	II	III	III	HARD	HARD
350	I	I	I	II	II	III	III	HARD	HARD	HARD
400	I	I	I	II	II	III	III	HARD	HARD	HARD
450	I	I	I	II	II	III	HARD	HARD	HARD	HARD
500	I	I	I	II	III	III	HARD	HARD	HARD	HARD

Notes:

[1] A “vee” ditch with a rounded bottom my be considered a trapezoidal ditch with bottom width equal to the width of the rounding. Side slopes are assumed to be 3:1. The recommendations provided by this table may be relaxed for flatter side slopes.

[2] The following codes designate the recommended type of ditch liner:

- “Sod” = Sod or seeded liner with erosion control blanket
- “I” = Class I Turf Reinforcement Mat
- “II” = Class II Turf Reinforcement Mat
- “III” = Class III Turf Reinforcement Mat
- “Hard” = Hard armoring with riprap or concrete[3]

[3] The designer should consider using ditch checks or other means to reduce the ditch slope.

Table 5A-16
Vegetated Liner Selection for a Trapezoidal[1] Ditch with a Bottom Width of 8 Feet

Flow	**Increasing Ditch Slope (ft/ft) →**									
(cfs)	**0.01**	**0.02**	**0.03**	**0.04**	**0.05**	**0.06**	**0.07**	**0.08**	**0.09**	**0.10**
5	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD
6	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD
8	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	I
10	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	I	I
15	SOD	SOD	SOD	SOD	SOD	SOD	I	I	I	I
20	SOD	SOD	SOD	SOD	SOD	I	I	I	I	I
25	SOD	SOD	SOD	SOD	I	I	I	I	I	I
30	SOD	SOD	SOD	SOD	I	I	I	I	I	I
40	SOD	SOD	SOD	I	I	I	I	I	I	I
50	SOD	SOD	SOD	I	I	I	I	I	I	I
60	SOD	SOD	I	I	I	I	I	I	I	I
70	SOD	SOD	I	I	I	I	I	I	I	I
80	SOD	SOD	I	I	I	I	I	I	I	I
90	SOD	SOD	I	I	I	I	I	I	I	I
100	SOD	SOD	I	I	I	I	I	I	I	II
120	SOD	I	I	I	I	I	I	I	II	II
140	SOD	I	I	I	I	I	I	II	II	II
160	SOD	I	I	I	I	I	I	II	II	II
180	SOD	I	I	I	I	I	II	II	II	II
200	SOD	I	I	I	I	I	II	II	II	III
250	SOD	I	I	I	I	II	II	II	III	III
300	SOD	I	I	I	II	II	II	III	III	HARD
350	I	I	I	I	II	II	III	III	HARD	HARD
400	I	I	I	II	II	III	III	III	HARD	HARD
450	I	I	I	II	II	III	III	HARD	HARD	HARD
500	I	I	I	II	II	III	III	HARD	HARD	HARD

Notes:

[1] A "vee" ditch with a rounded bottom my be considered a trapezoidal ditch with bottom width equal to the width of the rounding. Side slopes are assumed to be 3:1. The recommendations provided by this table may be relaxed for flatter side slopes.

[2] The following codes designate the recommended type of ditch liner:

"Sod" = Sod or seeded liner with erosion control blanket
"I" = Class I Turf Reinforcement Mat
"II" = Class II Turf Reinforcement Mat
"III" = Class III Turf Reinforcement Mat
"Hard" = Hard armoring with riprap or concrete[3]

[3] The designer should consider using ditch checks or other means to reduce the ditch slope.

Table 5A-17
Vegetated Liner Selection for a Trapezoidal[1] Ditch with a Bottom Width of 10 Feet

Flow (cfs)	Increasing Ditch Slope (ft/ft) →									
	0.01	**0.02**	**0.03**	**0.04**	**0.05**	**0.06**	**0.07**	**0.08**	**0.09**	**0.1**
5	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD
6	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD
8	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	I
10	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	I	I
15	SOD	SOD	SOD	SOD	SOD	SOD	SOD	I	I	I
20	SOD	SOD	SOD	SOD	SOD	SOD	I	I	I	I
25	SOD	SOD	SOD	SOD	SOD	I	I	I	I	I
30	SOD	SOD	SOD	SOD	I	I	I	I	I	I
40	SOD	SOD	SOD	SOD	I	I	I	I	I	I
50	SOD	SOD	SOD	I	I	I	I	I	I	I
60	SOD	SOD	SOD	I	I	I	I	I	I	I
70	SOD	SOD	I	I	I	I	I	I	I	I
80	SOD	SOD	I	I	I	I	I	I	I	I
90	SOD	SOD	I	I	I	I	I	I	I	I
100	SOD	SOD	I	I	I	I	I	I	I	I
120	SOD	I	I	I	I	I	I	I	I	II
140	SOD	I	I	I	I	I	I	I	II	II
160	SOD	I	I	I	I	I	I	I	II	II
180	SOD	I	I	I	I	I	I	II	II	II
200	SOD	I	I	I	I	I	II	II	II	II
250	SOD	I	I	I	I	II	II	II	II	III
300	SOD	I	I	I	I	II	II	III	III	III
350	SOD	I	I	I	II	II	II	III	III	HARD
400	I	I	I	I	II	II	III	III	III	HARD
450	I	I	I	I	II	II	III	III	HARD	HARD
500	I	I	I	II	II	III	III	HARD	HARD	HARD

Notes:

[1] A "vee" ditch with a rounded bottom my be considered a trapezoidal ditch with bottom width equal to the width of the rounding. Side slopes are assumed to be 3:1. The recommendations provided by this table may be relaxed for flatter side slopes.

[2] The following codes designate the recommended type of ditch liner:

"Sod" = Sod or seeded liner with erosion control blanket
"I" = Class I Turf Reinforcement Mat
"II" = Class II Turf Reinforcement Mat
"III" = Class III Turf Reinforcement Mat
"Hard" = Hard armoring with riprap or concrete[3]

[3] The designer should consider using ditch checks or other means to reduce the ditch slope.

Table 5A-18
Vegetated Liner Selection for a Trapezoidal[1] Ditch with a Bottom Width of 12 Feet

Channel Slope (ft/ft)	Increasing Channel Bottom Width (feet)[1] →					
	2	4	6	8	10	12
0.010	1427.7	1660.8	1898.6	2140.2	2385.2	2632.9
0.015	641.2	788.7	939.8	1093.7	1249.9	1407.8
0.020	369.9	476.7	586.4	698.3	811.7	926.4
0.025	226.5	303.7	383.1	464.1	546.1	629.0
0.030	122.3	169.7	218.4	268.0	318.3	369.0
0.035	79.1	112.9	147.8	183.3	219.2	255.4
0.040	56.4	82.6	109.6	137.1	164.8	192.8
0.045	42.8	64.1	86.1	108.4	130.9	153.6
0.050	33.9	51.8	70.3	89.0	107.9	126.9
0.055	27.8	43.2	59.0	75.1	91.3	107.6
0.060	23.3	36.8	50.7	64.7	78.9	93.2
0.065	19.9	31.9	44.2	56.7	69.3	81.9
0.070	17.3	28.1	39.2	50.4	61.6	73.0
0.075	15.2	25.0	35.1	45.2	55.4	65.6
0.080	13.6	22.5	31.7	40.9	50.2	59.6
0.085	12.2	20.4	28.8	37.4	45.9	54.5
0.090	11.0	18.7	26.5	34.3	42.2	50.1
0.095	10.1	17.2	24.4	31.7	39.0	46.4
0.100	9.3	16.0	22.8	29.7	36.6	43.5

Notes:

[1] A “vee” ditch with a rounded bottom my be considered a trapezoidal ditch with bottom width equal to the width of the rounding.

[2] The flow rates in this table will produce a shear stress of 3.0 lb/sf on an unvegetated turf reinforcement mat. In general, this is the maximum shear strength of these materials prior to the establishment of vegetative cover. The designer may check the unvegetated shear strength of a specific product with the vendor.

[3] Flow values for other slopes or bottom widths may be interpolated as required.

Table 5A-19

Maximum 2-Year Flow Rates in CFS Allowed on Unvegetated Turf Reinforcement Mats In Trapezoidal Ditches with 3:1 Side Slopes for Varying Ditch Slope and Bottom Width

Channel Slope (ft/ft)	Increasing Channel Bottom Width (feet)[1] →					
	2	4	6	8	10	12
0.010	1853.2	2086.3	2323.1	2563.1	2806.0	3051.3
0.015	818.0	965.0	1115.0	1267.5	1422.0	1578.2
0.020	464.7	570.9	679.6	790.3	902.5	1015.9
0.025	280.7	357.3	435.9	515.9	597.1	679.1
0.030	149.7	196.6	244.8	293.9	343.6	393.9
0.035	95.7	129.2	163.7	198.8	234.4	270.3
0.040	67.5	93.5	120.2	147.4	174.9	202.6
0.045	50.8	71.9	93.6	115.7	138.0	160.5
0.050	39.9	57.6	75.9	94.4	113.1	132.0
0.055	32.4	47.7	63.3	79.3	95.4	111.6
0.060	27.0	40.4	54.1	68.0	82.1	96.3
0.065	22.9	34.8	47.0	59.4	71.9	84.4
0.070	19.8	30.5	41.4	52.5	63.7	75.0
0.075	17.3	27.0	37.0	47.0	57.2	67.4
0.080	15.4	24.2	33.3	42.5	51.7	61.0
0.085	13.7	21.9	30.2	38.7	47.2	55.7
0.090	12.4	19.9	27.6	35.5	43.3	51.2
0.095	11.2	18.3	25.4	32.7	40.0	47.3
0.100	10.4	17.0	23.7	30.5	37.4	44.3

Notes:

[1] A “vee” ditch with a rounded bottom my be considered a trapezoidal ditch with bottom width equal to the width of the rounding.

[2] The flow rates in this table will produce a shear stress of 3.0 lb/sf on an unvegetated turf reinforcement mat. In general, this is the maximum shear strength of these materials prior to the establishment of vegetative cover. The designer may check the unvegetated shear strength of a specific product with the vendor.

[3] Flow values for other slopes or bottom widths may be interpolated as required.

Table 5A-20
Maximum 2-Year Flow Rates in CFS Allowed on Unvegetated Turf Reinforcement Mats
In Trapezoidal Ditches with 4:1 Side Slopes for Varying Ditch Slope and Bottom Width

Channel Slope (ft/ft)	Increasing Channel Bottom Width (feet)[1] →					
	2	4	6	8	10	12
0.010	2693.4	2925.9	3161.1	3398.6	3638.4	3880.2
0.015	1167.0	1313.1	1461.5	1611.9	1763.9	1917.5
0.020	651.7	757.0	864.2	973.1	1083.4	1194.8
0.025	387.5	463.3	540.7	619.4	699.1	779.6
0.030	203.7	250.0	297.4	345.7	394.5	443.9
0.035	128.5	161.6	195.4	229.9	264.9	300.2
0.040	89.6	115.1	141.4	168.1	195.1	222.4
0.045	66.6	87.3	108.6	130.3	152.3	174.5
0.050	51.8	69.2	87.1	105.3	123.8	142.4
0.055	41.6	56.6	72.0	87.7	103.5	119.5
0.060	34.3	47.5	61.0	74.7	88.6	102.6
0.065	28.9	40.6	52.6	64.8	77.1	89.5
0.070	24.8	35.3	46.0	57.0	68.0	79.2
0.075	21.5	31.0	40.8	50.7	60.7	70.8
0.080	18.9	27.6	36.5	45.6	54.8	64.0
0.085	16.8	24.8	33.0	41.4	49.8	58.2
0.090	15.0	22.4	30.1	37.8	45.6	53.4
0.095	13.6	20.5	27.5	34.7	42.0	49.2
0.100	12.4	18.9	25.6	32.3	39.1	46.0

Notes:

[1] A "vee" ditch with a rounded bottom my be considered a trapezoidal ditch with bottom width equal to the width of the rounding.

[2] The flow rates in this table will produce a shear stress of 3.0 lb/sf on an unvegetated turf reinforcement mat. In general, this is the maximum shear strength of these materials prior to the establishment of vegetative cover. The designer may check the unvegetated shear strength of a specific product with the vendor.

[3] Flow values for other slopes or bottom widths may be interpolated as required.

Table 5A-21
Maximum 2-Year Flow Rates in CFS Allowed on Unvegetated Turf Reinforcement Mats
In Trapezoidal Ditches with 6:1 Side Slopes for Varying Ditch Slope and Bottom Width

Bottom Width (feet)	Riprap Class	Side Slopes				
		2:1	3:1	4:1	5:1	6:1
0	A1	*	5	11	17	24
0	B	2	16	36	77	126
0	C	4	37	153	258	357
2	A1	3	15	23	28	35
2	B	8	28	53	102	157
2	C	13	59	207	325	428
4	A1	5	24	34	38	46
4	B	12	57	99	127	190
4	C	19	187	298	393	(3)
6	A1	7	33	45	50	58
6	B	17	74	123	154	223
6	C	25	236	392	462	(3)
8	A1	8	42	50	56	64
8	B	20	92	147	181	257
8	C	30	286	462	(3)	(3)
10	A1	8	51	56	62	68
10	B	24	110	172	208	292
10	C	36	336	(3)	(3)	(3)

Notes:

1. Bottom width of the ditch is equal to the width of curved bottom
2. An asterisk indicates a condition not recommended for any discharge
3. Applies to discharges less than 500 cfs
4. Discharge values assume a Factor of Safety equal to 1.5

Table 5A-22
Maximum Allowable Discharges for Riprap Ditches on 10% Slopes
Adapted From: USDOT, FHWA, HEC-15, Appendix C (1988)

Bottom Width (feet)	Riprap Class	Side Slopes				
		2:1	3:1	4:1	5:1	6:1
0	A1	*	1.5	4	7	10
0	B	*	6	14	23	33
0	C	0.9	11	29	46	62
2	A1	1	7	11	13	16
2	B	2	18	28	35	47
2	C	5	22	45	64	82
4	A1	2	12	17	20	24
4	B	4	29	41	48	61
4	C	8	48	71	83	102
6	A1	3	17	24	27	31
6	B	5	39	54	62	75
6	C	11	63	89	102	122
8	A1	4	22	31	34	39
8	B	6	50	67	75	90
8	C	15	79	108	122	143
10	A1	5	27	38	41	44
10	B	8	61	80	89	104
10	C	18	95	128	142	165

Notes:

1. Bottom width of the ditch is equal to the width of curved bottom
2. An asterisk indicates a condition not recommended for any discharge
3. Applies to discharges less than 500 cfs
4. Discharge values assume a Factor of Safety equal to 1.5

Table 5A-23
Maximum Allowable Discharges for Riprap Ditches on 15% Slopes
Adapted From: USDOT, FHWA, HEC-15, Appendix C (1988)

Bottom Width (feet)	Riprap Class	Side Slopes				
		2:1	3:1	4:1	5:1	6:1
0	A1	*	*	2	3	5
0	B	*	3	7	12	16
0	C	*	6	14	23	34
2	A1	*	3	5	7	9
2	B	1	11	17	20	25
2	C	2	18	29	36	47
4	A1	1	5	9	10	13
4	B	2	18	26	29	35
4	C	3	29	41	49	62
6	A1	2	7	12	14	17
6	B	4	26	35	39	45
6	C	5	39	54	62	76
8	A1	2	9	15	18	22
8	B	5	33	44	48	55
8	C	7	50	68	76	91
10	A1	3	11	19	21	26
10	B	6	40	53	58	66
10	C	8	61	81	90	107

Notes:

1. Bottom width of the ditch is equal to the width of curved bottom
2. An asterisk indicates a condition not recommended for any discharge
3. Applies to discharges less than 500 cfs
4. Discharge values assume a Factor of Safety equal to 1.5

Table 5A-24
Maximum Allowable Discharges for Riprap Ditches on 20% Slopes
Adapted From: USDOT, FHWA, HEC-15, Appendix C (1988)

Bottom Width (feet)	Riprap Class	Side Slopes				
		2:1	3:1	4:1	5:1	6:1
0	A1	*	*	0.9	1	2
0	B	*	1.5	4	7	10
0	C	*	3	9	14	19
2	A1	*	2	3	3	4
2	B	1	7	11	13	17
2	C	1.5	12	19	23	30
4	A1	1	4	5	5	6
4	B	2	12	18	20	25
4	C	3	21	29	33	41
6	A1	1	5	7	8	9
6	B	3	16	25	27	32
6	C	4	28	39	43	52
8	A1	2	7	9	10	11
8	B	3	21	31	35	40
8	C	5	36	48	53	63
10	A1	2	9	11	12	13
10	B	4	26	38	42	48
10	C	6	44	58	64	74

Notes:

1. Bottom width of the ditch is equal to the width of curved bottom
2. An asterisk indicates a condition not recommended for any discharge
3. Applies to discharges less than 500 cfs
4. Discharge values assume a Factor of Safety equal to 1.5

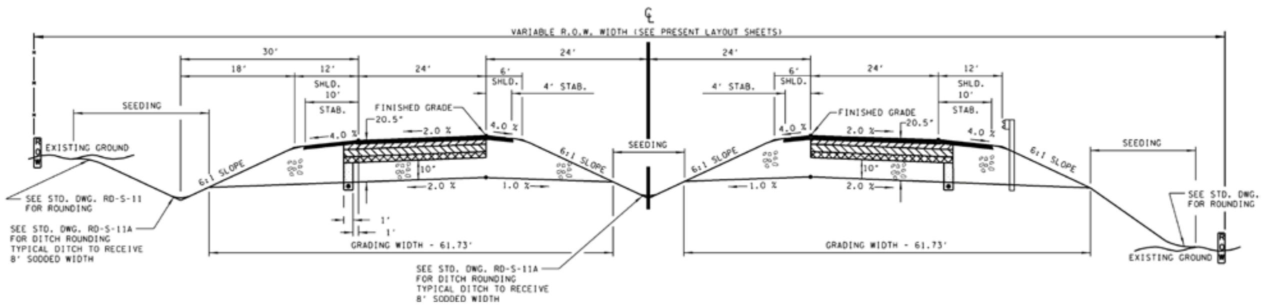
Table 5A-25
Maximum Allowable Discharges for Riprap Ditches on 25% Slopes
Adapted From: USDOT, FHWA, HEC-15, Appendix C (1988)

5.08.2 EXAMPLE PROBLEMS

5.08.2.1 EXAMPLE PROBLEM #1: VEGETATED DITCH DESIGN

GIVEN:

In Montgomery County, SR 76 is proposed to be a 4-lane, divided highway, which will be provided with the typical roadway cross section shown in Figure 5A-9



Roadway Cross-section Sketch
Typical Tangent Section – S.R. 76

Standard concrete Number 38 catch basins will be placed in the median at proposed roadway Stations 90+75 and 102+90. The proposed finished grades of these catchbasins are 629.57 and 623.49, respectively. The median will be seeded and the permanent vegetation will be maintained at an average height of 2 to 6 inches. Applying the analysis procedures from Chapter 4 of this Manual, the designer has computed a longitudinal slope of 0.5 percent and a peak discharge of 2.89 ft^3/s at Station 102+90. The area of a V-bottom ditch with rounding is approximately the same area of a trapezoidal ditch with a 2-foot bottom. Thus:

$Q = 2.89\ ft^3/s$
Ditch side slopes = 6H:1V
Ditch bottom width = 2 feet
Slope = 0.005 ft/ft

FIND:

a.) Determine the depth of flow in the median at station 102+90
b.) Compute the velocity of the flow
c.) Evaluate the adequacy of proposed channel lining material

SOLUTION:

As described in Section 5.06.1.2, the process of designing a ditch usually consists of assuming a type of channel lining and then determining the depth, velocity and shear stress that will occur at the design discharge. If the selected type of lining is found inadequate, a different type of lining is selected and the process is repeated.

Since the median is proposed to be seeded, the solution will begin with the assumption of a vegetated lining.

Step 1:

Select a retardance class based on the expected length of vegetation. Table 5A-4 provides a retardance class of “D” for a good stand of grass 2 to 6 inches high.

Step 2:

The depth of flow in the ditch may be determined using Manning’s equation as described in Section 5.03.2.4. However, since the Manning’s n-value of the lining will vary with depth of flow, it will be necessary to employ a trial and error solution.

As described in Section 5.06.1.3.1, a trial flow depth, d, must first be assumed. A depth of 1 foot is selected for the first trial run. For a trapezoidal cross section, the flow area, A, is computed from:

$$A = bd + zd^2 = 2.0(1.0) + 6\left(1.0^2\right) = 8.0 \text{ ft}^2$$ (see geometric relationships, Figure 5A-4)

Further, the wetted perimeter, P, is computed from:

$$P = b + 2d\left(1 + z^2\right)^{0.5} = 2.0 + 2(1.0)\left(1 + 6^2\right)^{0.5} = 14.17 \text{ feet}$$

Thus, the hydraulic radius, R, is equal to $\frac{A}{P} = \frac{8.0}{14.17} = 0.56$ feet

The effective n-value is computed using Equation 5-14. Since the selected lining is in retardance class “D”, the factor C_{rf} is equal to 34.6. Thus:

$$n = \frac{R^{1/6}}{C_{rf} + 19.97\log\left(R^{1.4}S^{0.4}\right)} = \frac{0.56^{1/6}}{34.6 + 19.97\log\left(0.56^{1.4}0.005^{0.4}\right)} = 0.098$$

This n-value is then used in Manning’s equation to compute the flow rate corresponding to a depth of 1.0 feet:

$$Q = \frac{1.486}{n}AR^{0.667}S^{0.5} = \frac{1.486}{0.098}(8.0)\left(0.56^{0.667}\right)\left(0.005^{0.5}\right) = 5.826 \text{ cfs}$$

Since the computed flow rate is much greater than the design flow rate of 2.89 ft^3/s, the assumed trial depth is too high. The trial flow depth is varied until the computed discharge is equal to the design discharge. The following table provides a summary of those computations:

Trial Depth (feet)	Flow Area (ft^2)	Wetted Perim. (feet)	R (feet)	Computed n	Computed Q (cfs)
0.9	6.66	12.95	0.514	0.110	4.09
0.8	5.44	11.73	0.464	0.128	2.68
0.81	5.56	11.85	0.469	0.126	2.81
0.82	5.67	11.98	0.474	0.123	2.93

It is only necessary to compute depth to the nearest 0.01 feet. Since a depth of 0.82 feet provides a computed discharge closest to the design discharge, it is selected as the flow depth. As seen in the roadway cross-section sketch, the proposed median ditch will be adequate to accommodate flows of this depth.

Step 3:

The flow area, A, for a discharge of 2.89 ft^3/s would be 5.63 ft^2. Using the Continuity equation, the flow velocity, V, is computed as:

$$V = \frac{Q}{A} = \frac{2.89}{5.63} = 0.51 \text{ ft/sec}$$

Using Equation 5-10, the maximum shear stress, τ_{max}, is computed as:

$$\tau_{max} = \gamma d S = (62.4)(0.82)(0.005) = 0.26 \text{ lb/ft}^2$$

Since the ditch is on a tangent section of roadway, it will not be necessary to adjust the computed maximum shear stress for curvature.

Step 4:

Table 5A-5 provides maximum allowable flow velocities for varying species of grass. The Standard Specifications call for different mixtures of grass seed depending on the time of year that the seed is sown. Thus, based on Table 5A-5, the maximum allowable flow velocity for a grass mixture would be 4 feet per second. Since the allowable velocity is greater than the velocity computed for the design flow rate, the proposed lining will be adequate for flow velocity.

Based on Table 5A-7, the maximum allowable shear stress for grasses in retardance class “D” is 0.60 lb/ft^2. Since this is greater than the computed shear stress of 0.26 lb/ft^2, the proposed lining will also be adequate for shear.

Step 5:

As discussed in Section 5.06.1.2, all seeded ditch linings should be considered to offer no erosion resistance. Therefore, it will be necessary to select a temporary erosion control blanket to protect the ditch while the grass is establishing. For this example problem, a Type I blanket is assumed first, and the hydraulic performance and erosion resistance of that blanket are checked for the design discharge.

Based on Table 5A-6, the Manning's n-value of a Type I erosion control blanket is 0.055 for depths up to 0.5 feet. Thus, the flow depth is computed by trial and error using Manning's equation and an n-value of 0.055. Although these computations are not shown, the process is similar to that employed in Step 2, above. The depth computed for an n-value of 0.055 is 0.57 feet. Although the computed depth is somewhat greater than the maximum allowable depth for an n-value of 0.055, an attempt to correct the n-value for depth as described in Section 5.06.1.3.2 would result in a computed depth difference of less than 0.01 feet. Therefore, the result is assumed to be adequate.

The computed flow area for a depth of 0.57 feet is 3.08 ft^2. The flow velocity, V, is computed from the Continuity equation as:

$$V = \frac{Q}{A} = \frac{2.89}{3.08} = 0.94 \text{ ft/sec}$$

The maximum shear stress, τ_{max}, is then computed as:

$$\tau_{max} = \gamma dS = (62.4)(0.57)(0.005) = 0.18 \text{ lb/ft}^2$$

Since the velocity will not be excessive, and the computed shear is less than the allowable shear stress of 1.55 lb/ft^2 (see Table 5A-7), a Type I erosion control blanket will be adequate.

Step 6:

Because of the straight alignment of the ditch and the relatively low flow velocity at the design discharge, it is judged that 6 inches of freeboard will be adequate at this site. The height to be protected with erosion control blanket would thus be the flow depth for the final lining of 0.82 feet plus 0.5 feet, or 1.3 feet. The ditch will be provided with 6H:1V side slopes; so the width of the area to be protected on one side would be $1.3 \times 6 = 7.9$ feet. Adequate protection may be provided by two 4-foot wide strips of erosion blanket on each side of the ditch.

5.08.2.2 EXAMPLE PROBLEM #2: TRAPEZOIDAL DITCH DESIGN

GIVEN:

A design project in Hamblen County requires S.R. 34 to bypass an existing small community. At a cross drain location requiring a moderate amount of fill, the designer has specified a trapezoidal ditch from the top of the slope to the toe of the fill with a 4 foot bottom width and 3H:1V side slopes. The proposed special ditch has an invert elevation of 937.2 at Station 310+00 and a bottom elevation of 912.7 at Station 313+50. Applying the analysis procedures from Chapter 4 of this Manual, the designer has computed a peak discharge of 21 ft^3/s. The receiving stream is a natural channel with a bottom of large cobbles and small boulders and good bank vegetation.

Q = 21 ft^3/s
Longitudinal slope = 0.070 ft/ft
Ditch bottom width = 4 feet
Ditch side slopes = 3H:1V

FIND:

a.) Design an appropriate lining for the proposed ditch
b.) Determine the velocity and depth of flow at the outlet
c.) Describe the flow regime in the ditch

SOLUTION:

As described in Section 5.06.1.2, the process of designing a ditch usually consists of assuming a type of channel lining and then determining the depth, velocity and shear stress that would occur for the design discharge. If the selected type of lining is found to be inadequate, a different type of lining is selected and the process is repeated.

Side ditches are usually lined with sod. Thus, the process will begin by assuming a vegetated ditch lining with a retardance classification of “C.”

Step 1:

The determination of flow depth in a vegetated ditch is a trial and error process that is demonstrated in detail in Example Problem 1. Thus, the trial and error flow depth solution for this problem is not detailed, but it yields a depth of 0.80 feet as shown in the following computations. The flow depth, A, is computed as:

$$A = bd + zd^2 = 4.0(0.80) + 3(0.80^2) = 5.12 \text{ ft}^2$$

Next, the wetted perimeter, P, is computed from:

$$P = b + 2d(1 + z^2)^{0.5} = 4.0 + 2(0.80)(1 + 3^2)^{0.5} = 9.06 \text{ feet}$$

The hydraulic radius, R, is equal to $\dfrac{A}{P} = \dfrac{5.12}{9.06} = 0.565$ feet

The effective n-value is computed using Equation 5-14. Since the selected lining is in retardance class “C”, the factor C_{rf} is equal to 30.2. Thus:

$$n = \frac{R^{1/6}}{C_{rf} + 19.97\,log\left(R^{1.4}S^{0.4}\right)} = \frac{0.565^{1/6}}{30.2 + 19.97\,log\left(0.565^{1.4}0.07^{0.4}\right)} = 0.065$$

This n-value is then used in Manning’s equation to compute the flow rate corresponding to a depth of 0.80 feet:

$$Q = \frac{1.486}{n}AR^{0.667}S^{0.5} = \frac{1.486}{0.065}(5.12)\left(0.565^{0.667}\right)\left(0.07^{0.5}\right) = 21.2 \text{ cfs}$$

This result is closest to the design flow rate of 21 ft^3/s, yielded for depth considered to the nearest 0.01 feet.

Step 2:

Based on Table 5A-3, the maximum allowable velocity for sod is 4 ft/sec. Further, based on Table 5A-7, the maximum allowable shear stress is 1.0 lb/ft^2 for retardance class ‘C’. Since the cross sectional area of the flow was computed in Step 1, the flow velocity may be computed form the Continuity equation as:

$$V = \frac{Q}{A} = \frac{21.0}{5.12} = 4.1 \text{ ft/sec}$$

Although this is somewhat above the limit, it may be permissible if the level of shear stress in acceptable. The maximum shear stress, τ_{max}, is computed as:

$$\tau_{max} = \gamma dS = (62.4)(0.80)(0.07) = 3.49 \text{ lb/ft}^2$$

Since this is much greater than the allowable shear stress, it is concluded that sod will not provide an adequate ditch lining.

Step 3:

Since it is apparent that a vegetated ditch lining will not be adequate for this site, Class A1 riprap is next selected for design. It is judged that the flow depth will be between 0.5 and 2.0 feet for the design discharge of 21 ft^3/s, thus, an n-value of 0.072 is selected from Table 5A-6. Manning’s equation is then utilized to determine the flow depth as follows:

$$Q = \frac{1.486}{n}AR^{0.667}S^{0.5} = \frac{1.486}{0.072}\left[4.0(d) + 3\left(d^2\right)\right]\left[\frac{4.0(d) + 3\left(d^2\right)}{4.0 + 2d\left(1 + 3^2\right)^{0.5}}\right]^{0.667} 0.07^{0.5} = 21.0 \text{ cfs}$$

Solving this expression by trial and error yields a flow depth of 0.84 feet. Since this depth is between 0.5 and 2.0 feet, the initial assumption of Manning’s n-value is good and this value may be used for design.

Step 4:

Based on Section 5.04.7.1.2, the maximum allowable flow velocity for Class A1 riprap is 5.0 ft/sec. From Table 5A-7, the maximum allowable shear stress is 3.0 lb/ft^2. To compute the flow velocity, V, the flow area, A, is first computed and then the Continuity equation is applied as follows:

$$A = bd + zd^2 = 4.0(0.84) + 3(0.84^2) = 5.48 \text{ ft}^2 \text{ and,}$$

$$V = \frac{Q}{A} = \frac{21.0}{5.48} = 3.83 \text{ ft/sec}$$

The maximum shear stress, τ_{max}, is computed as:

$$\tau_{max} = \gamma dS = (62.4)(0.84)(0.07) = 3.66 \text{ lb/ft}^2$$

Although the computed velocity is within the allowable limit, the computed shear stress of 3.66 lb/ft^2 is greater than the allowable 3.00 lb/ft^2, and Class A1 riprap is rejected as a liner for this site.

Step 5:

Class B riprap is selected next. As above, it is judged that the flow depth will be between 0.5 and 2.0 feet and an n-value of 0.086 is determined from Table 5A-6. Manning's equation is again utilized with trial and error as described in Step 3 to determine a flow depth of 0.92 feet.

Based on Section 5.04.7.1.2, the maximum allowable flow velocity for Class B riprap is 10.0 ft/sec. Again, from Table 5A-7, the maximum allowable shear stress is 5.0 lb/ft^2. To compute the flow velocity, the flow area is first computed and then the Continuity equation is applied.

$$A = bd + zd^2 = 4.0(0.92) + 3(0.92^2) = 6.22 \text{ ft}^2 \text{ and,}$$

$$V = \frac{Q}{A} = \frac{21.0}{6.22} = 3.38 \text{ ft/sec}$$

The maximum shear stress, τ_{max}, is computed as:

$$\tau_{max} = \gamma dS = (62.4)(0.92)(0.07) = 4.02 \text{ lb/ft}^2$$

Since the flow velocity and shear stress are both within the allowable limits for Class B riprap, it is selected as the lining material for this ditch section.

Step 6:

To determine the depth and velocity at the ditch outlet, it is first necessary to determine whether the flows in the ditch are in the subcritical or supercritical flow regime. It is assumed for this problem, that the depth of flow in the receiving stream will be less than the flow depth in the ditch. Thus, if the flow in the ditch is supercritical, the depth at the outfall will be the depth computed in Step 5, above. However, if the flow is in the subcritical regime, the depth and velocity at the outfall should be based on the critical flow depth in the ditch.

The flow regime may be determined by computing the Froude Number, Fr, for the normal flow in the ditch. To determine Fr, it is first necessary to determine the hydraulic depth, D, which is the flow area, A, divided by the top width, T. Thus:

$$D = \frac{A}{T} = \frac{6.22}{4 + 2(0.92)(3)} = 0.65 \text{ feet. Then:}$$

$$Fr = \frac{V}{[gD]^{0.5}} = \frac{3.37}{[32.2(0.65)]^{0.5}} = 0.736$$

Since the computed value of Fr is less than 1.0, the flow is in the subcritical regime and it is necessary to compute the critical depth at the outlet. Since critical flow occurs where Fr is equal to 1.0, the flow area, hydraulic depth, velocity, and Froude Number will be computed for varying depths until the depth resulting in a Froude Number of 1.0 is found. The trial and error computations are shown in the following table:

Depth (feet)	Area (sf)	Top Width (feet)	Hydraulic Depth (feet)	Velocity (ft/sec)	Froude Number
0.92	6.22	9.52	0.65	3.38	0.736
0.85	5.57	9.10	0.61	3.77	0.850
0.80	5.12	8.80	0.58	4.10	0.948
0.78	4.95	8.68	0.57	4.25	0.991
0.77	4.86	8.62	0.56	4.32	1.015

Since depth is determined to the nearest 0.01 feet, 0.78 feet is determined to be the critical depth. In addition, the flow velocity at the outlet is 4.10 ft/sec. Since the receiving stream includes a bottom of large cobbles and small boulders and good bank vegetation, the flow velocity from the special ditch is not expected to cause erosion problems.

5.08.2.3 EXAMPLE PROBLEM #3: STEEP GRADE TRAPEZOIDAL DITCH DESIGN

GIVEN:

A roadway project in Jackson County requires that a special design ditch connected to a cross drain be designed and evaluated for a lining material. The ditch is trapezoidal with a bottom width of 4 feet, side slopes of 3H:1V, and a slope along the ditch line of 17 percent. The discharge from the cross drain to the ditch has been calculated to be 11 cfs.

Q = 11.0 ft^3/s
Ditch bottom width = 4 feet
Ditch side slopes = 3H:1V
Longitudinal slope = 0.17 ft/ft

FIND:

a.) Design a lining for the ditch
b.) Compute the flow depth and velocity for the selected lining
c.) Determine the freeboard
d.) Determine whether special treatment is needed at the ditch outfall

SOLUTION:

Because the slope of the ditch is greater than 10 percent, this ditch should be designed according to the criteria provided in Section 5.04.7.1.2.1.

Step 1:

Based on Table 5A-23, the maximum allowable discharge for a ditch at 15% lined with Class A1 riprap and the proposed cross section is 12 ft^3/s. Further, Table 5A-24 indicates that the maximum discharge for the ditch at 20 percent is 5 ft^3/s. The maximum allowable discharge for the ditch at 17 percent is determined by interpolation to be 9.2 ft^3/s. Because this is less than the design discharge of 11 ft^3/s, the proposed lining will not meet the required safety factor of 1.5.

Step 2:

To provide an adequate lining, it will be necessary to use a heavier class of riprap or to flatten the side slopes of the ditch. Based on engineering judgment, it is decided to change the ditch side slopes to 4H:1V. Based on this side slope, the allowable discharge for Class A1 riprap on a 15 percent slope is 17 ft^3/s. For a 20 percent slope, the allowable discharge becomes 9 ft^3/s. Again based on interpolation, the allowable discharge is found to be 13.8 ft^3/s for a slope of 17 percent. Since this flow rate is greater than the design discharge of 11 ft^3/s, the proposed design should be adequate provided the side slopes are changed to 4H:1V.

Step 3:

Manning's equation is used to determine the depth of flow, d, in the proposed ditch. It is judged that the flow depth will be less than 0.5 feet for the design discharge of 11 ft^3/s, thus, an n-value of 0.124 is selected from Table 5A-6. The Equation is then set up as follows:

$$Q = \frac{1.486}{n} AR^{0.667} S^{0.5} = \frac{1.486}{0.124}\left[4.0(d) + 4\left(d^2\right)\right]\left[\frac{4.0(d) + 4\left(d^2\right)}{4.0 + 2d\left(1 + 4^2\right)^{0.5}}\right]^{0.667} 0.17^{0.5} = 11.0 \text{ cfs}$$

Solving this expression by trial and error yields a flow depth of 0.61 feet. Since this depth does not match the initial assumption that the depth would be less than 0.5 feet, the computation shown above is repeated assuming an n-value of 0.072, which applies to depths greater than 0.5 feet. The result of solving the equation this time is a depth of 0.45 feet, which is less than 0.5 feet. Thus, neither computation provides a result that strictly matches the initial assumption. However, since 0.45 feet is closer to 0.5 feet, it is taken as the best solution.

Step 4:

Once the depth has been determined it is possible to compute the cross sectional flow area, A, as:

$$A = bd + zd^2 = 4.0(0.45) + 4\left(0.45^2\right) = 2.61 \text{ ft}^2$$

The flow velocity, V, is then computed from the Continuity equation as:

$$V = \frac{Q}{A} = \frac{11.0}{2.61} = 4.21 \text{ ft/sec}$$

Since this velocity is less than 5 ft/sec, no special treatments, such as an energy dissipator, will be required at the downstream end of the ditch.

Step 5:

As discussed in Section 5.04.7.1.2.1, the freeboard in a steep ditch should be equal to depth of the flow, which is 0.45 feet in this case. Thus, the total height of the riprap above the ditch bottom should be 0.90 feet, which is twice the depth.

5.08.2.4 EXAMPLE PROBLEM #4: CONCRETE TRAPEZOIDAL DITCH DESIGN

GIVEN:

A concrete lining is proposed for a special ditch that conveys flows from the outlet to a cross drain. The discharge to the ditch is calculated to be 20 ft^3/s and the ditch alignment is curved with a radius of curvature of 50 feet. The ditch is to be placed at a slope of 17 percent. The design calls for a cross section with a bottom width of 4 feet with 3H:1V side slopes.

Discharge = 20 ft^3/s
Ditch bottom width = 4 feet
Ditch side slopes = 3H:1V
Longitudinal slope = 0.17 ft/ft
Manning's n-value = 0.013 (concrete ditch lining with a trowel finish)
Radius of curvature (R_o) = 50 feet

FIND:

a.) Compute the flow depth and velocity in the ditch
b.) Compute the superelevation of the flow in the curve
c.) Determine the needed freeboard
d.) Determine any special treatment that may be needed at the ditch outlet

SOLUTION:

A riprap lining is not desirable at this site because curved alignments are not recommended for steep ditches with riprap linings (see Section 5.04.7.1.2.1).

Step 1:

Since the Manning's n-value is considered to be constant for a concrete ditch lining, the slope-conveyance method may be used directly to solve for the depth of flow, d, in the ditch. Thus, Manning's equation is set up as follows:

$$Q = \frac{1.486}{n} AR^{0.667} S^{0.5} = \frac{1.486}{0.013}\left[4.0(d) + 3\left(d^2\right)\right]\left[\frac{4.0(d) + 3\left(d^2\right)}{4.0 + 2d\left(1 + 3^2\right)^{0.5}}\right]^{0.667} 0.17^{0.5} = 20.0 \text{ ft}^3\text{/s}$$

Solving this expression by trial and error yields a flow depth of 0.25 feet.

Step 2:

Once the flow depth has been determined, other parameters needed for the design are computed. The cross sectional area of the flow is computed as:

$$A = bd + zd^2 = 4.0(0.25) + 3\left(0.25^2\right) = 1.19 \text{ ft}^2$$

The velocity of flow may then be computed from the Continuity equation as:

$$V = \frac{Q}{A} = \frac{20.0}{1.19} = 16.81 \text{ ft/sec}$$

The top width of the flow, T, and the hydraulic depth, D, are computed from:

$$T = b + 2zd = 4.0 + 2(3)(0.25) = 5.50 \text{ feet, and}$$

$$D = \frac{A}{T} = \frac{1.19}{5.50} = 0.22 \text{ feet}$$

The Froude Number is then computed as:

$$Fr = \frac{V}{[gD]^{0.5}} = \frac{16.81}{[32.2(0.22)]^{0.5}} = 6.31$$

Since the Froude Number is greater than 1.0, the flow is supercritical.

Step 3:
Because the flow is supercritical, superelevation, Z, in the curve should be considered as discussed in Section 5.05.5.1. Thus, Z may be computed from Equation 5-13 as:

$$Z = C\left[\frac{V_a{}^2 \times T}{g \times R_c}\right] = 1.5\left[\frac{16.84^2 \times 5.50}{32.2 \times 50.0}\right] = 1.45 \text{ feet}$$

As discussed in Section 5.04.7.1.4, ditches with concrete linings and steep slopes should be provided with 1 foot of freeboard above the superelevated water level. Thus, the total height of the concrete lining above the bottom of the ditch should be $0.25 + 1.45 + 1.0 = 2.70$ feet. The ditch may also be provided with sod above the concrete lining as shown in the Standard Drawings.

Step 4:
Although the flow depth in the ditch will not be great, it will be at a high velocity. Further, the outlet of the concrete ditch will be to a natural stream where occasional high flow events could expose the end of the ditch to strong lateral currents. Both of these conditions can cause a washout at the end of the ditch lining resulting in the overall failure of the structure. To prevent this from occurring, the end of the concrete ditch lining will terminate a sufficient distance away from the receiving stream so that it will not be subject to significant stream currents during high-flow events. In addition, the ditch outfall will be provided with an energy dissipator to prevent erosion at the outlet due to high-energy flows in the special ditch. Based on the criteria provided in Table 9A-1, a USBR Type VI energy dissipator is selected. A detailed procedure and a sample problem for the design of this type of basin are provided in Chapter 9.

5.08.3 GLOSSARY

The following list of terms is representative of those used in channel analysis and design. All of the terms may not necessarily be used in the chapter text; but rather are commonly used by engineers, scientists, and planners.

BACKWATER - The rise of water level upstream due to a downstream obstruction or channel constriction.

BACKWATER AREA - The low-lying lands adjacent to a stream that may become flooded due to backwater effects.

BANK SLIPPAGE – (See Sloughing).

BED MATERIAL – The natural soils, rocks or other materials in which the channel of a given stream has formed.

CHANNEL (of a stream) – A clearly defined lower portion of a natural or man-made drainage way that carries the normal flows of a stream.

COMPOSITE LINING – A channel lining that utilizes two or more different types of materials to resist erosion, often providing one type of material on the bottom of the channel and another type on the sides.

CONTINUITY EQUATION – A simplified expression of the conservation of mass for the flow of a non-compressible fluid, such as water. The equation states that the mass flow rate through a given flow cross section is equal to the area of the cross section times the average velocity of the flow.

CONTRACTION – The squeezing or forcing together of stream flow lines imposed by a natural or man-made constriction.

CONTRACTION RATIO – The rate of change in width of the effective flow in the transition zone between the unconstricted cross section and a constriction to flow. It is usually expressed as the linear distance along the stream flow necessary for the effective flow width to contract by one foot on one side, for example, 2:1.

COVER (of a pipe) – The minimum vertical distance from the outside crown of a pipe to the bottom of the roadway subgrade.

CRITICAL DEPTH – The depth at which the gravitational and inertial forces acting on the flow are exactly balanced. Specific energy is at a minimum at critical depth. For a given discharge and cross-sectional geometry there is only one critical depth.

CRITICAL FLOW – An open channel flow condition where the depth is exactly at critical depth.

CROSS DRAIN – A drainage structure, usually a culvert, that conveys water from one side of a roadway to the other.

CULVERT – A drainage structure, usually used to convey flows through a constructed embankment, which may be considered hydraulically "long," that is, having a span that is significantly less than its length.

DEPTH OF FLOW – Vertical distance from the bed of a channel to the water surface.

DITCH – A man-made drainage way usually consisting of a regular, constant cross section.

DITCH CHECK – A temporary or permanent structure placed in a ditch to control sedimentation or flow velocity.

DRAINAGE AREA – All of the area that will contribute runoff to a given point.

ENERGY DISSIPATOR – Some means, usually structural, employed at a drainage structure outfall to reduce the force or velocity of the flow leaving the structure to prevent damage from erosion.

ENERGY GRADE LINE – A line that represents the total force available in water flow. It is a combination of energy due to the height of the water, internal pressure and velocity (pressure head + elevation head + velocity head).

EROSION – The removal of sediments or other soil from a site, especially by the force of moving water.

EROSION CONTROL BLANKET – A manufactured sheet composed of a combination of man-made and natural materials providing erosion protection to a ditch or stream channel, usually on a temporary basis while the permanent vegetated lining grows in.

EXPANSION RATIO – The rate of change in width of effective flow in the transition zone between a constriction to flow and the unconstricted cross section. It is usually expressed as the linear distance along the stream necessary for the effective flow width to expand by one foot on one side, for example, 2:1.

FLEXIBLE LINING – A channel lining material with the capacity to adjust to any settlement that may occur in the subgrade. Typically constructed of a porous material that allows infiltration and exfiltration.

FREEBOARD – The vertical distance from the water surface to the top of the channel at design condition.

FROUDE NUMBER – A parameter representing the ratio of the inertial forces to the gravitational forces acting on a flow of water and thus indicating whether the flow is in the subcritical or the supercritical flow regime.

GABION – A basket or compartmented rectangular container made of steel wire mesh. When filled with cobbles or other rock of suitable size, the gabion becomes a flexible and permeable block from which flow or erosion control structures can be built.

GEOTEXTILE – An artificial fabric, usually composed of one or more man-made materials, used to prevent the erosion of earthen materials subject to the flow of water. Geotextiles are often used beneath other erosion control measures, such as riprap, to prevent the piping of soils.

GRADUALLY VARIED FLOW – A non-uniform flow condition where the flow depth, velocity and water surface slope change in a relatively gradual manner over a given stream reach.

GRAVITATIONAL FORCES (acting on a flow of water) – The forces acting on a body of water due to its weight causing it to move in a downward direction.

GROUTED RIPRAP – A channel or embankment lining constructed by placing riprap and then filling the voids with concrete grout.

HEAD – One of a number of different measures of the energy available in a given unit of water, including any combination of elevation, velocity and pressure.

HEAD LOSS – The reduction of available energy (as measured by the energy grade line) occurring in the flow of water from a specified upstream point to a specified downstream point.

HEADCUTTING – Channel degradation associated with an abrupt drop in the stream bed elevation, generally migrating in an upstream direction.

HYDRAULIC DEPTH – A representative overall depth of a non-rectangular cross section computed by dividing the cross sectional flow area by the top width of the flow.

HYDRAULIC JUMP – A flow discontinuity occurring at an abrupt transition from subcritical to supercritical flow, usually dissipating a significant amount of energy.

HYDRAULIC RADIUS – A parameter used in the analysis of uniform flow computed as the flow area divided by the wetted perimeter.

HYDRAULIC ROUGHNESS – The frictional resistance of a given surface to the flow of water.

INERTIAL FORCES (acting on a flow of water) – The forces exerted on or by a body of water due to the tendency of a moving mass to continue moving in the same direction.

KEY (for revetments) – An extension of a hard revetment into the subgrade such as riprap or concrete at the toe of the slope being protected to prevent the undermining of the slope.

LATERAL MIGRATION – A shift in the horizontal alignment of a channel, often in the direction of the outside of a bend, caused by channel bank erosion.

LINING – Materials, usually placed by human intervention, covering the bed and sides of a channel providing protection against erosion.

LOW FLOW CHANNEL – A relatively small pilot channel placed in a larger channel cross section of a relocated stream reach to accommodate the everyday flow of the stream.

MANNING'S EQUATION – An empirical formula used to analyze flow conditions for a steady, uniform flow.

MANNING'S N-VALUE: – An empirical number assigned to a given material as a gage of its frictional resistance to the flow of water.

MATTRESS – A blanket of revetment of materials usually contained in wire mesh containers that are lashed together and placed to protect an area subject to erosion.

MEANDERING – Describes a stream for which the alignment of the channel is characterized by frequent sharp bends within a much straighter overall valley alignment.

MEDIAN DITCH – A drainage way formed at the low point of the depressed median of a divided highway.

MORPHOLOGY – The science which deals with the form of the earth, the general configuration of its surface, and the changes that take place due to erosion and sediment deposition. With regard to streams and channels, morphology examines the processes of meandering and bed material transport, as well as the geometry of the channel cross-section.

NOMOGRAPH – A chart providing solutions to a complex equation by means of projecting straight lines between two or more relative numeric scales.

NONUNIFORM FLOW – A flow condition characterized by changes in cross section, depth and velocity through a given reach of channel. Under this condition, the slopes of the energy grade line, the water surface and the channel bed may vary and will usually not be equal to one another.

OPEN CHANNEL FLOW – A flow condition where the water surface is open to the atmosphere and the behavior of the flow is determined only by gravity and momentum.

OUTFALL (or OUTLET) – The point at which flows in a closed drainage system, such as a storm sewer, pass into another drainage system, usually an open conveyance such as a ditch.

OVERBANK – An area above the channel of a stream subject to the flow of water only during flood events.

PIPING – The removal of fine soil particles caused by the motion of water, either through an embankment or through a porous channel lining material, such as riprap placed in a ditch.

POINT BAR – An alluvial deposit of sand or gravel lacking permanent vegetal cover occurring in a channel at the inside of a meander loop, usually somewhat downstream from the apex of the loop.

RADIUS OF CURVATURE – The radius of the circle that subtends a given curve.

RAPIDLY VARIED FLOW – A non-uniform flow condition where the depth, velocity and slope of the water surface change abruptly over a given stream reach. Examples of rapidly varied flow include free fall over a weir and the hydraulic jump.

REACH – A segment of stream length that is arbitrarily bounded for purposes of study.

REGIME – The condition of a stream or its channel with regard to stability. Also, the general pattern of variation around a mean condition, as in flow regime.

RETARDANCE CLASSIFICATION (Vegetal) – A category that describes the degree of resistance to flow offered by various types of vegetation, normally grasses, used as channel linings.

REVETMENT – A structural measure, such as riprap, placed on a slope to stabilize that slope against erosion or slippage.

RIGID LINING – An inflexible channel lining material offering a high level of erosion protection, but lacks the capacity to adjust to any settlement that may occur in the subgrade.

RIPARIAN – Pertaining to anything connected with or adjacent to the banks of a stream (e.g. corridor, vegetation, zone, etc.).

RIPRAP – Crushed rock, usually manufactured to a specific gradation and used to prevent erosion on slopes or in stream channels.

ROUGHNESS COEFFICIENT – A numerical measure of the frictional resistance to flow in a channel, such as the Manning's coefficient.

SHEAR STRESS – A force exerted by the flow of water on the wetted area of the channel, acting in the direction of the flow; expressed as force per unit wetted area.

SHEET FLOW – A stormwater runoff flow condition where the water moves as a broad, thin film over a surface.

SIDE DITCH – A man-made drainage way constructed at either side of a roadway.

SINUOSITY – The ratio between the thalweg length and the valley length of a stream.

SLOUGHING – Sliding or collapse of material on an earthen slope such as on an embankment or stream channel. Sloughing usually occurs when the material in the slope or an underlying stratum is saturated.

SLOPE CONVEYANCE METHOD – A process by which the normal depth of flow in a drainage way of a known slope is determined using Manning’s Equation with trial and error.

SOD – Pre-seeded grasses harvested with their roots and transported alive to another location to provide a lining for erosion prevention.

SPECIFIC ENERGY – The energy available in a flow of water, without consideration of its elevation; that is, the sum of the depth and velocity head.

SPIRAL VORTEX -- A turbulent zone in a flow field characterized by a circular motion running longitudinally with the overall stream flow and is often associated with a curved stream alignment or an obstruction that forces flows toward the center of the channel.

STABLE (CHANNEL) – A ditch or stream channel for which the shape of the cross section is not significantly affected by sediment transport, either by erosion or by deposition.

STANDARD STEP BACKWATER METHOD – A process by which the water surface profile is computed for gradually varied flow, based on the conservation of energy and computed head losses between successive cross sections a given distance apart.

STEADY FLOW – A flow condition under which the discharge and the water surface profile do not change with respect to time. Steady flow can be either uniform or non-uniform.

STORM SEWER – A system of catch basins, manholes and pipes designed to remove stormwater runoff from the ground surface and convey it to a suitable outlet point.

STORMWATER RUNOFF – The portion of the water from a rainfall event flowing across the surface of the ground.

STREAM – A natural drainage way of any size having an identifiable channel.

STREAM MODIFICATION – A change in the alignment or location of a natural stream to accommodate a proposed roadway or other type of development.

STREAMBED DEGREDATION – A general lowering, due to erosion, of the bottom of a channel across a given reach of a ditch or stream.

SUBCRITICAL FLOW – A flow condition where the behavior of the flow is determined more by gravitational forces than by inertial forces.

SUPERCRITICAL FLOW – A flow condition where the behavior of the flow is determined more by inertial forces than by gravitational forces.

SUPERELEVATION – An increase in water surface elevation above the natural depth of a flow occurring on the outside of a curved channel alignment due to centrifugal and other forces.

TAILWATER – Either the elevation or the depth of the water surface at the downstream end of a drainage structure, usually equivalent to the natural depth of flow in the waterway.

TAILWATER RATING CURVE – A relationship between the tailwater depth and discharge rate at the downstream end of a given structure.

THALWEG (or FLOW LINE) – The line extending down a channel that follows the lowest elevation of the bed.

TRACTIVE FORCE – Drag or shear on a streambed or bank caused by the force passing water, and that tends to move soil particles along with the stream flow.

TURBULENT FLOW – A flow condition where inertial forces are very much greater than viscous forces. As a result, individual water particles do not move in straight lines, but follow highly varying paths that, on the average, move in the downstream direction. Most flows in nature are turbulent.

TURF REINFORCEMENT MAT – A manufactured blanket composed of a combination of man-made and natural materials providing erosion protection for a ditch or stream channel. At least a portion of the turf reinforcement mat is designed to stay in place permanently to increase the erosion resistance of the vegetated channel lining.

UNDERMINING – Erosion extending beneath a structure which removes materials that are necessary to the integrity of its foundation.

UNIFORM FLOW – A flow condition characterized by a constant cross section and velocity through a given reach of channel. Under this condition, the slopes of the energy grade line, the water surface, and the channel bed are constant and equal.

UNSTEADY FLOW – A flow condition where the discharge and water surface profile change with respect to time. Unsteady flow can be difficult to analyze unless except with small time increments.

UV STABILIZED – A plastic material, used in geotextiles or pipes, having been chemically modified to resist decomposition in ultra violet light.

VEGETATED LINING – A channel lining composed of grasses or other types of vegetation that resist the erosive forces exerted by the flows in channel.

VORTEX – A turbulent zone in a flow field characterized by circular motion in the horizontal plane and often caused by an obstruction such as a bridge pier (as in a horseshoe vortex) or abutment.

WETTED PERIMETER – The length of that portion of the cross section of a channel or other drainage way that is in contact with the water, measured perpendicular to the direction of flow.

5.08.4 REFERENCES

U.S. Army Corps of Engineers, Hydraulic Engineering Center, *HEC-RAS River Analysis System, Hydraulic Reference Manual.* Davis, California, January, 2001.

U.S. Department of Transportation, Federal Highway Administration. *Design Charts for Open Channel Flow*. Hydraulic Design Series No. 3 (HDS-3). Report No. EPD-86-102. Washington, D.C. August 1961.

U.S. Department of Transportation, Federal Highway Administration. *Design of Roadside Channels*. Hydraulic Design Series No. 4 (HDS-4). Washington, D.C. May 1965.

U.S. Department of Transportation, Federal Highway Administration. *Introduction to Highway Hydraulics*. Hydraulics Design Series No. 4 (HDS-4), Publication No. FHWA NHI 01-019. Washington, D.C. August 2001.

U.S. Department of Transportation, Federal Highway Administration. *River Engineering for Highway Encroachments, Highways in the River Environment (HIRE)*. Hydraulics Design Series No. 6 (HDS-6), Publication No. FHWA NHI 01-004. Washington, D.C. December 2001.

U.S. Department of Transportation, Federal Highway Administration. *Design of Riprap revetment*. Hydraulic Engineering Circular No. 11 (HEC-11). Publication No. FHWA-IP-89-016. McLean, VA. March 1989.

U.S. Department of Transportation, Federal Highway Administration. *Design of Stable Channels with Flexible Linings*. Hydraulic Engineering Circular No. 15 (HEC-15). Washington, D.C. 1986.

U.S. Department of Transportation, Federal Highway Administration. *Design of Roadside Channels with Flexible Linings*. Hydraulic Engineering Circular No. 15 (HEC-15), Publication No. FHWA-IP-87-7. McLean, Virginia. April 1988.

U.S. Department of Transportation, Federal Highway Administration. *Design of Roadside Channels with Flexible Linings*. Hydraulic Engineering Circular No. 15 (HEC-15), Third Edition, Publication No. FHWA-NHI-05-114. Washington, D.C. September 2005.

U.S. Department of Transportation, Federal Highway Administration. *Urban Drainage Design Manual.* Hydraulic Engineering Circular No. 22 (HEC-22), Publication No. FHWA SA-96-078. Washington, D.C. November 1996.

U.S. Department of Transportation, Federal Highway Administration. *Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains*. Report No. FHWA-TS-84-204. Washington, D.C. April 1984.

U.S. Department of Agriculture. United States Geological Survey. *Roughness Characteristics of Natural Channels.* U.S.G.S. Water-Supply Paper 1849. 1967.

U. S. Department of Agriculture. Soil Conservation Service. Fasken, Guy B., *Guide For Selecting Roughness Coefficient "n" Values For Channels*. December 1963.

U.S. Department of Agriculture, Soil Conservation Service. *Permissible Velocities for Erodible*

Linings. Technical Paper No. SCS-TP-60. October 1985.

U.S. Department of Agriculture, Soil Conservation Service. Ree, W.O., *Handbook of Channel Design for Soil and Water Conservation.* Technical Paper No. SCS-TP-61. March 1947.
U.S. Department of Agriculture, Soil Conservation Service. *Hydraulics.* National Engineering Handbook. Section 5 (NEH-5). 1956.

U.S. Department of Interior, U.S. Geological Survey. *Determination of the Manning Coefficient from Measured Bed Roughness in Natural Channels*, Water Supply Paper 1898-B, 1970.

Cowan, W.L., *Estimated Hydraulic Roughness Coefficients.* Agriculture Engineering v. 37, no. 7. 1956.

Hankins, Jr., A.L. *Guidelines for Drainage Studies and Hydraulic Design*. North Carolina Department of Transportation. Raleigh, North Carolina. 1999.

Indiana Department of Transportation. *Indiana Design Manual Part IV Volume I*. Indianapolis, Indiana. 1999.

Tennessee Department of Transportation, Design Division, *Design Guidelines - English*. Nashville, Tennessee. April 2001.

Texas Department of Transportation, *Hydraulic Design Manual.* Austin, Texas. November 2002.

Virginia Department of Transportation. Location and Design Division. *Drainage Manual*. Richmond, Virginia. April 2002.

American Association of State Highway and Transportation Officials. *Model Drainage Manual*. [Metric Edition]. Washington, D.C. 1999.

Brater, Ernest; King, Horace; Lindell, James; Wei, C.Y.; *Handbook of Hydraulics*, 7th ed., McGraw Hill Book Company, Inc., New York, NY 1996.

Chow, V.T., *Open Channel Hydraulics*. McGraw Hill Book Company, Inc., New York, NY. 1959.

Chow, V.T., *Handbook of Applied Hydrology*. McGraw Hill Book Company, Inc., New York, NY. 1964.

Maynord, S.T., *Stable Riprap Size for Open Channel Flow.* Ph.D. Dissertation, Colorado State University, Fort Collins, Colorado. 1987.

Reese, A.J., *Nomographic Riprap Design.* Miscellaneous Paper HL 88-2. U.S. Army Engineers, Waterways Experiment Station. Vicksburg, Mississippi. 1988.

Reese, A.J., *Riprap Sizing, Four Method.* In Proceedings of ASCE Conference on Water for Resource Development, Hydraulics Division, ASCE. David L. Schreiber, ed. 1984.

5.08.5 ABBREVIATIONS

ADT – Average Daily Traffic
ASCE – American Society of Civil Engineers
DHV – Design Hourly Volume
DTM – Digital Terrain Model
EA – Environmental Assessment
EIS – Environmental Impact Statement
FEMA – Federal Emergency Management Agency
FHWA – Federal Highway Administration
HDS-3 – Hydraulic Design Series Number 3
HDS-4 – Hydraulic Design Series Number 4
HEC-15 – Hydrologic Engineering Circular Number 15
HEC-22 – Hydrologic Engineering Circular Number 22
HEC-RAS –- Hydrologic Engineering Center – River Analysis System
HIRE – Highways in the River Environment
HYCHL – Flexible and Rigid Channel Lining Design and Analysis
NEH – National Engineering Handbook
NRCS – Natural Resource Conservation Service
RAS – River Analysis System
SCS – Soil Conservation Service
TDOT – Tennessee Department of Transportation
TDEC – Tennessee Department of Environment and Conservation
TP – Technical Paper
TRM – Turf Reinforcement Mat
USDA – United States Department of Agriculture
USDOT – United States Department of Transportation
USGS – United States Geological Survey
WTEC – Watershed Technology Electric Catalog