COMPUTATION OF RECORDS OF STREAMFLOW AT CONTROL STRUCTURES

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Errata Sheet
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Page 5, figure 1 - h_1 under definition of symbols used in sketch should read Static headwater referenced to gate sill

Page 11, first line after equation 14 should read, where $\beta = \sin^{-1}[(a/(R + Z_o)]$, $\alpha = 90^o - \beta$, and h_3 is the average tailwater

Page 13, first line of page should read, Calibration of free weir flow requires the definition of the relation

Page 22, second line of first paragraph should read, tabulated in table 2. The individual turbine discharges are plotted as a function of

Page 34, Table heading should read, Table 5.-- (Continued)

Page 50, Table 8, reading from left to right, eighth column heading should read,

$$\frac{h_{3s}}{h_{1s}} \text{ instead of } \frac{h_{1s}}{h_{3s}} .$$

Page 43, figure 10 - The first four figures on the abscissa (horizontal) axes should read--0.03, 0.04, 0.06 and 0.08 instead of .03, .04, 0.6, and 0.8.

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SYMBOLS AND UNITS

Symbol	Definition	Unit
A	Plan area of lock chamber	ft^2
a	Elevation difference, trunnion centerline to sill	ft
B	Lateral width of a Tainter gate	ft
B_c	Lateral width of a crest gate	ft
B_s	Length of fixed spillway	ft
C	Free orifice flow coefficient of discharge	
c	Elevation difference, gate reference point (R.P.) to sill	ft
C_{gs}	Submerged orifice flow coefficient of discharge	
C_{SW}	Free weir flow coefficient of discharge, fixed spillway	
C_{SWS}	Submerged weir flow coefficient of discharge, fixed spillway	
C_W	Free weir flow coefficient of discharge, gated part of structure	
C_{WS}	Submerged weir flow coefficient of discharge, gated part of structure	
d	Elevation difference, gate R.P. to sill with gate in closed position	ft
g	Acceleration due to gravity	ft/s^2
H_1	Total headwater including velocity head referenced to gate sill	ft
h_1	Static headwater referenced to gate sill	ft
h_3	Static tailwater referenced to gate sill	ft
h_{1c}	Static headwater referenced to crest-gate sill	ft
H_{1s}	Total headwater including velocity head referenced to the fixed-spillway sill	ft
h_{1s}	Static headwater referenced to fixed-spillway sill	ft
h_{3s}	Static tailwater referenced to fixed-spillway sill	ft
h_g	Vertical gate opening	ft
K	Constant in turbine flow equation using piezometer taps	$ft^{5/2}/s$
K_1	Constant in turbine flow equation using a commercial discharge monitor	1/s
N	Number of lockages occurring between recordings	
Q	Computed discharge per gate	ft^3/s
Q_c	Computed discharge for a single crest gate	ft^3/s
Q_{cm}	Commercial monitor output	ac-ft
Q_L	Computed lockage discharge	ft^3/s
Q_{LL}	Computed lock leakage discharge	ft^3/s
Q_s	Computed fixed-spillway discharge	ft^3/s
Q_T	Total turbine discharge	ft^3/s
Q_t	Turbine discharge for one turbine	ft^3/s
q	Measured discharge as prorated per gate	ft^3/s

Symbol	Definition	Unit
q_{GL}	Gate leakage correction factor	ft^3/s
q_{LL}	Lock leakage correction factor	ft^3/s
R	Radius from trunnion centerline to upstream face of a Tainter gate	ft
r	Radius from trunnion centerline to gate R.P.	ft
Z_o	Effective gate opening width of a submergible gate with the gate lip at or below sill elevation	ft
α	An angle used in leakage calibration for submergible gates defined as $90^{\circ}-\beta$	
β	An angle used in leakage calibration for submergible gates defined as the angle whose sine is $a/(R + Z_o)$	
$\Delta h = h_1 - h_3$	Static head loss through structure, or differential head during lockage	ft
$(\Delta h)_d$	Design static head loss through the structure	ft
Δp	Scroll case pressure differential from Winter-Kennedy piezometer taps	ft
Δt	Time between recordings	sec
θ	Included angle between radial lines from the trunnion centerline through the R.P. and through the lower lip of the gate	
Φ_L	The angle measured from horizontal to the radial line from the trunnion centerline through the lower lip of the gate in a closed position	
Φ_U	The angle measured from horizontal to the radial line from the trunnion centerline through the gate R.P. with the gate in a closed position	
$<$	Less than	
$>$	Greater than	
$\geq$	Greater than or equal to	

CONVERSION FACTORS

The conversion factors for the terms used in this report are listed below. The metric equivalents are shown only to the number of significant figures consistent with the values for the English units within the text.

English	Multiply by	Metric
feet (ft)	0.3048	meters (m)
cubic feet per second (ft^3/s)	0.02832	cubic meters per second (m^3/s)

The nondimensionless constants used in some of the equations in this report can only be used with the English units.

COMPUTATION OF RECORDS OF STREAMFLOW AT CONTROL STRUCTURES

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ABSTRACT

Traditional methods of computing streamflow records on large, low-gradient streams require a continuous record of water-surface slope over a natural channel reach. This slope must be of sufficient magnitude to be accurately measured with available stage measuring devices. On highly regulated streams, this slope approaches zero during periods of low flow and accurate measurement is difficult. Methods are described to calibrate multipurpose regulating control structures to more accurately compute streamflow records on highly-regulated streams. Hydraulic theory, assuming steady, uniform flow during a computational interval, is described for five different types of flow control. The controls are; Tainter gates, hydraulic turbines, fixed spillways, navigation locks, and crest gates. Detailed calibration procedures are described for the five different controls as well as for several flow regimes for some of the controls. The instrumentation package and computer programs necessary to collect and process the field data are discussed briefly. Two typical calibration procedures and measurement data are presented to illustrate the accuracy of the methods.

INTRODUCTION

The purpose of this report is to describe methods that have been developed to compute continuous records of streamflow at flow-regulating structures. The development of the methods was necessary because the water-surface slope between control structures on highly-regulated streams is reduced considerably and can approach zero during periods of low flow. Therefore, traditional methods that require a water-surface slope are not satisfactory. With the additional demands being put on the available water supply, accurate determination of streamflow during periods of low flow becomes even more important. Therefore, a new method was needed that would be accurate during periods of low flow. This, in turn, meant that the new method would have to be independent of the water-surface slope in a channel reach. A flow-regulating structure was a logical point to gage because the computations would be independent of the slope, and the control would be stable except for operational changes. Instrumentation has been developed to measure the changes, and hydraulic theory has been used to develop procedures to calibrate the structure for discharge computations.

THEORY

The hydraulic theory used in the development assumes steady, uniform flow during a computational interval, normally 1 hour. Computational interval and recording interval are used interchangeably. The theory is based on the energy and continuity equations between the approach section and a section downstream of the structure.

Five different flow controls may be present on a multipurpose structure. These are; Tainter gates, hydraulic turbines, fixed spillways, navigation locks, and crest gates. Calibration procedures are described for each of the controls. Calibration relations must be developed from field measurements of discharge and other pertinent hydraulic variables for each control present at the structure. The developed relations are then used as input to a computer program to compute continuous discharge records. Information on instrumentation required and the computer program used are available from the Instrument Development Laboratory, U.S. Geological Survey, Water Resources Division, Bay St. Louis, MS 39529 and from the Automatic Data Section, U.S. Geological Survey, Water Resources Division, Reston, VA 22092, respectively.

The instrumentation package and generalized software package that have been developed to expedite the methods are briefly described. Both packages have been specifically designed for multipurpose structures with one or more of the five controls. Details concerning the design and operation of the instrumentation are beyond the scope of this paper.

Calibration and computation equations have been developed for five different flow controls. Table 1 summarizes the hydraulic conditions necessary for each control and for the different regimes of flow through the Tainter gates and over the fixed spillway.

Tainter Gate Flow

Flow through Tainter gates may be orifice flow or weir flow depending on the gate opening and its relation to the headwater. Both of the flow regimes may be free or submerged depending on the magnitude of the tailwater relative to the headwater and gate opening.

The gate opening, h_g, is the most important variable in distinguishing the regime of flow through Tainter gates. In most cases the gate opening cannot be measured directly in the field during operation of the structure. Therefore, the gate opening is computed indirectly using pertinent geometric properties of the gates and direct measurements of the elevation of a selected R.P. (reference point) on each gate.

Little known about submerged weir flow.

Table 1.--Flow controls and their respective hydraulic equations

Flow control	Flow regimes possible	Hydraulic conditions necessary	Equations used for calibration and computation	Equation number
Tainter gates	Leakage	Submergible gates and $h_g \simeq 0$	$Q = \sqrt{\frac{\Delta h}{(\Delta h)_d}}(q_{GL})$	(2)
	Free orifice	$h_g < 2/3h_1$ and $h_3 < h_g$	$Q = Ch_gB\sqrt{2gh_1}$	(3)
	Submerged orifice	$h_g < 2/3h_1$ and $h_3 \geq h_g$	$Q = C_{gs}h_3B\sqrt{2g\Delta h}$	(4)
	Free weir	$h_g \geq 2/3h_1$ and $h_3/h_1 < 0.6$	$Q = C_WBh_1^{3/2}$	(5)
	Submerged weir	$h_g \geq 2/3h_1$ and $h_3/h_1 \geq 0.6$	$Q = C_WC_{WS}Bh_1^{3/2}$	(6)
Turbines	--	$\Delta h > 0$	$Q_t = K\sqrt{\Delta p}$ or	(7)
			$Q_t = K_1Q_{cm}$	(8)
Fixed spillways	Free weir	$h_{3s}/h_{1s} < 0.6$	$Q_s = C_{SW}B_sh_{1s}^{3/2}$	(9)
	Submerged weir	$h_{3s}/h_{1s} \geq 0.6$	$Q_s = C_{SW}C_{SWS}B_sh_{1s}^{3/2}$	(10)
Locks	--	$\Delta h > 0$	$Q_L = \frac{NA\Delta h}{\Delta t}$	(11)
	Leakage	$\Delta h > 0$	$Q_{LL} = \sqrt{\frac{\Delta h}{(\Delta h)_d}}(q_{LL})$	(12)
Crest gates	Free weir	$h_{1c} > 0$	$Q_c = f(h_{1c}, B_c)$	

C can also be a f(h1)

@ hg = h1 Q should be same computed as Free orifice & submerged orifice

Lockmaster hold constant conditions (2)

Cw occurs in both Free & submerged.

TW HW TW free

The vertical gate opening is computed from the equation

$$h_g = R\left(\frac{c-a}{r}\right)\cos\theta + a - R\sqrt{1-\left(\frac{c-a}{r}\right)^2}\,\sin\theta \qquad (1)$$

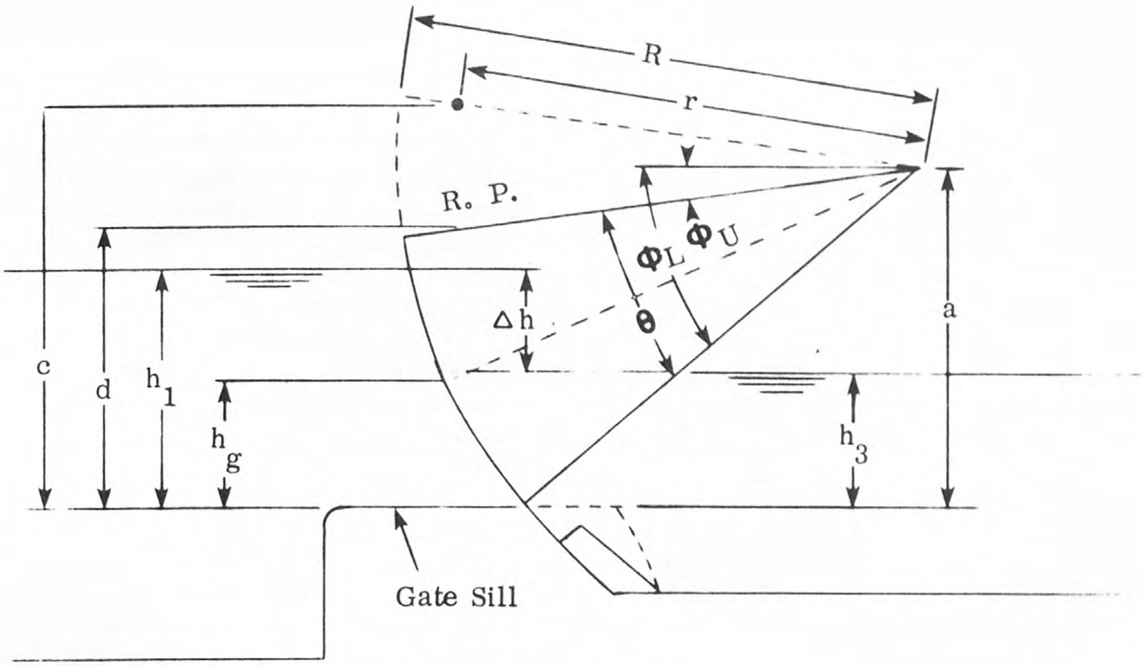
where $\theta = \Phi_L - \Phi_U = \sin^{-1}\left(\frac{a}{R}\right) - \sin^{-1}\left(\frac{a-d}{r}\right)$. The terms in the equation are defined in the symbols and units section and graphically displayed in figure 1. Accurate field measurements of each of the variables in equation 1 should be made before any vertical openings are computed. The gate-opening relation necessary in the software package is computed using equation 1 with R.P. elevations and gate monitor readouts at various gate settings. Experience has indicated that a single relation can be developed if all Tainter gates at a structure are of the same design.

If the structure has some submergible gates, relationships must be developed for the nonsubmergible gates and for the submergible gates. A submergible gate is designed to be lowered to allow flushing of debris over the top of the gate. When this is done, the bottom lip of the gate is below the normal sill elevation. This gate and sill configuration results in a leakage problem, which is described later, because a positive seal is not obtained between the gate lip and sill.

The criteria outlined in table 1 to separate orifice and weir flow is based on a critical depth analysis of flow in a rectangular section. That is, critical depth is 2/3 of the headwater. If the gate opening equals or exceeds the computed critical depth, the gate position is assumed to have no influence on the discharge through that gate and the flow is controlled by the gate sill acting as a broad-crested weir. If the gate opening is less than the computed critical depth, then orifice flow occurs under the gate.

The submerged orifice flow regime exists when the ratio of tailwater to gate opening is equal to or greater than 1. Free orifice flow exists if this ratio is less than 1.

The criteria for distinguishing free and submerged weir flow is not well defined in the literature. In fact, very little information is available on submerged broad-crested weir flow. Hulsing (1967) states that submergence has no effect on the discharge of a broad-crested weir if the submergence ratio, h_3/h_1, is less than 0.85. The geometric and hydraulic properties of gate sills are similar to the geometric and hydraulic properties of a large Parshall flume. Chow (1959) states that the discharge for a large Parshall flume is not affected by submergence if the ratio is less than 0.80. Hulsing (1967) also presents curves for ogee shaped spillways and highway embankments showing that the discharge is reduced slightly at submergence ratios greater than 0.5. After considering the above information, a submergence ratio of 0.6 was chosen as shown in table 1. However, the equations used for free and submerged weir flow allow this point to be flexible. If the known break point is greater than 0.6, the value of the submergence correction, C_{ws}, will be 1.0 for all submergence ratios between 0.6 and the known break point. Many structures where these methods would be used normally are not operated with weir control if the submergence ratio is less than about 0.8.



Definition of symbols used in sketch are:

a	= Elevation difference, trunnion centerline to sill
c	= Elevation difference, gate reference point (R. P.) to sill
d	= Elevation difference, gate R. P. to sill with the gate in a closed position
h_1	= Static ~~tailwater~~ headwater referenced to gate sill
h_3	= Static tailwater referenced to gate sill
h_g	= Vertical gate opening
r	= Radius from trunnion centerline to gate R. P.
R	= Radius from trunnion centerline to upstream face of a tainter gate
$\Delta h = h_1 - h_3$	= Static headloss through structure
Θ	= Included angle between radial lines from the trunnion centerline through the R. P. and through the lower lip of the gate
Φ_L	= The angle measured from horizontal to the radial line from the trunnion centerline through the lower lip of the gate with the gate in a closed position
Φ_U	= The angle measured from horizontal to the radial line from the trunnion centerline through the gate R. P. with the gate in a closed position

Figure 1. Tainter gate geometry

Leakage flow must be considered at a structure with submergible type gates. Leakage flow exists because the lower lip of the gate does not form a tight seal against the sill with the gate closed. As the gate lip is raised slightly above the sill elevation, the effective flow area, because of the sill shape, is greater than that computed using the recorded vertical gate opening. Therefore, the computed gate discharge must be increased to account for the greater flow area. This is accomplished in the computations by using equation 2 and a curve relating the leakage correction, q_{GL}, to the vertical gate opening, h_g. The development of the curve will be described in detail later in the calibration section of this report.

The hydraulic equations used for the various flow regimes for flow through gates are listed in table 1. The coefficients shown in most of the equations are unknowns and must be determined during calibration. Equation 2 is an empirical equation developed to estimate the leakage flow through submergible gates. Equation 3 is the standard orifice equation for free outfall and is described in most fluid mechanics textbooks. Equation 4 is a slightly different form of the orifice flow equation for submerged outflow. This equation can be derived by writing the energy and continuity equations between the approach section, section 1, and a downstream section, section 3. This particular form of the equation was selected because it simplifies the development of a calibration relation. This simplification will be discussed later. The broad-crested weir equation 5 and 6 with static head as the independent variable is used to calibrate both free and submerged weir flow through the gates. The standard form of the broad-crested weir equation uses total head rather than static head. The static-head form was selected because of the small magnitude of the velocity head relative to the total head at structures where this method would commonly be used. The minor effect of the velocity head is incorporated into the discharge coefficient relations during calibration. Also, the present computer program does not include a procedure to compute the velocity head from recorded variables which would be necessary if the standard broad-crested weir equation was used.

Turbine Flow

Two techniques are currently being used to monitor turbine flow. The better technique with regard to accuracy of the computed record is to monitor the turbine-scroll-case pressure differential using the piezometer taps (Winter, 1933) installed in most hydraulic turbines. This pressure differential must be integrated over time before recording because of extreme fluctuations in instantaneous pressure differentials. Discharge is related to pressure differential by equation 7 (table 1). The correct value of K must be determined during calibration. The second technique uses the output from commercial discharge monitors already installed at some structures. This output is also integrated over time before being recorded. Equation 8 relates discharge to the commercial monitor output. The value of K_1 must be determined during calibration.

Fixed-Spillway Flow

The fixed spillway on most structures has an ogee or rounded crest. The weir equation with static head as the independent variable, equation 9, is used to describe the flow for free weir flow. Equation 10, also using static head, describes the flow for submerged conditions. This head must be computed relative to the mean crest elevation of the fixed spillway. A submergence ratio (h_{3s}/h_{1s}) of 0.6 was again selected as the break point for free or submerged weir flow by the same criteria as described for the gated part of the structure.

Lockage Flow

Lockage flow is simply the total volume of water in all lockages in a selected time period, averaged over that time period, generally 1 or 2 hours. The average flow rate is computed using equation 11 (table 1).

A procedure is available in the software package to compute leakage flow through damaged lock gates if required. The computation procedure uses equation 12 where q_{LL} is a constant lock leakage term. The value of q_{LL} is determined from equation 12 after rearranging the equation with Q_{LL} = the measured leakage discharge, Δh = the average head loss during the measurement and $(\Delta h)_d$ = the design head loss for the structure. q_{LL} is entered into the program as another leakage correction factor.

Crest-Gate Flow

Crest gates are used to release high flows and are generally operated either fully open or fully closed. The amount of release is controlled by the number of gates that are open. The crests of the weir on which these gates rest when closed are rounded and at elevations where submergence cannot occur. Therefore, only the free weir flow regime must be calibrated. The calibration is expressed as a table of effective headwater versus discharge for a single gate. The functional relation illustrated at the bottom of table 1 is intended to imply such a table.

CALIBRATION

Field Inspection

Calibration of a structure requires the definition of discharge coefficients for each equation shown in table 1 that is applicable to the particular structure. Relations must be developed between the discharge coefficients and recorded variables. The first step in the calibration should be a field inspection to determine the different flow controls present. The operating rules for the structure should be discussed with the operator to ascertain the flow regimes that must be calibrated. The flow regimes that may exist at a structure are determined from expected ranges of headwater, tailwater, gate opening, and the limits separating flow regimes outlined in table 1. An estimate should be made, after consulting with the operator, of the expected maximum stage and discharge and the minimum stage and discharge. These estimates are required to determine the necessary instrumentation and the physical location for this instrumentation. For instance, if locks are not present and if the structure operates without submergence for all discharges, a tailwater sensor is not required. The necessary sensors and the central control console should be located at an elevation above the maximum expected stage if possible. One exception to this is the pressure-actuated lockage sensor which must be submerged when the lock chamber is full.

Another factor that must be considered when selecting and ordering the instrumentation is the physical location of some of the sensors. The headwater sensor should be located three to four times the maximum expected headwater (maximum h_1) upstream from the Tainter gate sill because the sill acts as a weir control when the gates are raised free of the water. The tailwater sensor should be located downstream of the turbulent zone created by the energy-dissipating blocks. At a structure with locks, the headwater sensor may be mounted on the lock guide wall if the guide wall extends far enough upstream to satisfy the distance requirements stated previously. If this distance requirement is not satisfied, a bank installation is required. The tailwater sensor can usually be mounted on the downstream lock guide wall in a protected location. For other structures, bank installations are required for both headwater and tailwater sensors.

Design Plans (as built)
Copy of model study
Files Picked, Vicksburg CoE

All required elevations should be determined at the outset of the calibration. These include datums of the headwater and tailwater sensors, average elevation of the Tainter gate sills, average trunnion centerline elevation, average crest gate sill elevation, average fixed spillway crest elevation, and reference mark elevations used in taping to the R.P.'s on the gates. The standard practice used to determine elevations of the R.P.'s is to tape down from known elevations on the walkway above the gates. Therefore, the R.P.'s must be clearly marked and visible from some distance. They must be vertically below the walkway reference marks for all gate openings from a closed position up to the maximum gate opening that might be used for the orifice flow regime. The maximum opening may be determined from an inspection of the operating log for the structure.

The average Tainter gate length, fixed-spillway length, average crest-gate length, and width and length of each lock chamber must be determined. Each Tainter gate radial arm length from trunnion centerline to reference point (r) and each Tainter gate radial arm length from the trunnion centerline to the upstream face (R) must be determined (fig. 1). The average length of the Tainter gate sill parallel to the direction of flow must be determined. Many of these elevations and length measurements are difficult to obtain in the field during operation. If final design drawings are available, most of the measurements can be obtained from these with spot checks by field measurements to verify them.

Optimum Calibration Procedure

An optimum calibration procedure should be outlined once the above items have been completed. The sequence of calibrating the various controls and flow regimes is critical only in minimizing the time required to begin computation of streamflow records once the instrumentation is operational. The predominant type of control and the predominant regime of flow should be calibrated first. Calibration is by current-meter measurement. However, measurements during high flow and extremely low flow should be made whenever the flow conditions exist because of the infrequency of these events. Weir flow through the gates and over the fixed spillway have been the most difficult to rate because of the lack of measurement data. As a general rule, at a structure with multiple controls, the calibration sequence should be as follows:

1. Leakage flow through submergible gates
2. Turbine flow
3. Free orifice flow through Tainter gates
4. Submerged orifice flow through Tainter gates
5. Free weir flow through the Tainter gates
6. Free weir flow over the fixed spillway
7. Submerged weir flow through the Tainter gates
8. Submerged weir flow over the fixed spillway
9. Free weir flow through crest gates

Items 5 and 6 will probably require simultaneous calibration because during high flow of sufficient magnitude to have the gates free of the water, the fixed spillway may also be conveying flow. This also applies to items 7 and 8. A problem of separating flow between the gates and the fixed spillway usually arises when calibrating items 5, 6, 7, and 8.

Occasionally, arrangements can be made with structure operators to adjust and hold certain controls prior to and during a discharge measurement to simplify the analysis of the data. Examples of beneficial changes would be for the operator to adjust all gates to the same setting, to close all gates and discharge the flow through the turbines or over the fixed spillway, or to hold all river traffic through the locks during a measurement.

The general calibration sequence should be used only as a guide in scheduling calibration measurements. In the early part of the calibration, measurements should be made each time one of the important variables changes appreciably. The calibration can be started prior to the installation of the instrumentation except at structures with turbines. All necessary variables, except turbine pressure differentials, can be obtained by some means other than through the instrumentation. Staff gages can be mounted to collect headwater and tailwater elevations. These staff gages should be mounted at the preselected locations for the headwater and tailwater sensors. Tape downs to the Tainter gates along with equation 1 can be used to compute the vertical gate opening for each gate.

The actual number of discharge measurements necessary to develop a complete calibration can vary. A structure with all five types of control will probably require 50 to 75 measurements if the measurements are well distributed over a complete range of variables.

Collection of Calibration Data

Calibration data include discharges, gate openings, headwater elevations, tailwater elevations, turbine pressure differentials or commercial monitor outputs, and number of crest gates open. All of these measurements should be made during each calibration measurement. Headwater and tailwater elevations should be measured several times during the discharge measurement in order to compute mean values.

The discharge measurements are usually made at a cross section downstream from the structure. In certain cases, measurements may be made in the forebay of each gate to separate the flow through gates from the flow through other controls. A measurement of the total flow should be made downstream at the same time as the measurements in the forebays. Measurements in the forebays are only possible on structures with an overhead walkway or other means of access. Reliable measurements in the forebays can only be obtained if streamlines at the cross section have no significant curvature either horizontally or vertically and the magnitude of the velocities is in a range that measurements can be made with available equipment.

Several methods of measuring discharge are satisfactory, such as the moving boat method (Smoot and Novak, 1969), the conventional method using a current meter from a boat using a tagline or sextant, or a single current meter or a bank of current meters from a bridge or another structure. The use of a sextant or electronic distance-measuring instruments is preferable to a tagline to locate the position of a boat on a stream with river traffic.

Calibration Data Analysis

The major problem encountered in reducing field-measured calibration data to discharge coefficients is the division of flow among the different controls. If more than one gate is open and at different settings, the measured flow must be divided among the gates. These divisions of flow usually require a trial-and-error solution unless field measurements have been made to determine the flow through each control.

Gate flow.--Calibration of leakage flow is usually necessary only when the structure has submergible gates. The calibration consists of the development of a relation between the gate leakage correction factor, q_{GL}, and the vertical gate opening, h_g. Discharge measurements can usually be made in the forebay of submergible gates with the gates closed. These discharge measurements can then be averaged and corrected for the Δh at the time of the measurement, if different than design Δh, to give one point on the gate leakage correction factor curve. This corrected discharge is the maximum gate leakage expected. The curve will decrease from this point to a zero leakage when the true gate opening (slant distance) is equal to the vertical opening computed in equation 1. Equation 2 is used to correct for Δh with Q = average measured discharge and Δh = average head loss during the measurement. That is, $q_{GL} = Q/\sqrt{\Delta h/(\Delta h)_d}$. From this computed value of q_{GL}, the effective gate opening width, Z_o, with the gate lip at or below sill elevation can be computed as

$$Z_o = \frac{q_{GL}}{(C_{gs})_{1.0} B\sqrt{2g\Delta h}} \tag{13}$$

where $(C_{gs})_{1.0}$ = the value of C_{gs} at $h_3/h_g = 1.0$, or if unknown, assumed to be 0.75. As the gate lip is raised slightly above the sill, the vertical distance from the sill to the gate lip is not in a plane perpendicular to the direction of flow because of the sill shape adjacent to the lip. Therefore, the correction curve must be extended to gate openings greater than zero. To compute intermediate values of the leakage correction factor to extend the curve, the following equation is used with various values of h_g up to the point where the leakage correction factor becomes zero.

$$q_{GL} = \frac{(C_{gs})_{1.0} B\sqrt{2g\Delta h\left[\left(\frac{Z_o}{\cos\beta} - \frac{h_g}{\tan\alpha}\right)^2 + h_g^{\,2}\right]} - (C_{gs})_{1.0}\, h_g B\sqrt{2g\Delta h}}{\sqrt{\frac{\Delta h}{(\Delta h)_d}}} \tag{14}$$

where $\beta = \sin^{-1}[(a/(R + Z_o)]$, $\alpha = 90^\circ - \beta$, and h_3 is the average tailwater observed during the leakage measurements. All other terms are defined in the symbols and units section and some are graphically displayed in figure 1.

Calibration of free orifice flow through the gates requires the development of a relation between the free orifice coefficient in equation 3 and the vertical gate opening, h_g. Values of C will vary inversely with h_g because the change in slope of the lower lip of the gate, as the gate is raised, progressively decreases the hydraulic efficiency of the orifice. There is also a tendency for C to increase with h_1, particularly at low stages, but that effect is usually minor compared to the effect of h_g alone. Navigation type structures very rarely operate with this type of control and therefore, development of a complete calibration relation may be difficult.

The calibration is developed for a single gate and requires a separation of the measured discharge if several gates are open at different settings. The separation is best achieved by assuming a coefficient for one or more of the gate openings and then solving for the remaining coefficients. The example calibration included (figs. 5 and 9) should be used as a guide to the general shape of the coefficient relation. If the assumed coefficients do not result in a smooth curve of appropriate shape, new coefficients should be assumed. If the structure operates with free orifice control, it should be possible to obtain several measurements with all open gates set at approximately the same settings. These measurements should be analyzed first to define the shape of the curve. Refinement of the high end of the relation (larger gate openings) can best be done after submerged orifice flow has been partially calibrated. This is done by computing the discharge as submerged flow with an h_3/h_g ratio of 1 and then using this discharge to compute the free orifice coefficient so as to give a smooth transition from free orifice flow to submerged orifice flow. The same vertical gate openings would be used in each computation.

If calibration measurements cannot be obtained because the structure is not operated with free orifice control, an assumed calibration must be developed. To do this, use the same general shape as illustrated in the examples and determine the magnitude of the coefficients by studying the transition to submerged orifice flow. A calibration relation is required in the discharge computation computer program even though it may seldom be used.

Submerged orifice flow is the predominant regime of flow at most navigation structures. Calibration requires the development of a relation between the discharge coefficient, C_{gs}, in equation 4 and the gate submergence ratio, h_3/h_g. This relation is also developed for a single gate. The C_{gs} and h_3/h_g values are plotted on logarithmic paper. The reduced data generally plot as a straight line except at gate submergence ratios less than 2. Here the computed C_{gs} values may be greater than those extrapolated from the straight-line relation. For many of the structures calibrated using these procedures, the submerged orifice flow coefficient has been found to be independent or nearly independent of the submergence. Experimental results described by King and Brater (1963) support these findings of independence. If the coefficient is independent of the submergence, the slope of the straight line will be -1. If the slope of the line is -1, the average gate opening and the average discharge can then be used to compute the value of C_{gs} for a measurement made with several gates open at different settings. If the slope of this line is not equal to -1, the discharge through each gate must be separated by a trial-and-error procedure. The best way to perform this separation is to select those measurements with all gates open approximately the same amount and compute the coefficients using average gate opening and average discharge. Next, those measurements made with several gates open but at only two different settings should be analyzed. The coefficient is assumed for one setting and the other coefficient can then be computed. If the computed value deviates from the straight line, assume a different coefficient for the one setting and compute the second coefficient. It is important in this trial-and-error computation scheme to assume coefficients that will result in a constant slope of the discharge coefficient relation for all measurements. By doing this, the overall submerged orifice flow calibration error will be minimized. If three different gate settings exist during a measurement, two coefficients must be assumed using the partially developed relation and the third coefficient computed. This same trial-and-error procedure should be continued until all measurements for this type of flow have been analyzed. Weaknesses in the calibration should be pinpointed and plans made to obtain discharge measurements to improve the relation where questionable. When the relation deviates from a straight line at submergence values less than 2, additional measurements can be made to define this part of the curve.

Calibration of free weir flow requires the definition of the relation between the discharge coefficient, C_W, and the headwater, h_1, for a single gate. Equation 5 is used to compute the coefficient from discharge and headwater measurements. Free weir flow is another regime that seldom exists except during transition periods where the flow regimes are changing rapidly. Therefore, calibration discharge measurements may be very difficult to obtain.

Coefficients are presented by Hulsing (1967) for broad-crested weirs which may be used to develop an assumed calibration for free weir flow. The average length of the weir parallel to the direction of flow, height of the weir above the stream channel, shape of the upstream and downstream faces of the weir, and the anticipated range of h_1 and of the velocity of approach must be determined to use the reference. The coefficients given in the reference are based on total head and can be used only when the velocity head is negligible.

Another problem that may arise while developing this calibration is separation of flow between the gated part of the structure and the fixed spillway. If discharge measurements are made in the field to separate the flow as described earlier, this problem is eliminated. If these measurements were not made, both the fixed spillway and the gated part of the structure must be calibrated using the same discharge measurements. A suggested approach is to develop a calibration relation for the fixed spillway from Hulsing (1967) using coefficient relations for round-crested weirs, the predominate cross-sectional shape of fixed spillways. Depending on the submergence ratio for the fixed spillway, a submerged weir flow coefficient relation may also have to be developed. An estimate of the fixed-spillway flow can now be obtained. The estimated discharge can be deducted from the measured flow to obtain a discharge for the gated part. The assumed calibrations for the fixed spillway may require alterations to obtain the best calibration relation for free weir flow through the gates. On most structures equipped with fixed spillways, the spillway and gates will be conveying discharge simultaneously so any errors resulting from the assumed calibrations will be introduced into the computed relation for the gates.

Calibration of submerged weir flow requires the development of a relation between the submerged weir coefficient, C_{WS}, and the submergence ratio, h_3/h_1, for a single gate. Computation of the submerged weir flow coefficients from measured discharge and headwater requires known or assumed values of the free weir coefficient.

Division of flow between the gated part of the structure and the fixed spillway will probably be required when performing calibration for submerged weir flow. The necessary calibration relations for the fixed spillway can be developed from Hulsing (1967). The developed relations can then be used to compute a first approximation of the fixed-spillway discharge which can be deducted from the measured discharge to obtain gate discharge. Revisions of the fixed-spillway relations may be required to develop a smooth relation for the gated part of the structure. Care should be exercised in computing the submerged weir coefficient to use only those gates operating under weir control. Some of the gates may be operating under submerged orifice control, and discharges should be computed for these using appropriate coefficients and equations.

An option to compute flow over the Tainter gates has been incorporated into the discharge computation program. Because of the hydraulic complexities involved and the limited use of this type of control, the calibration procedure will not be described. In general, a rating table of headwater stage minus gate top elevation versus discharge is required. The number of assumptions made to compute flow over Tainter gates makes the results uncertain; therefore, when flow over gates is a large percentage of the total flow, computed discharges may not be reliable.

Turbine flow.--Two methods are available for calibrating turbine flow. One method uses the differential pressure in the scroll case as measured at the piezometer taps (Winter, 1933). Calibration requires definition of the constant, K, in equation 7 for the expected range of discharge. Separate constants may have to be determined for each turbine if the structure has more than one turbine. The constant can be obtained by plotting measured turbine discharge versus average pressure differential on logarithmic paper. The best-fit line defining the relation must have a 0.5 slope because the square root of the pressure differential is being recorded. If unique constants are required for each turbine, the total measured turbine discharge must be prorated to each operating turbine through a trial-and-error process. The objective of the solution process is to minimize calibration errors.

The second calibration method uses output from a commercial discharge monitor. Discharge measurements must be made over the expected range of turbine flow to define the constant K_1 in equation 8. Since output from commercial monitors is usually in terms of a volume such as acre-feet, K_1 must include a factor to convert this to cubic feet per second. The time between recordings will also be required to determine the constant. K_1 may include a correction factor if the converted monitor output does not agree with the measured discharge.

Fixed-spillway flow.--Calibration of fixed-spillway flow has already been discussed in some detail under gate-flow calibration. The fixed spillway on most large structures is designed to convey water only during periods of high water and therefore, measurements are usually limited.

If discharge measurements are available and if the division of flow between the fixed spillway and the gated part of the structure is known, development of the necessary discharge coefficient relations is greatly simplified. Relations between the free weir coefficient, C_{SW}, and the effective headwater, h_{1s}, for free weir flow and between the submerged weir coefficient, C_{SWS}, and the fixed-spillway submergence ratio, h_{3s}/h_{1s}, must be developed. Equations 9 and 10 should be used to compute the coefficients.

If an assumed set of calibration relations for the fixed spillway was used in the gate flow calibration, additional measurements should be made to improve the reliability of these relations. If the additional measurements result in computed discharge coefficients that show large deviations from the assumed coefficients, all weir flow calibration relations should be re-analyzed including the gate flow relations.

Lockage flow.--Calibration of lockage flow requires the determination of the plan area of the lock or locks, and a factor to convert recorded lockages to the true number of lockages per cycle. If leakage through the closed lock gates is appreciable, a discharge measurement of the leakage should be made. This discharge measurement can be made in the lock chamber. The measured leakage can then be adjusted to design head and used to compute leakage discharge using equation 12.

Crest-gate flow.--Calibration of crest-gate flow requires the development of a single gate discharge rating table using the effective head on the crest-gate sill as the independent variable. This simple calibration is possible because crest gates are designed to be operated in a closed position with no flow or in a wide-open position with free weir flow controlled by the sill elevation and sill shape. The calibration table is computed from measured discharges and stages over the expected range of headwater.

Instrument calibration relations.--In addition to the above relations, a few other conversion-type relations must be developed before discharge can be computed using the computer program. These include:

1. A recorded headwater to true headwater stage (h_1) relation which may be a mathematical equation or a rating table.

2. A recorded tailwater to true tailwater stage (h_3) relation which may be a mathematical equation or a rating table.

3. A recorded gate opening to a vertical gate opening relation developed as a rating table using equation 1 and R.P. elevations at various Tainter gate settings.

4. A conversion table to convert the recorded number representing crest gates open to the actual number of gates open.

5. A conversion table or mathematical expression to convert recorded lockage counts to the number of lockages that occurred between recording cycles.

Tentative Calibration

Computation of streamflow records can be started using tentative calibration relations. The initial calibrations may have been developed from limited data or they may have been developed from data published in the literature. If the predominant types of control and flow regime are calibrated first, computation of records with the general program will be expedited, and initial results should help to locate deficiencies in the tentative calibration. Any calibration relation can be revised and entered into the program at any time.

An option to compute flow using a tailwater stage versus discharge rating table has been provided in the program to handle periods of high flow. This option was inserted so that the computation program could be used before the weir flow calibrations were developed. This option will only provide an estimate of the discharge, and the computed results should be reviewed very carefully.

Each of the tentative calibration relations should be checked after the analysis of the initial calibration measurements is complete to determine if there are flow conditions for which the calibration is not well defined. Plans should be made to obtain additional measurements to better define the weak parts of the relations. A detailed review of the discharges computed by the software package should assist in locating the uncertain parts of the entire calibration.

Checking the Final Calibration

After all calibrations have been revised and are considered final, approximately three to five measurements should be made annually for verification. Check measurements are necessary to identify possible shifts in the calibration relations. The measurements should be made to verify all calibration relations over the range of flow conditions during the year.

Each time the structure is visited to make a discharge measurement or to remove the record, the elevation of each of the gate R.P.'s should be measured; (1) to check the gate position sensors, (2) to check the gate opening calibration using equation 1, and (3) to furnish back-up data for discharge measurements in case the recorded values are in error.

DATA COLLECTION AND PROCESSING

The instrumentation package to collect and record the necessary field data and the general computer program used to compute the discharges have been developed and tested by the U.S. Geological Survey, Water Resources Division.

Instrumentation

The collection of accurate data at a site is another important part of the overall computation scheme. The instrumentation package monitors headwater elevation, tailwater elevation, individual gate settings, turbine pressure differentials or commercial turbine monitor outputs, number of lockages, and number of crest gates open. All of these variables are recorded on a digital recorder at a selected time interval, usually hourly or bihourly. Because of physical barriers which prohibit the wiring of individual sensors to a single recorder, two or more recorders may be necessary. The data are recorded on a 16-level paper tape in a preselected sequence by a master control console that queries the individual sensors and outputs information to the recorder. Most readings are instantaneous values at the time of recording. One exception is the lockage count which accumulates the number of lockages occurring between recording times. Another exception is the turbine monitor which integrates continuously the scroll-case-pressure differential between recordings. The information from the paper tape is transferred to a magnetic tape after the paper tape has been removed from the site. The magnetic tape is then used as input to the computer program which computes the streamflow records.

Computer Program

Figure 2 is a flow chart of the algorithm used in the computation of the streamflow records on a punch interval and a daily basis. The daily basis is necessitated by the fact that daily mean discharges are published. Not illustrated in this simplified flow chart are the variable comparisons necessary in each of the computation steps to compute the desired results. For example, in the gate flow computation block, bulkheading of each open gate is checked; all pertinent variables and their relation to one another are checked, such as h_1, h_3, and h_g; and then the flow is computed using the correct equation based on the variable comparisons. If a tailwater rating is used for extremely high flows (usually the case until weir flow is calibrated), then only one discharge is determined for the interval rather than determining gate flow, crest-gate flow, spillway flow, turbine flow, and lockage flow. Datum and time corrections can be applied to all variables read from the magnetic tape. All calibration relations or calibration constants can be changed by entering revised relations or constants. Space is provided in the program to store up to 20 different tables of coefficient relations and conversion tables for any given structure.

EXAMPLE CALIBRATIONS

The two structures chosen as examples are Markland Lock and Dam on the Ohio River, Ky., and Coffeeville Lock and Dam on the Tombigbee River, Ala.. Markland Dam has 12 Tainter gates, each 100 ft long; and of these 5 are submergible gates. This structure also has three turbines equipped with piezometer taps (Winter, 1933) and two lock chambers, one 110 ft by 600 ft, and the other 110 ft by 1,200 ft in plan. There is no fixed spillway at Markland Dam.

Coffeeville Lock and Dam has eight Tainter gates, each 60 ft long. The structure has no submergible gates. The structure has one lock chamber 84 ft by 600 ft. There is an ogee-shaped, fixed spillway 639 ft long.

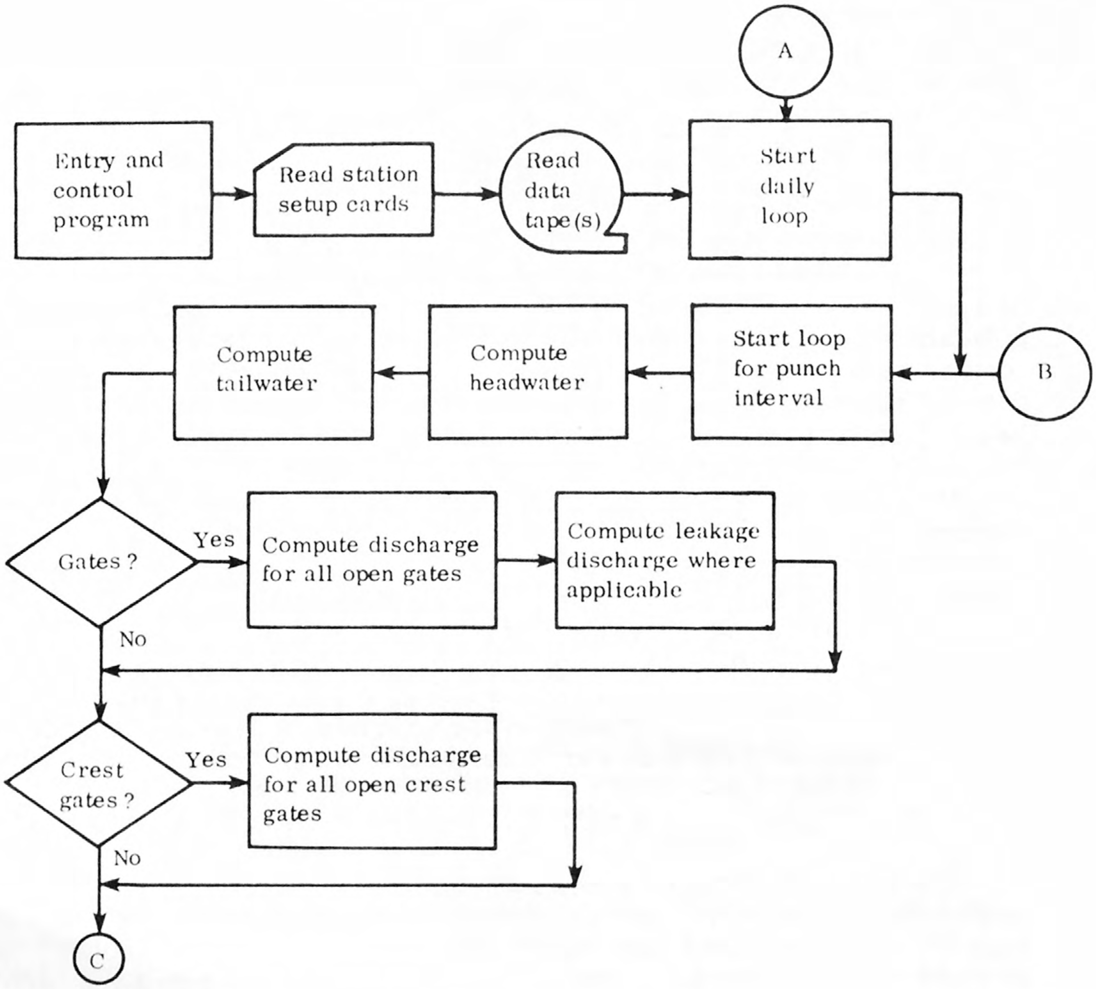


Figure 2. Computation sequence used in the generalized computer program for computation of streamflow records

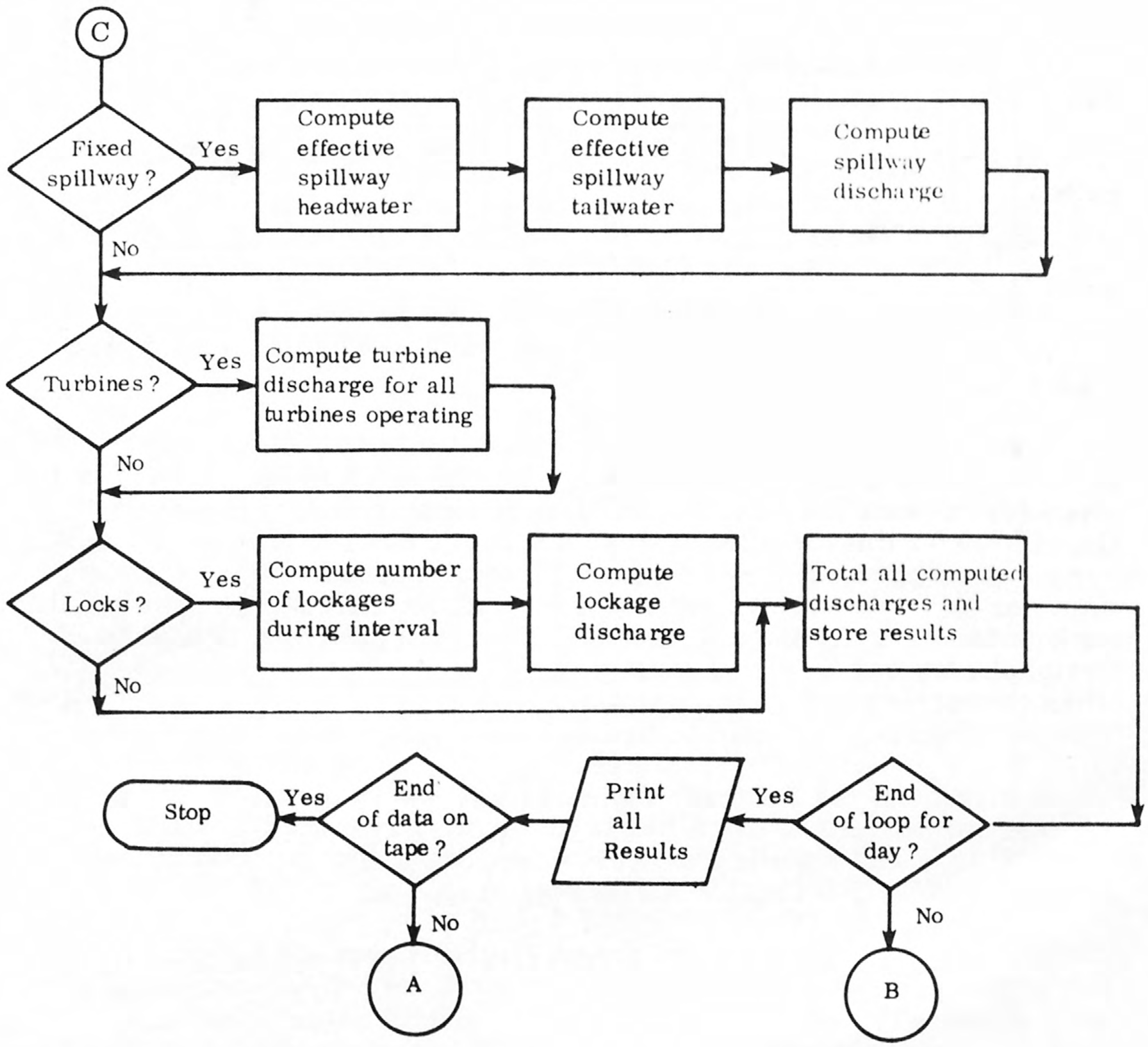


Figure 2.--(Continued)

Markland Lock and Dam

Calibration of Markland Lock and Dam required development of the following relations:

1. Gate opening versus recorded value relations for both submergible and nonsubmergible gates,

2. A gate leakage correction curve,

3. A turbine discharge calibration relation to define K,

4. A free orifice coefficient relation for flow through the Tainter gates,

5. A submerged orifice coefficient relation for flow through the Tainter gates,

6. A free weir flow coefficient relation for flow through the Tainter gates, and

7. A submerged weir flow coefficient relation for flow through the Tainter gates.

Because of the sequence of discharge measurements already available at Markland Lock and Dam, along with the various types of controls, it was advantageous to define leakage flow through submergible gates first. Current-meter measurements were made in the forebay of each of the five submergible gates with the gates in the closed position. Headwater and tailwater elevations were recorded during all measurements. The resulting mathematical relationships for leakage discharge are equations 2 and 12. Design Δh for this structure is 35 ft. q_{GL} varied from 950 ft^3/s to 0 ft^3/s when the corresponding vertical gate opening ranged from $\leq$ 0 ft to 0.40 ft. This variation is illustrated in figure 3.

A current-meter measurement was also made in the small lock chamber because one of the lock gates had been damaged resulting in considerable leakage. q_{LL} had a value of 1100 ft^3/s because of the damaged lock gate and had a value of zero after the gate was repaired.

The next control calibrated at this structure was the turbines. The value of K in equation 7 had to be determined. Where two or three turbines were operating, the total turbine discharge was divided among them. The division was made in proportion to the square root of the pressure differential. That is

$$(Q_t)_i = \frac{(\sqrt{\Delta p})_i}{\sum_{i=1}^{3} (\sqrt{\Delta p})_i} (Q_T) \qquad (15)$$

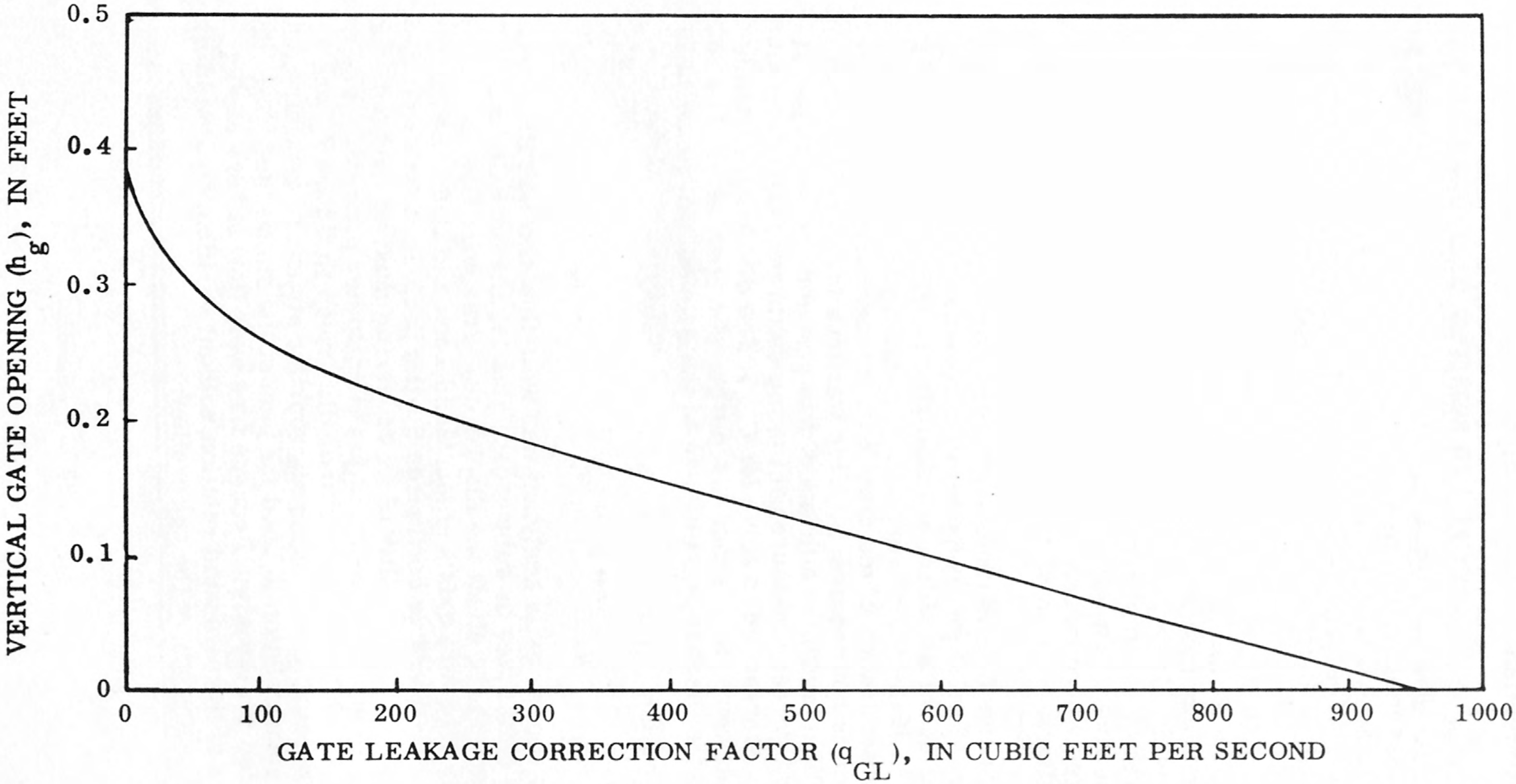


Figure 3. Gate leakage correction factor curve, Markland Lock and Dam

where $i = 1, 2,$ or 3, and $(Q_t)_i$ and $(\sqrt{\Delta p})_i$ are the individual discharges and pressure differentials for each turbine.

The total turbine discharges and individual pressure differentials are tabulated in table 2. The individual turbine discharges are plotted as a function of the pressure differentials in figure 4. A straight line averaging all the plotted points was drawn because none of the turbines seemed to have a unique calibration. The value of K for all turbines is 6600 ft$^{5/2}$/s, which is the discharge (fig. 4) for a pressure differential of 1 ft.

Tainter gate control was the next type of control analyzed. Free orifice flow was the first regime of flow calibrated. This regime will rarely, if ever, occur at this particular navigation structure; therefore, no measurements have been made with this regime of flow. The computer program, however, requires calibration results for this regime of flow. Therefore, an estimate of the coefficient curve was developed from calibration results at other structures where measurements have been made with free orifice flow. This relation is illustrated in figure 5.

Submerged orifice flow is the predominant flow regime at this navigation control structure. Therefore, considerably more calibration information is available. The calibration data are tabulated in table 3. As previously discussed (p. 12), if the h_3/h_g versus C_{gs} relation plots with a -1 slope, a trial-and-error separation of the discharge for measurements made with several gates open is not necessary. This was true for Markland Lock and Dam. Figure 6 illustrates the calibration data plot and the developed relation. C_{gs} was computed for each measurement using calibration data from table 3 and equation 4, rearranged to solve for C_{gs}. The discharges used for these computations were the average discharges per open gate. The resulting equation relating the discharge coefficient to the gate submergence ratio is

$$C_{gs} = 0.75 \left(\frac{h_3}{h_g}\right)^{-1.0} .$$

The last flow regime to be analyzed was weir flow through the gates. This flow may be either free or submerged; that is, the tailwater may or may not be high enough to affect the discharge. Free weir flow is another regime that rarely, if ever, exists at Markland Lock and Dam. Because of this, no measurements have been made during periods of free weir flow. However, as before, the possibility of its occurring must be covered with appropriate calibration results as input to the computer program. The free weir flow coefficient relation for this structure, illustrated in figure 7, was determined from Hulsing (1967) using appropriate structure geometry and h_1 values. This same relation is used for part of the submerged weir flow calibration as stated previously. Because free weir flow is rare at this structure, the use of the estimated relation without verification should not reduce the overall accuracy of the calibration.

TABLE 2.--Turbine discharge calibration data, Markland Lock and Dam

Measurement number	Pressure differential, in feet of water			Total measured turbine discharge, in cubic feet per second
	Turbine 1	Turbine 2	Turbine 3	
87	1.29	0.63	3.71	28,600
89	1.01	1.02	1.14	19,300
90	0	0	2.96	11,600
94	0	2.63	0	9,460
95	0	0.86	0	6,560
96	0	1.52	1.75	15,400
97	0	2.87	3.20	21,700
109	0	2.08	0	9,750
110	3.38	0	0	12,400
113	1.94	2.09	0	20,200
124	1.20	0	2.45	15,400
125	4.30	0	0	11,600
126	0	0	3.28	12,500
127	4.26	0	0	11,900
128	0	0	2.95	12,200
138	0	3.36	9.36	32,200
139	0	2.94	0	12,300
140	0	0	2.42	11,900

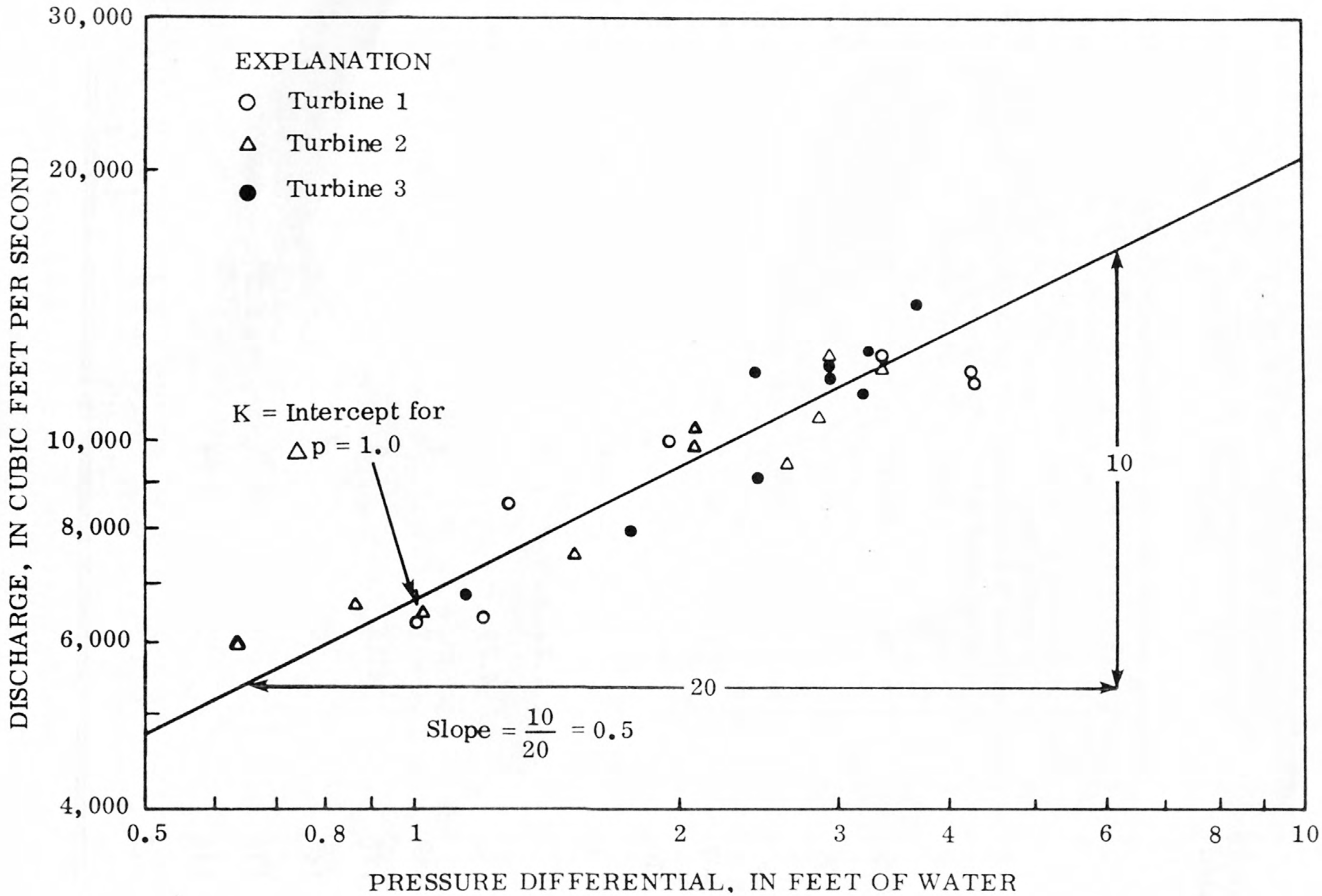


Figure 4. Turbine discharge calibration relation, Markland Lock and Dam

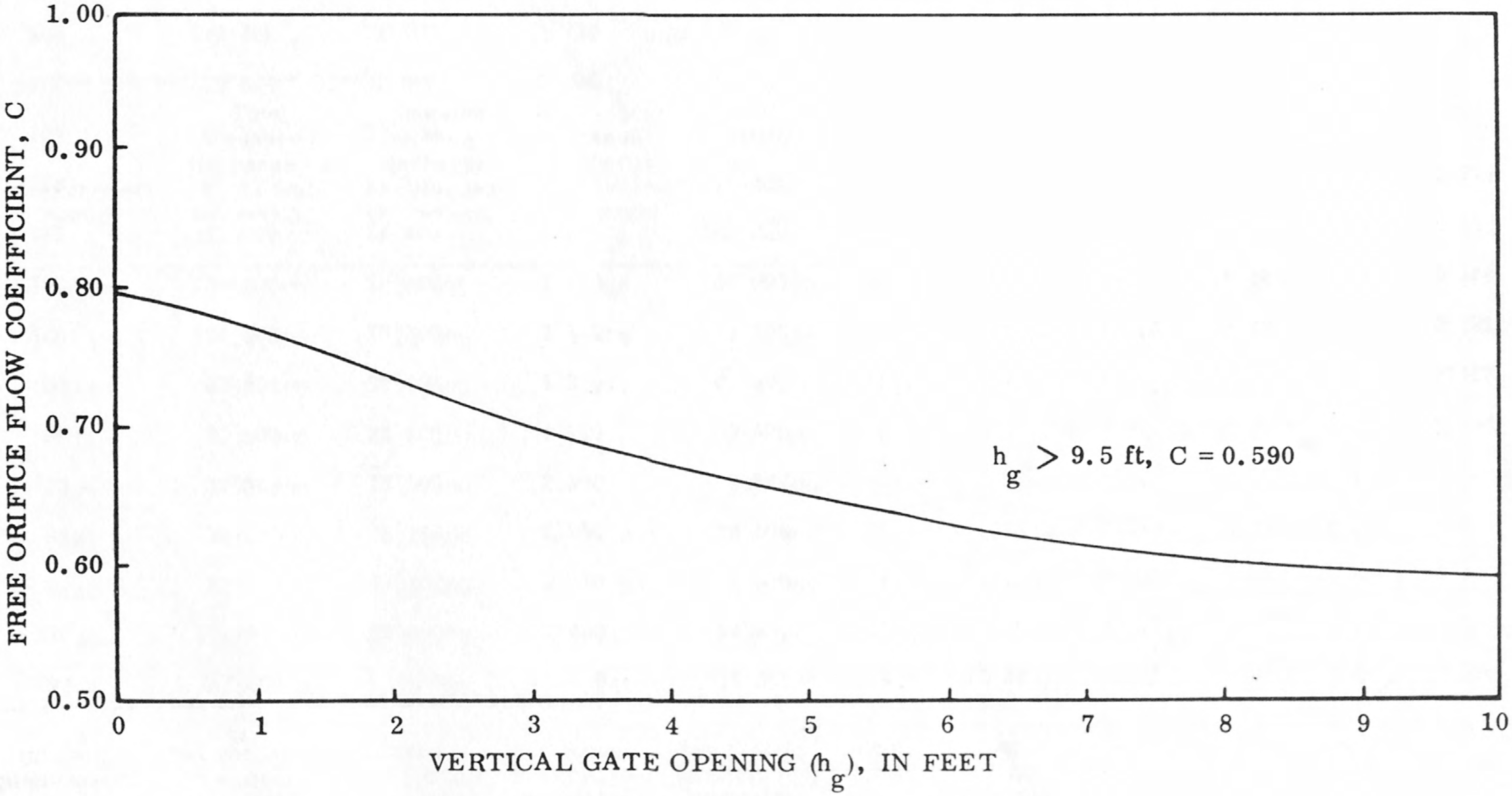


Figure 5. Free orifice flow coefficient relation, Markland Lock and Dam

Table 3.--Submerged orifice flow calibration data, Markland Lock and Dam

Measurement number	Total measured discharge, in cubic feet per second	Computed turbine discharge, in cubic feet per second	Computed leakage discharge, in cubic feet per second	Gate orifice discharge, in cubic feet per second	Number of gates open	Average h_g, in feet	h_1, in feet	h_3, in feet	$\frac{h_3}{\text{average } h_g}$	C_{gs}
65	272,000	0	0	272,000	12	10.94	40.32	28.53	2.61	0.289
86	115,000	38,000	2,490	74,500	10	2.60	40.11	15.89	6.10	0.119
91	21,800	11,900	5,810	4,090	1	1.09	40.33	5.85	5.37	0.148
92	39,900	6,190	5,690	28,000	7	1.12	40.13	6.96	6.19	0.124
93	25,200	12,200	5,760	7,240	1	1.82	40.07	6.08	3.34	0.255
98	30,700	22,200	4,670	3,830	1	1.05	40.44	6.61	6.30	0.124
99	95,900	26,400	1,810	67,700	11	2.03	40.40	13.16	6.48	0.112
100	104,000	25,900	5,110	73,000	7	3.27	40.12	13.43	4.11	0.187
101	124,000	26,500	2,460	95,000	10	3.49	40.03	16.56	4.74	0.148
102	222,000	14,400	608	207,000	11	9.16	40.59	26.27	2.87	0.236
103	96,600	27,100	2,140	67,400	11	1.83	40.04	12.83	7.02	0.114
104	62,200	25,500	2,810	33,900	9	1.22	40.59	9.83	8.06	0.086
105	82,800	25,600	2,740	54,500	9	1.80	40.31	11.01	6.11	0.127
106	159,000	26,100	2,350	131,000	10	4.65	40.01	18.46	3.97	0.191
107	54,000	18,600	4,680	30,700	4	1.41	40.19	8.21	5.83	0.206
108	35,300	24,100	4,650	6,550	1	1.98	40.40	6.91	3.49	0.204

Table 3.--(Continued)

Measurement number	Total measured discharge, in cubic feet per second	Computed turbine discharge, in cubic feet per second	Computed leakage discharge, in cubic feet per second	Gate orifice discharge, in cubic feet per second	Number of gates open	Average h_g, in feet	h_1, in feet	h_3, in feet	$\frac{h_3}{\text{average } h_g}$	C_{gs}
111	68,200	28,900	2,640	36,700	6	1.82	40.39	10.36	5.71	0.134
112	28,100	20,000	4,850	3,250	1	0.89	40.51	6.27	7.04	0.110
114	128,000	22,900	771	104,000	11	3.64	40.47	17.41	4.79	0.141
115	272,000	12,700	0	259,000	12	10.59	40.49	28.65	2.71	0.273
116	227,000	14,100	0	213,000	12	9.08	40.07	27.30	3.01	0.227
121	161,000	22,500	0	138,000	12	4.66	40.40	20.38	4.38	0.157
122	194,000	22,000	0	172,000	11	5.69	40.21	20.72	3.64	0.213
130	166,000	18,700	727	147,000	10	5.61	40.52	20.01	3.57	0.202
132	80,400	29,400	866	50,100	8	1.84	40.26	11.15	6.06	0.130
135	341,000	0	0	341,000	12	19.70[c]	40.00	34.19	1.74	0.430
141	71,700	40,700	1,760	29,200	5	1.79	40.31	10.43	5.81	0.128
142	293,000	0	0	293,000	12	14.07	40.01	31.15	2.21	0.328

[a] h_g determined from COE operations log.

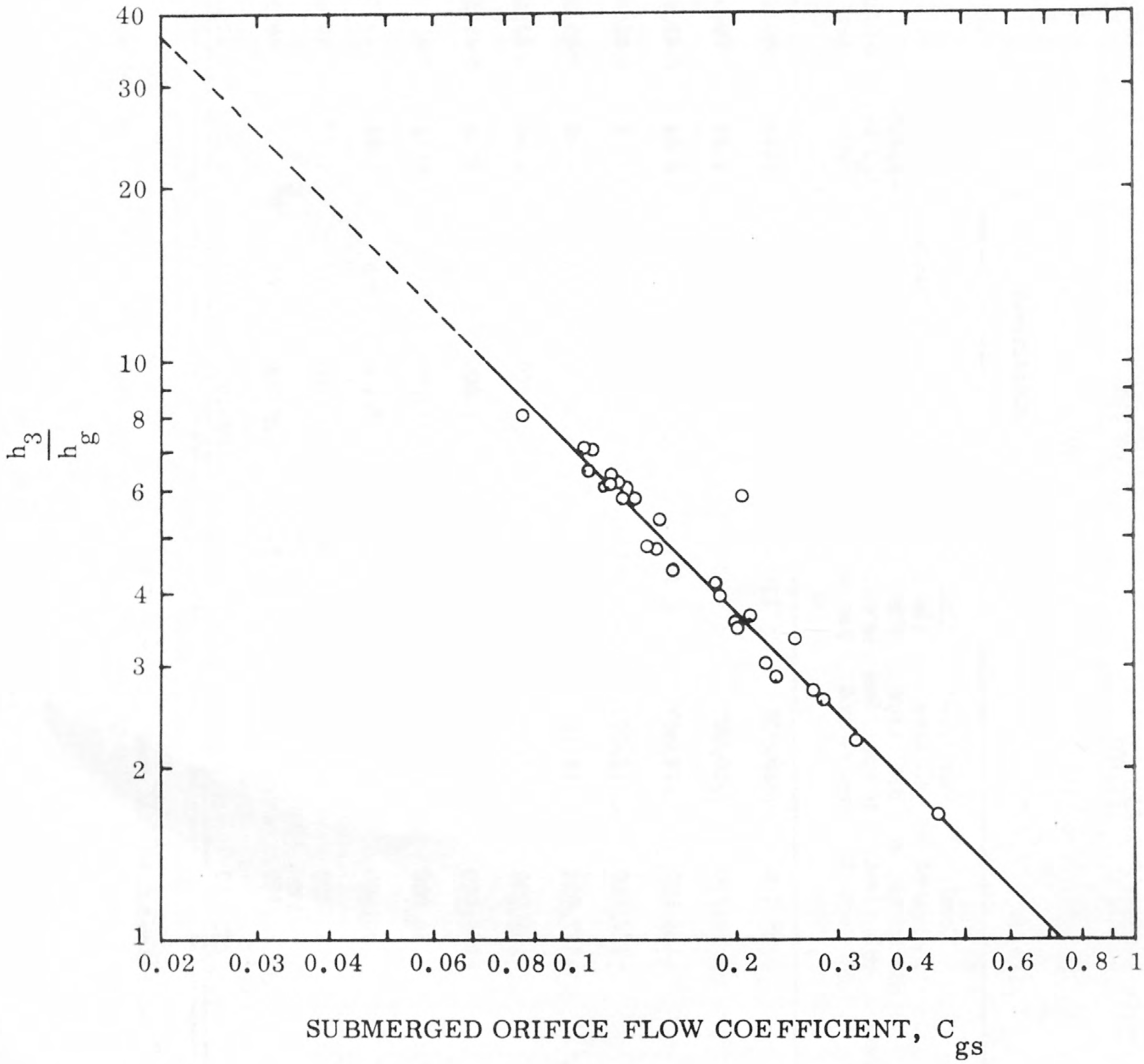


Figure 6. Submerged orifice flow coefficient relation, Markland Lock and Dam

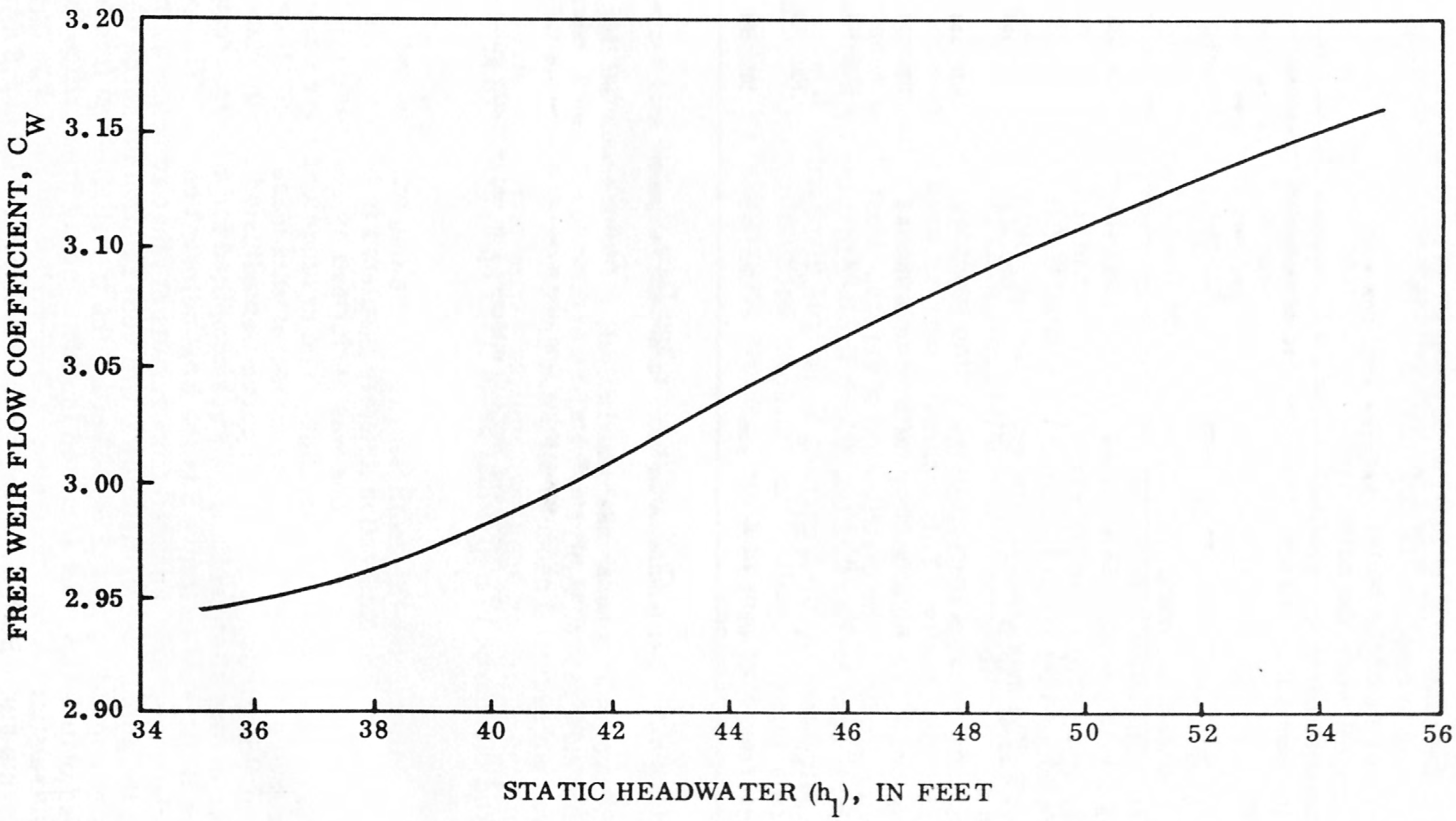


Figure 7. Free weir flow coefficient relation, Markland Lock and Dam

Eight discharge measurements were made under submerged weir control through one or more gates. Table 4 lists the pertinent data from the eight measurements, and figure 8 illustrates the submerged weir coefficient relation and the reduced data used to develop it. The tabulated data and equation 6 were used to compute the coefficients. The minor extrapolations of the line are extensions of the better defined relation. This structure is rarely operated with weir control when the submergence ratio drops below about 0.85. Therefore, no measurements are available to define the curve at lower submergence ratios. With less submergence, the gates are lowered resulting in submerged-orifice flow.

Table 5 summarizes the calibration data. The average absolute error between measured and computed discharges for the 54 measurements is 5.4 percent. The computed discharges are within 5 percent of the measured discharges for 61 percent of the cases, within 10 percent for 85 percent, and only 3, or 6 percent, are in error by more than 12 percent. The relations were all developed by visually fitting the plotted data to minimize the maximum errors. The maximum errors were also visually balanced. A detailed inspection of the calibration errors will reveal some bias. The bias could be eliminated by using a least-squares fitting technique which weighs all measurements equally. This technique was not used in developing the calibrations. The turbine flow calibration appears to be the weakest relation after studying the distribution of errors. Most of the measurements used for calibration were rated fair which implies that the hydrographer felt his results were within 8 percent of the true discharge. Some measurements were not used for calibration purposes because of questionable aspects of the measuring conditons and (or) changes occurring in pertinent variables during the measurement.

Coffeeville Lock and Dam

The first type of control calibrated at this structure was Tainter gate control, and the first flow regime analyzed was free orifice flow. Leakage flow calibration was not required because all gates are of the nonsubmergible type. The calibration of free orifice flow requires a trial-and-error division of measured discharge to individual gates if the open gates are at different settings.

Figure 9 illustrates the coefficient relation along with the reduced calibration data. The calibration data are tabulated in table 6. The trial-and-error part of the computations was performed by assuming coefficients for each of the different gate openings. The assumptions were based on a rough curve developed from those measurements made when all gates were at equal settings. This rough curve was adjusted to minimize the calibration errors after coefficients were computed for all measurements. The curve illustrated in figure 9 is the final adjusted curve. The extrapolation of the curve was estimated from results at other structures, and also from the submerged orifice flow coefficient relation for large gate openings at impending free flow. That is, the transition from free to submerged orifice flow was analyzed in extending the free orifice flow coefficient relation. The occurrence of free-orifice flow at large openings is rare at this site. Both U.S. Geological Survey and COE (U.S. Army Corps of Engineers) data were used to develop the relation illustrated in figure 9.

Table 4.--Submerged weir flow calibration data,

Markland Lock and Dam

Measurement number	Total measured discharge, in cubic feet per second	Weir discharge in cubic feet per second[a]	B, in feet	h_1, in feet	h_3, in feet	C_W[b]	$\frac{h_3}{h_1}$	C_{WS}
117	349,000	349,000	1,100	39.62	38.09	2.98	0.961	0.427
118	345,000	158,000	300	39.51	35.26	2.98	0.892	0.710
120	448,000	434,000	1,100	43.87	42.62	3.04	0.972	0.447
131	444,000	435,000	1,100	43.35	41.90	3.03	0.967	0.458
133	373,000	141,000	300	39.85	36.12	2.98	0.906	0.627
134	358,000	53,000	100	39.98	35.76	2.99	0.894	0.705
136	427,000	420,000	1,100	39.71	38.25	2.98	0.963	0.512
137	395,000	247,000	600	39.58	36.18	2.98	0.914	0.556

[a]Weir discharge = total measured discharge - computed submerged orifice discharge.

[b]From Hulsing (1967), with L = 52 ft, P = 5 ft, upstream radius of rounding, R = 4 ft and a 1:1 downstream slope. The symbols, L, P, and R are the same as those used in the reference and do not agree with the symbols and units page V-VI.

Note: All turbine discharges and leakage discharges were zero during these measurements.

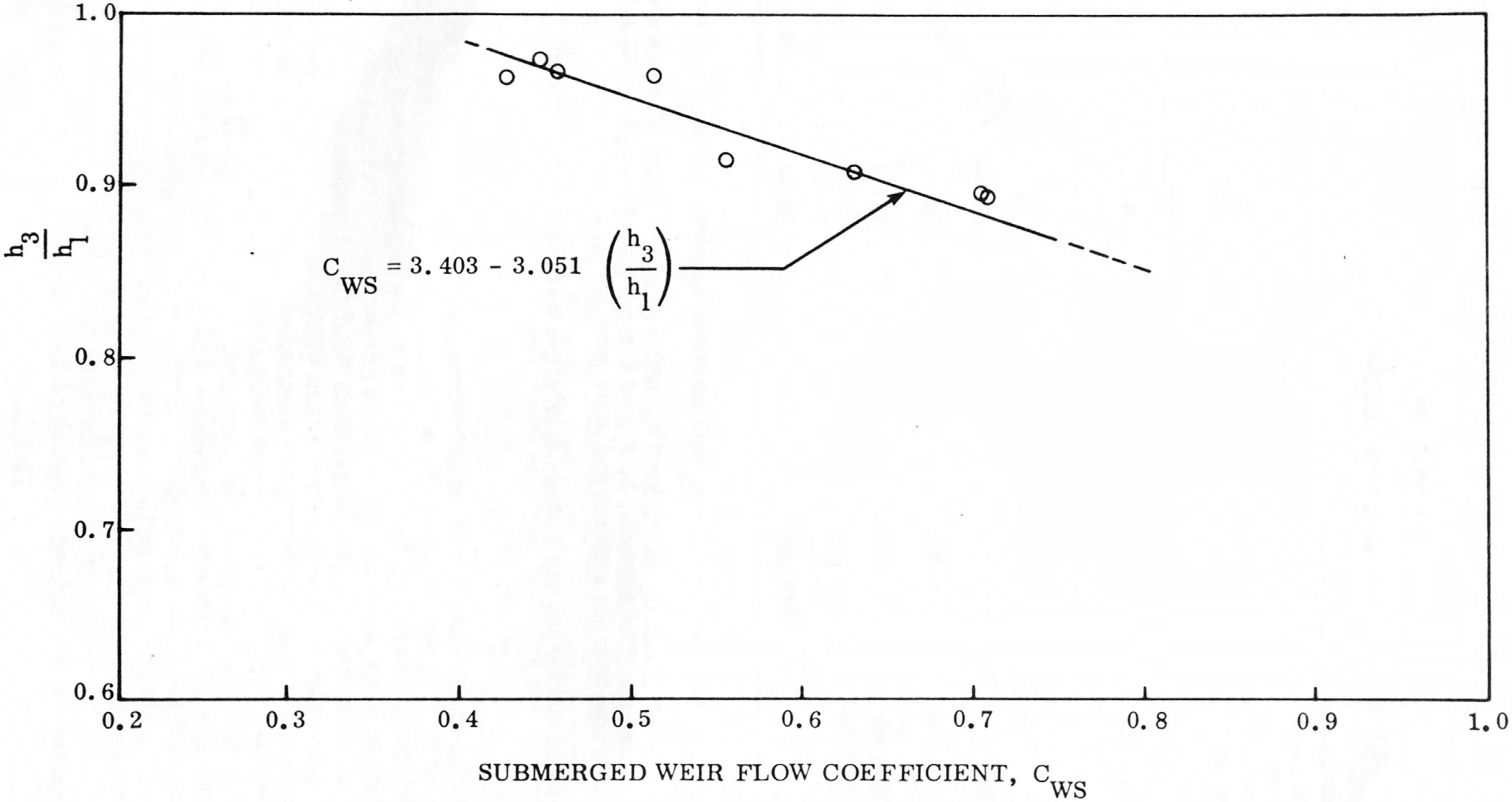


Figure 8. Submerged weir flow coefficient relation, Markland Lock and Dam

Table 5.--Summary of computed discharges using developed calibration results compared to actual measured discharges, Markland Lock and Dam

Measurement number	Total measured discharge, in cubic feet per second	Computed leakage discharge, in cubic feet per second	Computed turbine discharge, in cubic feet per second	Computed gate discharge, in cubic feet per second	Total computed discharge, in cubic feet per second	Calibration error, in percent
65	272,000	0	0	271,000	271,000	- 0.4
86	115,000	2,490	39,500	77,000	119,000	+ 3.5
87	34,300	5,730	25,500	0	31,200	- 9.0
89	25,100	5,820	20,400	778	27,000	+ 7.6
90	17,400	5,840	11,300	0	17,100	- 1.7
91	21,800	5,810	12,400	0	18,200	-16.5
92	39,900	5,690	6,430	27,300	39,400	- 1.2
93	25,200	5,760	12,700	6,380	24,800	- 1.6
94	15,300	5,840	10,700	0	16,500	+ 7.8
95	12,400	5,840	6,120	0	12,000	- 3.2
96	21,200	5,840	16,800	0	22,600	+ 6.6
97	27,500	5,800	23,000	0	28,800	+ 4.7
98	30,700	4,670	23,100	3,670	31,400	+ 2.3
99	95,900	1,810	27,400	70,200	99,400	+ 3.6
100	104,000	5,110	26,900	71,100	103,000	- 1.0
101	124,000	2,460	27,500	102,000	132,000	+ 6.5
102	222,000	608	15,000	229,000	245,000	+10.4
103	96,600	2,140	28,200	63,100	93,400	- 3.3
104	62,200	2,810	26,500	36,600	65,900	+ 5.9
105	82,800	2,740	26,600	52,800	82,100	- 0.8
106	159,000	2,350	27,100	130,000	159,000	0.0

Tabel 5.--(Continued)

Measurement number	Total measured discharge, in cubic feet per second	Computed leakage discharge, in cubic feet per second	Computed turbine discharge, in cubic feet per second	Computed gate discharge, in cubic feet per second	Total computed discharge, in cubic feet per second	Calibration error, in percent
107	54,000	4,680	19,300	19,200	43,200	-20.0
108	35,300	4,650	25,000	6,890	36,500	+ 3.4
109	14,500	4,750	9,520	0	14,300	- 1.3
110	17,100	4,730	12,200	0	16,900	- 1.2
111	68,200	2,640	30,000	35,900	68,500	+ 0.4
112	28,100	4,850	20,800	3,130	28,800	+ 2.5
113	24,900	4,700	18,700	0	23,400	- 6.0
114	128,000	771	23,800	116,000	141,000	+10.2
115	272,000	0	13,200	263,000	276,000	+ 1.5
116	227,000	0	14,700	234,000	249,000	+ 9.7
117	349,000	0	0	385,000	385,000	+10.3
118	345,000	0	0	338,000	338,000	- 2.0
120	448,000	0	0	438,000	438,000	- 2.2
121	161,000	0	23,400	150,000	173,000	+ 7.4
122	194,000	0	22,900	166,000	189,000	- 2.6
124	19,200	3,790	17,600	0	21,400	+11.4
125	15,400	3,800	13,700	0	17,500	+13.6
126	16,300	3,800	11,900	0	15,700	- 3.7
127	15,700	3,790	13,600	0	17,400	+10.8
128	16,000	3,780	11,300	0	15,100	- 5.6
130	166,000	727	19,400	153,000	173,000	+ 4.2

Table 5.--(Continued)

Measurement number	Total measured discharge, in cubic feet per second	Computed leakage discharge, in cubic feet per second	Computed turbine discharge, in cubic feet per second	Computed gate discharge, in cubic feet per second	Total computed discharge, in cubic feet per second	Calibration error, in percent
131	444,000	0	0	440,000	440,000	- 0.9
132	80,400	866	30,600	47,700	79,200	- 1.5
133	373,000	0	0	377,000	377,000	+ 1.1
134	358,000	0	0	356,000	356,000	- 0.6
135	341,000	0	0	343,000	343,000	+ 0.6
136	427,000	0	0	388,000	388,000	- 9.1
137	395,000	0	0	421,000	421,000	+ 6.6
138	35,900	3,720	32,300	0	36,000	+ 0.3
139	17,000	4,740	11,300	0	16,000	- 5.9
140	16,600	4,730	10,300	0	15,000	- 9.6
141	71,700	1,760	42,300	29,500	73,600	+ 2.6
142	293,000	0	0	302,000	302,000	+ 3.1

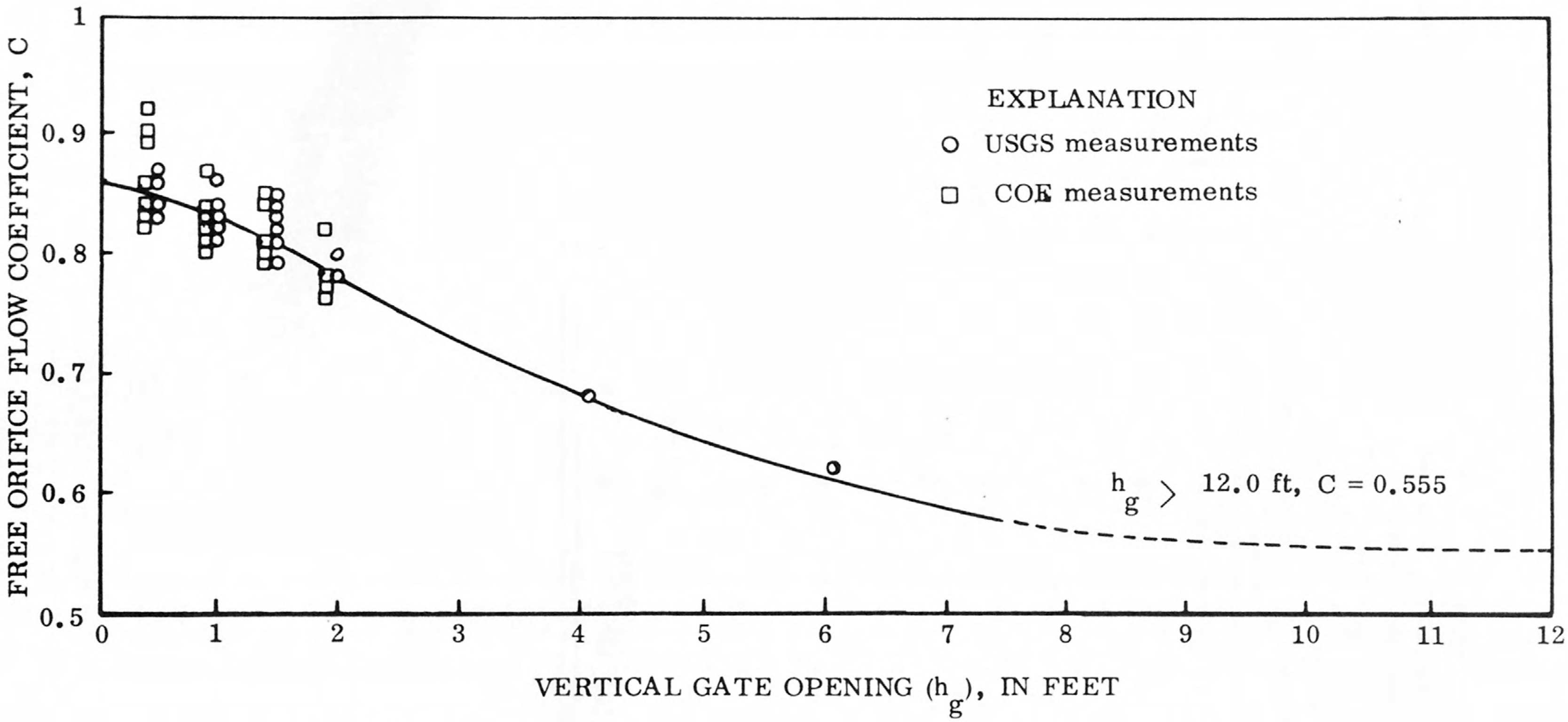


Figure 9. Free orifice flow coefficient relation, Coffeeville Lock and Dam

Table 6.--Free orifice flow calibration data, Coffeeville Lock and Dam

Measurement number	Total measured discharge, in cubic feet per second	h_1, in feet	h_3, in feet	Variable	Gate number 1	2	3	4	5	6	7	8
1	3,590	19.42	0.0	h_g[a]	0.0	0.0	0.0	0.0	0.0	0.0	0.50	1.50
				q[b]	0.0	0.0	0.0	0.0	0.0	0.0	923	2670
				C	-	-	-	-	-	-	0.87	0.84
2	3,660	19.43	0.0	h_g	0.0	0.50	0.0	0.50	0.0	0.50	0.0	0.50
				q	0.0	915	0.0	915	0.0	915	0.0	915
				C	-	0.86	-	0.86	-	0.86	-	0.86
3	8,220	19.47	0.0	h_g	0.0	0.50	0.50	0.50	0.50	0.0	1.0	1.50
				q	0.0	923	923	923	923	0.0	1824	2704
				C	-	0.87	0.87	0.87	0.87	-	0.86	0.85
5	6,010	19.49	0.0	h_g	0.0	0.50	0.50	0.0	0.0	0.0	1.00	1.50
				q	0.0	881	881	0.0	0.0	0.0	1720	2569
				C	-	0.83	0.83	-	-	-	0.81	0.79

Table 6.--(Continued)

Measurement number	Total measured discharge, in cubic feet per second	h_1, in feet	h_3, in feet	Variable	Gate number 1	2	3	4	5	6	7	8
6	6,930	19.50	0.0	h_g	0.0	0.50	0.50	0.50	0.0	0.0	1.00	1.50
				q	0.0	893	893	893	0.0	0.0	1744	2507
				C	-	0.84	0.84	0.84	-	-	0.82	0.79
7	3,560	19.50	0.0	h_g	0.0	0.0	0.0	0.0	0.0	0.0	0.50	1.50
				q	0.0	0.0	0.0	0.0	0.0	0.0	925	2635
				C	-	-	-	-	-	-	0.87	0.83
8	5,170	19.50	0.0	h_g	0.0	0.50	0.0	0.0	0.0	0.0	1.00	1.50
				q	0.0	893	0.0	0.0	0.0	0.0	1744	2533
				C	-	0.84	-	-	-	-	0.82	0.79
9	18,900	17.95	0.0	h_g	1.00	1.50	1.50	1.50	1.00	1.00	2.00	2.00
				q	1693	2478	2478	2478	1693	1693	3192	3192
				C	0.83	0.81	0.81	0.81	0.83	0.83	0.78	0.78
10	19,200	17.95	0.0	h_g	1.00	1.50	1.50	1.50	1.00	1.00	2.00	2.00
				q	1714	2509	2509	2509	1714	1714	3266	3266
				C	0.84	0.82	0.82	0.82	0.84	0.84	0.80	0.80
11	15,200	17.90	0.0	h_g	0.50	1.00	1.00	1.00	1.00	1.00	1.50	2.00
				q	875	1710	1710	1710	1710	1710	2503	3271
				C	0.86	0.84	0.84	0.84	0.84	0.84	0.81	0.80

Table 6.--(Continued)

Measurement number	Total measured discharge, in cubic feet per second	h_1, in feet	h_3, in feet	Variable	Gate number 1	2	3	4	5	6	7	8
15	17,200	18.99	0.0	h_g	0.0	0.0	4.00	0.0	0.0	0.0	4.00	4.00
				q	0.0	0.0	5733	0.0	0.0	0.0	5733	5733
				C	-	-	0.68	-	-	-	0.68	0.68
16	15,600	18.89	0.0	h_g	0.0	0.0	6.00	0.0	0.0	0.0	0.0	6.00
				q	0.0	0.0	7800	0.0	0.0	0.0	0.0	7800
				C	-	-	0.62	-	-	-	-	0.62
34	13,400	19.07	0.0	h_g	0.50	1.00	1.00	0.90	0.0	1.00	1.50	2.00
				q	882	1723	1723	1570	0.0	1723	2521	3258
				C	0.84	0.82	0.82	0.83	-	0.82	0.80	0.78
9C[c]	9,830	19.40	0.0	h_g	0.40[d]	0.90	0.90	0.90	0.90	0.90	0.90	0.0
				q	695	1522	1522	1522	1522	1522	1522	0.0
				C	0.82	0.80	0.80	0.80	0.80	0.80	0.80	-
10C	5,060	19.31	0.0	h_g	0.0	0.40	0.40	0.40	0.40	0.40	0.90	0.0
				q	0.0	702	702	702	702	702	1549	0.0
				C	-	0.83	0.83	0.83	0.83	0.83	0.81	-

Table 6.--(Continued)

Measurement number	Total measured discharge, in cubic feet per second	h_1, in feet	h_3, in feet	Variable	Gate number							
					1	2	3	4	5	6	7	8
11C	17,700	17.75	0.80	h_g	1.40	1.40	1.40	1.40	1.40	1.40	1.90	0.0
				q	2243	2243	2243	2243	2243	2243	2910	0.0
				C	0.79	0.79	0.79	0.79	0.79	0.79	0.76	-
20C	11,600	18.81	0.0	h_g	0.90	0.90	0.90	0.90	0.90	0.90	1.40	0.0
				q	1542	1542	1542	1542	1542	1542	2348	0.0
				C	0.82	0.82	0.82	0.82	0.82	0.82	0.80	-
21C	6,620	19.30	0.0	h_g	0.40	0.90	0.40	0.40	0.40	0.40	0.90	0.0
				q	711	1534	711	711	711	711	1534	0.0
				C	0.84	0.81	0.84	0.84	0.84	0.84	0.81	-
22C	2,340	19.40	0.0	h_g	0.0	0.40	0.40	0.0	0.0	0.0	0.40	0.0
				q	0.0	780	780	0.0	0.0	0.0	780	0.0
				C	-	0.92	0.92	-	-	-	0.92	-
23C	2,310	19.62	0.0	h_g	0.0	0.40	0.40	0.0	0.0	0.0	0.40	0.0
				q	0.0	770	770	0.0	0.0	0.0	770	0.0
				C	-	0.90	0.90	-	-	-	0.90	-
41C	19,800	17.51	0.0	h_g	1.40	1.40	1.40	1.40	1.40	1.40	1.90	1.90
				q	2283	2283	2283	2283	2283	2283	2950	2950
				C	0.81	0.81	0.81	0.81	0.81	0.81	0.77	0.77

Table 6.--(Continued)

Measurement number	Total measured discharge, in cubic feet per second	h_1, in feet	h_3, in feet	Variable	Gate number 1	2	3	4	5	6	7	8
42C	16,600	17.58	0.0	h_g	0.90	1.40	0.90	0.90	0.90	0.90	1.90	1.90
				q	1563	2402	1563	1563	1563	1563	3147	3147
				C	0.87	0.85	0.87	0.87	0.87	0.87	0.82	0.82
43C	13,600	17.61	0.0	h_g	0.40	0.90	0.90	0.90	0.90	0.90	1.40	1.90
				q	694	1526	1526	1526	1526	1526	2289	2986
				C	0.86	0.84	0.84	0.84	0.84	0.84	0.81	0.78
44C	7,730	18.50	0.0	h_g	0.0	0.40	0.40	0.40	0.40	0.40	0.90	1.40
				q	0.0	737	737	737	737	737	1622	2423
				C	-	0.89	0.89	0.89	0.89	0.89	0.87	0.84

[a]Gate opening, in feet.

[b]Discharge per gate, in ft^3/s.

[c]The C in measurement number denotes measurements made by COE.

[d]All gate openings from COE measurements were corrected.

The next flow regime analyzed was submerged orifice flow. Except for measurement numbers 22 and 31, this calibration required a trial-and-error division of measured discharge because several gates were open at different settings. The division was simplified by first assuming a coefficient distribution based on a typical relation from other calibrated structures and from the coefficients computed for measurements 22 and 31. This distribution was then refined after all coefficients had been computed and is illustrated in figure 10. The calibration data used to define the relation are tabulated in table 7. The mathematical equation for the relation illustrated in figure 10 is

$$C_{gs} = 0.865\left(\frac{h_3}{h_g}\right)^{-0.892}$$

The power on the independent parameter in this equation should be noted. For most structures investigated to date, this power was equal to -1.0. The calibration of this structure was selected as an example to illustrate the point that the slope of the line may deviate from the expected value of -1.0. The relation is fairly well defined except at higher gate submergence ratios where additional data would improve the definition. The extended part of the curve is based on a straight line extrapolation and on similar calibrations at other structures.

The last part of the calibration was for submerged weir flow through the Tainter gates and over the fixed spillway. These two types of control were analyzed at the same time because there were insufficient measurements available to define the submerged weir flow through the gates independent of flow over the fixed spillway. Because of this problem, several assumptions, based on a literature review and sound hydraulic principles, were required to separate the flow for calibration.

The assumptions concerned the rating of the fixed spillway. The first assumption was that a submergence correction curve (fig. 11) similar to that presented by Hulsing (1967), for a submerged ogee dam with $H = 1.0H_o$ where H and H_o are defined in the reference would be applicable. The curve from the reference was altered slightly at lower values of the submergence ratio to reduce calibration errors. The next assumption required was an expression for the free weir flow coefficient relation for the fixed spillway. Through a trial-and-error procedure using the data tabulated in table 8, a constant coefficient of 3.03 was selected. After these two assumptions were made, the development of the calibration curve illustrated in figure 12 was possible. The minor extensions of the curve on figure 12 are straight-line extrapolations.

The relation for the free weir flow coefficient, figure 13, for the gated control was also developed from Hulsing (1967) because no measurements have been made with free weir flow. The operation of the structure with free weir flow through the gates is rare, and the use of the relation without verification probably does not reduce the overall accuracy of the calibration.

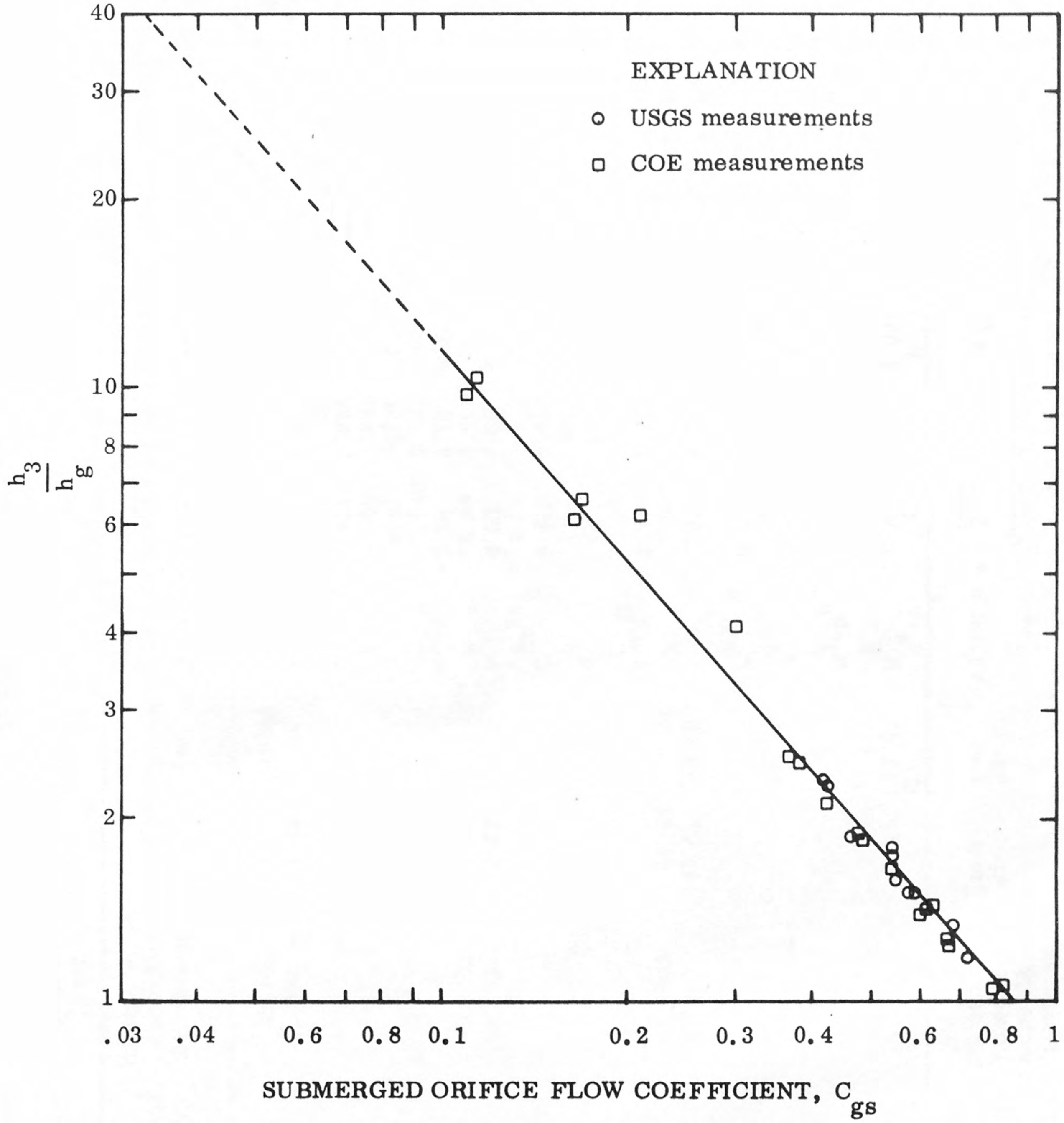


Figure 10. Submerged orifice flow coefficient relation, Coffeeville Lock and Dam

TABLE 7.--Submerged orifice flow calibration data, Coffeeville Lock and Dam

Measurement number	Total measured discharge, in cubic feet per second	h_1, in feet	h_3, in feet	Variable	Gate number 1	2	3	4	5	6	7	8
12	23,100	17.57	1.77	h_g[a]	1.50	2.00	2.00	2.00	1.50	1.50	2.00	2.00
				h_3/h_g	1.18	-[b]	-[b]	-[b]	1.18	1.18	-[b]	-[b]
				q	2450	3150	3150	3150	2450	2450	3150	3150
				C_{gs}	0.724	-[b]	-[b]	-[b]	0.724	0.724	-[b]	-[b]
13	41,400	16.27	9.25	h_g	4.00	4.00	4.00	4.00	4.00	4.00	4.00	6.00
				h_3/h_g	2.31	2.31	2.31	2.31	2.31	2.31	2.31	1.54
				q	4937	4937	4937	4937	4937	4937	4937	6839
				C_{gs}	0.419	0.419	0.419	0.419	0.419	0.419	0.419	0.580
14	42,700	15.93	9.16	h_g	4.00	4.00	4.00	4.00	4.00	4.00	6.00	6.00
				h_3/h_g	2.29	2.29	2.29	2.29	2.29	2.29	1.53	1.53
				q	4892	4892	4892	4892	4892	4892	6674	6674
				C_{gs}	0.427	0.427	0.427	0.427	0.427	0.427	0.582	0.582
21	47,000	14.63	10.76	h_g	6.00	6.00	6.00	6.00	6.00	6.00	8.00	8.00
				h_3/h_g	1.79	1.79	1.79	1.79	1.79	1.79	1.34	1.34
				q	5530	5530	5530	5530	5530	5530	6925	6925
				C_{gs}	0.543	0.543	0.543	0.543	0.543	0.543	0.680	0.680

TABLE 7.--(Continued)

Measurement number	Total measured discharge, in cubic feet per second	h_1, in feet	h_3, in feet	Variable	Gate number							
					1	2	3	4	5	6	7	8
22	45,500	14.72	10.48	h_g	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
				h_3/h_g	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
				q	5688	5688	5688	5688	5688	5688	5688	5688
				C_{gs}	0.548	0.548	0.548	0.548	0.548	0.548	0.548	0.548
31	39,400	17.03	14.94	h_g	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
				h_3/h_g	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.87
				q	4925	4925	4925	4925	4925	4925	4925	4925
				C_{gs}	0.474	0.474	0.474	0.474	0.474	0.474	0.474	0.474
2C [c]	11,400	18.45	9.24	h_g	0.90 [d]	1.40	1.40	0.0	0.90	0.90	1.40	0.0
				h_3/h_g	10.27	6.60	6.60	-	10.27	10.27	6.60	-
				q	1534	2266	2266	0.0	1534	1534	2266	0.0
				C_{gs}	0.114	0.168	0.168	-	0.114	0.114	0.168	-
3C	11,300	18.44	9.78	h_g	0.90	1.40	1.40	0.0	0.90	0.90	1.40	0.0
				h_3/h_g	9.62	6.19	6.19	-	9.62	9.62	6.19	-
				q	1523	2244	2244	0.0	1523	1523	2244	0.0
				C_{gs}	0.110	0.162	0.162	-	0.110	0.110	0.162	-

TABLE 7. -- (Continued)

Measurement number	Total measured discharge, in cubic feet per second	h_1, in feet	h_3, in feet	Variable	Gate number 1	2	3	4	5	6	7	8
12C	43,600	16.27	7.40	h_g	3.90	5.90	5.90	5.90	3.90	3.90	5.90	0.0
				h_3/h_g	1.90	1.25	1.25	1.25	1.90	1.90	1.25	-
				q	5037	7122	7122	7122	5037	5037	7122	0.0
				C_{gs}	0.475	0.672	0.672	0.672	0.475	0.475	0.672	-
13C	33,800	16.72	7.20	h_g	2.90	3.90	3.90	3.90	3.90	2.90	3.90	0.0
				h_3/h_g	2.48	1.85	1.85	1.85	1.85	2.48	1.85	-
				q	4061	5130	5130	5130	5130	4061	5130	0.0
				C_{gs}	0.380	0.480	0.480	0.480	0.480	0.380	0.480	-
14C	23,600	17.07	4.80	h_g	1.90	2.90	1.90	1.90	1.90	1.90	2.90	0.0
				h_3/h_g	2.53	1.66	2.53	2.53	2.53	2.53	1.66	-
				q	2977	4368	2977	2977	2977	2977	4368	0.0
				C_{gs}	0.368	0.540	0.368	0.368	0.368	0.368	0.540	-
15C	19,700	17.41	3.00	h_g	1.40	1.90	1.90	1.90	1.90	1.40	1.90	0.0
				h_3/h_g	2.14	1.58	1.58	1.58	1.58	2.14	1.58	-
				q	2329	3008	3008	3008	3008	2329	3008	0.0
				C_{gs}	0.425	0.549	0.549	0.549	0.549	0.425	0.549	-

TABLE 7.--(Continued)

Measurement number	Total measured discharge, in cubic feet per second	h_1, in feet	h_3, in feet	Variable	Gate number 1	2	3	4	5	6	7	8
17C	31,700	15.69	3.70	h_g	2.90	3.90	3.90	2.90	2.90	2.90	3.90	0.0
				h_3/h_g	1.28	-[b]	-[b]	1.28	1.28	1.28	-[b]	-
				q	4099	5099	5099	4099	4099	4099	5099	0.0
				C_{gs}	0.665	-[b]	-[b]	0.665	0.665	0.665	-[b]	-
18C	48,100	14.43	8.40	h_g	5.90	7.90	7.90	5.90	5.90	5.90	7.90	0.0
				h_3/h_g	1.42	1.06	1.06	1.42	1.42	1.42	1.06	-
				q	6103	7899	7899	6103	6103	6103	7899	0.0
				C_{gs}	0.615	0.796	0.796	0.615	0.615	0.615	0.796	-
19C	48,500	14.43	8.40	h_g	5.90	7.90	7.90	5.90	5.90	5.90	7.90	0.0
				h_3/h_g	1.42	1.06	1.06	1.42	1.42	1.42	1.06	-
				q	6153	7959	7959	6153	6153	6153	7959	0.0
				C_{gs}	0.620	0.802	0.802	0.620	0.620	0.620	0.802	-
37C	33,400	15.69	5.44	h_g	2.90	2.90	3.90	2.90	2.90	2.90	2.90	3.90
				h_3/h_g	1.88	1.88	1.40	1.88	1.88	1.88	1.88	1.40
				q	3863	3863	5111	3863	3863	3863	3863	5111
				C_{gs}	0.461	0.461	0.610	0.461	0.461	0.461	0.461	0.610

TABLE 7.--(Continued)

Measurement number	Total measured discharge, in cubic feet per second	h_1, in feet	h_3, in feet	Variable	Gate number 1	2	3	4	5	6	7	8
45C	20,700	17.49	11.79	h_g	1.90	2.90	2.90	0.0	1.90	1.90	2.90	0.0
				h_3/h_g	6.20	4.07	4.07	-	6.20	6.20	4.07	-
				q	2830	4062	4062	0.0	2830	2830	4062	0.0
				C_{gs}	0.209	0.300	0.300	-	0.209	0.209	0.300	-

[a]Gate opening, in feet.

[b]Not applicable because flow through the gate is free orifice flow.

[c]The C in the measurement number denotes measurements made by COE

[d]All gate openings from COE measurements were corrected.

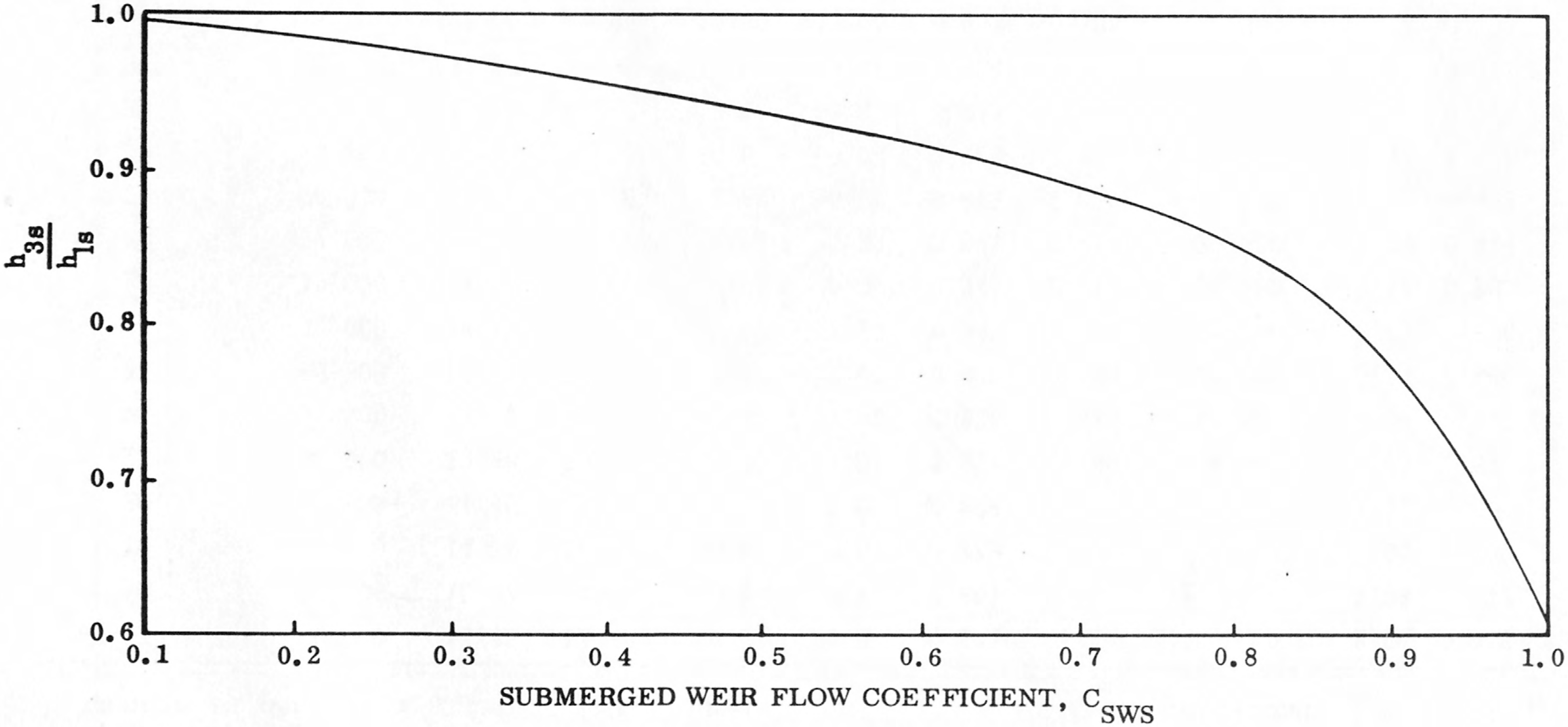


Figure 11. Submerged weir flow coefficient relation for fixed spillway, Coffeeville Lock and Dam

Table 8.--Submerged weir flow calibration data for both the gated and fixed spillways, Coffeeville Lock and Dam

Measurement number	Total measured discharge, in cubic feet per second	h_1, in feet	h_3, in feet	h_{1s}, in feet[a]	h_{3s}, in feet[b]	$\frac{h_3}{h_1}$	$\frac{h_{3s}}{h_{1s}}$	Computed spillway discharge, in cubic feet per second	C_W[c]	C_{WS}
17	70,000	16.86	14.74	0.0	0.0	0.874	-	0	2.94	0.715
18	66,800	16.37	14.42	0.0	0.0	0.881	-	0	2.93	0.717
19	53,600	14.34	12.60	0.0	0.0	0.879	-	0	2.90	0.709
20	56,800	14.89	13.07	0.0	0.0	0.878	-	0	2.91	0.708
23	92,900	22.40	20.54	2.90	1.04	0.917	0.359	9,660	3.02	0.541
24	96,500	23.12	21.36	3.62	1.86	0.924	0.514	13,500	3.04	0.512
25	98,200	23.64	21.94	4.14	2.44	0.928	0.589	16,500	3.05	0.486
26	131,000	28.17	26.67	8.67	7.17	0.947	0.827	42,000	3.13	0.396
27	119,000	27.27	25.80	7.73	6.30	0.947	0.815	36,100	3.12	0.389
28	112,000	26.15	24.72	6.65	5.22	0.945	0.785	29,900	3.09	0.414
29	72,300	21.24	20.16	1.74	0.66	0.949	0.379	4,500	3.00	0.481
30	60,800	19.23	18.16	0.0	0.0	0.944	-	0	2.97	0.506
32	71,700	19.47	17.86	0.0	0.0	0.917	-	0	2.97	0.585
33	149,000	30.37	28.98	10.87	9.48	0.954	0.872	53,200	3.17	0.376
35	186,000	33.00	31.45	13.50	11.95	0.953	0.885	70,000	3.22	0.396

[a]Effective headwater on fixed spillway
[b]Effective tailwater on fixed spillway

[c]From Hulsing (1967), with *L* = 37 ft, *P* = 4 ft. 1:1 upstream slope; 2:3 downstream slope. *L* and *P* are defined in the reference and do not agree with the symbols and units used in this report.

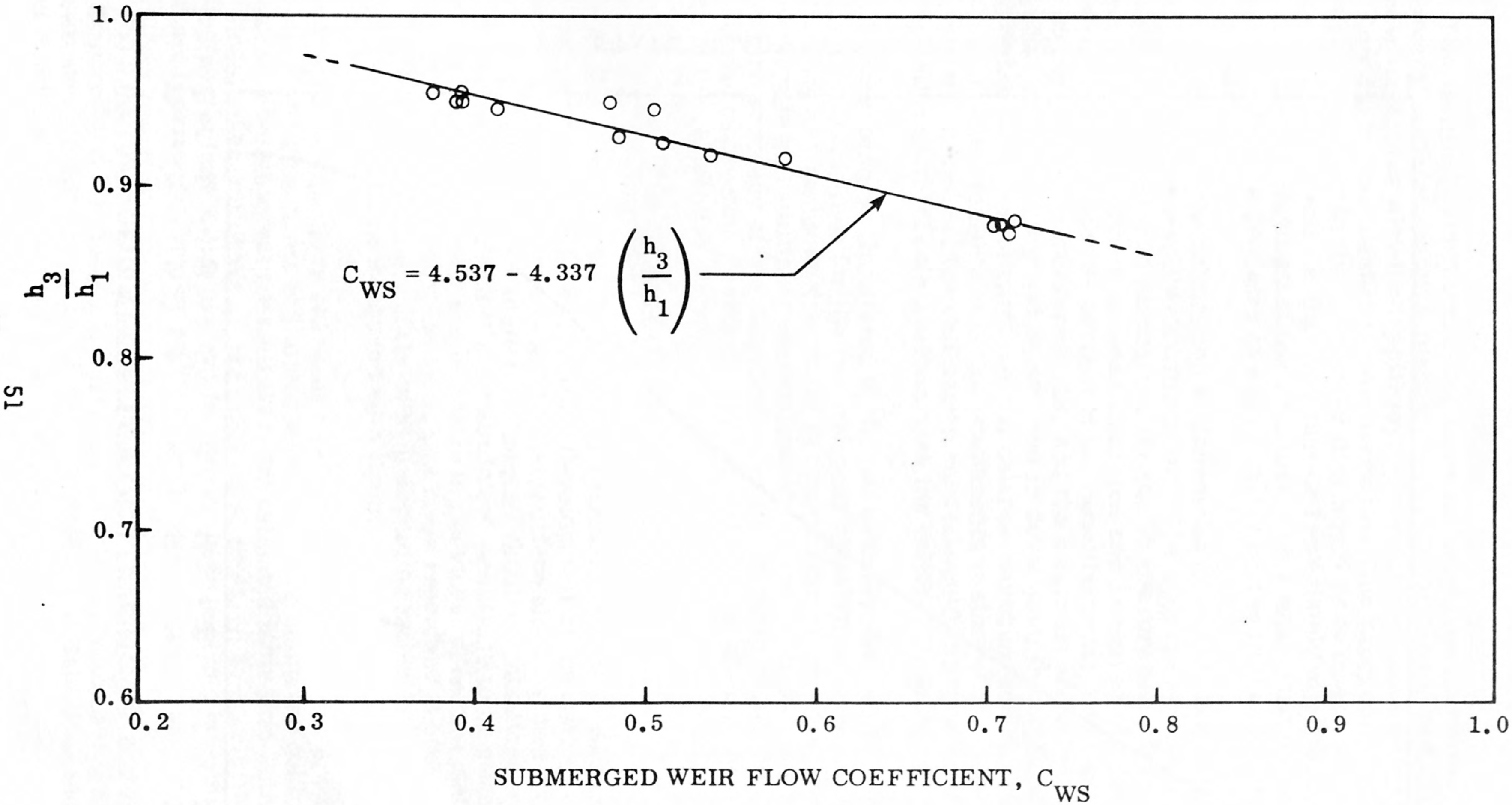


Figure 12. Submerged weir flow coefficient relation for flow through gates, Coffeeville Lock and Dam

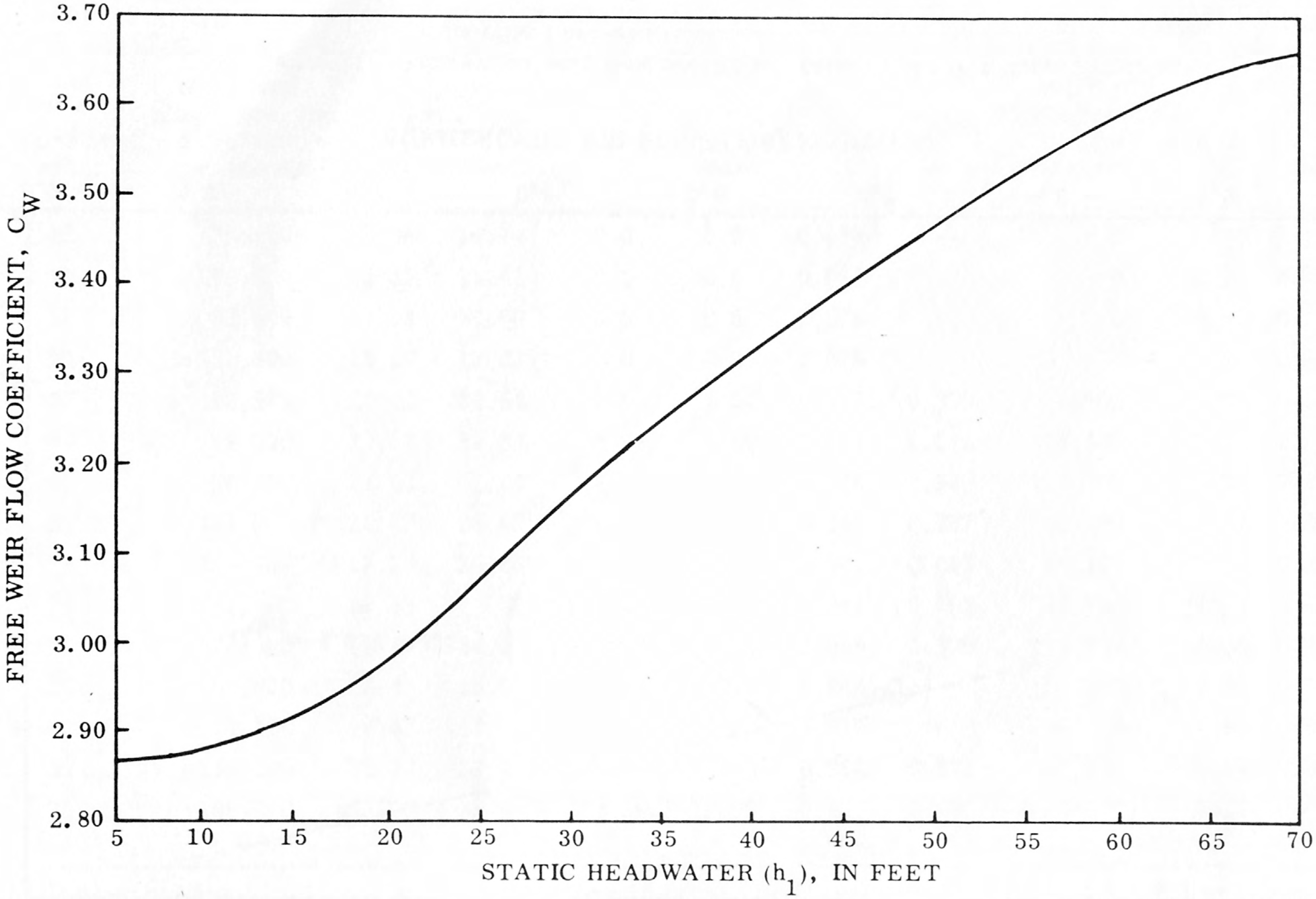


Figure 13. Free weir flow coefficient relation for flow through gates, Coffeeville Lock and Dam

The assumed calibration of the fixed spillway does, however, reduce the overall accuracy at high discharges. This calibration and calibrations at new structures with fixed spillways likely can be improved by separating the flow during the discharge measurements. One procedure, as described earlier, to determine fixed-spillway flow would be to measure in the forebay of each open gate and, at the same time or immediately afterward, measure the total flow downstream of the structure. This measuring procedure is feasible if the gate geometry is such to allow access in the forebay.

In summary, the calibration at Coffeeville Lock and Dam is fairly good except for the fixed-spillway calibration. The average error between the computed and measured discharges for the 56 measurements made is 3.6 percent. The difference between computed and measured discharge is less than 5 percent for 84 percent of the measurements; less than 10 percent for 95 percent of the measurements; and the maximum error is only 12.5 percent. Visual fitting was again used in developing the coefficient relations. The fitting was done to minimize and balance maximum errors. Selective discharge measurements to define coefficients in the range of the dashed extensions on three of the calibration curves would improve the reliability of the calibration. Table 9 summarizes the calibration data.

The procedures illustrated in the two examples are similar and can be used as guidelines for the calibration of other structures. The bulk of the time and manpower required to compute continuous streamflow records at a multipurpose structure is in the calibration phase. Likewise, the accuracy of the computed record is directly proportional to the number of calibration measurements and to the care taken in fully developing each of the calibration curves.

SUMMARY AND CONCLUSIONS

A method to compute continuous streamflow records at regulating control structures has been described. Development of the method was necessitated by the decrease in natural water-surface slope by man-made changes. Previous computation techniques required this slope in the procedures and required that it be of sufficient magnitude to be measured accurately with available stage-measuring devices. The new method is independent of water-surface slope in a river reach and it uses the structure as the control point. This control should be stable except for operational changes which can be measured with the developed instrumentation.

Hydraulic equations based on steady flow assumptions were used to calibrate the structures and to compute discharge using the calibration results. Five different controls were investigated including Tainter gates, turbines, fixed spillways, locks, and crest gates. The possibility of multiple flow regimes being present for two of these controls is pointed out and appropriate calibration procedures given.

The instrumentation package required in the collection and recording of the many field variables is described briefly. The computer programs necessary to compute discharge using the recorded field data and calibration results are discussed.

TABLE 9.--Summary of computed discharges using developed calibration results compared to actual measured discharge, Coffeeville Lock and Dam

Measurement number	Total measured discharge, in cubic feet per second	Computed gate discharge, in cubic feet per second	Computed fixed spillway discharge, in cubic feet per second	Total computed discharge, in cubic feet per second	Calibration error, in percent
1	3,590	3,470	0	3,470	- 3.3
2	3,660	3,600	0	3,600	- 1.6
3	8,220	7,940	0	7,940	- 3.4
5	6,010	6,140	0	6,140	+ 2.2
6	6,930	7,040	0	7,040	+ 1.6
7	3,560	3,480	0	3,480	- 2.2
8	5,170	5,240	0	5,240	+ 1.4
9	18,900	18,900	0	18,900	0.0
10	19,200	18,900	0	18,900	- 1.6
11	15,200	15,000	0	15,000	- 1.3
12	23,100	23,300	0	23,300	+ 0.9
13	41,400	40,800	0	40,800	- 1.4
14	42,700	42,000	0	42,000	- 1.6
15	17,200	17,100	0	17,100	- 0.6
16	15,600	15,400	0	15,400	- 1.3
17	69,000	72,900	0	72,900	+ 5.6
18	66,700	66,700	0	66,700	0.0
19	53,600	54,800	0	54,800	+ 2.2
20	56,800	58,500	0	58,500	+ 3.0

TABLE 9.--(Continued)

Measurement number	Total measured discharge, in cubic feet per second	Computed gate discharge, in cubic feet per second	Computed fixed spillway discharge, in cubic feet per second	Total computed discharge, in cubic feet per second	Calibration error, in percent
21	47,000	45,000	0	45,000	- 4.3
22	45,500	43,600	0	43,600	- 4.2
23	92,900	86,100	9,660	95,800	+ 3.1
24	96,500	85,900	13,500	99,400	+ 3.0
25	98,200	86,200	16,500	103,000	+ 4.9
26	131,000	96,600	42,000	139,000	+ 6.1
27	119,000	91,700	36,100	128,000	+ 7.6
28	112,000	87,000	29,900	117,000	+ 4.5
29	72,300	59,400	4,500	63,900	-11.6
30	60,800	53,200	0	53,200	-12.5
31	39,400	41,100	0	41,100	+ 4.3
32	71,700	68,600	0	68,600	- 4.3
33	149,000	102,000	53,200	155,000	+ 4.0
34	13,400	13,500	0	13,500	+ 0.8
35	186,000	118,000	70,000	188,000	+ 1.1
2C[a]	11,400	10,900	0	10,900	- 4.4
3C	11,300	11,800	0	11,800	+ 4.4
9C	9,830	10,300	0	10,300	+ 4.8
10C	5,060	5,180	0	5,180	+ 2.4
11C	17,700	17,000	0	17,000	- 4.0
12C	43,600	45,500	0	45,500	+ 4.4
13C	33,800	35,000	0	35,000	+ 3.6

TABLE 9. -- (Continued)

Measurement number	Total measured discharge, in cubic feet per second	Computed gate discharge, in cubic feet per second	Computed fixed spillway discharge, in cubic feet per second	Total computed discharge, in cubic feet per second	Calibration error, in percent
14C	23,600	24,200	0	24,200	+ 2.5
15C	19,700	20,600	0	20,600	+ 4.6
17C	31,700	32,500	0	32,500	+ 3.2
18C	48,100	49,400	0	49,400	+ 2 7
19C	48,500	49,400	0	49,400	+ 1.9
20C	11,600	11,800	0	11,800	+ 1.7
21C	6,620	6,770	0	6,770	+ 2.3
22C	2,340	2,160	0	2,160	- 7.7
23C	2,310	2,170	0	2,170	- 6.1
37C	33,400	35,600	0	35,600	+ 6.6
41C	19,800	19,800	0	19,800	0.0
42C	16,600	15,900	0	15,900	- 4.2
43C	13,600	13,900	0	13,900	+ 2.2
44C	7,730	7,430	0	7,430	- 3.9
45C	20,700	23,200	0	23,200	+12.1

[a] The C in measurement numbers denotes measurements made by COE.

Two example calibrations of multipurpose structures including the necessary data are given. Both examples are partial calibrations and require additional measurement data before they can be considered final. The average absolute calibration error for Markland Lock and Dam on the Ohio River was 5.4 percent. The average absolute calibration error for Coffeeville Lock and Dam on the Tombigbee was 3.6 percent. All the errors between the measured and computed discharges (calibration errors) are summarized in included tables. These errors are within the accuracy range of other techniques routinely used by the U.S. Geological Survey to gage streams. A fault of the error analysis used in this report is that all the measurements used to develop the calibration relations were also used in the error analysis.

The calibration procedures as described in this report and supported by two example field calibrations should allow most experienced hydrologists to apply the method to other structures. A definite attempt has been made throughout the report to keep the outlined procedures from appearing to be "cookbook" procedures. Anyone attempting to use the method must apply sound engineering judgement in order to develop a complete and reliable calibration.

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