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CHAPTER THIRTY

CHANNELS

30-1.0 INTRODUCTION

30-1.01 Definitions

An open channel is a natural or constructed conveyance for water in which the water surface is exposed to the atmosphere and the gravity-force component in the direction of motion is the driving force.

The types of open channels related to a transportation facility are as follows:

1. stream channels;
2. roadside channels or ditches;
3. interceptor ditches; and
4. drainage ditches.

The principles of open-channel-flow hydraulics are applicable to each drainage facility including a culvert or a storm drain.

A stream channel has the properties as follows:

1. is a natural channel with its size and shape determined by natural forces;

2. is compound in cross section with a main channel for conveying low flow and a floodplain to transport flood flow, and

3. is shaped geomorphologically by the long-term history of sediment load and water discharge which it experiences.

An artificial channel can be a roadside channel, interceptor ditch, or drainage ditch which can be a constructed channel with regular geometric cross section, and is unlined or lined with artificial or natural material to protect against erosion.

Although the principles of open-channel flow are the same regardless of the channel type, a stream channel and an artificial channel (primarily a roadside channel) will be treated separately in this Chapter as needed.

30-1.02 Significance [Rev. Jan. 2011]

Channel analysis is necessary for the design of a transportation drainage system to assess the following:

1. potential flooding caused by changes in water-surface profile;
2. disturbance of the river system upstream or downstream of the highway right of way;
3. changes in lateral flow distribution;
4. changes in velocity or direction of flow;
5. need for conveyance and disposal of excess runoff; and
6. need for channel lining to prevent erosion.
7. potential impacts to water quality.

30-1.03 Design

Hydraulic design associated with a natural channel or side ditch is a process which selects and evaluates alternatives according to established criteria. These criteria are the standards established by INDOT to ensure that a highway facility satisfies its intended purpose without endangering the structural integrity of the facility itself and without undue adverse effects on the environment or the public welfare.

30-1.04 Purpose

The purpose of this Chapter is as follows:

1. establish INDOT policy;
2. specify design criteria;
3. review design philosophy;
4. outline channel-design procedures; and
5. demonstrate design techniques by means of example problems.

30-1.05 Symbols

To provide consistency within this Chapter and throughout this *Manual*, see Figure 30-1A, Symbols for Open Channels.

30-2.0 POLICY

30-2.01 General

Policy is a set of goals that establish a definite course or method of action and that are selected to guide and determine present and future decisions. Policy is implemented through design criteria established as standards for making decisions. See Section 30-3.0.

30-2.02 Federal Policy

The following Federal policies apply.

1. Channel design or design of a highway facility that impacts a channel should satisfy the policies of the Federal Highway Administration applicable to floodplain management if Federal funding is involved.

2. Federal Emergency Management Agency floodway regulations and Corps of Engineers' wetland restrictions for permits should be satisfied.

30-2.03 INDOT Policy [Rev. Jan. 2011]

The following INDOT policies apply.

1. Coordination with other Federal, State, or local agencies concerned with water-resources planning should have high priority in the planning of a highway facility.

2. The safety of the general public should be a consideration in selection of the cross-sectional geometry of an artificial drainage channel.

3. The design of an artificial drainage channel or other facility should consider the frequency and type of maintenance expected, and should make allowance for the access of maintenance equipment.

4. A stable channel is the goal for each channel that is located on highway right of way or that impacts a highway facility.

5. The environmental impacts of channel modification, including disturbance of fish habitat, wetlands, water quality, or channel stability, should be assessed.

6. The range of design-channel discharges should be selected and approved by the designer based on roadway functional classification, the consequences of traffic interruption, flood hazard risks, economics, or local site conditions.

30-3.0 DESIGN CRITERIA

30-3.01 General

The design criteria establish the standards by which a policy is placed into action. They form the basis for the selection of the final design configuration. Listed below are examples of design criteria which should be considered for channel design.

30-3.02 Stream Channel

The following criteria apply to a natural channel.

1. The hydraulic effects of floodplain encroachment should be evaluated over a full range of frequency-based peak discharges from the mean annual or bank full flood through the 500-year flood on a major highway facility as deemed necessary by the designer.

2. If relocation of a stream channel is unavoidable, the cross-sectional shape, meander, pattern, roughness, sediment transport, and slope satisfy the existing conditions insofar as practical. A means of energy dissipation may be necessary where existing conditions cannot be duplicated. See Chapter Thirty-four.

3. Stream bank stabilization should be provided, where appropriate, as a result of a stream disturbance such as encroachment, and should include both upstream and downstream banks and the local site.

4. Incorporate provisions into the design and construction for access by maintenance personnel and equipment to maintain features such as a dike or a levee.

5. Realignment or change to a natural channel should be minimized. The conditions that warrant a channel change are as follows:

    a. the natural channel crosses the roadway at an extreme skew;

    b. the embankment encroaches on the channel;

    c. the natural channel has inadequate capacity; or

    d. the location of the natural channel endangers the highway embankment or adjacent property.

    The most important factor in channel design is the effect of scour and siltation.

30-3.03 Roadside Channel, or Side Ditch

A roadside channel is a channel, or side ditch, adjacent to the roadway which intercepts runoff and groundwater within the right of way and transports this flow to drainage structures or to a natural waterway.

> ** *PRACTICE POINTER* **
>
> If a property owner has a pipe instead of an open ditch on the property, an equivalent new pipe should be provided instead of an open ditch.

30-3.03(01) General

The following criteria apply to a roadside channel.

1. Safety. Clear-zone requirements should be satisfied (see Chapter Forty-nine). Channel side slopes should not exceed the angle of repose of the soil or lining, and should be 2H:1V or flatter for rock riprap lining. See Chapter Forty-five for more information on the cross section of a roadside channel.

2. Design Discharge. The design discharge for permanent roadside channel lining should have a 10-year frequency flow. A temporary lining should be designed for a 2-year frequency flow.

3. Freeboard. If an inadequate freeboard is provided, the depth of flow may exceed d_{max} and, thereby, increase the potential for scour in the channel. In addition, freeboard provides a margin of safety against channel overtopping and its consequences. Channel freeboard should be 6 to 12 in. or two velocity heads, whichever is greater, measured vertically. This should be adequate for a small drainage channel. However, more freeboard may be appropriate, or, no freeboard may be necessary.

30-3.03(02) Channel Lining

The selection of a roadside-channel lining must reflect both initial costs and long-term maintenance costs. The channel lining should be selected based on the method of allowable tractive force. This is discussed in Section 30-6.03. The following provides the INDOT practice for roadside-channel lining. However, the use of these criteria should be confirmed using the lining-selection methodology described in Section 30-6.03:

1. Seeded Channel ($G < 1\%$). A seeded channel is protected from erosion by means of fast-growing permanent seeding. This type of channel has the advantage of being low in initial cost and maintenance, aesthetically pleasing, and compatible with the natural environment. The use of an erosion control mat (e.g., straw, coconut fiber) is encouraged to help establish seed growth.

2. Sod-Lined Channel ($1\% \leq G < 3\%$). A sod-lined channel is protected from erosion by means of a sod cover. It is used as a roadside channel in a median or at a channel change of a small watercourse. It may also be used on steeper grades where ditch flow is a minimum. A sodded channel has the advantage of being low in initial cost, aesthetically pleasing, and compatible with the natural environment. This type of channel should be selected for use wherever practical. A sodded channel should be sodded to a point 1 ft above the flow line.

3. Paved Channel ($G \geq 3\%$). A paved concrete ditch is extremely resistant to erosion. Its principal disadvantages are its high maintenance and initial costs, susceptibility to failure if undermined by scour, and the tendency for scour to occur downstream due to an acceleration of flow.

   The INDOT *Standard Drawings* illustrate the paved channels used by the Department. Type A through H is used where the toe of the ditch is outside of the clear zone. Type J through M is used where the toe of the ditch is inside the clear zone. For Type J through M, place the 6H:1V sideslope nearest to the roadway. The INDOT *Standard Drawings* also indicate the type of paved channel that should be used based on the diameter of the pipe at the outlet and inlet.

4. Riprap-Lined Channel ($3\% \leq G \leq 10\%$). A riprap lining is effective for this slope range, depending on the design flow of the channel. However, riprap should be used on a slope steeper than 10% at a bridge cone. It is also appropriate to use riprap in a ditch where the grade is flatter than 3%. For example, if there is a hill in the ditch watershed, riprap should be placed to dissipate energy and minimize ditch erosion. A mild slope is constructed by dumping riprap into a prepared channel lined with geotextile filter cloth and grading to the desired shape. The advantages are low construction and maintenance costs and self-healing characteristics. Riprap has limited application on a steep slope where the flow will tend to displace the lining material.

5. Non-Erodible Channel ($3\% \leq G \leq 15\%$). A non-erodible channel has a lining of soil erosion matting that is highly resistant to erosion. This type of channel is moderately expensive to construct and, if properly designed, should have a very low maintenance cost.

The lining material should extend to the top of the channel or to at least 6 in. above the design water level measured vertically.

30-3.04 Drainage Ditch

A drainage ditch is a channel which is not immediately adjacent to the roadway but which is part of the roadway facility's overall drainage system. It includes, for example, an interceptor ditch, which is located in the natural ground near the top edge of a cut slope or down the backslope in a cut section from a small natural drainage course from outside the right of way. The criteria for a roadside channel are more stringent than those for a drainage ditch. Therefore, such criteria are listed separately. This is true for a ditch that may be located off the highway right of way.

The following criteria apply to a drainage ditch.

1. An unlined drainage ditch is considered erodible and should have a capacity equal to, or greater than, the 10-year frequency design flow with a velocity equal to or less than the maximum allowable velocity shown in Figure 30-3A, Maximum Velocity in Drainage Ditch.

2. A bend in an erodible drainage ditch should have a minimum radius to the center of the ditch of three times the bottom width. This will tend to minimize the scouring effect at the bend.

3. An erodible drainage ditch may need scour protection where it is located adjacent to a highway embankment, especially at bends in the ditch. Riprap or other suitable protection should be provided where necessary.

30-3.05 Other Criteria

The following applies to a roadside channel or other type of drainage ditch.

1. Transition. A paved-side-ditch transition is required at an intersection with an earth ditch or pipe culvert.

2. Cut-Off Wall. A cut-off wall is required at the beginning and end of each paved side ditch.

3. Lug. Lugs have been proven to prevent sliding on a steep slope. A lug should be provided at the locations as follows:

    a. 10 ft downslope from a grade change;
    b. 10 ft downslope from the intersection of different types of paved side ditches;
    c. at the downslope end of a transition between different types of paved side ditches; and
    d. as shown in Figure 30-3B, Lug Intervals.

30-4.0 OPEN-CHANNEL FLOW

30-4.01 General

Design analysis of both natural and artificial channels proceeds according to the basic principles of open channel flow (see Chow, 1970; Henderson, 1966). The basic principles of fluid mechanics continuity, momentum, and energy can be applied to open-channel flow with the additional complication that the position of the free surface is one of the unknown variables. The determination of this unknown is one of the principal problems of open-channel flow analysis and it depends on quantification of the flow resistance. A natural channel displays a much wider range of roughness values than an artificial channel.

30-4.02 Definitions

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

$$E = \frac{\alpha V^2}{2g} + y \qquad \text{(Equation 30-4.1)}$$

Where: y = depth, ft
α = velocity distribution coefficient (see Equation 30-4.2)
V = mean velocity, ft/s
g = gravitational acceleration, 32.2 ft/s^2

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

$$\alpha = \sum_{i=1}^{n}\left(\frac{K^3{}_i}{A^2{}_i}\right) \Big/ \left(\frac{K^3{}_t}{A^2{}_t}\right) \qquad \text{(Equation 30-4.2)}$$

Where: K_i = conveyance in subsection (see Equation 30-4.8)
K_t = total conveyance in section (see Equation 30-4.8)

A_i = cross-sectional area of subsection, ft^2
A_t = total cross-sectional area of section, ft^2
n = number of subsections

The velocity distribution coefficient should be taken as 1 for turbulent flow in a prismatic channel, but may be different in a natural channel.

3. Total Energy Head. The total energy head is the specific energy head plus the elevation of the channel bottom with respect to a datum. The locus of the energy head from one cross section to the next defines the energy grade line. See Figure 30-4A, Specific Energy and Discharge Diagram for Rectangular Channel.

4. Steady or Unsteady Flow. A steady flow is one in which the discharge passing a given cross section is constant with respect to time. The maintenance of steady flow in a reach requires that the rates of inflow and outflow be constant and equal. Where the discharge varies with time, the flow is unsteady.

5. Uniform Flow or Non-uniform Flow. A non-uniform flow is one in which the velocity and depth vary in the direction of motion while they remain constant in uniform flow. Uniform flow can only occur in a prismatic channel, which is a channel of constant cross section, roughness, and slope in the flow direction. However, non-uniform flow can occur either in a prismatic channel or in a natural channel with variable properties.

6. Gradually-Varied or Rapidly-Varied Flow. A non-uniform flow, in which the depth and velocity change gradually enough in the flow direction that vertical accelerations can be neglected, is referred to as a gradually-varied flow. Otherwise, it is considered to be rapidly-varied.

7. Froude Number. The Froude number, *Fr*, is a dimensionless parameter in open-channel flow. It represents the ratio of inertial forces to gravitational forces and is defined as follows:

$$Fr = \frac{Va}{(gd)^{0.5}}$$ (Equation 30-4.3)

Where: α = velocity distribution coefficient
V = mean velocity = Q/A, ft/s
g = gravitational acceleration, 32.2 ft/s^2
d = hydraulic depth = A/T, ft
A = cross-sectional area of flow, ft^2
T = channel top width at the water surface, ft
Q = total discharge, ft^3/s

This expression applies to a single-section channel. For a rectangular channel, the hydraulic depth is equal to the flow depth.

8. Critical Flow. Critical flow occurs if the specific energy is a minimum. The variation of specific energy with depth at a constant discharge shows a minimum in the specific energy at a depth called critical depth at which the Froude number has a value of 1. Critical depth is also the depth of maximum discharge if the specific energy is held constant. These relationships are illustrated in Figure 30-4A, Specific Energy and Discharge Diagram for Rectangular Channel. During critical flow, the velocity head is equal to half the hydraulic depth. The expression for flow at critical depth is as follows:

$$\frac{\alpha Q^2}{g} = \frac{A^3}{T}$$ (Equation 30-4.4)

Where: α = velocity distribution coefficient
Q = total discharge, ft^3/s
g = gravitational acceleration, 32.2 ft/s^2
A = cross-sectional area of flow, ft^2
T = channel top width at the water surface, ft

If flow is at critical depth, Equation 30-4.4 must be satisfied, regardless of the shape of the channel.

9. Subcritical Flow. A depth greater than the critical depth occurs in subcritical flow and the Froude number is less than 1. In this state of flow, small water surface disturbances can travel both upstream and downstream, and the control is located downstream.

10. Supercritical Flow. A depth less than the critical depth occurs in supercritical flow and the Froude number is greater than 1. Small water surface disturbances are swept downstream in supercritical flow, and the location of the flow control is always upstream.

11. Hydraulic Jump. A hydraulic jump occurs as an abrupt transition from supercritical to subcritical flow in the flow direction. There are significant changes in depth and velocity in the jump, and energy is dissipated. For this reason, the hydraulic jump is often employed to dissipate energy and control erosion at a highway-drainage structure.

30-4.03 Flow Classification

The classification of open-channel flow can be summarized as follows.

1. Steady Flow

   a. Uniform Flow
   b. Non-uniform Flow
      (1) Gradually-Varied Flow
      (2) Rapidly-Varied Flow

2. Unsteady Flow

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

Steady uniform flow and the steady non-uniform flow are the most fundamental types of flow treated in highway-engineering hydraulics.

30-4.04 Equations

The following equations are those used to analyze open-channel flow. The use of these equations in analyzing open-channel hydraulics is discussed in Section 30-5.0.

1. Continuity Equation. The continuity equation is the statement of conservation of mass in fluid mechanics. For one-dimensional, steady flow of an incompressible fluid, it assumes the simple form as follows:

$$Q = A_1V_1 = A_2V_2 \qquad \text{(Equation 30-4.5)}$$

Where: Q = discharge, ft^3/s
A = cross-sectional area of flow, ft^2
V = mean cross-sectional velocity perpendicular to the cross section, ft/s

The subscripts *1* and *2* refer to successive cross sections along the flow path.

2. Manning's Equation. For a given depth of flow in an open channel with a steady, uniform flow, the mean velocity, V, can be computed as follows:

$$V = \frac{R^{0.67} S^{0.5}}{n} \qquad \text{(Equation 30-4.6)}$$

Where: V = velocity, ft/s

n = Manning's roughness coefficient
R = hydraulic radius = A/P, ft
P = wetted perimeter, ft
S = slope of the energy gradeline, ft/ft. For steady uniform flow, S = channel slope
A = cross-sectional area of flow, ft^2

The selection of Manning's n is based on observation. However, considerable experience is essential in selecting appropriate n value. The selection of Manning's n is discussed in Section 30-5.02(01). The range of n values for each type of channel and floodplain is shown in Figure 30-4B, Uniform Flow (Value of Manning's n).

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

$$Q = [(1.486/n)AR^{2/3}S^{1/2}]$$ (Equation 30-4.7)

For a given channel geometry, slope, and roughness, and a specified value of Q, a unique value of depth occurs in steady, uniform flow. It is called normal depth and is computed from Equation 30-4.7 by expressing the area and hydraulic radius in terms of depth. The resulting equation may require a trial-and-error solution. See Section 30-5.03 for a more detailed discussion of the computation of normal depth.

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

3. Conveyance. In channel analysis, it is convenient to group the channel properties into a single term called the channel conveyance, K.

$$K = (1.486/n)AR^{2/3}$$ (Equation 30-4.8)

Equation 30-4.7 can then be written as follows:

$$Q = KS^{0.5}$$ (Equation 30-4.9)

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

Channel conveyance is useful in computing the distribution of overbank flood flows in the stream cross-section, or the flow distribution through the opening in a proposed stream crossing. It is also used to determine the velocity distribution coefficient, ά (see Equation 30-4.2).

4. Energy Equation. The energy equation expresses conservation of energy stated as energy per unit weight of fluid, which has the dimension of length, and is therefore called energy head. The energy head is composed of potential energy head (elevation head), pressure head, and kinetic energy head (velocity head). These energy heads are scalar quantities which give the total energy head at a given cross section once added. Between an upstream open channel cross section designated 1 and a downstream cross section designated 2, the energy equation is as follows:

$$h_1 + \frac{\alpha_1 V_1^{\,2}}{2g} = h2 + \frac{\alpha_2 V_2^{\,2}}{2g} + h_L \qquad \text{(Equation 30-4.10)}$$

Where: h_1 and h_2 = the upstream and downstream stages, respectively, ft
α = velocity distribution coefficient
V = mean velocity, ft/s
h_L = head loss due to local cross-sectional changes (minor loss) and boundary resistance, ft

The stage h is the sum of the elevation head z at the channel bottom and the pressure head, or depth of flow y, therefore, $h = z + y$. See Figure 30-4C, Terms in the Energy Equation. The energy equation states that the total energy head at an upstream cross section is equal to the energy head at a downstream section plus the intervening energy head loss. The energy equation can only be applied between two cross sections at which the streamlines are nearly straight and parallel so that vertical accelerations can be neglected.

30-5.0 HYDRAULIC ANALYSIS

30-5.01 General

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

Two methods are commonly used. The single-section method is a simple application of Manning's equation to determine tailwater rating curves for a culvert or to analyze other situations in which uniform or nearly-uniform flow conditions exist. Manning's equation can be used to estimate the high-water elevation for a bridge that does not constrict the flow. The step-backwater method is used to compute the complete water surface profile in a stream reach to evaluate the unrestricted water-surface elevations for bridge hydraulic design or to analyze other gradually-varied flow problems in a stream.

The single-section method will yield less-reliable results because it requires more judgment and assumptions than the step-backwater method. However, the single-section method is all that is justified (e.g., standard roadway ditch, culvert, storm drain outfall).

30-5.02 Cross Sections

Cross-sectional geometry of a stream is defined by coordinates of lateral distance and ground elevation which locate individual ground points. The cross section is taken normal to the flow direction along a single straight line where possible. In a wide floodplain or bend, it may be necessary to use a section along intersecting straight lines; i.e., a dog-leg section. The cross section should be plotted to reveal inconsistencies or errors.

Cross sections should be located to be representative of the subreaches between them. A stream location with major breaks in bed profile, abrupt changes in roughness or shape, control sections such as free overfalls, bends, or contractions, or other abrupt changes in channel slope or conveyance will require cross sections taken at shorter intervals to better model the change in conveyance.

Cross sections should be subdivided with vertical boundaries where there are abrupt lateral changes in geometry or roughness, such as in overbank flow. The conveyances of each subsection are computed separately to determine the flow distribution, and ά and are then added to determine the total flow conveyance. The subsection divisions must be chosen so that the distribution of flow or conveyance is nearly uniform in each subsection (Davidian, 1984). Selection of cross sections and vertical subdivision of a cross section are shown in Figure 30-5A, Hypothetical Cross Section Showing Reaches, Segments and Subsections Used in Determining *n* Value.

30-5.02(01) Manning's *n* Value Selection

Manning's *n* is affected by many factors, and its selection for a natural channel depends on engineering experience. Pictures of channels and floodplains for which the discharge has been measured and Manning's *n* has been calculated are useful (see Arcement and Schneider, 1984; Barnes, 1978). A more-regimented approach is provided in Arcement and Schneider, 1984. Once the Manning's *n* value has been selected, it should be verified or calibrated with historical high-water marks or gaged streamflow data.

Manning's *n* value for an artificial channel is more easily defined than for a natural stream channel. See Figure 30-4B, Uniform Flow (Value of Manning's *n*), for the *n* value for an artificial channel or a natural stream channel.

30-5.02(02) Calibration

The equations should be calibrated with historical high-water marks or gaged streamflow data to ensure that they accurately represent local channel conditions. The following parameters, in order of preference, should be used for calibrations: Manning's *n*, slope, discharge, cross section. Proper calibration is essential if accurate results are to be obtained.

30-5.02(03) Switchback Phenomenon

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

See Figure 30-5A(1) for the switchback phenomenon.

The phenomenon can occur in any type of conveyance computation, including the step-backwater method. Computer logic can be confused if a switchback occurs in a cross section being used in a step-backwater program. For this reason, the cross section should be subdivided with respect to both vegetation and geometric changes. The actual *n* value itself may be the same in adjacent subsections.

<u>30-5.03 Single-Section Analysis</u>

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

A stage-discharge curve is a graphical relationship of streamflow depth or elevation to discharge at a specific point on a stream. This relationship should include a range of discharges up to at least the base 100-year flood. The stage-discharge curve can be determined as follows.

1. Select the typical cross section at or near the location where the stage-discharge curve is needed.

2. Subdivide the cross section and assign *n* values to subsections as described in Section 30-5.02(01).

3. Estimate water-surface slope. Because uniform flow is assumed, the average slope of the streambed can be used.

4. Apply a range of incremental water-surface elevations to the cross section.

5. Calculate the discharge using Manning's equation for each incremental elevation. Total discharge at each elevation is the sum of the discharges from each subsection at that elevation. In determining hydraulic radius, the wetted perimeter should be measured only along the solid boundary of the cross section and not along the vertical water interface between subsections.

6. After the discharge has been calculated at several incremental elevations, a plot of stage versus discharge should be made. This plot is the stage-discharge curve, and it can be used to determine the water-surface elevation corresponding to the design discharge or other discharges of interest.

An example application of the stage-discharge curve procedure is provided in Section 30-8.0.

Alternatively, a graphical technique such as that shown in Figure 30-5B, Trapezoidal Channel Capacity Chart, or a nomograph as in Figure 30-5C, Nomograph for Normal Depth, can be used for a trapezoidal or prismatic channel. The best approach for a stream channel is to use a computer program such as WSPRO, HEC-RAS or HEC-2 to obtain the normal depth.

In a stream channel, the transverse variation of velocity in a cross section is a function of subsection geometry and roughness, and may vary considerably from one stage and discharge to another. This variation should be considered for the purpose of designing erosion-control measures and locating relief openings in a highway fill, for example. The best method of establishing transverse velocity variations is by means of current foot measurements. If this is not possible, the single-section method can be used by dividing the cross section into subsections of relatively uniform roughness and geometry. The energy-grade-line slope is assumed to be the same across the cross section so that the total conveyance, K_t, of the cross section is the sum of the subsection conveyances. The total discharge is then $K_t S^{1/2}$, and the discharge in each subsection is proportional to its conveyance. The velocity in each subsection is obtained from the continuity equation, $V = Q/A$.

An alluvial channel provides for a more-difficult problem in establishing stage-discharge relations by the single-section method because the bed itself is deformable and may generate bed forms such as ripples and dunes in lower-regime flows. These bed forms are highly variable with the addition of form resistance, and selection of a value of Manning's *n* is not straightforward. Instead, the methods outlined in Vanoni, 1977 have been developed for this situation (Einstein-Barbarossa; Kennedy-Alam-Lovera; and Engelund), and should be followed unless it is possible to obtain a measured stage-discharge relation.

There may be a location where a stage-discharge relationship has already been measured in a channel. This usually exists at a gaging station on a stream monitored by the USGS. Measured stage-discharge curves will yield more accurate estimates of water-surface elevation, and should take precedence over the analytical methods described above.

30-5.04 Step-Backwater Analysis

Step-backwater analysis is useful for determining unrestricted water surface profiles where a highway crossing is planned, or for analyzing how far upstream the water-surface elevation is affected by a culvert or bridge. Because the calculations involved in this analysis are tedious and repetitive, a computer program such as the FHWA/USGS program WSPRO or Corps of Engineers HEC-2 should be used.

30-5.04(01) Step-Backwater Models

The WSPRO program has been designed to provide a water-surface profile for the types of open-channel-flow situations as follows:

1. unconstricted flow;
2. single-opening bridge;
3. bridge opening with spur dikes;
4. single-opening embankment overflow;
5. multiple alternatives for a single site; and
6. multiple openings.

The HEC-2 or HEC-RAS programs developed by the Corps of Engineers are used for calculating water surface profile for steady gradually-varied flow in a natural or constructed channel. Both subcritical and supercritical flow profiles can be calculated. The effect of a bridge, culvert, weir, or other structure in the floodplain may be also considered in the computations. This program is also designed for application in a floodplain-management or flood-insurance study.

30-5.04(02) Step-Backwater Methodology

The computation of water-surface profiles by WSPRO, HEC-RAS, or HEC-2 is based on the standard step method in which the stream reach of interest is divided into a number of subreaches by cross sections spaced such that the flow is gradually varied in each subreach. The energy equation is then solved in a step-wise fashion for the stage at one cross section based on the stage at the previous cross section.

The method requires definition of the geometry and roughness of each cross section as discussed in Section 30-5.01. Manning's *n* values can vary both horizontally and vertically across the section. Expansion and contraction head-loss coefficients, variable main-channel and overbank flow lengths, and the method of averaging the slope of the energy grade line can all be specified.

To clarify the methodology, the energy equation from Section 30-4.04 is repeated below.

$$h_1 + \frac{\alpha_1 V_1^{\,2}}{2g} = h2 + \frac{\alpha_2 V_2^{\,2}}{2g} + h_L \qquad \text{(Equation 30-4.10)}$$

The total head loss is calculated as follows:

$$h_L = K_m \left(\frac{\alpha 1 V_1^{\,2} - \alpha 2 V_2^{\,2}}{2g} \right) + S_f L \qquad \text{(Equation 30-5.2)}$$

Where:
- K_m = expansion or contraction loss coefficient
- $\overline{S}_f$ = the mean slope of the energy grade line evaluated from Manning's equation and a selected averaging technique, ft/ft
- L = discharge-weighted or conveyance-weighted reach length, ft

These equations are solved numerically in a step-by-step procedure called the Standard Step Method from one cross section to the next.

The default values of the minor-loss coefficient, K_m, are 0 and 0.1 for a contraction, or 0.5 and 0.3 for an expansion, in WSPRO and HEC-2, respectively. HEC-RAS requires that the user input the value for K_m. The range of these coefficients, from an ideal transition to an abrupt change, is 0.0 to 1.0 for an expansion, or 0.0 to 0.5 for a contraction.

WSPRO calculates a conveyance-weighted reach length, L, as follows:

$$L = \frac{L_{lob}K_{lob} + L_{ch}K_{ch} + L_{rob}K_{rob}}{K_{lob} + K_{ch} + K_{rob}} \qquad \text{(Equation 30-5.3)}$$

Where: L_{lob}, L_{ch}, L_{rob} = flow distance between cross sections in the left overbank, main channel, and right overbank, respectively, ft

K_{lob}, K_{ch}, K_{rob} = conveyance in the left overbank, main channel, and right overbank, respectively, of the cross section with the unknown water-surface elevation

HEC-2 or HEC-RAS calculates a discharge-weighted reach length, L, as follows:

$$L = \frac{L_{lob}Q_{lob} + L_{ch}Q_{ch} + L_{rob}Q_{rob}}{Q_{lob} + Q_{ch} + Q_{rob}} \qquad \text{(Equation 30-5.4)}$$

Where: L_{lob}, L_{ch}, L_{rob} = flow distance between cross sections in the left overbank, main channel, and right overbank, respectively, ft

Q_{lob}, Q_{ch}, Q_{rob} = arithmetic average of flows between cross sections for the left overbank, main channel, and right overbank, respectively, ft^3/s

WSPRO, HEC-RAS, or HEC-2 allows the user the following options for determining the friction slope, S_f.

1. Average conveyance equation:

$$S_f = \left[\frac{(Q_u + Q_d)}{K_u + K_d}\right]^2 \qquad \text{(Equation 30-5.5)}$$

2. Average friction slope equation:

$$S_f = \frac{S_{fu} + S_{fd}}{2} \qquad \text{(Equation 30-5.6)}$$

3. Geometric mean friction slope equation:

$$S_f = \sqrt{S_{fu} S_{fd}}$$ (Equation 30-5.7)

4. Harmonic mean friction slope equation:

$$S_f = \frac{2 S_{fu} S_{fd}}{S_{fu} + S_{fd}}$$ (Equation 30-5.8)

Where: Q_u , Q_d = discharge at the upstream and downstream cross sections, respectively, ft^3/s

K_u , K_d = conveyance at the upstream and downstream cross sections, respectively

S_{fu} , S_{fd} = friction slope at the upstream and downstream cross sections, respectively, ft/ft

The default option is the geometric mean friction slope equation in WSPRO and the average conveyance equation in HEC-2 and HEC-RAS.

30-5.04(03) Profile Computation

Water surface profile computation requires a beginning value of elevation or depth (boundary condition) and proceeds upstream for subcritical flow, or downstream for supercritical flow. For supercritical flow, critical depth is often the boundary condition at the control section. For subcritical flow, uniform flow and normal depth may be the boundary condition. The starting depth can be found by the single-section method (slope-area method) or by computing the water surface profile upstream to the desired location for several starting depths and the same discharge. The profiles should converge toward the desired normal depth at the control section to establish one point on the stage-discharge relation. If the several profiles do not converge, the stream reach may need to be extended downstream, a shorter cross section interval should be used, or the range of starting water-surface elevations should be adjusted. A plot of the convergence profiles can be a useful tool in such an analysis (see Figure 30-5D, Profile Convergence Pattern Backwater Computations).

Given a long-enough stream reach, the water-surface profile computed by step-backwater will converge to normal depth at some point upstream for subcritical flow. Establishment of the upstream and downstream boundaries of the stream reach is required to define limits of data collection and subsequent analysis. Calculations must begin sufficiently far downstream to ensure accurate results at the structure site, and continued a sufficient distance upstream to accurately determine the impact of the structure on upstream water-surface profiles (see Figure 30-5E, Profile Study Limits).

The Corps of Engineers (USACOE, 1986) developed equations for determining upstream and downstream reach lengths as follows:

$$L_d = \frac{1.2(HD)^{0.8}}{S} \qquad \text{(Equation 30-5.9)}$$

$$L_u = 1000[(HD^{0.6})(HL^{0.5})]/S \qquad \text{(Equation 30-5.10)}$$

Where: L_d = downstream study length along main channel for normal-depth starting condition, ft

L_u = estimated upstream study length along main channel required for convergence of the modified profile to within 0.1 ft of the base profile, ft

HD = average hydraulic depth (1-percent-chance-event-flow area divided by the top width), ft

S = average reach slope, ft/ft

HL = head loss ranging between 0.50 ft and 5.0 ft at the channel crossing structure for the 1-percent-chance flood, ft

References (Davidian, 1984 and USCE, 1986) are valuable sources of additional guidance on the practical application of the step-backwater method to highway-drainage problems involving an open channel. The references include more-specific guidance on cross-section determination, location, spacing, and stream-reach determination. Reference (USACOE, 1986) investigates the accuracy and reliability of water-surface profile related to *n*-value determination and the survey or mapping technology used to determine the cross-section coordinate geometry.

The computation procedure is as follows.

A sample procedure is taken from *Hydrologic Engineering Methods for Water Resources Development - Volume 6, Water Surface Profiles*, The Hydrologic Engineering Center, Corps of Engineers, U.S. Army, Davis, California.

A convenient form for use in calculating water-surface profiles is shown in Figure 30-5F. An editable version of this form may also be found on the Department's website at www.in.gov/dot/div/contracts/design/dmforms/. In summary, Columns 2 and 4 through 12 are devoted to solving Manning's equation to obtain the energy loss due to friction; Columns 13 and

14 include calculations for the velocity distribution across the section; Columns 15 through 17 include the average kinetic energy; Column 18 includes calculations for other losses (expansion and contraction losses due to interchanges between kinetic and potential energies as the water flows); and Column 19 includes the computed change in water surface elevation. Conservation of energy is accounted for by proceeding from section to section down the computation form.

Column 1. CROSS SECTION NO. is the cross-section identification number. Distance in miles should be shown upstream from the mouth.

Column 2. ASSUMED is the assumed water-surface elevation which must agree with the resulting computed water-surface elevation within ± 0.05 ft, or an allowable tolerance, for trial calculations to be successful.

Column 3. COMPUTED is the rating-curve value for the first section, but thereafter is the value calculated by adding *WS* to the computed water-surface elevation for the previous cross section.

Column 4. *A* is the cross-sectional area. If the section is complex and has been subdivided into parts (e.g., left overbank, channel, and right overbank) use one line of the form for each subsection, then sum them to get the total area of cross section, A_t.

Column 5. *R* is the hydraulic radius. Use the same procedure as for Column 4 if the section is complex, but do not sum the subsection values.

Column 6. $R^{2/3}$ is two-thirds power of hydraulic radius.

Column 7. *n* is Manning roughness coefficient.

Column 8. *K* is conveyance and is defined as follows:

$$K = \frac{C_m A R^{0.67}}{n}$$

where C_m should be taken as 1.486. If the cross section is complex, sum the subsection *K* values to get K_t.

Column 9. $\overline{K}_t$ is average conveyance for the reach and is calculated as $0.5(K_{td} + K_{tu})$ where subscripts *d* and *u* refer to downstream and upstream ends of the reach, respectively.

Column 10. $\overline{S}_f$ is the average slope through the reach and is determined as follows:

$$S_f = \left(\frac{Q}{K_t} \right)^2$$

Column 11. L is the discharge-weighted or conveyance-weighted reach length.

Column 12. h_f is energy loss due to friction through the reach and is calculated as follows:

$$h_f = L \left(\frac{Q}{K_t} \right)^2 = LS_f$$

Column 13. $\Sigma(K^3/A^2)$ is part of the expression relating distributed flow velocity to an average value. If the section is complex, calculate one of these values for each subsection and sum all subsection values to get a total. If one subsection is used, Column 13 is not needed and α from Column 14 below should be taken as 1.

Column 14. α is the velocity distribution coefficient and is calculated as follows:

$$\alpha = \Sigma \left(\frac{K^3 A_t^{\ 2}}{A^2 K_t^{\ 2}} \right)$$

Column 15. V is the average velocity and is calculated as Q/A_t.

Column 16. $\alpha V^2/2g$ is the average velocity head corrected for flow distribution.

Column 17. $\alpha^2 V^2/2g$ is the difference between velocity heads at the downstream and upstream sections. A positive value indicates that velocity is increasing. Therefore, use a contraction coefficient for the other losses. A negative value indicates that the expansion coefficient should be used in calculating the other losses.

Column 18. h_o is the other losses, and is calculated by multiplying either the expansion or contraction coefficient, K_m, times the absolute value of that in Column 17.

Column 19. α*WS* is the change in water-surface elevation from the previous cross section. It is the algebraic sum of the values in Columns 12, 17, and 18.

30-5.05 Water and Sediment Routing

The BRI-STARS (Bridge Stream Tube Model for Sediment Routing Alluvial River Simulation) Model was developed by the National Cooperative Highway Research Program and FHWA. It is based on utilizing the stream-tube method of calculation which allows the lateral and longitudinal variation of hydraulic conditions and sediment activity at various cross sections along the study reach. Both energy and momentum functions are used in the BRI-STARS model so that the water-surface profile computation can be carried out through combinations of sub critical and supercritical flows without interruption. The stream-tube concept is used for hydraulic computations in a semi-two-dimensional way. Once the hydraulic parameters in each stream tube are computed, the scour or deposition in each stream tube, determined by sediment routing, will provide the variation of channel geometry in the vertical direction.

The BRI-STARS model includes a rule-based expert system program for classifying a stream by size, bed and bank-material stability, planform geometry, and other hydrologic and morphological features. Due to the complexities of a single classification system that utilizes all parameters, no universally-acceptable stream-classification method presently exists. Consequently, this model does not include a single methodology for classifying every stream. Instead, methodologies were first classified according to the channel-sediment sizes they were derived for then. Within each size group, one or more classification schemes have been included to cover a wider range of environments. The stream-classification information can be used to assist in the selection of model parameters and algorithms.

Applications of the BRI-STARS model can be summarized as follows.

1. Fixed-bed model to compute water-surface profile for subcritical, supercritical, or a combination of both flow conditions involving a hydraulic jump.

2. Movable-bed model to route water and sediment through alluvial channels.

3. Use of stream tubes to allow the model to compute the variation of hydraulic conditions and sediment activity in the longitudinal and the lateral directions.

4. The armoring option allows simulation of longer-term riverbed changes.

5. The minimization procedure option allows the model to simulate channel widening and narrowing processes.

6. The local bridge-scour option allows for the computation of pier or abutment scour.

7. The bridge routines for the fixed-geometry mode from WSPRO are available as an option in the program.

30-6.0 DESIGN PROCEDURE

30-6.01 General

The design procedure for each type of channel has some common elements and some substantial differences. This Section will outline a process for assessing a natural stream channel and a more-specific design procedure for a roadside channel.

30-6.02 Stream Channel

The analysis of a stream channel is in conjunction with the design of a highway hydraulic structure such as a culvert or bridge. The objective is to convey the water along or under the highway such that it will not cause damage to the highway, stream, or adjacent property. An assessment of the existing channel is necessary to determine the potential for problems that can result from a proposed action. The detail of studies necessary should be commensurate with the risk associated with the action and with the environmental sensitivity of the stream and adjoining flood plain. Additional information on stream morphology and factors that affect stream stability is provided in Section 30-7.0.

Although the following step-by-step procedure may not be appropriate for each application, it does outline a process which will usually apply.

1. Step 1: Assemble Site Data and Project File.

    a. Data Collection
        (1) Topographic, site, and location maps
        (2) Roadway profile
        (3) Photographs
        (4) Field reviews
        (5) Design data at nearby structures
        (6) Gaging records
        (7) Historic flood data and local knowledge
        (8) pH readings
    b. Studies by Other Agencies
        (1) Flood-insurance studies
        (2) Floodplain studies
        (3) Watershed studies
    c. Environmental Constraints
        (1) Floodplain encroachment
        (2) Floodway designation
        (3) Fish and wildlife habitat
        (4) Commitments in review documents
    d. Design Criteria. See Section 30-3.0.

2. <u>Step 2: Determine the Project Scope</u>.

   a. Determine Level of Assessment
      (1) Stability of existing channel
      (2) Potential for damage
      (3) Sensitivity of the stream
   b. Determine Type of Hydraulic Analysis
      (1) Qualitative Assessment
      (2) Single-Section Analysis
      (3) Step-Backwater Analysis
   c. Determine Additional Survey Information
      (1) Extent of streambed profiles
      (2) Locations of cross sections
      (3) Elevations of flood-prone property
      (4) Details of existing structures
      (5) Properties of bed and bank materials

3. <u>Step 3: Evaluate Hydrologic Variables</u>.

   a. Compute Discharges for Selected Frequencies
   b. See Chapter Twenty-nine

4. <u>Step 4: Perform Hydraulic Analysis</u>.

   a. Single-Section Analysis (Section 30-5.03)
      (1) Select representative cross section (Section 30-5.02)
      (2) Select appropriate *n* values from Figure 30-4B, Uniform Flow (Values of Manning's *n*)
      (3) Compute stage-discharge relationship
   b. Step-Backwater Analysis (Section 30-5.04)
   c. Calibrate with Known High Water

5. <u>Step 5: Perform Stability Analysis</u>.

   a. Geomorphic Factors
   b. Hydraulic Factors
   c. Stream Response to Change

6. <u>Step 6: Design Countermeasures</u>.

   a. Criteria for Selection

(1) Erosion mechanism
(2) Stream characteristics
(3) Construction and maintenance requirements
(4) Vandalism considerations
(5) Cost

b. Types of Countermeasures
(1) Meander migration countermeasures
(2) Bank stabilization (Chapter Thirty-eight)
(3) Bend control countermeasures
(4) Channel braiding countermeasures
(5) Degradation countermeasures
(6) Aggradation countermeasures

c. For Additional Information
(1) HEC 20 *Stream Stability*
(2) Highways in the River Environment
(3) See Reference List

7. Step 7: Documentation.

a. Prepare Report and File with Background Information
b. See Chapter Twenty-eight

30-6.03 Roadside Channel

A roadside channel is defined as an open channel paralleling the highway embankment and within the limits of the highway right of way. It is trapezoidal or V-shaped in cross section and lined with grass or a protective lining.

The primary function of a roadside channel is to collect surface runoff from the highway pavement and areas which drain to the right of way, and convey the accumulated runoff to acceptable outlet points.

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

The alignment, cross section, and grade of a roadside channel are constrained by the geometric and safety criteria applicable to the project. Such a channel should accommodate the design runoff in a manner which ensures the safety of the motorist and minimizes future maintenance, damage to adjacent properties, and adverse environmental or aesthetic effects.

The procedure described below will assist the designer in stable channel design and in determining the type of lining if necessary. Section 30-6.03(02) provides information on the computer program HYCHL.

30-6.03(01) Step-By-Step Procedure

Each project is unique, but the following basic design steps are applicable.

1. Step 1: Establish a Roadside Plan.

   a. Collect available site data.
   b. Obtain or prepare existing and proposed plan-and-profile layouts including highway, culverts, bridges, etc.
   c. Determine and plot on the plan the locations of natural basin divides and roadside channel outlets. An example of a roadside channel plan and profile is shown in Figure 30-6A, Sample Roadside Channel.
   d. Perform the layout of the proposed roadside channels to minimize diversion flow lengths.

2. Step 2: Obtain or Establish Cross Section Data.

   a. Provide channel depth adequate to drain the subbase and minimize freeze-thaw effects.
   b. Choose channel side slopes based on geometric design criteria including safety, economics, soil, aesthetics, and access.
   c. Establish bottom width of trapezoidal channel.
   d. Identify features which may restrict cross section design
      (1) right-of-way limits
      (2) trees or environmentally-sensitive areas
      (3) utilities
      (4) existing drainage facilities

3. Step 3: Determine Initial Channel Grades.

   a. Plot initial grades on the plan-and-profile layout. Slopes in a roadside ditch in a cut are controlled by the highway grades.
   b. Provide a minimum grade of 0.3% to minimize ponding and sediment accumulation.
   c. Consider influence of type of lining on grade.
   d. Where possible, avoid features which may influence or restrict grade, such as utility locations.

4. Step 4: Check Flow Capacities and Adjust As Necessary.

a. Compute the design discharge at the downstream end of a channel segment (see Chapter Twenty-nine).
b. Set preliminary values of channel size, roughness coefficient, and slope.
c. Determine maximum allowable depth of channel including freeboard.
d. Check flow capacity using Manning's equation and single-section analysis.
e. If capacity is inadequate, possible adjustments are as follows:
   (1) increase bottom width;
   (2) make channel side slopes flatter;
   (3) make channel slope steeper;
   (4) provide smoother channel lining; or
   (5) install drop inlets and a parallel storm drain pipe beneath the channel to supplement channel capacity.
f. Provide smooth transitions at changes in channel cross sections.
g. Provide extra channel storage where needed to replace floodplain storage or to reduce peak discharge.

5. Step 5: Determine Channel Lining or Protection Needed (HEC 15).

a. Select a lining and determine the permissible shear stress τ_p in lb/ft^2 from Figure 30-6B, Classification of Vegetal Covers as to Degrees of Retardancy, or Figure 30-6C, Summary of Permissible Shear Stress for Variable Protection Measures.

b. Estimate the flow depth and choose an initial Manning's *n* value from Figure 30-6D, Manning's Roughness Coefficients and Roughness Element Height, k_S, or from the figures as follows:

30-6E Manning's *n* Versus Relative Roughness for Selected Lining Types (HEC 15)
30-6F Manning's *n* Versus Hydraulic Radius, *R*, for Class A Vegetation (HEC 15)
30-6G Manning's *n* Versus Hydraulic Radius, *R*, for Class B Vegetation (HEC 15)
30-6H Manning's *n* Versus Hydraulic Radius, *R*, for Class C Vegetation (HEC 15)
30-6 I Manning's *n* Versus Hydraulic Radius, *R*, for Class D Vegetation (HEC 15)
30-6J Manning's *n* Versus Hydraulic Radius, *R*, for Class E Vegetation (HEC 15)

c. Calculate normal flow depth y_o (ft) at design discharge using Manning's equation and compare with the estimated depth. If they do not agree, repeat Steps 5.b. and 5.c.

d. Compute maximum shear stress at normal depth as follows:

$$\tau_d = 2990 y_o S$$, where S = channel slope, ft/ft

e. If $\tau_d < \tau_p$, the lining is acceptable. Otherwise, consider the following:
(1) choose a more resistant lining;
(2) use concrete, gabions, or other more-rigid lining either as full lining or composite;
(3) decrease channel slope;
(4) decrease slope in combination with drop structures; or
(5) increase channel width or flatten side slopes.

6. Step 6: Analyze outlet points and downstream effects.

a. Identify adverse impacts such as increased flooding or erosion to downstream properties which, at the channel outlet, may result from one of the following:
(1) increase or decrease in discharge;
(2) increase in velocity of flow;
(3) concentration of sheet flow;
(4) change in outlet water quality; or
(5) diversion of flow from another watershed.

b. Mitigate adverse impacts identified in Step 6.a. The possibilities include the following:
(1) enlarge outlet channel or install control structures to provide detention of increased runoff in channel;
(2) install velocity control structures (energy dissipators);
(3) increase capacity or improve lining of downstream channel;
(4) install sedimentation or infiltration basins;
(5) install weirs or other outlet devices to redistribute concentrated channel flow; or
(6) eliminate diversions which result in downstream damage and which cannot be mitigated in a less-expensive manner.

30-6.03(02) Design Considerations

To obtain the optimum roadside-channel-system design, it may be necessary to conduct more than one trial of the previous procedure before a final design is achieved.

More details on channel lining design are provided in HEC 15 including consideration of channel bends, steep slopes, and composite linings. The riprap design procedures described in HEC 15 are for a channel having a design discharge of 50 ft^3/s or less. Where the design discharge exceeds 50 ft^3/s, the design procedure provided in Chapter Thirty-eight on bank protection should be followed.

Stable channel design can be accomplished with the assistance of the HYCHL computer program. HYCHL is a module of the integrated system HYDRAIN. The basis for the program's algorithms is provided in FHWA publications HEC-11 and HEC-15. Although both documents address the analysis of lining stability, each document addresses different classes of problems. HEC 15 focuses on linings in a roadside channel which are characterized by relatively uniform cross sections on a constant slope. Alternatively, HEC 11 addresses a natural channel with irregular cross sections, varying bottom slopes, and carrying a larger flow. HEC 11 focuses on the design of riprap lining. Together, HEC 15 and HEC 11 provide a series of analysis and design tools that are present in HYCHL.

The computational elements of the program are all based in English-measurement units because these are the common units for all of the reference materials. HYCHL performs the necessary input and output conversions for an English-units design.

HEC 15 outlines procedures for analyzing channel linings based on tractive-force theory. The procedure involves comparing an estimated shear stress resulting from flow in a channel to the maximum permissible shear stress determined for a given lining type. If the shear from flowing water increases to where it is greater than the permissible shear of the lining, failure may occur. This concept allows for calculation of the maximum discharge that a channel can convey, if the calculated shear is assumed to equal permissible shear.

The analysis of a rigid, vegetative, gabion, or temporary lining in HYCHL is applicable to a channel of uniform cross section and constant bottom slope. A roadside channel exhibits such characteristics. HYCHL offers design and analysis options including the following:

1. rigid or flexible linings;
2. temporary or permanent linings;
3. single or composite linings;
4. straight or bending channel section;
5. alternative regular channel shape; and
6. constant or variable channel flow.

HEC 15 and HEC 11 both outline procedures for analyzing riprap-lined channels. These procedures are based on the tractive-force theory but include additional considerations not necessary for analyzing rigid, vegetative, gabion, or temporary lining types. A channel lined with riprap can be analyzed for stability given the riprap size, or the riprap size can be determined based on a user-supplied stability factor. A composite channel which has riprap for the low-flow lining and another lining type for the high-flow channel can be analyzed. HYCHL can also analyze an irregular channel shape which is lined with riprap only.

30-7.0 STREAM MORPHOLOGY

30-7.01 Introduction

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

A qualitative assessment of the river response to a proposed highway facility is possible through a thorough knowledge of river mechanics and the accumulation of engineering experience.

Equilibrium sediment-load calculations can be made by a variety of techniques and compared from reach to reach to detect an imbalance in sediment inflow and outflow and thus identify an aggradation or degradation problem. The BRI-STARS model (see Section 30-5.0) is recommended as a tool to quantify the expected scour or sedimentation of potential problem locations. References (FHWA, 1990, and Molinas, 1994) should be consulted to evaluate the problem and propose mitigation measures. The proposed methodology is subject to approval by the Hydraulics Team leader.

The natural stream channel will assume a geomorphological form which will be compatible with the sediment load and discharge history which it has experienced. To the extent that a highway structure disturbs this delicate balance by encroaching on the natural channel, the consequences of flooding, erosion, and deposition can be significant and widespread. The hydraulic analysis of a proposed highway structure should include a consideration of the extent of these consequences.

30-7.02 Levels of Assessment

The analysis and design of a stream channel will require an assessment of the existing channel and the potential for problems as a result of the proposed action. The necessary detail of studies should be commensurate with the risk associated with the action and with the environmental sensitivity of the stream. Observation is the best means of identifying potential locations for channel-bank erosion and subsequent channel stabilization. Analytical methods for the evaluation of channel stability can be classified as either hydraulic or geomorphic. These analytical tools should only be used to substantiate the erosion potential indicated through observation. Descriptions of the three levels of assessment are as follows.

1. Level 1. Qualitative assessment involving the application of geomorphic concepts to identify potential problems and alternative solutions. Data needed may include historic information, current site conditions, aerial photographs, old maps and survey notes, bridge-design files, maintenance records, or interviews with long-time residents.

2. Level 2. Quantitative analysis combined with a more detailed qualitative assessment of geomorphic factors. This includes water-surface profile and scour calculations. This level of analysis will be adequate if the problems are resolved and relationships between different factors affecting stability are adequately explained. Required data will include Level 1 data in addition to the information needed to establish the hydrology and hydraulics of the stream.

3. Level 3. Complex quantitative analysis based on detailed mathematical modeling and possibly physical hydraulic modeling. This is necessary only for a high-risk location, an extraordinarily complex problem, or an after-the-fact analysis where losses and liability costs are high. This level of analysis may require professionals experienced with mathematical modeling techniques for sediment routing (see Section 30-5.0) or physical modeling. Required data will include Level 1 and 2 data, field data on bed load and suspended load-transport rates, and properties of bed and bank materials such as size, shape, gradation, fall velocity, cohesion, density, or angle of repose.

30-7.03 Factors That Affect Stream Stability

Factors that affect stream stability and, potentially, bridge and highway stability at a stream crossing can be classified as geomorphic factors and hydraulic factors.

1. Geomorphic Factors.

    a. Stream size
    b. Flow variability

c. Valley setting
d. Floodplains
e. Natural levees
f. Apparent incision
g. Sinuosity
h. Channel boundaries
i. Width variability
j. Degree of braiding
k. Bar development
l. Degree of anabranching

Figure 30-7A, Geomorphic Factors That Affect Stream Stability, depicts examples of the geomorphic factors.

2. Hydraulic Factors.

a. Magnitude, frequency, and duration of flood
b. Bed configuration
c. Resistance to flow
d. Water-surface profiles

Figure 30-7B, Channel Classification and Relative Stability as Hydraulic Factors Are Varied, depicts the changes in channel classification and relative stability as related to the hydraulic factors.

Rapid or unexpected changes may occur in a stream in response to man's activities in the watershed such as alteration of vegetative cover. Changes in perviousness can alter the hydrology of a stream, sediment yield, and channel geometry. Channelization, stream channel straightening, stream levees and dikes, bridges and culverts, reservoirs, and changes in land use can have major effects on stream flow, sediment transport, channel geometry, and location. Knowing that man's activities can influence stream stability can help the designer anticipate some of the problems that can occur.

A natural disturbance such as a flood, drought, earthquake, landslide, volcano, or forest fire can also cause large changes in sediment load and thus major changes in the stream channel. Although it is difficult to plan for such a disturbance, if one does occur it is likely that changes will also occur to the stream channel.

30-7.04 Stream Response To Change

The complicating factors in river mechanics are the large number of interrelated variables that can simultaneously respond to natural or imposed changes in a stream system; and the continual evolution of stream channel patterns, channel geometry, bars, and forms of bed roughness with changing water and sediment discharge. To better understand the responses of a stream to the actions of man and nature, hydraulic and geomorphic concepts are described below.

The dependence of stream form on slope, which may be imposed independently of other stream characteristics, is illustrated schematically in Figure 30-7C, Sinuosity Versus Slope with Constant Discharge.

A natural or artificial change which alters channel slope can result in modifications to the existing stream pattern. For example, a cutoff of a meander loop decreases channel sinuosity and increases channel slope. In Figure 30-7C, this shift in the plotting position to the right could result in a shift from a relatively tranquil, meandering pattern toward a braided pattern that varies rapidly with time, has high velocities, is subdivided by sandbars, and carries relatively large quantities of sediment. Conversely, it is possible that a slight decrease in slope could change an unstable braided stream into a meandering one.

The different channel dimensions, shapes, and patterns associated with different quantities of discharge and amounts of sediment load indicate that, as these independent variables change, major adjustments of channel morphology can be anticipated. Further, a change in hydrology may cause changes in stream sinuosity, meander wave length, and channel width and depth. A long period of channel instability with considerable bank erosion and lateral shifting of the channel may be required for the stream to compensate for the hydrologic change.

Figure 30-7D, Slope-Discharge for Braiding- or Meandering-Bed Stream, illustrates the dependence of river form on channel slope and discharge, showing that if $SQ^{0.25} \leq 0.00070$ in a sand bed channel, the stream will meander. Similarly, if $SQ^{0.25} \geq 0.0041$, the stream is braided.

In these equations, S is the channel slope in feet per foot and Q is the mean discharge in cubic feet per second. The transitional range of $SQ^{0.25}$ is between these values.

Many rivers plot in the zone between the limiting curves defining a meandering or braided stream. If a stream is meandering, but its discharge and slope border on a boundary of the transitional zone, a relatively small increase in channel slope may cause it to change, in time, to a transitional or braided stream.

30-7.05 Countermeasures

A countermeasure is defined as a measure incorporated into a highway crossing of a stream to control, inhibit, change, delay, or minimize stream and bridge stability problems. It may be installed at the time of highway construction or retrofitted to resolve stability problems at an existing crossing.

Retrofitting is good economics and good engineering practice because the magnitude, location, and nature of potential stability problems are not always discernible at the design stage and, may take a period of several years to develop.

The selection of an appropriate countermeasure for a specific bank erosion problem is dependent on factors such as the erosion mechanism, stream characteristics, construction and maintenance requirements, potential for vandalism, and costs.

Below is a discussion of possible countermeasures for some common river-stability problems. Consult the references listed at the end of this Chapter for detailed information on the design and construction of the countermeasures.

30-7.05(01) Meander Migration

The best countermeasure against meander migration is a crossing location on a relatively straight reach of stream between bends. Other countermeasures include the protection of an existing bank line, the establishment of a new flow line or alignment, or the control and constriction of channel flow. Countermeasures identified for bank stabilization and bend control include bank revetment, spur, retardance structure, longitudinal dike, vane dike, bulkhead, or channel relocation. Measures may be used individually or in combination to combat meander migration at a site (FHWA, 1990; HEC-20, 1991).

30-7.05(02) Channel Braiding

Countermeasures used at a braided stream are intended to confine the multiple channels to one channel. This tends to increase sediment transport capacity in the principal channel and encourage deposition in secondary channels.

The measures consist of dikes constructed from the limits of the multiple channels to the channel over which the bridge is constructed. A spur dike at a bridge end used in combination with revetment on a highway fill slope, riprap on highway fill slope only, or a spurs arranged in the stream channels to constrict flow to one channel have also been used successfully.

30-7.05(03) Degradation

Degradation can cause the loss of a bridge pier in a stream channel, or a pier or abutment in a caving bank. A check dam, which is a low dam or weir constructed across a channel, is one of the most successful techniques for halting degradation on a small to medium stream.

A longitudinal stone dike placed at the toe of a channel bank can be an effective countermeasure for bank caving in a degrading stream. Precautions to prevent outflanking, such as tiebacks to the banks, may be necessary where installation is limited to the vicinity of the highway stream crossing. Channel lining alone is not a successful countermeasure against degradation problems (HEC-20).

30-7.05(04) Aggradation

Current measures in use to alleviate aggradation problems at a highway-stream crossing include channelization, bridge modification, continued maintenance, or combinations of these.

Channelization may include excavating and cleaning a channel, constructing cutoffs to increase the local slope, constructing flow control structures to reduce and control the local channel width, or constructing relief channels to improve flow capacity at the crossing. Except for relief channels, these measures are intended to increase the sediment transport capacity of the channel, thus reducing or eliminating problems with aggradation.

Another technique is the submerged vane technique developed by the University of Iowa. The studies suggest that the submerged vane structure may be an effective, economic, low-maintenance, and environmentally-acceptable sediment-control structure with a wide range of applications (HEC-20, Odgaard and others, 1986).

30-8.0 EXAMPLE PROBLEMS

30-8.01 Example 30-8.1

Given: Q_{25} = 175 ft^3/s and Q_{100} = 220 ft^3/s. Cross-section information is shown in the following table of surveyed data points for a typical cross section.

Table of Cross-Section Data (Section A, Sta. 1 + 36)

Distance	Elevation	*n* Value
0.00	745.23	0.06
8.13	742.90	0.06
40.63	742.50	0.035
45.73	738.63	0.035
50.80	738.63	0.035

53.83	742.30	0.05
77.98	741.07	0.05
79.23	742.70	0.05
109.73	745.73	0.05

Subsection 1 consists of an overbank area with light brush and trees. Subsection 2 is in the main channel of this stream and comprises a clean, straight stream with a few weeds and rocks. Subsection 3 is in the right-hand floodplain and includes some scattered brush with considerable weeds.

See Figure 30-8.1 for site data.

Find: Use the single-section method to develop a stage-discharge curve for the channel cross-section at Station 1 + 36 which is located downstream from a highway culvert. Determine the tailwater elevation at the outlet of the culvert (assume a channel station of 0 + 30 for this location) for the 25-year and 100-year floods.

See Figure 34-8.2 for stream cross section "A."

Solution: The slope of the stream can be determined by examining the reach from stream Station -0 + 91 to the typical section at Station 1 + 36. The flow line differential for this reach is 2 ft (in 757 ft of stream reach). Therefore, the slope, *S*, is 0.0027 ft/ft.

Figure 30-8A can be used to assist in the development of a stage-discharge curve for this typical section. Assuming water-surface elevations beginning at 739.63, calculate pairs of water surface elevation/discharge for plotting on a stage-discharge curve. Illustrative calculations in which arbitrary increments of water-surface elevation of 1 ft were used are shown in Figure 30-8A, Channel Computation Form. A plotted stage-discharge curve is shown in Figure 30-8B. The water elevation for Q_{25} is 175 ft^3/s and for Q_{100} is 220 ft^3/s.

Because the calculation section for the stream is downstream of the culvert site, it will be necessary to project the water-surface elevation as determined from the typical section at stream Station 1 + 36 to represent the tailwater elevation at stream Station 0 + 30. Therefore, the projected tailwater levels are calculated as follows:

TW_{25} = 742.60 + (453 – 100) (0.0027) = 743.55 ft

TW_{100} = 742.80 + 0.953 = 743.75 ft

<u>30-8.02 Example 30-8.2</u>

Given: A series of five cross sections are available for a creek flowing at a discharge of 10,000 ft^3/s. The ground data points, *GR*, roughness, *n*, and subsection data, *SA*, are included in the WSPRO data input shown in Figure 30-8C, WSPRO Input Data File, for cross sections A, B, C, D and E.

Find: For tailwater elevations of 607.57 ft, 608.60 ft, and 609.60 ft at cross section A, compute the water surface profiles using the FHWA/USGS program WSPRO.

Solution: The computer results for tailwater, *TW*, values of 607.75 ft, 608.60 ft, and 609.60 ft are shown in Figure 30-8D, WSPRO Results. The message no. 135 is ignored because the ratio of conveyances of cross sections A and B is only slightly outside the recommended limit of 1.4. If this ratio becomes too large (>1.4) or too small (< 0.6), additional cross sections may be required. The water-surface profiles are shown in Figure 30-8E, Water Surface Profiles for Q – 10,000 ft^3/s and Variable Tailwater Elevations. The critical water-surface elevations, CRWS, at each cross section are shown to emphasize that these profiles are all sub critical. The profiles tend to converge in the upstream direction, but the distance required for convergence at the desired cross section should be determined as discussed in Section 30-5.04(03).

Example 30-8.3

Given: A roadside drainage channel is trapezoidal with a bottom width of 4 ft and 3H:1V side slopes. The bed slope is 0.005 ft/ft and the design flow rate is 21 ft^3/s.

Find: Calculate the required diameter, D_{50}, of a gravel riprap that is to be used as a permanent channel lining and the design depth of flow.

Solution: The solution follows the procedure outlined in HEC 15 which is based on the tractive-force method.

1. Choose a rounded gravel with D_{50} = 1 in.

   Then τ_p = 0.40 lb/ft^2 (Figure 30-6C, Summary of Permissible Shear Stress for Variable Protection Measures)

2. Estimate *n* = 0.033 from Figure 30-6D, Manning's Roughness Coefficients, and Roughness Element Height, k_S, for *d* = 0.5 – 2 ft

3. Calculate *y* from Manning's equation (Figure 30-5B, Trapezoidal Channel Capacity Chart), as follows:

$$\frac{Qn}{b^{2.67}s^{0.5}} = \frac{(0.033)(21)}{(4)^{2.67}(0.005)^{0.5}} = 0.242$$

Then from Figure 30-5B with $Z = 3$: $y/b = 0.28$ and $y = (4.0)(0.28) = 1.12$ ft

4. Check n value as follows:

$$R = \frac{y(b+3y)}{b+(10)^{0.5}(2y)} = 0.74 \text{ ft, and } \frac{R}{k_s} = \frac{R}{D_{50}} = 8.9$$

From Figure 30-6E, Manning's n Versus Relative Roughness for Selected Lining Types (HEC 15), $n = 0.03\tilde{4} \approx 0.033$, therefore, acceptable.

5. Calculate maximum bed shear stress, τ_d:

$\tau_d = 9800Sy = (62.4)(1.12)(0.005) = 0.35$ lb/ft^2

Since $\tau_d < \tau_p$, accept D_{50} of approximately 1 in. Otherwise, repeat with another riprap diameter.

6. Sideslopes will be stable because they are not steeper than 3H:1V. If the sideslopes are steeper than 3H:1V or if the channel slope is steep, consult HEC 15 for additional computations.

Example 30-8.4

(From HEC 15)

Given: A median ditch is lined with a stand of Kentucky bluegrass of approximately 0.677 ft height. The ditch is trapezoidal with a bottom width of 4 ft and side slopes of 4H:1V. The ditch slope is 0.01 ft/ft.

Find: Compute the maximum discharge for which the lining will be stable, and the corresponding flow depth.

Solution: From Figure 30-6B, Classification of Vegetal Covers as to Degree of Retardancy, Kentucky bluegrass has a retardance class of C and, from Figure 30-6C, Summary of Permissible Shear Stress for Variable Protection Measures, the permissible shear stress is $\tau_p = 1$ lb/ft^2

The allowable depth can be determined by assuming $\tau_p = \tau_d$, as follows:

$y = \tau_p/(62.4\ S) = 1/(62.4)\ (0.01) = 1.60$ ft

Determine the flow area *A* and hydraulic radius *R*, as follows:

$$A = y(b + yz) = 1.60[4 + (4)(1.60)] = 16.6 \text{ ft}^2$$

$$P = b + 2y(1 + z^2)^{1/2} = 4 + 2(1.60)(1 + 16)^{1/2} = 17.19 \text{ ft}$$

$$R = \frac{A}{P} = \frac{16.6}{17.19} = 0.97\ ft$$

Finally, determine the Manning's *n* value from Figure 30-6H, Manning's *n* Versus Hydraulic Radius, *R*, for Class C Vegetation (HEC 15), and solve for *Q* from Manning's equation.

From Figure 30-6H, $n = 0.072$, and

$$Q = \frac{1.486 A R^{0.67} S^{0.5}}{n}$$

$$Q = \frac{1.486(16.6)(0.97)^{2.67}(0.01)^{0.5}}{0.072} = 33.6 \text{ ft}^3\text{/s}$$

This method is called the maximum discharge method and is useful for determining the stable channel capacity for a variety of different linings for purposes of comparison.

Example 30-8.5

Given: A rectangular channel on a slope $S = 0.001$ with a width of 6 ft expanding to a width $b = 10$ ft in a straight walled transition, and $Z = 0$. The design discharge is 300 ft^3/s and Manning's $n = 0.02$.

Find: Calculate the depth of flow in the upstream 6 ft wide channel if normal depth is the downstream control.

Solution: 1. Compute the downstream normal depth, y_2,as follows:

$$\frac{Qn}{S^{0.5}b^{2.67}} = \frac{(300)(0.02)}{(0.001)^{0.5}(10)2.67} = 0.41$$

From Figure 30-5B, Trapezoidal Channel Capacity Chart, with $z = 0$, $y_2 = 6.50$ ft. Therefore $y_2/b = 0.65$. For a rectangular channel,

$$y_c = \left[\frac{1}{g}\left(\frac{Q}{b}\right)^2\right]^{0.33} = 3.0\ ft \text{, therefore subcritical.}$$

2. The downstream specific energy is determined as follows:

$$E_2 = y_2 + \frac{Q^2}{2gA_2{}^2} = 6.5 + \frac{(300)^2}{2(32.2)[(10)(6.5)]^2} = 6.83\ ft$$

3. Choose a straight-walled transition with a divergence angle of 12.5 deg with an expansion-loss coefficient of 0.5 (HEC 14). The length of the transition is determined as follows:

$$L = \frac{\left[\frac{(10-6)}{2}\right]}{\tan 12.5} = 8.9\ ft$$

4. Check if sub critical flow is possible by assuming critical depth in the upstream channel as follows:

$$E_{1c} - y_{1c} + \frac{V_{1c}{}^2}{2g},\ and\ E_1 = E_2 + z_2 - z_1 + h_L$$

where: $z_2 - z_1 = 0.001(2.71) = 0.009$, say 0

$$y_{1c} = \left[\frac{\left(\frac{300}{6}\right)^2}{32.2}\right]^{1/3} = 4.27\ ft$$

$$V_{1c} = \frac{Q}{A_{1c}} = \frac{300}{(6)(4.27)} = 11.7\ ft/s$$

$$V_2 = \frac{Q}{A_2} = \frac{300}{(6.5)(10)} = 4.6\ ft/s$$

$$h_L = 0.5(11.7^2 - 4.6^2)/(2)(32.2) = 0.90$$

$then,\ E1c = 4.27 + 11.7^2/(2)(32.2) = 6.40\ \ ft,$
and, E_1 = 6.83 + 0 + 0.90 = 7.73 ft.

Since $E_1 > E_{1c}$, a sub critical solution exists. If this were not true, the width of 6.0 ft would have to be increased.

5. Solve the energy equation, Equation 30-4.10, by trial as follows:

$$z_1 + y_1 + \frac{Q^2}{2gA_1^{\ 2}} = z_2 + E_2 + h_L$$

$$y_1 + \frac{(1-0.5)(300)^2}{2(32.2)(6.0)^2\left(y_1^{\ 2}\right)} = 6.83 - \frac{0.5(300)^2}{2(32.2)[(10)(6.5)]^2}$$

where: $z_1 - z_2 = 0$

$$h_L = 0.5\left(\frac{Q^2}{\left(2gA_1^{\ 2}\right)} - \frac{Q^2}{\left(2gA_2^{\ 2}\right)}\right)$$

E_2 = 6.66 ft
A_2 = (10)(6.5) = 65 ft

with the result y_1 = 6.13 ft, and V_1 = 8.2 ft/s.

6. Calculate the water surface profile using the Standard Step Method if boundary-resistance losses are of concern.

<u>Example 30-8.6</u>

Given: A rectangular transition contracts from a width of 10 ft to a width of 5 ft. The approach flow rate is 300 ft^3/s with a depth of 1 ft.

Find: Calculate the depth in the contracted section and the angle and length of the contraction so that the transmission of downstream standing waves is minimized.

Solution: 1. Calculate the approach Froude number for a rectangular channel as follows:

$$F = \frac{V}{(gd)^{0.5}} = \frac{\left(\frac{300}{(10)(1)}\right)^{1/2}}{[(32.2)(1)]} = 5.3\text{, therefore supercritical.}$$

2. Determine the contraction ratio as follows:

$$\tau = \frac{b_3}{b_1} = \frac{5.0}{10.0} = 0.5$$

3. Use Figures 30-8F and 30-8G to determine the following:

θ = 5 deg and y_3/y_1 = 2.1, or y_3 = 2.1 ft

$$\frac{F_3}{F_1} = \tau^{-1}\left(\frac{y_3}{y_1}\right)^{-3/2} = 0.66,\ or\ F_3 = 3.6$$

$$L = \frac{\left(\frac{(b_3 - b_1)}{2}\right)}{\tan 5} = 28.6\ ft$$

4. This design satisfies the criterion $F_3 > 2$ and also is just to the left of curve A which means choking is not possible.

   For the complete equations, see HEC 14 and Sturm, 1985.

30-9.0 REFERENCES

The references shown are recommended additions to the designer's library of references.

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SYMBOL	DEFINITION	UNIT
A	Cross-sectional area of flow	ft^2
d	Hydraulic depth	ft
E	Energy of a system	ft
Fr	Froude number	--
n	Manning's roughness coefficient	--
P	Wetted perimeter	ft
q	Discharge per unit width of channel	$ft^3/s/ft$
Q	Total discharge	ft^3/s
R	Hydraulic radius	ft
S	Slope of the energy gradeline	ft/ft
T	Channel top width at the water surface	ft
V	Mean velocity	ft/s
V_c	Critical velocity	ft/s
y_c	Critical depth	ft
α	Velocity distribution coefficient	--
h	Elevation of channel bottom, with respect to a datum, plus y, depth of water	ft
h_L	Head loss in the reach under study	ft
y	Depth of water	ft
Z	Elevation above a datum	ft

SYMBOLS FOR OPEN-CHANNEL HYDRAULICS

Figure 30-1A

Material	Manning's *n*	Maximum Allowable Velocity (ft/s)
Fine Sand	0.20	2.5
Sandy Loam	0.20	2.5
Silty Loam	0.20	3.0
Clay Loam	0.20	3.6
Clay	0.20	5.0
Silty Clay	0.20	5.0
Shale	0.20	6.0
Fine Gravel	0.20	5.0
Coarse Gravel	0.25	6.0

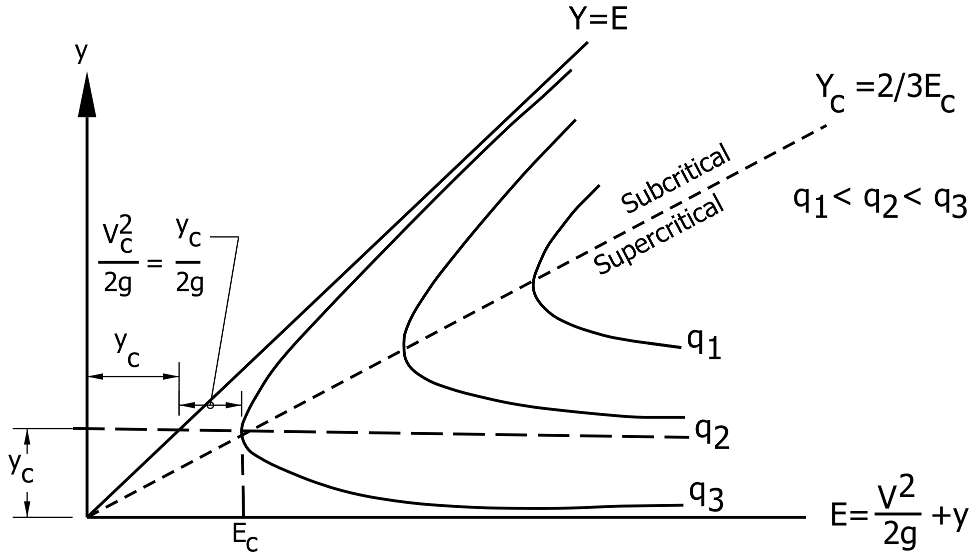
MAXIMUM VELOCITY IN A DRAINAGE DITCH

Figure 30-3A

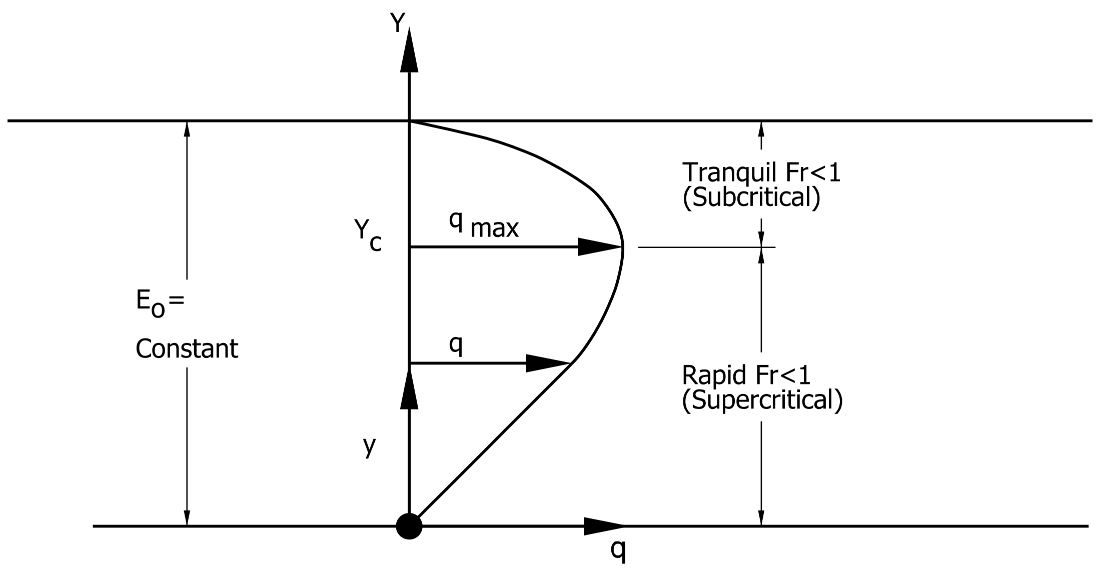
Grade, *G*	Interval
3% ≤ *G* < 5%	200 ft
5% ≤ *G* < 8%	150 ft
8% ≤ *G* < 10%	100 ft
≥ 10%	50 ft

LUG INTERVAL

Figure 30-3B



(a) Specific Energy Diagram



(b) Discharge Diagram

Note: See Figure 30-1A for a definition of terms.

SPECIFIC ENERGY AND DISCHARGE DIAGRAM FOR RECTANGULAR CHANNELS

Figure 30-4A

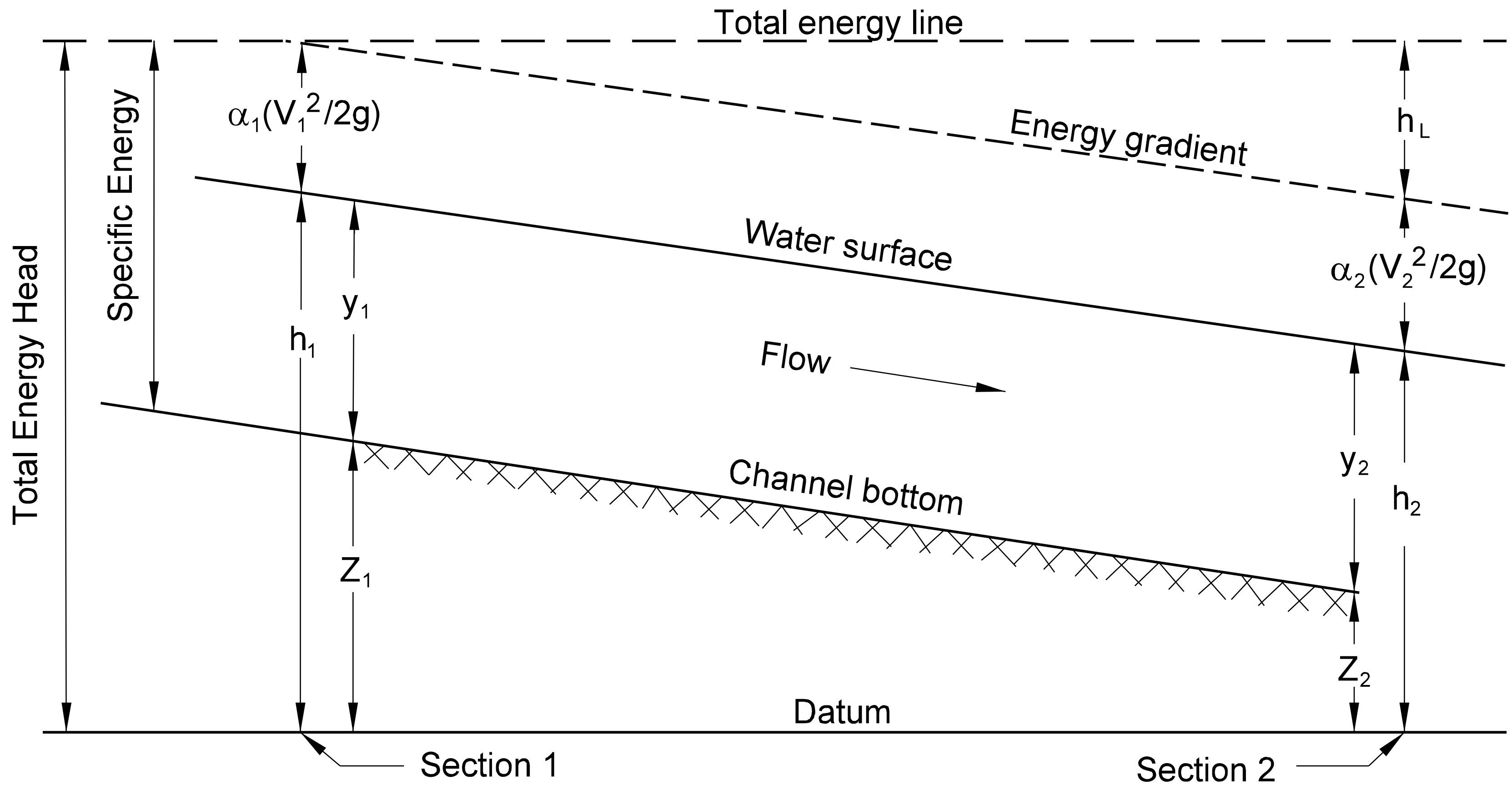
Type of Channel and Description	Minimum	Normal	Maximum
EXCAVATED OR DREDGED			
1. Earth, Straight and Uniform	0.016	0.018	0.020
a. Clean, recently completed	0.018	0.022	0.025
b. Clean, after weathering	0.022	0.025	0.030
c. Gravel, uniform section, clean	0.022	0.027	0.033
2. Earth, Winding and Sluggish			
a. No vegetation	0.023	0.025	0.030
b. Grass, some weeds	0.025	0.030	0.033
c. Dense weeds or aquatic plants in deep channel	0.030	0.035	0.040
d. Earth bottom and rubble sides	0.025	0.030	0.035
e. Stony bottom and weedy sides	0.025	0.035	0.045
f. Cobble bottom and clean sides	0.030	0.040	0.050
3. Dragline, Excavated or Dredged			
a. No vegetation	0.025	0.028	0.033
b. Light brush on banks	0.035	0.050	0.060
4. Rock Cut			
a. Smooth and uniform	0.025	0.035	0.040
b. Jagged and irregular	0.035	0.040	0.050
5. Channel Not Maintained, Weeds and Brush Uncut			
a. Dense weeds, high as flow depth	0.050	0.080	0.120
b. Clean bottom, brush on sides	0.040	0.050	0.080
c. Clean bottom, highest stage of flow	0.045	0.070	0.110
d. Dense brush, high stage	0.080	0.100	0.140
NATURAL STREAM			
1. Minor Stream (top width at flood stage < 100 ft)			
a. Stream 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 or weeds	0.030	0.035	0.040
(3) Clean, winding, some pools or shoals	0.033	0.040	0.045
(4) Same as above, but some weeds or stones	0.035	0.045	0.050
(5) Same as above, lower stages, more ineffective slopes and sections	0.040	0.048	0.055
(6) Same as (4), but more stones	0.045	0.050	0.060
(7) Sluggish reaches, weedy, deep pools	0.050	0.070	0.080
(8) Very weedy reaches, deep pools, or floodway with heavy stand of timber and underbrush	0.075	0.100	0.150

NATURAL STREAM (contd.)			
Type of Channel and Description	**Minimum**	**Normal**	**Maximum**
1. Minor Stream (contd.)			
b. Mountain stream, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
(1) Bottom: gravel, cobbles, and few boulders	0.030	0.040	0.050
(2) Bottom: cobbles with large boulders	0.040	0.050	0.07
2. Floodplain			
a. Pasture, no brush			
(1) Short grass	0.025	0.030	0.035
(2) High grass	0.030	0.035	0.050
b. Cultivated area			
(1) No crop	0.020	0.030	0.040
(2) Mature row crops	0.025	0.035	0.045
(3) Mature field crops	0.030	0.040	0.050
c. Brush			
(1) Scattered brush, heavy weeds	0.035	0.050	0.070
(2) Light brush and trees, in winter	0.035	0.050	0.060
(3) Light brush and trees, in summer	0.040	0.060	0.080
(4)Medium to dense brush, in winter	0.045	0.070	0.110
(5)Medium to dense brush, in summer	0.070	0.100	0.160
d. Trees			
(1) Dense willows, in summer, straight	0.110	0.150	0.200
(2) Cleared land with tree stumps, no sprouts	0.030	0.040	0.050
(3) Same as above, but with heavy growth of sprouts	0.050	0.060	0.080
(4) Heavy stand of timber, a few downed trees, little undergrowth, flood stage below branches	0.080	0.100	0.120
(5) Same as above, but with flood stage reaching branches	0.100	0.120	0.160
3. Major Stream (top width at flood stage > 100 ft). The *n* value is less than that for a minor stream of similar description, because banks offer less effective resistance.			
a. Regular section with no boulders or brush	0.025	n/a	0.060
b. Irregular and rough section	0.035	n/a	0.100

Source: Chow, V.T.

VALUES OF MANNING'S *n* FOR UNIFORM FLOW

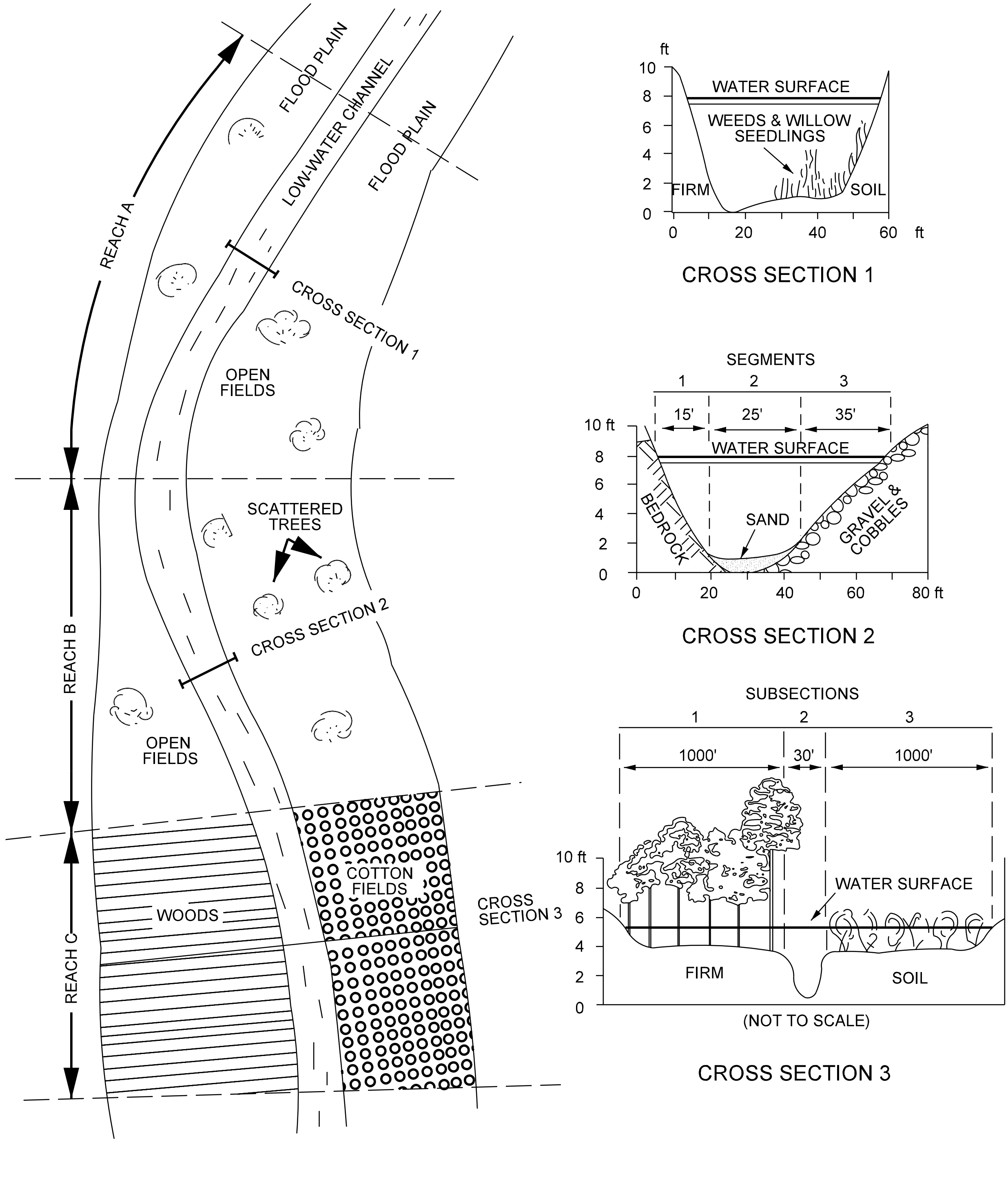
Figure 30-4B



Note: See Figure 30-1A for a definition of terms.

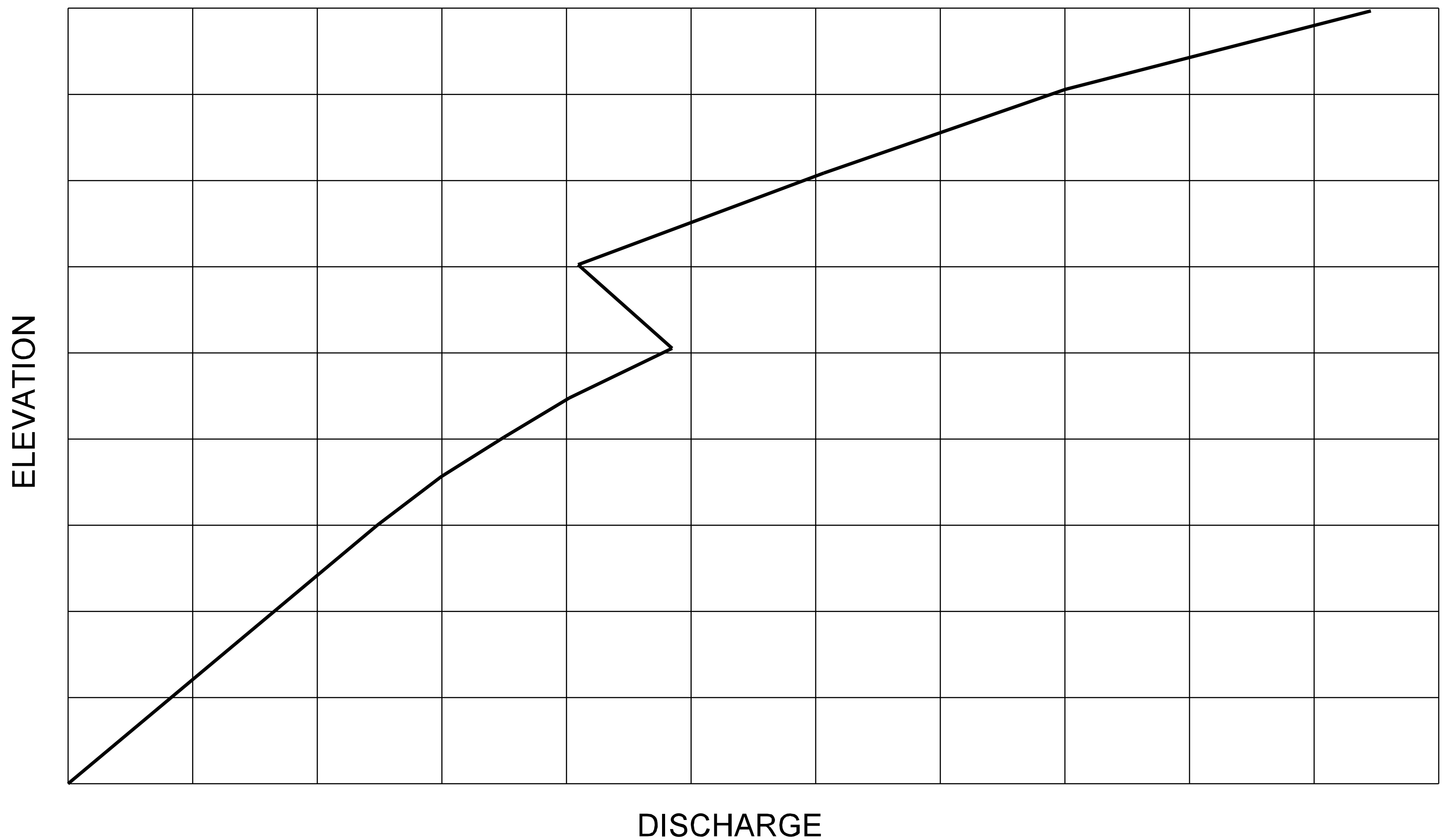
TERMS IN THE ENERGY EQUATION

Figure 30-4C



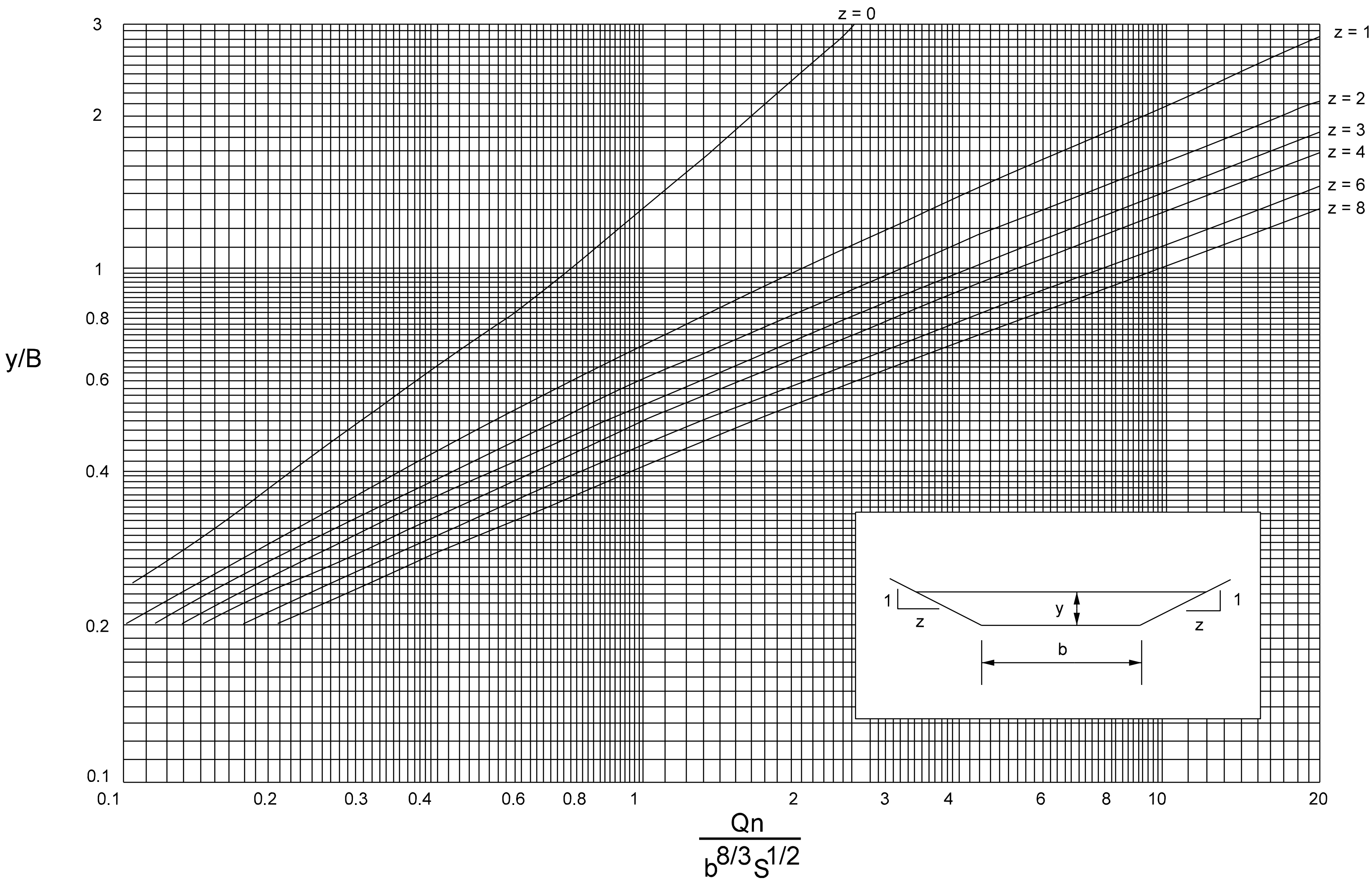
HYPOTHETICAL CROSS SECTION SHOWING REACHES, SEGMENTS AND SUBSECTIONS USED IN ASSIGNING n VALUES

Figure 30-5A



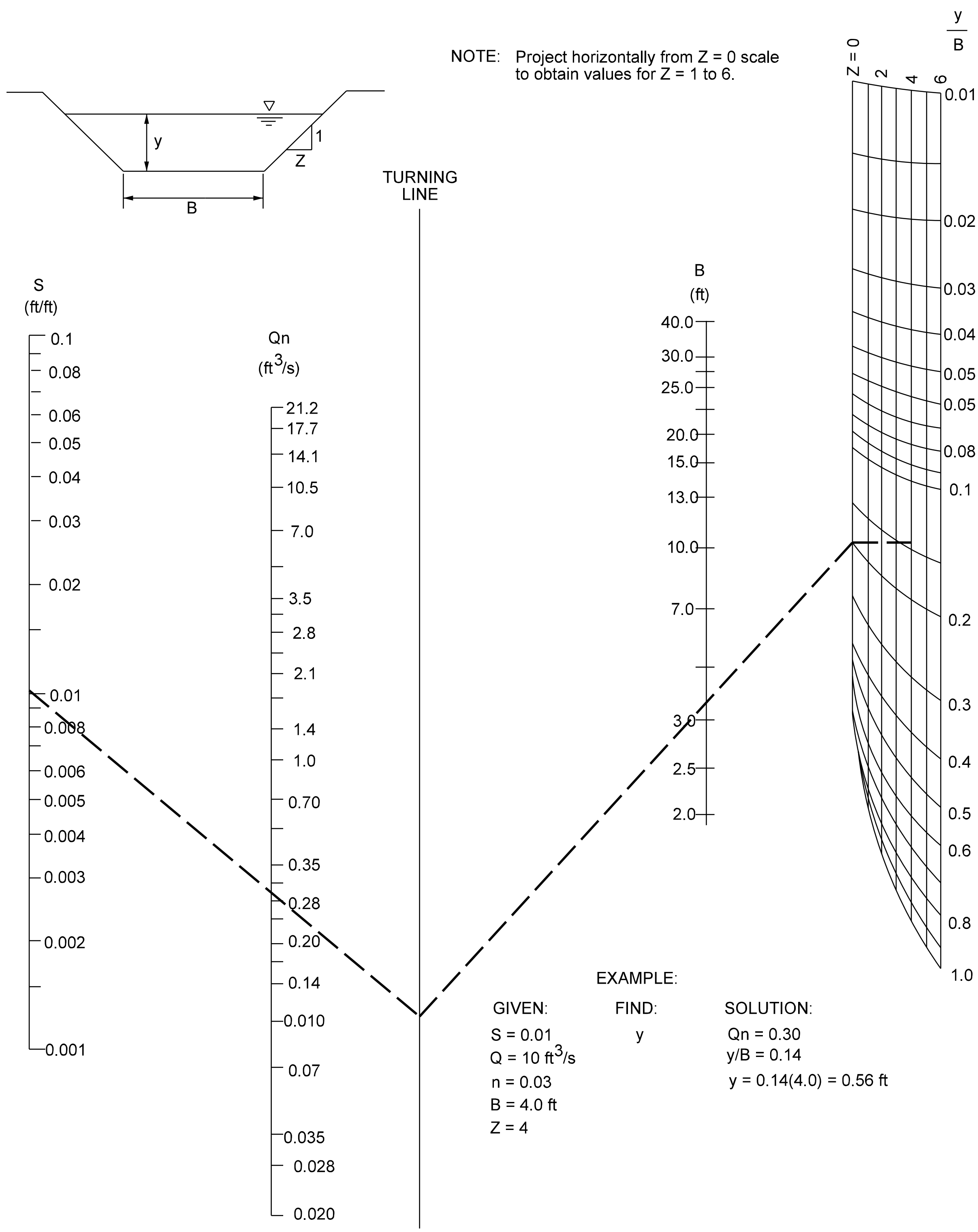
SWITCHBACK

Figure 30-5A.1



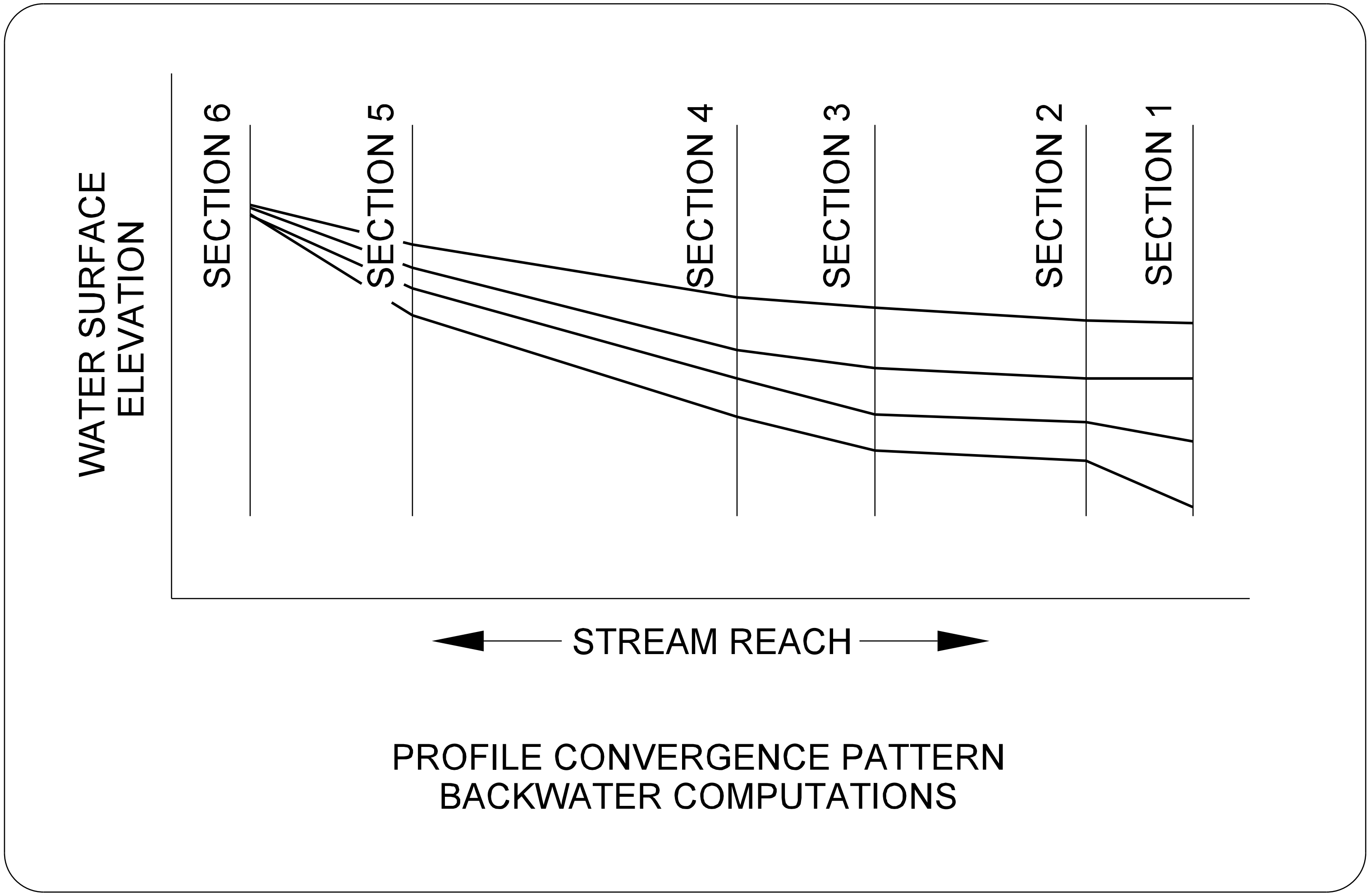
TRAPEZOIDAL CHANNEL CAPACITY CHART

Figure 30-5B



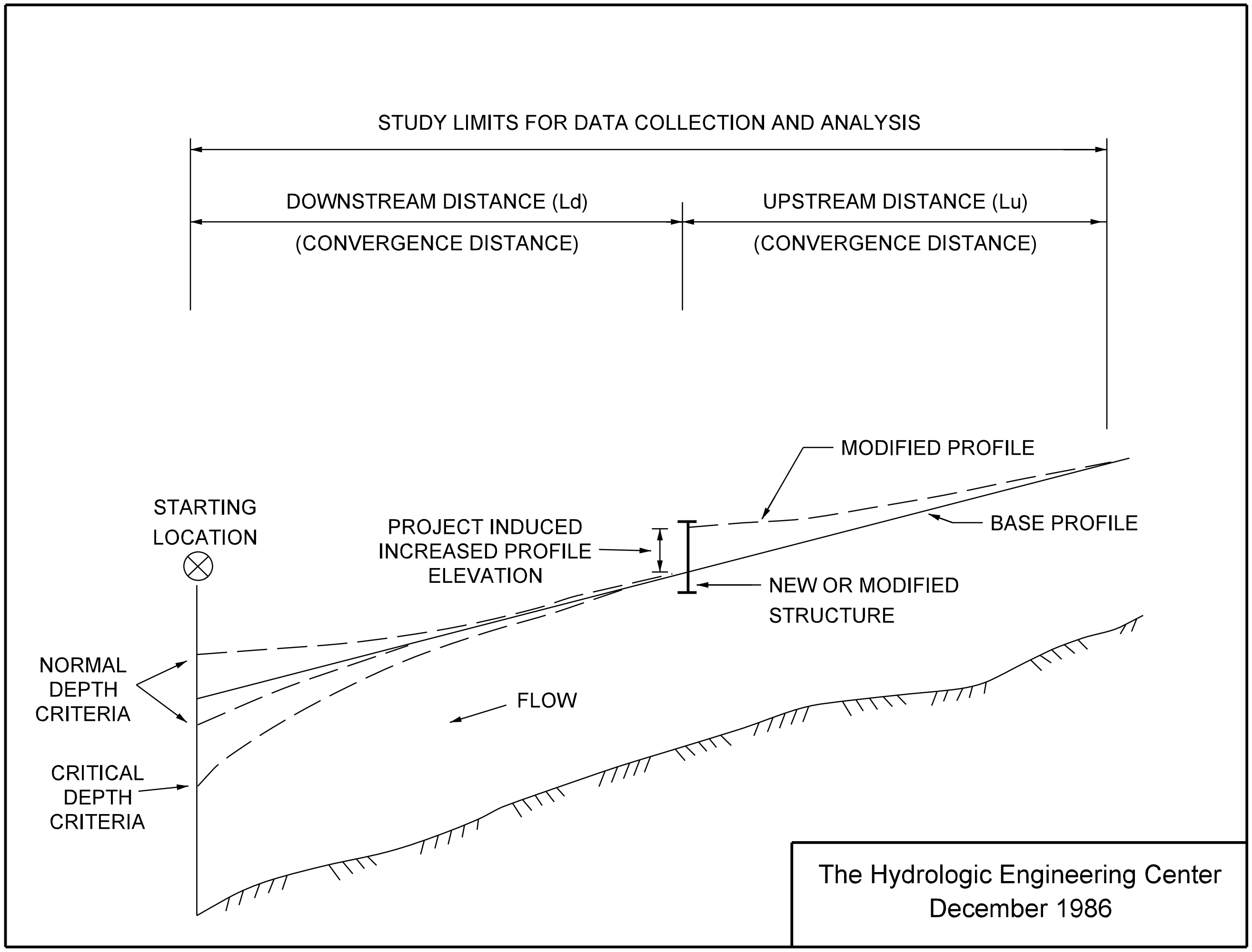
NOMOGRAPH FOR NORMAL DEPTH

Figure 30-5C



PROFILE CONVERGENCE PATTERN BACKWATER COMPUTATION

Figure 30-5D

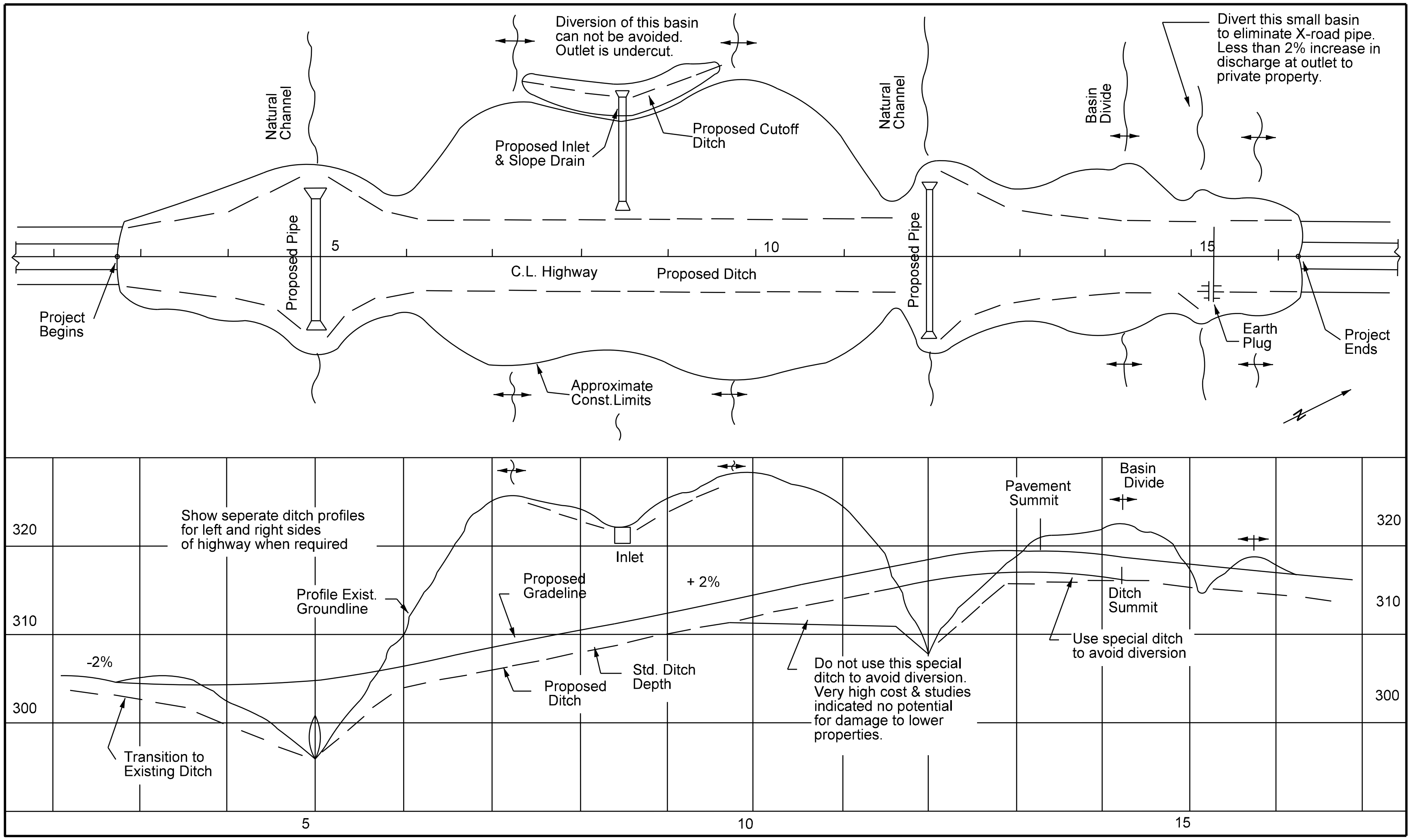


PROFILE STUDY LILMITS

Figure 30-5E

Cross Sec. No.	Water Surface Elevation		Area	Hydr. Rad. R	$R^{2/3}$	N	K	K_r	$\frac{1000}{S_r}$	L	h_f	$\frac{K^3}{A^2}$	ά	V	$\frac{\alpha V^2}{2g}$	$\Delta\left(\frac{\alpha V^2}{2g}\right)$	h_0	Δ Wtr. Surface Elev.
	Asmd.	Comp.																
col.1	col. 2	col. 3	col.4	col.5	cl.6	cl.7	cl.8	cl.9	col.10	cl.11	cl.12	cl.13	cl.14	cl.15	cl. 16	col. 17	cl.18	col. 19

WATER SURFACE PROFILE



SAMPLE ROADSIDE CHANNEL

Figure 30-6A

RETARD-ANCE	COVER	CONDITION
A	Ischaemum	Excellent stand, tall, average 30 in.
	Weeping lovegrass	Excellent stand, tall, average 36 in.
	Yellow bluestem	Excellent stand, tall, average 36 in.
B	Alfalfa	Good stand, unmowed, average 19 in.
	Bermuda grass	Good stand, tall, average 12 in.
	Blue gamma	Good stand, unmowed, average 13 in.
	Kudzu	Very close growth, uncut
	Lespedeza sericea	Good stand, not woody, tall, average 24 in.
	Native grass mixture: blue gamma, bluestem, little bluestem, other short- and long-stem Midwest grasses	Good stand, unmowed
	Weeping lovegrass	Good stand, unmowed, average 13 in.
C	Bermuda grass	Good stand, mowed, average 6 in.
	Centipedegrass	Very dense cover, average 6 in.
	Common lespedeza	Good stand, unmowed, average 11 in.
	Crabgrass	Fair stand, unmowed, 10 to 48 in.
	Grass-legume mixture, summer: common lespedeza, Italian ryegrass, orchard grass, redtop	Good stand, unmowed, 6 to 8 in.
	Kentucky bluegrass	Good stand, headed, 6 to 12 in.
D	Bermuda grass	Good stand, mowed to 2-½ in.
	Buffalo grass	Good stand, unmowed, 3 to 6 in.
	Common lespedeza	Excellent stand, unmowed, average 4-½ in.
	Grass-legume mixture, autumn: common lespedeza, Italian ryegrass, orchard grass, redtop	Good stand, unmowed, 4 to 5 in.
	Lespedeza sericea	Good stand, mowed to 2 in.
E	Bermuda grass	Good stand, mowed to 1-½ in.
	Bermuda grass	Burned stubble

Note: Covers classified as shown have been tested in an experimental channel. Covers were green and generally uniform. Source of table is HEC 15.

CLASSIFICATION OF VEGETAL COVERS AS TO DEGREE OF RETARDANCY

Figure 30-6B

PROTECTIVE COVER	UNDERLYING SOIL	τ_p (lb/ft^2)
Class A Vegetation	Erosion Resistant	3.70
	Erodible	3.70
Class B Vegetation	Erosion Resistant	2.10
	Erodible	2.10
Class C Vegetation	Erosion Resistant	1.00
	Erodible	1.00
Class D Vegetation	Erosion Resistant	0.60
	Erodible	0.60
Class E Vegetation	Erosion Resistant	0.35
	Erodible	0.35
Woven Paper	n/a	0.15
Jute Net	n/a	0.45
Single Fiberglass	n/a	0.60
Double Fiberglass	n/a	0.85
Straw with Net	n/a	1.45
Curled Wood Mat	n/a	1.55
Synthetic Mat	n/a	2.00
Plain Grass, Good Cover	Clay	n/a
Plain Grass, Average Cover	Clay	n/a
Plain Grass, Poor Cover	Clay	n/a
Grass, Reinforced with Nylon	Clay	n/a
Dycel with Grass	Clay	n/a
Petraflex with Grass	Clay	n/a
Armorflex with Grass	Clay	n/a
Dymex with Grass	Clay	n/a
Grasscrete	Clay	n/a
Gravel		
D_{50} = 1 in.	n/a	0.40
D_{50} = 2 in.	n/a	0.80
Rock		
D_{50} = 6 in.	n/a	2.50
D_{50} = 12 in.	n/a	5.00
6 in. Gabions	Type I	35
4 in. Geoweb	Type I	10
Soil Cement (8% cement)	Type I	> 45.00
Dycel w/o Grass	Type I	> 32.00
Petraflex w/o Grass	Type I	> 1532
Armorflex w/o Grass	Type I	12.00 – 20.00
Enkamat with 3 in. in Asphalt	Type I	13.00 – 16.00
Enkamat with 1 in. in Asphalt	Type I	< 5.00
Armorflex Class 30 with longitudinal and lateral cables, no grass	Type I	> 34.00
Dycell 100, longitudinal cables, cell filled with mortar	Type I	< 12.00
Concrete construction blocks, granular filter underlayer	Type I	> 20.00
Wedge-shaped blocks with drainage slot	Type I	> 25.00

Type I soil is a silty clay to silty sand (SC-SM) with AASHTO classification A-4(0). *Source: FHWA-RD-89-199*

SUMMARY OF PERMISSIBLE SHEAR STRESS FOR VARIABLE PROTECTION MEASURES

Figure 30-6C

Lining Category	Lining Type	k_s (ft)	*n* value		
			Depth Range		
			0 < 0.5 ft	0.5 ≤ depth ≤ 2.0 ft	> 2.0 ft
Rigid	Concrete	--	0.15	0.13	0.13
	Grouted Riprap	--	0.040	0.030	0.028
	Stone Masonry	--	0.042	0.032	0.030
	Soil Cement	--	0.025	0.022	0.020
	Asphalt	--	0.018	0.016	0.016
Unlined	Bare Soil	--	0.023	0.020	0.020
	Rock Cut	--	0.045	0.035	0.025
Temporary *	Woven Paper Net	0.003	0.016	0.015	0.015
	Jute Net	0.039	0.028	0.022	0.019
	Fiberglass Roving	0.036	0.028	0.022	0.019
	Straw with Net	0.121	0.065	0.033	0.025
	Curled Wood Mat	0.112	0.066	0.035	0.028
	Synthetic Mat	0.066	0.036	0.025	0.021
Gravel Riprap	1 in. D_{50}	0.082	0.044	0.033	0.030
	2 in. D_{50}	0.164	0.066	0.041	0.034
Rock Riprap	6 in. D_{50}	0.492	0.104	0.069	0.035
	12 in. D_{50}	0.984	--	0.078	0.040

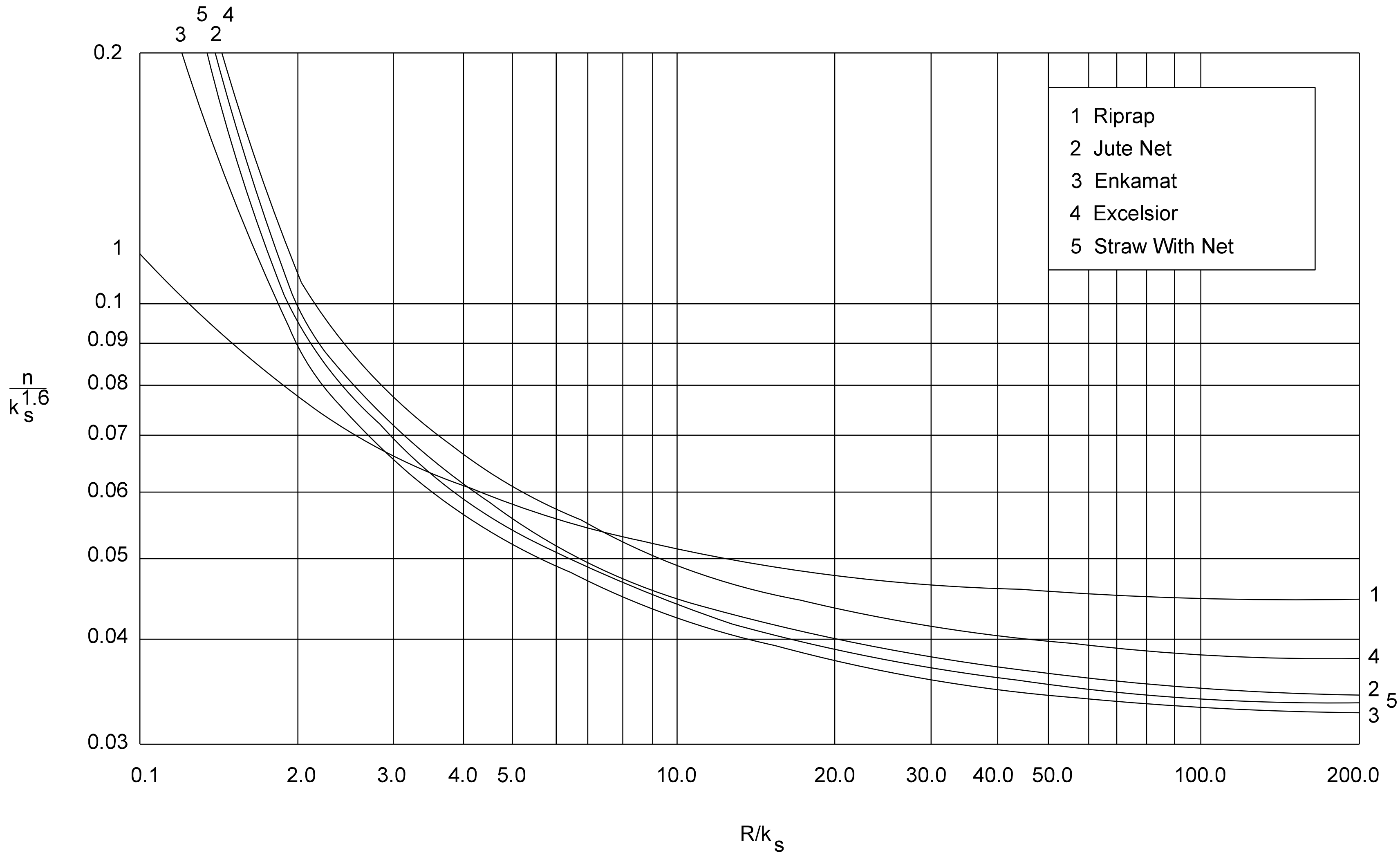
Note: The n *value listed is the representative value for the respective depth range, and varies with the flow depth. For riprap,* $k_s = D_{50}$.

** Some temporary linings become permanent if buried.*

Source: HEC 15

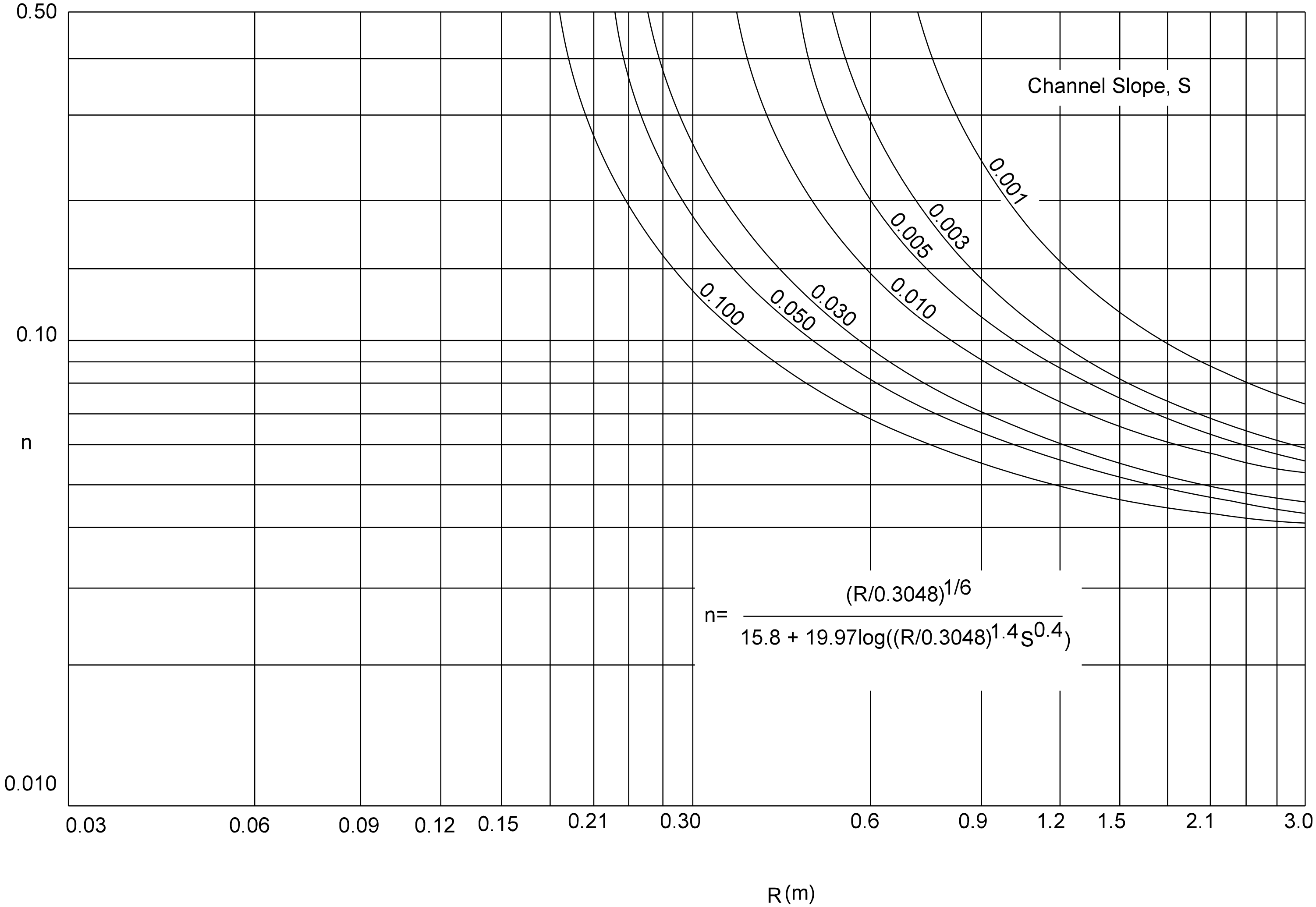
MANNING'S ROUGHNESS COEFFICIENT, *n*, AND ROUGHNESS-ELEMENT HEIGHT, k_S

Figure 30-6D



MANNING'S n VERSUS RELATIVE ROUGHNESS FOR SELECTED LINING TYPES (HEC 15)

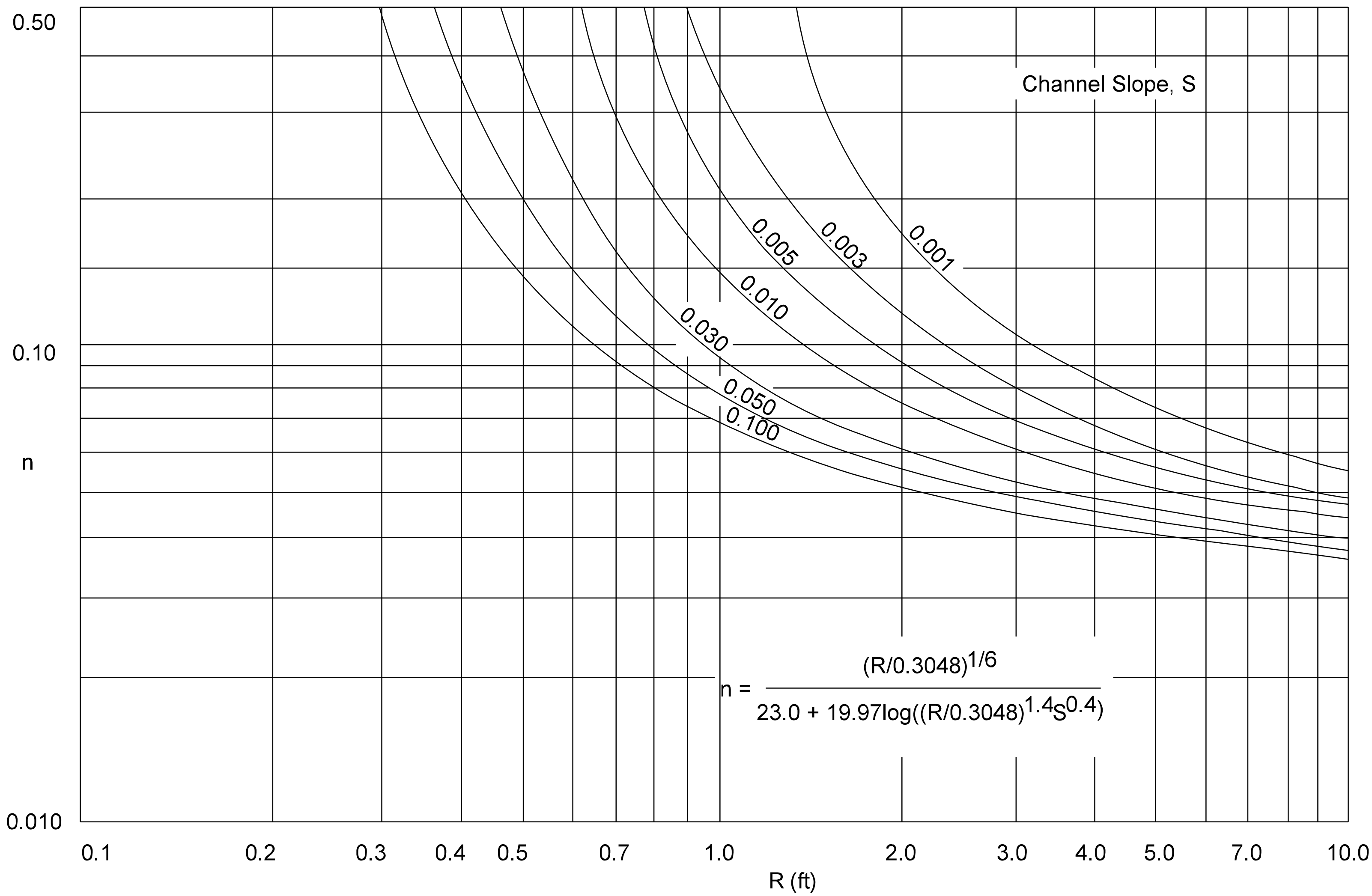
Figure 30-6E



$$n = \frac{(R/0.3048)^{1/6}}{15.8 + 19.97\log((R/0.3048)^{1.4} S^{0.4})}$$

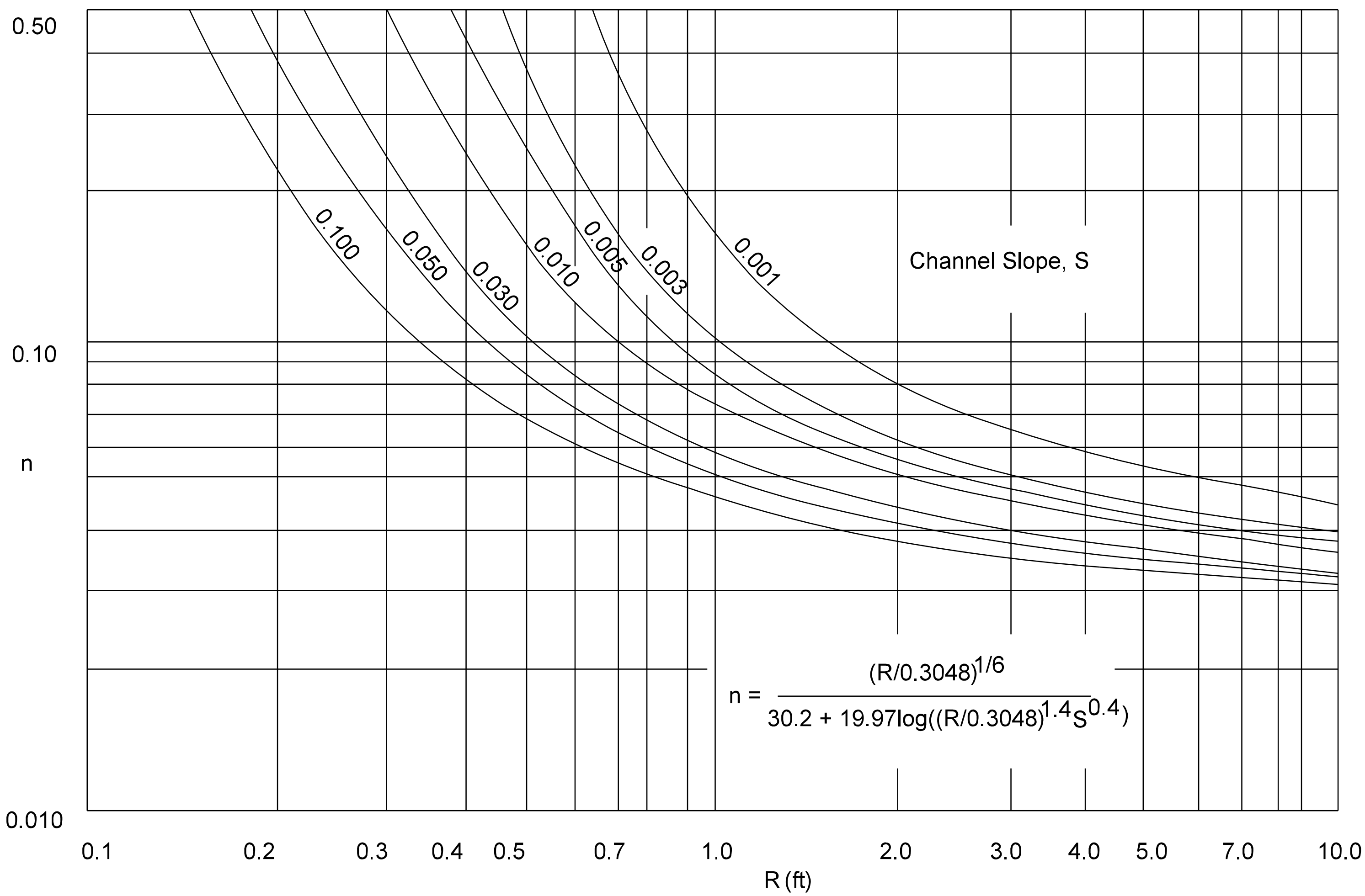
MANNING'S n VERSUS HYDRAULIC RADIUS, R, FOR CLASS A VEGETATION (HEC 15)

Figure 30-6F



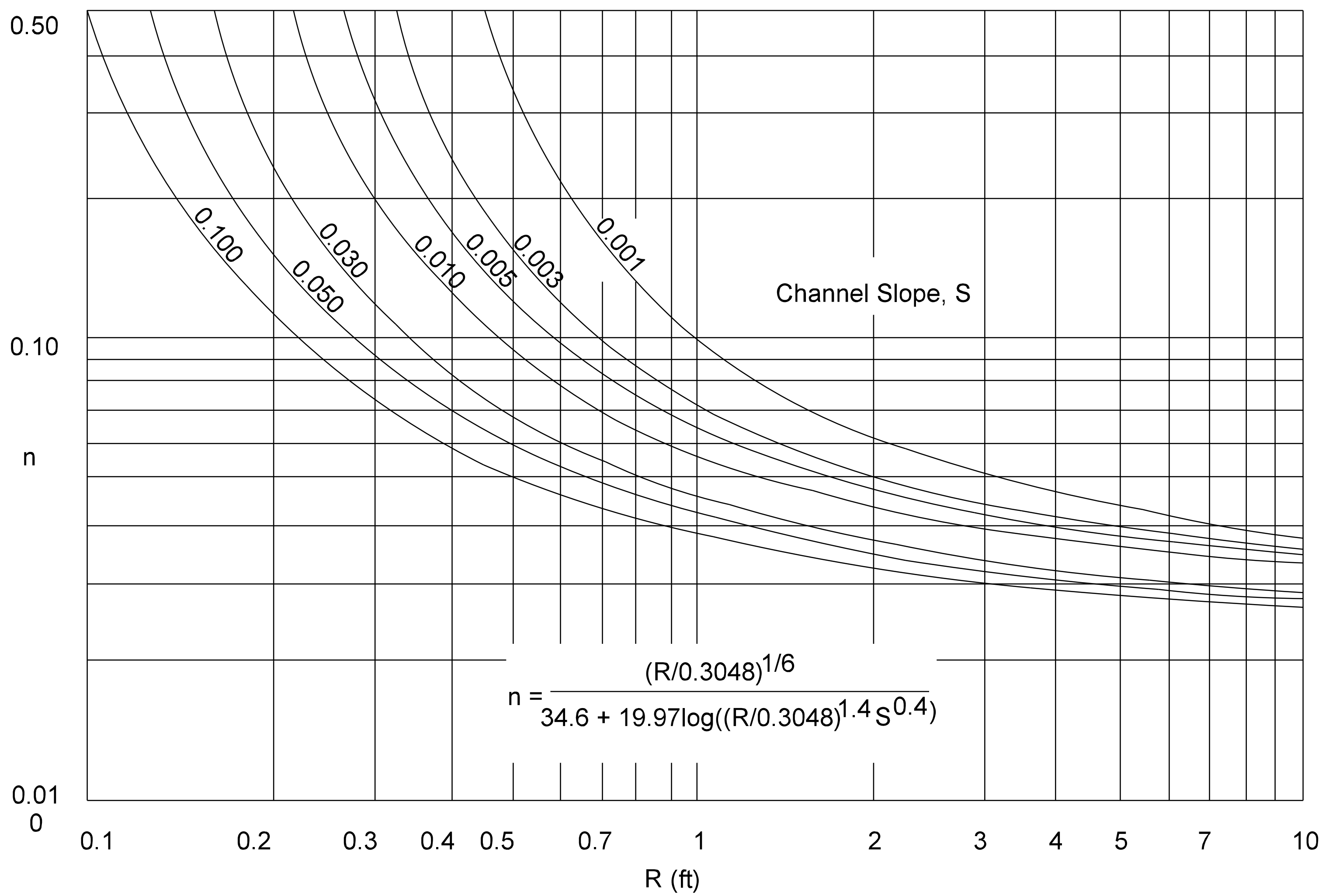
MANNING'S n VERSUS HYDRAULIC RADIUS, R, FOR
CLASS B VEGETATION (HEC 15)

Figure 30-6G



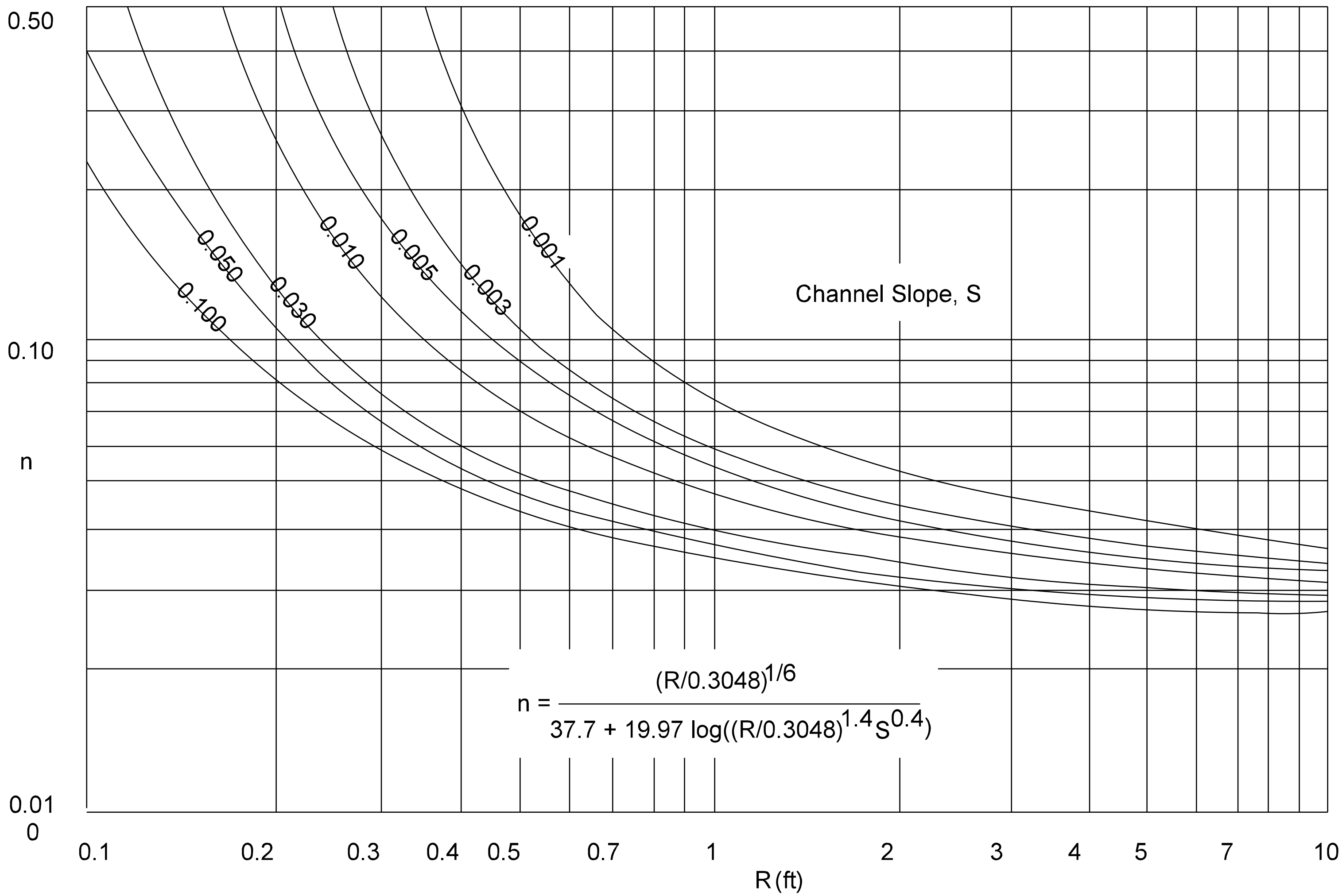
MANNING'S n VERSUS HYDRAULIC RADIUS, R, FOR CLASS C VEGETATION (HEC 15)

Figure 30-6H



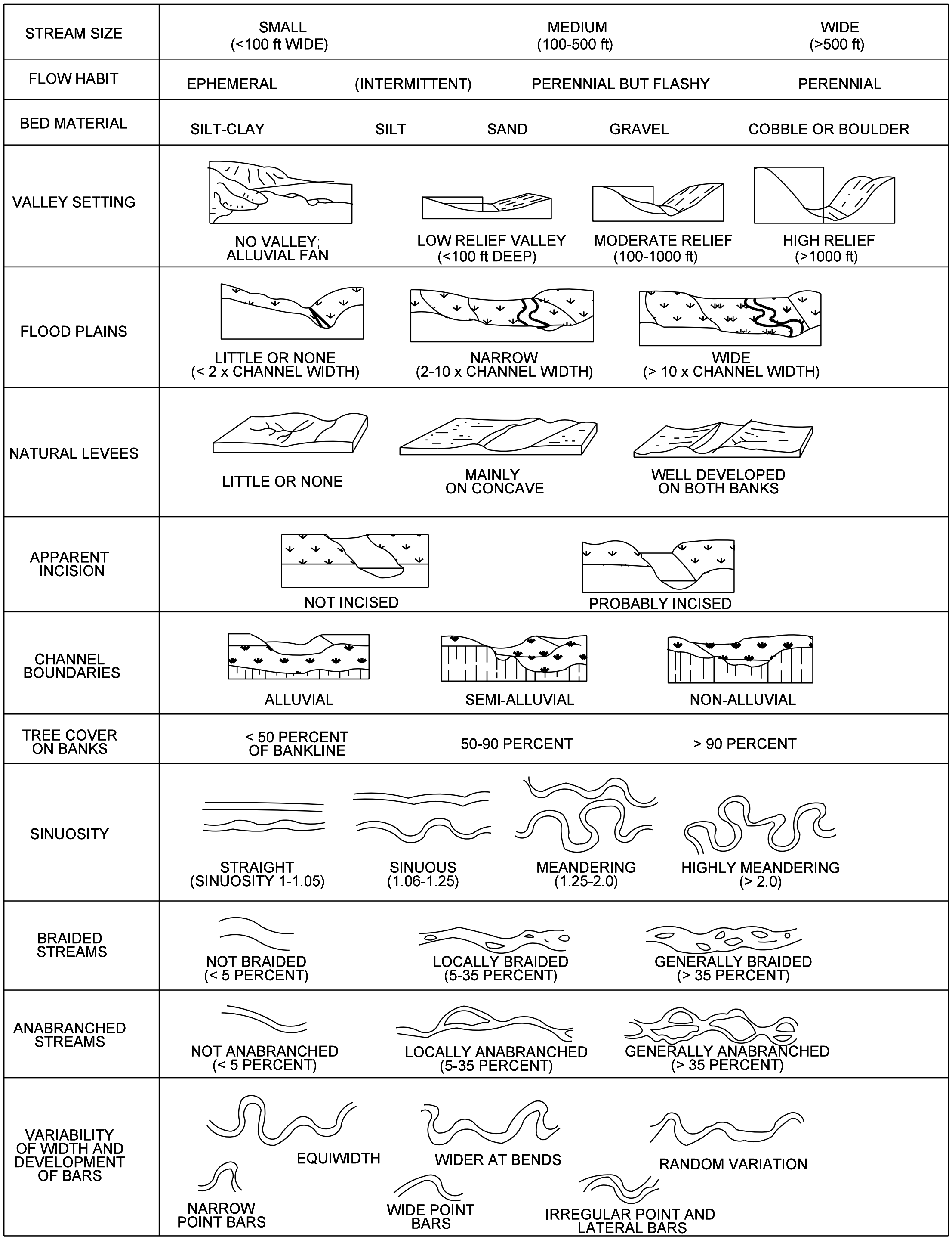
MANNING'S n VERSUS HYDRAULIC RADIUS, R, FOR CLASS D VEGETATION (HEC 15)

Figure 30-6I



MANNING'S n VERSUS HYDRAULIC RADIUS, R, FOR CLASS E VEGETATION (HEC 15)

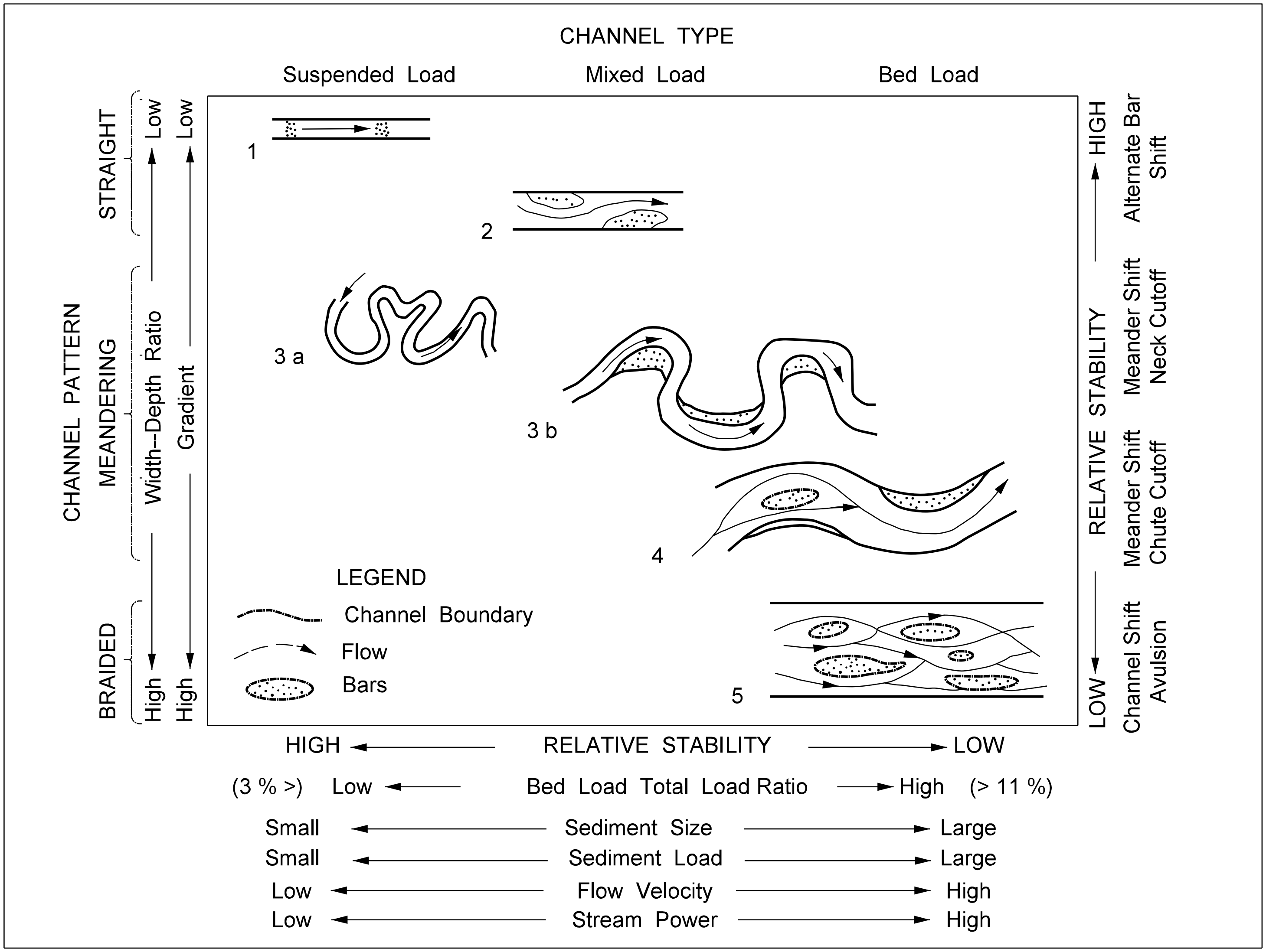
Figure 30-6J



Source: Adapted From Brice and Blodgett, 1978

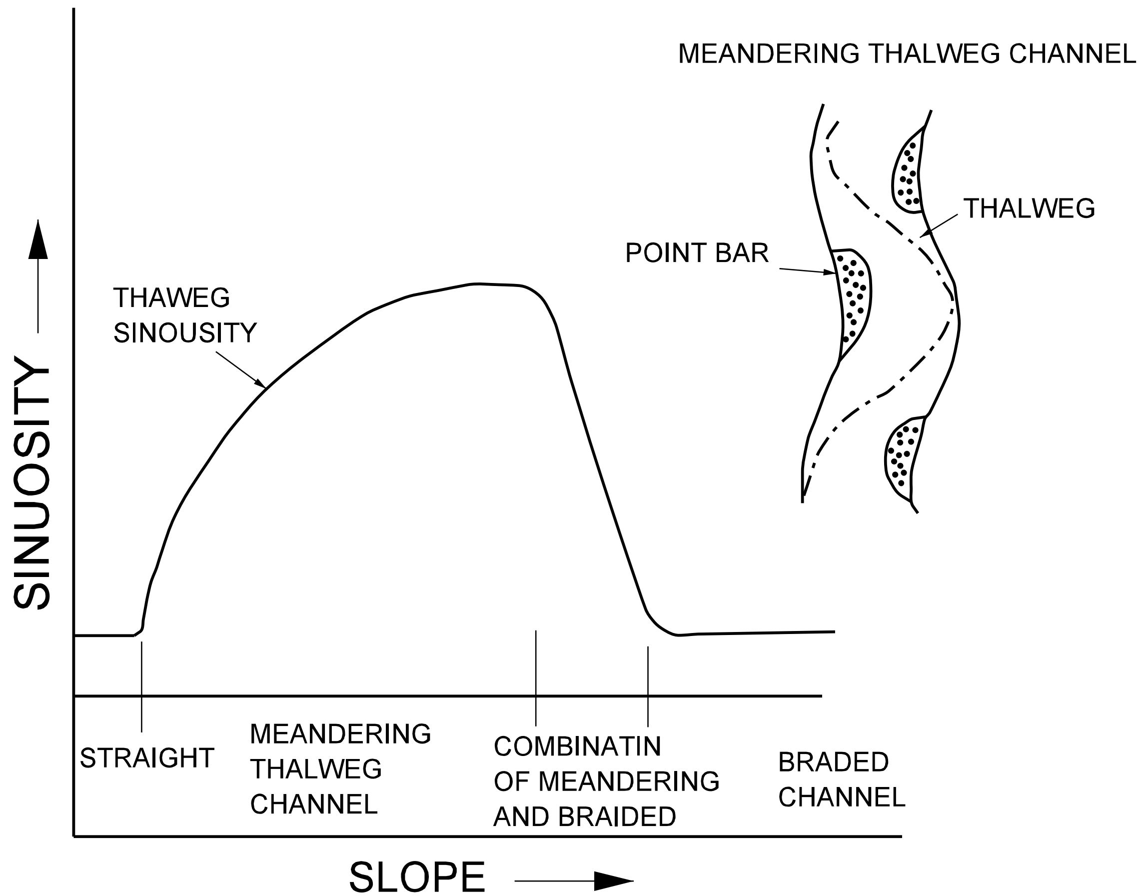
GEOMORPHIC FACTORS THAT AFFECT STREAM STABILITY

Figure 30-7A



CHANNEL CLASSIFICATION AND RELATIVE STABILITY AS HYDRAULIC FACTORS ARE VARIED

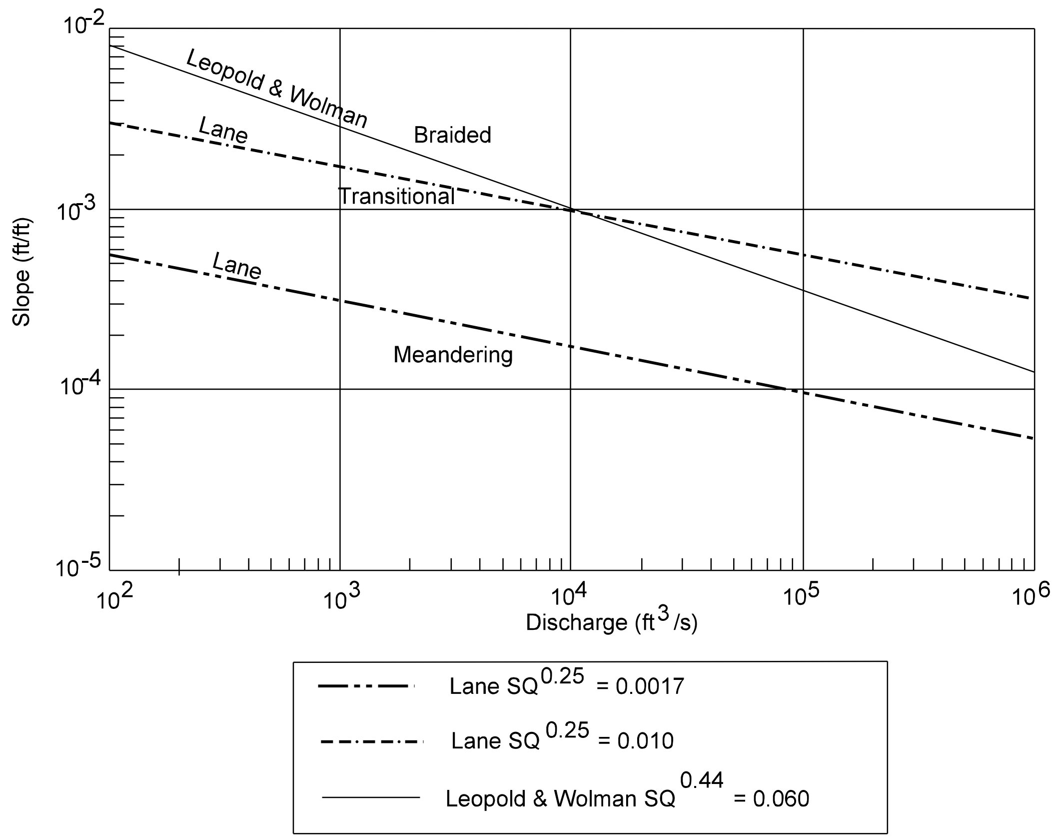
Figure 30-7B



Source: After Richardson et. al., 1988

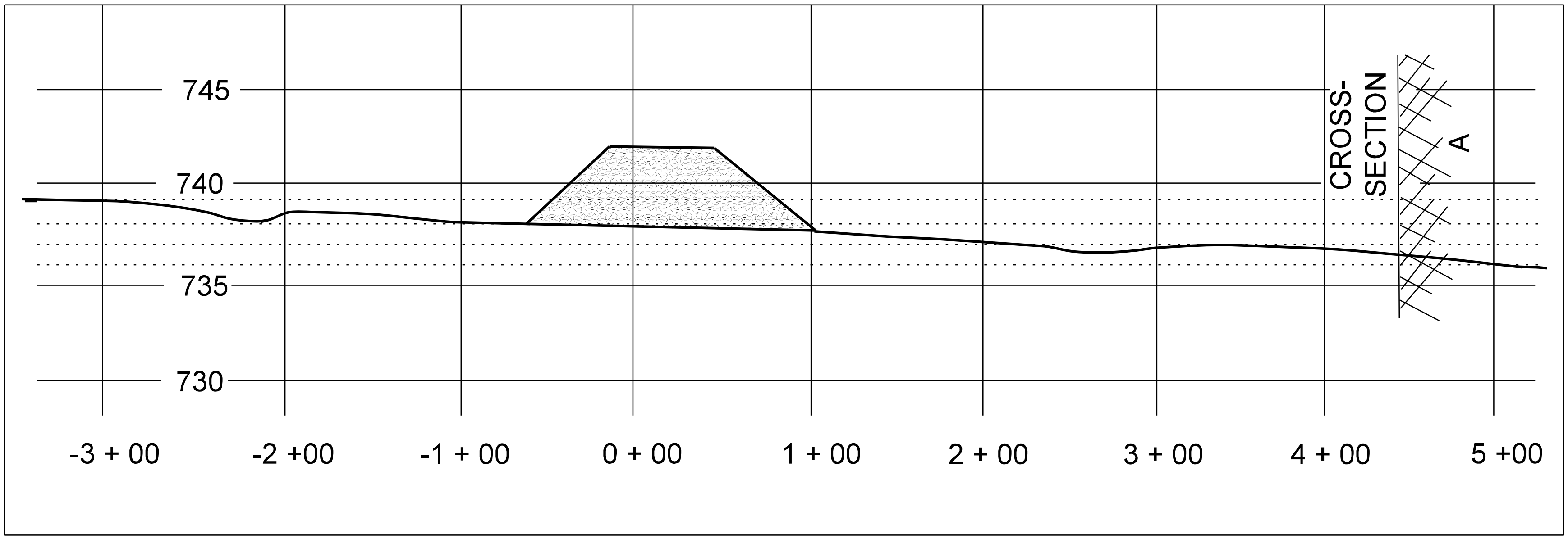
SINUOSITY VERSUS SLOPE WITH CONSTANT DISCHARGE

Figure 30-7C



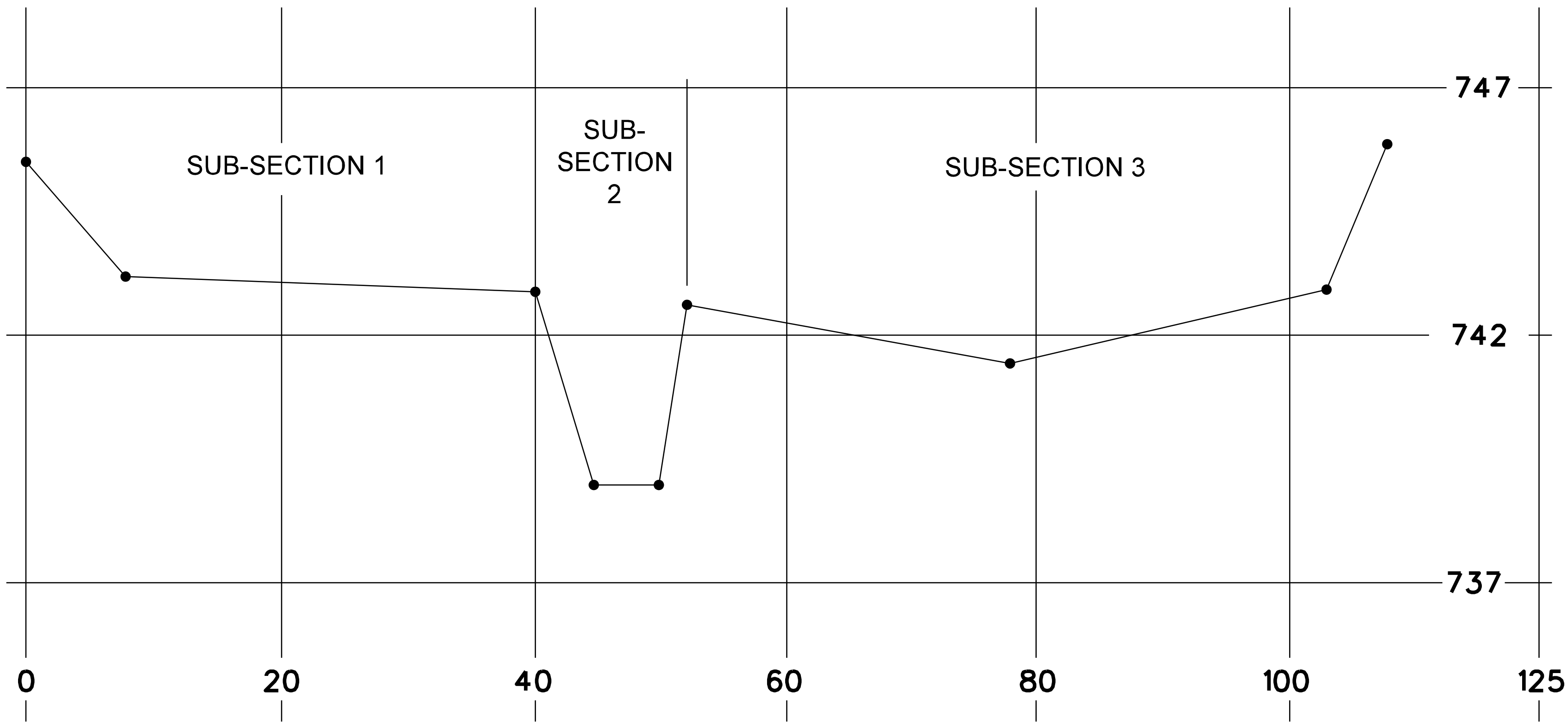
SLOPE-DISCHARGE FOR BRAIDING OR MEANDERING BED STREAMS

Figure 30-7D



SITE DATA EXAMPLE 30-8.1

Figure 30-8.1



STREAM CROSS-SECTION "A" FOR EXAMPLE 30-8.1

Figure 30-8.2

Elevation = 739.63, Slope = 0.0027							
Subsection ID	I	II	III	IV	V	VI	Totals/ Average
Area (ft^2)		6.22					6.22
Wetted Perimeter (ft)		8.03					
Hydraulic Radius (ft)		0.77					
$R^{2/3}$		0.84					
N	0.060	0.035	0.050				
ΔQ (ft^3/s)		11.53					11.53
Subsection Vel. (ft/s)		1.85					1.85

Elevation = 734.00							
Subsection ID	I	II	III	IV	V	VI	Totals/ Average
Area (ft^2)		14.78					14.78
Wetted Perimeter (ft)		11.07					
Hydraulic Radius (ft)		1.33					
$R^{2/3}$		1.21					
N	0.060	0.035	0.050				
ΔQ (ft^3/s)		39.45					39.45
Subsection Vel. (ft/s)		2.67					2.67

Elevation = 741.67							
Subsection ID	I	II	III	IV	V	VI	Totals/ Average
Area (ft^2)		25.44	6.78				32.2
Wetted Perimeter (ft)		15.13	22.27				
Hydraulic Radius (ft)		1.67	0.30				
$R^{2/3}$		1.41	0.45				
N	0.060	0.035	0.050				
ΔQ (ft^3/s)		79.14	4.71				83.85
Subsection Vel. (ft/s)		3.11	0.69				2.60

CHANNEL COMPUTATION SAMPLE

Figure 30-8A

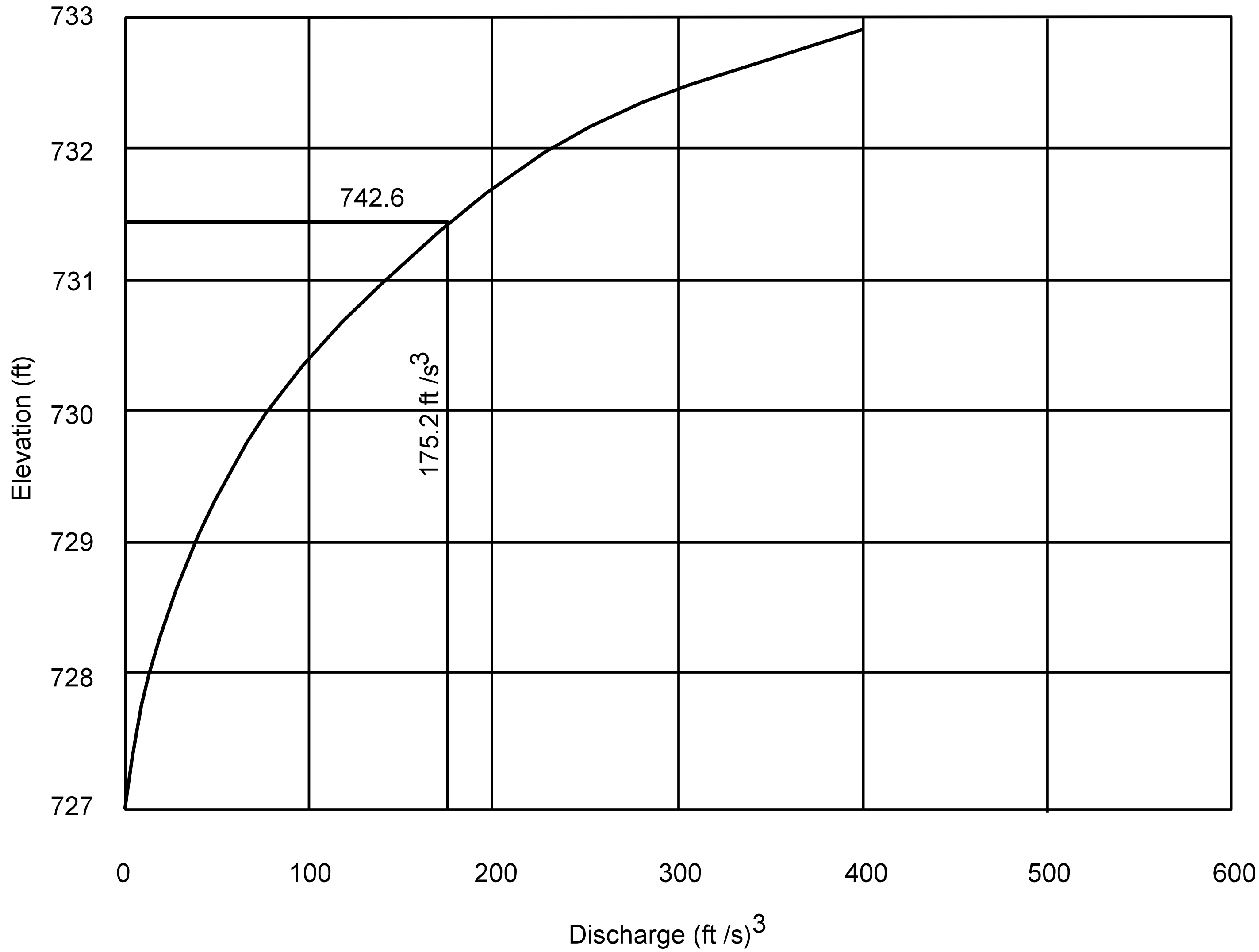
Elevation = 742.67, Slope = 0.0027							
Subsection ID	I	II	III	IV	V	VI	Totals/ Average
Area (ft^2)	1.67	38.33	46.44				86.44
Wetted Perimeter (ft)	16.27	16.27	50.90				
Hydraulic Radius (ft)	0.10	2.36	0.91				
$R^{2/3}$	0.22	1.77	0.94				
N	0.060	0.035	0.050				
ΔQ (ft^3/s)	0.47	149.7	67.4				217.57
Subsection Vel. (ft/s)	0.28	3.91	1.45				2.52

Elevation = 743.70							
Subsection ID	I	II	III	IV	V	VI	Totals/ Average
Area (ft^2)	43.22	50.56	98.89				192.7
Wetted Perimeter (ft)	35.37	16.27	52.93				
Hydraulic Radius (ft)	1.22	3.10	1.87				
$R^{2/3}$	1.14	2.13	1.52				
N	0.060	0.035	0.050				
ΔQ (ft^3/s)	63.41	237.6	232.1				553.1
Subsection Vel. (ft/s)	1.47	4.70	2.35				2.77

Elevation = _______, Slope = _______							
Subsection ID	I	II	III	IV	V	VI	Totals/ Average
Area (ft^2)							
Wetted Perimeter (ft)							
Hydraulic Radius (ft)							
$R^{2/3}$							
N							
ΔQ (ft^3/s)							
Subsection Vel. (ft/s)							

CHANNEL COMPUTATION SAMPLE

Figure 30-8A (Contd.)



EXAMPLE STAGE-DISCHARGE CURVE

Figure 30-8B

```
*F
T1 SOME CREEK WATER SURFACE PROFILE
T2 (WSPRO USER'S MANUAL, J.O. SHEARMAN
T3 SUBCRITICAL FLOW
SI 1
*
Q     283.13      283.13      283.13
WS    182.27      182.58      182.88
*
XS SEC-A 30.48
GR   32.6 , 189.82   40.2 , 186.25   51.8 , 183.42   57.9 , 181.04
GR   75.6 , 179.98   82.6 , 179.98   89.3 , 179.85   94.5 , 179.98
GR   96.9 , 180.77  103.0 , 181.62  106.7 , 183.02  112.2 , 184.03
GR  115.8 , 184.40  121.9 , 184.46
N    .065      .027   .065
SA   51.8    112.2
*
XS SEC-B 64.0
GR   43.9 , 189.61   55.5 , 184.55   62.5 , 181.50   66.7 , 180.92
GR   67.7 , 180.95   83.8 , 179.79   90.5 , 179.76   96.3 , 179.82
GR  105.2 , 180.01  108.8 , 180.95  117.0 , 184.12  117.3 , 184.46
GR  121.9 , 184.58
SA   55.5   117.0
*
XS SEC-C 114.3
GR   60.0 , 188.78   68.3 , 185.43   75.3 , 181.65   83.5 , 180.28
GR   84.1 , 179.67   89.6 , 179.61   93.0 , 179.37   96.6 , 179.24
GR   99.7 , 179.37  107.6 , 179.73  108.2 , 180.68  114.0 , 181.71
GR  119.8 , 183.91  121.0 , 184.27  121.9 , 184.30
SA   68.3   121.0
*
XS SEC-D 152.4
GR   67.1 , 188.69   73.1 , 184.00   77.1 , 180.89   83.2 , 180.80
GR   84.1 , 180.07   89.9 , 180.01   95.1 , 180.01   96.0 , 179.52
GR  100.0 , 179.55  103.6 , 179.58  103.9 , 180.07  113.4 , 181.29
GR  118.6 , 183.91  121.9 , 184.00
SA   73.1   118.6
*
XS SEC-E 195.1
GR   62.2 , 188.66   73.1 , 180.77   78.6 , 180.80   84.1 , 180.52
GR   89.3 , 180.46   94.8 , 180.46  100.3 , 180.37  105.8 , 180.74
GR  111.2 , 180.68  117.0 , 183.18  121.9 , 183.48  122.2 , 185.31
SA   73.1   111.2
*
EX
ER
END
```

WSPRO INPUT DATA FILE

Figure 30-8C

```
************************* W S P R O *******************************
    Federal Highway Administration  -  U. S. Geological Survey
           Model for Water-Surface Profile Computations
       Run Date & Time: 10/18/95  9:04 am   Version V092695
          Input File:  ex82.wsp    Output File:  ex82.LST
*-------------------------------------------------------------------*

*F
***                   Input Data In Free Format                  ***

T1  SOME CREEK WATER SURFACE PROFILE
T2  (WSPRO USER'S MANUAL, J.O. SHEARMAN
T3  SUBCRITICAL FLOW
SI  1


                        Metric (SI) Units Used in WSPRO

         Quantity            SI Units                 Precision
         ----------          -------------------      ---------
         Length              meters                   0.001
         Depth               meters                   0.001
         Elevation           meters                   0.001
         Widths              meters                   0.001

         Velocity            meters/second            0.001
         Discharge           cubic meters/second      0.001
         Slope               meter/meter              0.001

         Angles              degrees                  0.01
         ----------          -------------------      ---------

Q   283.13   283.13   283.13

 ***   Processing Flow Data; Placing Information into Sequence 1  ***

WS  182.27   182.58   182.88
```

```
*************************** W S P R O ************************
   Federal Highway Administration  -  U. S. Geological Survey
          Model for Water-Surface Profile Computations
         Input Units:  Metric   /  Output Units:  Metric
*---------------------------------------------------------------*
                  SOME CREEK WATER SURFACE PROFILE
                (WSPRO USER'S MANUAL, J.O. SHEARMAN
                          SUBCRITICAL FLOW
          *-----------------------------------------*
          * Starting To Process Header Record SEC-A *
          *-----------------------------------------*

XS SEC-A 30.48
GR   32.6 , 189.82   40.2 , 186.25   51.8 , 183.42   57.9 , 181.04
GR   75.6 , 179.98   82.6 , 179.98   89.3 , 179.85   94.5 , 179.98
GR   96.9 , 180.77  103.0 , 181.62  106.7 , 183.02  112.2 , 184.03
GR  115.8 , 184.40  121.9 , 184.46
N    0.065    0.027   0.065
SA   51.8    112.2

 *** Completed Reading Data Associated With Header Record SEC-A ***
 *** Storing X-Section Data In Temporary File As Record Number 1***

 ***          Data Summary For Header Record SEC-A              ***
SRD Location:      30.  Cross-Section Skew:   .0   Error Code   0
Valley Slope:  .00000   Averaging Conveyance By Geometric Mean.
Energy Loss Coefficients ->  Expansion:  .50   Contraction:   .00

                      X,Y-coordinates (14 pairs)
     X        Y          X           Y           X          Y
 --------  ---------  ----------  ----------  ---------  ---------
  32.600    189.820     40.200     186.250     51.800    183.420
  57.900    181.040     75.600     179.980     82.600    179.980
  89.300    179.850     94.500     179.980     96.900    180.770
 103.000    181.620    106.700     183.020    112.200    184.030
 115.800    184.400    121.900     184.460
 --------  ---------  ----------  ----------  ---------  ---------

                 Minimum and Maximum X,Y-coordinates
Minimum X-Station:    32.600  (associated Y-Elevation:  189.820)
Maximum X-Station:   121.900  (associated Y-Elevation:  184.460)
Minimum Y-Elevation: 179.850  (associated X-Station:     89.300)
Maximum Y-Elevation: 189.820  (associated X-Station:     32.600)

                       Roughness Data (3 Subareas)
                Roughness   Horizontal
         SubArea  Coefficient Breakpoint
         -------  ----------- ----------
            1        0.065        ---
                     ---        51.800
            2        0.027        ---
                     ---       112.200
            3        0.065        ---
         -------  ----------- ----------

          *-Finishing-Processing-Header-Record-SEC-A-*
          *-----------------------------------------*
```

```
 *************************** W S P R O ************************
   Federal Highway Administration  -  U. S. Geological Survey
          Model for Water-Surface Profile Computations
         Input Units:  Metric   /  Output Units:  Metric
 *-------------------------------------------------------------*
                  SOME CREEK WATER SURFACE PROFILE
                 (WSPRO USER'S MANUAL, J.O. SHEARMAN
                          SUBCRITICAL FLOW
           *-----------------------------------------*
           * Starting To Process Header Record SEC-B *
           *-----------------------------------------*

XS SEC-B 64.0
GR   43.9 , 189.61   55.5 , 184.55   62.5 , 181.50   66.7 , 180.92
GR   67.7 , 180.95   83.8 , 179.79   90.5 , 179.76   96.3 , 179.82
GR  105.2 , 180.01  108.8 , 180.95  117.0 , 184.12  117.3 , 184.46
GR  121.9 , 184.58
SA   55.5   117.0

 *** Completed Reading Data Associated With Header Record SEC-B ***
 *** Storing X-Section Data In Temporary File As Record Number 2***

 ***            Data Summary For Header Record SEC-B            ***
SRD Location:      64.  Cross-Section Skew:   .0   Error Code   0
Valley Slope:  .00000   Averaging Conveyance By Geometric Mean.
Energy Loss Coefficients ->  Expansion:  .50   Contraction:   .00

                         X,Y-coordinates (13 pairs)
      X         Y          X          Y          X          Y
 --------  ---------  ---------  ---------  ---------  ---------
  43.900   189.610      55.500    184.550     62.500    181.500
  66.700   180.920      67.700    180.950     83.800    179.790
  90.500   179.760      96.300    179.820    105.200    180.010
 108.800   180.950     117.000    184.120    117.300    184.460
 121.900   184.580
 --------  ---------  ---------  ---------  ----------  ---------

                     Minimum and Maximum X,Y-coordinates
Minimum X-Station:    43.900  (associated Y-Elevation:  189.610)
Maximum X-Station:   121.900  (associated Y-Elevation:  184.580)
Minimum Y-Elevation: 179.760  (associated X-Station:     90.500)
Maximum Y-Elevation: 189.610  (associated X-Station:     43.900)

                         Roughness Data (3 Subareas)
                  Roughness   Horizontal
         SubArea  Coefficient Breakpoint
         -------  ----------- ----------
            1        0.065       ---
                     ---        55.500
            2        0.027       ---
                     ---       117.000
            3        0.065       ---
         -------  ----------- ----------

           *------------------------------------------*
           * Finishing Processing Header Record SEC-B *
           *------------------------------------------*
```

```
*************************** W S P R O ************************
   Federal Highway Administration  -  U. S. Geological Survey
          Model for Water-Surface Profile Computations
         Input Units:  Metric   /  Output Units:  Metric
*-------------------------------------------------------------*
               SOME CREEK WATER SURFACE PROFILE
              (WSPRO USER'S MANUAL, J.O. SHEARMAN
                       SUBCRITICAL FLOW
          *-----------------------------------------*
          * Starting To Process Header Record SEC-C *
          *-----------------------------------------*

XS SEC-C 114.3
GR   60.0 , 188.78   68.3 , 185.43   75.3 , 181.65   83.5 , 180.28
GR   84.1 , 179.67   89.6 , 179.61   93.0 , 179.37   96.6 , 179.24
GR   99.7 , 179.37  107.6 , 179.73  108.2 , 180.68  114.0 , 181.71
GR  119.8 , 183.91  121.0 , 184.27  121.9 , 184.30
SA   68.3   121.0

 *** Completed Reading Data Associated With Header Record SEC-C ***
 *** Storing X-Section Data In Temporary File As Record Number 3***

 ***       Data Summary For Header Record SEC-C                ***
SRD Location:     114.  Cross-Section Skew:   .0   Error Code   0
Valley Slope:  .00000   Averaging Conveyance By Geometric Mean.
Energy Loss Coefficients ->  Expansion:  .50   Contraction:   .00

                         X,Y-coordinates (15 pairs)
    X          Y           X           Y           X          Y
 --------  ---------  ----------   ---------   ---------  ---------
  60.000    188.780     68.300     185.430      75.300    181.650
  83.500    180.280     84.100     179.670      89.600    179.610
  93.000    179.370     96.600     179.240      99.700    179.370
 107.600    179.730    108.200     180.680     114.000    181.710
 119.800    183.910    121.000     184.270     121.900    184.300
 --------  ---------  ----------   ---------   ---------  ---------

                    Minimum and Maximum X,Y-coordinates
Minimum X-Station:    60.000  (associated Y-Elevation:  188.780)
Maximum X-Station:   121.900  (associated Y-Elevation:  184.300)
Minimum Y-Elevation: 179.240  (associated X-Station:     96.600)
Maximum Y-Elevation: 188.780  (associated X-Station:     60.000)

                        Roughness Data (3 Subareas)
                  Roughness   Horizontal
         SubArea  Coefficient Breakpoint
         -------  ----------- ----------
            1        0.065        ---
                     ---        68.300
            2        0.027        ---
                     ---       121.000
            3        0.065        ---
         -------  ----------- ----------

          *------------------------------------------*
          * Finishing Processing Header Record SEC-C *
          *------------------------------------------*
```

```
*************************** W S P R O ************************
   Federal Highway Administration  -  U. S. Geological Survey
          Model for Water-Surface Profile Computations
        Input Units:  Metric   /  Output Units:  Metric
*-------------------------------------------------------------*
                  SOME CREEK WATER SURFACE PROFILE
                (WSPRO USER'S MANUAL, J.O. SHEARMAN
                         SUBCRITICAL FLOW
          *-----------------------------------------*
          * Starting To Process Header Record SEC-D *
          *-----------------------------------------*

XS SEC-D 152.4
GR   67.1 , 188.69   73.1 , 184.00   77.1 , 180.89   83.2 , 180.80
GR   84.1 , 180.07   89.9 , 180.01   95.1 , 180.01   96.0 , 179.52
GR  100.0 , 179.55  103.6 , 179.58  103.9 , 180.07  113.4 , 181.29
GR  118.6 , 183.91  121.9 , 184.00
SA   73.1   118.6

 *** Completed Reading Data Associated With Header Record SEC-D ***
 *** Storing X-Section Data In Temporary File As Record Number 4***

 ***          Data Summary For Header Record SEC-D              ***
SRD Location:     152.  Cross-Section Skew:   .0   Error Code   0
Valley Slope:  .00000   Averaging Conveyance By Geometric Mean.
Energy Loss Coefficients ->  Expansion:  .50   Contraction:   .00

                         X,Y-coordinates (14 pairs)
    X          Y          X          Y          X          Y
 --------  ---------  ----------  ---------  ---------  ---------
  67.100    188.690     73.100    184.000     77.100    180.890
  83.200    180.800     84.100    180.070     89.900    180.010
  95.100    180.010     96.000    179.520    100.000    179.550
 103.600    179.580    103.900    180.070    113.400    181.290
 118.600    183.910    121.900    184.000
 --------  ---------  ----------  ---------  ---------  ---------

                     Minimum and Maximum X,Y-coordinates
Minimum X-Station:    67.100  (associated Y-Elevation:  188.690)
Maximum X-Station:   121.900  (associated Y-Elevation:  184.000)
Minimum Y-Elevation: 179.520  (associated X-Station:     96.000)
Maximum Y-Elevation: 188.690  (associated X-Station:     67.100)

                         Roughness Data (3 Subareas)
                  Roughness   Horizontal
         SubArea  Coefficient Breakpoint
         -------  ----------- ----------
            1        0.065        ---
                     ---       73.100
            2        0.027        ---
                     ---      118.600
            3        0.065        ---
         -------  ----------- ----------

          *-----------------------------------------*
          * Finishing Processing Header Record SEC-D *
          *-----------------------------------------*
```

```
          *************************** W S P R O ***********************
            Federal Highway Administration  -  U. S. Geological Survey
                   Model for Water-Surface Profile Computations
                 Input Units:  Metric   /  Output Units:  Metric
         *---------------------------------------------------------------*
                            SOME CREEK WATER SURFACE PROFILE
                          (WSPRO USER'S MANUAL, J.O. SHEARMAN
                                   SUBCRITICAL FLOW
                   *-----------------------------------------*
                   * Starting To Process Header Record SEC-E *
                   *-----------------------------------------*

XS SEC-E 195.1
GR   62.2 , 188.66   73.1 , 180.77   78.6 , 180.80   84.1 , 180.52
GR   89.3 , 180.46   94.8 , 180.46  100.3 , 180.37  105.8 , 180.74
GR  111.2 , 180.68  117.0 , 183.18  121.9 , 183.48  122.2 , 185.31
SA   73.1   111.2

 *** Completed Reading Data Associated With Header Record SEC-E ***
 *** Storing X-Section Data In Temporary File As Record Number 5***

 ***          Data Summary For Header Record SEC-E              ***
SRD Location:     195.  Cross-Section Skew:   .0   Error Code   0
Valley Slope:  .00000   Averaging Conveyance By Geometric Mean.
Energy Loss Coefficients ->  Expansion:  .50   Contraction:   .00

                           X,Y-coordinates (12 pairs)
     X         Y           X          Y           X          Y
 --------  ---------  ----------  ---------  ---------  ---------
  62.200    188.660      73.100    180.770      78.600    180.800
  84.100    180.520      89.300    180.460      94.800    180.460
 100.300    180.370     105.800    180.740     111.200    180.680
 117.000    183.180     121.900    183.480     122.200    185.310
 --------  ---------  ----------  ---------  ---------  ---------

                       Minimum and Maximum X,Y-coordinates
Minimum X-Station:    62.200  (associated Y-Elevation:  188.660)
Maximum X-Station:   122.200  (associated Y-Elevation:  185.310)
Minimum Y-Elevation: 180.370  (associated X-Station:    100.300)
Maximum Y-Elevation: 188.660  (associated X-Station:     62.200)

                           Roughness Data (3 Subareas)
                  Roughness   Horizontal
         SubArea  Coefficient Breakpoint
         -------  ----------- ----------
            1        0.065        ---
                     ---        73.100
            2        0.027        ---
                     ---       111.200
            3        0.065        ---
         -------  ----------- ----------

                  *------------------------------------------*
                  * Finishing Processing Header Record SEC-E *
                  *------------------------------------------*
```

```
*************************** W S P R O *******************************
       Federal Highway Administration  -  U. S. Geological Survey
              Model for Water-Surface Profile Computations
             Input Units:  Metric   /  Output Units:  Metric
*--------------------------------------------------------------------*

                   SOME CREEK WATER SURFACE PROFILE
                  (WSPRO USER'S MANUAL, J.O. SHEARMAN
                           SUBCRITICAL FLOW
EX

          *=================================================*
          *    Summary of Boundary Condition Information    *
          *=================================================*

          Reach        Water Surface     Friction
 #      Discharge        Elevation        Slope      Flow Regime
---     ---------      -------------    ---------    -----------
 1       283.12           182.279         ******     Sub-Critical
 2       283.12           182.589         ******     Sub-Critical
 3       283.12           182.889         ******     Sub-Critical
---     ---------      -------------    ---------    -----------

             *===========================================*
             *    Beginning 3 Profile Calculation(s)    *
             *===========================================*
```

```
*************************** W S P R O ********************************
      Federal Highway Administration  -  U. S. Geological Survey
             Model for Water-Surface Profile Computations
           Input Units:  Metric   /  Output Units:  Metric
*---------------------------------------------------------------------*

                    SOME CREEK WATER SURFACE PROFILE
                   (WSPRO USER'S MANUAL, J.O. SHEARMAN
                           SUBCRITICAL FLOW

                    WSEL       VHD        Q         AREA       SRDL       LEW
                    EGEL        HF        V           K        FLEN       REW
                    CRWS        HO      FR #         SF       ALPHA       ERR
                  ---------  -----   -------    -------  ---------  -------
Section: SEC-A      182.278  .518    283.124     88.821  *********   54.749
Header Type: XS     182.797  *****     3.187    4791.65  *********  104.723
SRD:     30.481     181.963  *****      .763      *****      1.000   ******

===135 CONVEYANCE RATIO OUTSIDE OF RECOMMENDED LIMITS.
                  "SEC-B"   KRATIO = 1.42

Section: SEC-B      182.554   .324   283.124    112.218     33.521   60.102
Header Type: XS     182.879   .082     2.522    6807.56     33.521  112.933
SRD:     64.003     181.799   .000      .553      .0025      1.000     .000

Section: SEC-C      182.603   .415   283.124     99.251     50.302   73.554
Header Type: XS     183.018   .093     2.852    6305.92     50.302  116.337
SRD:    114.305     181.855   .045      .598      .0019      1.000     .000

Section: SEC-D      182.652    .49   283.124     91.159     38.101   74.848
Header Type: XS     183.144   .086     3.105    5581.40     38.101  116.091
SRD:    152.407     182.094   .038      .667      .0023      1.000     .002

Section: SEC-E      182.729   .579   283.124     88.929     42.702   70.408
Header Type: XS     183.308   .119     3.183    5113.09     42.702  115.939
SRD:    195.109     182.357   .043      .770      .0028      1.120     .003
```

```
*************************** W S P R O ********************************
      Federal Highway Administration  -  U. S. Geological Survey
             Model for Water-Surface Profile Computations
            Input Units:  Metric   /  Output Units:  Metric
*---------------------------------------------------------------------*
```

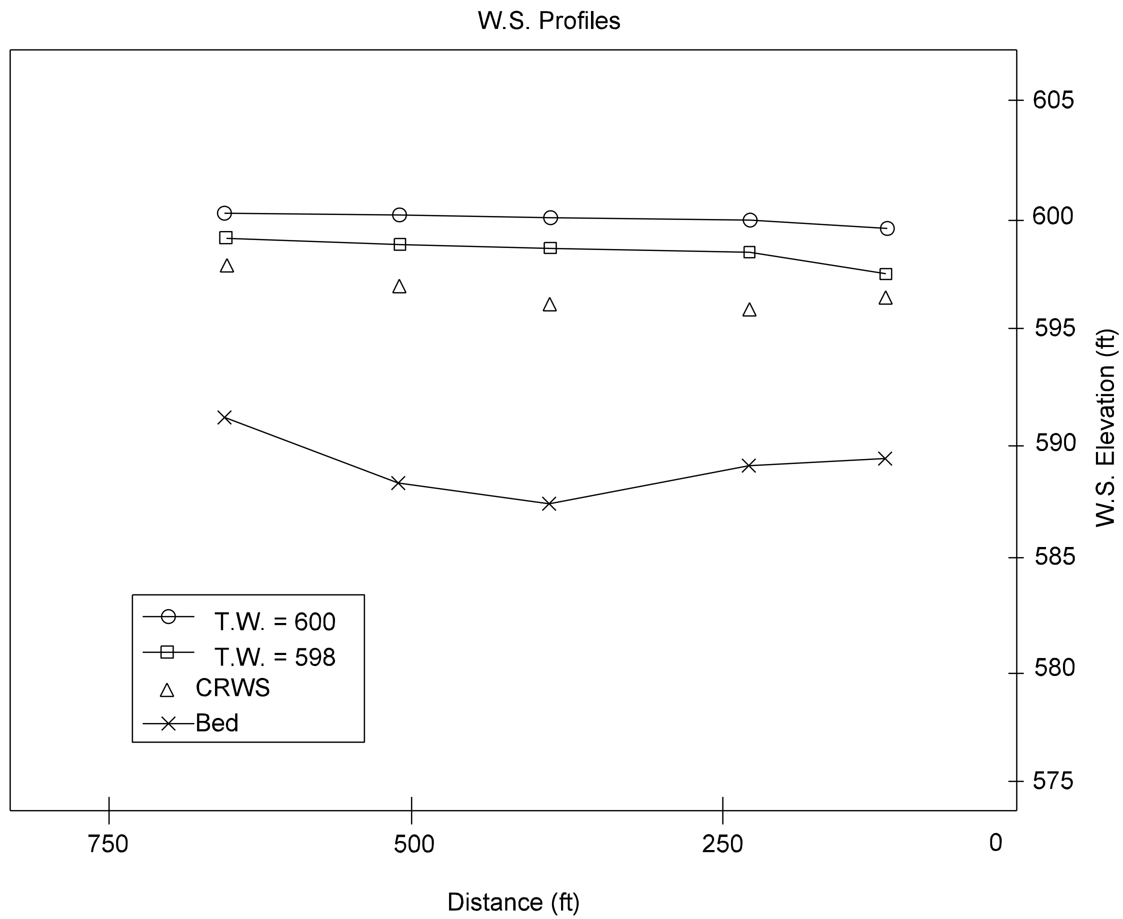
SOME CREEK WATER SURFACE PROFILE
(WSPRO USER'S MANUAL, J.O. SHEARMAN
SUBCRITICAL FLOW

	WSEL / EGEL / CRWS	VHD / HF / HO	Q / V / FR #	AREA / K / SF	SRDL / FLEN / ALPHA	LEW / REW / ERR
Section: SEC-A	182.588	.373	283.124	104.563	*********	53.954
Header Type: XS	182.962	*****	2.707	6149.63	*********	105.542
SRD: 30.481	181.963	*****	.607	*****	1.000	******
Section: SEC-B	182.746	.272	283.124	122.420	33.521	59.662
Header Type: XS	183.018	.056	2.312	7772.47	33.521	113.428
SRD: 64.003	181.799	.000	.489	.0017	1.000	-.001
Section: SEC-C	182.776	.358	283.124	106.739	50.302	73.232
Header Type: XS	183.135	.073	2.652	7028.30	50.302	116.795
SRD: 114.305	181.855	.043	.541	.0015	1.000	.000
Section: SEC-D	182.812	.427	283.124	97.804	38.101	74.642
Header Type: XS	183.239	.069	2.894	6216.38	38.101	116.409
SRD: 152.407	182.094	.034	.604	.0018	1.000	.000
Section: SEC-E	182.868	.508	283.124	95.291	42.702	70.216
Header Type: XS	183.376	.096	2.970	5687.75	42.702	116.262
SRD: 195.109	182.357	.040	.701	.0023	1.129	-.001

```
*************************** W S P R O *******************************
Federal Highway Administration  -  U. S. Geological Survey
Model for Water-Surface Profile Computations
Input Units:  Metric   /  Output Units:  Metric
*-------------------------------------------------------------------*

SOME CREEK WATER SURFACE PROFILE
(WSPRO USER'S MANUAL, J.O. SHEARMAN
SUBCRITICAL FLOW

                      WSEL      VHD       Q        AREA      SRDL      LEW
                      EGEL       HF       V          K       FLEN      REW
                      CRWS       HO     FR #        SF      ALPHA      ERR
                   ---------   -----  -------    -------  ---------  -------
Section: SEC-A     182.888     .282   283.124    120.274  *********   53.185
Header Type: XS    183.171    *****     2.353    7604.10  *********  106.335
SRD:      30.481   181.963    *****      .500     *****       1.000   ******

Section: SEC-B     182.987     .222   283.124    135.562     33.521   59.107
Header Type: XS    183.210     .038     2.088    9071.46     33.521  114.054
SRD:      64.003   181.799     .000      .425     .0012       1.000     .000

Section: SEC-C     183.004     .299   283.124    116.770     50.302   72.811
Header Type: XS    183.304     .055     2.424    8030.60     50.302  117.395
SRD:     114.305   181.855     .038      .478     .0011       1.000     .000

Section: SEC-D     183.028     .357   283.124    106.930     38.101   74.363
Header Type: XS    183.386     .053     2.647    7122.06     38.101  116.839
SRD:     152.407   182.094     .028      .533     .0014       1.000     .000

Section: SEC-E     183.067     .427   283.124    104.524     42.702   69.941
Header Type: XS    183.494     .073     2.708    6554.45     42.702  116.723
SRD:     195.109   182.357     .034      .618     .0017       1.141    -.001

ER

 *******************  Normal end of WSPRO execution.  *******************
 ****************  Elapsed Time:  0 Minutes  8 Seconds  ****************
```

WSPRO RESULTS

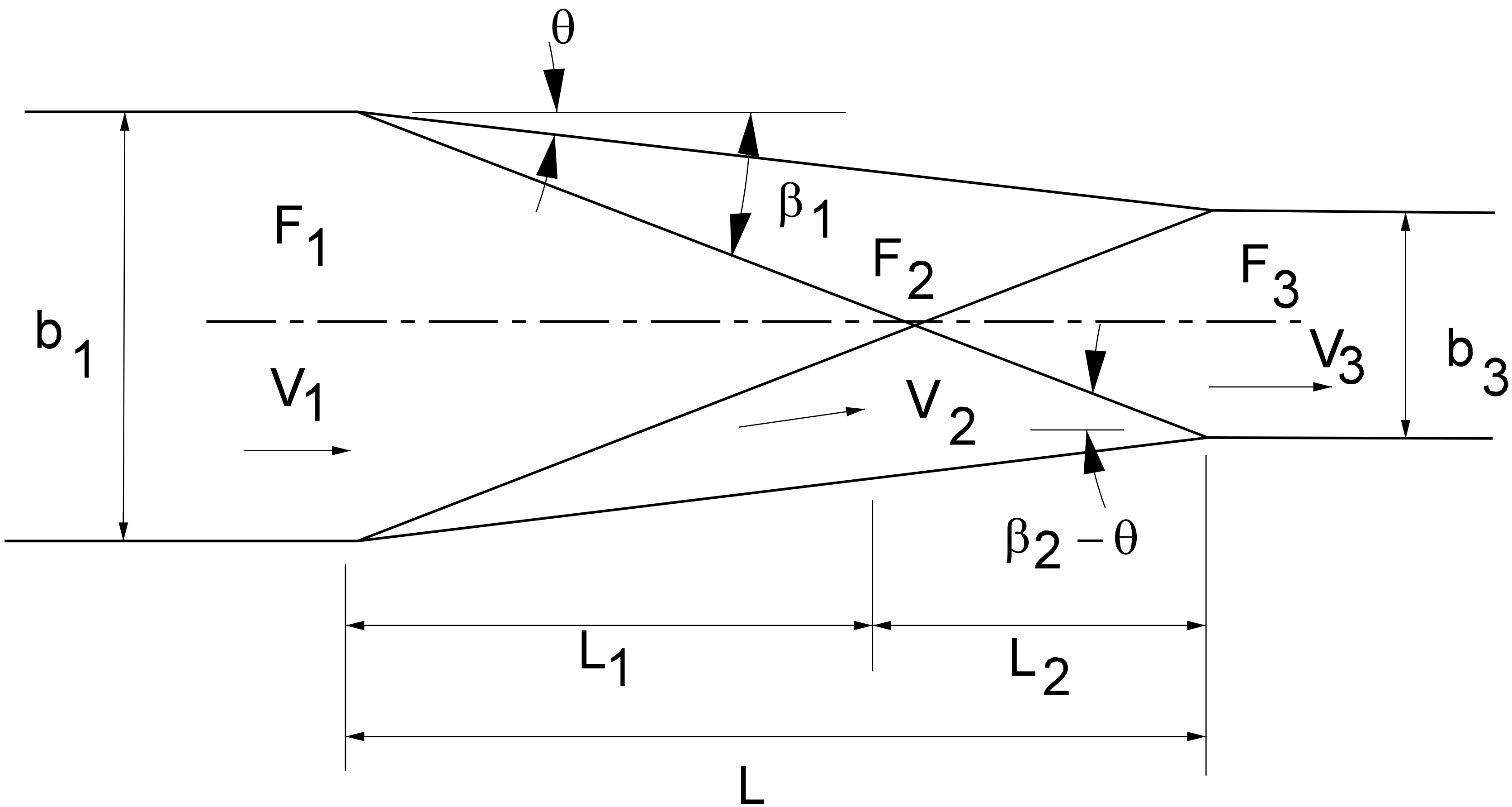
Figure 30-8D



Note: CRWS = Critical Water Surface Profiles for Q = 1000 ft^3/s

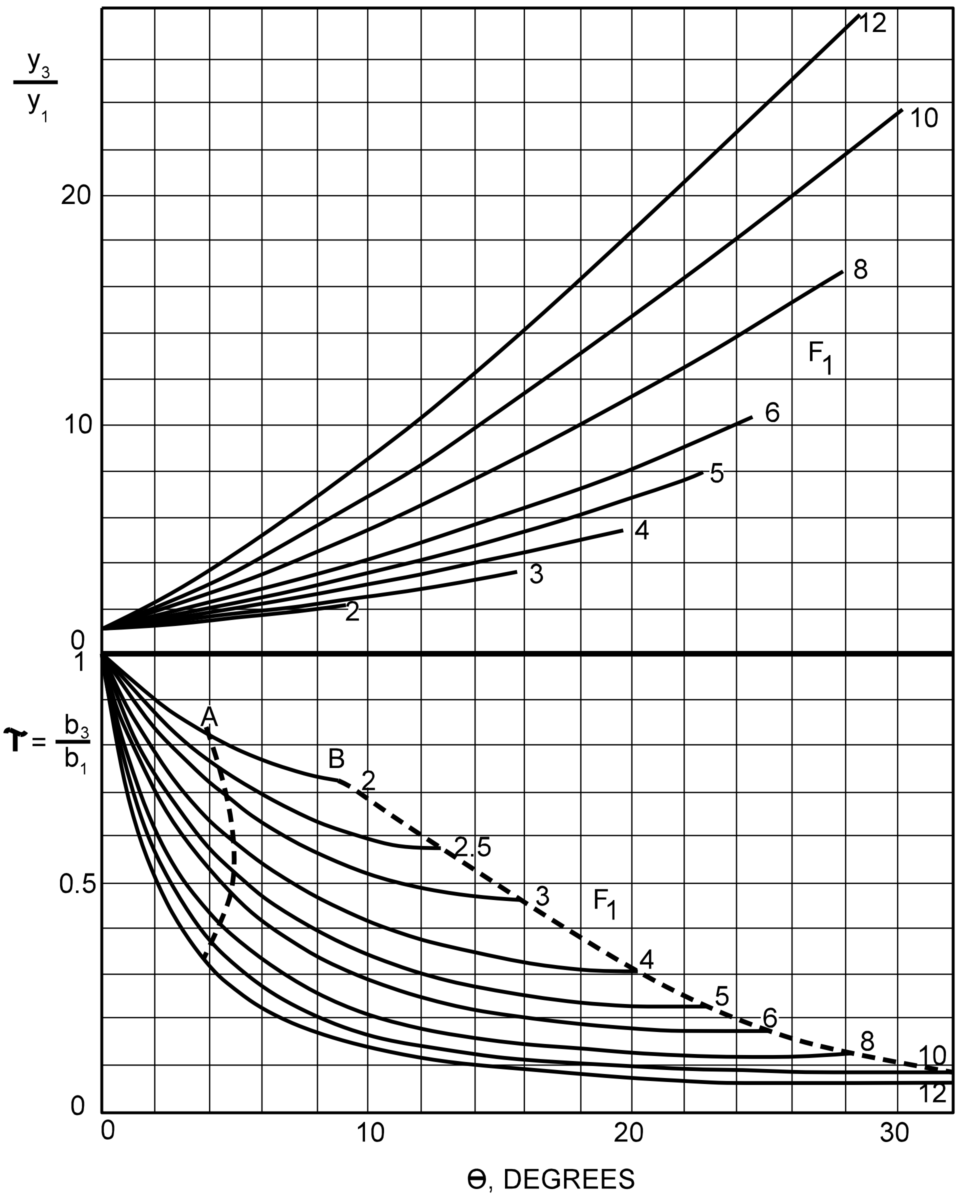
WATER SURFACE PROFILES FOR Q = 1000 ft^3/s AND VARIABLE TAILWATER (TW) ELEVATIONS

Figure 30-8E



DESIGN OF STRAIGHT-WALL CONTRACTIONS IN SUPERCRITICAL FLOW
Example 30-8.6

Figure 30-8F



CONTRACTION RATIO τ AND DEPTH RATIO y_3 / y_1 FOR SUPERCRITICAL FLOW IN CONTRACTION OF ANGLE Θ

EXAMPLE 30-8.6

Figure 30-8G