CHAPTER 4

NATURAL CHANNELS AND ROADSIDE DITCHES

NOTE: **All questions and comments should be directed to the Drainage Specialist, Design Support Area.**

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4.1 INTRODUCTION/PURPOSE

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 MDOT to ensure 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 public welfare.

While the principles of open channel flow are the same regardless of the channel type, stream channels and artificial channels (primarily roadside ditches) will be treated separately in this chapter as needed. The principles of open channel flow hydraulics are also applicable to all drainage facilities, including culverts and storm drains. Open channel theory is discussed in Appendix 4-C.

The purpose of this chapter is to:

- Discuss MDOT and Federal policies.
- Specify design criteria.
- Review design philosophy.
- Outline channel design procedures.
- Demonstrate design techniques with example problems.

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

- Potential flooding caused by changes in water surface elevations.
- Potential disturbance of the river system upstream or downstream of the highway right-of-way (R.O.W.).
- Changes in lateral flow distributions.
- Changes in velocity or direction of flow.
- Need for conveyance and disposal of excess runoff.
- Need for bank protection to prevent erosion.

The various types of open channels encountered by the designer of transportation facilities include:

- Stream channels.
- Artificial channels.
- Roadside ditches.
- County drains.

4.2 DEFINITIONS

Alluvial - Deposits of silts, sands, gravels, or similar detrital material which has been transported by running water.

Alluvial Channels - Formed wholly in alluvium with no bedrock exposed in the channel at low flow or likely to be exposed by erosion. A channel whose processes are controlled by flow and boundary interactions.

Artificial Channels - Include roadside channels, irrigation channels, and county or agricultural drains which are:

- Constructed channels with regular geometric cross-sections.
- Unlined, or lined with artificial or natural material to protect against erosion.

Conveyance - A measure, K, of the ability of a stream, channel, or conduit to convey water. In Manning's formula, $K = (1.49/n)\ AR^{2/3}$.

County Drain - May be an open ditch, stream or underground pipe, retention pond, or swale that conveys stormwater. These drains become designated as county drains through a petition process where either property owners or a local city, village or township petitions the Drain Commissioner to establish a county drain (see Chapter 2, Legal Policy and Procedure, Appendix 2-B).

Freeboard - The vertical distance between the level of the water surface, usually corresponding to design flow and a point of interest such as a low chord of a bridge beam or specific location on the roadway grade, for example, the bottom of subbase grade.

Open Channels - A natural or constructed conveyance for water in which:

- The water surface is exposed to the atmosphere.
- The gravity force component in the direction of motion is the driving force.

Roadside Ditches - Artificial channels distinguished from canals or streams by their smaller size. Roadside ditches convey runoff from roads and adjacent tributary areas.

Stream Channels - are usually:

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

Symbols and acronyms used in this chapter are listed in Appendix 4-A.

4.3 POLICY AND DESIGN CRITERIA

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 policy and design criteria which shall be considered for channel design.

4.3.1 Federal Policy

Please see Chapter 2, Legal Policy and Procedure.

4.3.2 MDOT Policy

For MDOT Policy, please see the State of Michigan Executive Order 1977-4 included in Chapter 2, Legal Policy and Procedure, Appendix 2-F.

4.3.3 Stream Channel Design

The following criteria apply to natural channels and may be revised as approved by the Design Engineer - Hydraulics.

- The hydraulic effects of floodplain encroachments shall be evaluated over a range of peak discharges from the 10 percent chance (10-year) through the 1 percent chance (100-year) storm on any major highway facility as deemed necessary.
- 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 as practical. Some means of energy dissipation may be necessary when existing conditions cannot be duplicated. The designer shall attempt to match the energy grade line (EGL) elevations at the upstream and downstream ends of projects.
- Stream bank stabilization should be provided, when appropriate, as a result of any stream disturbance.

4.3.4 Roadside Ditches

The following criteria apply to roadside ditches and may be revised as approved by the Design Engineer - Hydraulics. Further discussion of roadside ditches is in Section 4.4.4.

- Channel side slopes should not exceed the angle of repose of the soil and/or lining, and should be 1V:3H or flatter in the case of rock riprap lining.
- Channel freeboard should be at least 1.5 feet below edge of shoulder.
- The grade for ditches is 0.1 percent minimum and 0.3 percent desirable minimum.

4.4 DESIGN GUIDANCE AND PROCEDURE

4.4.1 Hydraulic Analysis for Stream and Roadside Ditches

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. Open channel flow theory is discussed in Appendix 4-C.

Two methods are commonly used in hydraulic analysis of open channels: the normal depth and the standard step method. The normal depth method (Section 4.4.1.5) is a simple application of Manning's equation. This method may be used to determine tailwater rating curves for culverts in which uniform or nearly uniform flow conditions exist. Manning's equation can be used to estimate high-water elevations for bridges that do not constrict the flow. The standard step method (Section 4.4.1.7) 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 normal depth method will generally yield less reliable results because it requires more judgment and assumptions than the standard step method. In many situations, however, the normal depth method is all that is justified, e.g., a standard roadway ditch, or tailwater for culverts and storm drain outfalls.

Open channel flow analysis occasionally justifies a more detailed method of analysis than the normal depth method or the computation of a water surface profile using the standard step method. Such analyses are usually accomplished by using computer models such as the USACE’s Hydraulic Engineering Center’s - River Analysis System (HEC-RAS). Special analysis techniques include two-dimensional analysis, water and sediment routing, and unsteady flow analysis.

4.4.1.1 Cross Sections

Cross-sections of the stream are needed for all water surface profile calculations (see Figure 4-1, Cross Section of Reaches, Segments, and Subsections Used in Assigning n Values, for example locations of cross-section). Cross-sectional geometry of streams is defined by coordinates of lateral distance (offsets) and ground elevation, which locate individual ground points. The cross-section is taken normal (perpendicular) 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 bend section. It is especially important to make a plot of the cross-section to reveal any inconsistencies or errors. The cross-section should represent the typical shape of the reach. Directional preference is looking downstream for left and right orientation.

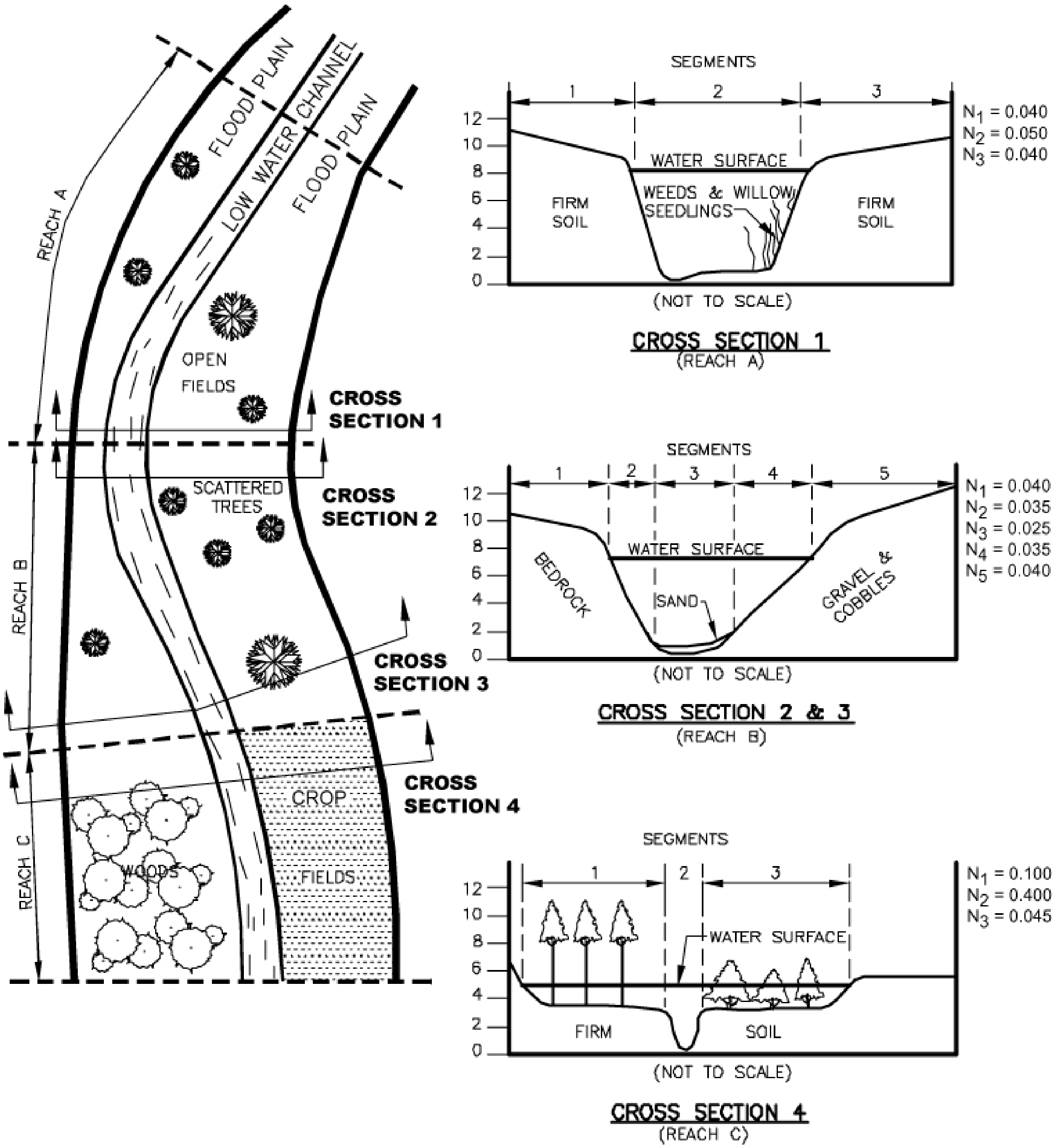


Figure 4-1 Cross Section of Reaches, Segments, and Subsections used in Assigning n Values

The number of and distance between cross-sections varies with the size and slope of stream and the type of work being proposed at the crossing. Because this varies from site to site, all requests for hydraulic surveys must be made by the MDOT Hydraulics Unit.

The hydraulic design engineer must accompany the survey crew when selecting cross-sections. The computation of water surface profiles requires cross sections at representative locations throughout the river reach. When a river reach is fairly straight and uniform, cross sections may be taken at regular intervals. Cross sections should fully define transitional elements of a stream such as: the cross-sectional area increasing or decreasing, channel or overbank roughness changes, or marked breaks in bottom slope. When an abrupt change in cross section occurs, such as at bridges, dams, or other manmade or natural restrictions, several cross sections should be used to describe the change, regardless of the distance.

Cross sections must be taken perpendicular to the direction of the estimated center of mass of the flood flow. In some instances, this direction may differ materially from that of the normal flow in the channel. Every effort should be made to obtain cross sections that accurately represent the river geometry at all stages.

The number of points in each cross section varies with the size of stream. There must be a sufficient number of points to accurately represent the shape of the channel and overbanks. Points should be located at any changes in topography or vegetation. See MDEQ cross-section guidance, Appendix 4-B for illustration.

4.4.1.2 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 floodplains for which the discharge has been measured and Manning's n has been calculated are very useful in selection of n values (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 initial Manning's n values have been selected, it is highly recommended that they be verified or calibrated with historical high water marks and/or gaged stream flow data. Once calibrated, Manning’s n values should be adjusted to match observed water surface profiles.

Manning's n values for artificial channels are more easily defined than for natural stream channels. See Table 4-1 for typical n values of both artificial channels and natural stream channels.

4.4.1.3 Calibration

Whenever possible, it is important to calibrate and validate hydraulic models. Unfortunately, sufficient observed data does not always exist to calibrate models. However, by calibrating models, a greater level of confidence can be developed in their results. A suggested procedure for calibration is described below.

Step 1 Obtain site hydrology (see Chapter 3, Hydrology, Section 3.3.13).

Step 2 Develop model using parameters (Manning’s n, expansion losses, contraction losses, ineffective flow areas) obtained from best judgment.

Step 3 Using observed flow rate, compare model calculated water elevations to observed elevations.

Step 4 Revise model parameters in a systematic manner until model-predicted water elevations match observed water elevations. Generally a correspondence within 6 inches is considered satisfactory.

Step 5 Repeat Step 4 with other storms, if available. Select model parameters that work reasonably well for the set of all observations.

Step 6 Validate the selected model parameters by re-running the model to simulate an observed condition not used as part of the calibration procedure.

Step 7 Assuming the validation run is satisfactory, use the model to predict existing conditions for design storms.

Table 4-1 Values of Manning's Roughness Coefficient n (Uniform Flow)

Type of Channel and Description	Minimum	Normal	Maximum
EXCAVATED OR DREDGED			
a. Earth, straight and uniform:			
1. Clean, recently completed	0.016	0.018	0.020
2. Clean, after weathering	0.018	0.022	0.025
3. Gravel, uniform section, clean	0.022	0.025	0.030
4. With short grass, few weeds	0.022	0.027	0.033
b. Earth, winding and sluggish:			
1. No vegetation	0.023	0.025	0.030
2. Grass, some weeds	0.025	0.030	0.033
3. Dense weeds or aquatic plants in deep Channels	0.030	0.035	0.040
4. Earth bottom and rubble sides	0.025	0.030	0.035
5. Stony bottom and weedy sides	0.025	0.035	0.045
6. Cobble bottom and clean sides	0.030	0.040	0.050
c. Dragline - excavated or dredged:			
1. No vegetation:	0.025	0.028	0.033
2. Light brush on banks:	0.035	0.050	0.060
d. Rock cuts:			
1. Smooth and uniform:	0.025	0.035	0.040
2. Jagged and irregular:	0.035	0.040	0.050
e. Channels not maintained, weeds and brush uncut:			
1. Dense weeds, high as flow depth:	0.050	0.080	0.120
2. Clean bottom, brush on sides:	0.040	0.050	0.080
3. Same, highest stage of flow:	0.045	0.070	0.110
4. Dense brush, high stage:	0.080	0.100	0.140
NATURAL STREAMS			
1. Minor streams (top width at flood stage < 100 feet)			
a. Streams on Plain:			
1. Clean, straight, full stage, no rifts or deep pools:	0.025	0.030	0.033
2. Same as above, but more stones/weeds	0.030	0.035	0.040
3. Clean, winding, some pools/shoals	0.033	0.040	0.045
4. Same as above, but some weeds/stones	0.035	0.045	0.050
5. Same as above, lower stages, more ineffective slopes and sections:	0.040	0.048	0.055
6. Same as 4, but more stones:	0.045	0.050	0.060
7. Sluggish reaches, weedy, deep pools:	0.050	0.070	0.080
8. Very weedy reaches, deep pools, or floodways with heavy stand of timber and underbrush:	0.075	0.100	0.150

Table 4-1 Values of Manning's Roughness Coefficient n (Uniform Flow) (continued)

Type of Channel and Description	Minimum	Normal	Maximum
b. Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high stages			
1. Bottom: Gravels, cobbles and few boulders:	0.030	0.040	0.050
2. Bottom: Cobbles with large boulders:	0.040	0.050	0.070
2. 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	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 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 feet) The n value is less than that for minor streams of similar description because banks offer less effective resistance.			
a. Regular section with no boulders or brush	0.025	--	0.060
b. Irregular and rough section	0.035	--	0.100

Source: Chow, V.T., 1970

4.4.1.4 Switchback Phenomenon

If the cross section is improperly subdivided, the mathematics of Manning's equation causes a switchback. A switchback results when the calculated discharge decreases with an associated increase in elevation. This occurs when, with a minor increase in water depth, there is a large increase of wetted perimeter. Simultaneously, there is a corresponding small increase in cross-sectional area which causes a net decrease in the hydraulic radius from the value 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. See Figure 4-2, Switchback Phenomenon.

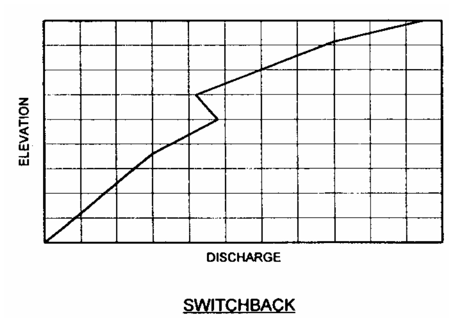


Figure 4-2 Switchback Phenomenon

This phenomenon can occur in any type of conveyance computation, including the standard step method. The computer model may not run correctly if a switchback occurs in any cross section being used in a standard step 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 may be the same in adjacent subsections.

4.4.1.5 Normal Depth Analysis

The normal depth analysis uses a normal depth method (slope area method). It is a solution of Manning's equation for the normal depth of flow given the discharge and cross-section properties including geometry, channel, slope, and roughness (EGL is assumed to be equal to the channel slope). It implicitly assumes the existence of steady, uniform flow; however, uniform flow rarely exists in either artificial or stream channels. Nevertheless, the normal depth 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 stream flow 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 1 percent chance (100-year) flood. The stage-discharge curve can be determined as follows:

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

Step 2 Subdivide cross section and assign n values to subsections as described in Section 4.4.1.1.

Step 3 Estimate water surface slope. Since uniform flow is assumed, the average slope of the streambed can usually be used.

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

Step 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.

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

Alternatively, a graphical technique such as that given in Figure 4-3, Trapezoidal Channel Capacity Chart, or a nomograph as in Figure 4-4, Trapezoidal Channel Nomograph for Normal Depth, 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 HEC-RAS to obtain the normal depth.

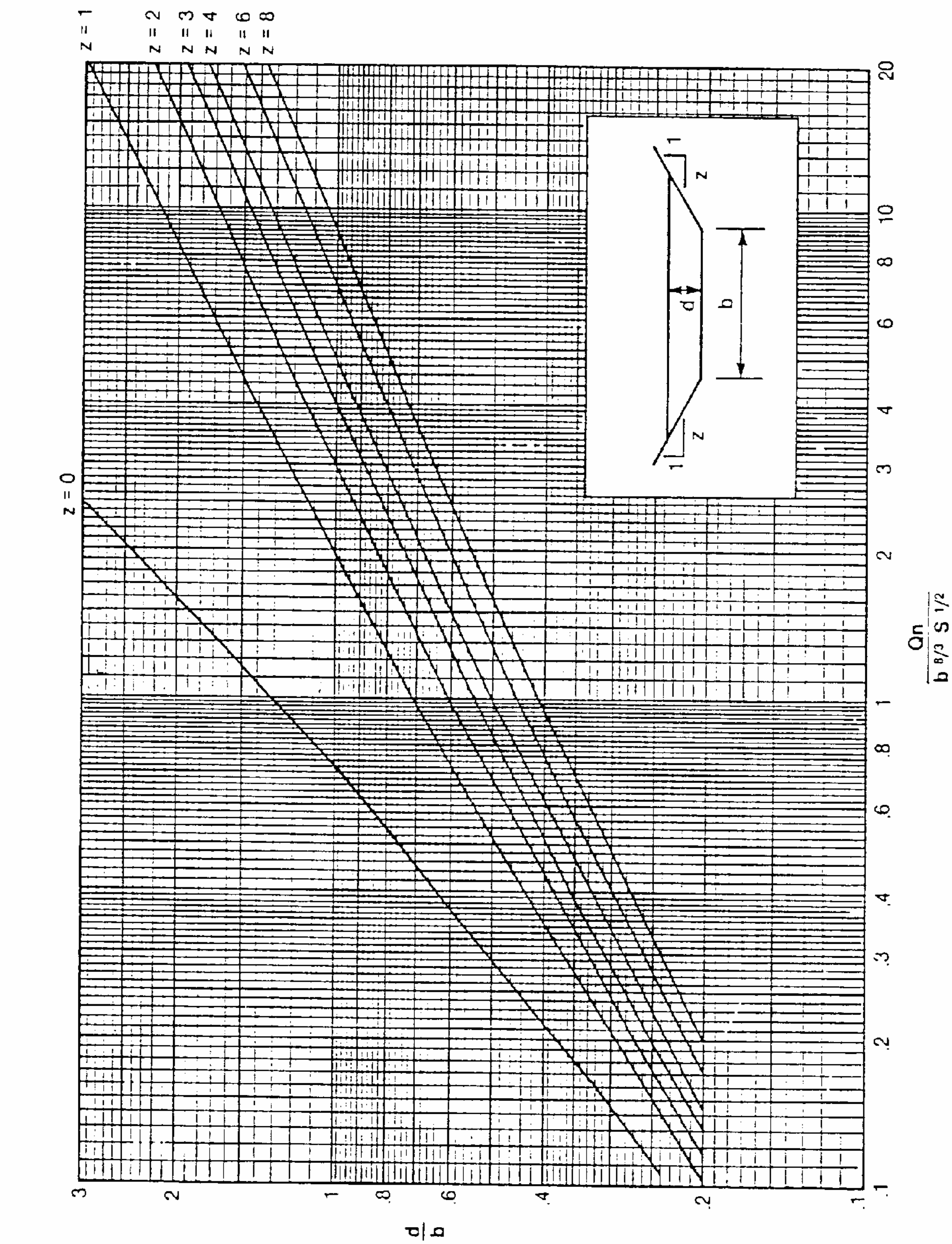


Figure 4-3 Trapezoidal Channel Capacity Chart

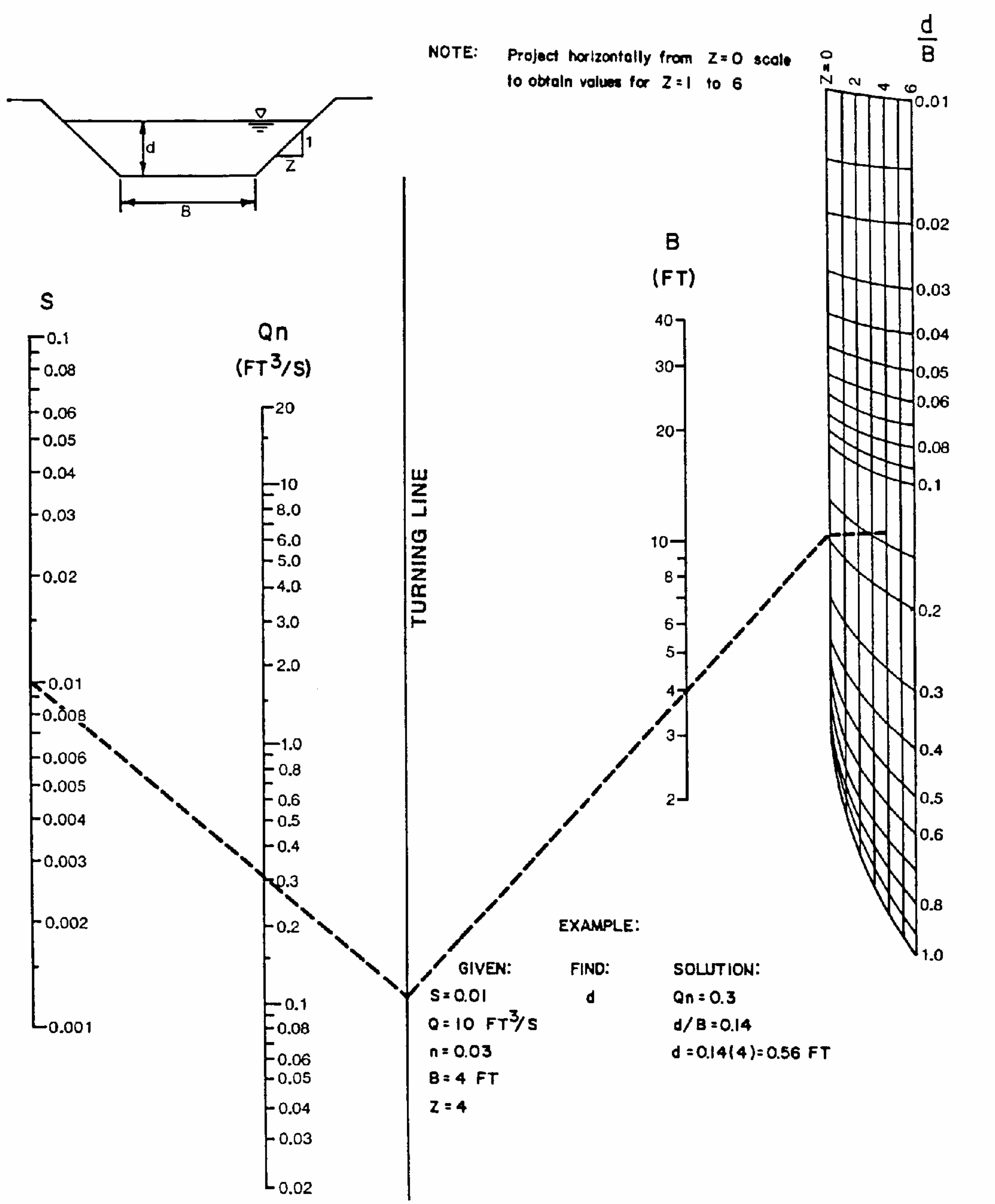


Figure 4-4 Trapezoidal Channel Nomograph for Normal Depth

Alluvial channels present a more difficult problem in establishing stage-discharge relations by the normal depth 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.

4.4.1.6 Example - Normal Depth Analysis for Culvert Tailwater Determination

Given: For the stream segment in Figure 4-5, Stream Profile, the 10 percent chance (10-year) and 2 percent chance (50-year) peak discharges equal Q_{10} = 175 cfs and Q_{50} = 220 cfs. Cross-section information is given in the following table of surveyed data points for a typical cross section.

Table 4-2 Cross Section Data (Station 4+46)

Station along Cross Section (feet)	Elevation (feet)	n-value
0.0	733.3	0.06
8.6	731.0	0.06
40.0	730.6	0.035
45.0	726.8	0.035
50.0	726.8	0.035
53.0	730.4	0.05
78.0	729.2	0.05
103.0	730.8	0.05
108.0	733.8	0.05

As referred to in Figure 4-6, Cross Section, Subsection 1 consists of a left 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 overbank area and includes some scattered brush with considerable weeds.

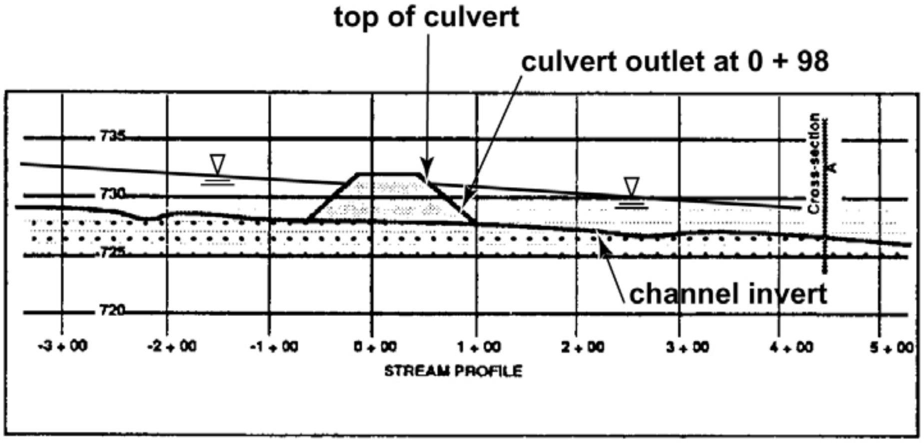


Figure 4-5 Stream Profile

Find: A stage-discharge curve for the channel cross-section at Station 4+46, which is located downstream from a highway culvert using the normal depth method. Determine the tailwater elevation at the outlet of the culvert (assume a channel Station of 0+98 for this location) for the 10 percent chance (10-year) and 2 percent chance (50-year) floods.

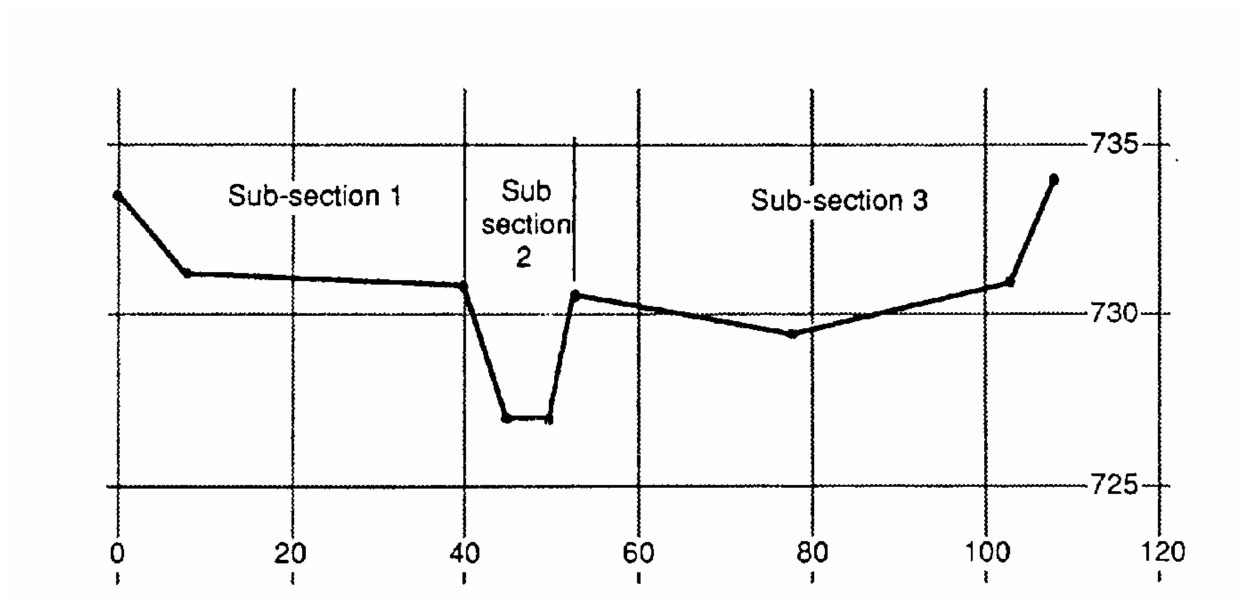


Figure 4-6 Cross Section (Station 4+46)

Solution: The slope of the stream can be determined by examining the reach from stream station -2+98 to our typical station of 4+46. The channel bottom falls 2.0 feet along 766.6 feet of reach. Therefore, the slope is 0.0027 feet/foot. When available, it is best to use the slope of the channel downstream of the station in question (station 4+46). In this application, the downstream channel is also sloped at 0.0027 feet/foot.

The Channel Computation Form, Figure 4-7, Channel Computation, can be used to assist in the development of a stage discharge curve for this typical section; use Manning's equation (4.C.13). Assuming water surface elevations begin at 727.8 feet, calculate pairs of water surface elevation/discharge for plotting on a stage-discharge curve. Calculations are shown in Figure 4-7, Stream Profile, which uses arbitrary water surface elevation increments of 1.0 foot. A plotted discharge curve is shown in Figure 4-8, Cross Section. The water elevation for Q_{10} (175 cfs) is 730.7 feet and for Q_{50} (220 cfs) is 730.9 feet.

Since 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 4+46 to represent the tailwater elevation at stream station 0+98. Therefore, the projected tailwater levels are calculated as follows:

TW_{10} = 730.7 + (446 - 98) (0.0027) = 731.6 feet

TW_{50} = 730.9 + (446 - 98) (0.0027) = 731.8 feet

Elevation = 728.0	Slope, S = 0.0027			
Sub-section ID	1	2	3	Totals
Area, A (sf)		6.0		6.0
Wetted Perimeter, WP (feet)		7.92		
Hydraulic Radius, R (feet)		0.76		
$R^{2/3}$		0.83		
n	0.060	0.035	0.050	
Q (cfs)		11.0		11.0
Velocity, V (fps)		1.8		

Note: All flow in channel, i.e., Subsection 2.

Elevation = 729.0	Slope, S = 0.0027			
Sub-section ID	1	2	3	Totals
Area, A (sf)		14.3		14.3
Wetted Perimeter, WP (feet)		10.9		
Hydraulic Radius, R (feet)		1.31		
$R^{2/3}$		1.20		
n	0.060	0.035	0.050	
Q (cfs)		37.9		37.9
Velocity, V (fps)		2.6		

Figure 4-7 Channel Computation Form

Elevation = 730.0	Slope, S = 0.0027			
Sub-section ID	1	2	3	Totals
Area, A (sf)		24.6	6.6	31.2
Wetted Perimeter, WP (feet)		14.9	21.9	
Hydraulic Radius, R (feet)		1.65	0.30	
$R^{2/3}$		1.40	0.45	
n	0.060	0.035	0.050	
Q (cfs)		76.0	4.6	80.6
Velocity, V (fps)		3.1	0.7	

Elevation = 731.0	Slope, S = 0.0027			
Sub-section ID	1	2	3	Totals
Area, A (sf)	1.6	37.1	45.0	83.7
Wetted Perimeter, WP (feet)	16.0	16.0	50.1	
Hydraulic Radius, R (feet)	0.1	2.25	0.9	
$R^{2/3}$	0.22	1.72	0.93	
n	0.060	0.035	0.050	
Q (cfs)	0.5	140.8	64.6	205.9
Velocity,V(fps)	0.3	3.8	1.4	

Figure 4-7 Channel Computation Form (continued)

Elevation = 732.0	Slope, S = 0.0027			
Sub-section ID	1	2	3	Totals
Area, A (sf)	36.5	49.0	95.8	181.3
Wetted Perimeter, WP (feet)	34.8	16.0	52.1	
Hydraulic Radius, R (feet)	1.05	3.06	1.84	
$R^{2/3}$	1.03	2.11	1.50	
n	0.060	0.035	0.050	
Q (cfs)	48.4	228.1	221.9	498.4
Velocity, V (fps)	1.3	4.7	2.3	

Figure 4-7 Channel Computation Form (continued)

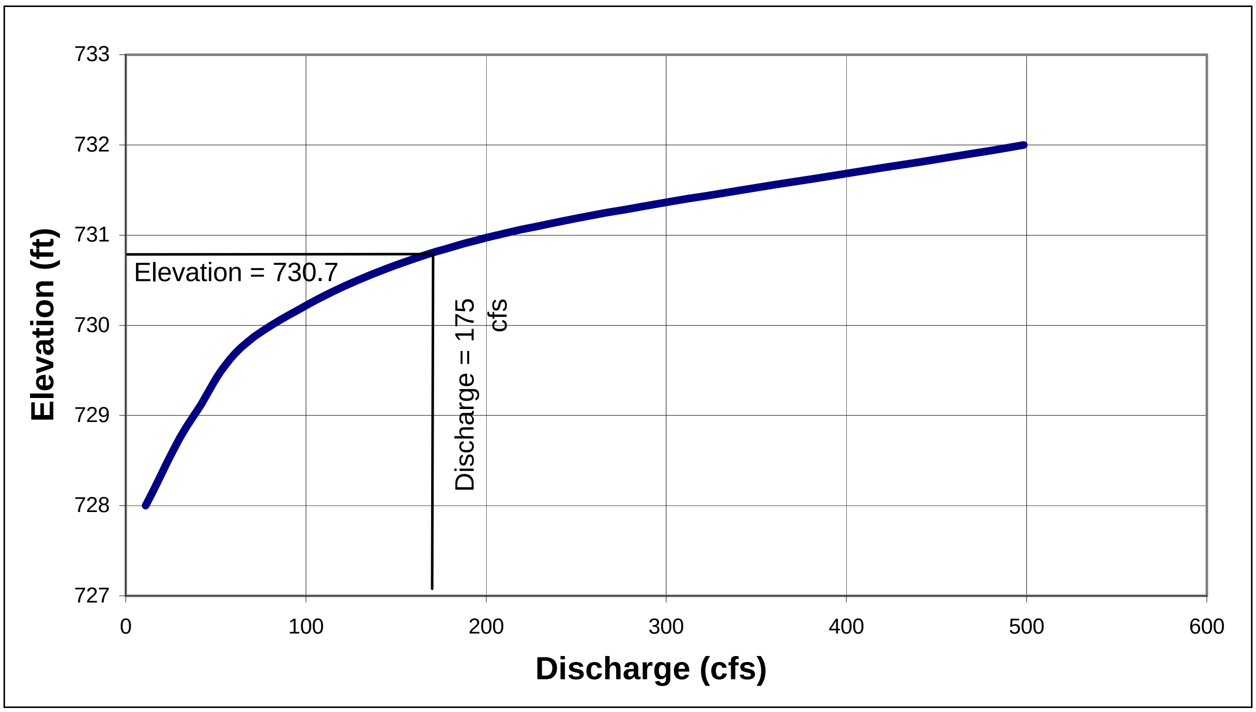


Figure 4-8 Stage Discharge Curve for Cross Section 4+46

4.4.1.7 Standard Step Analysis

Standard Step 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 USACE HEC-RAS program, be used. Standard step calculations are shown in Appendix 4-C along with a calculation worksheet.

Special analysis techniques should be considered for complex situations (such as rapidly varied flow near a control structure) where a standard step analysis might not give the desired level of accuracy.

4.4.1.7.1 Standard Step Model

The HEC-RAS program developed by the USACE is widely used for calculating water surface profiles for steady gradually varied flow (see Section 4.4.2) in natural or constructed channels. Both subcritical and supercritical flow profiles can be calculated. The effects of bridges, culverts, weirs, and structures in the floodplain may also be considered in the computations. This program is also designed for application in floodplain management and Flood Insurance Studies (FIS).

Designers may wish to obtain flood flows from Flood Insurance Studies for initially setting up the model. However, flood flows must be requested from the MDEQ for final design.

4.4.1.7.2 Standard Step Method

The computation of water surface profiles by HEC-RAS is based on the standard step method, in which the stream reach of interest is divided into a number of subreaches. The cross sections are 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 4.4.1. Manning's n values can vary 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. For more information on the standard step method, see Appendix 4-C.

4.4.1.7.3 Profile Calculation Concepts

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. However, for subcritical flow, normal depth, or a backwater elevation based on a downstream condition may be the boundary condition. Calculating water surface profiles to the desired location is MDOT's preferred method. A sensitivity analysis on the starting water surface is recommended. The sensitivity analysis should be performed by calculating water surface profiles with varying stating elevations to demonstrate that the profiles converge downstream of the project area. If the several profiles do not converge, 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 4-9, Profile Convergence Pattern Standard Step Computation).

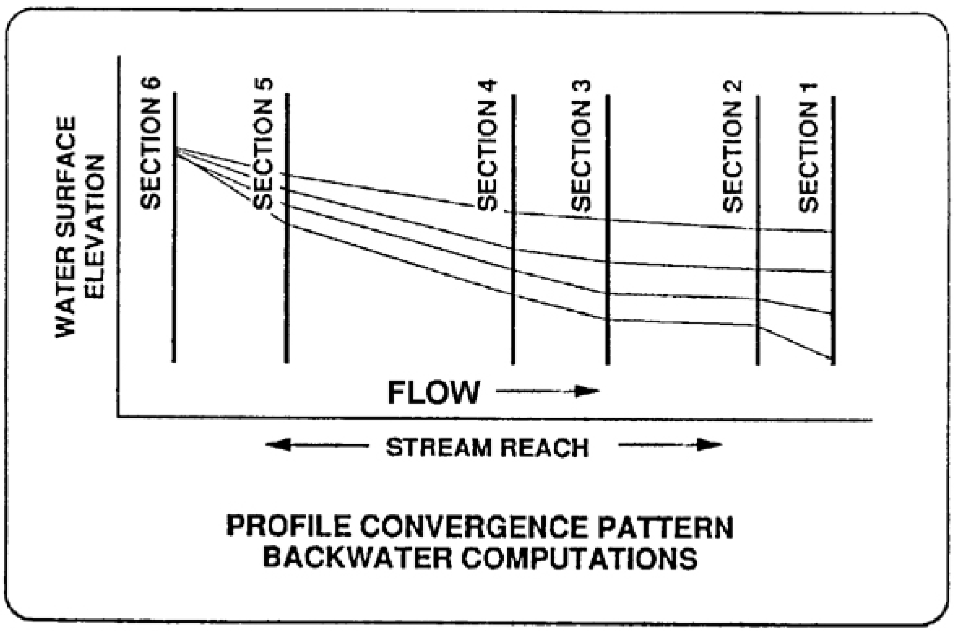
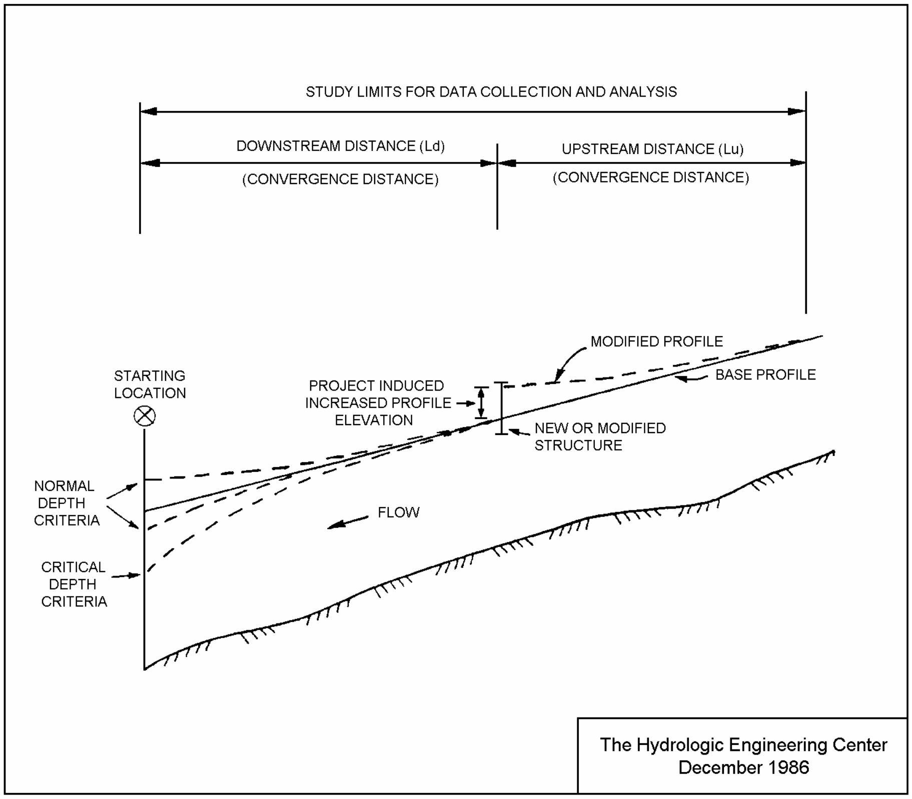


Figure 4-9 Profile Convergence Pattern Standard Step Computation

Enough cross sections should be included in the analysis so that the existing and proposed condition analyses also converge upstream of the project area (see Figure 4-10, Profile Study Limits).



Note: Water surface must converge with normal depth at the last upstream cross section.

Figure 4-10 Profile Study Limits

References (*Computation of Water Surface Profiles in Open Channels*, Davidian, 1984 and *Accuracy of Computed Water Surface Profiles*, USACE, 1986) are valuable sources of additional guidance on the practical application of the standard step method to highway drainage problems involving open channels. These references contain more specific guidance on cross-section determination, location, spacing, and stream reach determination. Reference (USACE, 1986) investigates the accuracy and reliability of water surface profiles related to n-value determination and the survey or mapping technology used to determine the cross-section coordinate geometry.

4.4.2 Example: Calculation of Effect of Tailwater Condition on Channel Water Surface Profile

<u>Given</u>: A series of five cross sections are available for a creek flowing at a discharge of 9,990 cfs. The section station and elevation points (X, Y), distance upstream and bank station locations are given in Table 4-3 for cross-sections A, B, C, D, and E. Cross sections are also shown in Figure 4-11, Example Cross Sections. The Manning n is 0.027 in the center channel and 0.065 in the overbanks. (Note: This example is similar to that conducted to analyze bridges. See Chapter 6, Bridges, for additional details.)

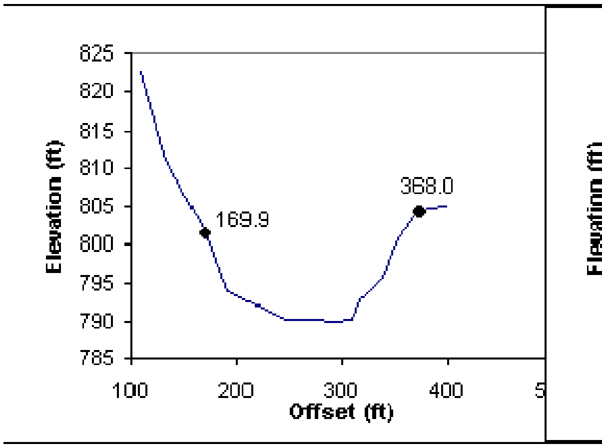
<u>Find</u>: The water surface profile using HEC-RAS for three tailwater conditions: critical depth, normal depth, and a known water surface elevation of 801.25 feet. Determine if significant cross sections are taken downstream to conveyance before the steady reach (Station15+000 to 30+000).

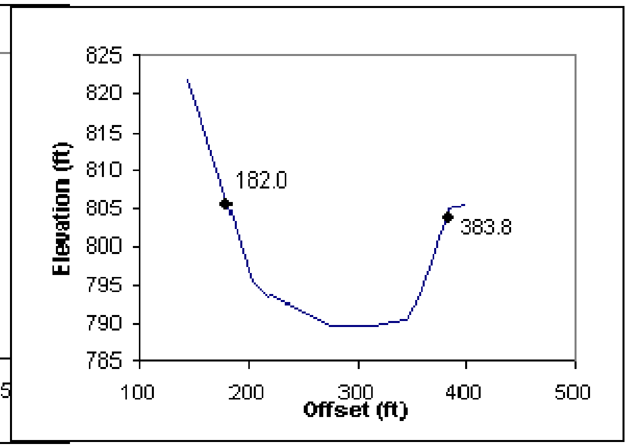
<u>Solution</u>: The water surface profile is shown in Figure 4-12, Channel Profile, and the HEC-RAS output data is presented in Table 4-3. The profiles converge at the most upstream station. The downstream-most cross section is far enough downstream that the reach being analyzed from station 15+000 to 30+000 is not sensitive to the tailwater conditions.

Table 4-3 Cross Section Data

Section A		**Section B**		**Section C**		**Section D**		**Section E**	
Station=	0	Station=	6,600	Station=	16,500	Station=	24,000	Station=	32,400
L Bank offset	169.9	L Bank offset	182.0	L Bank offset	224.0	L Bank offset	239.8	L Bank offset	239.8
R Bank offset	368.0	R Bank offset	383.8	R Bank offset	396.9	R Bank offset	389.0	R Bank offset	364.7
X (ft.)	Y (ft.)	X (ft.)	Y (ft.)	X (ft.)	Y (ft.)	X (ft.)	Y (ft.)	X (ft.)	Y (ft.)
106.9	822.6	144.0	821.9	196.8	819.2	220.1	818.9	204.0	818.8
131.9	810.9	182.0*	805.3	224.0*	808.2	239.8*	803.5	239.8*	792.9
169.9*	801.6	205.0	795.3	247.0	795.8	252.9	793.3	257.8	793.0
189.9	793.8	218.8	793.4	273.9	791.3	272.9	793.0	275.8	792.1
248.0	790.3	222.1	793.5	275.8	789.3	275.8	790.6	292.9	791.9
270.9	790.3	274.9	789.7	293.9	789.1	294.9	790.4	310.9	791.9
292.9	789.9	296.8	789.6	305.0	788.3	311.9	790.4	329.0	791.6
310.0	790.3	315.9	789.8	316.8	787.9	314.9	788.8	347.0	792.8
317.8	792.9	345.1	790.4	327.0	788.3	328.0	788.9	364.7*	792.6
337.8	795.7	356.9	793.5	352.9	789.5	339.8	789.0	383.8	800.8
350.0	800.3	383.8*	803.9	354.9	792.4	340.8	790.6	399.8	801.8
368.0*	803.6	384.7	805.0	373.9	796.0	372.0	794.6	400.8	807.8
379.8	804.8	399.8	805.4	392.9	803.2	389.0*	803.2		
399.8	805.0			396.9*	804.4	399.8	803.5		
				399.8	804.5				

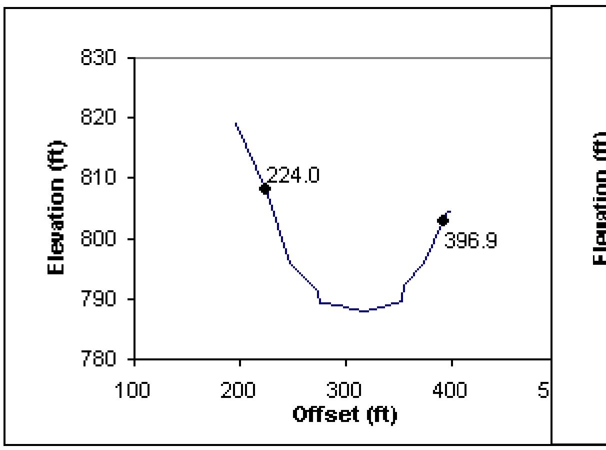
* Bank Station

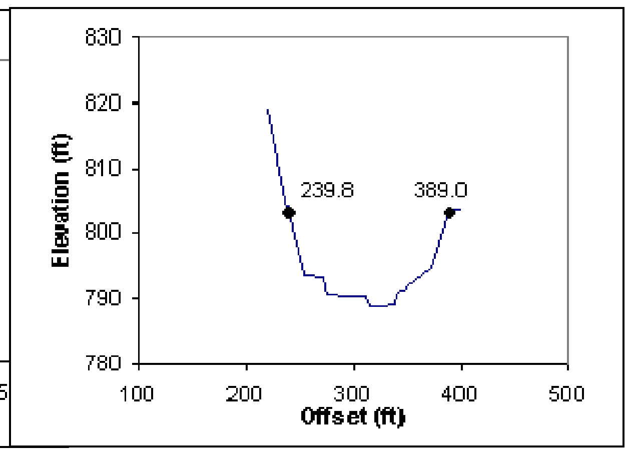




Section A (Station 0)

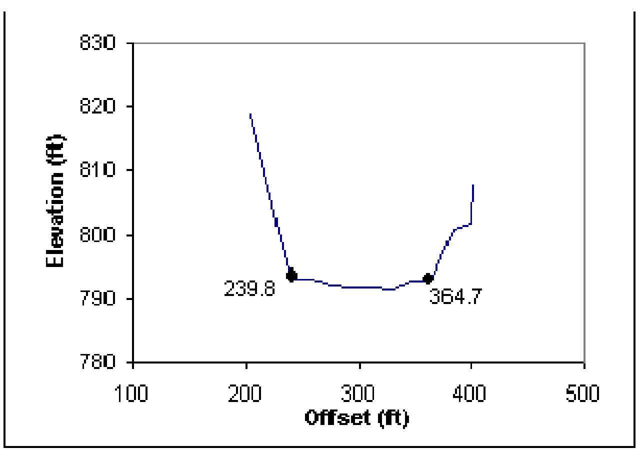
Section B (Station 6+600)





Section C (Station 16+500)

Section D (Station 24+000)



Section E (Station 32,400)

Figure 4-11 Example Cross Sections

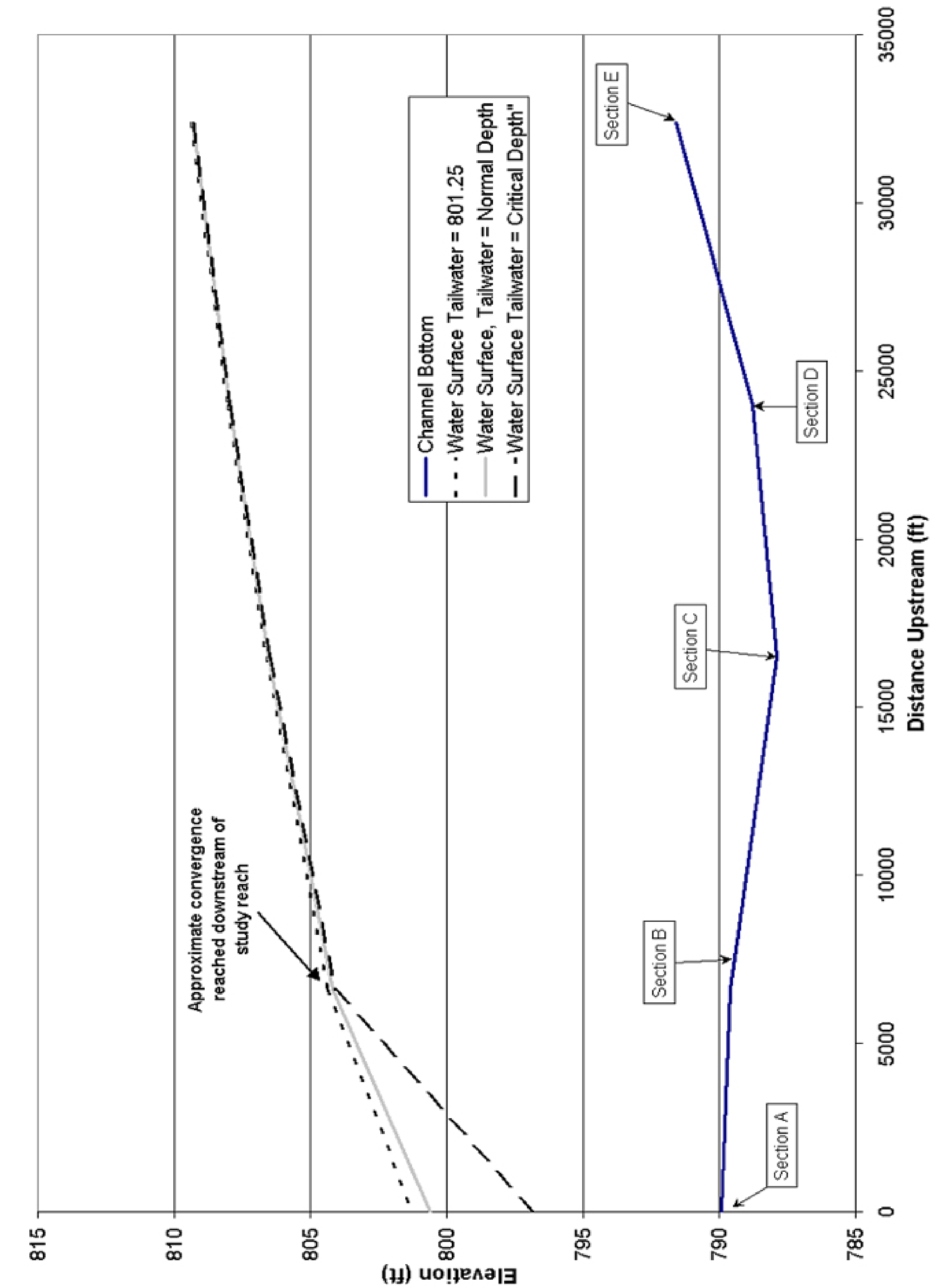


Figure 4-12 Channel Profile

Table 4-4 Output Table from HEC-RAS for Profile shown in Figure 4-12

River Station	Profile I.D.	Min Channel Elev (feet)	W.S. Elev (feet)	E.G. Elev (feet)	Channel Velocity (ft./s)	Flow Area (sq ft.)	Top Width (feet)
0	TW=801.25	789.90	801.25	801.88	6.39	1548.78	184.38
0	TW=Normal	789.90	800.63	801.37	6.89	1436.35	179.43
0	TW=Critical	789.90	796.75	799.24	12.66	782.27	158.24
6600	TW=801.25	789.60	804.38	804.68	4.37	2264.23	200.09
6600	TW=Normal	789.60	804.19	804.50	4.45	2225.73	199.49
6600	TW=Critical	789.60	804.12	804.43	4.48	2211.14	199.26
16500	TW=801.25	787.90	806.64	806.93	4.33	2294.26	172.91
16500	TW=Normal	787.90	806.54	806.84	4.36	2277.04	172.73
16500	TW=Critical	787.90	806.51	806.80	4.37	2270.67	172.66
24000	TW=801.25	788.80	808.05	808.33	4.30	2358.64	165.82
24000	TW=Normal	788.80	807.98	808.27	4.32	2346.92	165.73
24000	TW=Critical	788.80	807.95	808.24	4.32	2342.61	165.69
32400	TW=801.25	791.60	809.37	809.64	4.36	2695.34	183.76
32400	TW=Normal	791.60	809.31	809.59	4.37	2685.65	183.69
32400	TW=Critical	791.60	809.29	809.57	4.38	2682.10	183.66

4.4.3 Channel Design Procedure

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 ditches.

4.4.3.1 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 floodplain (see Section 4.4.4). Information on erosion controls in channels can be found in HEC-11.

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 Assemble site data and project file.

A. Data Collection:
- Topographic, site and location maps
- Roadway profile
- Photographs
- Field reviews
- Design data at nearby structures
- Gaging records
- Historic flood data and local knowledge

B. Studies by other agencies:
- Flood Insurance Studies (FIS)
- Floodplain studies (done by SCS, NRCS, USACE)

C. Environmental constraints (see Chapter 2, Legal Policy and Procedure):
- Floodplain encroachment (Part 31, NREPA)
- Floodway designation
- Fish and wildlife habitat
- Environmental clearance documents (MDOT Form 1775)

D. Design criteria (Section 4.3).

Step 2 Determine the project scope.

A. Determine level of assessment:
- Stability of existing channel
- Potential for damage
- Sensitivity of the stream
- Special analysis techniques

B. Determine type of hydraulic analysis:
- Normal depth analysis (Section 4.4.1.5)
- Standard step method (HEC-RAS)
- Special analysis techniques

C. Determine hydraulic survey information:
- Extent of study limits (convergence downstream of study area)
- Locations of cross-sections
- Elevations of flood-prone property
- Elevation of existing structures
- Soil properties of bed and bank materials

Step 3 Obtain hydrologic data (see Chapter 3, Hydrology).

Step 4 Perform hydraulic analysis.

A. Normal depth analysis (Section 4.4.1.5):
- Select representative cross section (Section 4.4.1)
- Select appropriate n values (Table 4-1)
- Compute stage-discharge relationship

B. Standard step analysis (Section 4.4.1.7)

C. Calibrate model with known high water and flow rate (Section 4.4.1.3)

Step 5 Perform stream stability analysis (if required).
(Tentative, dependent on stream morphology.)

A. Geomorphic factors

B. Stream response to change

Step 6 Design stream instability countermeasures.

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

B. Types of countermeasures:
- Meander migration countermeasures
- Channel bank stabilization (HEC-11)
- Bend control countermeasures

- Channel braiding countermeasures
- Degradation countermeasures
- Aggradation countermeasures

C. For additional information, see reference list.

Step 7 Documentation

- Prepare report for MDOT project manager and file with background information. For streams under MDEQ's floodplain regulatory authority, report guidelines are contained in Chapter 6, Bridges, Appendix 6-C.

4.4.3.2 Roadside Ditches

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

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

4.4.3.2.1 Design Guidelines

Open ditches for drainage areas within MDOT's R.O.W. shall be designed for a 2 percent chance (50-year) storm. The effects of a 1 percent chance (100-year) storm should be checked for possible harmful interference to adjacent properties. Normally, the standard ditch section (Section 4.4.1) will be adequate for a 2 percent chance (50-year) storm, unless the ditch is unusually long or has ditches from outside the R.O.W. that flow into it. The ditch should be designed to have the water surface elevation either outside the clear zone or the depth should not exceed 2 feet. Channel freeboard should be at least 1.5 feet below edge of shoulder.

4.4.3.2.2 Standard Ditch Types

The ditch types discussed here are as shown on MDOT's Standard Plan R-105-Series, "Grading Cross-Sections." The type, width, depth, and backslope of the ditch to be used in any given location depends on many factors, including soil, depth of subbase, surface drainage, built-up conditions along the roadside, excavation requirements, and snow conditions. Any variation from the standard-type ditches must be covered by note or sketch on the typical cross section.

Round Bottom Ditch

In rural areas, the standard ditch is a round bottom ditch, 4 feet below plan grade, 6 feet in width, and a 1:6 front and backslope. R.O.W. restrictions may require the backslope to be steeper and the ditch width reduced to 4 feet.

Berm or Swamp Ditch

A berm or swamp ditch is called for when the normal round bottom ditch would be too deep, such as in areas of low fill and the ditch centerline is a specified distance from the edge of pavement.

Independent Ditches

Independent ditches are called for when it is necessary to crest the ditch at a different location from plan grade. Independent ditches should not be called for if ditches are adverse to steep road grades. The grade for ditches, independent or dependent, is 0.3 percent desirable minimum. The use of shallower slopes must be approved by Design, Plan Review Engineer. Ditches in the transition section of super-elevated curves must be designed to avoid flat spots or pockets created by combinations of relatively flat grades and the super-elevation transition.

Toe of Slope Ditch

A toe of slope ditch is a type of independent ditch that is placed at the slope stake line where the grade is too high for a standard road ditch and the volume of water too small to justify a swamp ditch. They are used only in agricultural and similar areas to prevent drainage from running over the adjacent road.

Valley and No-Ditch Sections

In sandy soils or in semi-urban areas, where space is limited, valley type ditches or no-ditch sections may be used. An underdrain may be required to drain the subbase in conjunction with these ditches where subbase is used.

4.4.3.2.3 Erosion Control in Ditches

There are both permanent and temporary erosion control measures in relation to drainage ditches. The road designer should design the permanent erosion control measures to be applied in the establishment of ditches. The Region Soils and Materials Engineer will design the temporary erosion control measures for the ditches during construction activity (see *Michigan Road Design Manual*, Section 2.05; Standard Plan R-96-Series, and *MDOT Soil Erosion and Sedimentation Control Manual*).

Listed below in Table 4-5 are guidelines for permanent stabilization treatments for various ditch grades. The designated treatment for all situations should include installation in the ditch bottom and 4.5 feet up both slopes. The soil type should be considered for borderline situations. The lesser treatment can be used for cohesive soils, while the higher level treatment should be used for noncohesive soils. If questions arise regarding soil suitability for a particular ditch flow or unusual conditions, further guidance can be sought from the Region Soils and Materials Engineer, the Environmental Section of the Project Planning Division, or the Geotechnical Services Unit of the Construction and Technology Division.

Table 4-5 Permanent Stabilization Treatments for Various Ditch Grades

PERMANENT STABILIZATION TREATMENTS FOR VARIOUS DITCH GRADES	
Ditch Bottom Treatment	**Ditch Grades**
Seed and Mulch *	0.3% to 0.5%
Standard Mulch Blanket *	0.5% to 1.5%
High Velocity Mulch Blanket or Sod *	1.5% to 3.0%
Turf Reinforcement Mat or Cobble Ditch	3.0% to 6.0%
Specific Design Required **	6.0% +

* When within 200 feet of a stream, the permanent ditch treatment will be mulch blanket for ditch grades 0.5 percent or less and sod for ditch grades between 0.5 and 3.0 percent. The designer should set up a miscellaneous quantity of mulch blanket (if not already set up) and high velocity mulch blanket to use in case sod is not immediately available or it is outside of seasonal sodding limits.

** Downspouts, see Standard Plan R-32-Series; paved ditches, see Standard Plan R-46-Series; for spillways consult with the Design Engineer - Hydraulics/ Hydrology.

4.4.4 Stream Morphology

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

A qualitative assessment of the river response to proposed highway facilities is possible through a thorough knowledge of river mechanics and accumulation of engineering experience. The detailed calculation of sediment transport is outside the scope of this manual.

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. For more information refer to HEC-20, Stream Stability at Highway Structures.

4.5 MAINTENANCE

4.5.1 Ditch Maintenance

Ditches convey water away from roadways and other areas. Ditches may be unlined or lined with Portland cement concrete, gunite, masonry, concrete or aggregate lining, quarry rock, bituminous concrete, or other appropriate engineered materials. Ditches should be kept free of silt, debris, large amounts of vegetation, or any other materials that restrict the flow of water.

The flow lines of unlined roadside ditches can be maintained by motorized equipment supplemented with hand work.

Large roadside ditches are sometimes located at an elevation well below the roadway and not accessible to a motor grader. These may be reached with a truck-mounted hydraulic excavator opened from the shoulder.

Interceptor ditches on slopes and along excavation or embankment benches and inlet ditches from culverts may require hand cleaning using shovels and wheelbarrows.

4.5.2 Erosion and Vegetation

Ditch erosion is the loss of soil caused by the rapid flow of water. It is controlled by lining the ditch or by constructing check dams to dissipate energy locally.

Because erosion is one of the major problems which occur in ditches, the growth of vegetation is essential. The vegetation is occasionally maintained by adjoining property owners, but more often must be maintained by the roadway owner or designated personnel. Regular maintenance enables ditches to perform as designed.

If the hydraulic properties of the ditch are detrimentally impacted by growth of woody vegetation, the ditch banks should be mowed or cut back as needed.

4.5.3 Repairs

Joint separation is a common problem associated with concrete-lined ditches. Once water gets under the concrete or asphalt, the underlying soil will erode and deterioration may occur. Frequent inspection is important and corrective action should be timely. If not, damage could be extensive resulting in excessive repair costs.

If the vegetative lining has eroded, the repair will consist of, but will not be limited to, restoration of ditch cross section and re-establishment of vegetation using topsoil, seed, mulch blanket, or high-velocity mulch blanket.

References

AASHTO Vol. VI-Highway Drainage Guidelines, Hydraulic Analysis and Design of Open Channels. AASHTO Task Force on Hydrology and Hydraulics. 1982.

American Society of Civil Engineers, High Velocity Flow in Open Channels: A Symposium: Design of Channel Curves for Supercritical Flow. Transactions, Vol. 116. 1951.

Arcement, G.J., Jr., and V.R. Schneider. Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains, Report No. FHWA-TS-84-204, Federal Highway Administration. 1984.

Barnes, Harry H., Jr. Roughness Characteristics of Natural Channels, U.S. Geological Survey Water Supply Paper 1849, U.S. Government Printing Office, Washington, D.C. 1978.

Behlke, C.E. The Design of Supercritical Flow Channel Junctions, Highway Research Record No. 123, Transportation Research Board. 1966.

Blodgett, J.C. Rock Riprap Design for Protection of Stream Channels Near Highway Structures, Vol. 1, Water Resources Investigations Report 86-4127, U.S. Geological Survey, prepared in Cooperation with Federal Highway Administration. 1986.

Blalock, M.E., and T.W. Sturm. Minimum Specific Energy in Compound Open Channel, Journal of Hydraulics Division, ASCE, Vol. 107, No. HY6, pp. 699-717. June 1981.

Blodgett, J.C., and C.E. McConaughy. Rock Riprap Design for Protection of Stream Channels Near Highway Structures," Vol. 2, Water Resources Investigations Report 86-4127, U.S. Geological Survey, prepared in Cooperation with Federal Highway Administration. 1986.

Brice, J.C., and J.C. Blodgett. Countermeasures for Hydraulic Problems at Bridges, Vol. 1, Analysis and Assessment, FHWA-RD-78-162, Federal Highway Administration, Washington, D.C. 1978.

Brigham Young University. SMS, Surface Water Modeling System Reference Manual, Engineering Computer Graphics Laboratory, Provo, UT. 1995.

Brown, S.A. Streambank Stabilization Measures for Stream Crossings--Executive Summary, FHWA/RD-84/099, FHWA, Washington, D.C. 1985.

Brown, S.A. Design of Spur-Type Streambank Stabilization Structures, FHWA/RD-84/101, FHWA, Washington, D.C. 1985.

Brown, S.A. Streambank Stabilization Measures for Highway Engineers, FHWA/RD-84/100, FHWA, Washington, D.C. 1985.

Chow, V.T. Open Channel Hydraulics, McGraw-Hill. 1970.

Clopper, Paul E. Hydraulic Stability of Articulated Concrete Block Revetment Systems During Overtopping Flow, FHWA-RD-89-199, FHWA, Washington, D.C. November 1989.

Davidian, Jacob. Computation of Water Surface Profiles in Open Channels, Techniques of Water Resources Investigation, Book 3, Chapter A15, U.S. Geological Survey. 1984.

Federal Highway Administration. Highways in the River Environment, Training and Design Manual. 1990.

Federal Highway Administration. Hydraulic Design of Energy Dissipaters for Culverts and Channels, Hydraulic Engineering Circular No. 14, FHWA-EPD-86-110, FHWA, Washington, D.C. 1983.

Federal Highway Administration. Design of Roadside Channels with Flexible Linings, Hydraulic Engineering Circular No. 15, U.S. DOT, U.S. Government Printing Office, Washington, D.C. 1988.

Federal Highway Administration. Design Of Riprap Revetments, Hydraulic Engineering Circular No. 11, FHWA-IP-89-016, FHWA, Washington, D.C. 1989.

Federal Highway Administration. Stream Stability at Highway Structures, Hydraulic Engineering Circular No. 20, FHWA-IP-90-014, FHWA, Washington, D.C. 2001.

Federal Highway Administration. Design of Roadside Channels with Flexible Linings, Hydraulic Engineering Circular No. 15, FHWA-IP-87-7, FHWA, Washington, D.C. 1988.

Froehlich, David C. Finite Element Surface-Water Modeling System: Two-Dimensional Flow in a Horizontal Plane, Users Manual, FHWA-RD-88-177, FHWA, Washington, D.C. 1989.

Froehlich, David C. and Lee, J.K. Two-Dimensional Finite-Element Hydraulic Modeling of Bridge Crossings: Research Report, FHWA-RD-88-146, FHWA, Washington, D.C. 1989.

Henderson, F.M. Open Channel Flow, Macmillan. 1966.

Lane, E.W. A Study of the Shape of Channels Formed by Natural Stream Flowing in Erodible Material, M.R.D. Sediment Series No. 9, U.S. Army Engineers Division, Missouri River, Corps of Engineers, Omaha, Nebraska. 1957.

Molinas, Albert. Users Manual For BRI-STARS, NCHRP Project HR 15-11A. 1994.

Odgaard, A. Jacob, and Anita Spoljaric. Sediment Control by Submerged Vanes, Journal of Hydraulic Engineering, ASCE, Vol. 112, No. 12. December 1986.

Odgaard, A. Jacob, and Carlos E. Mosconi. Streambank Protection by Submerged Vanes, Journal of Hydraulic Engineering, ASCE, Vol. 113, No. 4. April 1987.

Richardson, E.V., D.B. Simons, and P.Y. Julien. Highways in the River Environment, prepared for the Federal Highway Administration, Washington, D.C. June 1990. By the Department of Civil Engineering, Colorado State University, Fort Collins, Colorado, June 1990.

Rosgen, D.L. A Classification of Natural Rivers, Catena 77, Pages 169-199. 1994.

Rouse, Hunter, ed. Engineering Hydraulics, John Wiley & Sons, Inc. 1950.

Shen, H.W., S.A. Schumm, J.D. Nelson, D.O. Doehring, and M.M. Skinner. Methods for Assessment of Stream-Related Hazards to Highways and Bridges, FHWA/RD-80/160, Federal Highway Administration, Washington, D.C. 1981.

Sturm, T.W. Simplified Design of Contractions in Supercritical Flow, Journal of Hydraulic Engineering, ASCE, Vol. 11, No. 5. May 1985.

U.S. Army Corps of Engineers. Accuracy of Computed Water Surface Profiles, The Hydrologic Engineering Center, Davis, California. December 1986.

U.S. Army Corps of Engineers. HEC-2 Water Surface Profiles, User's Manual, The Hydrologic Engineering Center, Davis, CA, CPD-2A. 1990 (Revised 1991).

U.S. Army Corps of Engineers. HEC-RAS, River Analysis System, Hydraulic Reference Manual, The Hydrologic Engineering Center, Davis, CA., Version 3.0. 2002.

U.S. Army Corps of Engineers. HEC-RAS, River Analysis System, User's Manual, The Hydrologic Engineering Center, Davis, CA., Version 3.0. 2002.

U.S. Army Corps of Engineers. HEC-RAS, River Analysis System, Applications Guide, The Hydrologic Engineering Center, Davis, CA, Version 3.0. 2002.

U.S. Army Corps of Engineers. UNET, One-Dimensional Unsteady Flow Through a Full Network of Open Channels, User's Manual. The Hydrologic Engineering Center, Davis, CA. Version 3.1. July 1996.

Vanoni, Vito A., ed. Sedimentation Engineering, ASCE Manual No. 54, ASCE, 345 East 47th St., New York, NY. 1977.

Note: References in bold type are recommended reading for the engineer's library.

Weblinks

Federal Aid Policy Guides:

www.fhwa.dot.gov/legsregs/directives/fapgtoc.htm

- Current policies, regulations, and non-regulatory procedural guidance information related to the Federal Aid Highway Program.

Federal Highway Administration:

www.fhwa.gov/bridge/hydpuba.htm

- HEC-20, Stream Stability at Highway Structures
- Other publications

Geological Survey Water-Supply Paper:

www.engr.utk.edu/hydraulics/openchannels/cover.htm

- Photos of channels and their corresponding roughness coefficients.

U.S. Army Corps of Engineers Hydrologic Engineering Center:

www.hec.usace.army.mil/software/software_distrib/index.html

- HEC-RAS software
- Other publications

Note: MDOT does not claim responsibility for the information at these links or their maintenance.