THE USE OF THREE-PARAMETER RATING TABLE LOOKUP PROGRAMS, RDRAT AND PARM3, IN HYDRAULIC FLOW MODELS

By Curtis L. Sanders, Jr.

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
foot (ft)	0.3048	meter
foot per second squared (ft/s^2)	0.3048	meter per second squared
cubic foot per second (ft^3/s)	0.0283	cubic meter per second

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ABSTRACT

Subroutines RDRAT and PARM3 enable computer programs such as the BRANCH open-channel unsteady-flow model to route flows through or over combinations of critical-flow sections, culverts, bridges, road-overflow sections, fixed spillways, and(or) dams. The subroutines also obstruct upstream flow to simulate operation of flapper-type tide gates. A multiplier can be applied by date and time to simulate varying numbers of tide gates being open or alternative construction scenarios for multiple culverts. The subroutines use three-parameter (headwater, tailwater, and discharge) rating table lookup methods. These tables may be manually prepared using other programs that do step-backwater computations or compute flow through bridges and culverts or over dams. The subroutine, therefore, precludes the necessity of incorporating considerable hydraulic computational code into the client program, and provides complete flexibility for users of the model for routing flow through almost any affixed structure or combination of structures. The subroutines are written in Fortran 77 language, and have minimal exchange of information with the BRANCH model or other possible client programs. The report documents the interpolation methodology, data input requirements, and software.

INTRODUCTION

Subroutines RDRAT and PARM3 enable "client" computer programs such as the U.S. Geological Survey (USGS) branch-network one-dimensional (BRANCH model) unsteady flow model (Schaffranek and others, 1981) to route flows through subreaches of natural streams or structures, where flow can alternate between super- and sub-critical flow regimes. The subroutines also route flows through or over complex combinations of culverts, bridges, road overflow sections, fixed spillways, and (or) dams. In addition, the subroutines account for the operation of flapper-type tide gates, which obstruct upstream flow and a multiplier can be applied to computed discharges based on date and time. The multiplier can be used to simulate varying numbers of operational flapper gates or alternative construction scenarios for multiple culverts.

Flows are routed within the client program for all structures by use of three-parameter (headwater, tailwater, and discharge) rating table lookup methods. Input for the subroutines is prepared external to the BRANCH Model by the user, using output from hydraulic programs such as the Water Surface Profile Computations (WSPRO) program (Shearman, 1990) or the culvert-flow computation program A526 (H.F. Matthai, H.E. Stull, and Jacob Davidian, U.S. Geological Survey, written commun., undated). Complex hydraulic data entry and computations, therefore, do not have to be incorporated into the client program, and the user has total flexibility, except for coding conventions, as to how the ratings are constructed. A knowledge of hydraulics and the interpolation methods is necessary, however, to construct the ratings. Several three-parameter ratings can be added together graphically to create a single rating where several structure types exist at a single location. The subroutines presented in this report also do simpler two-parameter (headwater and discharge) rating table lookups.

Inclusion of these subroutines in the BRANCH Model allow routing of hydrographs from non-uniform sub-basins through stream reaches where the storage-basin outflow ratings are in backwater or where flow can go upstream into large storage areas. In addition, these subroutines can be used by the National Water Information System (NWIS) to compute flow through culverts using recorded headwater and tailwater stages. The NWIS is the USGS computerized computation and storage system for its national treasury of water data. The subroutines also can be modified to do interpolations for three-parameter relations used to compute entrance-loss coefficients for indirect computations of flows through culverts and bridges.

This report documents the three-parameter rating table interpolation method, data input, and the required software. Subroutine RDRAT reads the necessary input data, and subroutine PARM3 computes the discharge for the client program based on rating numbers, headwater elevations, and tailwater elevations. Subroutine RDRAT also can apply a multiplier based on date and time, and prevents negative flows for simulations of flapper-type tide gates.

FUNCTIONAL SPECIFICATIONS

Subroutines were designed to minimize the interaction with the client program (BRANCH model) by using data encapsulation in a manner similar to that suggested by Delong and others (1992). Subroutine RDRAT reads all necessary data using only the name of the American Standard Code for Information Interchange (ASCII) file holding the rating table and a Fortran 77 (F77) unit number as provided to subroutine RDRAT by the client program. Subroutine PARM3 does all the computations. The client program provides subroutine PARM3 with date and time, the rating numbers, and headwater and tailwater elevation. The PARM3 subroutine returns the discharge and error flags to the client program. The client program does not have to share large common blocks of information with either subroutine, because most of the necessary data are read by the subroutines from the ASCII file.

Computational specifications are:

1. Interpolations can be arithmetic or logarithmic with log offset.

2. Two-parameter (headwater and discharge) interpolations can be done for:

   a. Critical-flow sections
   b. Highway embankments
   c. Fixed spillways at dams

3. Three-parameter (headwater, tailwater, and discharge) interpolations can be done for flow at:

   a. cross sections where flows can change back and forth from supercritical to subcritical,
   b. cross sections where flows are affected by variable backwater,
   c. culverts,
   d. bridges, and
   e. electric turbines.

4. Interpolations can be done for any combinations of flows in (2) and (3) above by graphical or numerical combinations of these ratings into one rating. For example, assume that separate tailwater ratings for a tailwater elevation of 8.0 ft are available for two bridges. Assume that at a headwater elevation of 8.5 ft, the flow through the bridges are 1,000 and 1,500 ft^3/s, as determined from the ratings. Then, for a headwater of 8.5 ft and a tailwater of 8.0 ft the total flow would be 2,500 ft^3/s. The process can be repeated for all the tailwater ratings for the two bridges. The process is easier if done graphically:

   a. Plot the tailwater ratings as a series of smooth curves on arithmetic paper with headwater elevation on the vertical axis and discharge on the horizontal axis.
   b. Project a horizontal line at selected headwater increments, and use a pair of dividers to cumulate flows through all structures along this horizontal line for each tailwater curve. Use a plotting symbol to represent the cumulated flow for the flows associated with the tailwater curve.
   c. Draw a smooth line through the plotting symbols, and read off the cumulated flows at increments small enough for straight-line interpolation to be sufficiently accurate.

5. Different ratings for positive and negative flow can be used.

6. Flapper-type tide gates can be simulated by preventing negative flow when negative falls exceed a specified amount.

7. A multiplier can be applied to discharge based on beginning date and time to simulate varying numbers of active tide gates or varying numbers of structures for testing of alternative multiple-culvert construction scenarios.

THREE-PARAMETER RATINGS

The complex rating in figure 1 is shown to demonstrate all the interpolation methods used by the subroutines. The coding and theory for a simple three-parameter rating without changes in flow type is simpler. The three-parameter rating shown in figure 1 is for a 100-ft long, 3-ft diameter concrete-pipe culvert with zero slope. Data for the rating were computed by USGS program A526 (H.F. Matthai, H.E. Stull, and Jacob Davidian, U.S. Geological Survey, written commun., undated). Bodhaine (1969) gives a detailed description of culvert hydraulics and flow types. A rating from step-backwater program WSPRO (Shearman, 1990) is not shown, but would be similar to the rating below the horizontal line where (HW-Z)/D=1.2 in figure 1, for a cross-section that undergoes subcritical and supercritical flow. In the equation above, HW is the headwater elevation, Z is the elevation of the upstream invert of the culvert, and D is the maximum vertical opening of the culvert in feet. Headwater elevation is shown on the ordinate, and discharge is shown on the abscissa (fig. 1) for designated tailwater curves. Enough points and tailwater curves must be obtained by the user for straight-line arithmetic or logarithmic interpolation to be valid.

Types 1, 2, and 3 flow are open-pipe culvert flow. Critical flow exists at the entrance for type 1 flow and at the outlet for type 2 flow. Tranquil flow exists throughout the culvert for type 3 flow. In type 4 flow, the whole culvert is submerged. In flow types 5 and 6, high-head flow exists at the entrance of the culvert and the outlet of the culvert is not submerged. The culvert flows full for type 6 flow, but not for type 5 flow (Bodhaine, 1969).

The limiting-flow curve shown in figure 1 is the limiting headwater-discharge rating for a critical-flow section in a natural stream or for types 1, 2, 5, or 6 culvert flow. The tailwater curves may or may not be tangential to the limiting-flow curve (points 4 and 6 in figure 1), but they do intersect it at fairly uniform intervals.

For culverts, there is an indeterminate transitional zone for flow types between headwater elevations corresponding to (HW-Z)/D=1.2 and 1.5 (fig. 1). Flow in this zone can be alternating between high-head parallel construction flow (types 5 or 6) and open-pipe flow (types 1, 2, or 3). Usually, straight lines are constructed between the computations for headwater elevations where (HW-Z)/D=1.2 and 1.5 (points 10 and 12 and points 11 and 12 in figure 1).

The method of interpolation, where the rating is defined only by the tailwater curves, is to interpolate a tailwater curve from the input tailwater curves, as shown by the dashed line through points 1 and 2 (fig. 1), and to lookup the discharge from this curve using the input headwater. It is important to remember that when coding input data for this type of rating, sufficient upper and lower bounds of input-tailwater curves need to be provided. Interpolation is done in the vertical and only from tailwater curves. It is incorrect to interpolate a tailwater curve in this zone using a tailwater curve and a limiting-headwater discharge-rating curve. Tailwater curves, therefore, must be coded bounding the zones where the tailwater curve is to be interpolated. For example, points 1 and 2 (fig. 1) are interpolated in the vertical from data points on the 2.5 and 3.0 ft tailwater curves.

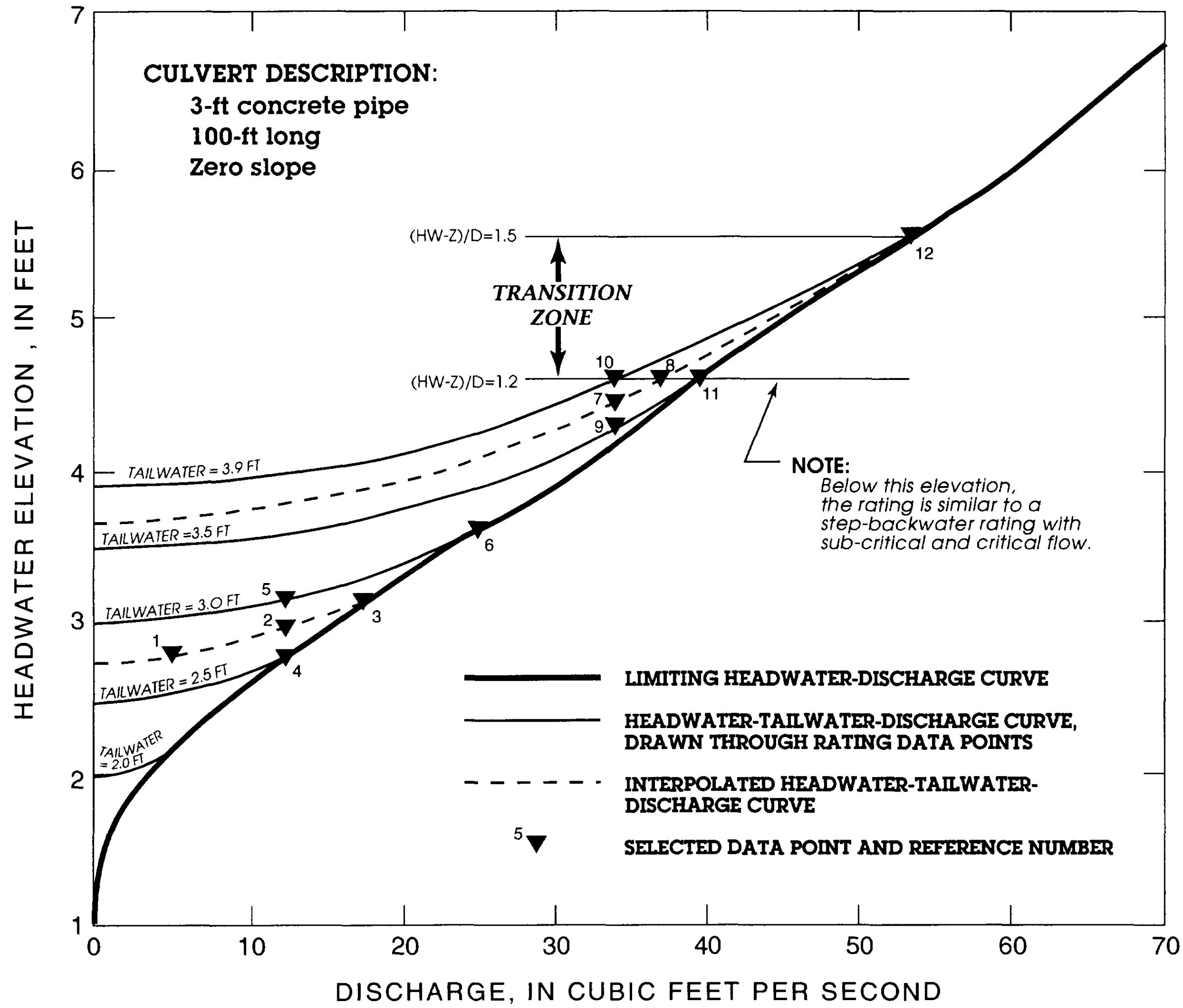

Figure 1.--Three-parameter rating with types of curves and input data points.

Interpolation within triangles defined by points 4-5-6, 9-10-11, and 10-11-12 (fig. 1), do not qualify for the interpolation method described above. The dashed line or tailwater curve between points 2 and 3 is defined by interpolating point 2 from points 4 and 5 and by interpolating point 3 from points 4 and 6.

The dashed line between points 7 and 8 is determined by interpolating point 7 from points 9 and 10 and by interpolating point 8 from points 10 and 11. The dashed line between points 8 and 12 is determined by interpolating point 8 from points 10 and 11 as before, and using point 12 directly. Point 12 is the point where the culvert type 5 or 6 flow intersects the line where (HW-Z)/D=1.5. Points 4, 6, 10, 11, and 12 are at intersections of graphically extended rating lines with other rating lines or lines marking a change of flow type. The user must select rating points with a full understanding of the above linear-logarithmic-interpolation schemes.

For the special case of type 4 culvert flow (submerged culvert flow), discharge is computed directly by:

$$Q = K(HW-TW)^{0.5}, \tag{1}$$

where

Q is the discharge, in cubic feet per second,
HW is the headwater elevation, in feet,
K is a constant, in feet $^{2.5}$ per second, and
TW is the tailwater elevation, in feet.

The constant K, is determined by the equation:

$$K = CA_o \sqrt{\frac{2g}{1 + \frac{29\ C^2\ n^2\ L}{R_o^{4/3}}}}, \tag{2}$$

where

A_o is the area of the culvert, in square feet,
C is the entrance coefficient,
g is the constant acceleration of gravity, 32.2 feet per second squared,
L is the length of culvert, in feet,
n is the Manning's roughness coefficient for the culvert, and
R_o is the hydraulic radius of the culvert, in feet.

Equations 1 and 2 are applicable when HW and TW are greater than or equal to the sum of the largest vertical dimension of the culvert and the elevation of the upstream invert, in feet.

INPUT DATA

Input data for ratings can be extracted from graphs such as figures 1 and 2 (fig. 2 at end of report). The data may be entered into an ASCII file, as presented in the appendix of this report, for input to program RDRAT.

A graph such as figure 1 is essential for the coding of input data for complex culvert ratings and three-parameter ratings that include a limiting-flow curve. In general, the limiting-flow curve should be constructed first. For culverts, construct a straight line between the limiting-flow curve points at (HW-Z)/D = 1.2 and 1.5. Next, construct the tailwater curves, and smooth them with the limiting-flow curve [below (HW-Z)/D = 1.2, for culvert ratings]. Terminate tailwater curves at (HW-Z)/D = 1.2 for culvert ratings, and draw straight lines from these points to the limiting-flow curve at (HW-Z)/D = 1.5.

The record types of the dataset are identified by the first two columns of each record by "TA," "T1-4," and "TD" as described below. Subroutine RDRAT searches any flat file for their record types; therefore, the records are either in a master control file with other data used by the client program or in its own separate file. The remaining data in columns 2 to 80 are entered in list format, and are separated by blanks. The maximum number of ratings on the "TA" record, rating points for each of the TI-4 records, and dates coded on the TD record are 5, 100 and 50, respectively. These limits can be easily changed, however, as described in the "software description" section of this report.

Input data needed by the subroutine are:

"TA" Record:

Column 1-2, Code "TA" for record type.
Column 3-80, Code the following, separated by blanks:

Rating number:

Should be sequential, starting with the number 1.

Rating type:

0 = arithmetic interpolation
1 = logarithmic interpolation

Logarithmic stage offset, in feet; code 0.0 if not applicable

Number of parameters in rating:

2 = headwater-discharge rating
3 = headwater-tailwater-discharge rating

Culvert type 4 "K" factor (eq. 1) for positive flow; code 0.0 if not applicable

Culvert type 4 "K" factor for negative flow; code 0.0 if not applicable.

Tailwater elevation, in feet, above which culvert type 4 submerged flow exists; code 999999.0, if not applicable.

Tailwater elevation, in feet, below which only the limiting headwater discharge rating will be used; code -999999.0, if not applicable.

Headwater elevation, in feet, above which only the limiting headwater-discharge rating will be used; code -999999.0 if not applicable. This is also point 12 in figure 1, where culvert type 5 or 6 flow intercepts the (HW-Z)/D=1.5 line.

Fall, in feet, across tide gates, at which water is to be prevented from flowing upstream through the gates. This will normally be set to 0.0 or a small negative number. Code 0.0 if tide gates are not present.

Datum correction[1] to be ADDED to the input headwaters and tailwater elevations before application to rating.

"T1" Record:

Columns 1-2, Code "T1" for record type; this record describes a rating point located only on the limiting headwater-discharge curve as indicated in figure 2.

Columns 3-80, Code the following, separated by blanks:

Discharge, in cubic feet per second, and headwater elevation, in feet.

Note: It is not necessary to code a value for tailwater elevation.

"T2" Record:

Columns 1-2, Code "T2" for record type; this record type describes a rating point common to the limiting headwater-discharge rating curve and to a headwater-tailwater-discharge rating curve as identified in figure 2.

Columns 3-80, Code the following, separated by blanks:

Discharge, in cubic feet per second,
Headwater elevation, in feet, and
Tailwater elevation, in feet.

---

[1] The datum correction can be used to adjust output from program A526, which does not allow negative elevations, to experimentally raise or lower structures, or to use one rating for several structures at different datums.

"T3" Record:

Columns 1-2, Code "T3" for record type; this record type describes a rating point located only on a headwater-tailwater-discharge rating curve as identified in figure 2.

Columns 3-80, Code the following, separated by commas:

Discharge, in cubic feet per second,
Headwater elevation, in feet, and
Tailwater elevation, in feet - for parallel construction with "T2" record.

"T4" Record:

Columns 1-2, Code "T4" for record type; this record type describes a rating point located on a headwater-tailwater-discharge rating curve and also at the (HW-Z)/D=1.2 line, such as is identified in figure 2.

Note: The (HW-Z)/D=1.2 line need not be horizontal as shown in figure 1; it can be a series of segments as described by the "T4" record. This is usable if there is a skewed upper boundary for three-parameter rating lookup, such as for turbine ratings.

Column 3-80, Code the following, separated by blanks:

Discharge, in cubic feet per second,
Headwater elevation, in feet, and
Tailwater elevation, in feet - for parellel construction with "T2" record.

"TD" Record:

Columns 1-2, Code "TD" for record type; if this record type exists, the multiplier defined below will be applied to the computed discharge if the date and time below are equalled or exceeded. This can be used to simulate varying numbers of tide gates open at specified times or to simulate the effects of varying the numbers of structures at a site.

Columns 4-9, YYMMDD, date to begin multiplier, where YY is the year, MM is the month, and DD is the day of the month.

Columns 11-14, HHMM, time to begin multiplier, where HH is the hour and MM is the minute.

Columns 15-24, Multiplier to be applied to computed discharge. The multiplier is not prorated between adjacent date-times.

Outputs from culvert program A526 and step-backwater program WSPRO are generally sorted by discharge, tailwater, and headwater, as is required for input to this subroutine. However, output from these programs should not be input blindly to this subroutine, without a hydraulic analysis of plots of the three-parameter ratings. For example, points 4, 6, 9, 10, 11, and 12 (fig. 1) are not automatically output by these two programs. These points had to be determined from the graphic plot for coding on the "T2" and "T4" records.

Points shown on figure 2 are a guide for coding the "T1-4" records as described above and tabulated in the appendix of this report, based on the interpolation schemes. Enough points and tailwater curves are coded to maintain accuracy of straight-line interpolation. The rating points should be vertically aligned as shown in figure 2. A vertical string of points also should be created from the tailwater curves and limiting headwater discharge curve for "T2" and "T4" records as shown in figure 2. In general, as shown in the appendix, the "T1-4" records are all sorted by discharge, tailwater elevation, and headwater elevation. For a simple two-parameter headwater-discharge rating, the "T2-4" records are not needed.

SOFTWARE DESCRIPTION

The client program calls only the RDRAT and PARM3 subroutines described below. Subroutine RDRAT reads the rating-input data, and subroutine PARM3 does the interpolation using the rating data and other data provided by the client program. Ratings are identified by a rating number and are fully described by the "TA," "T1-4," and "TD" records. The client program needs only the rating number to access all respective rating data on these records. A rating from a master file of ratings also can be used by reference to the rating number in several calls without repetitive coding of the rating. Both subroutines are written in F77 programming language. The number of ratings, rating points, and dates allowed by the subroutines on the "TA," "TI-4," and "TD" records can be modified by changing the "parameter" declaration of the subroutine variable "NORATS," "RTPTS," and "NORTDT," respectively, in the subroutine-source code before compilation.

Subroutine RDRAT reads into common blocks the data necessary for the PARM3 rating table lookup subroutine, and the data are kept in memory for subsequent access by the PARM3 subroutine. Arguments for the RDRAT subroutine are:

1. Name of the file holding the rating data (input, 48 character maximum). The subroutine assumes the file to be closed, opens it, reads the data, and closes the file. This can be a file separate from control files used by the client program, or the TA, TI-4, and TD records can be part of the control files. The program searches the file for records having "TA," "T1-4," or "TD" coded in the first two columns.

2. Unit number to be assigned to the file (input, integer).

3. Fatal warning flag (output, integer). If this flag is not zero, an error occurred in reading the data, and the client program should issue warning messages and discontinue computations. Fatal warning flags are:

   1 = error in opening file
   2 = error in reading file
   3 = error in closing file
   4 = error due to attempt to take the logarithm of a number less than or equal to zero.

Subroutine PARM3 tests all the conditions for interpolation and does the interpolation. It also checks to see if the multiplier described above exists, applies it if it exists, and checks the date to see when it is to be changed. It also tests for negative flow, changes ratings, if the rating for negative flow is not the same as for positive flow, and prevents negative flow if tide gates are present. Arguments for subroutine PARM3 are:

1. Year, month, day, hour, and minute of the values being computed (input, integer), for use in applying multiplication factors to the computed discharge.

2. Positive and negative flow-rating numbers (input, integer).

3. Headwater and tailwater elevations (input, real).

4. Discharge (output, real).

5. A warning error flag (not used).

6. A fatal error flag (output, integer). If this flag is not zero, a fatal error occurred, and the client program should issue a warning message and discontinue all computations. Fatal warning flags are:

   4 = error because of an attempt to take the logarithm of a number less than or equal to zero
   5 = error because more dates were input than allowed by program dimension statement
   6 = error because a rating table was exceeded
   7 = error because the program was unable to arrive at a discharge solution, probably because of a programming error from not identifying all solution cases
   8 = error because more rating points were input than allowed by limits defined by the program dimension statement
   9 = error because more ratings were input than allowed by limits defined by the program dimension statement
   10 = error because of an attempt to divide by zero in interpolation equations because two consecutive rating-input (not output) values were equal.

Subroutine PARM2 does a simple arithmetic rating-table lookup for subroutine PARM3. Logarithmic conversions are already made prior to its being called.

Subroutine INTERP does simple interpolation for subroutine PARM2.

Subroutine LOGX applies logarithmic offsets and takes logarithms of headwater, tailwater, and discharge.

SUMMARY

Subroutines RDRAT and PARM3 were developed to route flows through or over constrictions of natural channels (such as bridges or dams) and through multiple flapper-type tide gates using three-parameter (headwater elevation, tailwater elevation, and discharge) rating-table lookup methods. The subroutines also use two-parameter (headwater elevation and discharge) rating-table lookup methods and can interpolate both arithmetically and logarithmically. Different ratings for positive and negative flows can be used, and a multiplier can be applied to discharge based on beginning date and time to simulate varying numbers of tide gates or varying numbers of structures for the testing of multiple-culvert construction scenarios.

The two- and three-parameters rating tables are prepared external to the client program (the U.S. Geological Survey BRANCH one-dimensional unsteady flow model, in particular) by using any valid hydraulic method or program. Therefore, the subroutines can be used for almost any fixed structure and relieve the calling program from having to accommodate a huge variety of hydraulic computational methods. The theory of two- and three-parameter rating-table lookup methodology, interpolation methods used, data input, and software are described.

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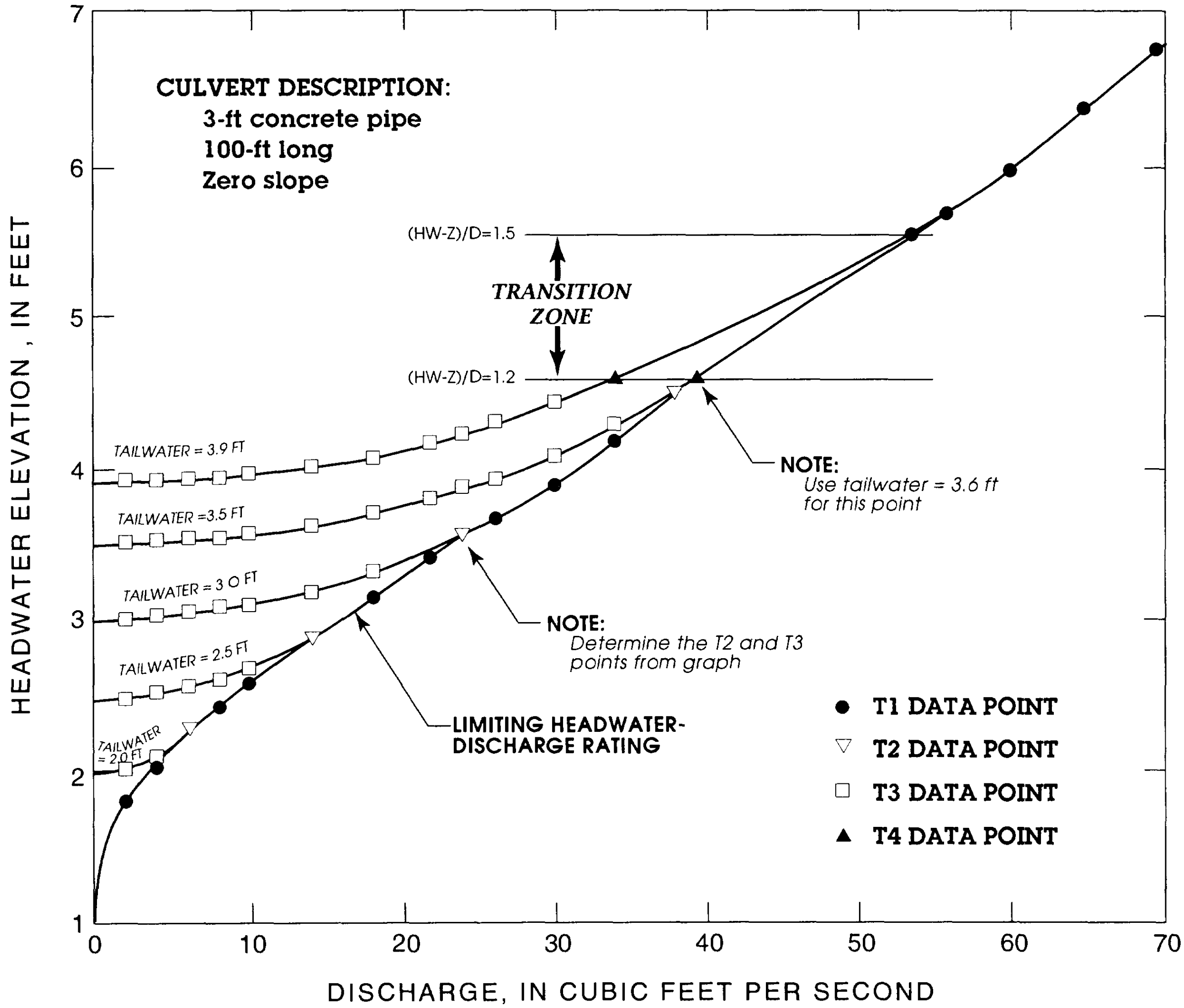

Figure 2.--Three-parameter rating with input data points.

APPENDIX

Input data set

Appendix --Input data set											
TA	1	0	0.0	3	38.28	20.0	4.0	2.0	5.5	-999999.	0.0
T1	2.0	1.79	0.0								
T3	2.0	2.03	2.0								
T3	2.0	2.51	2.5								
T3	2.0	3.00	3.0								
T3	2.0	3.50	3.5								
T3	2.0	3.90	3.9								
T1	4.0	2.06	0.0								
T3	4.0	2.12	2.0								
T3	4.0	2.53	2.5								
T3	4.0	3.02	3.0								
T3	4.0	3.51	3.5								
T3	4.0	3.91	3.9								
T2	6.0	2.26	2.0								
T3	6.0	2.57	2.5								
T3	6.0	3.03	3.0								
T3	6.0	3.52	3.5								
T3	6.0	3.92	3.9								
T1	8.0	2.45	0.0								
T3	8.0	2.63	2.5								
T3	8.0	3.06	3.0								
T3	8.0	3.54	3.5								
T3	8.0	3.93	3.9								
T1	10.0	2.62	0.0								
T3	10.0	2.70	2.5								
T3	10.0	3.09	3.0								
T3	10.0	3.56	3.5								
T3	10.0	3.95	3.9								
T2	14.0	2.91	2.5								
T3	14.0	3.18	3.0								
T3	14.0	3.62	3.5								

T3	14.0	4.01	3.9								
T1	18.0	3.17	0.0								
T3	18.0	3.31	3.0								
T3	18.0	3.69	3.5								
T3	18.0	4.08	3.9								
T1	22.0	3.42	0.0								
T3	22.0	3.47	3.0								
T3	22.0	3.80	3.5								
T3	22.0	4.17	3.9								
T2	24.0	3.55	3.0								
T3	24.0	3.86	3.5								
T3	24.0	4.20	3.9								
T1	26.0	3.66	0.0								
T3	26.0	3.92	3.5								
T3	26.0	4.29	3.9								
T1	30.0	3.91	0.0								
T3	30.0	4.07	3.5								
T3	30.0	4.43	3.9								
T1	34.0	4.16	0.0								
T3	34.0	4.26	3.5								
T4	34.0	4.60	3.9								
T2	38.0	4.49	3.5								
T1	39.2	4.60	0.0								
T4	39.2	4.60	3.6								
T1	53.6	5.50	0.0								
T1	56.0	5.67	0.0								
T1	60.0	5.95	0.0								
T1	65.0	6.34	0.0								
T1	70.0	6.76	0.0								
TD	911001	0100	1.0								
TD	911005	0400	2.0								
TD	911005	1000	0.0								