8. Channels

8.1. Introduction

8.1.1 Definitions

Open channels are a natural or man-made 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.

There are various types of open channels encountered by the designer of transportation facilities in Alaska:

- stream channel,
- roadside channel or ditch, and
- drainage ditch.

The principals of open channel flow hydraulics are applicable to all drainage facilities including culverts.

Stream channels are:

- usually natural channels with their size and shape determined by natural forces,
- usually compound in cross section with a main channel for conveying low flows and a floodplain to transport flood flows, and
- usually shaped geomorphologically by the long term history of sediment load and water discharge which they experience.

Artificial channels include roadside channels and drainage ditches which are:

- man-made channels with regular geometric cross sections, and
- unlined, or lined with artificial or natural material to protect against erosion.

While the principles of open channel flow are the same regardless of the channel type, stream channels and artificial channels (primarily roadside channels) will be treated separately in this chapter as needed.

8.1.2 Significance

Channel analysis is necessary for the design of transportation drainage systems in order to assess:

- potential flooding caused by changes in water surface profiles,
- disturbance of the river system upstream or downstream of the highway right-of-way,
- changes in lateral flow distributions,
- changes in velocity or direction of flow,
- need for conveyance and disposal of excess runoff, and
- need for channel lining to prevent erosion.

8.1.3 Design

Hydraulic design associated with natural channels and roadway ditches is a process which selects and evaluates alternatives according to established criteria. These criteria are the standards established by the Department to insure that a highway facility meets its intended purpose without endangering the structural integrity of the facility itself and without undue adverse effects on the environment or the public welfare.

8.1.4 Purpose

The purpose of this chapter is to:

- establish Department policy,
- specify design criteria,
- review design philosophy,
- outline channel design procedures, and
- demonstrate design techniques by example problems.

8.2. Policy

8.2.1 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. (see Policy Chapter). Policy is implemented through design criteria established as standards for making decisions. (see Section 8.3).

8.2.2 Federal Policy

- Channel designs and/or designs of highway facilities that impact channels should satisfy the policies of the Federal Highway Administration applicable to flood plain management if Federal funding is involved.
- Federal Emergency Management Agency floodway regulations and Corps Of Engineers wetland restrictions for permits should be satisfied.

8.2.3 DOT&PF Policy

- Coordination with other Federal, State, and local agencies concerned with water resources planning shall have high priority in the planning of highway facilities.
- Safety of the general public be an important consideration in the selection of cross-sectional geometry of artificial drainage channels.
- The design of artificial drainage channels or other facilities shall consider the frequency and type of maintenance expected and make allowance for access of maintenance equipment.
- A stable channel is the goal for all channels that are located on highway right-of-way or that impact highway facilities.
- Environmental impacts of channel modifications, including disturbance of fish habitat, wetlands, and streambank stability should be assessed.
- The range of design channel discharges should be selected and approved by the designer based on class of roadway, consequences of traffic interruption, flood hazard risks, economics, and local site conditions.

8.3. Design Criteria

8.3.1 General

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.

8.3.2 Stream Channels

The following criteria applies to natural channels and may be revised as approved by the State Hydraulic Engineer.

- The hydraulic effects of flood plain encroachments should be evaluated over a full range of frequency-based peak discharges from the 2-year through 100-year (or FEMA flood whichever is greater) recurrence intervals on any major highway facility as deemed necessary by the designer.
- If relocation of a stream channel is unavoidable, the cross-sectional shape, meander, pattern, roughness, sediment transport, and slope shall conform to the existing conditions insofar as practicable. Some means of energy dissipation may be necessary when existing conditions cannot be duplicated.
- Streambank stabilization shall be provided, when appropriate, as a result of any actual or potential stream disturbance and shall include both upstream and downstream banks as well as the local site.
- Features such as dikes and levees associated with natural channel modifications shall have a 16 foot minimum top width with access for maintenance equipment. The design shall facilitate ease of maintenance such as access and turn-around points.

8.3.3 Roadside Channels

The following criteria applies to roadside channels and may be revised as approved by the State Hydraulic Engineer.

- Channel side slopes shall not exceed the angle of repose of the soil and/or lining and shall be 2:1 or flatter in the case of rock-riprap lining.

- Flexible linings shall be designed according to the method of allowable tractive force.
- The design discharge for permanent roadside ditch linings shall have a 10-year frequency while temporary linings shall be designed for a minimum of the 2-year frequency flow.
- Channel freeboard shall be one foot or twice the velocity head, whichever is larger.
- Roadside channel design shall consider accomodation of snow storage.

8.4. Open Channel Flow

8.4.1 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 usually one of the unknown variables. The determination of this unknown is one of the principle problems of open channel flow analysis and it depends on quantification of the flow resistance. Natural channels display a much wider range of roughness values than artificial channels.

8.4.2 Definitions

Specific Energy: Specific energy E is defined as the energy head relative to the channel bottom. If the channel is not too steep (slope less than 10 percent) and the streamlines are nearly straight and parallel (so that the hydrostatic assumption holds), the specific energy E becomes the sum of the depth and velocity head:

$$\mathbf{E = y + \alpha\,(V^2/2g)} \qquad \textbf{(8-1)}$$

Where:

y = depth, ft

α = kinetic energy correction coefficient

V = mean velocity, ft/s

g = gravitational acceleration, 32.2 ft/s^2

The kinetic energy correction coefficient is taken to have a value of one for turbulent flow in prismatic channels but may be significantly different than one in natural channels.

Kinetic Energy Coefficient: As the velocity distribution in a river varies from a maximum at the design portion of the channel to essentially zero along the banks, the average velocity head, computed as $(Q/A)^2/2g$ for the stream at a section, does not give a true measure of the kinetic energy of the flow. A weighted average value of the kinetic energy is obtained by multiplying the average velocity head, above, by a kinetic energy coefficient, α, defined as:

$$\boldsymbol{\alpha = [\Sigma(qv^2)/(QV^2]}$$

Where:

v = average velocity in subsection, ft/s

q = discharge in same subsection, cfs

Q = total discharge in river, cfs

V = average velocity in river at section or Q/A, ft/s

Total Energy Head: The total energy head is the specific energy head plus the elevation of the channel bottom with respect to some datum. The locus of the energy head from one cross section to the next defines the energy grade line. See Figure 8-1 for a plot of the specific energy diagram.

Steady and 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 any reach requires that the rates of inflow and outflow be constant and equal. When the discharge varies with time, the flow is unsteady.

Uniform Flow and Nonuniform Flow: A nonuniform 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, nonuniform flow can occur either in a prismatic channel or in a natural channel with variable properties.

Gradually-varied and Rapidly-Varied: A nonuniform 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.

Froude Number: The Froude number is an important dimensionless parameter in open channel flow. It represents the ratio of inertia forces to gravity forces and is defined by:

$$\mathbf{F = V/(gd)^{.5}} \qquad (8.3)$$

Where:

- V = mean velocity = Q/A, ft/s
- g = acceleration of gravity, ft/s^2
- d = hydraulic depth = A/B, ft
- A = cross-sectional area of flow, ft^2
- B = channel topwidth at the water surface, ft

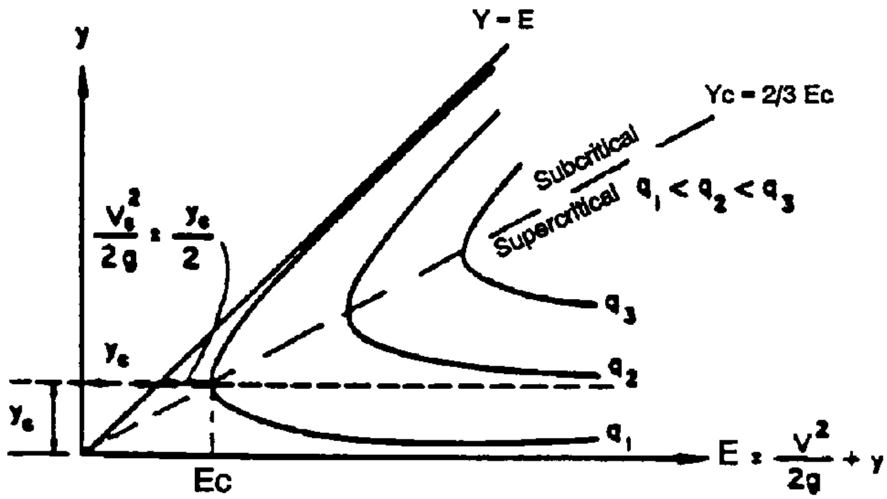
This expression for Froude number applies to any single section channel of nonrectangular shape.

Critical Flow: The variation of specific energy with depth at a constant discharge shows a minimum in the specific energy at a depth called critical depth at which the Froude number has a value of one. Critical depth is also the depth of maximum discharge when the specific energy is held constant. These relationships are illustrated in Figure 8-1.

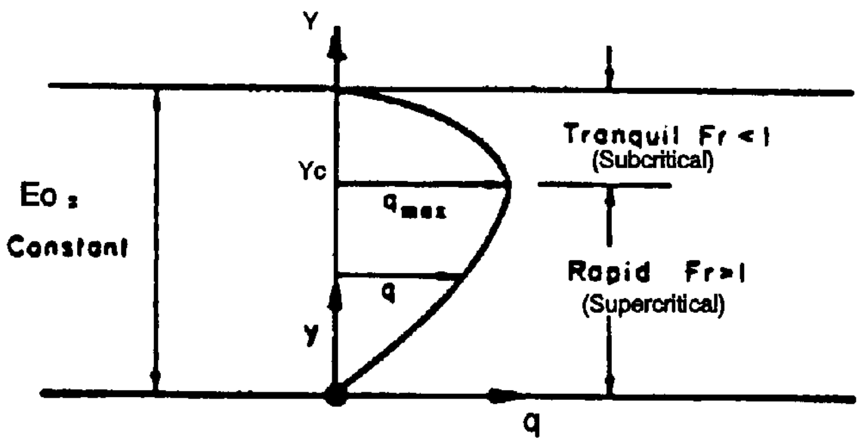
Subcritical Flow: Depths greater than critical occur in subcritical flow and the Froude number is less than one. In this state of flow, small water surface disturbances can travel both upstream and downstream, and depth is always controlled by downstream conditions.

Supercritical Flow: Depths less than critical depth occur in supercritical flow and the Froude number is greater than one. Small water surface disturbances are always swept downstream in supercritical flow, and the depth is controlled by upstream conditions.

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 highway drainage structures.



(a) Specific Energy Diagram



(b) Discharge Diagram

Figure 8-1

Specific Energy And Discharge Diagram For Rectangular Channels

(Adopted From Highways In The River Environment)

8.4.3 Flow Classification

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

Steady Flow

1. Uniform Flow
2. Nonuniform Flow
    a. Gradually Varied Flow
    b. Rapidly Varied Flow

Unsteady Flow

1. Unsteady Uniform Flow (rare)
2. Unsteady Nonuniform Flow
    a. Gradually Varied Unsteady Flow
    b. Rapidly Varied Unsteady Flow

The steady uniform flow case and the steady nonuniform flow case are the most fundamental types of flow treated in highway engineering hydraulics.

8.4.4 Equations

The following equations are those most commonly used to analyze open channel flow. The use of these equations in analyzing open channel hydraulics is discussed in Section 8.5.

Manning's Equation

For a given channel geometry, slope, and roughness, and a specified value of discharge Q, a unique value of depth occurs in steady uniform flow. It is called the normal depth. The normal depth is used to design artificial channels in steady, uniform flow and is computed from Manning's equation:

$$\mathbf{Q = [(1.49/n)AR^{2/3}S^{1/2}]} \qquad \mathbf{(8.4)}$$

Where:

Q = discharge, cfs

n = Manning's roughness coefficient

A = cross-sectional area of flow, ft^2

R = hydraulic radius = A/P, ft

P = wetted perimeter, ft

S = channel slope, ft/ft

The selection of Manning's n is generally based on observation; however, considerable experience is essential in selecting appropriate n values. The range of n values for various types of channels and floodplains is given in Table 8-1.

If the normal depth computed from Manning's equation is greater than critical depth, the slope is classified as a mild slope, while 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.

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

$$\mathbf{K = (1.49/n)AR^{2/3}}$$

and then Manning's Equation can be written as:

$$\mathbf{Q = KS^{1/2}}$$

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 or of downstream conditions.

The concept of channel conveyance is useful when computing the distribution of overbank flood flows in the stream cross section and the flow distribution through the opening in a proposed stream crossing. Manning's Equation shall not be used for determining highwater elevations in a bridge opening. At a minimum, a step-backwater analysis shall be performed

Continuity Equation

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

$$\mathbf{Q = A_1V_1 = A_2V_2}$$

Where:

Q = discharge, cfs

A = flow cross-sectional area, ft^2

V = mean cross-sectional velocity, ft/s (which is perpendicular to the cross section)

The subscripts 1 and 2 refer to successive cross sections along the flow path. The continuity equation can be used together with Manning's Equation to obtain the steady uniform flow velocity as:

$$V = Q/A = [(1.49/n)R^{2/3}S^{1/2}]$$

Table 8-1

Uniform Flow

Values of Roughness Coefficient n (Uniform Flow)

Type Of Channel and Description	Minimum	Normal	Maximum
EXCAVATED OR DREDGED			
a. Earth, straight and uniform	0.016	0.018	0.020
1. Clean, recently completed	0.018	0.022	0.025
2. Clean, after weathering	0.022	0.025	0.030
3. Gravel, uniform section, clean	0.022	0.027	0.033
b. Earth, winding and sluggish			
1. No vegetation	0.023	0.025	0.030
2. Grass, some weeds	0.025	0.030	0.033
3. Dense Weeds or aquatic plants in deep channels	0.030	0.035	0.040
4. Earth bottom and rubble sides	0.025	0.030	0.035
5. Stony bottom and weedy sides	0.025	0.035	0.045
6. Cobble bottom and clean sides	0.030	0.040	0.050
c. Dragline-excavated or dredged			
1. No vegetation	0.025	0.028	0.033
2. Light brush on banks	0.035	0.050	0.060
d. Rock cuts			
1. Smooth and uniform	0.025	0.035	0.040
2. Jagged and irregular	0.035	0.040	0.050
e. Channels not maintained, weeds and brush uncut			
1. Dense weeds, high as flow depth	0.050	0.080	0.120
2. Clean bottom, brush on sides	0.040	0.050	0.080
3. Same, highest stage of flow	0.045	0.070	0.110
4. Dense brush, high stage	0.080	0.100	0.140
NATURAL STREAMS			
1. Minor streams (top width at flood stage < 100 ft)			
a. Streams on Plain			
1. Clean, straight, full stage, or deep pools no rifts	0.025	0.030	0.033
2. Same as above, but more stones and weeds	0.030	0.035	0.040
3. Clean, winding, some pools and shoals	0.033	0.040	0.045

4. Same as above, but some weeds and some 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 floodways with heavy stand of timber and underbrush	0.075	0.100	0.150
b. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
1. Bottom: gravels, cobbles, and few bolders	0.030	0.040	0.050
2. Bottom: cobbles with large bolders	0.040	0.050	0.070
2. Flood Plains			
a. Pasture, no brush			
1. Short grass	0.025	0.030	0.035
2. High grass	0.030	0.035	0.050
b. Cultivated area			
1. No crop	0.020	0.030	0.040
2. Mature row crops	0.025	0.035	0.045
3. Mature field crops	0.030	0.040	0.050
c. Brush			
1. Scattered brush, heavy weeds	0.035	0.050	0.070
2. Light brush and trees in winter	0.035	0.050	0.060
3. Light brush and trees, in summer	0.040	0.060	0.080
4. Medium to dense brush, in winter	0.045	0.070	0.110
5. Medium to dense brush, in summer	0.070	0.100	0.160
d. Trees			
1. Dense Willows, summer, straight	1.110	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 spouts	0.050	0.060	0.080
4. Heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.080	0.100	0.120
5. Same as above, but with flood stage reaching branches	0.100	0.120	0.160
3. Major Streams (top width at flood stage > 100 ft). The n value is less than that for minor streams of similar description, because banks offer less effective resistance.			
a. Regular section with no boulders or brush	0.025	.....	0.060
b. Irregular and rough section	0.035	.....	0.100

Energy Equation

The energy equation expresses conservation of energy in open channel flow expressed as energy per unit weight of fluid which has dimensions 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 any cross section when added. Written between an upstream open channel cross section designated 1 and a downstream cross section designated 2, the energy equation is:

$$\mathbf{h_1 + \alpha_1(V_1^2/2g) = h_2 + \alpha_2(V^2_2/2g) + h_L} \qquad \mathbf{(8.9)}$$

Where:

h_1 and h_2 are the upstream and downstream stages, respectively, ft

α = kinetic energy correction coefficient

V = mean velocity, ft/s

h_L = head loss due to local cross-sectional changes (minor loss) as well as 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, i.e. h=z+y. The terms in the energy equation are illustrated graphically in Figure 8-2. 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.

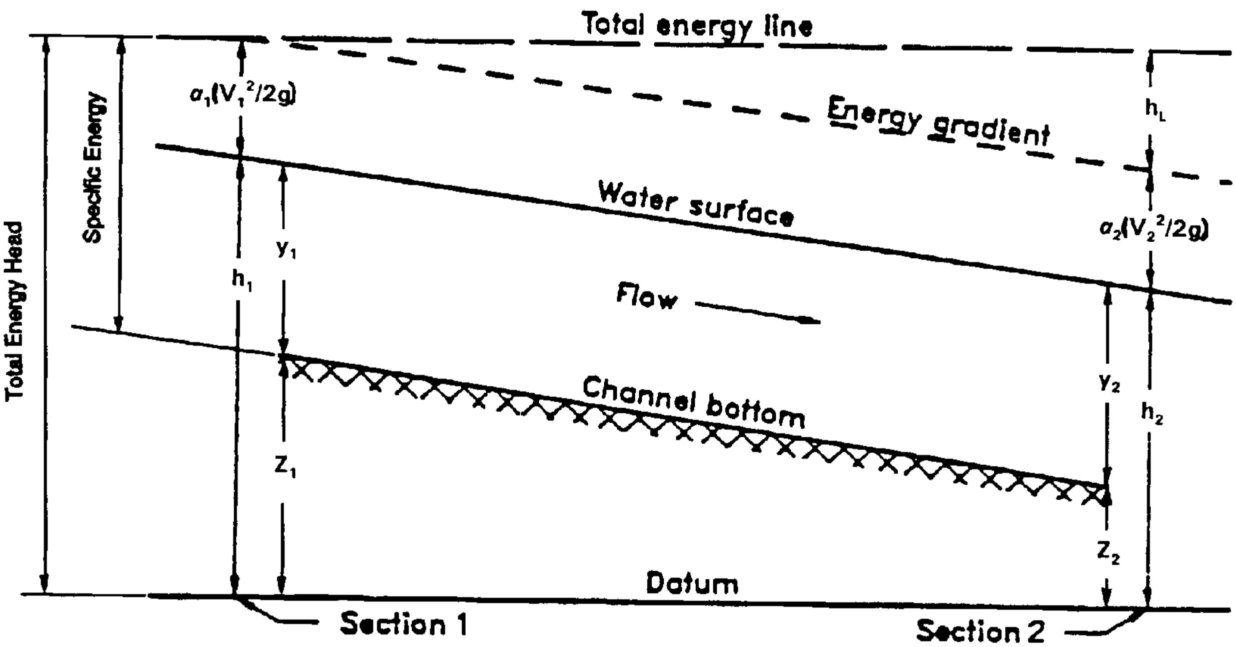


Figure 8-2

Terms In The Energy Equation

Source: FHWA, 1990

8.5. Hydraulic Analysis

8.5.1 General

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

Two methods are commonly used in hydraulic analysis of open channels. The single-section method is a simple application of Manning's Equation to determine tailwater rating curves for culverts, or to analyze other situations in which uniform or nearly uniform flow conditions exist. The step-backwater method is used to compute the complete water surface profile in a stream reach to evaluate the unrestricted water surface elevations for bridge hydraulic design, or to analyze other gradually-varied flow problems in streams.

The single-section method will generally yield less reliable results because it requires more judgment and assumptions than the step-backwater method. In many situations, however, the single-section method is all that is justified, e.g., a standard roadway ditch, culverts, storm drain outfalls, etc.

8.5.2 Cross Sections

Cross-sectional geometry of streams 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, but in wide floodplains or bends it may be necessary to use a section along intersecting straight lines, i.e. a "dog-leg" section. It is especially important to make a plot of the cross section to reveal any inconsistencies or errors.

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

Cross sections should be subdivided with vertical boundaries where there are abrupt lateral changes in geometry and/or roughness as in the case of overbank flows. The conveyances of each subsection are computed separately to determine the flow distribution and α, and are then added to determine the total flow conveyance. The subsection divisions must be chosen carefully so that the distribution of flow or conveyance is nearly uniform in each subsection (Davidian, 1984). Selection of cross sections and vertical subdivision of a cross section are shown in Figure 8-3.

Manning's n Value Selection

Manning's n is affected by many factors and its selection in natural channels depends heavily on engineering experience. Pictures of channels and flood plains for which the discharge has been measured and Manning's n has been calculated are very useful (see Arcement and Schneider, 1984; Barnes, 1978).

For situations lying outside the engineer's experience, a more regimented approach is presented in (Arcement and Schneider, 1984). Once the Manning's n values have been selected, it is highly recommended that they be verified with historical high water marks and/or gaged streamflow data.

Manning's n values for artificial channels are more easily defined than for natural stream channels. See Table 8-1 in Section 8.4.4 for typical n values of both artificial channels and natural stream channels.

Calibration

The equations should be calibrated 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, and cross-section. Proper calibration is essential if accurate results are to be obtained.

Switchback Phenomenon

If the cross-section is improperly subdivided, the mathematics of the Manning's Equation causes a switchback. A switchback results when the calculated discharge decreases with an associated increase in elevation. This occurs when, with a minor increase in water depth, there is a large increase of wetted perimeter. Simultaneously, there is a corresponding small increase in cross-sectional area which causes a net decrease in the hydraulic radius from the value 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 in order to avoid the switchback.

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

8.5.3 Single Section Analysis

The single-section analysis method (slope-area method) is simply a solution of Manning's Equation for the normal depth of flow given the discharge and cross-section properties including geometry, slope, and roughness. It implicitly assumes the existence of steady, uniform flow; however, uniform flow rarely exists in either artificial or stream channels. Nevertheless, the single-section method is often used to design artificial channels 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 cover a range of discharges up to at least the base (100-year) flood. The stage-discharge curve can be determined as follows:

- Select the typical cross-section at or near the location where the stage-discharge curve is needed.
- Subdivide cross-section and assign n-values to subsections as described in Section 8.5.2.1
- Estimate water-surface slope. Since uniform flow is assumed, the average slope of the streambed can usually be used.
- Apply a range of incremental water surface elevations to the cross-section.
- 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.
- 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 discharge of interest.

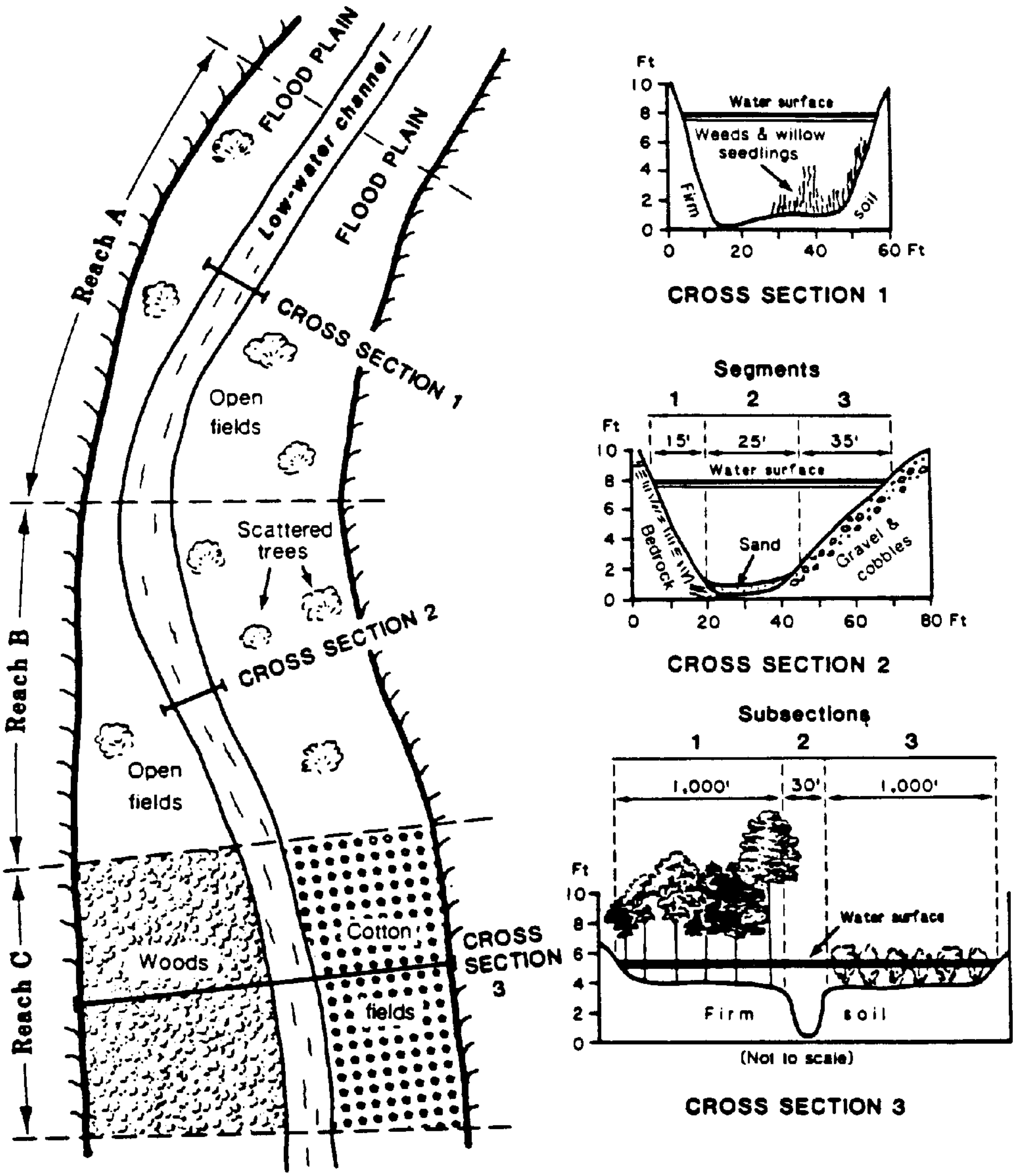


Figure 8-3

Hypothetical Cross Section Showing Reaches, Segments, And Subsections Used In Assigning n Values

Source: FHWA, 1984

An example application of the stage-discharge curve procedure is presented in Appendix A.

Alternatively, a graphical technique such as that given in Figure 8-4 or a nomograph as in Figure 8-5 can be used for trapezoidal and prismatic channels. The best approach, especially in the case of stream channels, is to use a computer program such as WSPRO to obtain the normal depth.

In stream channels the transverse variation of velocity in any cross section is a function of subsection geometry and roughness and may vary considerably from one stage and discharge to another. It is important to know this variation for purposes of designing erosion control measures and locating relief openings in highway fills, for example. The best method of establishing transverse velocity variations is by current meter 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. It is assumed that the energy grade line slope is the same across the cross section so that the total conveyance K_T of the cross section is the sum of the subsection conveyances. The total discharge is then $K_T S^{1/2}$ and the discharge in each subsection is proportional to its conveyance. The velocity in each subsection is obtained from the continuity equation, $V = Q/A$.

Alluvial channels present 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, several methods outlined in (Vanoni, 1977) have been developed for this case (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 locations where a stage-discharge relationship has already been measured in a channel. These usually exist at gaging stations on streams monitored by the USGS. Measured stage-discharge curves will generally yield more accurate estimates of water surface elevation and should take precedence over the analytical methods described above.

8.5.4 Step-Backwater Analysis

Step-backwater analysis is useful for determining unrestricted water surface profiles where a highway crossing is planned, and for analyzing how far upstream the water surface elevations are affected by a culvert or bridge. Because the calculations involved in this analysis are tedious and repetitive, it is recommended that a computer program such as the FHWA/USGS program WSPRO or Corps of Engineers HEC-2 be used. However, it is important that the designer know the computational methodology and limitations of the programs.

Step-Backwater Models

The WSPRO program has been designed to provide a water surface profile for six major types of open channel flow situations:

- unconstricted flow,
- single opening bridge,
- bridge opening(s) with spur dikes,
- single opening embankment overflow,
- multiple alternatives for a single site, and
- multiple openings.

The HEC-2 program developed by the Corps of Engineers is widely used for calculating water surface profiles for steady gradually varied flow in a natural or man-made channels. Both subcritical and supercritical flow profiles can be calculated. The effects of bridges, culverts, weirs, and structures in the floodplain may be also considered in the computations. This program is also designed for application in flood plain management and flood insurance studies.

Step-Backwater Methodology

The computation of water surface profiles by both WSPRO and 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 8.5.1. Manning's n values can vary both horizontally across the section as well as vertically. 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 amplify on the methodology, the energy equation is repeated from Section 8.4.4:

$$h_1 + \alpha_1(V_1^2/2g) = h_2 + \alpha_2(V_2^2/2g) + h_L \quad (8.10)$$

Where:

h_1 and h_2 are the upstream and downstream stages, respectively, ft

α = kinetic energy correction coefficient

V = mean velocity, ft/s

h_L = head loss due to local cross-sectional changes (minor loss) as well as 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, i.e., h = z+y. The energy equation is solved between successive stream reaches with nearly uniform roughness, slope, and cross-sectional properties.

The total head loss is calculated from:

$$h_L = K_m[(\alpha_1 V_1^2/2g) - (\alpha_2 V_2^2/2g)] + S_e L \quad (8.11)$$

Where:

K_m = the minor loss coefficient

S_e = the mean slope of the energy grade line evaluated from Manning's equation and a selected averaging technique (Shearman, 1990 and HEC-2), ft/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 zero and 0.1 for contractions and 0.5 and 0.3 for expansions in WSPRO and HEC-2, respectively.

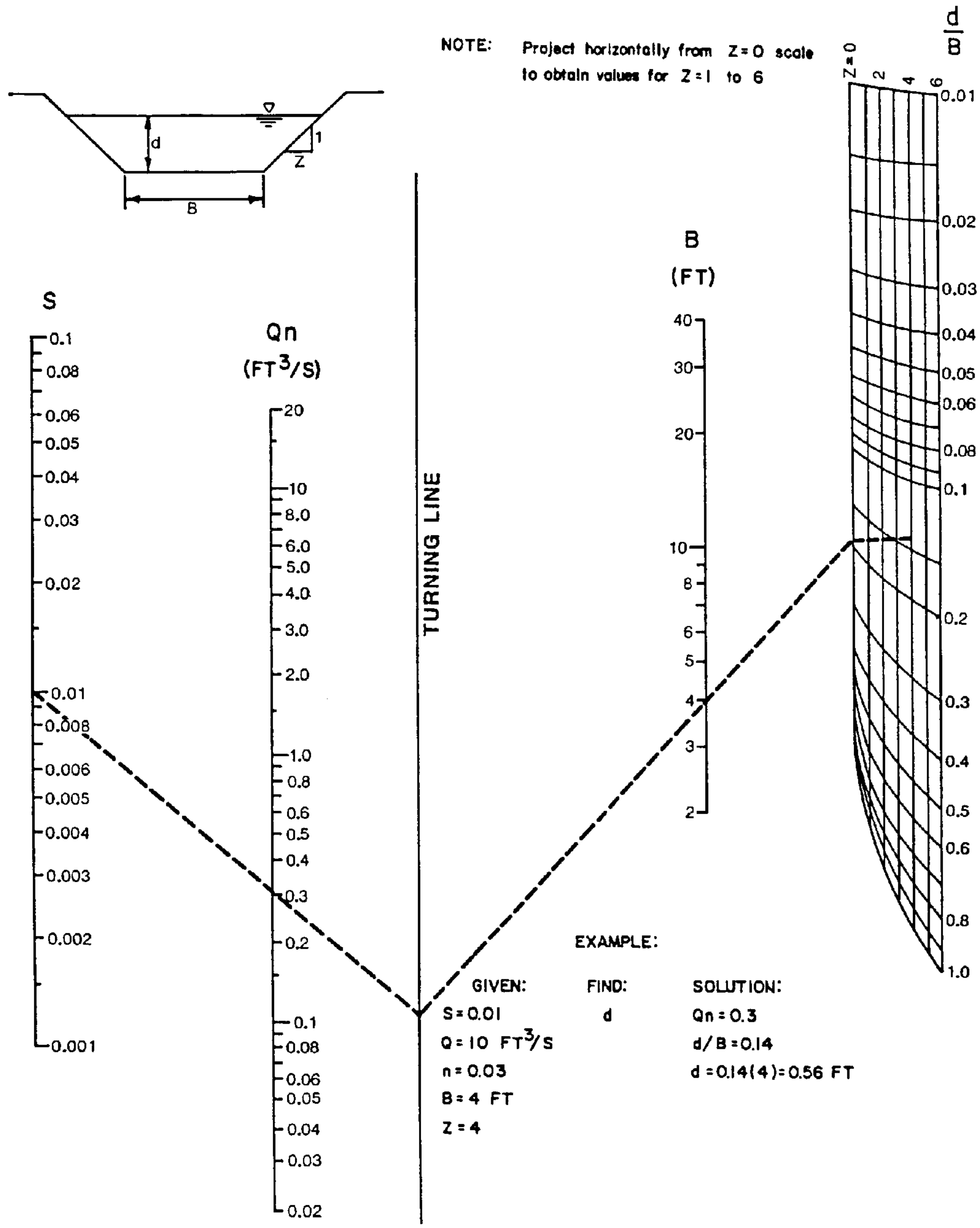


Figure 8-4

Trapezoidal Channel Capacity Chart

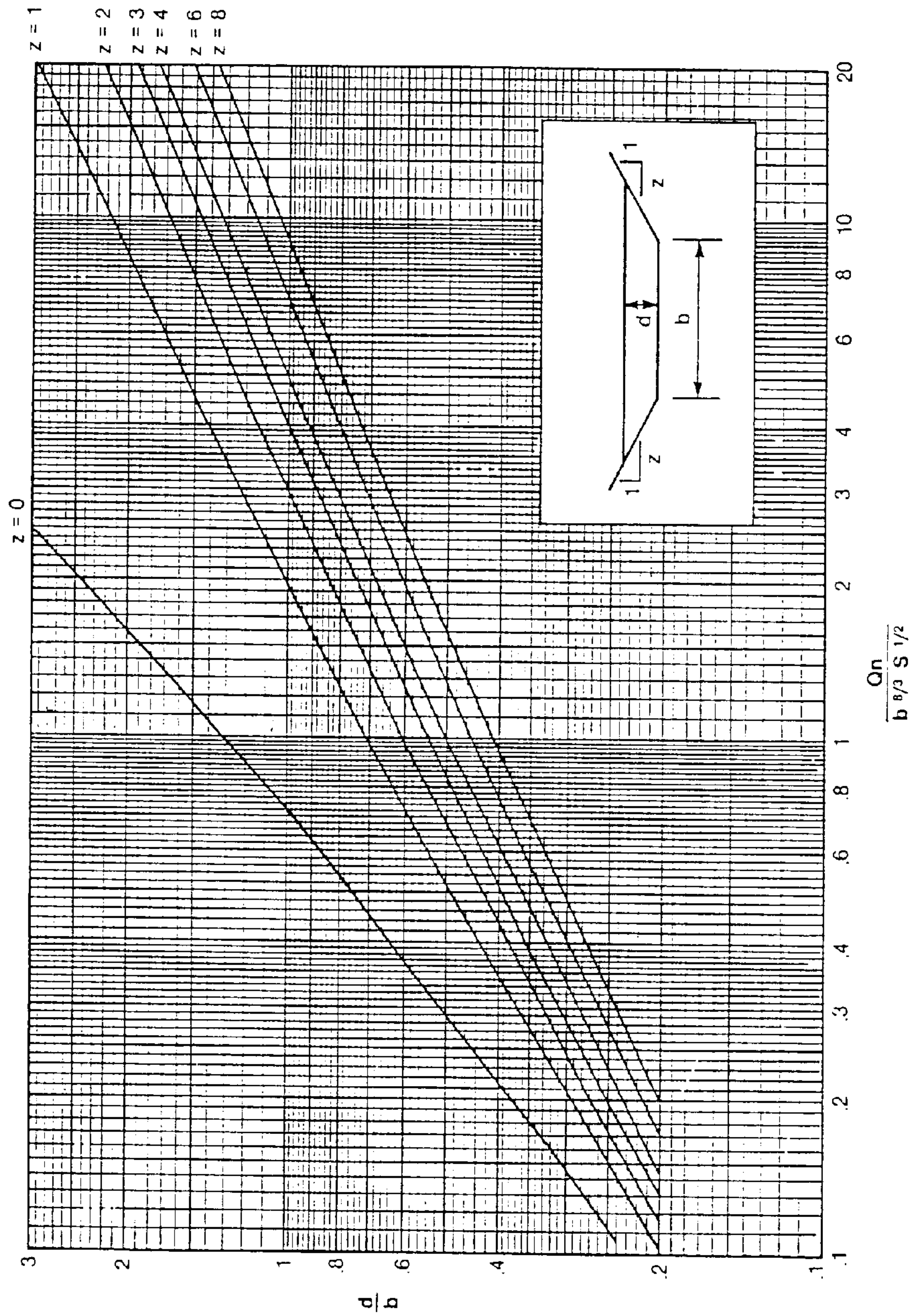


Figure 8-5

Nomograph For Normal Depth

Source: HEC-15

Profile Computation

Water surface profile computation requires a beginning value of elevation or depth (boundary condition) and proceeds upstream for subcritical flow and downstream for supercritical flow. In the case of supercritical flow, critical depth is often the boundary condition at the control section, but in subcritical flow, uniform flow and normal depth may be the boundary condition. The starting depth in this case can either 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 latter is the preferred method. These 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, then the stream reach may need to be extended downstream, or a shorter cross-section interval should be used, or the range of starting water-surface elevations should be adjusted. In any case, a plot of the convergence profiles can be a very useful tool in such an analysis (see Figure 8-6).   It is important that surveyed cross sections be taken, at a set interval far enogh downstream of the reach of interest to be useful for the above technique.

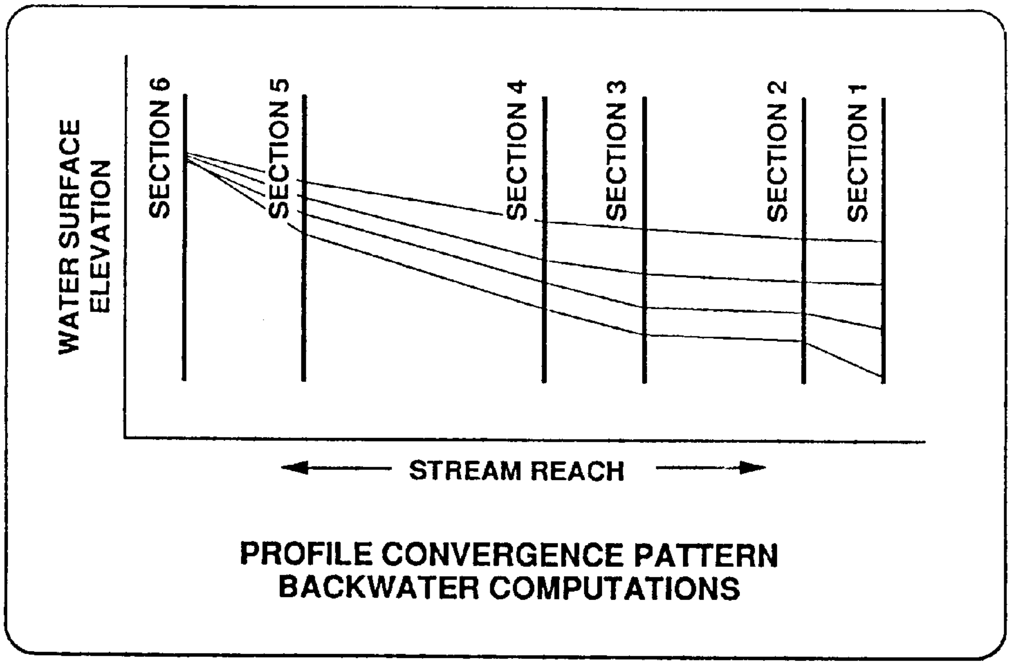


Figure 8-6

Profile Convergence Pattern Backwater Computation

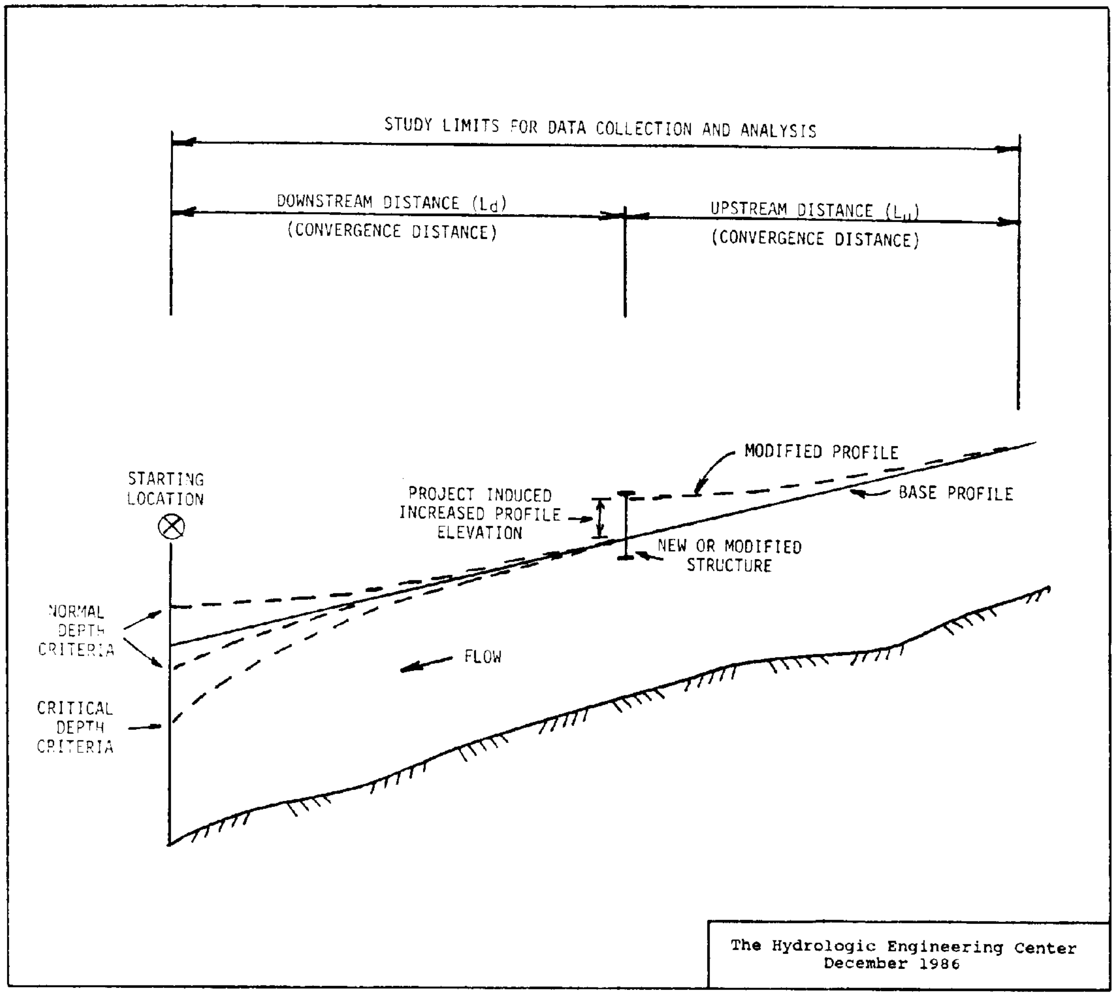


Figure 8-7

Profile Study Limits

Source: USACE, 1986

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 assure 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 8-7).

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

$$\mathbf{Ldn = 8{,}000\ (HD^{0.8}/S)} \quad \textbf{(8.12)}$$

$$\mathbf{Lu = 10{,}000\ [(HD^{0.6})(HL^{0.5})]/S} \quad \textbf{(8.13)}$$

Where:

Ldn = downstream study length (along main channel), ft (for normal depth starting conditions)

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

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

S = average reach slope, ft/mile

HL = headloss ranging between 0.5 and 5.0 feet at the channel crossing structure for the 1-percent chance flood, ft

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

8.5.5 Two-dimensional Flow Analysis

Two-dimensional flow analyses use computer models to provide an approximation of the three-dimensional river system by averaging velocity in the vertical direction and computing the two orthogonal horizontal directions. These models are most often used for river systems with significant flow in both longitudinal and lateral directions such as estuaries, highly irregular channels, and large floodplain encroachments. Various programs exist for two-dimensional analysis, usually to model specific conditions. Two of the more general programs are FastTABS, and FESWMS.

FastTABS combines a graphical pre- and post-processor interface developed by Brigham Young University with the TABS system developed by the U.S. Army Waterways Experiment Station. The TABS system is a two-dimensional depth averaged, free surface, finite element program for solving hydrodynamic problems. It also has a contaminant modelling portion to it. The model can be used to compute water surface elevations and flow velocities at nodal points in a finite element mesh representing a body of water such as a river, harbor, or estuary, with both steady-state and transient solutions (BYU and Boss Int'l, 1993).

FESWMS is a modular set of computer programs that simulate surface water flows that are essentially two dimensional in the horizontal plane using finite element methods. This modeling system was developed primarily to analyze flow at highway bridge crossings where complicated hydraulic conditions exist, by the Federal Highway Administration, the U.S. Geological Survey, and Dr. David C. Froehlich (Froehlic, 1988).

Costs associated with data collection needs and office effort are higher for two-dimensional modelling compared to standard step-backwater methods. Calibration and verification of a two-dimensional model is mandatory. However, when complex conditions exist where one-dimensional methods are not adequate, two-dimensional modeling may be the most cost effective avenue for reaching design recommendations.

8.5.6 Water And Sediment Routing

Various computer programs provide sediment routing routines within them. These programs include BRI-STARS, FLUVIAL-12, and HEC-6.

The BRI-STARS (Bridge Stream Tube Model for Sediment Routing Alluvial River Simulation) Model was developed by Dr. Albert Molinas for the National Cooperative Highway Research Program. It is a quasi-two dimensional steady-flow model based on utilizing the stream tube method of calculation which allows the lateral and longitudinal variation of hydraulic conditions as well as sediment activity at various cross sections along the study reach. The BRI-STARS program also contains a rule-based expert system program for classifying streams by size, bed and bank material stability, planform geometry, and other hydrologic and morphological features. Stream classification information can be used to assist in the selection of model parameters and algorithms (See Section 8.8).

FLUVIAL-12 is also a quasi two-dimensional program developed by Dr. Howard Chang and San Diego State University, which simulates the combined effects of flow hydraulics, sediment transport, and channel changes for a given flow period.

HEC-6 is a one-dimensional steady-flow model developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center for analyzing scour and deposition by modeling the interaction among the water-sediment mixture, the sediment material forming the channel bed, and the hydraulics of flow.

Sediment transport, erosion and deposition computer modeling is at the very least a two-dimensional process. One-dimensional and quasi two-dimensional models (e.g. the division of the stream channel into multiple stream tubes) can predict changes in channel area but not neccessarily changes in channel shape. These programs require large efforts in field data gathering, model calibration, and verification to give useful results.

8.6. Design Procedure

8.6.1 General

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

8.6.2 Stream Channels

The analysis of a stream channel in most cases is in conjunction with the design of a highway hydraulic structure such as a culvert or bridge. In general, the objective is to convey the water along or under the highway in such a manner that will not cause damage to the highway, stream, or adjacent property. An assessment of the existing channel is usually necessary to determine the potential for problems that might result from a proposed action. The 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 (see Section 8.7).

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

Step 1
<u>Assemble site data and project file.</u>

1. Data Collection (see Data Collection Chapter).
   - Topographic, site, and location maps.
   - Roadway profile.
   - Photographs.
   - Field reviews.
   - Design data at nearby structures.
   - Gaging records.
2. Studies by other agencies.
   - Flood insurance studies.
   - Floodplain studies.
   - Watershed studies.
3. Environmental constraints.
   - Floodplain encroachment.
   - Floodway designation.
   - Fish habitat.
   - Commitments in review documents.
4. Design criteria.

See Section 8.3.

Step 2
<u>Determine the project scope.</u>

1. Determine level of assessment.
   - Stability of existing channel.
   - Potential for damage.
   - Sensitivity of the stream.
2. Determine type of hydraulic analysis.
   - Qualitative assessment.

- Single-section analysis.
- Step-backwater analysis.

3. Determine additional survey information.
   - Extent of streambed profiles.
   - Locations of cross sections.
   - Elevations of flood-prone property.
   - Details of existing structures.
   - Properties of bed and bank materials.

Step 3
Evaluate hydrologic variables.

1. Compute discharges for selected frequencies.
2. Consult Hydrology Chapter.

Step 4
Perform hydraulic analysis.

1. Single-section analysis (8.5.3).
   - Select representative cross section (8.5.2).
   - Select appropriate n values (Table 8-1).
   - Compute stage-discharge relationship.
2. Step-backwater analysis (8.5.4).
3. Calibrate with known high water.

Step 5
Perform stability analysis.

1. Geomorphic factors.
2. Hydraulic factors.
3. Stream response to change.

Step 6
Design countermeasures.

1. Criteria for selection.
   - Erosion mechanism.
   - Stream characteristics.
   - Construction and maintenance requirements.
   - Vandalism considerations.
   - Cost.
2. Types of countermeasures.
   - Meander migration countermeasures.
   - Bank stabilization (Bank Protection Chapter).
   - Bend control countermeasures.
   - Channel braiding countermeasures.
   - Degradation countermeasures.
   - Aggradation countermeasures.
3. For additional information.
   - HEC-20 Stream Stability.
   - Highways in the River Environment.
   - See Reference List.

Step 7
Documentation.

- Prepare report and file with background information.
- See Documentation Chapter.

8.6.3 Roadside Channels

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

The primary function of roadside channels is to collect surface runoff from rainfall and stored snow from the highway and areas which drain to the right-of-way and convey the accumulated runoff to acceptable outlet points.

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

The alignment, cross section, and grade of roadside channels is usually constrained to a large extent by the geometric and safety standards applicable to the project. These channels should accommodate the design runoff in a manner which assures the safety of motorists, minimizes future maintenance (including spring clennout of snow), damage to adjacent properties, and adverse environmental or aesthetic effects.

Step-By-Step Procedure

Each project is unique, but the following six basic design steps are normally applicable:

Step 1

Establish a roadside plan.

1. Collect available site data.
2. Obtain or prepare existing and proposed plan-profile layout including highway, culverts, bridges, etc.
3. Determine and plot on the plan the locations of natural basin divides and roadside channel outlets. An example of a roadside channel plan/profile is shown in Figure 8.9.
4. Perform the layout of the proposed roadside channels to minimize diversion flow lengths.

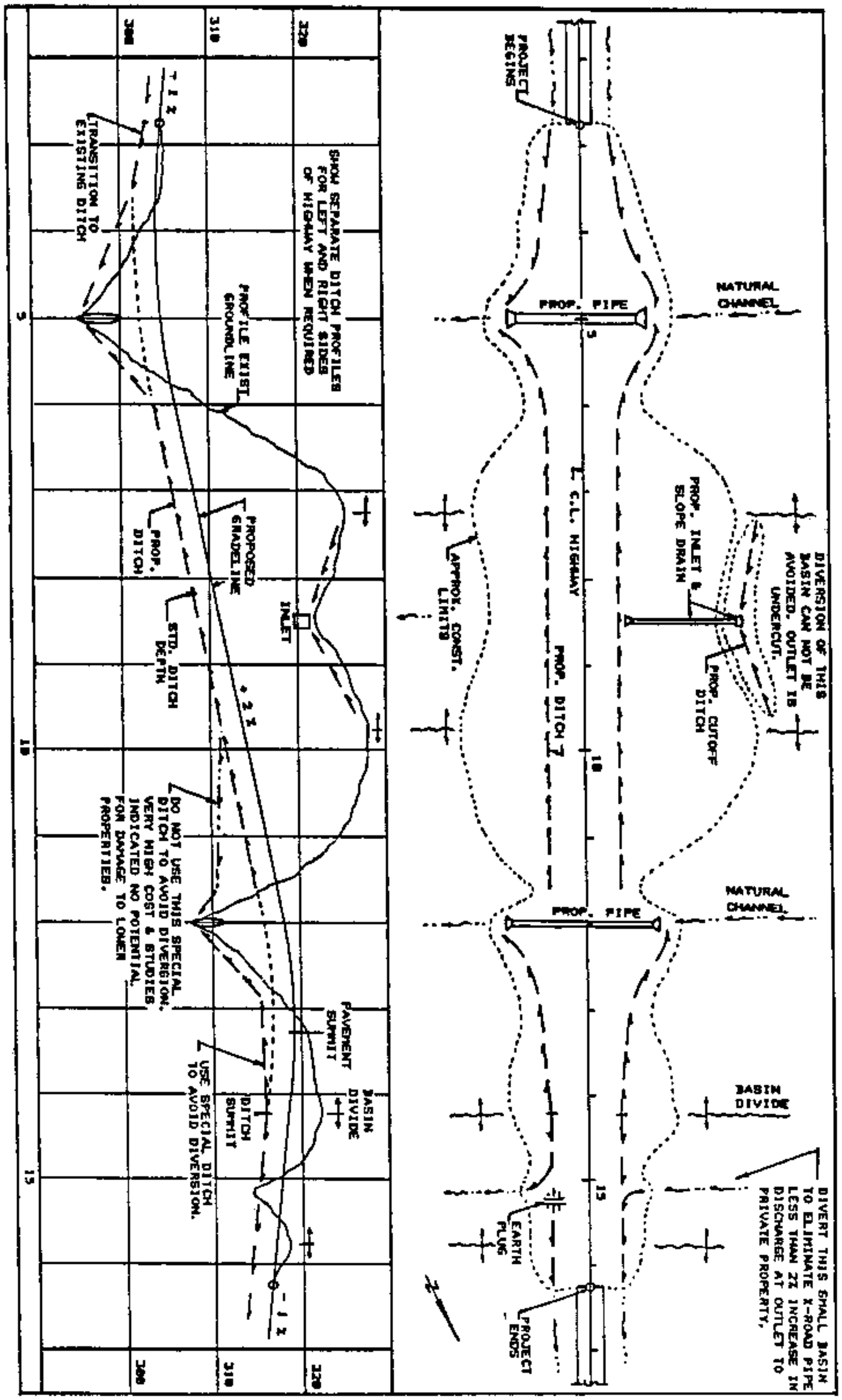


Figure 8-9

Sample Roadside Channel

Step 2
<u>Obtain or establish cross section data.</u>

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

Step 3
<u>Determine initial channel grades.</u>

1. Plot initial grades on plan-profile layout. (Slopes in roadside ditch in cuts are usually controlled by highway grades.)
2. Provide minimum grade of 0.3% to minimize ponding and sediment accumulation.
3. Consider influence of type of lining on grade.
4. Where possible, avoid features which may influence or restrict grade, such as utility locations.

Step 4
<u>Check flow capacities and adjust as necessary.</u>

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

Step 5
<u>Determine channel lining/protection needed.</u>

Follow the procedures as outlined in FHWA Hydraulic Engineering Circular No. 15, "Design of Roadside Channels with Flexible Linings" (HEC-15). A computer program within the HYDRAIN software called HYCHL automates many of the procedures. The following is a synopsis of these procedures:

1. Select a lining and determine the permissible shear stress.
2. Estimate the flow depth and choose an initial Manning's n value.
3. Calculate normal flow depth at design discharge using Manning's Equation and compare with the estimated depth. If they do not agree, repeat steps 5B and 5C.
4. Compute maximum shear stress at normal depth.
5. If maximum shear stress is less than permissible shear stress then lining is acceptable. Otherwise consider the following options:
   - choose a more resistant lining,
   - use concrete, gabions, or other more rigid lining either as full lining or composite,
   - decrease channel slope,
   - decrease slope in combination with drop structures, and/or
   - increase channel width and/or flatten side slopes.

Step 6

Analyze outlet points and downstream effects.

1. Identify any adverse impacts to downstream properties which may result from one of the following at the channel outlet:

    - increase or decrease in discharge,
    - increase in velocity of flow,
    - confinement of sheet flow,
    - change in outlet water quality, or
    - diversion of flow from another watershed.

2. Mitigate any adverse impacts identified in 6A. Possibilities include:

    - enlarge outlet channel and/or install control structures to provide detention of increased runoff in channel,
    - install velocity control structures,
    - increase capacity and/or improve lining of downstream channel,
    - install sedimentation/infiltration basins,
    - install sophisticated weirs or other outlet devices to redistribute concentrated channel flow, and
    - eliminate diversions which result in downstream damage and which cannot be mitigated in a less expensive fashion.
    - identify need for drainage easements.

Design Considerations

In order to obtain the optimum roadside channel system design, it may be necessary to make several trials of the previous procedure before a final design is achieved.

More details on channel lining design may be found in HEC-15 including consideration of channel bends, steep slopes, and composite linings.

Table 8-2

Classification of Vegetal Covers as to Degrees of Retardancy

(NOTE: This Table is under development for Alaska)

Retardance	Cover	Condition
A	Weeping Lovegrass	Excellent stand, tall (average 30")
	Yellow Bluestem	
	Ischaemum	Excellent stand, tall (average 36")
B	Kudzu	Very dense growth, uncut
	Bermuda grass	Good stand, tall (average 12")
	Native grass mixture little bluestem, bluestem, blue gamma other short and long stem midwest grasses	Good stand, unmowed
	Weeping lovegrass	Good Stand, tall (average 24")
	Laspedeza sericea	Good stand, not woody, tall (average 19")
	Alfalfa	Good stand, uncut (average 11")
	Weeping lovegrass	Good stand, unmowed (average 13")
	Kudzu	Dense growth, uncut
	Blue gamma	Good stand, uncut (average 13")
C	Crabgrass	Fair stand, uncut (10 - 48")
	Bermuda grass	Good stand, mowed (average 6")
	Common lespedeza	Good stand, uncut (average 11")
	Grass-legume mixture: summer (orchard grass redtop, Italian ryegrass, and common lespedeza	Good stand, uncut (6-8")
	Centipedegrass	Very dense cover (average 6")
	Kentucky bluegrass	Good stand, headed (6 - 12")
D	Bermuda grass	Good stand, cut to 2.5"
	Common lespedeza	Excellent stand, uncut (average 4.5")
	Buffalo grass	Good stand, uncut (3-6")
	Grass-legume mixture: fall, spring (orchard grass, redtop, Italian ryegrass, and common lespedeza	Good Stand, uncut (4-5")
	Lespedeza serices	After cutting to 2" (very good before cutting)
E	Bermuda grass	Good stand, cut to 1.5"
	Bermuda grass	Burned stubble

Note: Covers classified have been tested in experimental channel. Covers were green and generally uniform.

8.7. Stream Morphology

8.7.1 Introduction

The form assumed by a natural stream, which includes its cross-sectional shape as well as its planform, is a function of many variables for which cause-and-effect relationships are difficult to establish. The stream may be graded or in equilibrium with respect to long time periods, which means that on the average it discharges the same amount of sediment that it receives although there may be short-term adjustments in its bedforms in response to flood flows. On the other hand, the stream reach of interest may be aggrading or degrading as a result of deposition or scour in the reach, respectively. The 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.

The natural stream channel will assume a geomorphological form which will be compatible with the sediment load and discharge history which it has experienced over time. 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.

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

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/degradation problem. References (FHWA, 1990 and Molinas, 1990) should be consulted to evaluate the problem and propose mitigation measures, and the proposed methodology should be approved by the Staewide Hydraulic Engineer. Normally, this type of analysis requires a large effort and would likely be contracted with an expert agency.

8.7.2 Levels Of Assessment

The analysis and design of a stream channel will usually require an assessment of the existing channel and the potential for problems as a result of the 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. 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, and it is important to recognize that these analytical tools should only be used to substantiate the erosion potential indicated through observation. A brief description of the three levels of assessment are as follows.

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, and interviews with long-time residents.

Level 2

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

Level 3

Complex quantitative analysis based on detailed mathematical modeling and possibly physical hydraulic modeling. Necessary only for high risk locations, extraordinarily complex problems, and possibly 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 and/or physical modeling*. Data needed will require Level 1 and 2 data as well as 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, and angle of repose. A significant investment in time and money is required for this type of analysis.

8.7.3 *Factors That Affect Stream Stability*

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

Geomorphic Factors

- Stream size
- Flow variability.
- Valley setting
- Flood plains.
- Natural levees
- Apparent incision.
- Sinuosity
- Channel boundaries.
- Width variability
- Degree of braiding.
- Bar development
- Degree of anabranching.

Figure 8-10 depicts examples of the various geomorphic factors.

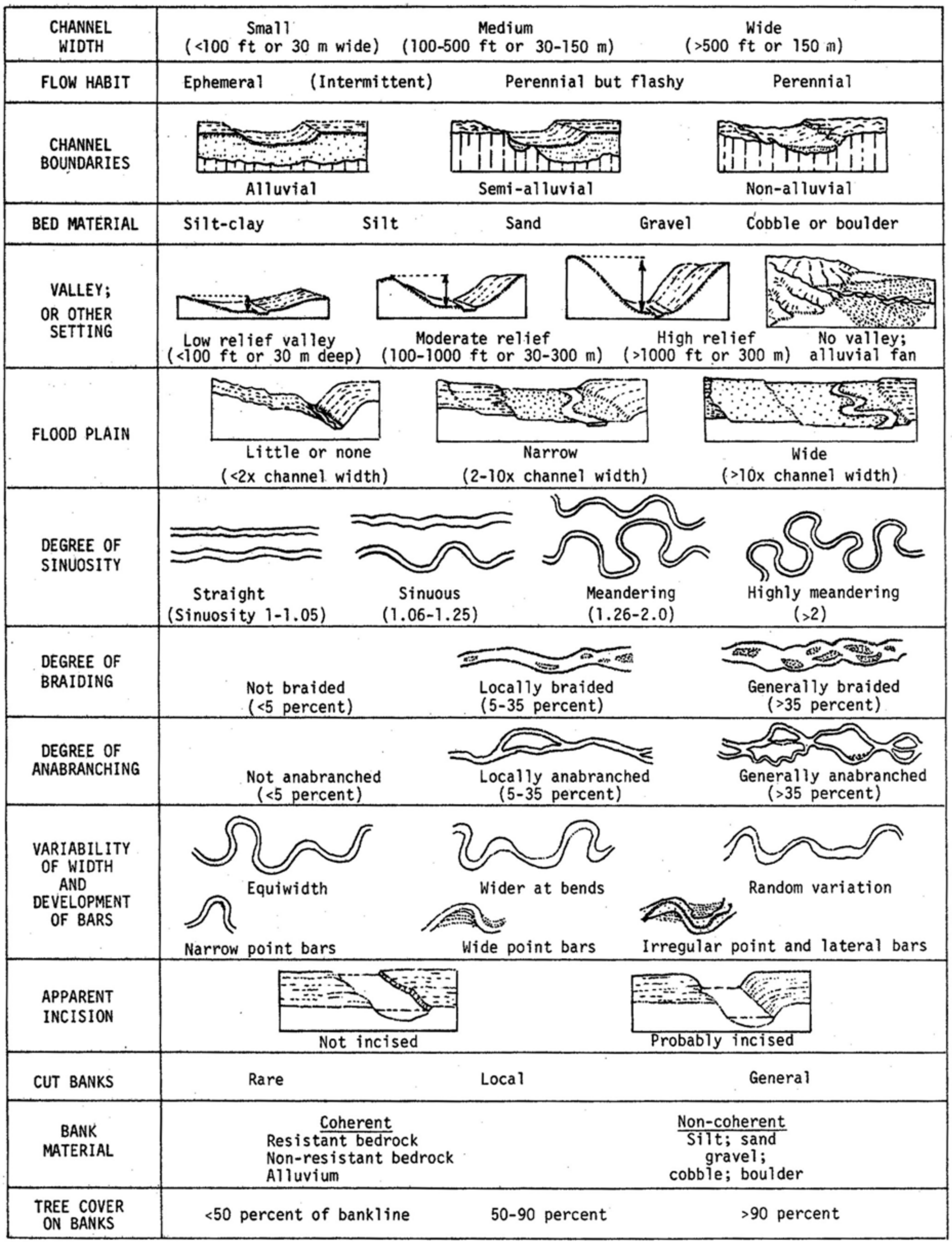


Figure 8-10

Geomorphic Factors That Affect Stream Stability
Source: Adapted From Brice and Blodgett, 1978

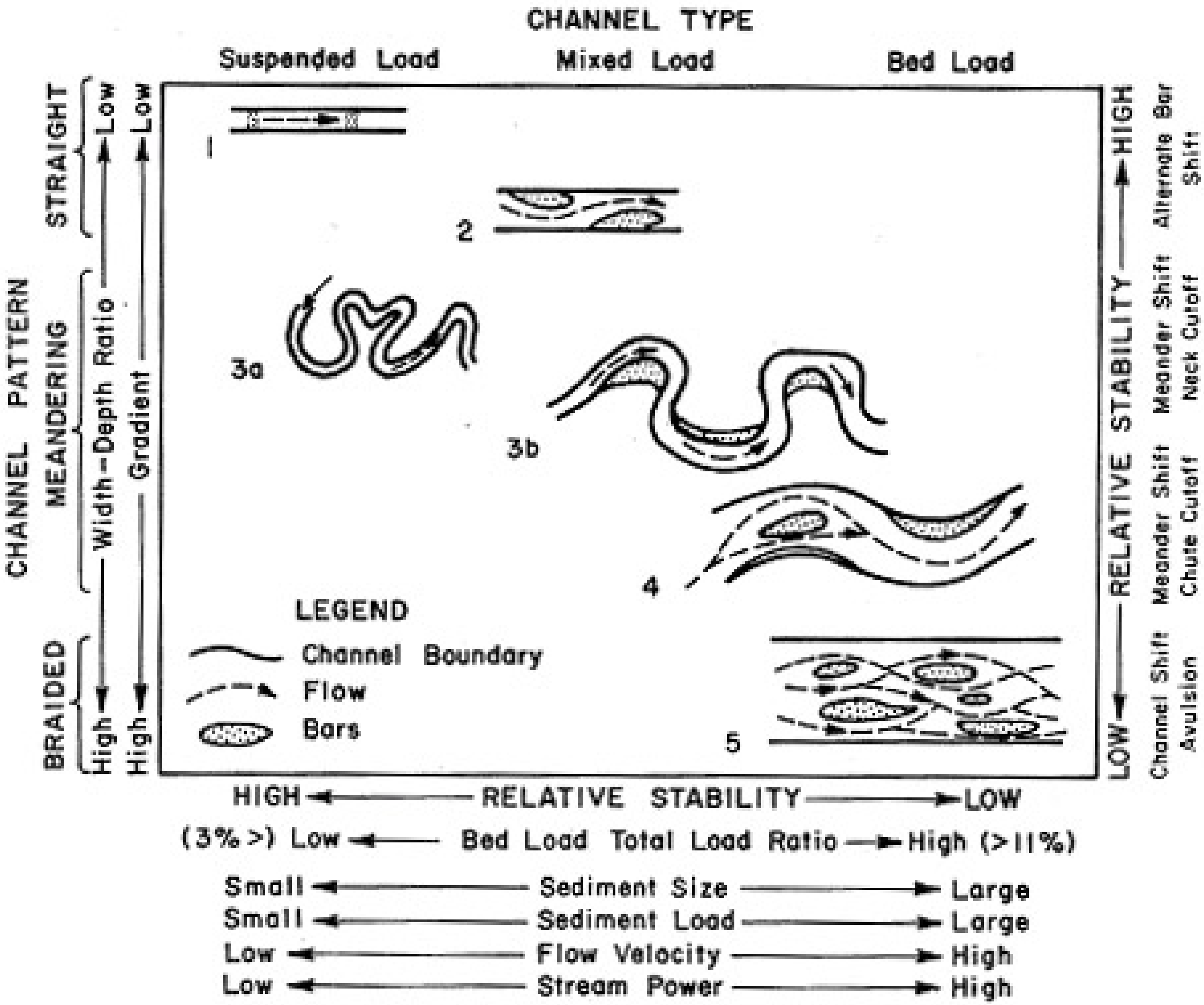


Figure 8-11

Channel Classification And Relative Stability As Hydraulic Factors Are Varied

Source: Atter, Shen et. al., 1981

Hydraulic Factors

- Magnitude, frequency and duration of floods.
- Bed configuration.
- Resistance to flow.
- Water surface profiles.

Figure 8-11 depicts the changes in channel classification and relative stability as related to hydraulic factors.

Rapid and unexpected changes may occur in streams in response to man's activities in the watershed such as alteration of vegetative cover(e.g. logging, parking lots, gravel mining). 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, and 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.

Natural disturbances such as floods, drought, earthquakes, landslides, volcanoes, and forest fires can also cause large changes in sediment load and thus major changes in the stream channel. Although difficult to plan for such disturbances, it is important to recognize that when natural disturbances do occur, it is likely that changes will also occur to the stream channel.

8.7.4 Stream Response To Change

The major complicating factors in river mechanics are: 1) the large number of interrelated variables that can simultaneously respond to natural or imposed changes in a stream system; and 2) the continual evolution of stream channel patterns, channel geometry, bars, and forms of bed roughness with changing water and sediment discharge. In order to better understand the responses of a stream to the actions of man and nature, a few simple hydraulic and geomorphic concepts are presented herein.

The dependence of stream form on slope, which may be imposed independently of other stream characteristics, is illustrated schematically in Figure 8-12.

Any 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. Referring to Figure 8-18, 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 8-13 illustrates the dependence of river form on channel slope and discharge. It shows that when $SQ^{1/4} \leq .0017$ in a sandbed channel, the stream will meander. Similarly, when $SQ^{1/4} \geq .010$, the stream is braided.

In these equations, S is the channel slope in feet per foot and Q is the mean discharge in cfs. Between these values of $SQ^{1/4}$ is the transitional range.

Many U.S. rivers plot in this zone between the limiting curves defining meandering and braided streams. 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.

8.7.5 Counter measures

A counter measure 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. They may be installed at the time of highway construction or retrofitted to resolve stability problems at existing crossings.

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

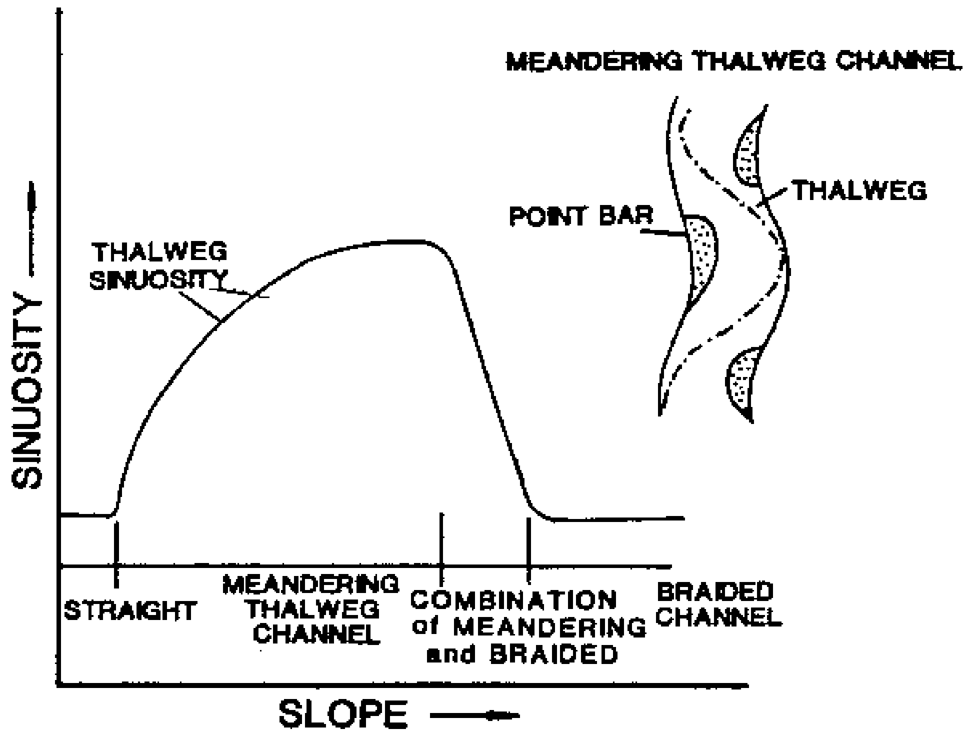


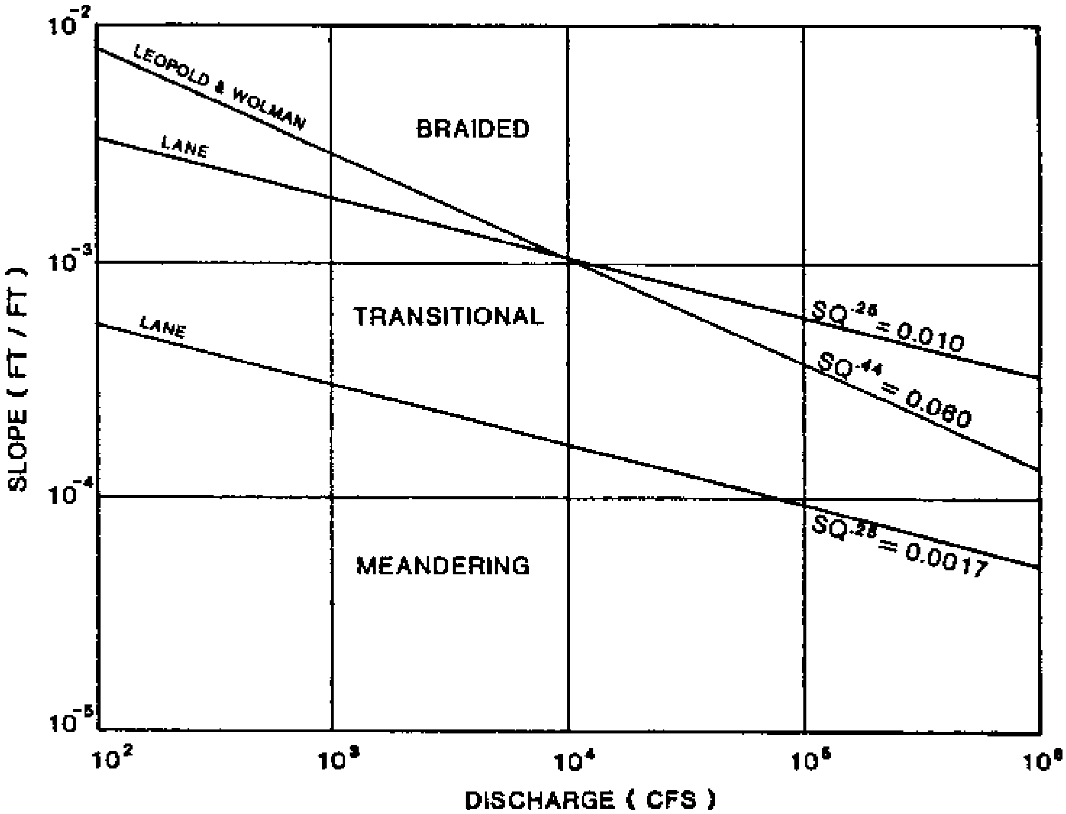
Figure 8-12

Sinuosity Vs Slope With Constant Discharge

The selection of an appropriate counter measure 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 brief discussion of possible counter measures for some common river stability problems.

Note: The reader is encouraged to consult with the references listed at the end of this chapter for detailed information on the design and construction of the counter measures.



Source: After Richardson et. al., 1988

Figure 18-13

Slope-Discharge For Braiding Or Meandering Bed Streams

Source: After, Lane, 1957

Meander Migration

The best counter measure against meander migration is a crossing location on a relatively straight reach of stream between bends. Other counter measures include the protection of an existing bank line, the establishment of a new flow line or alignment, and the control and constriction of channel flow. Counter measures identified for bank stabilization and bend control are bank revetments, spurs, retardance structures, longitudinal dikes, vane dikes, bulkheads, and channel relocations. Measures may be used individually or a combination of two or more measures may be used to combat meander migration at a site (FHWA, 1990; and HEC-20, 1991).

Channel Braiding

Counter measures used at braided streams are usually 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 usually consist of dikes constructed from the limits of the multiple channels to the channel over which the bridge is constructed. Spur dikes at bridge ends used in combination with revetment on highway fill slopes, riprap on highway fill slopes only, and spurs arranged in the stream channels to constrict flow to one channel have also been used successfully.

Degradation

Degradation in streams can cause the loss of bridge piers in stream channels, and piers and abutments in caving banks. A check dam, which is a low dam or ir constructed across a channel, is one of the most successful techniques for halting degradation on small to medium streams.

Longitudinal stone dikes placed at the toe of channel banks can be effective counter measures for bank caving in degrading streams. Precautions to prevent outflanking, such as tiebacks to the banks, may be necessary where installations are limited to the vicinity of the highway stream crossing. In general, channel lining alone is not a successful counter measure against degradation problems (HEC-20).

Aggradation

Current measures in use to alleviate aggradation problems at highways include channelization, bridge modification, continued maintenance, or combinations of these.

Channelization may include excavating and cleaning channels, constructing cutoffs to increase the local slope, constructing flow control structures to reduce and control the local channel width, and 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 which shows promise 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).

8.8. Stream Classification Scheme

An expert system for stream classification was developed by Dr. Albert Molinas as part of the NCHRP Project No. 15-11, BRI-STARS. (Molinas, 1986 and 1990) The purpose of the stream classification system is to assist the users in assessing stream stability and in choosing the appropriate sediment transport equation. The methods utilized in the expert system are predicated on bed material sediment size and stream channel slope. Stream morphology and related channel patterns are directly influenced by the width, depth, velocity, discharge, slope, roughness of channel material, sediment load and sediment size. Changes in any of these variables can result in altered channel patterns. As stream morphology is a result of these mutually adjustable variables, those most directly measurable were incorporated into Rosgen's criteria for stream classification. This criteria was selected for use in the expert system as it is a detailed analysis of hundreds of streams over many hydrophysiographic regions and from portions of other existing classification schemes. Stream channel patterns are classified based upon bed material size, channel gradients, and channel entrenchment and confinement.

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Appendix A: Example Problems

(Under development)