USER'S GUIDE TO THE U.S. GEOLOGICAL SURVEY CULVERT ANALYSIS PROGRAM, VERSION 97-08

Water-Resources Investigations Report 98-4166

U.S. Department of the Interior
U.S. Geological Survey

User's Guide to the U.S. Geological Survey Culvert Analysis Program, Version 97-08

By JANICE M. FULFORD

U.S. GEOLOGICAL SURVEY WATER-RESOURCES INVESTIGATIONS
REPORT 98-4166

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CONVERSION FACTORS

Multiply	By	To obtain
inch(in)	25.4	millimeter
foot(ft)	0.3048	meter
square foot (ft^2)	0.09290	square meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second

User’s Guide to the U.S. Geological Survey Culvert Analysis Program, Version 97-08

By Janice M. Fulford

Abstract

This user's guide contains information on using the culvert analysis program (CAP), version 97-08. The procedure used is based on that presented in Techniques of Water-Resources Investigations of the United States Geological Survey, book 3, chapter A3, "Measurement of Peak Discharge at Culverts by Indirect Methods." The program uses input files that have formats compatible with those used by the Water-Surface Profile (WSPRO) program. The program can be used to compute rating surfaces or curves that describe the behavior of flow through a culvert or to compute discharges from measurements of upstream and downstream water-surface elevations. Improvements have been made that reduce the effort required to assemble the input data over the program’s previous version, 94-10. Additionally, several corrections have been made and are documented in the appendix.

INTRODUCTION

This user's guide contains information on the culvert analysis program (CAP). Users can determine discharges from measured high-water marks or compute rating surfaces or curves that represent the hydraulic behavior of the culvert with CAP. The resulting rating surfaces or curves can be used to simulate culvert hydraulics in other flow models.

The culvert analysis procedure followed by the program computes headwater elevations for specified combinations of tailwater elevations and discharge. The procedure is based on the U.S. Geological Survey (USGS) method documented by Bodhaine (1968) in Techniques of Water-Resources Investigations (TWRI) book 3, chapter A3, which is based on USGS field investigations (Carter, 1957) and on laboratory investigations made by the USGS, the Bureau of Public Roads, and many universities. The USGS procedure has been adapted to provide solutions that minimize the need for the user to determine the flow regime in the culvert.

The guide contains sections on the installation of the program onto computer systems; an overview of the culvert analysis procedure used by the program; details of program operation; and examples demonstrating the use of the program. Additionally, the guide contains an appendix that lists corrections made to previous versions. Users should be familiar with basic hydraulic principles. Detailed explanation of the culvert analysis procedure and determination of discharge coefficients is not contained in this guide. Users should refer to the TWRI by Bodhaine to determine discharge coefficients or if they are unfamiliar with culvert analysis.

The program source code, written in Fortran 77, has some routines that are loosely based on an antecedent program, A526 (Matthai and others, circa 1970), used by the USGS. The antecedent program was initially written for a Burroughs 220 in BALGOL by W.P. Somers and G.I. Selner of the USGS and was subsequently converted to Fortran IV by J.V. Tanida, O.G. Lara, and H.E. Stull of the USGS.

Interactive entry and editing of the input data is not supported by CAP. Discharges are computed from an ASCII text input file that is prepared by the user with a text editor before CAP is run. The input file format is based on the Water-Surface Profile (WSPRO) computer program input files (Shearman, 1990).

NEW FEATURES

New features added to the program eliminate the need to refer to tables and graphs of discharge coefficients in TWRI Book 3, Chapter A3 and allow the input data and output results to be in either meter-second or feet-second units. Two new input-file record types, SI and *CC, are available to provide these features. Computations for culverts with elliptical sections have been added. The previous version, 94-10, documented in Open-File Report 95-137, did not have these features.

PROGRAM INSTALLATION

This section contains information on installing the program. Details on system requirements, program testing, and array sizes are included.

Computer System Requirements

The culvert analysis program has been compiled for DOS, DGUX, and other Unix-based computers. It does not use or require graphics capability, color, or a mouse. Disk space of approximately 250 kilobytes (K) is sufficient for many applications. A typical executable file on a PC is 230K. Additional disk space is needed for input, output, and temporary files.

Installing on New Computer Systems

The program installer should copy CAP files from the source media (floppy disk or remote computer system) onto the hard disk of the target computer system. CAP files include the following:

README packing list and update information.
CAP.EXE executable file (not available for all computer systems)
MERCER.DAT test data set, circular culvert with an approach section.
PIGEON.DAT test data set, non-standard culvert section with an approach section.
RIOGRAN.DAT test data set, multiple pipe arches with an approach section.
CULTWRI.DAT test data set, TWRI example with an approach section.
TWRI8.DAT test data set, TWRI example with an approach section.

Program Array Sizes

The default array sizes in CAP allow computations of headwater (or upstream water-surface elevations) for combinations of up to 50 tailwater elevations and 48 discharges through the culvert. The approach section is allowed to have up to 20 subareas and 150 coordinates.

CULVERT ANALYSIS OVERVIEW

The culvert analysis procedure followed by CAP is similar to that described by G.L. Bodhaine (1968) in "Measurement of Peak Discharge at Culverts by Indirect Methods." A few adaptations and modifications have been made to allow solutions to be computed without user intervention.

Bodhaine's procedure for computing flow through culverts is cited by numerous texts on hydraulics and classifies culvert flow into six flow types. Equations for the six flow types are based on continuity and energy equations. Classification depends on whether the culvert inlet or outlet controls the flow and whether the culvert barrel flows full.

The following is a brief overview of the flow equations and solution procedure. Users unfamiliar with the culvert analysis procedure should refer to Bodhaine (1968) for a detailed explanation.

Flow Equations

The equations for culvert flow are based on the conservation of energy and mass between the approach section and a downstream section in the culvert. The equation for each particular state of flow in the culvert is derived by applying the energy equation (Bernoulli's equation) and continuity equation (mass conservation) between the appropriate downstream culvert section that governs that flow state and the approach section. Depending on the flow regime in the culvert, the downstream section in the culvert is located either at the control section or at the outlet section of the culvert. The control section is the section where the flow changes from subcritical to supercritical flow. For a simple flow reach, illustrated in figure 1, the energy equation for gradually varied flow is

$$h_1 + \alpha_1 \frac{V_1^2}{2g} = h_2 + \alpha_2 \frac{V_2^2}{2g} + h_{f_{1-2}} + h_{e_{1-2}} , \qquad (1)$$

where h_1 is the upstream water-surface elevation, h_2 is the downstream water-surface elevation, V_1 and V_2 are mean water velocity at sections 1 and 2, g is the acceleration of gravity, α_1 and α_2 are velocity coefficients at sections 1 and 2, $h_{f_{1-2}}$ is the energy loss due to boundary (or bed) friction over the length of the flow reach, and $h_{e_{1-2}}$ is the energy loss due to contraction or expansion of the flow. The frictional energy loss term in the equation is computed as

$$h_{f_{1-2}} = \frac{LQ^2}{K_1 K_2} , \qquad (2)$$

where Q is the discharge, L is the reach length, and K_1 and K_2 are the upstream and downstream conveyances, respectively. Conveyance, is defined using Manning's equation as

$$K = \frac{1.49}{n} AR^{2/3} , \qquad (3)$$

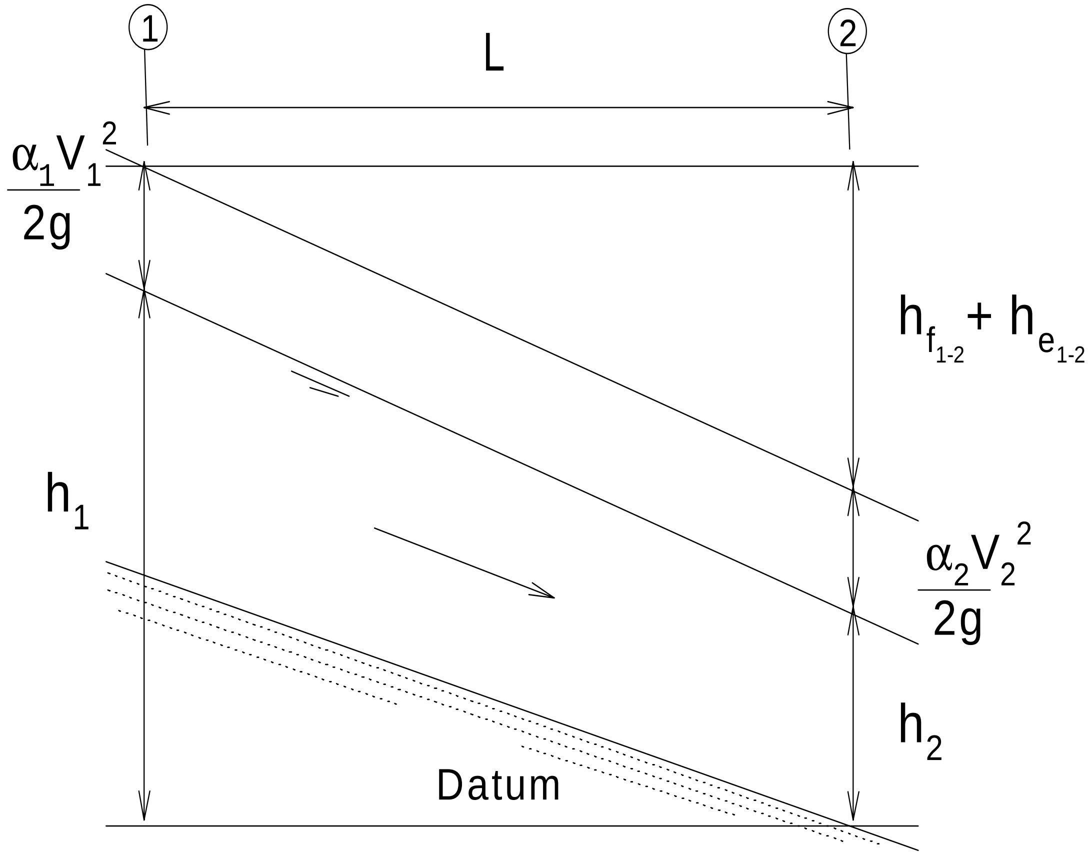

Figure 1. Definition sketch for a simple stream reach. *L* is reach length; h_1 and h_2 are water-surface elevations; V_1 and V_2 are mean velocities; and α_1 and α_2 are the velocity head coefficients. Subscripts 1 and 2 denote sections 1 and 2, respectively. *g* is the acceleration of gravity and h_f is the friction loss over the reach length.

where *n* is Manning's coefficient of roughness, *A* is cross-sectional area, and *R* is hydraulic radius. The expansion or contraction energy loss term is computed as

$$h_{e_{1-2}} = k\left|\frac{\alpha_1 V_1^2}{2g} - \frac{\alpha_2 V_2^2}{2g}\right| \text{ ,} \qquad (4)$$

where *k* is the coefficient for energy losses due to expansion or contraction of the flow. For a detailed derivation of gradually varied flow and conveyance and a discussion of Manning's equation refer to Chow (1959, p. 217-248).

The equations for the six culvert flow types--(1) critical depth at inlet, (2) critical depth at outlet, (3) part full culvert barrel and tranquil flow throughout, (4) submerged outlet and inlet, (5) rapid flow at inlet and part full culvert barrel, and (6) full culvert barrel flow with free outfall--are special cases of the energy equation for gradually varied flow. Because the contraction loss in the culvert entrance is computed in the culvert equations as a function of velocity, the contraction or entrance loss and velocity head in the control section are combined into a single velocity head term that contains the discharge coefficient. This results in discharge coefficients being a function of flow type and approach depth, as well as a function of culvert and entrance geometry. Figure 2 is a

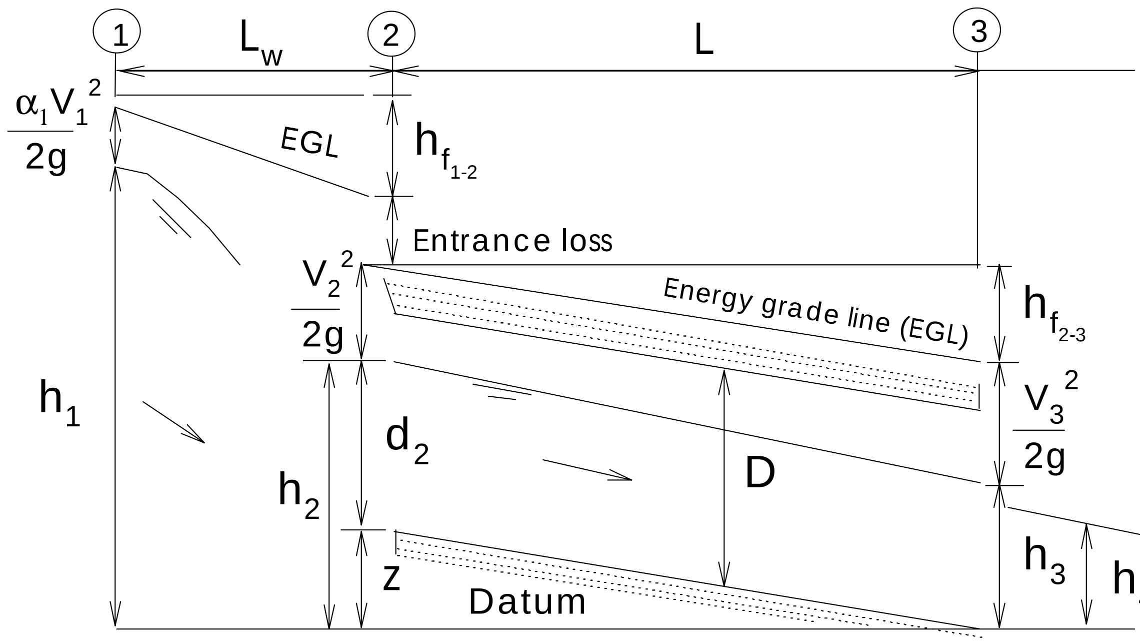

Figure 2. Definition sketch for a stream reach with flow through a culvert. 1 is at the approach section, 2 is at the culvert inlet section, and 3 is at the culvert outlet section. L_w is the reach length between sections 1 and 2; L is the culvert barrel length; D is the culvert barrel height; d_2 is the flow depth in the culvert inlet and z is the fall over the culvert length. h is the water-surface elevation and V is the mean velocity in the section denoted by the numeric subscript. h_f is friction loss over L_w for subscript 1-2 and over L for subscript 2-3.

definition sketch for culvert flow.

For flow type 1, critical depth at inlet, the energy equation is written from the approach section to the inlet section of the culvert. Vertical datum is the invert of the culvert outlet. Flow is supercritical in the culvert barrel and tranquil upstream of the culvert inlet. Critical depth is assumed in the inlet section of the culvert. For culvert flow type 1, the energy equation is

$$h_1 + \alpha_1 \frac{V_1^2}{2g} = d_c + z + \frac{V_2^2}{C_{123}^2 2g} + h_{f_{1-2}} . \quad (5)$$

The discharge coefficient C_{123} is for flow types 1, 2, and 3, where the culvert does not flow full at the inlet, z is the fall of the culvert, and d_c is the critical flow depth in the culvert for the discharge. The fall of the culvert is computed by subtracting the elevation of the downstream culvert invert from the elevation of the upstream culvert invert. The frictional energy loss term is computed as

$$h_{f_{1-2}} = \frac{L_w Q^2}{K_1 K_{d_c}} , \quad (6)$$

where L_w is the length of the reach between the approach section and the culvert inlet, and K_{d_c} is the conveyance of the culvert at critical flow depth.

For flow type 2, critical depth at the outlet, the energy equations are written from the approach section of the culvert through the inlet and then to the exit section. Flow is tranquil in the culvert barrel. Critical depth is assumed in the outlet section of the culvert. For culvert flow type 2, the energy equation is

$$h_1 + \alpha_1 \frac{V_1^2}{2g} = d_c + \frac{V_3^2}{C_{123}^2 2g} + h_{f_{1-2}} + h_{f_{2-3}} . \quad (7)$$

The frictional energy losses for type 2 flow are computed as

$$h_{f_{1-2}} = \frac{L_w Q^2}{K_1 K_2} \quad (8a)$$

and

$$h_{f_{2-3}} = \frac{LQ^2}{K_2 K_{d_c}} . \quad (8b)$$

The conveyance of the culvert inlet, K_2, in equations 8a and 8b requires the determination of the flow depth in the culvert inlet. The flow depth in the inlet is determined by routing the discharge from critical depth at the exit to the inlet using the energy equation.

For flow type 3, part full culvert barrel and tranquil flow throughout, the energy equations are written from the approach section of the culvert through the inlet and then to the exit section. Tranquil flow is assumed throughout the culvert approach, barrel, outlet, and exit sections. For culvert flow type 3, the energy equation is

$${}_1 + \alpha_1 \frac{V_1^2}{2g} = h_3 + \frac{V_3^2}{C_{123}^2 2g} + h_{f_{1-2}} + h_{f_{2-3}} . \quad (9)$$

The frictional energy losses for flow type 3 are computed as

$$h_{f_{1-2}} = \frac{L_w Q^2}{K_1 K_2} \quad (10a)$$

and

$$h_{f_{2-3}} = \frac{LQ^2}{K_2 K_3} . \quad (10b)$$

The computation of the culvert inlet conveyance, K_2, in equations 10a and 10b requires the determination of the flow depth in the culvert inlet. The flow depth is determined by routing the discharge from the known tailwater elevation at the culvert exit to the inlet using the energy equation.

For flow type 4, submerged outlet and inlet, the energy equation is written from the approach section to the exit section assuming full culvert flow and submerged inlet and outlet conditions. Essentially, the culvert functions as a pipe. In contrast to Bodhaine (1968), ponded conditions (no approach velocity or friction loss) are not assumed in the approach to the culvert inlet. However, the assumptions that the friction loss between sections 3 and 4 is equal to zero and the energy loss coefficient for the expansion between sections 3 and 4 is equal to one have been retained. For culvert flow type 4, the energy equation is

$$h_1 + \alpha_1 \frac{V_1^2}{2g} = h_4 + \frac{V_o^2}{C_{46}^2 2g} + h_{f_{2-3}} + h_{f_{1-2}} \quad . \tag{11}$$

The discharge coefficient, C_{46} , is for flow types 4 and 6, where the inlet and culvert barrel flows full. The frictional energy losses for flow type 4 are a function of velocity and roughness in the culvert barrel and the approach section. They are computed as

$$h_{f_{2-3}} = L V_o^2 \frac{n^2}{a^2 R_o^{4/3}} = \frac{LQ^2}{K_o^2} \tag{12a}$$

and

$$h_{f_{1-2}} = \frac{L_w Q^2}{K_1 K_2} \ , \tag{12b}$$

where R_o is the hydraulic radius and K_o is the conveyance for the full culvert barrel. The variable a is equal to 1.49 for feet-second units and 1.0 for meter-second units.

For flow type 5 and type 6 the approach section water-surface elevation is at least 1.5 times the culvert barrel height above the culvert inlet invert. These flows are categorized as high head flows. For flow type 5, rapid flow at the inlet and part full culvert, the energy equation is written from the approach section of the culvert to the inlet section. The culvert functions as a sluice gate in this case. The outlet is not submerged. Ponded conditions in the approach are assumed. For type 5 culvert flow, the energy equation is

$$h_1 = z + \frac{V_o^2}{C_5^2 2g} \quad . \tag{13}$$

The discharge coefficient, C_5, is the coefficient used for type 5 flow where the inlet acts as an unsubmerged sluice gate.

For type 6 flow, full culvert barrel flow with free outfall, the energy equation is written from the approach section of the culvert through the inlet to the exit section. This case is similar to type 5 except that the culvert barrel flows full. The culvert acts as an orifice. As for type 5 flow conditions, the outlet is not submerged and ponded conditions in the approach are assumed. For type 6 culvert flow, the energy equation is

$$h_1 = h_3 + \frac{V_o^2}{C_{46}^2 2g} + h_{f_{2-3}} . \tag{14}$$

To solve this equation, the program uses a functional relation that has been defined by laboratory experiments. This functional relation is documented in the TWRI by Bodhaine (1968, figure 17, p. 34).

The continuity equation, $Q = VA$, is substituted for velocity in the energy equation. CAP solves the six equations for the approach section water-surface elevation. Bodhaine, however, solved for discharge to facilitate hand calculation of discharge, resulting in the following equations where A_{d_c} is the culvert area at critical depth, A_3 is the culvert area at the outlet flow depth and A_0 is the area of a full culvert:

$$Q_{type1} = C_{123} A_{d_c} \sqrt{2g\left(h_1 - z + \alpha_1 \frac{V_1^2}{2g} - d_c - h_{f_{1-2}}\right)} \quad (15a)$$

$$Q_{type2} = C_{123} A_{d_c} \sqrt{2g\left(h_1 + \alpha_1 \frac{V_1^2}{2g} - d_c - h_{f_{1-2}} - h_{f_{2-3}}\right)} \quad (15b)$$

$$Q_{type3} = C_{123} A_3 \sqrt{2g\left(h_1 + \alpha_1 \frac{V_1^2}{2g} - h_3 - h_{f_{1-2}} - h_{f_{2-3}}\right)} \quad (15c)$$

$$Q_{type4} = C_{46} A_0 \sqrt{\frac{2g\,(h_1 - h_4)}{1 + 29 C_{46}^2 n^2 L R_o^{-4/3}}} \quad (15d)$$

$$Q_{type5} = C_5 A_0 \sqrt{2g\,(h_1 - z)} \quad (15e)$$

$$Q_{type6} = C_{46} A_0 \sqrt{2g\,(h_1 - h_3 - h_{f_{2-3}})} \quad (15f)$$

Solution Procedure

The program solves the appropriate form of the energy equation and the continuity equation for the approach-section water-surface elevation by using simple flow routing. Simple flow routing, or step backwater calculations, uses the energy equation to compute the water-surface elevation upstream at fixed locations in the reach. Given a discharge and a tailwater elevation (water-surface elevation at the culvert-exit section), the appropriate flow type and equation or equations are determined and solved for the approach-section water-surface elevation using a bisection root solver (Conte and DeBoor, 1980). The appropriate set of equations is determined by applying the criteria used by the USGS culvert method for determining type of flow. These criteria are listed in table 1. For some flow types, such as type 5 or type 6, the proper flow type is determined in the program by first attempting to solve for the occurrence of type 1, 2, or 3 flow. Upon failure to bracket a root, the program then solves for type 5 and/or type 6 flow.

The solution procedure used in either CAP or the preceding culvert program, A526, (Matthai and others, 1970?), is based on using three sections in the computations: the approach, culvert inlet, and culvert outlet. This procedure does not ensure numerical convergence; that is, the solution will not change as a result of increasing the number of sections used in the computations. The procedure used does not use sections other than or in addition to the three sections, except for certain cases noted in the following section. For some solutions, this may result in error in the approach water-surface elevation computed or in the type 3 water-surface elevation being computed somewhat lower than the type 2 water-surface elevations for the same discharge. Users can refer to a discussion of numerical convergence in 1-D steady flow models presented by Thompson and Rogers (1993) for examples of the effects of convergence on the accuracy of the water surface computed.

Table 1. Classification criteria for the six culvert flow types [h_1, elevation of approach-section water-surface; z, culvert fall; D, culvert height; h_4, elevation of exit-section water-surface elevation; d_c, critical flow depth in culvert; S_0, culvert slope; S_c, critical slope]

Flow type	Classification criteria		
	Approach depth range (above upstream invert)	Outlet depth range (above downstream invert)	Culvert slope
Type 1	$(h_1\text{-}z) < 1.5D$	$h_4 < (d_c+z)$	$S_0 > S_c$
Type 2	$(h_1\text{-}z) < 1.5D$	$h_4 < d_c$	$S_0 < S_c$
Type 3	$(h_1\text{-}z) < 1.5D$	$h_4 \le D, h_4 > d_c+z$ $h_4 \le D, h_4 > d_c$	$S_0 > S_c$ $S_0 < S_c$
Type 4	$(h_1\text{-}z) > D$	$h_4 > D$	no criteria
Type 5	$(h_1\text{-}z) \ge 1.5D$	$h_4 \le D$	no criteria
Type 6	$(h_1\text{-}z) \ge 1.5D$	$h_4 \le D$	no criteria

Transitions Between Flow Types

Transitions between the various flow type equations are not always smooth and continuous. These transitions are either the result of real flow phenomenon or numerical discontinuity between the flow equations.

Low to high head flow

Flows with the approach water-surface elevation ranging from $1.2D + z$ to $1.5D + z$ can change dramatically back and forth between low (types 1, 2, and 3) and high head (types 5 and 6) flows. Bodhaine (1968) assumes that an abrupt reduction in discharge does not occur. The transition between type 1 and type 5 flow is approximated by fitting a straight line between the type 1 solution at a headwater-diameter ratio of 1.2 and the type 5 solution at a headwater-diameter ratio of 1.5. For the transition between type 2 and type 6, flow is approximated by fitting a straight line between type 2 and type 6 solutions at headwater-diameter ratios of 1.25 and 1.75, respectively. Bodhaine (1968) does not suggest techniques for the other transitions between low head and high head flow types.

CAP uses methodology similar to Bodhaine's to compute low to high head transitions. Transitions between low and high head flows are approximated by fitting a straight line between the low head solution at headwater-diameter ratios of 1.2 for type 1, and 1.25 for type 2 and 3, and the high head solution at headwater-diameter ratios of 1.5 for type 5 and 1.75 for type 6. Transition cases for which critical depth is greater than the culvert height and headwater-diameter ratios are between 1.2 and 1.5 for type 5 and 1.2 and 1.75 for type 6 are interpolated between flow type 1 and the high head flow types.

Critical depth to tranquil flow

The tranquil flow (type 3) equation often can not be solved near the transition between flow types with a critical depth control (types 1 and 2) and tranquil flow (type 3). Flow is tranquil in the culvert exit section. However, the energy equation can not be appropriately solved for the inlet water-surface depth assuming tranquil flow in the culvert barrel.

Two flow scenarios are possible when this occurs. If the culvert barrel is steep, supercritical flow and tranquil flow occur in the barrel, separated by a hydraulic jump. Critical flow depth occurs at the inlet and the approach water-surface elevation is computed from type 1 flow equations.

If the culvert barrel slope is mild, only tranquil flow occurs in the barrel. However, significant water-surface curvature in the culvert makes the assumption of a constant water slope in the barrel invalid. The flow equation is numerically discontinuous and cannot be solved. The discontinuity results from poor spatial convergence and is analogous to trying to draw an arc with connected straight line segments. One line segment does not look like an arc. Multiple connected line segments, however, can look like an arc. To compute a solution, an additional section in the culvert at which flow parameters can be computed is necessary to account for the water surface curvature.

Simple routing is used to determine the location in the culvert at which normal depth of flow occurs. The energy equation (1) is solved for the location of normal depth using the known discharge and flow depth at the culvert exit. The inlet depth is then determined by routing the flow from the location in the culvert at which normal depth occurs to the inlet. The approach water-surface elevation is determined using the type 3 flow equation. Friction losses are determined for the culvert by summing the friction lost in the normal depth portion with the friction lost in the remaining portion of the culvert. If normal depth is located outside the culvert pipe a program warning message is issued and normal depth is assumed in the inlet.

Culvert flowing full and part full

Additional numerical discontinuities between flow types occur when flow types 3 and 4 exist simultaneously in the culvert barrel. The culvert flows full for part of its length and flows tranquilly for the remainder of its length. Simple routing through the culvert is used to determine the length of culvert barrel flowing full or part full.

When the culvert flows part full (type 3) at the entrance and full (type 4) at the exit, the type 4 flow equation is used to determine the length of culvert that is flowing as type 3 conditions. The type 3 equation is then solved for approach water-surface elevation using this length.

Similarly, when the culvert flows full (type 4) at the entrance and part full (type 3) at the exit, the type 3 flow equation is used to determine the length of culvert flowing as type 4. The type 4 equation is then solved for approach water-surface elevation using this length.

Unusual Conditions

Some culvert conditions are inappropriate for the procedure. These conditions are (1) variation in cross-sectional dimensions or material through the culvert barrel, (2) nonuniform slope or break in slope along the culvert barrel or (3) severe adverse slope.

Additionally, some flow conditions are inappropriate for the procedure. Inappropriate flow conditions include nonponded conditions for type 5 and 6 and supercritical flow in the approach section. When significant approach velocity (nonponded condition) occurs for flow types 5 and 6, flows are not computed accurately because approach velocity head and friction losses are ignored in the procedure. The flow equations cannot be solved for culverts with supercritical flow in the approach section, because of the routing technique used in setting up and solving the equations and because the discharge coefficients assume subcritical flow conditions in the approach section.

Rating Surfaces for Culverts

The flow behavior of hydraulic structures such as culverts can be represented by a three-dimensional surface. The surface is described by a set of points with coordinates corresponding to the discharge through the structure, the tailwater elevation, and the approach-section water-surface elevation. An example rating surface is shown in figure 3. The familiar technique of representing discharge ratings as a function of discharge and approach elevation shown in figure 4 requires a curve for each tailwater. Representing flow behavior of hydraulic structures by a three-dimensional surface does not require separate curves for each tailwater and illustrates the relationship between changing tailwater and discharge and approach water-surface elevation. Numerical surface-water flow models often employ tabled values of cross-section hydraulic properties. Tabled values of approach water-surface elevation, discharge and tailwater elevation for culverts can be produced by CAP to serve a similar purpose. Flow models can interpolate intermediate values and gradients from the tabled values.

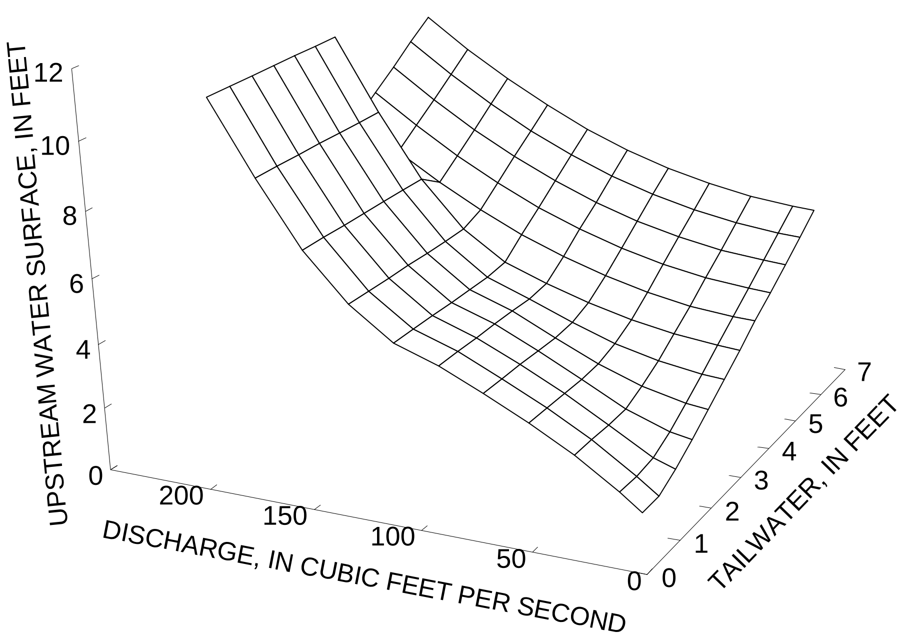

Figure 3. Rating surface for a rectangular culvert.

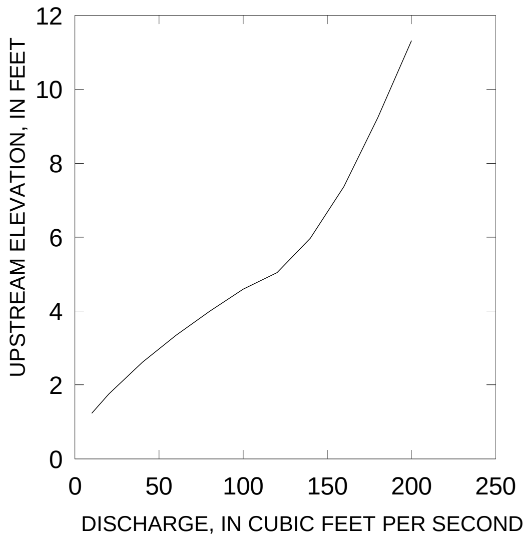

Figure 4. Rating curve for a rectangular culvert with a tailwater depth of 0.5 foot.

Rating Curves for Mitered Pipe Culverts

Rating curves for mitered pipes present additional challenges because culvert flow length is a function of flow depth. CAP uses a constant culvert flow length for computation, but rating curves for mitered pipes can be produced by repetitively changing the culvert flow length and executing CAP. For the rating, combinations of discharge, approach water-surface elevation, and tailwater elevation should be selected from the output that has the culvert length that most closely matches the actual flow length in the culvert. Enough runs at various culvert lengths should be made so that the approach water-surface elevation is computed at sufficient accuracy. L_{miter}, the average culvert flow length in a mitered pipe, can be estimated from the culvert geometry using

$$L_{miter} = L_{max} - \frac{d_2}{2D}(L_{max} - L_{min}) \tag{16}$$

where d_2 is the inlet water depth, L is the culvert flow length and the subscripts, *miter*, *min*, and *max* denote average culvert flow length, minimum flow length (the length between the tops of the culvert barrel ends), and maximum flow length (the length between the inverts of the culvert barrel ends). Bodhaine (1968, p. 8) describes in detail the proper computation of pipe length.

PROGRAM OPERATION

Culvert computations require data that describe the geometry of the approach section, the geometry of the culvert, roughness parameters, and discharge coefficients. Data for the input file are usually obtained by field survey if the analysis is for an existing culvert. For a discussion of the field surveying requirements see Bodhaine (1968, p. 6-9).

Execution of CAP requires first the preparation of an input file, or files, containing the data that describe the culvert, the approach section, and values of tailwater elevation and discharge. Except for field surveying, input file preparation is normally the most time-consuming step in the analysis of culvert flow. CAP does not support interactive input of data. A text editor that produces ASCII files is required to create the input files.

The input data files are based on WSPRO (Shearman, 1990) input file formats. Each record is 80 characters in length. Any characters after the eightieth column are ignored. The first 10 columns of each record are reserved for fixed-field format. Columns 11 through 80 are available for free-field format. Data items entered in the free-field format area are separated by either a comma, one or more blank spaces or any combination of blanks and a comma. Null values must be specified, unless they occur at the end of the list of data items entered on the record. Null values are specified by either an asterisk or two successive commas. Data items may be entered in whatever precision is required. Approach-section data formatted for CAP are compatible with the WSPRO program. Use of WSPRO compatible data formats provides users with a simple and well-documented format in which to enter data.

Input Files

Culvert data may reside in a file either separate from or with the approach-section data. The position of the culvert data or the approach-section data in the input file is not important. The culvert and approach section are located in the stream reach by assigning a section reference distance (SRD) to each section. All elevations, including the culvert entrance and exit invert elevations, tailwater elevations and approach-section geometry, are referenced to a common datum. The relationships between section reference distances and elevations are shown in figure 5. All data should be input in a consistent system of units, either inches, feet, seconds (the default) or centimeters, meters, seconds. The following are descriptions of the data records used by CAP. They are organized into two sections: culvert records, and approach-section records

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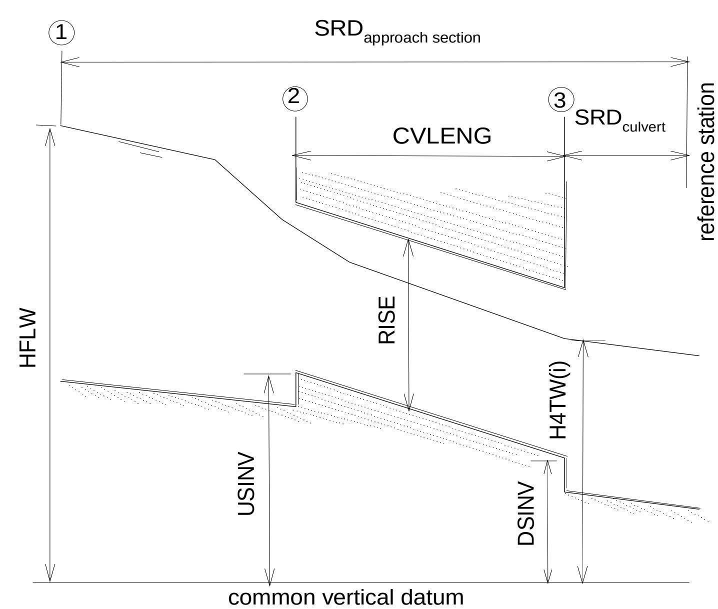

Figure 5. Distance and elevation relations between the culvert and approach section. *[Approach section, 1; culvert inlet section, 2; culvert exit section, 3; HFLW, approach section water-surface elevation; USINV, culvert inlet invert elevation; DSINV, culvert outlet invert elevation; H4TW(i), tailwater elevation; RISE, culvert height; CVLENG, culvert length; $SRD_{approach\ section}$, section reference distance for approach section; $SRD_{culvert}$, section reference distance for culvert outlet]*

Culvert Records

Culvert records include data that describe the location of the culvert in the reach, culvert geometry, the culvert barrel roughness, the inlet discharge coefficients, culvert barrel slope, and the tailwater elevation and discharge combinations for which to compute approach-section water-surface elevations. Formats used by CAP for culvert records include the WSPRO culvert header record, CV; the WSPRO culvert section geometry record, CG; and records specific to CAP. Because WSPRO uses FHWA techniques to compute culvert flow, CAP requires the input of culvert records in addition to those used by WSPRO. These records have the two-letter record identifier preceded by an asterisk.

A typical data sequence describing a culvert is listed in figure 6. An input file describing a culvert section must have a CV, *CX, *CQ, *CN and either a *CS or a CG record for proper execution. The CG record is used for standard culvert shapes; circular pipes, boxes, and pipe arches. The *CS record is used for all other shapes. Default values are used if *C1, *C3, *C5, *CC and *CF records are not included in the input file. Descriptions of the culvert records used by CAP follow.

CG - culvert geometry record

Purpose: WSPRO culvert geometry record. This record is replaced by *CS records for nonstandard culvert sections. Bracketed variables are optional. Material type must be specified for pipe arches.

Format:

Column	Format	Contents
1-2	A2	CG
3-10	8X	blanks
11-80	free	*ICODE, RISE, [SPAN, BOTRAD, TOPRAD, CORRAD]*

Definition of variables:

ICODE Three digit culvert code, IJK, in which the individual digits indicate the following:

I -- Shape code: 1 = box; 2 = circular or elliptical; 3 = pipe-arch

J -- Material code required for pipe and pipe-arch culverts: 1 = concrete pipe; 2 = mitered corrugated metal pipe; 3 = aluminum pipe; 4 = corrugated metal pipe, corner radius < = 18"; 5 = corrugated metal pipe, corner radius = 31"; 6 = corrugated metal pipe, corner radius = 47". These codes may not be compatible with WSPRO J codes for some cases.

K -- not used by CAP; enter any single integer. Inlet codes for CAP are entered either on the*CC record or *C3 record.

```
SI        0
CV   TEST 100.,0.,50.,1.06,1.39,1
CG        100,48.,48.,0,0,0
*C1       0.98,0,0,0,0
*C5       0.87 0.47,7.39, 0.53,9.39, 0.58,13.39, 0.62,21.39
*CX       1.6, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6.46
*CQ       20, 40, 60, 80, 100, 125, 150, 180, 210, 250
*CN       0.015
```

Figure 6. Typical data sequence used to describe culvert sections and computations.

RISE The maximum vertical inside dimension of the culvert barrel in the appropriate system of units, either in inches or centimeters. The rise equals the diameter for circular culverts.

SPAN The maximum horizontal inside dimension of the culvert barrel, in the same units as RISE. SPAN must be coded for box, elliptical, and pipe-arch culverts but should not be coded for circular culverts. For multiple barrel box culverts, it is the gross horizontal inside dimension of the barrels excluding thickness due to webs.

BOTRAD, TOPRAD, CORRAD Bottom, top, and corner radii, respectively, of pipe-arch culvert barrel, in the same units as RISE. If not specified, approximate values of these variables will be computed on the basis of ICODE, SPAN, and RISE.

CV - culvert location record

Purpose: WSPRO culvert header record.

Format:

Column	Format	Contents
1-2	A2	CV
3-5	3X	blanks
6-10	A5	*SECID*
11-80	free	$SRD_{culvert}$, *XCTR, CVLENG, DSINV, USINV, NBBL*

Definition of variables:

SECID Unique cross-section identification code which allows selection of a particular culvert section from a file containing several culvert sections. Even if only one culvert section exists in a file, the culvert section must be identified.

$SRD_{culvert}$ Section reference distance in the appropriate system of units, either feet or meters. The SRD for the culvert is referenced from the downstream end of the barrel to the common reference station (figure 5).

XCTR The horizontal stationing of the center of the culvert measured relative to an arbitrary origin on the left bank. This variable is not used by CAP, but an arbitrary value must be included.

CVLENG Length of the culvert barrel in the same units as $SRD_{culvert}$. Culvert flow length for mitered pipes is a function of flow depth. CAP does not automatically adjust the effective barrel length for flow depth and requires a constant culvert length for computation.

DSINV Elevation of downstream invert above the common elevation datum in the same units as $SRD_{culvert}$. For nonstandard culvert sections, this is the minimum elevation of the downstream culvert section.

USINV Elevation of upstream invert above the common elevation datum in the same units as $SRD_{culvert}$. For nonstandard culvert sections, this is the minimum elevation of the upstream culvert section.

NBBL The number of culvert barrels. Used by CAP to compute the number of webs for a rectangular or box culvert. The default value is 1. For one web in a culvert, enter 2 for NBBL. Note that the shape specified by RISE and SPAN on the CG record is for the gross dimensions of the culvert including all barrels. Not for use at multiple barreled pipe, elliptical, or pipe arch culverts.

SI - data units record

Purpose: Data units record. This record indicates the input data units and the units for the output results. The record is not required. Omission of the record results in the program assuming that units are in feet, inches, and seconds. If two input files are used (separate approach and culvert files) an SI record should be included in each file unless the default feet, inches, and seconds units is desired.

Format:

Column	Format	Contents
1-2	A2	SI
3-10	8X	blanks
11-80	free	*SICODE*

Definition of variables:

SICODE A single digit code that indicates the units of the input data and the desired units for the printed results.

0 -- input in feet, inches, seconds; output in feet, seconds.
1 -- input in meters, centimeters, seconds; output in meters, seconds.
2 -- input in feet, inches, seconds; output in meters, seconds.
3 -- input in meters, centimeters, seconds; output in meters, seconds.

*ID - 16-character culvert or section identifier record

Purpose: Provides input of a 16-character identifier for either a culvert or approach section. Should be placed after the CV record in the input file. The record is not required.

Format:

Column	Format	Contents
1-3	A3	*ID
4-5	3X	blanks
6-21	A16	*BIGID*

Definition of variables:

BIGID Unique culvert or approach section identification code of up to sixteen characters. Used in addition to the SECID on the CV or XS records.

*CC - inlet geometry record

Purpose: Detailed inlet geometry measurement data. Discharge coefficients and coefficient adjustments are determined from this data and data entered on the CG record. Adjustment factors for C_{123} discharge coefficients are determined from polynomial equations determined by regression techniques from figures in Bodhaine for entrance rounding and for entrance beveling. Adjustment factors for projecting culverts are determined similarily using the table listed in the text on page 42 of Bodhaine.

Inclusion of a *CC record results in the appropriate selection of C_{46} and C_5 coefficients if the culvert inlet has rounding or beveling. Omission of this record will result in a default adjustment factor of 1 for rounding and beveling being used for determining the default value of C_{46} and C_5 coefficients.

This record can be used in place of a *C3 record. Data on this record is used to determine rounding and beveling ratios, and the projection ratio. The addition of the *CC record does not affect the computations if a *C3 record is entered for the culvert. Information on the *C3 record will be used and a warning message will be printed to the user screen: *C3 record used, *CC record ignored -WARNING.

Format:

Column	Format	Contents
1-3	A3	*CC
4-10	8X	blanks
11-80	free	*R*,*W*,*THETA*,*INLET*,*LPROJ*

Definition of variables:

R radius of rounding of the inlet sides and top in the appropriate system of units, either inches or centimeters. *R* is illustrated in figure 7. This value is used to determine r/D, the rounding ratio. Default is 0.

W the width of beveling of the inlet sides and top in the same units as *R*. This value is used to determine w/D, the beveling ratio. *W* is illustrated in figure 7. If bevel width, *W*, is greater than 0.1 times the culvert diameter, depth, or width, the bevels are considered to act as a wingwall. The bevel angle is entered as THETA. Default is 0. The equations used to compute the bevel adjustment factor for C_{123} are derived from Bodhaine (figure 24, pg. 40) and do not extrapolate values for bevel angles greater than 60 °.

THETA wingwall angle or bevel angle in degrees. Default is 0 degrees. The equation used to compute the adjustment factor is derived from Bodhaine (figure 24, pg. 42).

INLET code for the program where: 1-vertical headwall or vertical end culvert (also bevel angle), 2-mitered end, 3-bellmouth or tongue and groove concrete pipe, 4-flared-pipe ends. Default is 1.

LPROJ length of culvert projection from embankment or headwall in the same units used to enter culvert RISE on the CG record (either inches or centimeters). The discharge coefficient adjustment factor is computed based on Bodhaine (p. 42)

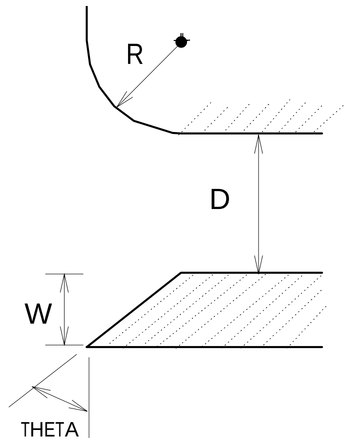

Figure 7. Definition sketch of *R*, radius of inlet rounding; *W*, width of inlet bevel; *D*, culvert height; and *THETA*, wingwall angle or bevel angle in degrees.

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*CF - high head flow record

Purpose: Determines how program will handle type 5 and 6 flow conditions. This record is in addition to the standard WSPRO records. If this record is omitted high head flows will be computed for type 5 and type 6 flow conditions. See pages 30-31 and 47 in Bodhaine (1968) for discussion on determining occurrence of high head flows.

Format:

Column	Format	Contents
1-3	A3	*CF
4-10	7X	blank
11-80	free	*TFLW*, *HFLW*

Definition of variables:

TFLW integer value for type of high head flow computations.

6 -- high head flows are computed using only type 6 computation.

5 -- high head flows are computed using only type 5 computation unless *HFLW* is entered. If *HFLW* is entered, type 5 is used when the computed approach water-surface elevations using type 5 equations are less than *HFLW*. Type 6 is used when the computed approach water-surface elevations using type 5 equations are greater than or equal to *HFLW*.

65 -- high head flows are computed twice regardless of *HFLW* entered, using both type 5 and 6 computations. Use of this value prohibits the output of three parameter tables. Set *TFLW* to either 5 or 6 for three parameter tables.

HFLW approach water-surface elevation referenced to the common vertical datum (figure 5) at which computations change from type 5 to type 6 in the appropriate system of units, either feet or meters. Caution should be used when applying this variable. The approach water-surface elevation, *HFLW*, is compared against the approach water-surface elevation computed for the type 5 (sluice gate) flow. The computation then switches to type 6 (orifice) flow and does not compare the computed approach water-surface elevation against the *HFLW* value. This can result in the type 6 computed elevation being lower than the *HFLW* value. The TWRI tables for determining when to switch between high head flow types have not been included in the program.

The use of *HFLW* is applicable for rough pipes and arches. Figure 16 in Bodhaine (1968) can be used to estimate *HFLW* for pipe culverts with rough barrels. Determine $29n^2(h_1\text{-}z)/R_o^{4/3}$ from plotting on figure 16 in Bodhaine the culvert slope and ratio of culvert length to culvert height. Then solve the equation $HFLW = z + C/(29n^2R_o^{4/3})$ for *HFLW* where C is $29n^2(h_1\text{-}z)/R_o^{4/3}$ determined from figure 16 in Bodhaine, R_o is the hydraulic radius of the full culvert barrel, n is the Manning's coefficient of roughness for the culvert barrel and z is the culvert fall.

*CN - culvert roughness record

Purpose: The culvert roughness, expressed as Manning's roughness coefficient, *n*.

Format:

Column	Format	Contents
1-3	A3	*CN
4-10	7X	blank
11-80	free	*n*

Definition of variable:

n Manning's coefficient of roughness for the culvert barrel.

*CS - nonstandard culvert record

Purpose: Coordinate pairs record for describing geometry of nonstandard culvert sections. When used, this record replaces the *CG record. Coordinates must be entered in counterclockwise order. The first coordinate and the last coordinate pairs must be the same for closure. The first entered coordinate should be either the highest coordinate pair or the leftmost pair of the highest coordinate pairs. An example of using the *CS record is in the Examples section of the user's guide.

If no discharge coefficient records (*CC, *C1, *C5, *C3) are entered for the nonstandard section, pipe discharge coefficients for a vertical headwall (inlet = 1) are used.

If a *CC or *C3 record is included, the coefficients for pipe culverts will be adjusted according to those records.

Format:

Column	Format	Contents
1-3	A3	*CS
4-10	7X	blank
11-80	free	*SCUL(1), GCUL(1), SCUL(2), GCUL(2), ... SCUL(N), GCUL(N)*

Definition of variables:

The parenthetical notation indicates the order number, *i*, assigned by the program to each x,y coordinate pair. For the first pair, *i*=1, and, for the last pair, *i*=N. The number of coordinate pairs, N, must be less than or equal to 50. No more than 12 coordinate pairs should be entered on a single *CS record.

SCUL(i) station from an arbitrary horizontal reference station on the left bank (facing downstream) of a point on the culvert section in the appropriate system of units, either feet or meters.

GCUL(i) ground elevation, referenced to the common vertical datum of a point on the culvert section in the same units as *SCUL(i)*.

*CQ - discharge record

Purpose: Discharges in the appropriate system of units, either cubic feet per second or cubic meters per second, for which computations of upstream water-surface elevations are made.

Format:

Column	Format	Contents
1-3	A3	*CQ
4-10	7X	blank
11-80	free	*Q(1), Q(2), ... Q(N)*

Definition of variable:

The parenthetical notation indicates the order number, *i*, assigned by the program to each discharge; *i*=1 and *i*= N for the first and last discharges. The number of discharges, N, is ≤ 48.

Q(i) the discharges at which the culvert computation will be made, in the appropriate system of units.

*CX - tailwater elevation record

Purpose: Tailwater elevations for which computations of upstream water-surface elevation are made in the appropriate system of units, either feet or meters.

Format:

Column	Format	Contents
1-3	A3	*CX
4-10	7X	blank
11-80	free	*H4TW(1), H4TW(2),... H4TW(N)*

Definition of variable:

The parenthetical notation indicates the order number, *i*, assigned by the program to each tailwater depth; *i*=1 and *i*= N for the first and last tailwater elevations. The number of tailwater elevations, N, is ≤ 50.

H4TW(i) tailwater elevations ordered in increasing height for which the culvert computation will be made. Tailwater elevations are referenced to the common vertical datum. A small or zero tailwater elevation may be entered to ensure computation of flow types 1 and 2.

*C1 - C_{123} culvert discharge coefficient record

Purpose: Culvert discharge coefficients for type 1 to 3 flow. This record is optional. This record allows users to specify the discharge coefficients. Nonstandard culverts should use this record to provide discharge coefficients. The presence of this record overrides the program coefficient computation. If only CB12 is entered, the graphs from the TWRI for box culverts will be used for computing coefficients for type 3 flow. All coefficients entered on this record will be appropriately adjusted by CAP for channel contraction effects, but are not adjusted by terms on the *C3 record for rounding, beveling, wingwalls or projections. If the record is omitted, default discharge coefficients are computed by the program.

The default discharge coefficients for box culverts for type 1 and 2 flow are set equal to 0.95 and for type 3 flow are computed based on figure 23 in Bodhaine (1968). The default discharge coefficient for bellmouth and tongue and groove pipe is set equal to 0.95 for flow types 1, 2 and 3. The type 1, 2, and 3 default discharge coefficients for mitered entrance pipe culverts are computed based on figure 25 in Bodhaine (1968) and on the inlet type specified on the *C3 record. All other pipes culverts are computed using figure 20 in Bodhaine.

Format:

Column	Format	Contents
1-3	A3	*C1
4-10	7X	blank
11-80	free	*CB12*, or *CP(1)*, *HP(1)*, *CP(2)*, *HP(2)*, ... *HP(4)*, *CP(4)*

Definition of variables:

The parenthetical notation indicates the order number, *i*, assigned by the program to each pair of discharge coefficients and ratios of approach flow depth and culvert height. For the first pair, *i*=1, and, for the last pair, *i*=4. Number of pairs entered is 4. The first coding option allows the use of single value coefficient for type 1 and 2 flows.

CB12 culvert discharge coefficient for type 1 and 2 flow for culverts with coefficient not dependent on $(h_1\text{-}z)/D$. The graphs from Bodhaine (1968) will be used for computing coefficients for type 3 flow. Allowable values are 0.98 ≥ CB12 ≥ 0.85. This term is only applicable to box culverts and will be ignored for all other culvert shapes.

The second coding option varies C_{123} with flow depth in the approach section. C_{123} is linearly interpolated between entered values of CP(i) for ratios of $(h_1\text{-}z)/D$ greater than HP(1) and less than HP(4).

C_{123} is equal to CP(1) for ratios less than or equal to HP(1) and CP(4) for ratios greater than or equal to HP(4).

CP(i) culvert discharge coefficient for type 1, 2, and 3 flow when the culvert flows part full at HP(i). Allowable values are 0.98 ≥ CP(i) ≥ 0.65.

HP(i) ratios of $(h_1\text{-}z)/D$, where h_1 is the water-surface elevation in the approach section referenced to the culvert outlet elevation, ***z*** is the culvert drop, and *D* is the culvert height.

*C3 - discharge coefficient adjustment record

Purpose: Adjustment factors for type 1, 2, and 3 flow discharge coefficients. This record does not include an adjustment factor for degree of channel contraction. Type 1, 2, and 3 default base discharge coefficients are appropriately adjusted by the program for the degree of channel contraction. This record is not required and default values are used if this record is omitted. Bodhaine lists values of rounding ratios, r/D, and beveling ratios, w/D, for standard riveted corrugated metal pipe on page 40, which apply only to corrugations with a 1/2" depth and 2(3/8)" pitch. Radius of entrance rounding, r, and bevel width, w, must be measured in the field for all other corrugations. If a *C1 record is present, the *KR*, *KW*, *THETA*, and *KPROJ* variables are ignored. The *CC record computes adjustment coefficients from culvert dimensions.

Format:

Column	Format	Contents
1-3	A3	*C3
4-10	7X	blank
11-80	free	*KR, KW, THETA, INLET, KPROJ*

Definition of variables:

KR entrance-rounding adjustment to discharge coefficient (Bodhaine, p. 39). Default is KR=1. This value is multiplied with the default base coefficient.

KW entrance-beveling adjustment to discharge coefficient (Bodhaine, p. 40). Default is KW=1. This value is multiplied with the default base coefficient.

THETA wingwall angle in degrees. Default is 0 degrees. Equation used to compute adjustment factor is derived from Bodhaine (figure 24, p. 42).

INLET code for program where: 1 vertical headwall flush, 2 mitered, 3 bellmouth, or tongue and groove concrete pipe (TWRI, p. 39-40), 4 flared pipe ends. Default value is 1.

KPROJ projecting-pipe adjustment to discharge coefficient (Bodhaine, p. 42). Default is KPROJ=1.

*C5 - C_{46} and C_5 culvert discharge coefficient record

Purpose: Culvert discharge coefficients for flow types 4, 5, and 6. This record is optional. All coefficients entered on this record are not adjusted by the terms on the *C3 record. Default values for these coefficients are calculated by the program if this record is not entered.

Default values for C_{46} are computed using a polynomial equation that is a function of rounding and beveling ratios. The polynomial equation was determined by regression techniques from the data in table 5 of the TWRI (Bodhaine, p. 42) that lists discharge coefficients for box or pipe culverts flowing full (C_{46}).

Default values for C_5 are computed in CAP by using look-up tables of coefficients and linearily interpolating between the tabulated coefficients. The look-up tables used are based on tables in Bodhaine: table 6 (Bodhaine, p. 44) for C_5 coefficients for pipe and box culverts as a function of rounding or beveling; table 7 (Bodhaine, p. 44) for C_5 coefficients for box culverts as a function of wingwall angle; and the table in the text on page 44 of Bodhaine for C_5 coefficients for flared pipe ends.

Format:

Column	Format	Contents
1-3	A3	*C5
4-10	7X	blank
11-80	free	*C46, (C5(1), H5(1), C5(2), H5(2),...C5(4), H5(4))*

Definition of variables:

The parenthetical notation indicates the order number, *i*, assigned by the program to each pair of discharge coefficients and ratios of approach flow depth and culvert height. For the first pair, *i*=1, and, for the last pair, *i*=4. Minimum number of pairs is 1. Maximum number of pairs is 4. Extra pairs are ignored. C_5 is linearly interpolated between entered values of C_5 for ratios of $(h_1\text{-}z)/D$ greater than H5(1) and less than H5(4). C_5 is equal to C5(1) for ratios less than or equal to H5(1) and C5(4) for ratios greater than or equal to H5(4).

C46 culvert discharge coefficient for flow types 4 and 6. Allowable values are 0.98 ≥ C46 ≥ 0.65. Values entered should be appropriately adjusted for any projection effects.

C5(i) culvert discharge coefficient for type 5 flow at the ratio of *H5(i)*. Allowable values are 0.75 ≥ *C5(i)* ≥ 0.39.

H5(i) ratios of $(h_1\text{-}z)/D$, where h_1 is the water-surface elevation in the approach section referenced to the culvert outlet elevation, *z* is the culvert drop, and *D* is the culvert height.

Approach-Section Records

The approach-section data include data that describe the location of the approach section in the reach, approach-section geometry, and roughness parameters. The approach section is located sufficiently upstream from the culvert opening, before the region of drawdown. Usually the approach section is located one opening width from the culvert entrance or, if wingwalls exist, a distance upstream from the end of the wingwalls equal to the width between the wingwalls at their upstream end.

The following sections present the descriptions of the XS, GR, N, ND, and SA WSPRO records and the *PD records used by CAP. Shearman (1990) presents a complete description of all WSPRO records and instructions on using those records to describe cross-section geometry. The approach-section data file follows the same basic format as WSPRO valley sections. A typical sequence of records describing a culvert approach section is shown in figure 8. The *PD record must be included in the file containing the approach-section records.

GR - approach section geometry record

Purpose: Specifies the x,y coordinates that define the shape of the cross-section. This is a WSPRO record. The cross-section side (or sides) are extended vertically if the water-surface elevation exceeds either (or both) the ground elevation of the leftmost or the rightmost coordinate pairs entered.

Format:

Column	Format	Contents
1-2	A2	GR
3-10	8X	blank
11-80	free	*X(1), Y(1), X(2), Y(2), ... X(N), Y(N)*

Definition of variables:

The parenthetical notation indicates the order number, *i*, assigned by the model to each x,y coordinate pair. For the first pair, *i*=1, and, for the last pair, *i*= N. The number of coordinate pairs, N, must be less than or equal to 150. Coordinates are ordered from left to right in a counterclockwise direction.

X(i) Station from an arbitrary horizontal reference station on the left bank (facing downstream) specified for the *i*th station in the appropriate system of units, either feet or meters.

Y(i) Ground elevation of the *i*th elevation, specified in the same units as station above the common vertical datum.

N - approach section roughness record

Purpose: Specifies Manning's coefficient of roughness, n, for the approach section. Proper selection of Manning's coefficient of roughness is explained by Chow (1959), Benson and Dalrymple (1967), Arcement and Schneider (1989), and Jarrett (1985). Barnes (1967), and Hicks and Mason(1991) present photos and verified Manning's n for a variety of reaches. This is a

```
*PD       0.   9.6 1.
XS   APPR 159.
GR        1,11.0 2,10.0 8,6.3 13,1.4 25,1.4 30,6.3 36,10.0 37,11.0
N         0.060 0.040
ND        5. 6.
```

Figure 8. Typical sequence of records used to describe the approach section.

WSPRO record.

Format:

Column	Format	Contents
1	A1	N
2-10	9X	blank
11-80	free	either *NVAL(1) [,NVAL(2)... NVAL(nsa)]* or *BOTN(1), TOPN(1) [,BOTN(2), TOPN(2)...BOTN(nsa), TOPN(nsa)]*

Definition of variables:

The parenthetical notation indicates the subarea to which the roughness coefficient is applicable. For the leftmost subarea, *i*=1, and for the rightmost subarea, *i*=nsa (number of subareas). The first coding option must be used when the value does not vary with depth. Only one roughness coefficient value is needed for each subarea.

NVAL(i) Roughness coefficient (Manning's coefficient of roughness, n) applicable to the full depth of the *i*th subarea.

The second coding option is used when the values vary with depth. ND records specifying the depths must be coded when this option is used. A pair of roughness coefficients is coded for each subarea.

BOTN(i) Roughness coefficient applicable to the depths equal to and less than the bottom hydraulic depth specified for the ith subarea on the ND record.

TOPN(i) Roughness coefficient applicable to the depth equal to and greater than the bottom hydraulic depth specified for the ith subarea on the ND record.

ND - approach section roughness depths record

Purpose: Specifies the hydraulic depth breakpoints for vertical variation of roughness coefficients (Manning's coefficient of roughness, n) in the appropriate system of units, either feet or meters. This is a WSPRO record.

Format:

Column	Format	Contents
1-2	A2	ND
3-10	8X	blank
11-80	free	*BOTD(1), TOPD(1) [,BOTD(2), TOPD(2)... BOTD(nsa), TOPD(nsa)]*

Definition of variables:

The parenthetical notation indicates the subarea to which the depths are applicable: *i*=1 for the leftmost subarea and *i*=nsa for the rightmost subarea (nsa≤20).

BOTD(i) Hydraulic depth (area divided by top width) in the *i*th subarea at or below which the roughness coefficient BOTN (*i*) (specified for the *i*th subarea in the N record) is applicable.

TOPD(i) Hydraulic depth in the *i*th subarea at or above which the roughness coefficient of TOPN(i) (specified for the *i*th subarea in the N record) is applicable.

Values of roughness for the depths between *BOTD* and *TOPD* are determined by straight-line interpolation.

*PD - hydraulic properties range record

Purpose: Specifies the computation of depths over a range of values for which the hydraulic properties are computed at 25 depths. This record is included with the approach sections records and is used for all sections in that file. Only one *PD record is permitted per file.

Format:

Column	Format	Contents
1-3	A3	*PD
4-10	7X	blank
11-80	free	*DMIN*, *DMAX*, *RATIO*

Definition of variables:

DMIN minimum depth at which to compute approach section hydraulic properties in the appropriate system of units, either feet or meters. Must be 0 when running CAP.

DMAX maximum depth at which to compute hydraulic properties in the same units as *DMIN*. The depth entered should be greater than or equal to 2 times the culvert height. If it is less than 1.5 times the culvert height, the program will fail to execute. Depending on the tailwater elevations entered on the *CX record and the minimum ground elevation in the approach section, it may be necessary to input a DMAX greater than 2 times the culvert depth.

RATIO the common ratio used to compute depths as a geometric progression between minimum and maximum areas. Ratio must be greater than 0. If a value less than or equal to zero or no value is entered, the program defaults to a ratio of 1. A ratio value of 1 computes equally spaced areas. Ratios less than 1 result in the intervals between depths decreasing as depth increases. Ratios greater than 1 result in the intervals between depths increasing as depth increases.

SA - approach section subdivision record

Purpose: Specifies the horizontal breakpoints for subdivision of cross section for roughness variation. This record is only necessary for subdivided approach sections. This is a WSPRO record.

Format:

Column	Format	Contents
1-2	A2	SA
3-10	8X	blank
11-80	free	*XSA(1), XSA(2) ... XSA(nsa-1)*

Definition of variables:

The parenthetical notation indicates the subarea number, *i*, assigned by the program to each subarea of a cross section. *i*=1 for the leftmost subarea and *i*=nsa for the rightmost subarea (nsa≤20). The number of breakpoints entered is always one less than the total number of subareas in the cross section and are located at the boundaries between subareas.

XSA(i) The horizontal coordinate, or station of the rightmost limit of the *i*th subarea in the appropriate system of units, either feet or meters.

XS - approach section location record

Purpose: Required; header record for unconstricted approach cross section. This is a WSPRO record.

Format:

Column	Format	Contents
1-2	A2	XS
3-5	3X	blank
6-10	A5	*SECID*
11-80	free	$SRD_{approach}$, *SKEW*

Definition of variables:

SECID Unique cross-section identification code.

$SRD_{approach}$ Section reference distance in the appropriate system of units, either feet or meters. Cumulative distance along the stream measured from the common reference station (figure 5). The difference between the SRD values of culvert outlet and the approach is the flow distance between those sections (figure 5).

SKEW The acute angle, in degrees, that the section must be rotated to orient the section normal to the flow direction. The cosine of SKEW is applied to the horizontal dimension of the section before the computation of cross-section properties. Default is zero degrees.

Output Files

Two outputs are available from CAP. A detailed report that summarizes the culvert computations is always produced. An additional table of the discharges, tailwaters, and upstream water-surface elevations computed is produced optionally for use with other computer programs.

Detailed Report

The detailed report can be used to determine discharge for an indirect measurement or a rating for a culvert. It includes input data for the selected approach and culvert section (always listed on page 0); computed hydraulic properties for the culvert section and the approach section; and a summary of the culvert computations. The hydraulic properties for the approach section include an estimated critical discharge that is computed from $A\sqrt{gD}$ (D, the hydraulic depth; A, area; g, acceleration of gravity). The summary of the culvert computations lists for each combination of discharge and tailwater elevation the discharge, flow type, and water-surface elevations at the approach, culvert inlet, culvert outlet, and exit sections. It also lists the discharge coefficient, the velocity head, velocity coefficient (α), and Froude number computed for the approach section, the specific energy and Froude number computed for the control section, and the fall and losses computed between various sections. The discharge coefficients listed includes the effect of the adjustment for channel contraction effects and all adjustments entered on the *C3 record unless a *C1 record is used.

Two falls, entry and effective, are listed on the detailed report. The entry fall is the difference in water-surface elevation between the approach section and the downstream section that governs the flow state. The effective fall for flow types 1, 2, 3, and 4 is the energy loss between the approach section and the downstream section that governs the flow state. For type 5 flow, the effective fall is the difference between the approach water-surface elevation and the invert elevation of the culvert outlet. For type 6 flow, the effective fall is the velocity head in the culvert barrel. Fall computations are listed in table 2. The losses, entry, (1-2), and (2-3), listed on the detailed report are the entrance losses, friction loss in the reach between the approach section and culvert inlet ($h_{f_{1-2}}$), and the friction losses in the culvert barrel ($h_{f_{2-3}}$), respectively.

Table 2. Detailed report fall computations [h_i, water-surface elevation; h_{v_i}, velocity head; $h_{f_{i-(i+1)}}$, friction loss, where *i* is an integer indicating the location in the culvert reach; h_e, entrance loss; *z*, culvert drop

Flow Type	Entry Fall	Effective Fall
1	$h_1 - h_2$	$(h_1 + h_{v_1}) - (h_2 + h_{f_{1-2}})$
2	$h_1 - h_3$	$(h_1 + h_{v_1}) - (h_3 + h_{f_{1-2}} - h_{f_{2-3}})$
3	$h_1 - h_4$	$(h_1 + h_{v_1}) - (h_4 + h_{f_{1-2}} + h_{f_{2-3}})$
4	$h_1 - h_4$	$(h_1 + h_{v_1}) - (h_4 + h_{f_{1-2}} + h_{f_{2-3}})$
5	$h_1 - h_4$	$h_1 - z$
6	$h_1 - h_4$	h_{v_2}

A sample detailed report of culvert computations is shown in figure 9. The flow type is usually a single integer 1, 2, 3, 4, 5, or 6. However, in cases where the upstream water-surface elevation is linearly interpolated from two flow types, the entry has two digits representing the flow types from which the water-surface elevation is interpolated. When critical depth exceeds the culvert height, type 1 flow is always used for the low head value because type 2 flow is not possible in all culverts. In these cases, the low head flow type is designated by a zero to distinguish it from the other low head flow cases. The first digit represents the flow type in the upstream end of the culvert and the second digit the flow type in the downstream end of the culvert.

If an approach elevation cannot be computed for a combination of discharge and tailwater

```
CAP -USGS culvert analysis program VER 97-08                              page  4

TEST CULVERT 1 WALNUT CRK
                     CULVERT                                   APPROACH SECTION
 I.D. CUL1             n= .015  Height      4.50ft      I.D. AXS1
 Station      200.0 ft          Length     65.0 ft      Station       287.7 ft
 Inlet el.       .78ft       Outlet el.      .43ft      Minimum el.      .50ft

         Discharge  Flow     Water Surface Elevations (feet) Critical  Error
   no.     (cfs)    type     appr.   inlet   outlet   exit     Dc       code@
    1        15.00   3        2.825   2.818   2.820   2.820    1.097    0
    2        25.00   3        2.837   2.812   2.820   2.820    1.427    0
    3        30.00   3        2.852   2.807   2.820   2.820    1.568    0
    4        40.00   3        2.947   2.786   2.820   2.820    1.821    0
    5        80.00   1        4.271   3.396********   2.820    2.616    0
    6        90.00   2        4.576   3.626   3.212   2.820    2.782    0
    7       100.00   2        4.903   3.852   3.368   2.820    2.938    0

             Fall (ft)     Losses (ft)       Appr. Section  Control Section
  no.   C   entry  eff.  entry(1-2) (2-3)    VH  alph   F    energy    F
   1    .98   .00   .05   .00   .02   .02    .09 1.00   .36     2.87   .22
   2    .98   .02   .14   .01   .07   .06    .25 1.00   .59     2.95   .37
   3    .98   .03   .20   .01   .09   .09    .35 1.00   .70     3.01   .45
   4    .98   .13   .35   .01   .16   .16    .54 1.00   .87     3.16   .59
   5    .95   .87  1.21   .13   .16 *****    .49 1.00   .67     4.48  1.00
   6    .94  1.36  1.34   .16   .15   .35    .48 1.00   .63     4.39  1.00
   7    .93  1.54  1.48   .20   .15   .36    .45 1.00   .59     4.65  1.00
______________________________________________________________________________
Abrevs. used: appr.-approach  C-discharge coefficient  eff.-effective
VH-velocity head  alph-velocity coefficient  n-Manning's roughness coef.
energy-specific energy  F-Froude number  entry,(1-2),(2-3)-part of reach

      @Error codes:  -1,1-7 fatal error; 8-11 warning; 0 no error

          ---------Warning Messages-------------
```

Figure 9. Sample of a detailed report of culvert computations.

elevation, a -1.00 is printed in the column for the approach elevation. An error number is printed in the error code column and the error message is printed in the section where the Fall and Losses are normally printed for that computation. Warning messages are printed at the end of the detailed report. Additional input error messages and warnings are printed with the input data section of the report.

Three-Parameter Table

The three-parameter table report can be used as input to another flow modeling program or graphics program. It provides less information than the detailed report; the discharge, tailwater elevation, water-surface elevation at the approach, a datum elevation, and a culvert identification string.

The table is formatted to facilitate its use by computer programs that can interpolate the tabulated values, draw a rating surface for the culvert, or that need to include the culvert effects in a flow model. The format used by the table is listed in table 3. A sample table report is shown in figure 10. Elevations printed in the table are referenced to the culvert outlet invert, the reference datum for the table. If an approach elevation cannot be computed for a given combination of discharge and tailwater elevation, a -1.00 is printed in the table for the approach water-surface elevation.

The table is generated by responding appropriately to a prompt. The eight digit table number is entered by the user during program execution and allows the use of an eight digit station number as the table number. If *CF records are used with *TFLW*=65 or no *CF record is entered, the three parameter table will not be produced. The table report is always printed to a file named TABLES30.DAT and users should rename or delete the file prior to creating new table reports.

Table 3. Fortran formats used by CAP to generate output for the three-parameter table report

Record Number	Fortran Format	Content Description
1	A12	Table file identifier, always TABLES30.DAT
2	A3	Start of table for culvert flag, always TAB
3	I8,I2,2I3	Eight-digit table number, two-digit number for table type, number of tailwater depths, number of discharges
4	F9.3	Reference datum for table
4-k	12F7.2	Tailwater depths
k-m	10F8.0	Discharges
m-n	11F7.2	Computed upstream water-surface elevations for a discharge for each tailwater

```
TABLES30.DAT
TAB
       130 10 10
0.000
     .0    .54    .94   1.44   1.94   2.44   2.94   3.44   3.94   5.40
     20.   40.    60.   80.    100.   125.   150.    180.    210.    250.
   2.80   2.80   2.80   2.81   3.16   3.60   4.07   4.55   5.04   6.50
   3.61   3.61   3.61   3.61   3.61   3.86   4.25   4.68   5.15   6.62
   4.29   4.29   4.29   4.29   4.29   4.31   4.53   4.89   5.31   6.82
   4.90   4.90   4.90   4.90   4.90   4.90   4.95   5.17   5.52   7.10
   5.47   5.47   5.47   5.47   5.47   5.47   5.46   5.55   5.80   7.46
   6.14   6.14   6.14   6.14   6.14   6.14   6.14   6.13   6.25   8.02
   7.49   7.49   7.49   7.49   7.49   7.49   7.49   7.49   7.49   8.71
   8.84   8.84   8.84   8.84   8.84   8.84   8.84   8.84   8.84   9.70
  10.45  10.45  10.45  10.45  10.45  10.45  10.45  10.45  10.45  10.87
  12.90  12.90  12.90  12.90  12.90  12.90  12.90  12.90  12.90  12.71
```

Figure 10. Sample three-parameter table report.

Executing the Program

The commands required to run the program are dependent on the computer system. On most systems, however, entering the program name, CAP, will start the program. The user is then queried for the output file name, a header title, the culvert data file name, and culvert section id (SECID), and the approach section file name and approach section id (SECID). The header title allows users to enter descriptive text of up to 80 characters that is printed on all output pages except for page 0. Depending on the computer operating system, the input file names may be case sensitive. Section id (SECID) is always case sensitive. Several culvert sections and approach sections may be included in the file or files. Figure 11 is an example of a typical session running the program.

CAP-USGS culvert analysis program VER 97-08
Specify program output, 1-detailed report; 2-table
`1`
ENTER OUTPUT FILE NAME
`REPORT.CUL`

ENTER HEADER TITLE FOR OUTPUT FILE
`Test Data for Culvert, 10-11-1994`

Input file name containing culvert geometry
`TSTDATA.EX3`
file requested is TSTDATA.EX3

Enter culvert section id
`EX01`

Input file name containing approach section geometry
`TSTAPPR.EX3`
file requested is TSTAPPR.EX3

Enter approach section id
`AP01`
EXIT CAP? (enter YES or NO)
`Y`

Figure 11. Sample CAP session. *[Screen prompts and messages issued by the program are shown in bold type. Other text is entered by user.]*

EXAMPLES

This section contains five examples that demonstrate how to use CAP. The examples are separated into three subsections, indirect measurement of peak discharge from field data for a specific flow event, computation of a three-parameter table, and an example using new records.

Indirect Measurement of Peak Discharge

Three example problems are presented in this section. The first example is a simple rectangular (box) culvert and demonstrates the basic operation of CAP. The second example is a nonstandard culvert section, and the third is a multiple culvert example.

Standard Culvert Section

Standard culvert sections are either rectangular, circular, or pipe arch in shape. These culverts are not silted up and the effective shape of the culvert section is unchanged throughout the culvert length. Discharge coefficients have been determined for standard culvert sections by laboratory investigations.

Location: Tributary to Mercer Creek near Bellevue, Washington.

Culvert section description: 30-inch-diameter pipe of smooth concrete with a bell-mouth inlet. Culvert length is 41 feet. Manning's coefficient of roughness, n, is estimated at 0.015. Elevation of downstream invert is 6.05 feet and upstream invert 6.28 feet. Top of culvert inlet is 8.78 feet and top of culvert outlet is 8.55 feet. Culvert bevel width is 2.4 inches.

Approach section description: Approach located 6.4 feet from upstream invert of culvert. Manning's coefficient of roughness, n, is estimated at 0.025. Coordinates of approach section are plotted in figure 12.

High-water marks: High-water mark elevations are 8.65 feet in the approach and 8.14 feet downstream of culvert outlet.

In this example, both the culvert section and approach section are in the same file. Appropriate discharge coefficients for types 4 and 6 flows are entered explicitly by using a *C5 record. If this record was omitted, default values would be computed. Initially, discharges from 10 to 50 cubic feet

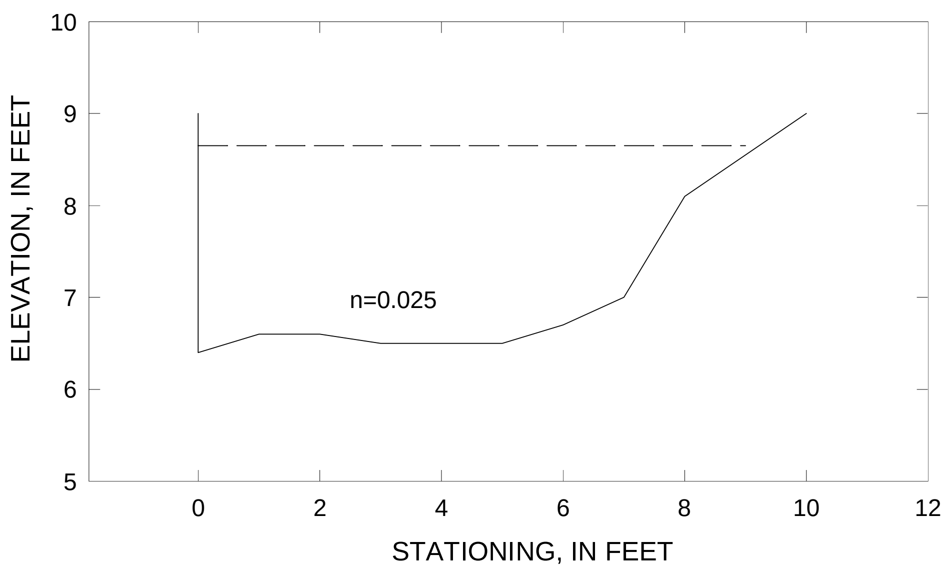

Figure 12. Approach section for culvert in tributary to Mercer Creek near Bellevue, Washington. *[n, Manning's roughness coefficient]*

per second were entered with the measured tailwater elevation (8.14 ft). After running CAP, new discharges were entered over a smaller range and incremented to get the desired upstream water-surface elevation. The input file for this example follows.

```
*    Tributary to Mercer Creek Culvert
CV   EX01 10.,0.,41.,6.05,6.28,1
CG        213,30.
*C3       1,1,0,3,1
*C5       0.96, 0.50,1.4, 0.55,1.6, 0.58,1.8, 0.61,2.0
*CF       6
*CX       8.14
*CQ       20., 21.5, 22.5, 25.
*CN       0.015
*PD       0.   20.0 1.0
XS   AP01 57.4
GR        0.,9.0 0.,6.4 1.,6.6 2.,6.6 3.,6. 5.,6.5 6.,6. 7.,7
GR        8.,8.1 10.,9.
N         0.025
```

The output from this input file is in figure 13. Note that the upstream water-surface elevation is bracketed by discharges of 20 and 21.5 cubic feet per second. This example is based on a culvert verification done in the 1950's by USGS personnel. The measured discharge (by current meter) was 21.5 cubic feet per second. Linear interpolation from the output gives the discharge as 20.86 cubic feet per second, a difference of about three percent. Alternatively, discharge could have been bracketed during the first execution of the program by using smaller increments over the same range of discharge. This technique may not be successful for all culverts.

```
CAP -USGS culvert analysis program VER 97-08                     page  0

CV   EX01 10.,0.,41.,6.05,6.28,1
CG        213,30.
*C3       1,1,0,3,1
*C5       0.96, 0.50,1.4, 0.55,1.6, 0.58,1.8, 0.61,2.0
*CF       6
*CX       8.14
*CQ       20., 21.5, 22.5, 25.
*CN       0.015
*PD       0.   20.0 1.0
     *C3 record ignored except inlet code - WARNING
XS   AP01 57.4
GR        0.,9. 0.,6.4 1.,6.6 2.,6.6 3.,6.5 5.,6.5 6.,6.7 7.,7
GR        8.,8.1 10.,9.
N         0.025
```

Figure 13. CAP output for Mercer Creek example.

```
CAP -USGS culvert analysis program VER 97-08                        page 1

Mercer Creek Culvert example, 02-19-1998
               CULVERT SECTION PROPERTIES - ID: EX01
                          Culvert section type: circular/pipe
                     (r or w)/D  KR or KW  Ktheta  Kproj    n      Inlet
                         0.00      1.00   1.00   1.00   0.015       3

                    <<User supplied discharge coefficients>>
                      CB12 =  .00          C46 =  .96
                      For type123 flow     For type 5 flow
                         C    (h1-z)/D        C    (h1-z)/D
                        .00      .00         .50     1.40
                        .00      .00         .55     1.60
                        .00      .00         .58     1.80
                        .00      .00         .61     2.00

         Barrel                                  Top        Wetted
         depth        Area        Conveyance     width      perimeter
           (ft)       (sq.ft)        (cfs)         (ft)        (ft)
           .00          .0             .0         .00           .0
           .08          .1             .7         .90           .9
           .17          .1            3.2        1.25          1.3
           .25          .3            7.4        1.50          1.6
           .33          .4           13.6        1.70          1.9
           .42          .5           21.5        1.86          2.1
           .50          .7           31.2        2.00          2.3
           .58          .9           42.6        2.11          2.5
           .67         1.1           55.5        2.21          2.7
           .75         1.2           69.8        2.29          2.9
           .83         1.4           85.4        2.36          3.1
           .92         1.6          102.3        2.41          3.3
          1.00         1.8          120.1        2.45          3.4
          1.08         2.0          138.8        2.48          3.6
          1.17         2.2          158.3        2.49          3.8
          1.25         2.5          178.2        2.50          3.9
          1.33         2.7          198.5        2.49          4.1
          1.42         2.9          219.0        2.48          4.3
          1.50         3.1          239.5        2.45          4.4
          1.58         3.3          259.7        2.41          4.6
          1.67         3.5          279.4        2.36          4.8
          1.75         3.7          298.4        2.29          5.0
          1.83         3.9          316.5        2.21          5.1
          1.92         4.0          333.2        2.11          5.3
          2.00         4.2          348.4        2.00          5.5
          2.08         4.4          361.6        1.86          5.8
          2.17         4.5          372.3        1.70          6.0
          2.25         4.7          379.9        1.50          6.2
          2.33         4.8          383.4        1.25          6.5
          2.42         4.9          380.7         .90          6.9
          2.50         4.9          356.4         .00          7.9
```

Figure 13. CAP output for Mercer Creek example-continued. *[ft, feet; sq.ft, square feet; cfs, cubic feet per second]*

CAP -USGS culvert analysis program VER 97-08 page 2

Mercer Creek Culvert example, 02-19-1998

APPROACH SECTION PROPERTIES - ID: AP01

Water Surface el.(ft)*	Area (sq.ft)	Conveyance (cfs)	Top width (ft)	Alpha	Critical discharge (cfs)
6.40	.0	.0	.0	1.00	.0
7.23	4.6	183.1	7.2	1.00	20.6
8.07	10.9	677.5	8.0	1.00	72.2
8.90	18.3	1363.4	9.8	1.00	141.6
9.73	26.6	2337.4	10.0	1.00	245.9
10.57	34.9	3429.9	10.0	1.00	370.2
11.40	43.2	4595.6	10.0	1.00	510.4
12.23	51.6	5814.0	10.0	1.00	664.8
13.07	59.9	7071.5	10.0	1.00	832.2
13.90	68.2	8359.0	10.0	1.00	1011.8
14.73	76.6	9670.0	10.0	1.00	1202.6
15.57	84.9	10999.8	10.0	1.00	1404.2
16.40	93.2	12344.9	10.0	1.00	1615.8
17.23	101.6	13702.5	10.0	1.00	1837.2
18.07	109.9	15070.5	10.0	1.00	2067.9
18.90	118.2	16447.4	10.0	1.00	2307.4
19.73	126.6	17831.8	10.0	1.00	2555.6
20.57	134.9	19222.6	10.0	1.00	2812.1
21.40	143.3	20619.0	10.0	1.00	3076.6
22.23	151.6	22020.2	10.0	1.00	3348.9
23.07	159.9	23425.7	10.0	1.00	3628.8
23.90	168.3	24834.8	10.0	1.00	3916.2
24.73	176.6	26247.3	10.0	1.00	4210.7
25.57	184.9	27662.6	10.0	1.00	4512.2
26.40	193.2	29080.6	10.0	1.00	4820.7

*elevation referenced to common vertical datum

Figure 13. CAP output for Mercer Creek example-continued. *[ft, feet; sq.ft, square feet; cfs, cubic feet per second]*

```
CAP -USGS culvert analysis program VER 97-08                          page  3

Mercer Creek Culvert example, 02-19-1998
                     CULVERT                                     APPROACH SECTION
 I.D. EX01                  Mannings n      .015        I.D. AP01
 Height        2.50 ft           Width       2.5ft      Station        57.4 ft
 Station       10.0 ft          Length     41.0 ft      Minimum el.     6.40ft
 Inlet el.      6.28ft       Outlet el.     6.05ft

         Discharge  Flow     Water Surface Elevations (feet) Critical  Error
   no.     (cfs)    type     appr.   inlet   outlet   exit     Dc       code@
    1        20.0   3         8.61    8.23    8.14    8.14      1.5    0
    2        21.5   3         8.68    8.25    8.14    8.14      1.6    0
    3        22.5   3         8.74    8.26    8.14    8.14      1.6    0
    4        25.0   3         8.88    8.31    8.14    8.14      1.7    0

             Fall (ft)     Losses (ft)        Appr. Section  Control Section
  no.   C   entry  eff.  entry(1-2) (2-3)    VH  alph   F    energy    F
   1    .95   .47   .36   .03   .01   .13    .03 1.00   .17     8.46   .52
   2    .95   .54   .41   .04   .01   .15    .03 1.00   .18     8.51   .56
   3    .95   .60   .45   .04   .01   .17    .03 1.00   .18     8.55   .59
   4    .95   .74   .56   .05   .01   .20    .03 1.00   .18     8.65   .65
______________________________________________________________________________

Abrevs. used: appr.-approach  C-discharge coefficient  eff.-effective
VH-velocity head  alph-velocity coefficient  n-Manning's roughness coef.
energy-specific energy  F-Froude number  entry,(1-2),(2-3)-part of reach

      @Error codes:  -1,1-7 fatal error; 8-14 warning; 0 no error


          ---------Warning Messages-------------
```

Figure 13. CAP output for Mercer Creek example-continued. *[ft, feet; cfs, cubic feet per second]*

Nonstandard Culvert Section

Nonstandard culvert sections are sometimes encountered. These culverts may have been built from nonstandard sections (not pipe, rectangular, or pipe arch), or they may be standard sections that have silted up to a uniform depth. These culverts do not have standard tables of discharge coefficients measured for them, so judgment must be used to determine the discharge coefficients.

Location: Pigeon House Creek at Cameron Village at Raleigh, North Carolina.

Culvert section description: 10-foot-diameter corrugated metal pipe cut in half and atop a rectangular section 9.25 foot by 1.0 foot. The culvert length is 53 feet. Manning's coefficient of roughness, n, is estimated as 0.015 and 0.034 for the rectangular and pipe parts of the culvert section, respectively. The inlet has a flat vertical face. The minimum elevation of the upstream invert is 0.55 foot, and the minimum elevation of the downstream invert is 0.22 foot. The discharge coefficient for types 1, 2, and 3 flows is estimated to be 0.95. The culvert section is illustrated in figure 14. The ratio r/D is 0.02.

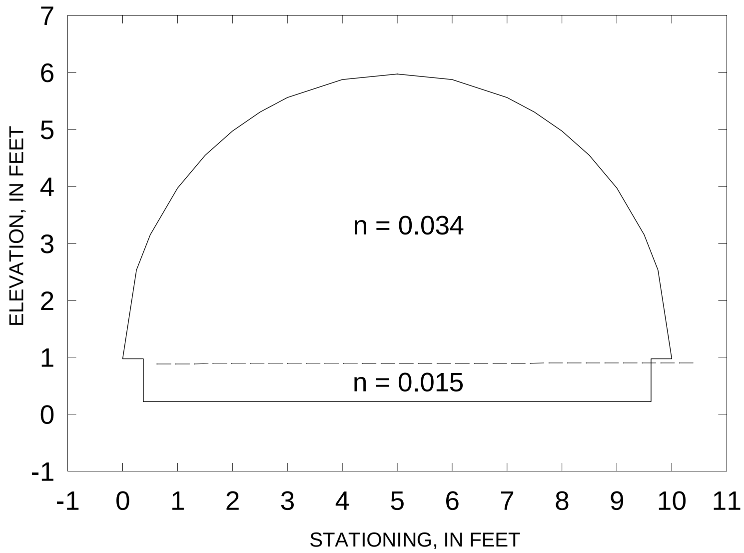

Figure 14. Cross-section of Pigeon House Creek culvert. *[n, Manning's roughness coefficient]*

Approach section description: The approach is located 15.8 feet from the inlet of the culvert. Manning's coefficient of roughness, n, varies from 0.04 to 0.03 by the flow depth and subarea. The approach section is illustrated in figure 15.

High-water marks: The tailwater elevation does not affect the discharge (type 3 not possible). The approach section high water mark is 1.50 feet.

Because the culvert is not affected by the downstream water elevation, the tailwater depth used is small enough to ensure either type 1 or type 2 flow. The culvert-section coordinates are input carefully in counterclockwise order, and the first and last coordinate pairs are the same, closing the figure. The CG - culvert geometry record is not included and would have caused a fatal error in the program had it been entered. Because this is a nonstandard culvert section, discharge coefficients are estimated and entered on the *C1 - C_{123} culvert discharge coefficient record. Estimated discharge coefficients can be computed from direct discharge measurements. However, the coefficients in this example were estimated from values given in Bodhaine (1968). Below 1.0 ft depth in the box shaped portion of the culvert section a discharge coefficient of 0.95 is used. Above 1.0 ft depth of flow, the coefficient is computed as a depth-weighted average of the box section coefficient with the appropriate pipe section coefficient. The pipe discharge coefficients used are for flow depths that fill the pipe section half full and greater. These coefficients better account for the effects of the top shape of the pipe on the flow. Type 5 flow coefficients (C_5) are from Bodhaine (table 6, p. 44). Roughness values for various culvert materials can be found in engineering texts such as Chow (1959, pg. 110).

Culvert roughness varies with flow depth. The roughness value used in the input file for the culvert is estimated for a flow depth of 1.5 ft by weighing each n value by its respective wetted perimeter at a flow depth of 1.5 ft so that,

$$n' = \frac{P_u}{P}n_u + \frac{P_l}{P}n_l \tag{17}$$

where *P* is the wetted perimeter, *n'* is the weighted roughness, *n* is the roughness and the subscripts *u* and *l* denote values for the upper and lower portions of the culvert.

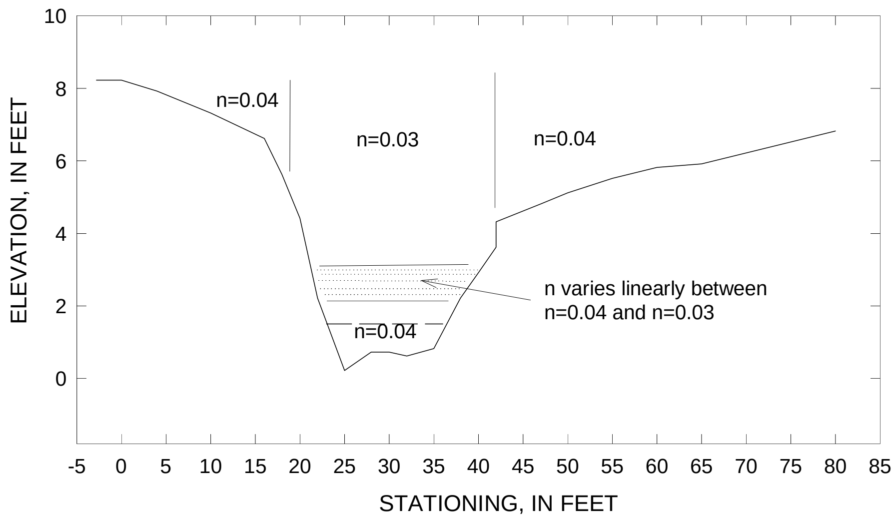

Figure 15. Approach section for Pigeon House Creek culvert. *[n, Manning's roughness coefficient]*

As in the Mercer Creek example, both the approach-section and culvert-section data are entered in the same file. A broad range of discharges is run first and then the discharges are changed until the upstream head agrees with the measured high-water mark. The input file follows:

```
*     Pigeon House Creek culvert and approach section
CV    PCUL 200.,0.,53.,0.22,0.55,1
*C1        0.95,0.16  0.938,0.333  0.892,1.0  0.873,1.2
*C3        1.04,1,0,1
*C5        0.88, 0.46,1.4  0.51,1.6  0.54,1.8  0.56,2.0
*CF        6
*CS        5.,5.97 4.0,5.86898 3.0,5.55257 2.5,5.3001 2.,4.97
*CS        1.5,4.5407 1.,3.97 0.5,3.149 0.25,2.5312 0.,0.97 0.375,0.97
*CS        0.375,0.22 9.625,0.22 9.625,0.97 10.,0.97 9.75,2.5312
*CS        9.5,3.149 9.,3.97 8.5,4.542 8.,4.97 7.5.3001 7.,5.55257
*CS        6.,5.86898 5.,5.97
*CX        .62
*CQ        20., 25.7, 27.9, 30.
*CN        0.017
*PD        0.   20.0 1.0
XS    PCRK 268.8
GR         -2,8.22 0.,8.22 4,7.92 10,7.32 16,6.62 18,5.62
GR         20,4.42 22,2.22 25,0.22 28,0.72 30,0.72 32,0.62
GR         35.,0.82 38.,2.22 40.,2.92 42.,3.62 42.,4.32 47.,4.82
GR         50.,5.12 55.,5.52 60.,5.82 65.,5.92 70,6.22 75,6.52 80.,6.82
N          0.040,0.040  0.040,0.030 0.040,0.040
ND         2,2  2,3  2,2
SA         18.0  42.0
```

The output from this input file, except for page 0, is shown in figure 16. Page 0 echoes the input data listed previously. Note that the upstream water-surface elevation is bracketed by discharges of 20.00 and 25.7 cubic feet per second. Linear interpolation from the output gives the discharge as 25.26 cubic feet per second. If the computed approach water-surface elevation had been significantly different from the estimated 1.5ft the Manning's coefficient of roughness, n, would be recomputed for that flow depth and the program run with the new n value to verify the computed water-surface elevation.

```
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Pigeon Creek Culvert example, 02-19-1998
               CULVERT SECTION PROPERTIES - ID: PCUL

                          Culvert section type: nonstandard
                     (r or w)/D  KR or KW  Ktheta  Kproj    n      Inlet
                         0.00      1.04   1.00   1.00   0.017       1


                    <<User supplied discharge coefficients>>
                      CB12 =  .95          C46 =  .88
                      For type123 flow     For type 5 flow
                         C    (h1-z)/D        C    (h1-z)/D
                        .95      .16         .46     1.40
                        .94      .33         .51     1.60
                        .89      .80         .54     1.80
                        .87     1.20         .56     2.00

         Barrel                                     Top        Wetted
         depth         Area        Conveyance      width      perimeter
           (ft)       (sq.ft)         (cfs)          (ft)         (ft)
           .00           .0             .0          .00           .0
           .19          1.8           50.3         9.25          9.6
           .38          3.5          155.5         9.25         10.0
           .58          5.3          298.1         9.25         10.4
           .77          7.1          450.8         9.99         11.5
           .96          9.0          655.7         9.93         11.9
          1.15         10.9          882.5         9.87         12.3
          1.34         12.8         1127.6         9.81         12.7
          1.53         14.7         1387.9         9.75         13.1
          1.73         16.5         1661.1         9.69         13.5
          1.92         18.4         1945.3         9.63         13.9
          2.11         20.2         2238.7         9.56         14.3
          2.30         22.1         2540.0         9.50         14.6
          2.49         23.9         2843.2         9.35         15.1
          2.68         25.6         3147.7         9.20         15.5
          2.88         27.4         3452.2         9.04         15.9
          3.07         29.1         3751.1         8.83         16.3
          3.26         30.8         4043.0         8.60         16.8
          3.45         32.4         4328.3         8.37         17.2
          3.64         34.0         4606.3         8.13         17.7
          3.83         35.5         4871.2         7.85         18.1
          4.03         37.0         5117.3         7.52         18.6
          4.22         38.4         5349.3         7.18         19.2
          4.41         39.7         5559.6         6.80         19.7
          4.60         41.0         5742.6         6.35         20.3
          4.79         42.2         5901.1         5.87         20.9
          4.98         43.2         6020.0         5.29         21.6
          5.18         44.2         6098.6         4.62         22.4
          5.37         45.0         6119.0         3.78         23.3
          5.56         45.6         6040.0         2.57         24.6
          5.75         45.9         5710.4          .00         27.2
```

Figure 16. CAP output for Pigeon House Creek example of a non-standard culvert section. *[ft, feet; sq.ft, square feet; cfs, cubic feet per second]*

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Pigeon Creek Culvert example, 02-19-1998

APPROACH SECTION PROPERTIES - ID: PCRK

Water Surface el.(ft)*	Area (sq.ft)	Conveyance (cfs)	Top width (ft)	Alpha	Critical discharge (cfs)
.22	.0	.0	.0	1.00	.0
1.05	4.8	95.3	11.8	1.00	17.2
1.89	15.8	595.3	14.8	1.00	92.8
2.72	29.4	1458.9	17.9	1.00	214.1
3.55	45.6	2819.3	21.0	1.00	381.5
4.39	63.6	5717.0	22.6	1.00	605.5
5.22	86.5	8835.3	32.6	1.07	800.4
6.05	119.9	12798.2	50.1	1.22	1052.0
6.89	168.3	18400.0	66.3	1.39	1521.4
7.72	226.6	25946.9	74.0	1.45	2250.1
8.55	292.3	35170.3	82.0	1.47	3132.1
9.39	360.7	46137.7	82.0	1.45	4292.2
10.22	429.0	58463.6	82.0	1.42	5568.1
11.05	497.3	71994.8	82.0	1.39	6950.1
11.89	565.7	86616.7	82.0	1.37	8430.7
12.72	634.0	102238.4	82.0	1.35	10003.6
13.55	702.3	118785.5	82.0	1.34	11663.7
14.39	770.7	136195.0	82.0	1.33	13406.7
15.22	839.0	154413.4	82.0	1.32	15228.7
16.05	907.3	173393.9	82.0	1.32	17126.6
16.89	975.7	193095.8	82.0	1.32	19097.3
17.72	1044.0	213482.8	82.0	1.32	21138.4
18.55	1112.3	234522.9	82.0	1.32	23247.3
19.39	1180.7	256187.1	82.0	1.33	25422.1
20.22	1249.0	278449.2	82.0	1.33	27660.8

*elevation referenced to common vertical datum

Figure 16. CAP output for Pigeon House Creek example of a non-standard culvert section- continued. *[ft, feet; sq.ft, square feet; cfs, cubic feet per second]*

```
CAP -USGS culvert analysis program VER 97-08                         page  3

Pigeon Creek Culvert example, 02-19-1998
                     CULVERT                                  APPROACH SECTION
 I.D. PCUL                  Mannings n      .017        I.D. PCRK
 Height        5.75 ft          Width      10.0ft       Station       268.8 ft
 Station      200.0 ft         Length     53.0 ft       Minimum el.      .22ft
 Inlet el.       .55ft       Outlet el.      .22ft

        Discharge  Flow     Water Surface Elevations (feet) Critical  Error
   no.     (cfs)    type     appr.   inlet   outlet   exit     Dc       code@
    1        20.0   1         1.38    1.08********     .62       .5    0
    2        25.7   1         1.51    1.18********     .62       .6    0
    3        27.9   1         1.56    1.21********     .62       .7    0
    4        30.0   1         1.60    1.25********     .62       .7    0

            Fall (ft)     Losses (ft)       Appr. Section  Control Section
  no.   C   entry  eff.  entry(1-2) (2-3)    VH  alph   F    energy    F
   1    .96   .30   .28   .02   .10 *****    .08 1.00   .49     1.34  1.00
   2    .96   .33   .33   .02   .10 *****    .09 1.00   .49     1.48  1.00
   3    .96   .34   .35   .03   .10 *****    .10 1.00   .49     1.53  1.00
   4    .96   .35   .36   .03   .09 *****    .10 1.00   .49     1.58  1.00
______________________________________________________________________________

Abrevs. used: appr.-approach  C-discharge coefficient  eff.-effective
VH-velocity head  alph-velocity coefficient  n-Manning's roughness coef.
energy-specific energy  F-Froude number  entry,(1-2),(2-3)-part of reach

      @Error codes:  -1,1-7 fatal error; 8-14 warning; 0 no error


          ---------Warning Messages-------------
```

Figure 16. CAP output for Pigeon House Creek example of a non-standard culvert section- continued. *[ft, feet; cfs, cubic feet per second]*

Multiple Culvert Openings

Computations can be made for two or more culverts that share a common approach cross section. The culverts may be of different or similar geometry but must be located far enough apart so that the space between them cannot be considered as a web. However, except for ponded conditions in the approach, the energy and continuity equations are insufficient for the number of unknowns that occur for a multiple-opening reach. An additional equation is required for nonponded approach conditions.

Typically, the additional equation is for apportioning the approach section. Each culvert is then treated separately by dividing the approach section between the culverts and assigning the appropriate portion of the approach section to each culvert. If the velocity is near zero (ponded conditions) in the approach section, the approach section should not be subdivided.

Several techniques can be used to apportion the approach section. These techniques are somewhat arbitrary and each technique yields somewhat different results. The technique demonstrated requires the user to manually apportion the approach section. The technique assumes that the approach section can be divided rationally into strips corresponding to each culvert by proportioning the discharge through the culverts and the approach section. Each appropriate portion of the divided approach section is used as an approach section for the corresponding culvert.

The dividing point between the strips on the separating embankment section is located a weighted distance from the edge of the left opening (looking upstream). The weighted distance is equal to the length of embankment between the culverts multiplied by the ratio of the left opening flow area to the total flow area of both openings. For the culverts in figure 17, the dividing points (stagnation points) located on the embankment between the culverts are computed from,

$$x_{d_{1-2}} = L_{1-2}\frac{A_1}{A_1 + A_2} \qquad (18a)$$

and

$$x_{d_{2-3}} = L_{2-3}\frac{A_2}{A_2 + A_3} , \qquad (18b)$$

where A_1, A_2, and A_3 are the opening area of one of the adjacent culverts, $L_{1\text{-}2}$ and $L_{2\text{-}3}$ are the embankment lengths between the adjacent culverts, and $x_{d_{1-2}}$ and $x_{d_{2-3}}$ are the location of the dividing points referenced to the edge of the adjacent culvert. Numeric subscripts indicate the appropriate culvert. From the dividing points on the embankment, lines are projected upstream parallel to the mean direction of flow to the approach section.

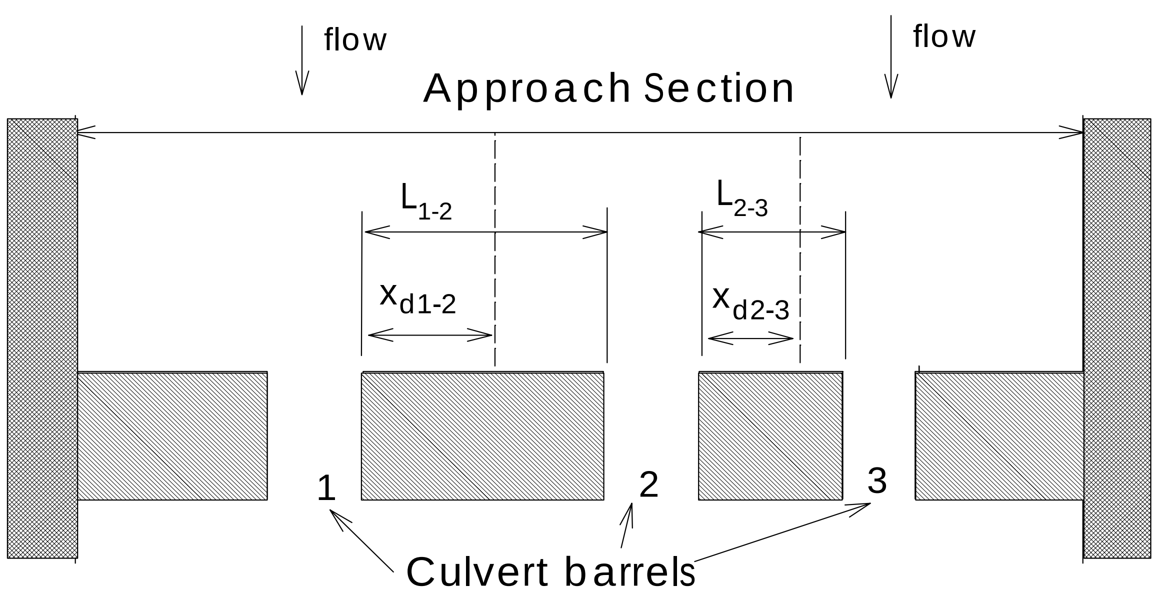

Figure 17. Location of dividing points on embankments for multiple culvert sections.

Location: Rio Grande conveyance channel near San Acacia, New Mexico.

Culvert section description: Two-barrel mitered multiplate pipe-arch culverts made from corrugated metal. Manning's coefficient of roughness, n, is estimated as 0.032. The inlet and outlets are mitered and set flush with the slope embankments. Each barrel is 50.0 feet long measured along the top of the pipe and 68.5 feet measured along the bottom. Pipe arch dimensions are 15-foot 4-inch by 9-foot 3-inch nominal and 15-foot 6-inch by 8-foot 10-inch actual. The elevation of the upstream invert for barrel 1 is 1.00 foot and the downstream invert is 0.62 foot. The elevation of the upstream invert for barrel 2 is 0.94 foot and the downstream invert is 0.65 foot.

Approach section description: The approach section is located 60 feet before barrel 1 and 59 feet before barrel 2. The reach is straight and Manning's roughness coefficient, n, is estimated as 0.035. The approach section is illustrated in figure 18.

High-water marks: For barrel 1, the approach section high-water mark is 9.03 feet and the tailwater mark is 5.41 feet. For barrel 2, the approach-section high-water mark is 9.03 feet and the tailwater mark is 5.24 feet. Figures 19 and 20 are longitudinal views of the water surface and culvert geometry for each barrel.

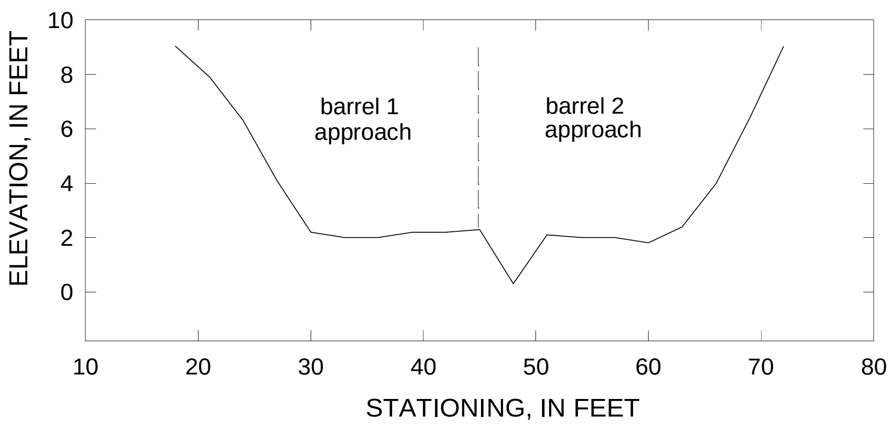

Figure 18. Approach section for the Rio Grande conveyance channel culvert.

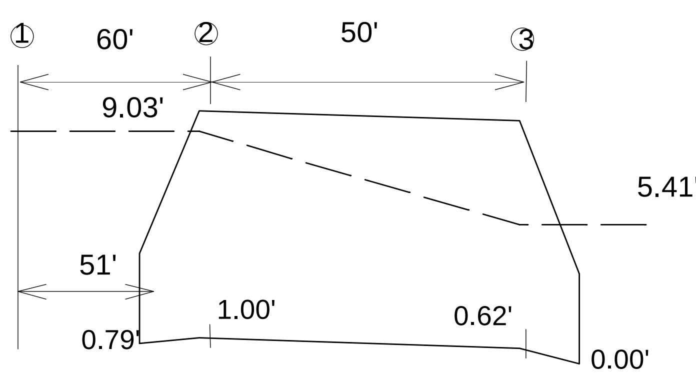

Figure 19. Longitudinal view of barrel 1 of the Rio Grande conveyance channel culvert.

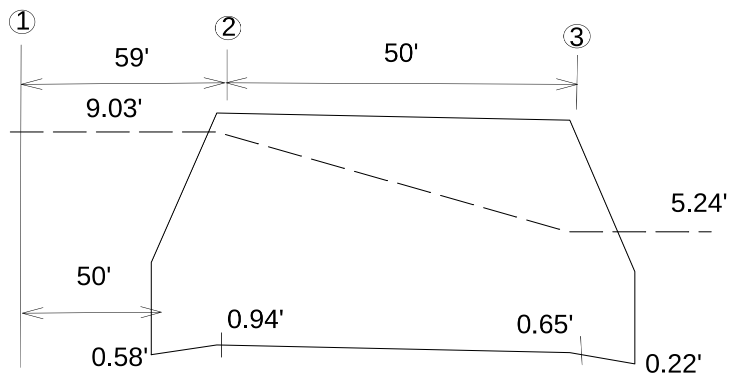

Figure 20. Longitudinal view of barrel 2 of the Rio Grande conveyance channel culvert.

Because the pipe-arches are mitered at the ends, the actual length of the barrels (68.5 feet) is not used in the computations. The effective length of a mitered pipe is a function of the flow depth in the pipe. The program does not automatically adjust effective pipe length for flow depth. For this example, the effective length is approximated by the length of pipe between the top of the inlet and outlet inverts (50 feet) and is entered as the culvert length. Alternatively, an average length could have been computed by using equation 16.

The default discharge coefficients for mitered pipes are used for flow types 1, 2, and 3 by setting the inlet equal to 2 on the *C3 record. Other discharge coefficients are entered on the *C5 record.

Each barrel has a separate set of input records that describe geometry and roughness and the tailwater and discharges for which to compute the approach-section water-surface elevation. Each barrel also has the appropriate portion of the approach section coded as a separate approach section. The entire approach section was initially coded (the APPR section) and then copied and edited into the approach section for barrel 1 (APP1) and barrel 2 (APP2). For reference purposes, the entire approach section was left in the input file but is not used. The culvert program is executed twice, once for each barrel using the same strategy as used in the two previous examples. One *PD record is used for APP1 and APP2. Only one *PD record can be included in the file containing the approach sections. The input file follows:

```
*    Rio Grande multiple culvert example
CV   BAR1 14.,0.,50.,0.62,1.00,1
CG        327,106.,186.
*C3       1.,1.,0.,2
*C5       0.74, 0.405,1.4, 0.432,1.6, 0.451,1.8, 0.469,2.0
*CF       6
*CX       5.41
*CQ       800, 820, 840, 860
*CN       0.032
CV   BAR2 15.,0.,50.,0.65,0.94,1
CG        327,106.,186.
*C3       1.,1.,0.,2
*C5       0.74, 0.405,1.4, 0.432,1.6, 0.451,1.8, 0.469,2.0
*CF       6
*CX       5.24
*CQ       836, 837, 838, 839
*CN       0.032
*PD       0.   19.0 1.0
XS   APPR 124.
```

```
GR        18.,9.04 21.,7.9 24.,6.3 27.,4.1 30.,2.2 33.,2.0 36.,2.0
GR        39.,2.2 42.,2.2 45.,2.3 48.,0.3 51.,2.1 54.,2.0 57.,2.
GR        60.,1.8 63.,2.4 66.,4. 69.,6.4 72.,9.02
N         0.035
XS   APP1 124.
GR        18.,9.04 21.,7.9 24.,6.3 27.,4.1 30.,2.2 33.,2.0 36.,2.0
GR        39.,2.2 42.,2.2 45.,2.3 45.,9.04
N         0.035
XS   APP2 124.
GR        45., 9.04 45.,2.3 48.,0.3 51.,2.1 54.,2.0 57.,2.
GR        60.,1.8 63.,2.4 66.,4. 69.,6.4 72.,9.02
N         0.035
```

The output from this input file for barrel 1 is in figure 21 and for barrel 2 is in figure 22. The computed discharges for which the computed upstream water-surface elevation matches the measured water-surface elevation of 9.03 feet are 860 cubic feet per second for barrel 1 (BAR1) and 836 cubic feet per second for barrel 2 (BAR2). The total computed discharge (the discharge computed for barrel 1 plus the discharge computed for barrel 2) is 1,696 cubic feet per second. These data are from a verification done in 1961 by USGS personnel. The current-meter-measured discharge for both barrels was 1,743 cubic feet per second. The computed discharge differs from the measured discharge by less than 3 percent.

```
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CV   BAR1 14.,0.,50.,0.62,1.00,1
CG        327,106.,186.
*C3       1.,1.,0.,2
*C5       0.74, 0.405,1.4, 0.432,1.6, 0.451,1.8, 0.469,2.0
*CF       6
*CX       5.41
*CQ       800, 820, 840, 860
*CN       0.032
     *C3 record ignored except inlet code - WARNING
XS   APP1 124.
GR        18.,9.04 21.,7.9 24.,6.3 27.,4.1 30.,2.2 33.,2.0 36.,2.0
GR        39.,2.2 42.,2.2 45.,2.3 45.,9.04
N         0.035
```

Figure 21. CAP output for barrel 1 of Rio Grande conveyance channel culvert.

```
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Rio Grande Conveyance Channel multi-culvert barrel 1, 02-19-1998
               CULVERT SECTION PROPERTIES - ID: BAR1

                          Culvert section type: pipe-arch
                     (r or w)/D  KR or KW  Ktheta  Kproj    n      Inlet
                         0.00      1.00   1.00   1.00   0.032       2

                    <<User supplied discharge coefficients>>
                      CB12 =  .00          C46 =  .74
                      For type123 flow     For type 5 flow
                         C    (h1-z)/D        C    (h1-z)/D
                        .00      .00          .41     1.40
                        .00      .00          .43     1.60
                        .00      .00          .45     1.80
                        .00      .00          .47     2.00
```

Barrel depth (ft)	Area (sq.ft)	Conveyance (cfs)	Top width (ft)	Wetted perimeter (ft)
.00	.0	.0	.00	.0
.29	1.5	23.6	7.66	7.7
.59	4.3	105.8	10.81	10.9
.88	7.8	253.7	13.20	13.4
1.18	11.9	480.9	14.39	14.7
1.47	16.2	778.2	14.94	15.5
1.77	20.7	1133.2	15.27	16.2
2.06	25.2	1537.4	15.45	16.8
2.36	29.8	1982.1	15.50	17.4
2.65	34.3	2457.7	15.21	18.0
2.94	38.8	2947.2	15.08	18.6
3.24	43.2	3452.5	14.92	19.2
3.53	47.6	3969.0	14.73	19.8
3.83	51.9	4492.0	14.52	20.4
4.12	56.1	5017.5	14.28	21.1
4.42	60.3	5541.1	14.02	21.7
4.71	64.4	6058.9	13.72	22.4
5.01	68.3	6566.8	13.39	23.1
5.30	72.2	7060.7	13.03	23.7
5.59	76.0	7536.5	12.62	24.5
5.89	79.7	7989.9	12.18	25.2
6.18	83.2	8416.2	11.69	26.0
6.48	86.5	8810.5	11.14	26.8
6.77	89.7	9167.5	10.54	27.6
7.07	92.7	9480.9	9.86	28.5
7.36	95.5	9743.3	9.10	29.5
7.66	98.1	9945.1	8.22	30.5
7.95	100.4	10073.2	7.20	31.7
8.24	102.3	10106.1	5.93	33.1
8.54	103.8	9997.8	4.24	34.9
8.83	104.7	9380.3	.00	39.2

Figure 21. CAP output for barrel 1 of Rio Grande conveyance channel culvert-continued. *[ft, feet; sq.ft, square feet; cfs, cubic feet per second]*

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Rio Grande Conveyance Channel multi-culvert barrel 1, 02-19-1998

APPROACH SECTION PROPERTIES - ID: APP1

Water Surface el.(ft)*	Area (sq.ft)	Conveyance (cfs)	Top width (ft)	Alpha	Critical discharge (cfs)
2.00	.0	.0	3.0	1.00	.0
2.79	10.2	313.8	15.9	1.00	46.3
3.58	23.3	1142.0	17.2	1.00	154.1
4.38	37.4	2331.6	18.4	1.00	302.8
5.17	52.4	3833.1	19.5	1.00	487.7
5.96	68.2	5614.3	20.5	1.00	705.4
6.75	84.9	7633.6	21.8	1.00	950.5
7.54	102.8	9913.7	23.3	1.00	1224.9
8.33	121.9	12423.9	25.1	1.00	1524.1
9.13	142.7	15264.4	27.0	1.00	1860.9
9.92	164.0	18715.7	27.0	1.00	2294.4
10.71	185.4	22328.3	27.0	1.00	2757.2
11.50	206.8	26079.6	27.0	1.00	3247.4
12.29	228.2	29951.0	27.0	1.00	3763.7
13.08	249.5	33927.4	27.0	1.00	4304.8
13.88	270.9	37996.1	27.0	1.00	4869.6
14.67	292.3	42146.5	27.0	1.00	5457.2
15.46	313.7	46369.6	27.0	1.00	6066.6
16.25	335.0	50657.6	27.0	1.00	6697.2
17.04	356.4	55003.9	27.0	1.00	7348.2
17.83	377.8	59402.8	27.0	1.00	8019.0
18.63	399.2	63849.3	27.0	1.00	8709.1
19.42	420.5	68338.9	27.0	1.00	9418.0
20.21	441.9	72867.9	27.0	1.00	10145.0
21.00	463.3	77432.8	27.0	1.00	10889.9

*elevation referenced to common vertical datum

Figure 21. CAP output for barrel 1 of Rio Grande conveyance channel culvert-continued. *[ft, feet; sq.ft, square feet; cfs, cubic feet per second]*

```
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Rio Grande Conveyance Channel multi-culvert barrel 1, 02-19-1998
                     CULVERT                                   APPROACH SECTION
 I.D. BAR1                   Mannings n      .032        I.D. APP1
 Height        8.83 ft           Width      15.5ft       Station       124.0 ft
 Station       14.0 ft          Length     50.0 ft       Minimum el.     2.00ft
 Inlet el.      1.00ft       Outlet el.      .62ft


         Discharge  Flow     Water Surface Elevations (feet) Critical  Error
   no.     (cfs)    type     appr.   inlet   outlet   exit     Dc       code@
    1        800.0   3         8.54    6.77    5.41    5.41      4.7    0
    2        820.0   2         8.72    6.87    5.43    5.41      4.8    0
    3        840.0   2         8.87    6.96    5.50    5.41      4.9    0
    4        860.0   2         9.02    7.06    5.57    5.41      5.0    0

             Fall (ft)     Losses (ft)       Appr. Section  Control Section
  no.    C   entry  eff.  entry(1-2) (2-3)    VH  alph   F    energy    F
   1    .93  3.13  2.71   .39   .37   .66    .61 1.00   .50     7.73   .98
   2    .92  3.28  2.84   .42   .37   .68    .60 1.00   .49     7.85  1.00
   3    .92  3.37  2.91   .45   .37   .69    .59 1.00   .48     7.97  1.00
   4    .92  3.45  2.99   .47   .36   .69    .59 1.00   .47     8.08  1.00
______________________________________________________________________________

Abrevs. used: appr.-approach  C-discharge coefficient  eff.-effective
VH-velocity head  alph-velocity coefficient  n-Manning's roughness coef.
energy-specific energy  F-Froude number  entry,(1-2),(2-3)-part of reach

      @Error codes:  -1,1-7 fatal error; 8-14 warning; 0 no error


          ---------Warning Messages-------------
```

Figure 21. CAP output for barrel 1 of the Rio Grande conveyance channel culvert- continued. *[ft, feet; cfs, cubic feet per second]*

```
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CV   BAR2 15.,0.,50.,0.65,0.94,1
CG        327,106.,186.
*C3       1.,1.,0.,2
*C5       0.74, 0.405,1.4, 0.432,1.6, 0.451,1.8, 0.469,2.0
*CF       6
*CX       5.24
*CQ       836, 837, 838, 839
*CN       0.032
     *C3 record ignored except inlet code - WARNING
*PD       0.   19.0 1.0
XS   APP2 124.
GR        45., 9.04 45.,2.3 48.,0.3 51.,2.1 54.,2.0 57.,2.
GR        60.,1.8 63.,2.4 66.,4. 69.,6.4 72.,9.02
N          0.035
```

Figure 22. CAP output for barrel 2 of Rio Grande conveyance channel culvert.

```
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Rio Grande Conveyance Channel multi-culvert barrel 2, 02-19-1998
               CULVERT SECTION PROPERTIES - ID: BAR2

                         Culvert section type: pipe-arch
                     (r or w)/D  KR or KW  Ktheta  Kproj    n      Inlet
                         0.00      1.00   1.00   1.00   0.032       2

                    <<User supplied discharge coefficients>>
                      CB12 =  .00          C46 =  .74
                      For type123 flow     For type 5 flow
                          C    (h1-z)/D        C    (h1-z)/D
                         .00      .00          .41     1.40
                         .00      .00          .43     1.60
                         .00      .00          .45     1.80
                         .00      .00          .47     2.00

         Barrel                                   Top       Wetted
         depth        Area        Conveyance      width      perimeter
           (ft)       (sq.ft)        (cfs)          (ft)        (ft)
           .00           .0             .0         .00           .0
           .29          1.5           23.6        7.66          7.7
           .59          4.3          105.8       10.81         10.9
           .88          7.8          253.7       13.20         13.4
          1.18         11.9          480.9       14.39         14.7
          1.47         16.2          778.2       14.94         15.5
          1.77         20.7         1133.2       15.27         16.2
          2.06         25.2         1537.4       15.45         16.8
          2.36         29.8         1982.1       15.50         17.4
          2.65         34.3         2457.7       15.21         18.0
          2.94         38.8         2947.2       15.08         18.6
          3.24         43.2         3452.5       14.92         19.2
          3.53         47.6         3969.0       14.73         19.8
          3.83         51.9         4492.0       14.52         20.4
          4.12         56.1         5017.5       14.28         21.1
          4.42         60.3         5541.1       14.02         21.7
          4.71         64.4         6058.9       13.72         22.4
          5.01         68.3         6566.8       13.39         23.1
          5.30         72.2         7060.7       13.03         23.7
          5.59         76.0         7536.5       12.62         24.5
          5.89         79.7         7989.9       12.18         25.2
          6.18         83.2         8416.2       11.69         26.0
          6.48         86.5         8810.5       11.14         26.8
          6.77         89.7         9167.5       10.54         27.6
          7.07         92.7         9480.9        9.86         28.5
          7.36         95.5         9743.3        9.10         29.5
          7.66         98.1         9945.1        8.22         30.5
          7.95        100.4        10073.2        7.20         31.7
          8.24        102.3        10106.1        5.93         33.1
          8.54        103.8         9997.8        4.24         34.9
          8.83        104.7         9380.3         .00         39.2
```

Figure 22. CAP output for barrel 2 of Rio Grande conveyance channel culvert-continued. *[ft, feet; sq.ft, square feet; cfs, cubic feet per second]*

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Rio Grande Conveyance Channel multi-culvert barrel 2, 02-19-1998
APPROACH SECTION PROPERTIES - ID: APP2

Water Surface el.(ft)*	Area (sq.ft)	Conveyance (cfs)	Top width (ft)	Alpha	Critical discharge (cfs)
.30	.0	.0	.0	1.00	.0
1.09	1.0	20.4	2.5	1.00	3.5
1.88	4.0	112.7	6.7	1.00	17.8
2.68	16.6	619.6	18.5	1.00	89.0
3.47	31.8	1701.1	20.0	1.00	227.7
4.26	48.2	3185.2	21.3	1.00	411.4
5.05	65.5	5032.6	22.3	1.00	636.7
5.84	83.5	7190.7	23.3	1.00	897.7
6.63	102.4	9644.8	24.3	1.00	1193.3
7.42	122.0	12385.2	25.2	1.00	1523.1
8.22	142.2	15393.8	26.1	1.00	1885.0
9.01	163.2	18665.3	27.0	1.00	2278.3
9.80	184.6	22281.8	27.0	1.00	2739.5
10.59	206.0	26039.3	27.0	1.00	3228.7
11.38	227.4	29917.3	27.0	1.00	3744.1
12.18	248.7	33900.3	27.0	1.00	4284.3
12.97	270.1	37975.8	27.0	1.00	4848.2
13.76	291.5	42132.8	27.0	1.00	5434.9
14.55	312.9	46362.5	27.0	1.00	6043.5
15.34	334.2	50657.0	27.0	1.00	6673.3
16.13	355.6	55009.6	27.0	1.00	7323.6
16.93	377.0	59414.7	27.0	1.00	7993.7
17.72	398.4	63867.2	27.0	1.00	8683.1
18.51	419.7	68362.7	27.0	1.00	9391.3
19.30	441.1	72897.4	27.0	1.00	10117.7

*elevation referenced to common vertical datum

Figure 22. CAP output for barrel 2 of Rio Grande conveyance channel culvert-continued. *[ft, feet; sq.ft, square feet; cfs, cubic feet per second]*

```
CAP -USGS culvert analysis program VER 97-08                           page 3

Rio Grande Conveyance Channel multi-culvert barrel 2, 02-19-98
                     CULVERT                                   APPROACH SECTION
 I.D. BAR2                  Mannings n      .032        I.D. APP2
 Height        8.83 ft           Width      15.5ft      Station       124.0 ft
 Station       15.0 ft          Length     50.0 ft      Minimum el.      .30ft
 Inlet el.       .94ft       Outlet el.      .65ft

        Discharge  Flow     Water Surface Elevations (feet) Critical  Error
   no.     (cfs)    type     appr.   inlet   outlet   exit     Dc       code@
    1       836.0   2         9.03    7.03    5.52    5.24      4.9    0
    2       837.0   2         9.03    7.03    5.52    5.24      4.9    0
    3       838.0   2         9.04    7.04    5.52    5.24      4.9    0
    4       839.0   2         9.05    7.04    5.53    5.24      4.9    0


            Fall (ft)     Losses (ft)       Appr. Section  Control Section
  no.    C   entry  eff.  entry(1-2) (2-3)    VH  alph   F    energy    F
   1    .91  3.51  2.98   .53   .27   .67    .40 1.00   .37     7.97  1.00
   2    .91  3.51  2.98   .53   .27   .67    .40 1.00   .37     7.98  1.00
   3    .91  3.52  2.99   .53   .27   .67    .40 1.00   .36     7.98  1.00
   4    .91  3.52  2.99   .53   .27   .67    .40 1.00   .36     7.99  1.00
______________________________________________________________________________

Abrevs. used: appr.-approach  C-discharge coefficient  eff.-effective
VH-velocity head  alph-velocity coefficient  n-Manning's roughness coef.
energy-specific energy  F-Froude number  entry,(1-2),(2-3)-part of reach

      @Error codes:  -1,1-7 fatal error; 8-14 warning; 0 no error


          ---------Warning Messages-------------
```

Figure 22. CAP output for barrel 2 of Rio Grande conveyance channel culvert-continued. *[ft, feet; cfs, cubic feet per second]*

Computation of a Three-Parameter Table

One example of a three-parameter table is presented in this section. It is based on examples 3 and 5 in the TWRI on culverts. In this example, a rating surface is computed for a range of discharges and tailwaters. The output table can be used either to plot a rating surface that depicts the hydraulic behavior of the culvert or as inputs into other flow models.

Location: TWRI creek

Culvert section description: 10-foot-diameter corrugated-metal pipe set in vertical headwall. Manning's coefficient of roughness, n, is estimated as 0.024 and r/D is 0.006. The elevation of the upstream and downstream inverts is 1.6 feet.

Approach section description: Ponded conditions exist.

Computation requirement: Compute upstream water-surface elevations for discharges ranging from 220 to 280 cubic feet per second and tailwaters from 2.00 to 5.00 feet.

Because ponded conditions exist, the adopted cross section must give approach velocities near zero. The input file used follows.

```
CV   TWRI 200.,0.,100.,1.6,1.6,1
CG        227,120.
*C3       1.012,1,0,1
*C5       0.8412, 0.446,1.4, 0.471,1.6, 0.492,1.8, 0.512,2.0
*CF       6
*CX       2.6, 3.6, 4.6, 5.6, 6.6
*CQ       220, 230, 240, 250, 260, 270, 280
*CN       0.024
*PD       0.   20.0 1.0
XS   ADOP 310.
GR        1,11.0 2,10.0 8,6.3 13,1.4 9971,1.4 9976,6.3 9992,10.0 9993,11.0
N         0.024
```

The summary output from this file, except for page 0 containing the echoed input, is shown in figure 23. The three-parameter table is output to a file named by default as TABLES30.DAT. This output is shown is figure 24. From this table, discharge, upstream water-surface elevation, and downstream water-surface elevation can be interpolated given any two of the parameters. A rating surface that visually describes the flow behavior for this culvert is shown in figure 25. The figure was produced with a commercially available 3-D plotting program.

```
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Example using 3 parameter table output
               CULVERT SECTION PROPERTIES - ID: TWRI

                           Culvert section type: circular/pipe
                      (r or w)/D  KR or KW  Ktheta  Kproj    n      Inlet
                          0.00      1.00   1.00   1.00   0.024       1

                     <<User supplied discharge coefficients>>
                       CB12 =  .00          C46 =  .84
                       For type123 flow     For type 5 flow
                           C    (h1-z)/D        C    (h1-z)/D
                         .00      .00          .45     1.40
                         .00      .00          .47     1.60
                         .00      .00          .49     1.80
                         .00      .00          .51     2.00
```

Barrel depth (ft)	Area (sq.ft)	Conveyance (cfs)	Top width (ft)	Wetted perimeter (ft)
.00	.0	.0	.00	.0
.33	.8	18.1	3.59	3.7
.67	2.2	79.6	4.99	5.2
1.00	4.1	187.5	6.00	6.4
1.33	6.2	342.1	6.80	7.5
1.67	8.6	542.3	7.45	8.4
2.00	11.2	786.5	8.00	9.3
2.33	13.9	1072.5	8.46	10.1
2.67	16.8	1397.6	8.84	10.9
3.00	19.8	1758.9	9.17	11.6
3.33	22.9	2153.2	9.43	12.3
3.67	26.1	2577.0	9.64	13.0
4.00	29.3	3026.7	9.80	13.7
4.33	32.6	3498.4	9.91	14.4
4.67	35.9	3987.8	9.98	15.0
5.00	39.3	4490.8	10.00	15.7
5.33	42.6	5002.8	9.98	16.4
5.67	45.9	5519.0	9.91	17.0
6.00	49.2	6034.3	9.80	17.7
6.33	52.4	6543.4	9.64	18.4
6.67	55.6	7040.6	9.43	19.1
7.00	58.7	7519.8	9.17	19.8
7.33	61.7	7974.4	8.84	20.6
7.67	64.6	8397.0	8.46	21.3
8.00	67.4	8779.3	8.00	22.1
8.33	69.9	9111.5	7.45	23.0
8.67	72.3	9381.4	6.80	23.9
9.00	74.5	9572.7	6.00	25.0
9.33	76.3	9660.0	4.99	26.2
9.67	77.7	9591.9	3.59	27.7
10.00	78.5	8981.7	.00	31.4

Figure 23. CAP output for TWRI creek example problem using three-parameter table output. *[ft, feet; sq.ft, square feet; cfs, cubic feet per second]*

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Example using 3 parameter table output

APPROACH SECTION PROPERTIES - ID: ADOP

Water Surface el.(ft)*	Area (sq.ft)	Conveyance (cfs)	Top width (ft)	Alpha	Critical discharge (cfs)
1.40	.0	.0	9958.0	1.00	.0
2.23	8299.0	456216.6	9959.7	1.00	42988.0
3.07	16599.5	1448373.0	9961.4	1.00	121593.5
3.90	24901.4	2846809.0	9963.1	1.00	223391.0
4.73	33204.7	4598138.0	9964.8	1.00	343947.6
5.57	41509.4	6669472.0	9966.5	1.00	480702.0
6.40	49815.5	9037389.0	9968.6	1.00	631914.2
7.23	58124.8	11682890.0	9973.5	1.00	796241.5
8.07	66438.1	14593420.0	9978.5	1.00	972794.7
8.90	74755.6	17757470.0	9983.5	1.00	1160788.0
9.73	83077.2	21165320.0	9988.4	1.00	1359573.0
10.57	91402.3	24811620.0	9991.1	1.00	1568760.0
11.40	99728.8	28688110.0	9992.0	1.00	1787856.0
12.23	108055.5	32786670.0	9992.0	1.00	2016377.0
13.07	116382.1	37100660.0	9992.0	1.00	2253882.0
13.90	124708.8	41624720.0	9992.0	1.00	2500042.0
14.73	133035.5	46353980.0	9992.0	1.00	2754564.0
15.57	141362.1	51283960.0	9992.0	1.00	3017180.0
16.40	149688.8	56410560.0	9992.0	1.00	3287651.0
17.23	158015.5	61729980.0	9992.0	1.00	3565752.0
18.07	166342.1	67238650.0	9992.0	1.00	3851280.0
18.90	174668.8	72933320.0	9992.0	1.00	4144048.0
19.73	182995.5	78810870.0	9992.0	1.00	4443880.0
20.57	191322.1	84868420.0	9992.0	1.00	4750612.0
21.40	199648.8	91103220.0	9992.0	1.00	5064095.0

*elevation referenced to common vertical datum

Figure 23. CAP output for TWRI creek example problem using three-parameter table output-continued. *[ft, feet; sq.ft, square feet; cfs, cubic feet per second]*

```
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Example using 3 parameter table output
                     CULVERT                                    APPROACH SECTION
 I.D. TWRI                   Mannings n      .024        I.D. ADOP
 Height       10.00 ft           Width      10.0ft       Station       310.0 ft
 Station      200.0 ft          Length    100.0 ft       Minimum el.     1.40ft
 Inlet el.      1.60ft       Outlet el.     1.60ft

        Discharge  Flow     Water Surface Elevations (feet) Critical  Error
   no.     (cfs)    type     appr.   inlet   outlet   exit     Dc       code@
    1        220.0   2         7.04    6.29    5.08    2.60      3.5    0
    2        220.0   2         7.04    6.29    5.08    3.60      3.5    0
    3        220.0   2         7.04    6.29    5.08    4.60      3.5    0
    4        220.0   3         6.98    6.30    5.60    5.60      3.5    0
    5        220.0   3         7.37    6.88    6.60    6.60      3.5    0
    6        230.0   2         7.16    6.39    5.16    2.60      3.6    0
    7        230.0   2         7.16    6.39    5.16    3.60      3.6    0
    8        230.0   2         7.16    6.39    5.16    4.60      3.6    0
    9        230.0   3         7.10    6.38    5.60    5.60      3.6    0
   10        230.0   3         7.44    6.91    6.60    6.60      3.6    0
   11        240.0   2         7.28    6.49    5.24    2.60      3.6    0
   12        240.0   2         7.28    6.49    5.24    3.60      3.6    0
   13        240.0   2         7.28    6.49    5.24    4.60      3.6    0
   14        240.0   3         7.22    6.46    5.60    5.60      3.6    0
   15        240.0   3         7.52    6.95    6.60    6.60      3.6    0
   16        250.0   2         7.41    6.59    5.32    2.60      3.7    0
   17        250.0   2         7.41    6.59    5.32    3.60      3.7    0
   18        250.0   2         7.41    6.59    5.32    4.60      3.7    0
   19        250.0   3         7.35    6.55    5.60    5.60      3.7    0
   20        250.0   3         7.59    6.98    6.60    6.60      3.7    0

            Fall (ft)     Losses (ft)       Appr. Section  Control Section
  no.    C   entry  eff.  entry(1-2) (2-3)     VH  alph    F    energy    F
   1    .94  1.96  1.44   .17    .00   .52    .00 1.00   .00      6.35  1.00
   2    .94  1.96  1.44   .17    .00   .52    .00 1.00   .00      6.35  1.00
   3    .94  1.96  1.44   .17    .00   .52    .00 1.00   .00      6.35  1.00
   4    .94  1.38   .99   .11    .00   .40    .00 1.00   .00      6.47   .76
   5    .94   .77   .55   .07    .00   .22    .00 1.00   .00      7.09   .50
   6    .94  2.00  1.48   .17    .00   .52    .00 1.00   .00      6.47  1.00
   7    .94  2.00  1.48   .17    .00   .52    .00 1.00   .00      6.47  1.00
   8    .94  2.00  1.48   .17    .00   .52    .00 1.00   .00      6.47  1.00
   9    .94  1.50  1.08   .13    .00   .42    .00 1.00   .00      6.55   .80
  10    .94   .84   .61   .07    .00   .24    .00 1.00   .00      7.13   .52
  11    .94  2.05  1.52   .18    .00   .52    .00 1.00   .00      6.58  1.00
  12    .94  2.05  1.52   .18    .00   .52    .00 1.00   .00      6.58  1.00
  13    .94  2.05  1.52   .18    .00   .52    .00 1.00   .00      6.58  1.00
  14    .94  1.62  1.18   .14    .00   .44    .00 1.00   .00      6.64   .83
  15    .94   .92   .66   .08    .00   .26    .00 1.00   .00      7.18   .54
  16    .94  2.09  1.56   .19    .00   .53    .00 1.00   .00      6.69  1.00
  17    .94  2.09  1.56   .19    .00   .53    .00 1.00   .00      6.69  1.00
  18    .94  2.09  1.56   .19    .00   .53    .00 1.00   .00      6.69  1.00
  19    .94  1.75  1.28   .15    .00   .47    .00 1.00   .00      6.73   .87
  20    .94   .99   .72   .09    .00   .27    .00 1.00   .00      7.23   .57
______________________________________________________________________________

Abrevs. used: appr.-approach  C-discharge coefficient  eff.-effective
VH-velocity head  alph-velocity coefficient  n-Manning's roughness coef.
energy-specific energy  F-Froude number  entry,(1-2),(2-3)-part of reach

      @Error codes:  -1,1-7 fatal error; 8-14 warning; 0 no error
```

Figure 23. CAP output for TWRI creek example problem using three-parameter table output-continued. *[ft, feet; cfs, cubic feet per second]*

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Example using 3 parameter table output

CULVERT				APPROACH SECTION	
I.D. TWRI		Mannings n	.024	I.D. ADOP	
Height	10.00 ft	Width	10.0ft	Station	310.0 ft
Station	200.0 ft	Length	100.0 ft	Minimum el.	1.40ft
Inlet el.	1.60ft	Outlet el.	1.60ft		

no.	Discharge (cfs)	Flow type	Water Surface Elevations (feet) appr.	inlet	outlet	exit	Critical Dc	Error code@
21	260.0	2	7.53	6.68	5.39	2.60	3.8	0
22	260.0	2	7.53	6.68	5.39	3.60	3.8	0
23	260.0	2	7.53	6.68	5.39	4.60	3.8	0
24	260.0	3	7.48	6.64	5.60	5.60	3.8	0
25	260.0	3	7.67	7.02	6.60	6.60	3.8	0
26	270.0	2	7.65	6.77	5.47	2.60	3.9	0
27	270.0	2	7.65	6.77	5.47	3.60	3.9	0
28	270.0	2	7.65	6.77	5.47	4.60	3.9	0
29	270.0	3	7.61	6.74	5.60	5.60	3.9	0
30	270.0	3	7.75	7.06	6.60	6.60	3.9	0
31	280.0	2	7.76	6.86	5.54	2.60	3.9	0
32	280.0	2	7.76	6.86	5.54	3.60	3.9	0
33	280.0	2	7.76	6.86	5.54	4.60	3.9	0
34	280.0	3	7.75	6.85	5.60	5.60	3.9	0
35	280.0	3	7.83	7.10	6.60	6.60	3.9	0

no.	C	Fall (ft) entry	eff.	Losses (ft) entry	(1-2)	(2-3)	Appr. Section VH	alph	F	Control Section energy	F
21	.94	2.14	1.60	.19	.00	.53	.00	1.00	.00	6.80	1.00
22	.94	2.14	1.60	.19	.00	.53	.00	1.00	.00	6.80	1.00
23	.94	2.14	1.60	.19	.00	.53	.00	1.00	.00	6.80	1.00
24	.94	1.88	1.39	.17	.00	.49	.00	1.00	.00	6.82	.90
25	.94	1.07	.78	.09	.00	.29	.00	1.00	.00	7.28	.59
26	.94	2.18	1.64	.20	.00	.54	.00	1.00	.00	6.91	1.00
27	.94	2.18	1.64	.20	.00	.54	.00	1.00	.00	6.91	1.00
28	.94	2.18	1.64	.20	.00	.54	.00	1.00	.00	6.91	1.00
29	.94	2.01	1.50	.18	.00	.51	.00	1.00	.00	6.92	.94
30	.94	1.15	.84	.10	.00	.31	.00	1.00	.00	7.33	.61
31	.94	2.22	1.68	.21	.00	.54	.00	1.00	.00	7.01	1.00
32	.94	2.22	1.68	.21	.00	.54	.00	1.00	.00	7.01	1.00
33	.94	2.22	1.68	.21	.00	.54	.00	1.00	.00	7.01	1.00
34	.94	2.15	1.61	.20	.00	.53	.00	1.00	.00	7.01	.97
35	.94	1.23	.90	.11	.00	.33	.00	1.00	.00	7.39	.63

Abrevs. used: appr.-approach C-discharge coefficient eff.-effective
VH-velocity head alph-velocity coefficient n-Manning's roughness coef.
energy-specific energy F-Froude number entry,(1-2),(2-3)-part of reach

@Error codes: -1,1-7 fatal error; 8-14 warning; 0 no error

---------Warning Messages-------------

Figure 23. CAP output for TWRI creek example problem using three-parameter table output-continued. *[ft, feet; cfs, cubic feet per second]*

```
TABLES30.DAT
TAB
1234567830  5  7
    1.600
   1.00   2.00   3.00   4.00   5.00
    220.    230.    240.    250.    260.    270.    280.
   5.44   5.44   5.44   5.38   5.77
   5.56   5.56   5.56   5.50   5.84
   5.68   5.68   5.68   5.62   5.92
   5.81   5.81   5.81   5.75   5.99
   5.93   5.93   5.93   5.88   6.07
   6.05   6.05   6.05   6.01   6.15
   6.16   6.16   6.16   6.15   6.23
```

Figure 24. Tabled output for TWRI creek example.

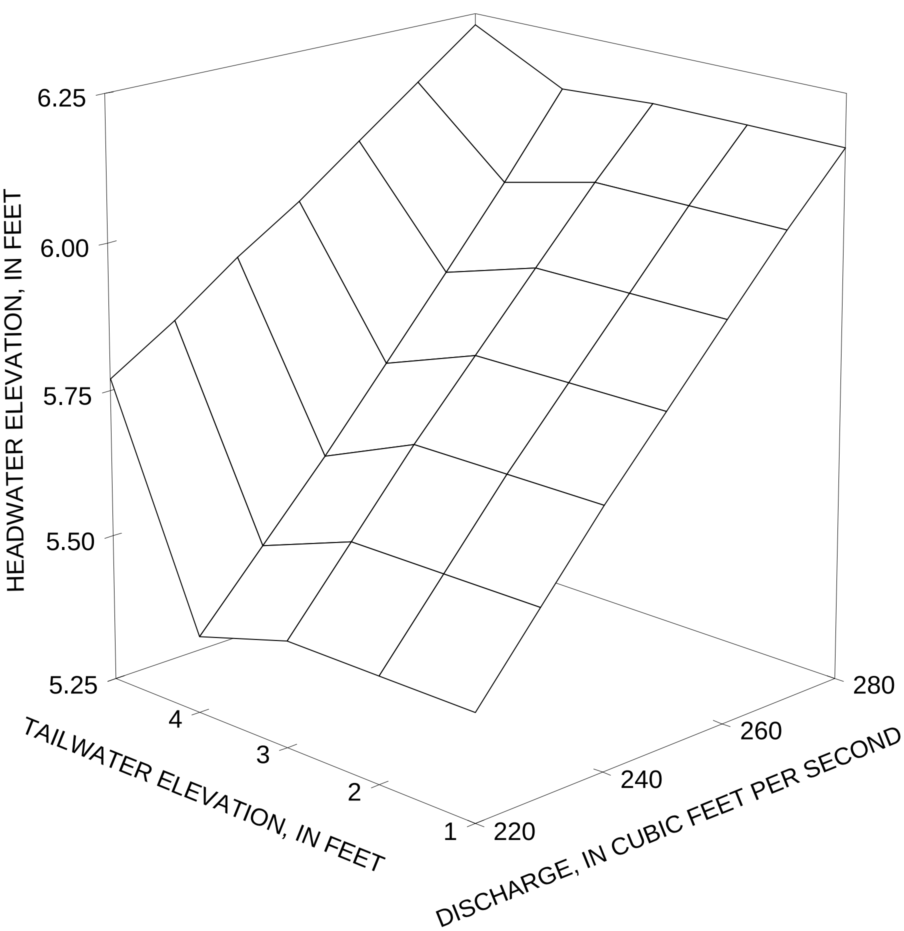

Figure 25. TWRI creek three-parameter rating surface.

Example Using New Records

This example is based on example 8 of the TWRI on culverts. It illustrates how the SI record for units and the *CC record for inlet geometry measurement data are used.

Location: Example creek

Culvert section description: 4-foot-diameter concrete pipe culvert set in a vertical headwall. Manning's coefficient of roughness, n, is estimated as 0.012. The inlet pipe edge has a 3.6 inch bevel. Elevation of the upstream and downstream inverts are 6.4 feet and 5.4 feet, respectively.

Approach section description: The approach section is located 8 feet before the culvert inlet. The reach is straight and Manning's n is estimated as 0.024.

Computation requirement: Compute upstream water-surface elevations for discharges ranging from 190 to 220 cubic feet per second for a tailwater elevation of 6.4 feet. Output is to be in meters and seconds. The input file is as follows:

```
*    Example 8 in TWRI concrete pipe culvert type 6 flow
SI        2
CV   EX01 5.0,0,50.,5.4,6.4,1
CG        211,48.
*CC       0,3.6,0,1,0
*CX       6.4
*CQ       190., 200., 209., 210., 220.
*CN       0.012
*PD       0.   20.0 1.0
XS   AP01 63.0
GR        0.,9. 0.,6.4 1.,6.6 2.,6.6 3.,6.5 5.,6.5 6.,6.7 7.,7
GR        8.,8.1 10.,9.
N         0.025
```

The SI record will result in the detailed output in meter-seconds units. No *C5 record is included, so default discharge coefficient computations will be used for type 4, 5, and 6 flows. The detailed report for the data is in figure 26. The first page of the detailed report, page 0, is an echo of the input file and is omitted from figure 26.

```
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Using SI and *CC records for culvert computations
               CULVERT SECTION PROPERTIES - ID: EX01

                    Culvert section type: circular/pipe
               (r or w)/D  KR or KW  Ktheta  Kproj    n      Inlet
                   0.07      1.00   1.00   1.00   0.012       1

                    <<User supplied discharge coefficients>>
                      CB12 = 0.00          C46 = 0.95
                      For type123 flow     For type 5 flow
                         C    (h1-z)/D        C    (h1-z)/D
                       0.00     0.00         0.00     0.00
                       0.00     0.00         0.00     0.00
                       0.00     0.00         0.00     0.00
                       0.00     0.00         0.00     0.00
```

Barrel depth (m)	Area (sq. m)	Conveyance (cms)	Top width (m)	Wetted perimeter (m)
0.000	0.00	0.00	0.000	0.00
0.041	0.01	0.09	0.438	0.45
0.081	0.03	0.39	0.608	0.64
0.122	0.06	0.92	0.732	0.78
0.163	0.09	1.68	0.829	0.91
0.203	0.13	2.67	0.909	1.03
0.244	0.17	3.87	0.975	1.13
0.284	0.21	5.28	1.031	1.23
0.325	0.25	6.88	1.078	1.32
0.366	0.29	8.65	1.117	1.41
0.406	0.34	10.59	1.149	1.50
0.447	0.39	12.68	1.175	1.59
0.488	0.44	14.89	1.195	1.67
0.528	0.48	17.21	1.208	1.75
0.569	0.53	19.62	1.216	1.83
0.610	0.58	22.09	1.219	1.92
0.650	0.63	24.61	1.216	2.00
0.691	0.68	27.15	1.208	2.08
0.732	0.73	29.68	1.195	2.16
0.772	0.78	32.19	1.175	2.24
0.813	0.83	34.63	1.149	2.33
0.853	0.87	36.99	1.117	2.42
0.894	0.92	39.23	1.078	2.51
0.935	0.96	41.31	1.031	2.60
0.975	1.00	43.19	0.975	2.70
1.016	1.04	44.82	0.909	2.80
1.057	1.07	46.15	0.829	2.92
1.097	1.11	47.09	0.732	3.05
1.138	1.13	47.52	0.608	3.19
1.179	1.16	47.19	0.438	3.38
1.219	1.17	44.18	0.000	3.83

Figure 26. Detailed report for example using new records. *[m, meter; sq. m, square meter; cms, cubic meters per second]*

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Using SI and *CC records for culvert computations

APPROACH SECTION PROPERTIES - ID: AP01

Water Surface el.(m)*	Area (sq. m)	Conveyance (cms)	Top width (m)	Alpha	Critical discharge (cms)
1.951	0.00	0.00	0.00	1.000	0.00
2.205	0.42	5.18	2.20	1.000	0.58
2.459	1.01	19.18	2.43	1.000	2.04
2.713	1.70	38.61	2.98	1.000	4.01
2.967	2.47	66.19	3.05	1.000	6.96
3.221	3.24	97.12	3.05	1.000	10.48
3.475	4.02	130.13	3.05	1.000	14.45
3.729	4.79	164.63	3.05	1.000	18.83
3.983	5.57	200.24	3.05	1.000	23.57
4.237	6.34	236.70	3.05	1.000	28.65
4.491	7.11	273.82	3.05	1.000	34.05
4.745	7.89	311.48	3.05	1.000	39.76
4.999	8.66	349.57	3.05	1.000	45.76
5.253	9.44	388.01	3.05	1.000	52.02
5.507	10.21	426.75	3.05	1.000	58.56
5.761	10.99	465.74	3.05	1.000	65.34
6.015	11.76	504.94	3.05	1.000	72.37
6.269	12.53	544.32	3.05	1.000	79.63
6.523	13.31	583.87	3.05	1.000	87.12
6.777	14.08	623.54	3.05	1.000	94.83
7.031	14.86	663.34	3.05	1.000	102.76
7.285	15.63	703.24	3.05	1.000	110.89
7.539	16.41	743.24	3.05	1.000	119.23
7.793	17.18	783.32	3.05	1.000	127.77
8.047	17.95	823.47	3.05	1.000	136.51

*elevation referenced to common vertical datum

Figure 26. Detailed report for example using new records-continued. *[m, meter; sq. m, square meter; cms, cubic meters per second]*

```
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Using SI and *CC records for culvert computations
                     CULVERT                                    APPROACH SECTION
 I.D. EX01                    Mannings n     0.012        I.D. AP01
 Height       1.219 m             Width       1.22m       Station       19.20 m
 Station       1.52 m            Length    15.24 m        Minimum el.    0.000m
 Inlet el.     1.951m         Outlet el.    1.646m

         Discharge  Flow     Water Surface Elevations(meter) Critical  Error
   no.     (cms)    type     appr.   inlet   outlet   exit     Dc       code@
    1        5.38    5       4.831   3.170   1.951   1.951     1.16    0
    2        5.38   16       4.028   3.170********   1.951     1.16   11
    3        5.66    5       5.064   3.170   1.951   1.951     1.17    0
    4        5.66   16       4.093   3.170********   1.951     1.17   11
    5        5.92    5       5.213   3.170   1.951   1.951     1.18    0
    6        5.92    6       4.138   3.170   2.865   1.951     1.18    0
    7        5.95    5       5.230   3.170   1.951   1.951     1.18    0
    8        5.95    6       4.151   3.170   2.865   1.951     1.18    0
    9        6.23    5       5.394   3.170   1.951   1.951     1.18    0
   10        6.23    6       4.289   3.170   2.865   1.951     1.18    0

             Fall (m)      Losses (m)        Appr. Section  Control Section
  no.    C   entry  eff.  entry(1-2) (2-3)    VH  alph   F    energy    F
   1   0.61****** 0.878 0.548 0.000******  0.007 1.00  0.13 ******** *****
   2   0.95******************************  0.014 1.00  0.22 ******** *****
   3   0.62****** 0.949 0.583 0.000******  0.006 1.00  0.12 ******** *****
   4   0.95******************************  0.014 1.00  0.22 ******** *****
   5   0.63****** 0.994 0.595 0.000******  0.006 1.00  0.12 ******** *****
   6   0.95****** 0.438 0.039 0.001 0.083  0.015 1.00  0.22 ******** *****
   7   0.63****** 0.999 0.597 0.000******  0.006 1.00  0.12 ******** *****
   8   0.95****** 0.442 0.040 0.001 0.084  0.015 1.00  0.22 ******** *****
   9   0.65****** 1.050 0.607 0.000******  0.006 1.00  0.11 ******** *****
  10   0.95****** 0.486 0.043 0.000 0.092  0.014 1.00  0.21 ******** *****
________________________________________________________________________________
Abrevs. used: appr.-approach  C-discharge coefficient  eff.-effective
VH-velocity head  alph-velocity coefficient  n-Manning's roughness coef.
energy-specific energy  F-Froude number  entry,(1-2),(2-3)-part of reach

      @Error codes:  -1,1-7 fatal error; 8-14 warning; 0 no error


          ---------Warning Messages-------------

  11   WARNING -- linearily interpolated between high head flows
                 and low head flows
```

Figure 26. Detailed report for example using new records-continued. *[m, meter; cms, cubic meters per second]*

ERROR MESSAGES

Error messages are printed to the screen and to the output file. Messages printed to the screen during program execution are usually the result of errors in the input file. Messages printed to the output file are either warning messages, indicating potential problems, or fatal error messages for a particular combination of discharge and tailwater elevation.

Input Error Messages

Input error messages are usually generated when data have been entered incorrectly into the input file or when the data array sizes exceed the defaults set in the program code. These messages are printed to the screen and with the print out of the input file(s) included in the detailed report. Other messages are runtime messages generated by the compiler. The following is an alphabetized list of screen error messages that may be generated by the CAP during execution. Runtime messages generated by the compiler are not listed here and are dependent on the compiler used to produce the executable version of CAP. In the following messages, *nn* is the number of array entries allowed by the program for that particular array.

***nn* allowable computation records, EXCEEDED**
Too many *PD records specified in input file. Enter only one *PD for the culvert analysis.
***nn* allowable discharge entries ------- EXCEEDED**
Number of discharges entered exceeds the array size. Reduce the number of discharges.
***nn* allowable roughness depths, ----- EXCEEDED for ID ____**
Number of roughness values entered exceeds the array sized for the cross-section ID listed. Reduce the number of roughness depths.
***nn* allowable roughness values, -----EXCEEDED for ID ____**
Number of roughness values entered exceeds the array size for the cross-section ID listed. Reduce the number of roughness values.
***nn* allowable tailwater entries ------- EXCEEDED**
Number of tailwater depths entered exceeds the array size. Reduce the number of depths.
***nn* allowable x,y coordinates, ----- EXCEEDED for ID _____**
Number of coordinates entered exceeds the array size for the cross-section ID listed. Reduce the number of coordinates.
***nn* allowable x,y culvert coordinates, - EXCEEDED**
Number of coordinates entered exceeds the array size for the culvert section. Reduce the number of coordinates.
Approach section ID NOT FOUND IN FILE ------
The program failed to find the approach ID entered in the file specified. A mistyped ID (either case or spelling) will not be found.
Approach section located incorrectly - FATAL
The approach section is not located upstream of the culvert inlet. Check reference distances for the culvert, approach section, and the culvert length.
Approach section located too close --WARNING
The approach section is located within one culvert height of the culvert entrance.
CB12 coefficient unreasonable ------- FATAL
The coefficient, CB12, entered on the *C1 record is outside the range of valid discharge coefficients (either greater than 0.98 or less than 0.85).
CP coefficients unreasonable --------- FATAL
The coefficients entered on the *C1 record are outside the range of valid discharge coefficients (either

greater than 0.98 or less than 0.65).

Culvert data incomplete, check data -- FATAL

The data in the input file is not sufficient to describe the culvert section and to run the program. The input file describing the culvert section must have a CV, *CX, *CQ, *CN, and either a *CS or a CG record.

Culvert section ID NOT FOUND IN FILE -------

The program failed to find the culvert ID entered in the file specified. A mistyped ID (either case or spelling) will not be found.

C46 coefficient unreasonable --------- FATAL

The coefficient, C46, entered on the *C5 record is outside the range of valid discharge coefficients (either greater than 0.98 or less than 0.65).

C5 coefficients unreasonable --------- FATAL

The coefficients entered on the *C5 record are outside the range of valid discharge coefficients (either greater than 0.75 or less than 0.39).

Depth ratios for CP values chaotic ----- FATAL

The depth ratios entered on the *C1 record are not in increasing order.

Depth ratios for C5 values chaotic ----- FATAL

The depth ratios entered on the *C5 record are not in increasing order.

Inconsistent no. of roughnesses & roughness depths @ ID _____

If two roughness values per subarea are entered, the number of roughness depths should equal the number of roughnesses, otherwise, no depths should be entered.

Inconsistent no. of roughnesses and subareas for ID _______

Number of roughness values and subareas do not match. Number of entered roughnesses should be equal either to the number of subareas or to twice the number of subareas.

INLET code not valid, default of 1 used

The inlet code entered on the *C3 or *CC record must be either 1, 2, or 3. See section on *C3 or *CC record.

KPROJ >1, default of 1 used

The adjustment for projecting entrances entered on the *C3 record must be less than or equal to 1.

KR <1, default of 1 used

The adjustment for rounding entered on the *C3 record must be greater than or equal to 1.

KW <1, default of 1 used

The adjustment for beveling entered on the *C3 record must be greater than or equal to 1.

NBBL, no. of barrels <1, default of 1 used

The number for NBBL is used for calculating the effects of webs on culvert properties. Enter the number of barrels per culvert.

No *CF record, type 6 and 5 flows computed

No high head flow type specified. Type 6, the default, is used.

No *CQ record, ------------------------

A *CQ record has not been entered. Discharges must be specified for culvert computations.

No *CX record, -------------------------

A *CX record has not been entered. Tailwater elevations must be specified for culvert computations.

No *C5 record, -------------------------

A *C5 record has not been entered. Discharge coefficients for type 4, 5 and 6 flow must be specified.

Range on *PD swapped to ascending order-------------

The minimum and maximum range on the *PD record were ordered incorrectly. The values were swapped. This is a warning message only and does not halt the program.

RATIO on *PD set to default of 1--------------------

The value entered on the *PD record for RATIO was either not entered or less than or equal to zero. This is a warning message only and a default value of 1 is used by the program for RATIO.

***nn* subarea breakpoints allowed. ----- EXCEEDED for ID ______**

Number of breakpoints entered exceeds the array size for the cross-section ID listed. Reduce the number of subareas.

THETA <0 or >90, default of 0 used

The angle for wingwalls entered on the *C3 record must be greater than or equal to 0 and less than or equal to 90 degrees.

x,y coordinates are ordered improperly ID _____

Coordinates should be entered in counterclockwise order. If an enclosed section is being used, the first and last coordinate must be the same.

No *C5, *C1 for nonstandard culvert -- WARNING

A nonstandard culvert has been described using *CS records. Discharge coefficients should be specified using *C1 and *C5 records. Default values for the discharge coefficients will be computed assuming a concrete pipe.

***C3 record ignored except inlet code -- WARNING**

Both a *C1 and *C3 record or a *C5 and *C3 record have been entered. Only the inlet code on the *C3 record is used. All adjustment for rounding, beveling, wingwalls or projections that are indicated on the *C3 record will not be used to adjust any coefficients entered on a *C5 or *C1 record.

Output File Messages

Two types of error messages are printed to the output file; fatal messages and warning messages. Fatal messages are printed in the location where the computed values would have been printed. Warning messages are designated by a number in the error code column of the output and are printed at the end of the output after the warning messages heading. The following is a list of error code numbers and associate output error messages that can be written to the output file.

-1, Root did not close to tolerance

A tolerance, set in the program, is used to determine when the flow equation has been successfully solved. For this computation, the flow equation root did not close to the criteria specified in the program.

-2,-3, Root not bracketed

The upper and lower bounds of flow depths in the culvert computed by the program did not bracket a solution to the flow equation. This is a fatal error for that combination of discharge and tailwater elevation.

-4, Root not bracketed in approach section

The upper and lower bounds computed for the water-surface elevation in the approach did not bracket a solution to the flow equation. This is a fatal error for that combination of discharge and tailwater elevation. This error may result from a lack of spatial convergence. The water surface can not be approximated by a straight line between the culvert inlet and the approach section successfully. A possible solution may be to translate the approach section closer to the inlet if the approach is located more than one culvert height upstream from the inlet.

1, FAILED INTERPOLATION, -- for approach section properties

The program was unable to interpolate needed values from the table of hydraulic properties computed for the range of depth given on the *PD record. Check range of depths entered on *PD record and increase range. Range should be at least two times the culvert height. Depending on conditions in the approach section and the culvert exit, the range may need to be greater than two times the culvert height. Refer to the section on the *PD record.

2, FAILED INTERPOLATION, -- for culvert properties

The program was unable to interpolate needed values from the table of hydraulic properties for the culvert section. Check that datum used in approach and culvert section descriptions are consistent.

3, FAILED INTERPOLATION, -- for discharge coefficients

The program was unable to interpolate needed values from the range of discharge coefficients given. Expand range of $(h_1\text{-}z)/D$ versus discharge coefficients, or enter necessary discharge coefficients if none have been entered.

4, No solution type one flow ---SUPERCRITICAL FLOW at approach section

The program is unable to route the flow in the upstream direction. This is a fatal error and usually results when flow is supercritical in the approach. However, poor interpolation of approach section properties may result in this error. Setting RATIO greater than 1, so that approach properties are computed more frequently at the lowest depths may eliminate this error.

5, No solution type 2 or 3 flow ---SUPERCRITICAL FLOW at approach section

The program is unable to route the flow in the upstream direction. This is a fatal error and usually results when flow is supercritical in the approach. However, poor interpolation of approach section properties may result in this error. Setting RATIO greater than 1, so that approach properties are computed more frequently at the lowest depths may eliminate this error.

6, DISCHARGE out of range of critical discharges

The program estimates a first guess at the upstream water-surface elevation by computing critical discharges for the range of depths over which the approach-section properties are computed. This error may result if the range of depths over which the approach-section properties are computed is not large enough or if the intervals between water-surface elevations used to compute the properties is too large. See the section on *PD record and the RATIO variable.

7, No solution type five flow

The program is unable to compute the type 5 flow equations. Type 5 flow may not be applicable for these parameters. The root of the type 5 flow equation is not bracketed by type 5 flow criteria.

8, WARNING -- flow type 1 & 3 in barrel used type 1

The program has determined that barrel losses and length are such that type 1 flow will occur in the inlet section of the culvert. The approach water-surface elevation is computed using the type 1 flow equations.

9, WARNING -- No solution for type 3 inlet, assumed normal flow depth in inlet

The program was unable to find an appropriate solution for the inlet equation for type 3 flow. Because the culvert slope is mild, normal depth is assumed to occur in the inlet. Refer to the section on flow transitions for an explanation.

10, WARNING -- linearly interpolated between high head flows and type 2 instead of type 3

The upstream water-surface elevation is between the lower limit for high head flows and the upper limit for the low head flows. Because the type 3 equation for tailwater control could not be solved, the type 2 equation for critical depth in the culvert outlet was used. This may reduce the upstream water-surface elevation below what actually occurs.

11, WARNING -- linearly interpolated between high head flows and critical depth flows

The upstream water-surface elevation is between the lower limit for high head flows and the upper limit for the low head flows . The upstream water-surface elevation is interpolated between either type 1 and types 5 or 6 or type 2 and types 5 or 6 or type 3 and types 5 or 6 as suggested in Bodhaine. If the flow type is listed with a zero, critical depth is larger than the culvert height. Refer to the section on flow transitions for details.

13, WARNING -- culvert is flowing full and part full

If flow type is 34, entrance is flowing as type 3 and exit as type 4; if flow type is 43, entrance is flowing as type 4 and exit as type 3.

15, WARNING -- h/D exceeds 6.5 for type 6

Solution of type 6, orifice flow, is computed from a functional relationship defined by laboratory experiments. The relationship is extrapolated for values of h/D greater than 6.5. See figure 17 on page 34 of Bodhaine (1968).

16, ERROR -- in type 6 flow computation

The computed flow depth in the approach section is less than zero. An error in data may exist.

SUMMARY

The user's guide contains information on the culvert analysis program and examples that demonstrate appropriate use of the program. The program uses the basic procedure described in previous work on culverts with a few modifications to allow solutions to be computed between flow type transitions. Rating curves or rating surfaces that describe the hydraulic behavior of the culvert can be plotted from the program results. The program can also be used to determine discharges for culverts from measured high-water marks.

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APPENDIX

Program corrections to versions previous to 97-08.

PROGRAM CORRECTIONS

Several bugs have been detected in the previous version of CAP, 96-01. The following describes the bugs and the corrections made.

The CG record variable, ICODE, did not affect pipe arch computations appropriately. The previous user's manual (Fulford, 1997) also neglected to state that the J portion of the ICODE is required for pipe arches. The J portion of the ICODE should be entered for pipe arches and indicates the material used and for corrugated pipe, the corner radius of the pipe when BOTRAD, TOPRAD, and CORRAD are not specified. Omission of a valid J value will result in the program failing to work. The J codes are as follows:

1- concrete pipe, 2,4- corrugated metal pipe, corner radius<= 18"
3- aluminum pipe, 5- corrugated metal pipe, corner radius = 31"
6- corrugated metal pipe, corner radius = 47"

These codes may not be compatible with WSPRO J codes for some cases.

The *CF record variable, HFLW, did not affect computations as was stated in OFR 95-137. This has been corrected. HFLW, the approach water-surface elevation at which to switch from type 5 to type 6 calculations, works as documented in the OFR. Caution should be used when applying this variable. The approach water-surface elevation, HFLW, is compared against the approach water-surface elevation computed for the type 5 (sluice gate) flow. The computation then switches to type 6 (orifice) flow and does not compare the computed approach water-surface elevation against the HFLW value. This can result in the type 6 computed elevation being lower than the HFLW value. The TWRI tables for determining when to switch between high head flow types has not been included in the program.

The *C5 record was sensitive to the number of C5 coefficient and depth ratio pairs entered. The program was altered to allow less than four pairs and more than four pairs to be entered without causing program errors. The program ignores any pairs past four and will compute with as few as one pair. As was stated previously, this record is no longer required for the program to run.

The previous version detailed report contained meaningless fall and loss values for computations made by linearily interpolating between high head and low head flows. For these computations the fields have been blanked. Additionally, the culvert section properties output for detailed reports had minor reformatting and additional information added. Culvert type is now indicated by text at the top of the page and beveling or rounding ratio is added to the data section that contains the adjustment coefficients.

The *CS record, used to describe the geometry of nonstandard culvert sections, allowed only 7 coordinate pairs to be entered on a line. This was not a sufficient number for the field length and has been increased to 12 pairs. This change does not affect the total number of coordinate pairs allowed to describe the culvert, which is 50 pairs.

For nonstandard culvert descriptions using the *CS record, if the leftmost coordinate pair was not entered first on the *CS record an erroneous width was printed in the results. This has been corrected. This bug affected only the width that was printed in the detailed report. It is still recommended to enter the leftmost coordinate pair first and then to enter the remaining pairs in counterclockwise order.

Skew angles entered on the XS record that describes the approach section geometry did not affect the computations. This error has been corrected and coordinate pairs entered will be adjusted by the cosine of the skew angle. The section reference distance is not affected by the skew angle. Section reference distances should be determined using the center of the main channel of the reach.

Appendix II

ROUGHNESS COEFFICIENTS FOR CULVERTS

Corrugated Steel Pipe

Table 1: Manning's roughness values for corrugated steel pipe.

	Manning's roughness coefficient, n					
	Riveted				Structural-Plate	
	Corrugation, Pitch x Rise, inches					
Pipe Diameter (feet)	2-2/3 x 1/2	3 x 1	5 x 1	6 x 1	6 x 2	9 x 2-1/2
	Annular Corrugations					
1	0.027					
2	0.025					
3	0.024	0.028		0.025		
4	0.024	0.028	0.026	0.024		
5	0.024	0.028	0.026	0.024	0.035	0.036
6	0.023	0.028	0.026	0.024	0.035	0.035
7	0.023	0.028	0.026	0.023	0.035	0.034
8	0.023	0.028	0.025	0.023	0.034	0.034
9	0.023	0.028	0.025	0.023	0.034	0.034
10	0.022	0.027	0.025	0.023	0.034	0.034
11	0.022	0.027	0.025	0.022	0.034	0.033
12		0.027	0.024	0.022	0.033	0.033
16		0.026[a]	0.023[a]	0.021[a]		
18						0.033[a]
21					0.033[a]	
	Helical (Spiral) Corrugations					
1	0.011		Use values for annular corrugations for all other corrugation sizes and pipe diameters.			
2	0.016					
3	0.019	0.021				
4	0.020	0.023				
5	0.022	0.024				
6		0.026				
Range of pipe diameters commonly encountered with indicated corrugation sizes, in feet						
	<9	3-13	5-13	3-13	5-25	5-25

[a]extrapolated beyond Federal Highway Administration curves. See page 16 HDS-5 for extrapolation.
Note: n values apply to pipes in good conditions. Severe deterioration of metal or pipe section misalignment may cause slightly higher values.

Corrugated Steel Pipe with Paved Inverts

For corrugated steel pipe with paved inverts, use a composite Manning's roughness, n_c, computed from the following equation for the culvert Manning's roughness,

$$n_c = \frac{0.012P_p + n_b(P - P_p)}{P}$$

where n_c is the composite roughness, n_b is the base Manning's n for unpaved inverts (see previous table), P_b is the length of wetted perimeter that is paved and P is the total length of wetted perimeter.

Materials other than Corrugated Steel Pipe

Table 2: Manning's roughness values for materials other than corrugated steel pipe

Culvert Material	Manning's Roughness, n
concrete - smooth (cast or tamped pipe)	0.011 - 0.015
concrete - field construction	0.012 - 0.015
concrete - badly spalled	0.015 - 0.020
welded steel	0.012
wood stave	0.012
cast iron	0.013
vitrified clay	0.013
riveted steel	0.015
polyethylene[1], corrugated	0.020
polyethylene[1], smooth lining	0.012
steel, smooth rib pipe[2] - ribs 7.5" to 12" o.c.	0.012

[1]plastic pipe

[2]pipe is fabricated by forming external rectangular rib sections and a helical lock seam. Ribs are spaced far apart.