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COMPUTATION OF FLOW-THROUGH WATER CONTROL STRUCTURES

by

Jose' Maria Otero, P.E.

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Hydrologic Data Management Division
Water Resources Evaluation Department
South Florida Water Management District
West Palm Beach, Florida

EXECUTIVE SUMMARY

This publication details the procedures used in the discharge computation (Flow) computer program for calculating discharge through water control structures operated by the South Florida Water Management District. The Flow program, which is maintained by the Hydrologic Data Management Division, calculates discharge for more than 200 structures in the Kissimmee-Okeechobee-Everglades canal and water body network. The discharge computations performed by the Flow program are averaged into daily values and stored in DBHYDRO, the District's hydrologic database. Daily flow values stored in DBHYDRO are used by District staff; by local, state and federal agencies; and by companies involved in environmental and water resources projects in South Florida.

In 1985, Andrew Fan documented the discharge computation for gated culverts. Other procedures have been partially documented utilizing comment lines intermixed with the source code of the Flow program. Outside the District, procedures for discharge computation of various types of water control structures are found scattered throughout the literature. However, a comprehensive document which addresses discharge computation for all types of water control structures operated by the District is not found. This document addresses discharge computation for pumps, gated spillways, weirs, gated culverts, flumes and unregulated open channel reaches.

FLOW PROGRAM

Flow equations in the Flow program are mostly a function of the upstream stage, the downstream stage, and the level of control (e.g., gate opening). Flow equations for all control structures, including the various flow regimes that occur at each structure, are presented here. The coefficients, parameters, exponents, logical flags, and variables in each equation are explained. For flow calculations which require multiple equations, the relationship between the equations is outlined.

The information pertaining to each structure include the physical characteristics of the structure and the calibration coefficients, parameters, and exponents for the equations. The Flow program retrieves this information by querying DBHYDRO.

An input file must be provided to the Flow program. Each input record in the input file contains a structure identifier, the date and time, the upstream stage, the downstream stage, the number of devices in the structure, and the value for the level of control in each device. Qualifying tags may accompany the stage and control values. For example, an "E" tag accompanies a value which is estimated.

An output file is produced by the Flow program and includes one output record for every input record. Each output record contains a structure identifier, the date and

time, and the resulting discharge. A qualifying tag may be attached to the discharge value, if warranted, based upon the input record tags.

TYPES OF STRUCTURES

The computation of flow is presented according to the following classification: (1) pump station, (2) gated spillway, (3) gated culvert, (4) weir, (5) trapezoidal flume, and, (6) unregulated open channel.

(1) The flow through a pump station is computed for either the pumping or siphoning modes. The District operates constant- and variable-speed pumps. For pumps with significant variability in operating speeds, interpolation and extrapolation is performed using pump affinity laws between two discharge rating equations at both extremes of the operating range. Provisions are made for pumps with the possibility of exposed outlets and for loss of efficiency due to the presence of outlet flap gates.

(2) The flow through a gated spillway is calculated by first establishing the type of restrictions imposed on the flow. The level of gate restriction determines whether the flow is controlled or uncontrolled. The downstream water elevation dictates whether the flow is free or submerged. Based on these restrictions to the discharge, the flow regime may be uncontrolled free, controlled free, uncontrolled submerged, or controlled submerged. In addition, provisions are made for flow which overtops the gate, reverse flow, and flow which bypasses the structure.

(3) The flow regime through a gated culvert may be like that of a weir, a pipe, an open channel, or an orifice according to the type of control device, the level of control, and the water elevation at the inlet and at the outlet. The culvert cross-section may be circular, oval, or rectangular. A reasonable Manning's coefficient is determined and used in the flow computation. The configuration of the inlet may be flush against a headwall, projected into the approach channel, or angled to a wingwall. Provisions are made for reverse flow.

(4) A typical weir at the District consists of a rectangular notch in a dam. There are three types of weirs according to the crest and notch configuration: (1) ogee, (2) trapezoidal, and, (3) variable. An ogee weir comprises a rounded crest and a downstream apron. A trapezoidal weir refers to the shape of the notch, and includes V-notch weirs and rectangular weirs. A variable weir contains a movable crest which can be lowered or raised. Flow through weirs may occur through the notch, over the dam, or over both. Reverse flow is computed for trapezoidal and variable weirs. Ogee weirs at the District are designed for one-directional free flow only.

(5) A trapezoidal flume consists of a wide approach section, a gradual transition section, and a throat section. The flow through a trapezoidal flume is computed by estimating the discharge through the critical depth at the throat.

(6) The flow through an unregulated open channel reach is computed from an established stage-discharge relationship. One or two rating equations may be used according to the variability of stage at the reach and the uniformity of the channel cross section. Overbank flow is accounted for.

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INTRODUCTION

The South Florida Water Management District (SFWMD) operates control structures to regulate the movement of surface water either by gravitational or mechanical force. The amount of water moved through a particular location per unit of time is called the flow rate and is expressed in cubic feet per second (cfs). A discharge computation program (Flow) was developed to calculate the instantaneous flow at any pump, gated spillway, weir, gated culvert, flume, or unregulated open channel reach. The instantaneous values are subsequently time-averaged into daily mean values and stored in the SFWMD's corporate hydrologic database, DBHYDRO. Inside and outside the SFWMD, scientists, engineers, planners, and managers use the daily mean flows to obtain the best estimates of volumes of water and loadings of water quality parameters throughout South Florida.

In 1963, the U.S. Army Corps of Engineers published a report suggesting generic equations and discharge coefficients for the computation of discharge through a typical gated spillway structure in South Florida. In 1977, Collins documented various flow computation procedures utilized by the U.S. Geological Survey. In 1985, Andrew Fan documented the procedures for computation of discharge through culverts equipped with control devices. Other procedures have been partially documented utilizing comment lines intermixed with the source code of the Flow program. Procedures for discharge computation of various types of water control structures are found scattered throughout the literature. However, a comprehensive document which addresses discharge computation for all types of water control structures operated by the SFWMD is not found.

The main intent of this publication is to document the current form of the discharge equations in the Flow program. It is not the intent to explain the hydraulics of the equations or to analyze their statistical significance. The English system of units (feet-pound-second) is used throughout this document.

HISTORY OF DISCHARGE COMPUTATION PROGRAM

The Flow program is based on the E034 program that was written in FORTRAN on the District's Cyber computer. This program was used to calculate instantaneous flow. The instantaneous flows were averaged into daily values and stored into the DBHYDRO database. However, updating the program became very inefficient because discharge equations for each flow station were coded into the program. Every new flow station was added as a new subroutine and the whole program was recompiled. These subroutine additions made E034 a tremendously large and cumbersome program with which to work. As new flow stations were added, the program size continued to grow.

In 1991, the Hydrologic Data Management Division migrated all its computer processing and storage from the Cyber to the VAX computer. The E034 program was extensively modified during this migration and is now called the Flow program. The Flow program in the VAX applies a more structured programming approach than the old E034 program, but flow computation algorithms are the same. The interface with the District't corporate hydrologic database (DBHYDRO) and the development of generic flow equations minimize the frequency of code changes in the Flow program. In 1995, the Flow program and DBHYDRO were moved from the Vax to a Unix computer.

The computation of discharge through a culvert equiped with a control device, such as a riser, offers the most challenging problem of all types of water control structures in the District. The control devices for culverts used in the District are not common outside of South Florida. A special subroutine was required to establish a generalized and simplified way to compute flow through District culverts. Andrew Fan (1985) wrote the culvert subroutine in FORTRAN. This subroutine represents a thorough approach to the theoretical calculation of discharge through a gated culvert considering all flow regimes and all types of control devices. This subroutine was incorporated into the E034 program in the Cyber computer in 1985. The core of the culvert subroutine remains part of the Flow program in its original form.

The required input to the Flow program are instantaneous values of water elevation upstream and downstream of the structure, the level of control (e.g., gate opening) for each device within the structure, and a structure identifier. The DBHYDRO database holds information about the type of water control structure (pump, gated spillway, gated culvert, weir, flume, or unregulated open channel reach), the dimensions and shape of the structure, the loss coefficients associated with the flow through the structure, and the coefficients and exponents of generic flow equations. The DBHYDRO tables have been populated with information for more than 200 water control structures. The database is designed to accommodate increases in the number of control structures for which flow is computed.

DATA STRUCTURE

DATA PROCESSING FOR FLOW COMPUTATION

Instantaneous values of upstream and downstream stage, and level of control (e.g., gate opening) are stored in the District's Data Collection and Verification Program (DCVP) database. Figure 1 shows how DCVP data are processed to compute daily mean flows, which are stored in DBHYDRO. The data used by the Flow program are instantaneous values of stage and control. An interpolation program is used to synchronize instantaneous values of stage and control. These values are fed into the Flow program to compute instantaneous flow. To obtain daily mean flows, an interval value generation program is used to time-average the instantaneous flows. For the purpose of computing the daily mean flow, the discharge through a structure for one day is considered to consist of a series of intervals, starting at 0:00 and ending at 24:00 the same day, each interval having constant flow but not necessarily of equal duration. The number of intervals is equal to the number of instantaneous flow values available for that day minus one. Each interval extends from one instantaneous measurement to the next. The volume of water computed using the daily mean flow is the same as the volume of water computed from all the discharge time intervals in that day. Mathematically, the daily mean flow is calculated using the trapezoidal rule of integration (Swokoski, 1975):

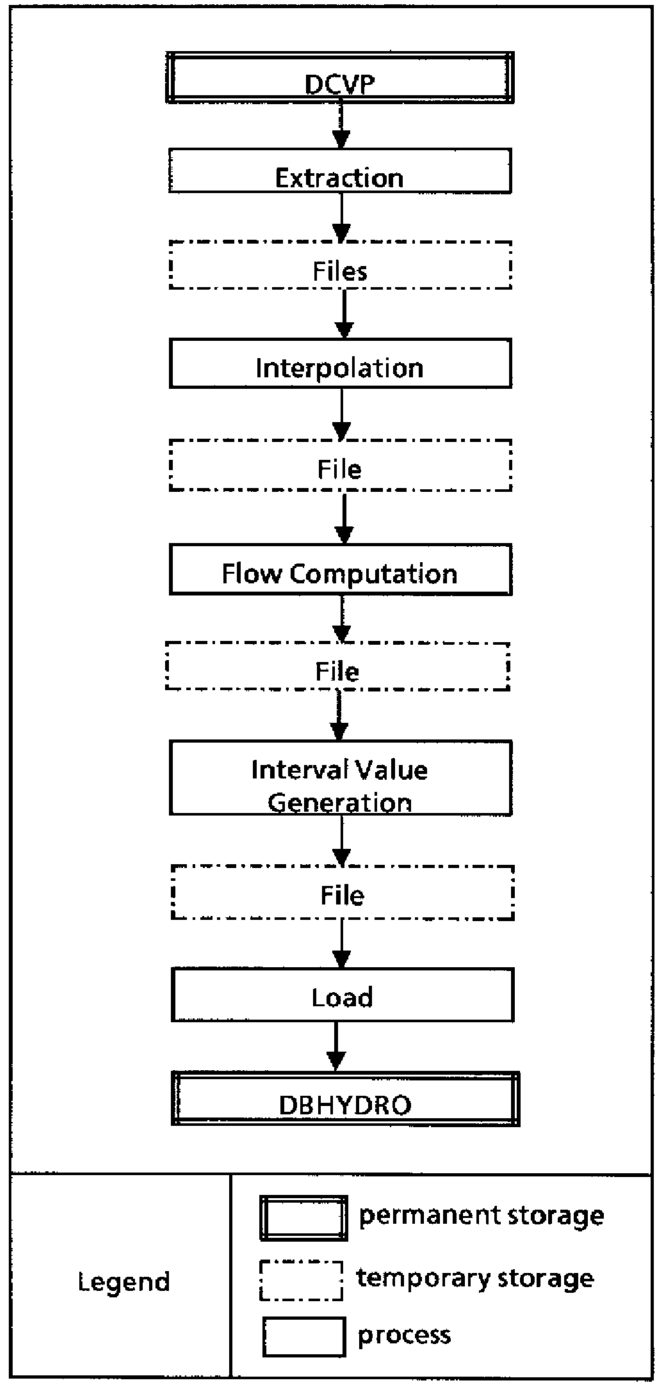

FIGURE 1. Flow Chart of Data Processing for Discharge Computation

$$\overline{Q} = \frac{\sum_{i=1}^{n-1} \left\{ \left(\frac{q_i + q_{i+1}}{2} \right) (t_{i+1} - t_i) \right\}}{t_n - t_1}$$

$$\overline{Q} = \frac{1}{2(1440\text{-}0)} \sum_{i=1}^{n-1} \left\{ (q_i + q_{i+1}) (t_{i+1} - t_i) \right\}$$

$$\overline{Q} = \frac{1}{2880} \sum_{i=1}^{n-1} \left\{ (q_i + q_{i+1}) (t_{i+1} - t_i) \right\} \qquad (1)$$

in which: $\overline{Q}$ = daily mean flow
q_i = instantaneous flow at time *i*
t_i = time *i*, in minutes
n = number of instantaneous flow values available for that day

A load program inserts daily mean flow values into DBHYDRO for general access.

THE HYDROLOGIC DATABASE

Dozens of parameters (coefficients, constants, exponents, descriptors, and logical flags) are stored in the hydrologic database for each structure. By using a relational database, this information is easily and logically updated without the need to code additional algorithms into the program. The use of a relational database for hydraulic computations is described in more detail by Turcotte and Mtundu (1992).

The water control structure identifier, the date, and the time on the input record determine which information is retrieved from the database tables and dictate which subroutines are run by Flow.

During the life of a flow station, structural modifications or recalibration of the discharge rating may warrant changing different flow algorithms. For example, a gate may be added at a spillway, an engine overhauled at a pumping station, or a new discharge rating may be obtained from additional discharge measurements. An effective date is the beginning of a period for which the flow algorithms pertaining to a structure are unchanged. A succeeding effective date for the same structure indicates a change in the flow algorithms. This succeeding effective date signals the end of the previous period and the beginning of a new period. The number of effective dates for a structure is unlimited and represents the number of modifications to the flow algorithms or to the physical structure.

All hydraulic parameters necessary for flow computation are stored in database tables. For example, tables containing culvert information specify the slope of the barrels and the Manning's coefficient for each barrel. The sources of hydraulic and structural information are: (1) the as-built drawings of the structures, (2) the U.S. Army Corps of Engineers (USCOE) Technical Memoranda of the Central & South Florida Flood Control District, (3) the source code of the E034 program, and, (4) the field measurements and observations by the staff of the Hydrologic Data

Management Division. Most of this information is compiled in the Structure Information Binders, held by the Hydrologic Data Management Division.

The sources of the discharge rating information contained in the database tables are: (1) the pump performance curves developed by the pump manufacturers, (2) the discharge capacity curves for spillways, developed by the USCOE, (3) the discharge rating calibration from flow measurements performed by the U.S. Geological Survey (USGS) and the District, and, (4) the source code of the E034 program.

WATER STAGE DATA

Water stage is the elevation, above mean sea level or NGVD, of the water upstream or downstream of a control structure. The head is the difference between the upstream stage and the higher of: (1) the downstream stage or (2) the elevation at the bottom of the outlet (Cheremisinoff, 1981). For example, the head for free flow over a weir is the difference between the upstream stage and the elevation at the bottom of the outlet, which is the crest elevation. All discharge computation algorithms used in Flow are primarily a function of the head.

Instantaneous stage data are available from various recorders. Table 1 summarizes the types of stage recorders, the typical recording frequency, and the processing required before utilizing the data.

WATER CONTROL DATA

Water control information is the level of control for a device within a structure. The engine speed in revolutions per minute (rpm) is the control information for a pump unit within a pump station. The gate opening in feet is the control information for a gate within a spillway or a culvert. The crest elevation in feet NGVD (National Geodetic Vertical Datum) is the control information for a stop log in a barrel within a culvert, or a notch in a bay within a weir.

Instantaneous water control data are available from fewer sources than stage data. The sources of water control data are: telemetry, graphic, solid state, and manual log sheets. Telemetry data are available for all remotely operated structures, as well as for major pumps, spillways, and culverts. Log sheets are available for all manually operated structures. Table 2 summarizes the types of water control data for each type of structure.

TABLE 1. Types of Water Stage Recorders

Type of Recorder	Typical Recording Frequency	Processing Required
Graphic	Continuous	Offers continuous recording. Charts are digitized to computer media, verified, and archived.
Telemetry	1 to 60 minutes	Data is collected by the computer in Operations[1] through the telemetry network. Data is transferred nightly to the computer in Data Management[2], verified, and archived.
Solid State	5 to 15 minutes[3]	Data storage media picked up from field, loaded to computer media, verified, and archived.
Punch Tape	15 to 60 minutes	Punched tape is picked up from field, converted to computer media by digital reader, verified, and archived.
Daily Water Readings	6 to 24 hours	Field staff readings are called in to Operations and manually entered into its computer. Data is transferred nightly to the computer in Data Management, verified, and archived.

1 Operations Division
2 Hydrologic Data Management Division
3 Sampling frequencies may be one minute or less

TABLE 2. Types of Water Control Data

Control Structure	Control Data	Units	How Control Data are Obtained
Pump Station	Engine or Impeller Speed	rpm	Engine tachometer, the ratio of engine speed to impeller speed is known
Gated Spillway	Gate Opening	ft	The distance from the bottom of the gate to the crest of the spillway
Gated Culvert	Gate Opening	ft	The distance from the bottom of the gate to the invert elevation of the barrel
	Stop Log Elevation	ft	The elevation above mean sea level or NGVD of the uppermost stop log. The distance from a reference point to the stop log is measured and subtracted from the reference elevation.
Weir	Crest Elevation	ft	The elevation above mean sea level or NGVD of the crest of the weir notch
Flume	N/A	N/A	N/A
Open Channel	N/A	N/A	N/A

PROGRAM STRUCTURE

The flow computation program is contained in one single source file. It is written in FORTRAN with embedded SQL statements. These embedded SQL statements enable the program to retrieve information from the hydrologic database. The hydrologic database contains information such as the values of the physical characteristics of control structures, and the parameters and coefficients for the flow equations.

PROGRAMMING APPROACH

The basic principles of structured programming are: (1) sequence structures, (2) decision structures, and, (3) loop structures (Ageloff, 1981). These principles are followed for the most part in the FLOW program. Instructions occur one after the other following a sequence structure. Branching is done only for exiting from subprograms. Block IF statements are used as decision structures. Loop structures are also used. Explicit DO-WHILE and DO-UNTIL loop structures in the FORTRAN language are not used because they are specific to the operating system. However, implicit versions of these loop structures are used, such as the loop to read every record of the input file. The culvert subroutine is the only subprogram which does not follow the principles of structured programming because it predates the FLOW program.

The following are the desired properties of a module: (1) it acts like a "black box"; it has one point of entry and one point of exit, (2) it is independent from other modules, and, (3) it is not too large (Ageloff, 1981). For the most part, the subprograms in FLOW adhere to the first property. They have a single point of entry and a single point of exit. However, subroutines are not independent from each other because they share global variables defined in COMMON blocks. Also, some subroutines are longer than 100 lines of code, and they cannot be considered small.

MAIN PROGRAM STRUCTURE

The main program follows a structured approach. The logic path begins at the top and ends at the bottom. Calls are made to subroutines where specialized functions are needed. Figure 2 is a flow diagram of the main program.

The main program reads one input record at a time and checks it. Subroutines are called to perform validation procedures on the input data. The database tables are queried to retrieve the pertinent information about the control structure. If the input record refers to the same structure as the previous input record, and the input date falls within the effective dates of the previous record, the database is not accessed and the information already available is used.

The discharge computation is accomplished by a single call from the main program to the discharge computation subroutine. However, because a control structure may

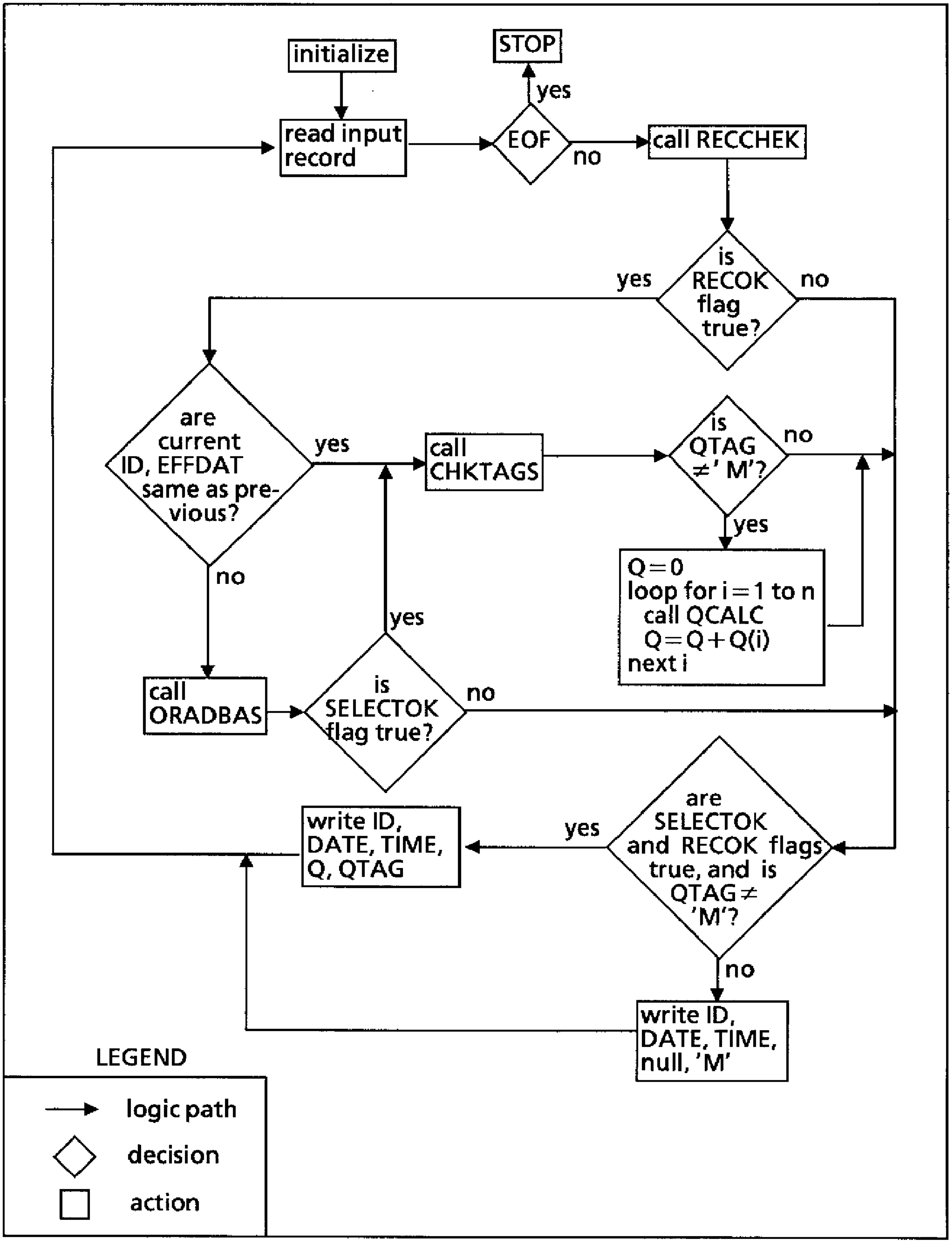

FIGURE 2. Flow Diagram of the Main Program

contain multiple control devices (e.g., multiple pumps), the discharge is computed individually for each control device. The discharge values for all control devices are summed to obtain the total discharge through the structure.

There is one output record written for every input record read. The validation procedures set flags to establish the validity of the input record. If all the validation flags accept the input record, then the output record includes a discharge value and a corresponding qualifying tag. Otherwise, the output record contains a null value for discharge and an "M" qualifying tag, indicating the discharge value is missing. The main program continues to process input records until the end of the input file.

SUBROUTINES

Seven subroutines are called from the main program. Only a few arguments are passed to the subroutines. Most of the information is passed to the subroutines via common blocks, because of the large number of variables used.

RECCHEK. The input record is checked for a valid input date. Check that the date is an actual calendar date (e.g., day is between 1 and 31) and that the time is an actual clock time (e.g., minutes are between 0 and 59). Also, check that the input date and time are not greater than the computer's clock date and time.

CHKTAGS. A tag is a symbol which qualifies a numeric value. The information provided by the tag cannot be expressed by the numeric value alone. A tag may accompany the upstream stage, the downstream stage, and each of the control values. The resultant discharge may carry a tag if the input information warrants it. If the value is not accompanied by a tag, then the value is not qualified. The following is a list of tag symbols and their meaning:

> = value is greater than number shown
< = value is less than number shown
L = value is a line average. Sometimes analog data will show great variability in a relatively short period of time. Such traces are very difficult to digitize. Therefore, a representative average line is substituted.
E = value is estimated
M = value is missing
N = value is not available or not computed
null = value is not qualified

Table 3 shows a matrix for determining the discharge tag from the upstream and downstream stage tags. The value for the level of control in a device normally carries one of only three tags: (1) null, (2) "M", or (3) "N". If all devices carry an "M" tag or if all devices carry an "N" tag, the discharge tag is "M" or "N", respectively. Otherwise, the discharge tag remains as described in Table 3.

CHKVALUES. The values of upstream stage, downstream stage, and level of control are validated. The values of downstream stage and level of control are checked only when required for flow computation. The downstream stage is not required for gravity free flow or for pumps discharging freely into air. Fixed weirs, flumes, and unregulated open channel reaches do not require values for level of control.

TABLE 3. Resultant Discharge Tag Matrix

Upstream Tag	Downstream Tag						
	null	>	<	L	E	M	N
null	null	<	>	L	E	M	N
>	>	E	>	E	E	M	N
<	<	<	E	E	E	M	N
L	L	E	E	E	E	M	N
E	E	E	E	E	E	M	N
M	M	M	M	M	M	M	N
N	N	N	N	N	N	N	N

In Table 3, the "E" tag for the case when the upstream and the downstream stage tags are both " > " or both " < " should be changed to "?" (questionable). The " > " and " < " tags do not quantify the amount by which the stage is being underestimated or overestimated. Therefore, the actual discharge amount may be very different from the computed discharge value and it may even have a direction opposite than the one assumed. A new approach for determining the discharge tag is suggested in the Conclusions and Recommendations section of this document.

Control data, when identical for multiple devices within a structure, have traditionally been verified and archived only for the first device to save processing time. Beginning on June 1, 1992, control data are processed for all devices at all structures. The text of the pertinent memorandum by Dunn and Morris is reproduced in Appendix B. For data prior to June 1, 1992, the value of level of control for the first device is copied to all other devices having a blank value and an "N" tag.

CHKZEROFLOW. The discharge is zero if all the pumps are turned off and the structure is not bypassed; or if all the gates are closed, the gates are not overtopped, and the structure is not bypassed. A pump is off or a gate is closed when the control value is zero.

ORADBAS. This subroutine allows the flow computation program to access the hydrologic database. Pro*FORTRAN is the FORTRAN precompiler for embedded SQL statements. For one single source file, Pro*FORTRAN allows only one DECLARE section, which for practical purposes means embedded SQL statements in only one subprogram or subroutine. Due to this constraint, all embedded SQL statements are contained in ORADBAS. In addition, Pro*FORTRAN does not allow FORTRAN INCLUDE statements within the SQL DECLARE section. Therefore, the common blocks, which are INCLUDED as text files in all other subroutines, are hard-coded in ORADBAS.

The structure identifier and the date of the input record provide the key to access all the database tables containing dated information about the water control structure. A database connection is made for every unique pair of stations and effective date identified in the input file. For further explanation on how the database tables are configured for hydraulic computations, refer to Turcotte and Mtundu (1992).

ERRDIS. This subroutine handles all the reporting of error conditions detected by the program. Error reporting encompasses various levels of error conditions. Some errors cause the program to stop execution, other errors cause the program to stop processing an input record and skip to the next, while still others are only warnings. Whatever the action taken by the error trapping logic in the program, the error reporting subroutine informs the user of what is happening.

QCALC. If no error condition exists after the input record is validated and the database is queried, then the discharge is computed. The QCALC subroutine calls the appropriate discharge computation algorithm according to the structure type. The QCALC subroutine returns the value of the instantaneous discharge for one control device. The main program sums the discharges for all control devices at a structure.

The next section explains in detail the computational procedures followed by the algorithms in QCALC.

COMPUTATIONAL PROCEDURES

The algorithms used in the flow computation program are mathematical simplifications of physical phenomena. The number of variables involved in water flow is so great as to defy a rigorous analytical approach for each type of structure. Flow equations are defined for each particular case of each type of control structure. For example, flow equations are defined for each of five cases of flow through a gated spillway: (1) controlled free, (2) controlled submerged, (3) uncontrolled free, (4) uncontrolled submerged, and (5) over-the-top. Certain assumptions are necessary to define flow equations:

1. It is possible to obtain a satisfactory approximation of the true value of flow either through a theoretical approach, such as the energy equation; or through applying regression techniques to field measurements.
2. Steady-state flow. The rate of change of flow with time is assumed to be zero for each input record.
3. A transition zone ensures continuity between flow equations for different cases. A transition zone exists where flow equations for two separate cases apply.

PUMPS

Flow computation for pumps is divided into two major categories, pumping and siphoning. Pumping is the normal mode of operation of a pump station, where water is pumped from a lower stage to a higher stage. There are cases (e.g. S-331) where water is pumped from a higher stage to a lower stage for a short period of time before the stages reverse and normal pumping continues. Siphoning is an alternate mode of operation where gravity moves water through the pump from a higher stage to a lower stage.

The head is the difference between the upstream stage and the downstream stage. The engine speed is the angular velocity of the engine. The discharge rating curves are based on the hydraulic characteristics of the pump and account for the gear ratio between the engine and the impeller as well as any losses in the piping and appurtenances. Figure A-1 shows station S-332 during a pumping operation. This structure pumps water from Taylor Slough to Everglades National Park.

When a pump station is built, a set of performance curves is provided by the pump manufacturer. The discharge performance curve provides the discharge rate if the engine speed and the head are known. It is possible to describe performance curves mathematically in the form of an equation. Discharge rating curve(s) can be produced for a pump by calibrating the performance curve equation(s) with discharge measurements thus improving the accuracy of flow estimation.

The USCOE, directed the construction of most of the pump stations at the District, and developed and calibrated the rating equations for the pumps. The District inherited these rating equations and has continued to recalibrate them with new discharge measurements. The District has also developed and calibrated rating equations for pump stations constructed under its direction.

Constant-Speed Pump. The discharge for a pump with a constant-speed engine is a function of the head. A third-order model with one independent variable is used (Draper and Smith, 1966). The coefficients of the polynomial are obtained through regression analysis of the head and discharge values read from the manufacturer's performance curve or collected from field measurements. The discharge for pumps with constant-speed engines is given by:

$$Q = C_0 + C_1H + C_2H^2 + C_3H^3 \tag{2}$$

in which:
- Q = discharge rate, in cfs
- C_0 thru C_3 = regression coefficients
- H = head, difference between upstream stage and downstream stage, in feet

Variable-Speed Pump. The discharge for a pump with a variable-speed engine is a function of the head and the engine speed. Pump manufacturers usually provide two or more discharge performance curves for variable speed engines. Two constant-speed rating curves are used by the District which represent the bounds of the normal range of operation. The problem becomes one of determining the discharge for an engine speed somewhere between two constant-speed curves.
Pump affinity laws for constant diameter are used to correctly adjust the head and interpolate the discharge :

$$\frac{H_1}{H_2} = \left(\frac{N_1}{N_2}\right)^2 \tag{3}$$

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \tag{4}$$

in which:
- H_1, Q_1 = head and discharge at pump speed N_1
- H_2, Q_2 = head and discharge at pump speed N_2

Figure 3 shows graphically the interpolation technique. The lower bound has a pump speed N_{lwr} and the upper bound has a pump speed N_{upr}. H is the head during operation at a pump speed N somewhere in the vicinity of N_{lwr} and N_{upr}. The corresponding heads at the lower and upper bounds are obtained from Equation (3):

$$H_{lwr} = H\left(\frac{N_{lwr}}{N}\right)^2 \tag{5}$$

$$H_{upr} = H\left(\frac{N_{upr}}{N}\right)^2 \tag{6}$$

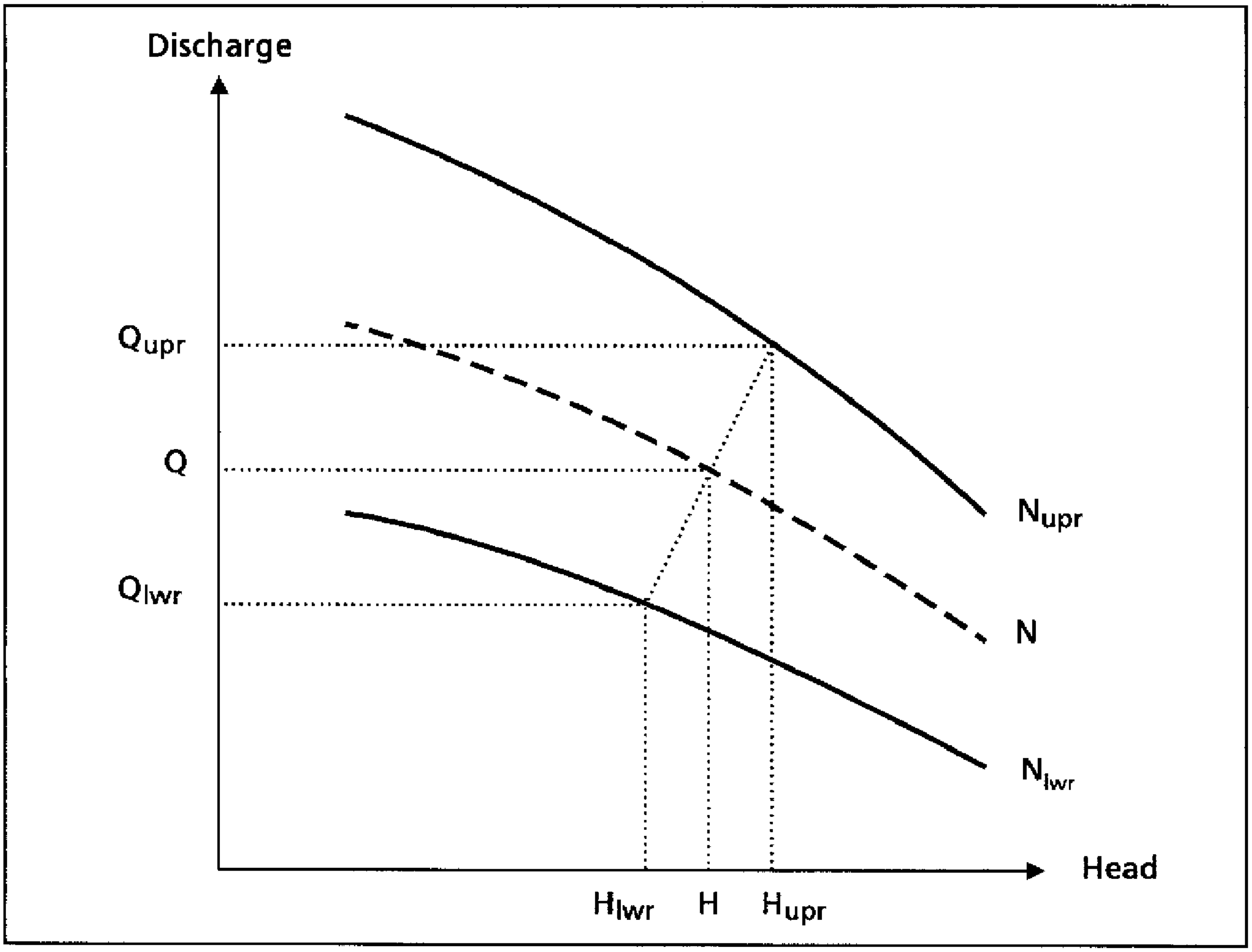

FIGURE 3. Discharge Interpolation for Variable-Speed Pump

The discharge at the lower and upper bounds are obtained using Equation (2):

$$Q_{lwr} = C_{10} + C_{11}\, H_{lwr} + C_{12}\, H_{lwr}^2 + C_{13} H_{lwr}^3 \tag{7}$$

$$Q_{upr} = C_{20} + C_{21}\, H_{upr} + C_{22}\, H_{upr}^2 + C_{23} H_{upr}^3 \tag{8}$$

Finally, the discharge at pump speed N is obtained from Equation (4):

$$\frac{Q - Q_{lwr}}{Q_{upr} - Q_{lwr}} = \frac{N - N_{lwr}}{N_{upr} - N_{lwr}}$$

$$Q = Q_{lwr} + \left(Q_{upr} - Q_{lwr} \right) \left(\frac{N - N_{lwr}}{N_{upr} - N_{lwr}} \right) \tag{9}$$

Care should be exercised when applying Equation (9). If N is outside the range between N_{lwr} and N_{upr}, application of Equation (9) will result in extrapolation. Extrapolation does not necessarily result in less accurate estimates than interpolation. However, if the minimum or maximum pump speeds are well outside the interpolation range, extrapolation should be checked for accuracy.

Two-Variable Polynomial. Used for pump station S-9, a variable-speed pump, where the engine speed varies considerably during operation. The discharge equation is a third order model with two independent variables (Draper and Smith, 1966):

$$Q = C_0 + C_1X + C_2Y + C_3X^2 + C_4XY + C_5Y^2 + C_6X^3 + C_7YX^2 + C_8XY^2 + C_9Y^3 \tag{10}$$

in which:

Q	=	discharge rate in cfs
C_0 thru C_9	=	coefficients
X	=	dimensionless head parameter, H/H_{fact}
H	=	head, in feet
H_{fact}	=	head factor, in feet
Y	=	dimensionless engine speed parameter expressed as fraction of effective range, $(N-N_{min})/N_{fact}$
N	=	engine speed, in rpm
N_{max}	=	maximum engine speed, in rpm
N_{min}	=	minimum engine speed necessary to move water, in rpm
N_{fact}	=	engine speed factor, $N_{max} - N_{min}$, in rpm

The head and engine speed parameters are the dimensionless, normalized values of head and engine speed ranging from 0 to 1. They are normalized by subtracting the minimum value possible and dividing by the difference between the maximum and minimum values possible -- for head, the minimum value is zero. By normalizing the head and engine speed, the domain of these parameters is confined between zero and one. In this way, the use of large values for head and engine speed is avoided, the magnitude of each of the coefficients C_0 through C_9 is minimized, and the handling of the two-variable polynomial is simplified.

The head parameter X is obtained by dividing the head value H by the head factor H_{fact}. For example, H_{fact} at pump station S-13 is the maximum possible head, or nine feet. For an H of five feet, X is 5/9 = 0.556.

To obtain the engine speed parameter Y, the minimum engine speed necessary to move water, N_{min}, is subtracted from the engine speed value N. The result is divided by the engine speed factor N_{fact}. For example, N_{min} at S-13 is 300 rpm, N_{max} is 1200 rpm, and N_{fact} is 1200 - 300 = 900 rpm. For an N of 1050 rpm, Y is (1050-300)/900=0.833.

Constant-Speed Pump with the Possibility of an Unsubmerged Outlet. This type of pump has a constant speed and has an outlet which may be unsubmerged if the downstream stage is below the outlet crown. Figure 4 shows schematically the three possibilities under this pump consideration, which are as follows:

(1) Unsubmerged outlet. The downstream stage is below the invert of the outlet pipe. The head is the difference between the elevation of the center of mass of the water in the pipe near the outlet and the upstream stage.

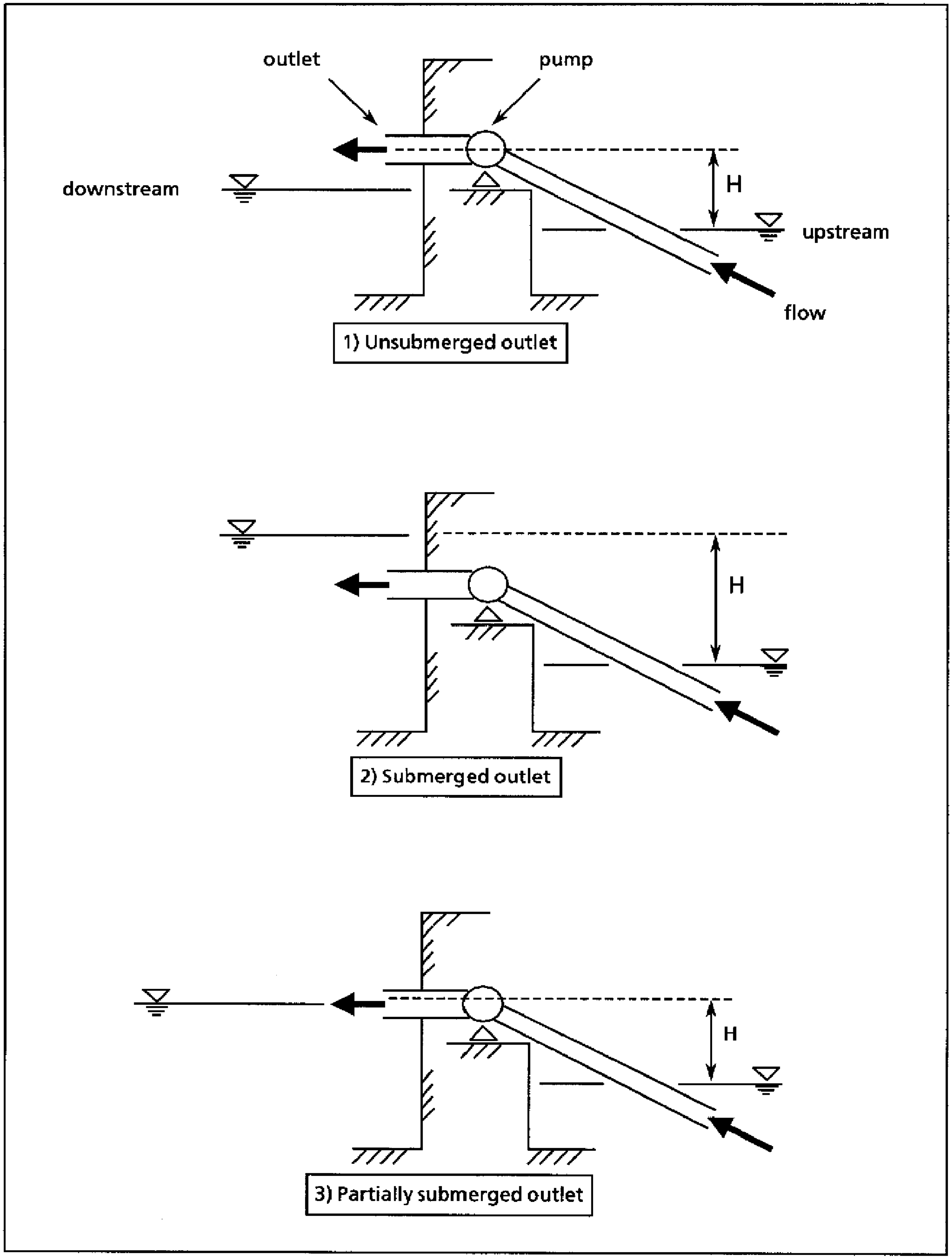

FIGURE 4. Unsubmerged, submerged, and partially submerged outlet

(2) Submerged outlet. The downstream stage is above the crown of the outlet pipe. The head is the difference between the dowstream and the upstream stages.

(3) Partially submerged outlet. The downstream stage is above the invert and below the crown of the outlet. The head is the difference between the elevation of a point between the center of mass and the crown, proportional to the amount of pipe covered by the downstream stage,.and the upstream stage.

A second-order polynomial is used for pumps with the possibility of an exposed outlet:

$$Q = C_0 + C_1 H + C_2 H^2 \tag{11}$$

Correction for Pumps with Flap Gate. Pumps are equipped with flap gates in the outlet to prevent back flow. When a pump is on, the force of the water flowing out pushes the flap open. The force exerted by the flap gate against the water being discharged by the pump reduces the flow. The pump discharge adjusted by the flap gate reduction is given by:

$$Q_{adj} = C_{flap}\, Q \tag{12}$$

in which:

in which:	C_{flap}	=	flap coefficient, the ratio of pump discharge with flap gate to pump discharge without flap gate. This coefficient must be rated, but it is usually 0.9 for engine speeds below the normal range of operation. Otherwise, it is usually 1.0 for engine speeds within the normal range or operation.
	Q	=	pump discharge without flap gate

As an alternative to the approach discussed here, it is suggested that the head loss due to the flap gate be accounted for in the discharge rating curve(s), which is how the head losses due to all other appurtenances are accounted for.

Siphoning. Water is siphoned through a pump when the head is sufficient to drive the flow in the desired direction without assistance from the pump. For siphoning to occur, both the intake and the outlet must be submerged, and gravity flow must be possible in the direction desired. Applying the Bernoulli equation at the upstream pool and at the center of mass of the outlet (Brater and King, 1976):

$$Q = A \sqrt{\frac{2g}{\alpha_a \alpha_b}} \sqrt{H} \tag{13}$$

in which:	Q	=	siphon discharge, in cfs
	A	=	area of pipe
	g	=	universal gravity constant
	α_a	=	coefficient for velocity head
	α_b	=	coefficient for friction loss
	H	=	same as head for pump with possibility of submerged outlet

Since siphon discharge is a secondary concern at the District, α_a and α_b are not estimated but rather combined with A and $(2g)^{0.5}$ into a single coefficient, C. The siphoning discharge is expressed as a regression equation from field measurements and is given by:

$$Q = CH^n \tag{14}$$

in which: Q = discharge rate, in cfs
C = regression coefficient, estimate of A $\{(2g)/(\alpha_a\alpha_b)\}^{0.5}$
n = regression exponent, usually expected to be 0.5
H = head, in feet

GATED SPILLWAYS

A gated spillway, or simply a spillway, is a water control structure which allows discharge into a passage and through a gate opening by means of gravity. A spillway may have one or more gates or passages. Figure A-2 shows spillway S-49 on the C-24 canal operating under controlled free flow conditions. The two gates are partially open and water falls over the crest of the spillway into the downstream side.

History of Spillway Equations

From September 1960 to December 1961, the U.S. Army Engineer Waterways Experiment Station conducted a model study of the typical District (then Central and Southern Florida Project) gated spillway structure (Corps of Engineers, 1963). The discharge characteristics of free and submerged, controlled and uncontrolled flows were satisfied by certain equations. These equations were stated, the discharge coefficients evaluated, and the limits of each flow regime established in terms of dimensionless quantities.

The District has applied the USCOE equations and calibrated them for each individual structure. The District has also simplified accordingly the limits of the flow regimes (Steve Lin, September 29, 1992). In reviewing this publication, important comments regarding the improvement of the gated spillway equations were made in a memorandum by Damisse and Cadavid (1993) reproduced in Appendix B. It is suggested that these comments are studied for their implementation in the Flow program.

Gate and Pool Restrictions

Flow through a spillway may be controlled or uncontrolled, depending on the position of the gate with reference to the upstream stage. When the bottom of the gate is lower than the upstream stage, the flow through the spillway is controlled. When the bottom of the gate is higher than the upstream stage, the flow through the spillway is uncontrolled.

Flow through a spillway may be free or submerged depending on the downstream stage. When the flow is not restricted by the downstream pool and the downstream stage is below the sill elevation, the flow is said to be free. Submerged flow refers to a downstream stage which is above the sill elevation and a downstream pool which partially restricts the flow. Figure 5 is a schematic of the longitudinal profile of a gated spillway showing the two levels of gate restriction and the two levels of downstream pool restriction.

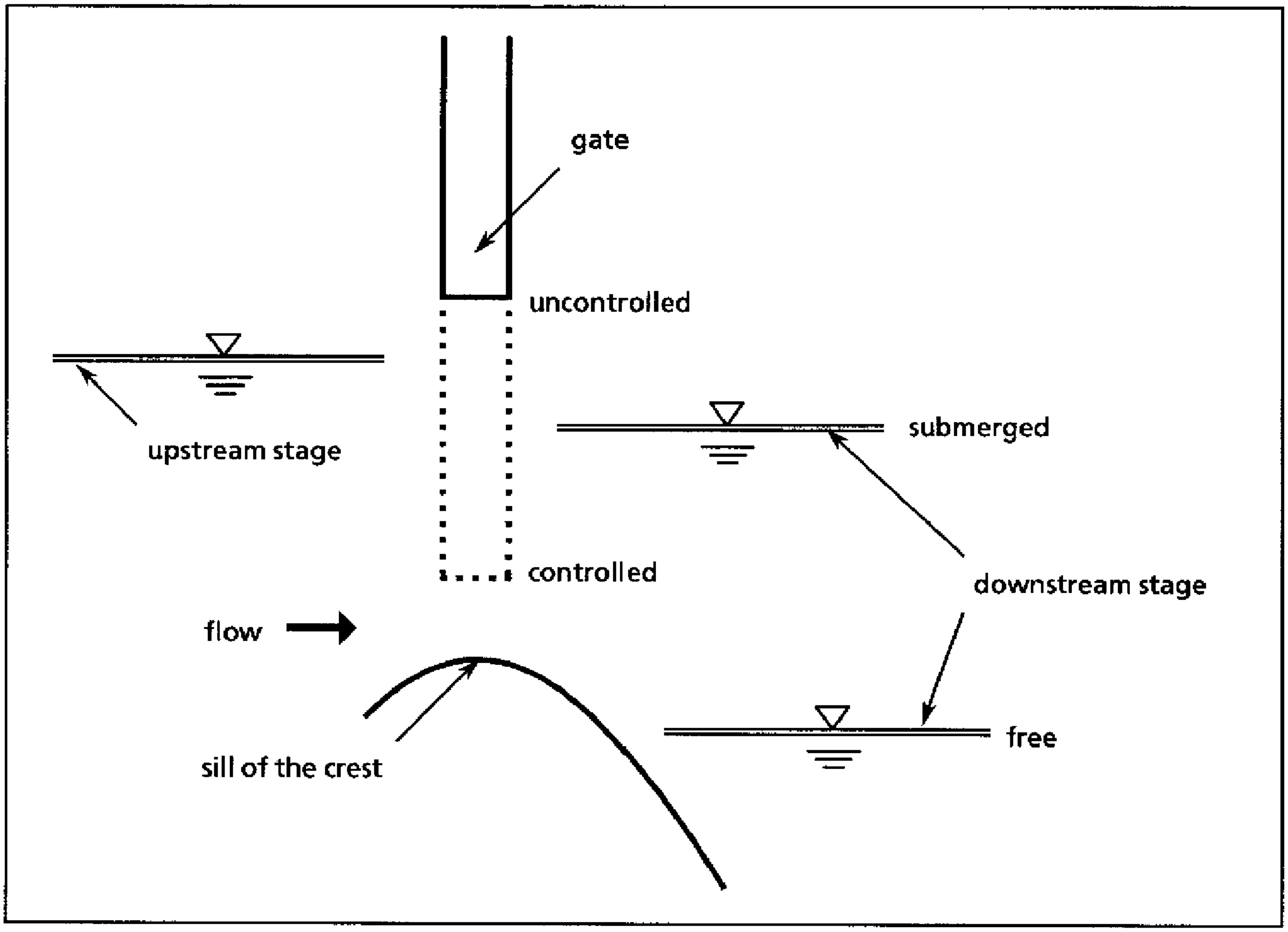

FIGURE 5. Flow Regimes in a Gated Spillway

Spillway Flow Computation

To mathematically describe flow through a gated spillway, the flow is classified into four regimes: (1) free uncontrolled, (2) submerged uncontrolled, (3) free controlled, and (4) submerged controlled. The terms used in the dimensionless parameters for the determination of flow regimes and in the flow equations are defined as follows:

- g = acceleration of gravity, 32.2 ft/sec^2
- G_o = gate opening, ft
- h = submergence head calculated as the difference between the downstream stage and the sill elevation, ft
- H = approach head calculated as the difference between the upstream stage and the sill elevation, ft
- H_d = design approach head, ft
- L = net length of the crest perpendicular to the direction of flow, ft

In applying the USCOE criteria, the District made the following modifications:

1. The controlled flow criteria was reduced from $H/G_o > 2.0$ to $H/G_o > 1.7$.
2. The uncontrolled flow criteria was reduced from $H/G_o < 2.0$ to $H/G_o < 1.0$.
3. The boundary between uncontrolled free and uncontrolled submerged flow was fixed at $h/H = 0.5$. The USCOE boundary varies between h/H values of 0.2 and 0.6, according to H/H_d.
4. The boundary between controlled free and controlled submerged flow was fixed at $h/G_o = 0.5$. The USCOE boundary varies between h/H values of 0.2 and 0.6, according to H/G_o.
5. A transition zone was created between the new limits of controlled and uncontrolled flow, that is, between H/G_o values of 1.7 and 1. In the transition zone, the flow is computed as the minimum of the controlled and uncontrolled flows.

Figure 6 is a longitudinal schematic of the levels of gate restriction as applied by the District. The District version of the criteria for determining the limits of the flow regimes is shown in Table 4.

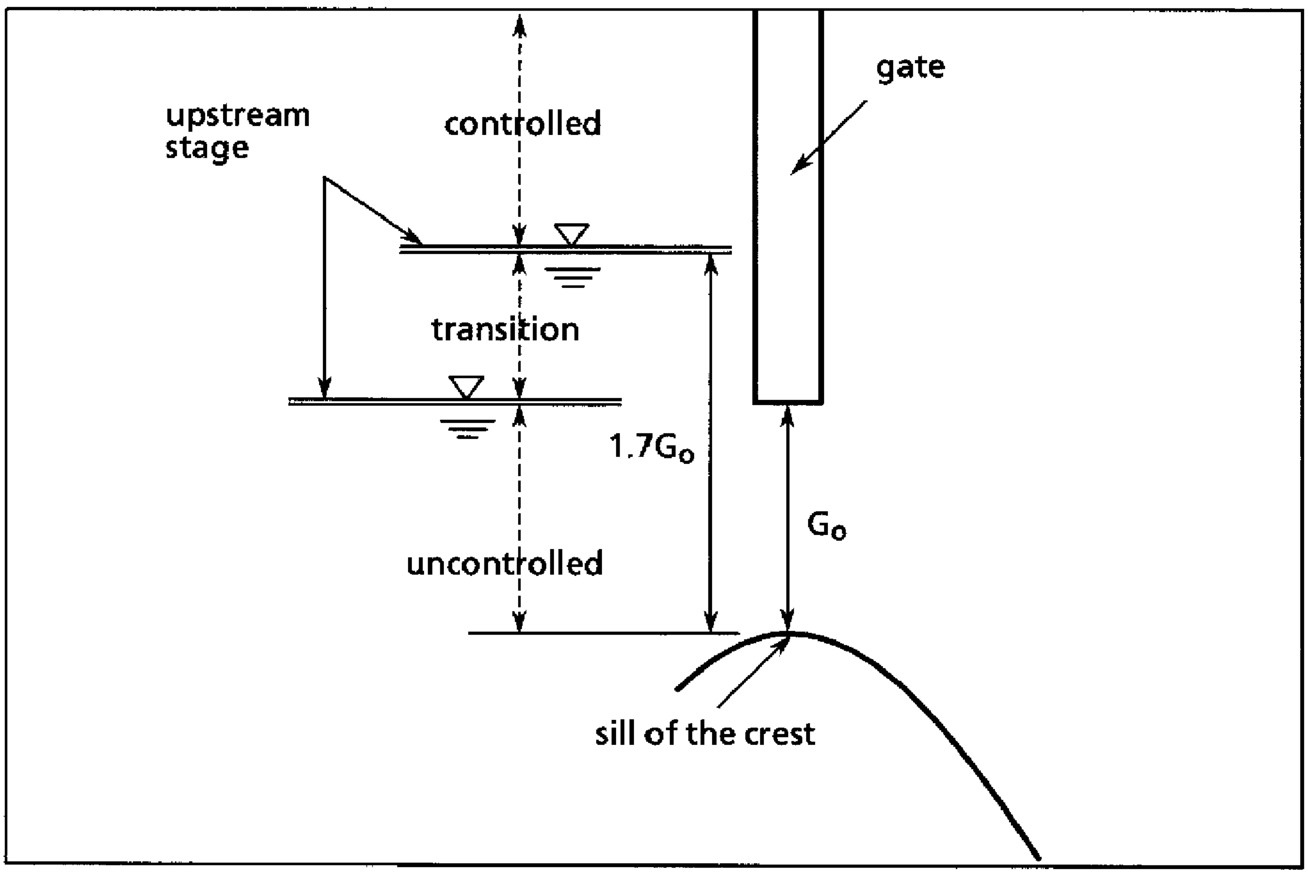

FIGURE 6. Levels of Gate Restriction on a Spillway

The current method for computation of discharge in the transition zone presents problems in some cases, as shown in Figure 7. The uncontrolled free flow and the transition flow are discontinuous at $H/G_o = 1$. The laws of mechanics of incompressible fluids are violated for H/G_o between 1.7 and 1, in which the transition flow decreases as the gate opening increases.

TABLE 4. Spillway Flow Regimes, District Version

Flow Regime		Criterion for Gate Restriction	Criterion for Downstream Pool Restriction
UNCONTROLLED	free	$H/G_o < 1$	$h/H < 0.5$
	submerged		$h/H \geq 0.5$
CONTROLLED	free	$H/G_o > 1.7$	$h/G_o < 0.5$
	submerged		$h/G_o \geq 0.5$
TRANSITION minimum of: 1) uncontrolled free or submerged 2) controlled free or submerged		$1 \leq H/G_o \leq 1.7$	test for both controlled and uncontrolled

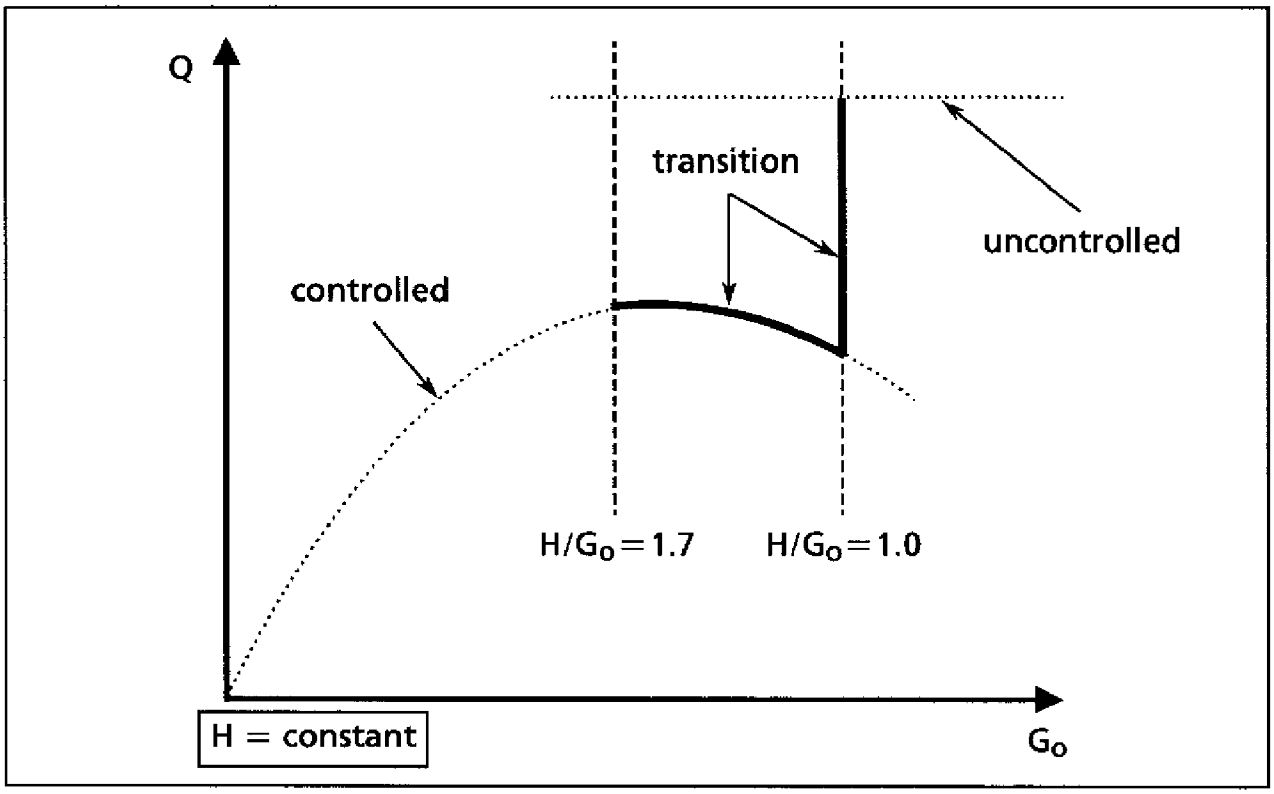

FIGURE 7. Current Transition Discharge for Free Flow

In light of these problems, it is recommended to abandon the current use of a transition zone for computation of flow through a spillway. It is also recommended to study the implementation of the original USCOE criteria. Figure 8 is a flow diagram for use in the full implementation of the USCOE criteria. Plates 41, 42 and 43, created by the USCOE for the determination of flow regimes based on dimensionless parameters, are reproduced in Appendix B. To determine the dimensionless parameters, the terms H, G_o, and H_d must all have values greater than zero to avoid division by zero. Also, If the downstream stage is below the spillway crest, then *h* must be set to zero to avoid negative dimensionless parameters.

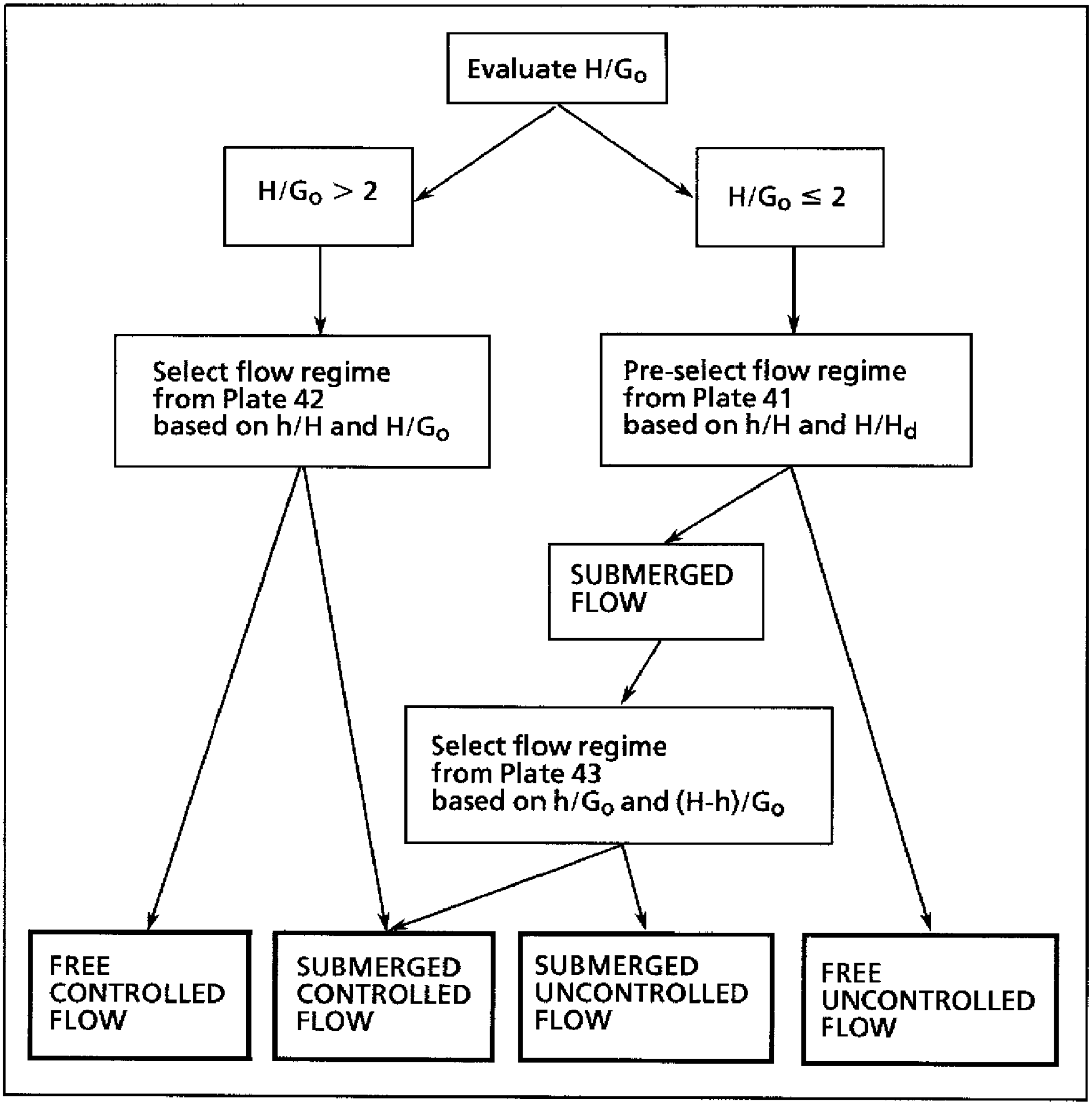

FIGURE 8. Flow Diagram of USCOE Criteria for Determining Spillway Flow Regimes

Controlled Free Flow. Only the gate restricts the flow. Figure 9 is a longitudinal schematic of controlled free flow. The USCOE equation for controlled free flow is given by:

$$Q = C_g \sqrt{2g}\, L\, G_o \sqrt{H - 0.5G_o} \tag{15}$$

in which:

Q = discharge in cfs

C_g = discharge coefficient for controlled free flow, which is a function of G_o.

L = gate width in feet

G_o = gate opening in feet

H = approach head calculated as the difference between the upstream stage and the sill elevation, in feet

g = acceleration of gravity, 32.2 ft/sec^2

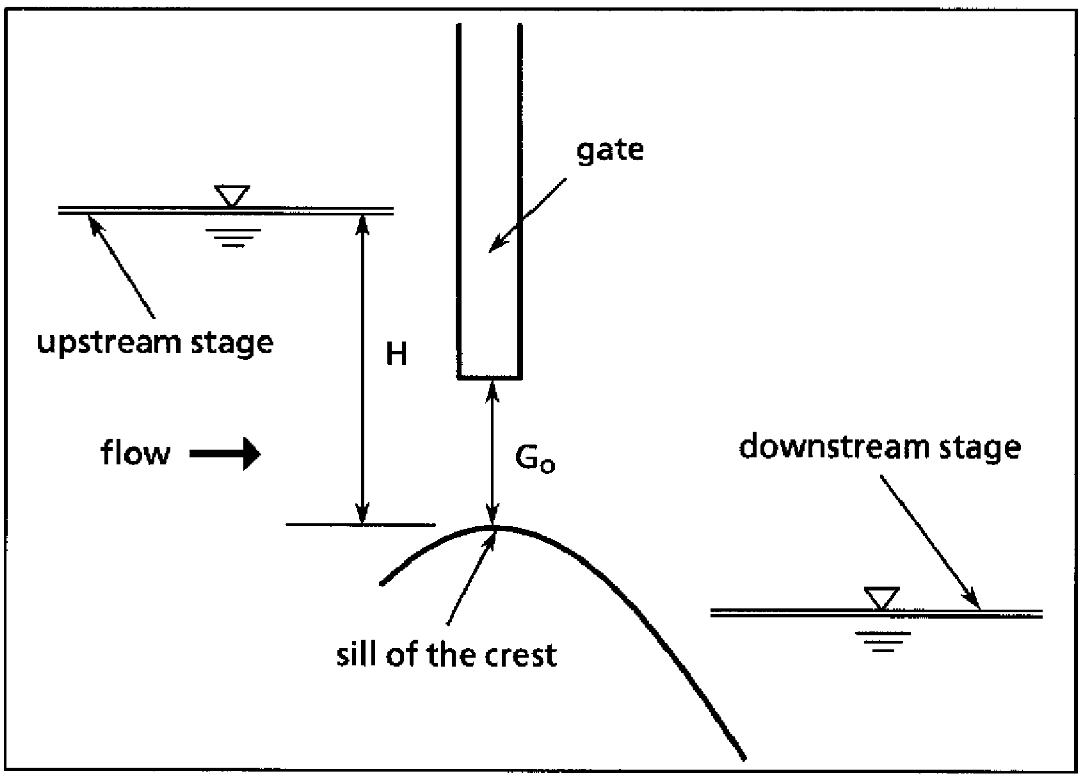

FIGURE 9. Controlled Free Flow

Controlled Submerged Flow. The gate and the downstream pool restrict the flow. Figure 10 is a longitudinal schematic of controlled submerged flow. The USCOE equation for controlled submerged flow is given by:

$$Q = C_{g_s} \sqrt{2g}\, L \sqrt{H\text{-}h}\; G_o \tag{16}$$

in which: C_{g_s} = discharge coefficient for controlled submerged flow, which is a function of h/G_o

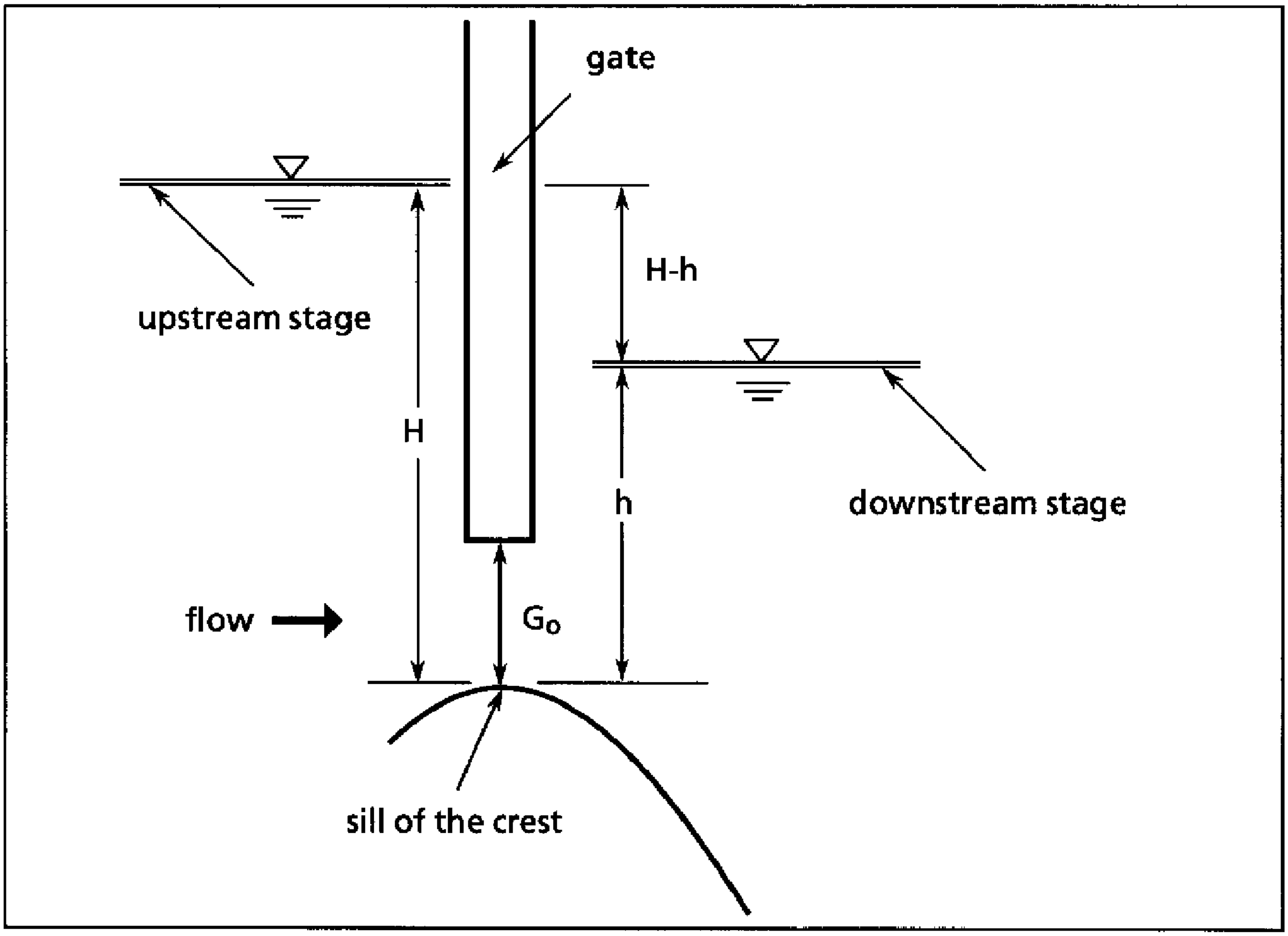

FIGURE 10. Controlled Submerged Flow

Uncontrolled Free Flow. Neither the gate nor the downstream pool restrict the flow. Figure 11 is a longitudinal schematic of uncontrolled free flow. The USCOE equation for uncontrolled free flow is given by:

$$Q = C L H^{1.5} \tag{17}$$

in which:

- C = discharge coefficient for uncontrolled free flow, which is a function of H/H_d
- H = approach head, in feet
- H_d = design head, head at which design discharge will occur, in feet

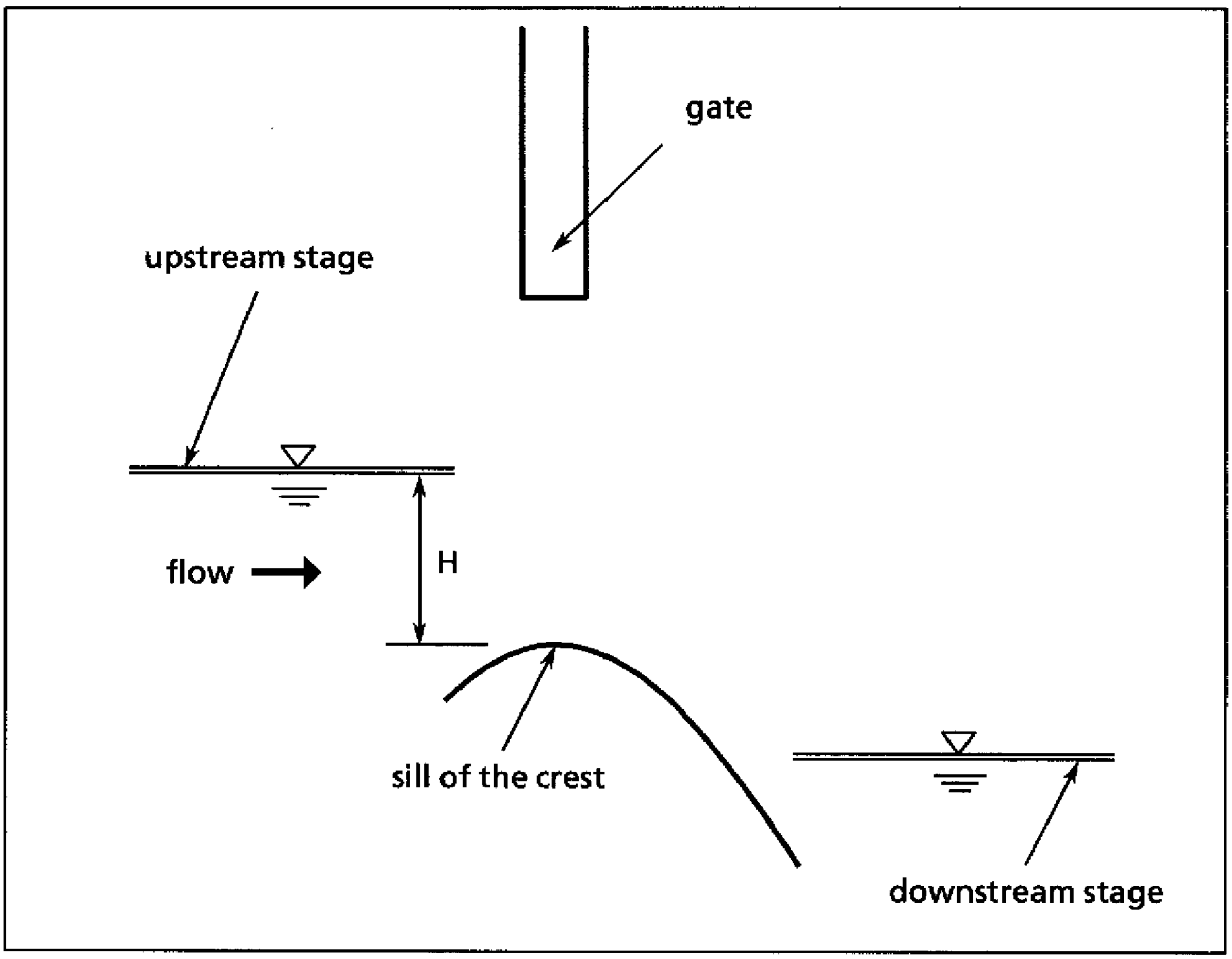

FIGURE 11. Uncontrolled Free Flow

Uncontrolled Submerged Flow. The gate does not restrict the flow, but the downstream pool does. Figure 12 is a longitudinal schematic of uncontrolled submerged flow. The USCOE equation for uncontrolled submerged flow is given by:

$$Q = C_s\, L \sqrt{2g}\; h \tag{18}$$

in which: C_s = discharge coefficient for uncontrolled submerged flow, which is a function of h/H

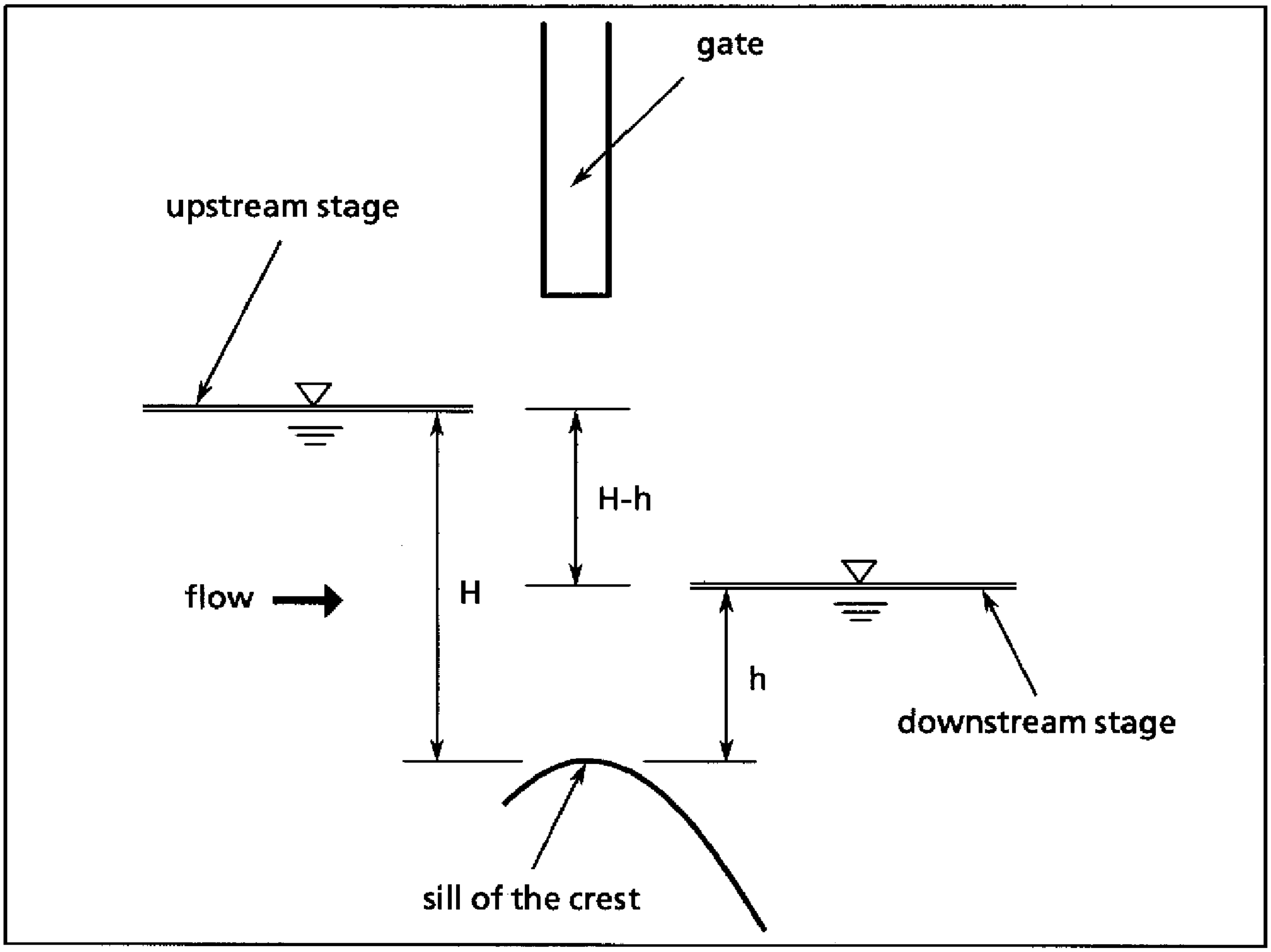

FIGURE 12. Uncontrolled Submerged Flow

Over-the-top Flow. It is possible, after heavy precipitation or other extreme hydrologic events, that the upstream stage rises so quickly as to overtop the gate. The gate itself may be closed or partially opened. Figure 13 is a schematic of the longitudinal profile for over-the-top flow. The discharge for over-the-top flow is given by:

$$Q = C_{ot}\, W\, H_g^{1.5} \tag{19}$$

in which:

	C_{ot}	=	discharge coefficient for over-the-top flow, usually 3.3
	W	=	width of the gate, in feet
	H_g	=	approach head over the gate, in feet

If the gate is partially open, the flow through the gate is added to the over-the-top flow.

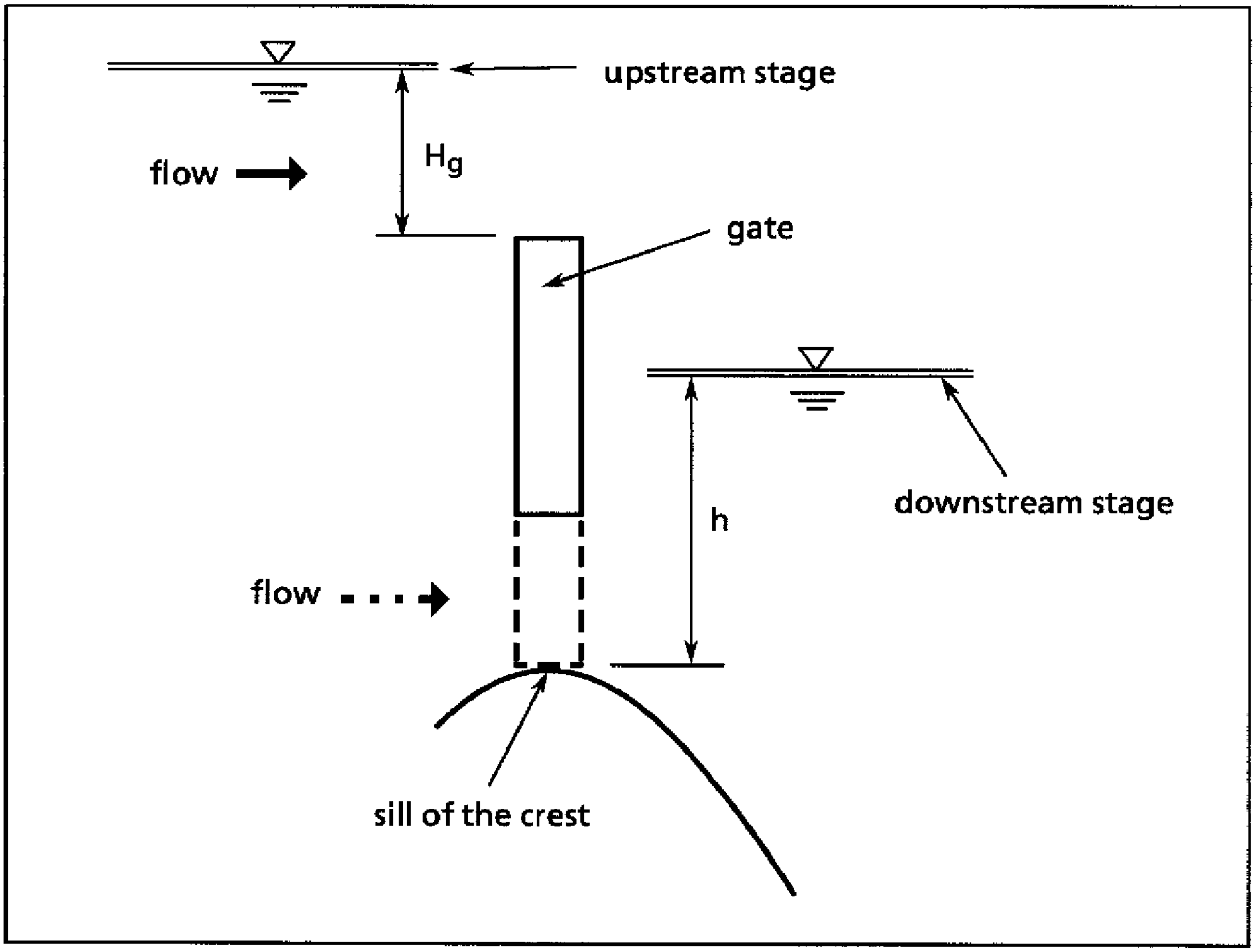

FIGURE 13. Over-the-Top Flow

Reverse Flow. When a coastal gated spillway is operated under uncontrolled submerged conditions to drain a basin after a heavy storm, it is not unusual for a rising tide to flow inland for a short period of time. In this case, and in any other case where the downstream stage is found to be higher than the upstream stage, reverse flow occurs. For computational purposes, the upstream and downstream stage values are interchanged and a negative sign precedes the resultant flow.

Discharge measurements for reverse flow conditions at spillways are rarely carried out due to the lack of advance notice, the short duration of these conditions, and the unconventional flow patterns present in the stream during reverse flow. Whenever verification is not available, it is suggested that a reverse flow estimate (negative flow) at a spillway be interpreted as an indicator of flow direction or as a warning of a possible gauge datum error, rather than an estimate of reverse flow quantity.

Bypassing the Spillway. The bypass stage is the elevation above which part or all of the flow circumvents the spillway. For example, if a spillway is built on a levee, the elevation of the crown of the levee is the bypass stage. The flow discharging through the spillway and the flow overtopping the spillway can be estimated. However, the flow bypassing the spillway cannot be estimated. Therefore, the actual flow under these conditions is greater than what can be estimated with the flow equations. Nevertheless, the appropriate flow equations are applied and a ">" (greater than) tag is attached to the resultant flow.

Total Flow. The total flow through a gated spillway, computed by the flow program, considers the direction of the flow, the restrictions imposed by the gate and the downstream pool, and the provisions for overtopping and bypassing. Figure 14 is a flow chart of the discharge computation. The logic is structured from top to bottom in a simple and concise path.

District Use of USCOE Spillway Equations

The District applies the USCOE spillway equations to the computation of discharge by calibrating the equations with discharge measurements. In applying the equations, the District has classified its spillways into three cases according to: (1) the degree of similarity between the spillway and the typical spillway (S-71) used by the USCOE in developing its equations, (2) the availability of discharge measurements at the spillway, and (3) the level of calibration accomplished.

Case 1. The USCOE spillway equations are used in their original form except for the discharge coefficient, which is a constant. Case 1 is used when the spillway is hydraulically similar to S-71 and no relationship is found between the discharge coefficient and any of the hydraulic variables (H, h or G_o), in any of the flow regimes. Median values of the discharge coefficient most often used at the District and the range of values used are shown in Table 5 for each flow regime. For example, the discharge coefficients for the G-56 spillway in the Hillsboro Canal are as follows:

1) Controlled free: $C_g = 0.75$
2) Controlled submerged: $C_{gs} = 0.72$
3) Uncontrolled free: $C = 2.90$
4) Uncontrolled submerged: $C_s = 0.90$

Case 2. The USCOE spillway equations are used in their original form. However, the discharge coefficient may be a constant or a function of one or more hydraulic

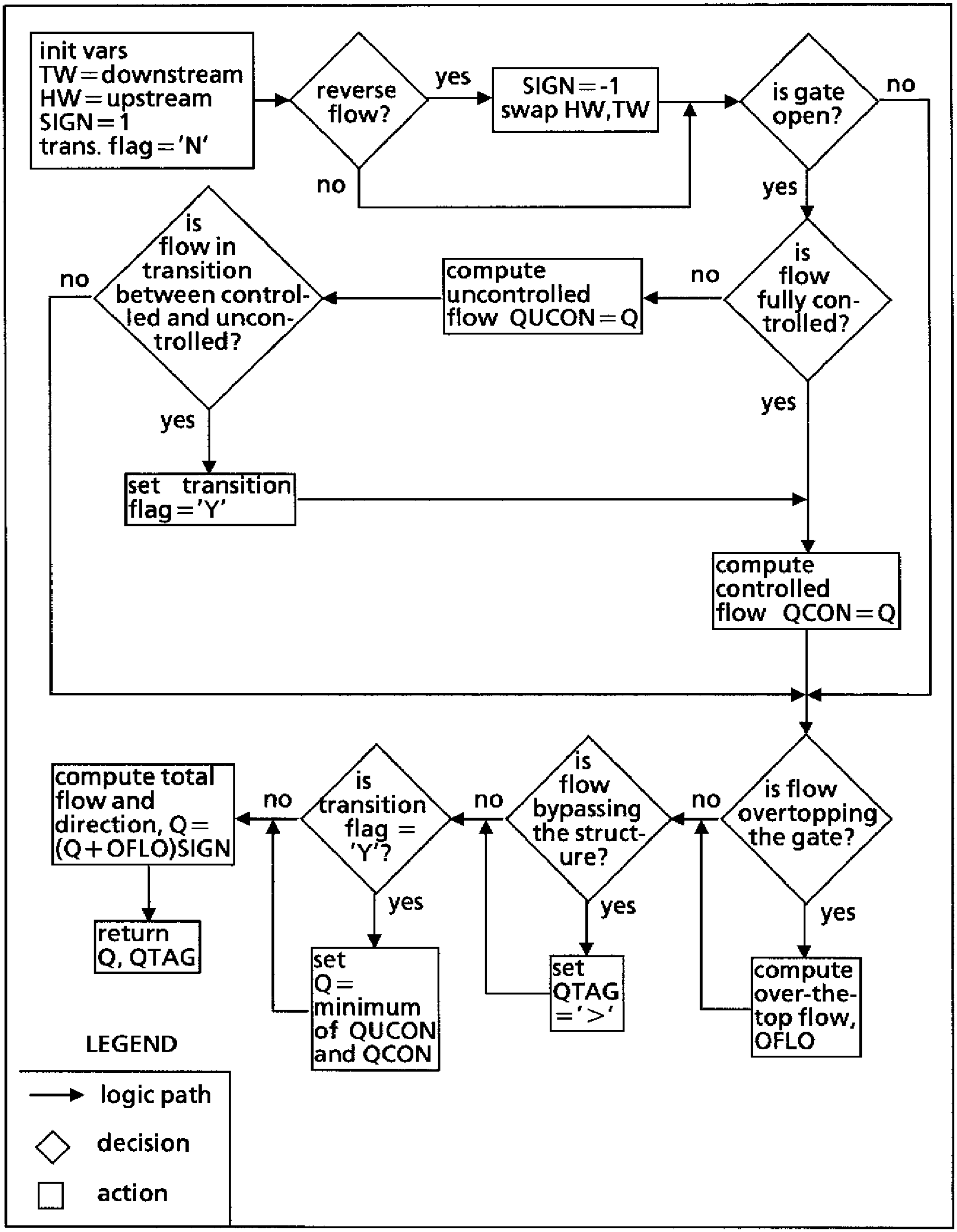

FIGURE 14. Flow Chart of the Spillway Discharge Computation

TABLE 5. Discharge Coefficients for Case 1 Equations

Flow Regime	Discharge Coefficient	
	Range of Values	Median (most often used)
Controlled free	0.74 - 0.75	0.75
Controlled submerged	0.72 - 0.86	0.75
Uncontrolled free	2.90 - 3.28	2.90
Uncontrolled submerged	0.85 - 1.20	0.90

variables. Case 2 is used when the spillway is hydraulically similar to S-71, and a relationship is found between the discharge coefficient and at least one hydraulic variable, in at least one flow regime. For example, the discharge coefficients for the S-5AS spillway in Water Conservation Area 1 are as follows:

1) Controlled free: $C_g = 0.75$
2) Controlled submerged: $C_{gs} = 0.75$
3) Uncontrolled free: $C = 2.40\,(H)^{0.155}$
4) Uncontrolled submerged: $C_s = 1.23 - 0.43\,(h/H)$

Case 3. Modified versions of the USCOE spillway equations (non-standard equations) are used. The discharge coefficient may be a constant or a function of one or more hydraulic variables. The exponents in the equation may be adjusted through regression analysis. Case 3 equations are used when the spillway is hydraulically not similar to S-71 and a relationship is found between the discharge coefficient and at least one hydraulic variable, in at least one flow regime. For example, the discharge through the S-62 spillway is computed by the following non-standard equations:

1) Controlled free: $Q = 6.8\,(L)\,G_o^{0.956}\,(H - 0.5\,G_o)^{0.353}$
2) Controlled submerged: $Q = 6.015\,(L)\,G_o\,(H - h)^{0.5}$
3) Uncontrolled free: $Q = 6.1071\,(L)\,H^{1.315}$
4) Uncontrolled submerged: $Q = C_s\,L\,h\,(2g)^{0.5}\,(H - h)^{0.5}$
$C_s = 1.43 - 0.43\,(h/H)$

GATED CULVERTS

Flow through a gated culvert may be like that of a weir, a pipe, an orifice, or an open channel depending on the upstream and downstream stages, the type of inlet or outlet control, and the degree of control. All the procedures for computing flow through culverts were assembled and documented by Andrew Fan (1985). Modifications to Fan's original culvert program, as implemented in the Flow program, have been introduced in three areas: (1) reverse flow, (2) free flow over flashboards, and (3) adjusted entrance loss coefficient.

Reverse Flow. Reverse flow may occur when the downstream stage is higher than the upstream stage. For the culvert program to compute reverse flow, the upstream stage and the inlet invert elevation must be interchanged with the downstream stage and the outlet invert elevation, respectively. In Fan's version, the head over the inlet invert and the head over the outlet invert are computed before the stage and invert elevations are interchanged. Consequently, the heads are incorrectly calculated. This results in an incorrect flow estimate since the heads are used throughout the culvert program for selecting flow regimes, calculating depths of flow, and adjusting the entrance loss coefficient. The problem is corrected in Flow's version by first interchanging the stages and invert elevations and then computing the heads.

Although the stage and invert elevations at either end of the gated culvert are correctly interchanged for reverse flow computation, the entrance loss properties of the outlet are assumed to be the same as those of the inlet. Since the outlet is usually not designed as an entrance, it is likely that the entrance losses under reverse flow are greater than under normal flow conditions. Therefore, it is suggested to assign appropriate entrance loss properties to the outlet and to use these when reverse flow is computed.

Free Flow Over Flashboards. Flashboards are sometimes used at culverts instead of gates. A flashboard elevation that is lower than the upstream stage, but higher than the downstream stage, enables a discharge condition known as free flow. As long as free flow exists and the flow over the flashboard does not exceed the culvert capacity, the discharge through the culvert is estimated by computing the discharge over the flashboard. Fan's original version incorrectly assigns zero flows to certain free flow circumstances. The Flow program correctly computes free flow over a flashboard. The memorandum by Otero documenting the problem and its solution is reproduced in Appendix B.

Adjusted Entrance Loss Coefficient. The entrance loss coefficient, K, accounts for the head loss due to sudden contraction at the inlet. K has a range from 0.1 to 0.9. The head loss is higher for lower values of K.

Fan recognized that the entrance loss coefficient is not the same for different flow regimes such as open channel, weir, or pipe flow. Therefore, an adjusted entrance loss coefficient, K_e, is defined for each flow regime. Differences in computing K_e between Fan's and Flow's versions suggest that fine-tuning was performed between 1982 and 1990.

A study was performed on the applicability of the culvert program to a wide range of culvert types. The study concluded that the calculation of the K_e for different flow regimes should be further improved. (Straley, August 1991)

It is recommended that a study be performed to evaluate the entrance loss coefficient for the three main inlet shapes found in the District: (1) projecting inlet, (2) flush headwall, and (3) wingwall. The coefficients should be evaluated for culverts flowing under the following regimes: (1) full pipe flow, (2) open channel flow, and (3) orifice flow. In addition, the entrance loss coefficient should be evaluated for small inlet gate restrictions where the flow regime is not shifted but the coefficient is adjusted.

Miscellaneous Modifications. Some array elements are used in the main section of Flow's version instead of the simple variables used in Fan's version. Array elements are necessary to handle database information on multiple barrels at a culvert structure. This does not affect the logic of the culvert program. Array elements from the main section are passed as simple variables to internal subroutines.

WEIRS

A typical weir at the District consists of a rectangular notch in a dam. There are three types of weirs according to the crest and notch configuration: (1) ogee, (2) trapezoidal, and (3) variable. Figure A-3 in Appendix A shows free flow conditions at weir S-48.

The terms used in the flow equations for weirs are defined as follows:

- B = width of the channel, in feet
- d = depth of the notch, in feet
- h = submergence head over the crest, difference between the downstream stage and the crest elevation, in feet
- H = approach head over the crest, difference between the upstream stage and the crest elevation, in feet
- L = measured length of the crest perpendicular to the flow, in feet
- n = exponent, usually expected to be 1.5
- W_c = width of the crest in the direction of flow, in feet

Ogee Weir

An ogee, or parabolic, weir is a spillway structure without a gate. There are only two ogee weirs at the District, S-48 and S-50. Both are coastal structures whose crest elevations are 8 and 12 ft above m.s.l., respectively. Submerged flow or reverse flow can only occur during a tidal surge high enough to overtop the crest elevation. In addition, ogee weirs lack downstream stage recorders. Therefore, submerged flow or reverse flow are not contemplated in ogee weir discharge computations.

Figure 15 is a schematic of an ogee weir. The length of the crest is measured at the critical depth of flow. This is the point where the slow moving, subcritical flow of the approach channel changes over to the fast moving, super critical flow of the downstream apron of the weir. This change occurs near the crest of the weir. At the crest, another phenomenon takes place. The sudden contraction of the area of flow creates an effective length of the crest which is shorter than the measured length. The effective length of the crest is given by:

$$L_e = L + C_e H \tag{20}$$

in which: C_e = effective length coefficient, must be a negative value

or similarly (Chow, 1959):

$$L_e = L - 0.1\, N H \tag{21}$$

in which: N = number of contractions; 0, 1, or 2

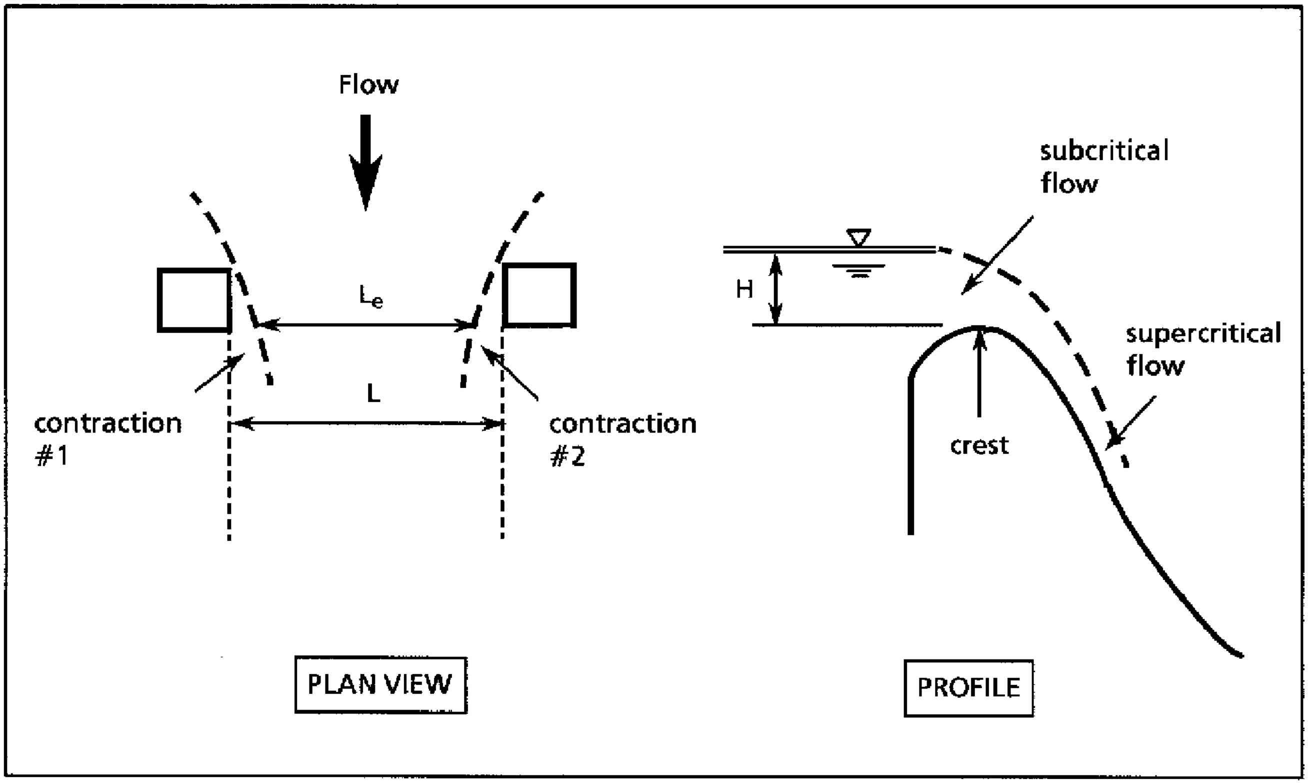

FIGURE 15. Ogee Weir

A weir may be designed in such a way as to avoid the need to compute an effective length. If the walls at both ends of the length of the crest are shaped to follow the pattern of contraction, then the number of contractions is zero and the effective length is the same as the measured length. If one side is rounded and the other is not, the number of contractions is one. If neither side is rounded, the number of contractions is two.

The discharge over an ogee weir is given by (Brater and King, 1976):

$$Q = C_o L_e H^n \tag{22}$$

in which: C_o = ogee coefficient of discharge, varies from 3.0 to 4.0

Trapezoidal Weir

A trapezoidal weir has a fixed crest with a trapezoidal cross-section or notch, as shown in Figure 16. Normally, water flows over the crest of the weir, but not over the dam. If water flows over the dam, the dam is said to be overtopped.

Free Flow Over Crest Only. The upstream stage is above the crest but below the dam. The downstream stage is below the crest. The Bernoulli equation is used to compute discharge for free flow (Brater and King, 1976):

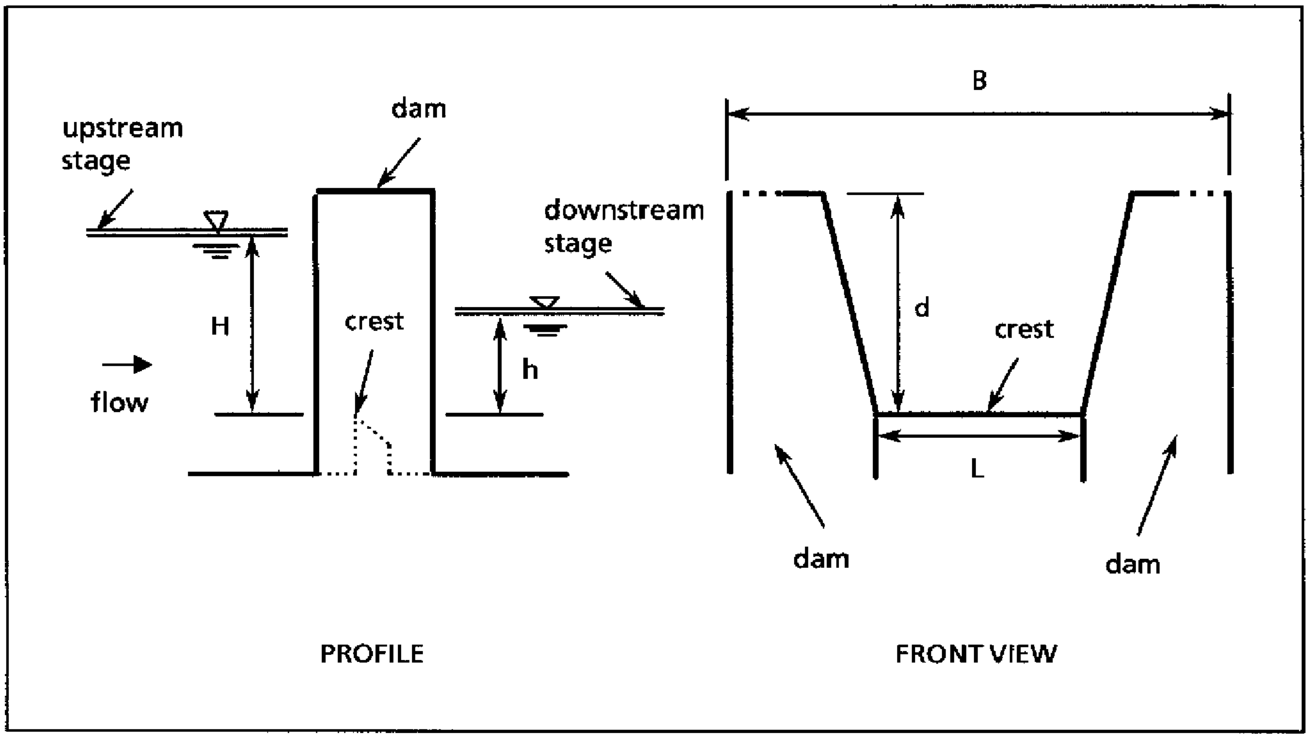

FIGURE 16. Trapezoidal Weir

$$Q = Q_{free\ crest} = C_f L H^n \tag{23}$$

in which: C_f = free flow coefficient, usually 3.0

Submerged Flow Over Crest Only. The upstream stage is above the crest but below the dam. The downstream stage is also above the crest but below the upstream stage. The Villemonte equation is used to compute discharge for submerged flow (Brater and King, 1976):

$$Q = Q_{subm.\ crest} = Q_{free\ crest} \left[1 - \left(\frac{h}{H} \right)^n \right]^{0.385} \tag{24}$$

Free Flow Over Dam and Crest. The upstream stage is above the dam and the downstream stage is below the crest. The discharge over the dam portion only is given by:

$$Q_{free\ dam} = C\,(B - L)\,(H - d)^n \tag{25}$$

The discharge over the dam and crest is given by:

$$Q = Q_{free\ crest} + Q_{free\ dam} \tag{26}$$

Free Flow Over Dam, Submerged Flow Over Crest. The upstream stage is above the dam. The downstream stage is above the crest but below the dam. The discharge is given by:

$$Q = Q_{subm.\,crest} + Q_{free\,dam} \tag{27}$$

Submerged Flow Over Dam and Crest. The upstream stage is above the dam. The downstream stage is above the dam but below the upstream stage. The discharge over the dam portion only is given by:

$$Q_{subm.\,dam} = Q_{free\,dam}\left[1\text{-}\left(\frac{h\text{-}d}{H\text{-}d}\right)^{n}\right]^{0.385} \tag{28}$$

The discharge over the dam and crest is given by:

$$Q = Q_{subm.\,crest} + Q_{subm.\,dam} \tag{29}$$

Reverse Flow. Reverse flow occurs when the downstream stage is higher than the weir crest and the upstream stage. To account for reverse flow, the upstream and downstream stages are interchanged and the discharge computation is performed as shown in Equations (23) through (29). A negative sign is added to the resultant discharge value.

It is suggested that reverse flow computation be checked with discharge measurements, as weir coefficients may not be applicable in reverse flow.

Variable Weir

A variable crest weir is a dam in which the depth of the notch can be regulated by raising or lowering the crest.

Crest width. The width of the crest of a variable weir is measured in the direction of flow. The width of a variable weir with stop logs is the width of the stop logs. The width of a thin-plate weir depends on the position of the movable plate. If the plate is sufficiently raised above the fixed part of the weir, the width is the thickness of the plate. However, if the plate is nearly flush with the fixed part of the weir, the width of the crest is the sum of the thickness of the plate and the width of the fixed part of the weir. A "transition elevation" of the crest is determined empirically below which the plate is considered flush with the fixed part of the weir.

Discharge coefficient. The discharge coefficient for a variable weir depends on whether the weir is sharp-crested, broad-crested, or somewhere in between. A sharp crest is sufficiently narrow so that water flowing over the weir is detached from the crest. A broad crest is rectangular in section and acts like a sharp crest when the head over the crest is one and one half times the width of the crest, in the direction of flow. Table 6 summarizes the computation of the discharge coefficient.

Free flow. The upstream stage is above the crest but below the dam. The downstream stage is below the crest. The discharge is given by:

$$Q = Q_{free} = C_V L H^n \tag{30}$$

in which: C_V = discharge coefficient for variable weir, see Table 6

TABLE 6. Computation of the Coefficient of Discharge for a Variable Weir

Type of Crest	Condition	Coefficient of Discharge, C_V
Broad	$H < 0.4\,W_c$	2.62
Transition	$0.4\,W_c \leq H \leq 1.5\,W_c$	$2.62 + 0.64(H/W_c - 0.4)$
Sharp	$H > 1.5\,W_c$	3.32

Source: Flow program code

Submerged flow. The downstream stage is above the crest but below the dam. The upstream stage is above the downstream stage but below the dam. The discharge is given by:

$$Q = Q_{free}\left[1 - \left(\frac{h}{H}\right)^n\right]^{0.385} \tag{31}$$

Overtopped flow. The upstream stage is above the dam. The discharge is computed for the weir portion of the dam according to Equations (30) and (31). A ">" (greater than) tag is attached to the discharge value.

TRAPEZOIDAL FLUME

The flow computation program calculates discharge for trapezoidal flumes. A trapezoidal flume consists of a wide approach section, a gradual transition section, and a throat section. The elevation of the sill of the throat section is higher than the elevation of the bottom of the approach section. The height of the sill is the difference between these elevations.

The following are constants defined in the flow computation program:

η = kinematic viscosity of fluid, 1.228×10^{-5} ft^2/sec for water at 64^{o}F
α_1 = energy-distribution coefficient for approach section, 1.04 for section long enough to develop flow profile
α_3 = energy-distribution coefficient for throat section, 1.04 for section long enough to develop flow profile

Figure 17 is a schematic of a trapezoidal flume. The subscripts 1, 2, and 3 denote the approach, transition, and throat sections, respectively. The following dimensional constants for each flume are defined in the hydrologic database:

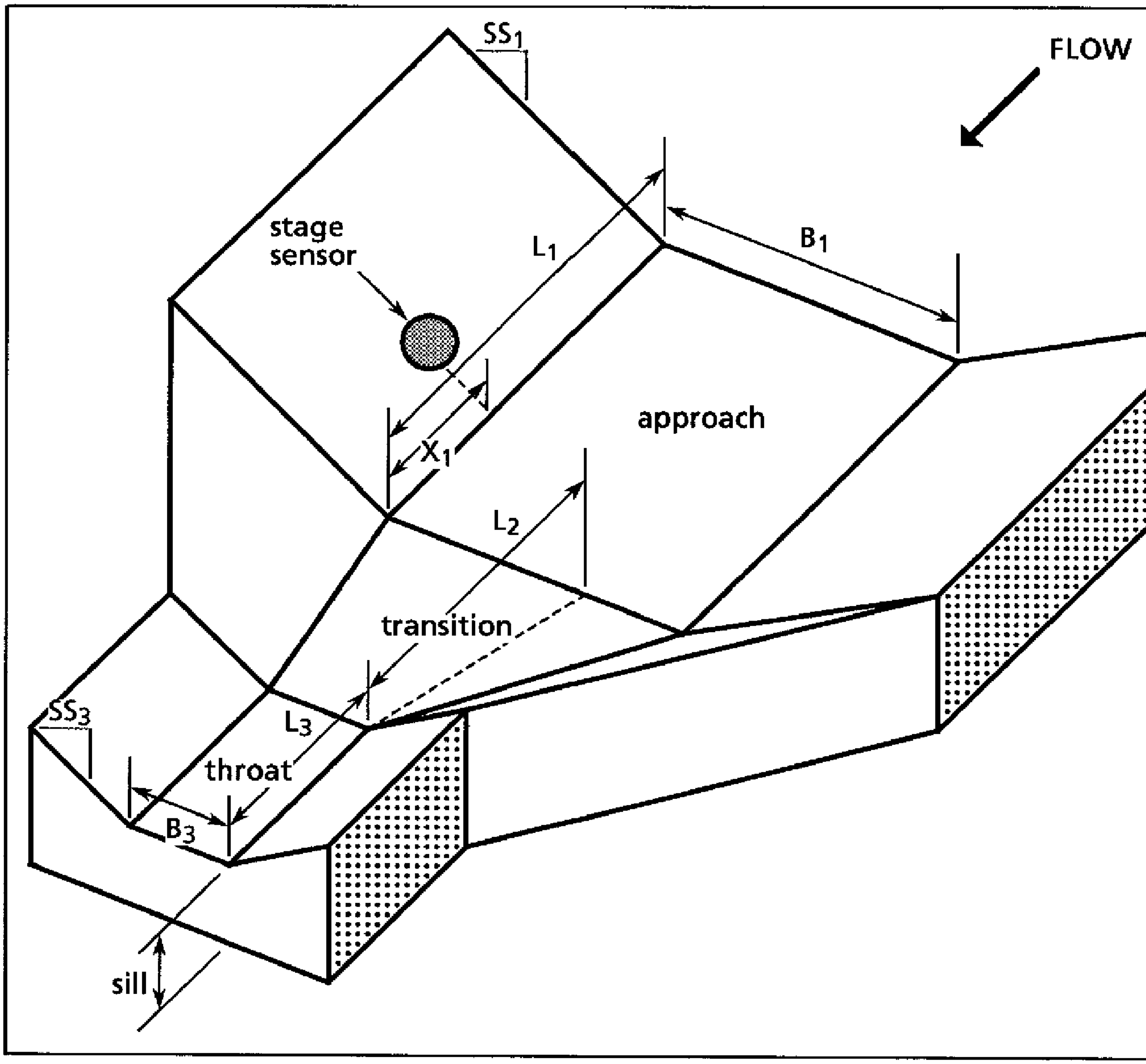

FIGURE 17. Trapezoidal Flume

K	=	absolute roughness height of material in flume throat, in feet (Chow, 1959)
B_1	=	bottom width of the approach section, in feet
B_3	=	bottom width of the throat section, in feet
E_{sill}	=	elevation of sill at throat section, in feet above m.s.l. or NGVD
SILL	=	sill height, or difference between sill elevation and bottom of approach section, in feet
L_2	=	length of the transition section, in feet
L_3	=	length of the throat section, in feet
X_1	=	distance, in the direction of flow, from the stage sensor in the approach section to the beginning of the transition section, in feet

The explanation of the algorithms used for flow computation of trapezoidal flumes is beyond the scope of this publication. A detailed discussion of these algorithms is found in Replogle (1975) and Schlichting (1960).

UNREGULATED OPEN CHANNEL

An unregulated open channel is a stream such as a canal or a river. To compute the flow through a reach of an unregulated open channel, a relationship is established between the upstream stage, the downstream stage, and the discharge. This relationship is known as a rating curve. At least three discharge measurements must be performed at varying stages to establish the rating curve. The rating curve should only be applied within the range of discharge measurements.

The terms used in the flow equations for unregulated open channels are defined as follows:

A	=	constant for fixed stage difference between E_{dwn} and E_{up}, in feet
C	=	regression coefficient
E	=	stage, in feet
E_0	=	base stage, in feet
E_{dwn}	=	downstream stage, in feet
E_{up}	=	upstream stage, in feet
n	=	regression exponent

Low Hydraulic Gradient and Uniform Cross Section. The reach presents very little difference between upstream stage and downstream stage. The cross-section selected is fairly uniform. Figure 18 shows a uniform cross section. A rating is established for a single stage location. The rating equation is given by:

$$Q = C\,(E - E_o)^n \qquad (32)$$

Low Hydraulic Gradient and Non-Uniform Cross Section. The reach is rated at a single stage location, but the cross-section is not uniform. Figure 19 shows a cross section which is not uniform. Two rating equations are necessary for two ranges of stage elevations. The rating equation for the lower stage rating is given by:

$$Q = C_{lo}\,(E - E_{lo_0})^{n_{lo}} \qquad (33)$$

in which:

C_{lo}	=	regression coefficient for low grade
E_{lo_0}	=	base stage for low grade, in feet
n_{lo}	=	regression exponent for low grade

The rating equation for the higher stage rating is given by:

$$Q = C_{hi}\,(E - E_{hi_0})^{n_{hi}} \qquad (34)$$

in which:

C_{hi}	=	regression coefficient for low grade
E_{hi_0}	=	base stage for low grade, in feet
n_{hi}	=	regression exponent for low grade

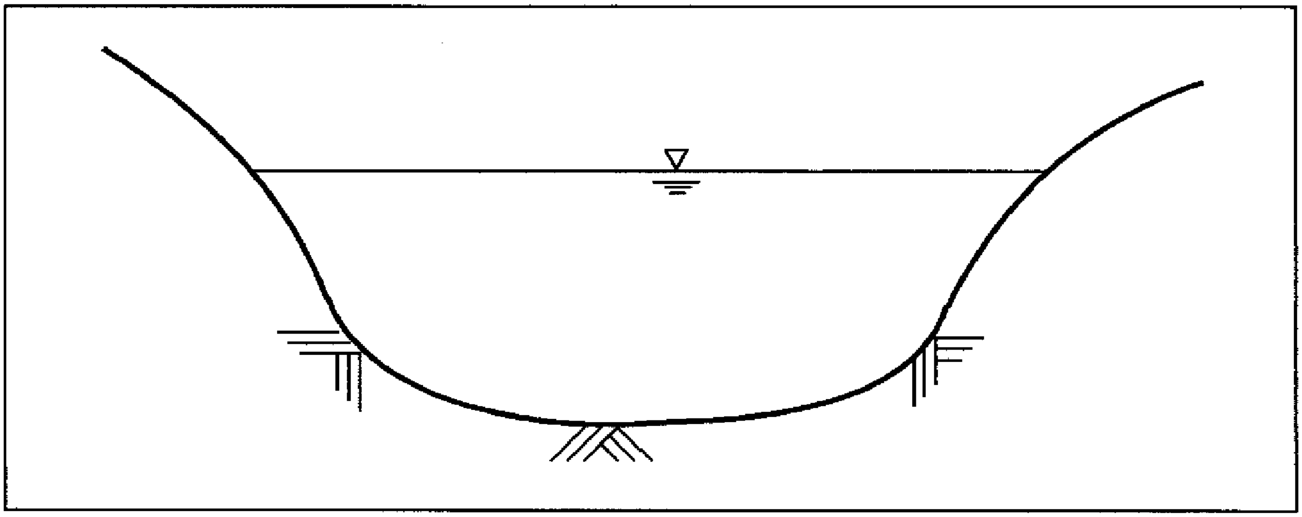

FIGURE 18. Uniform Cross Section

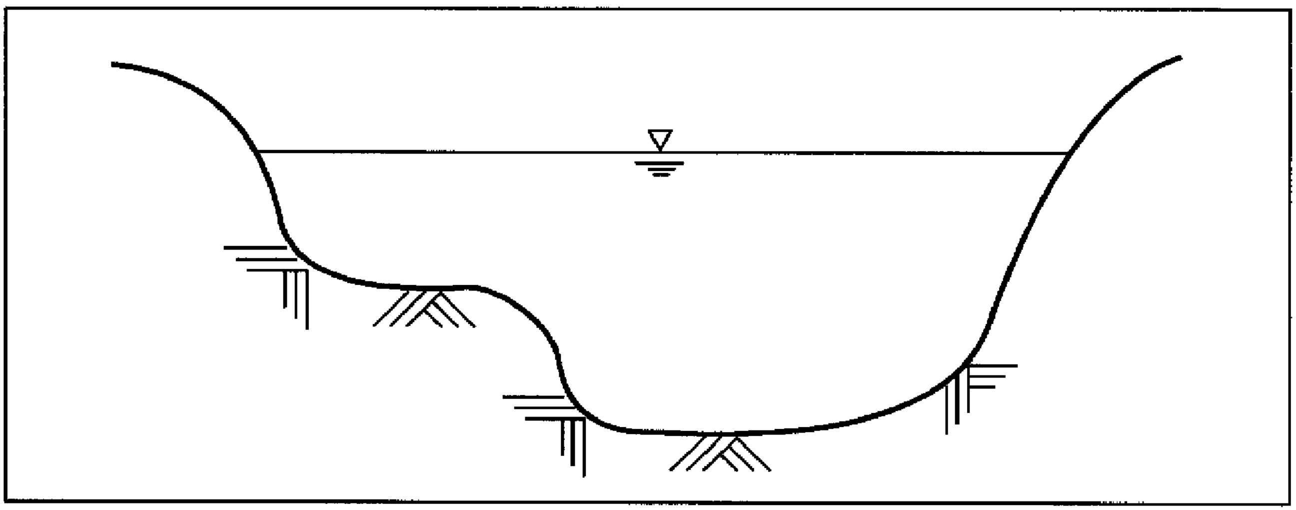

FIGURE 19. Cross Section Not Uniform

Moderate Hydraulic Gradient and Upstream Base. The reach presents a significant difference between the upstream and downstream stages. The upstream stage has a wider range of stages. The rating equation is given by:

$$Q = C_{up}\,(E_{up} - E_{up_0})^{n1}\,(E_{up} - E_{dwn} + A)^{n2} \tag{35}$$

in which: C_{up} = regression coefficient for upstream base
E_{up_0} = base stage for upstream stage, in feet
n_1, n_2 = regression exponents

Moderate Hydraulic Gradient and Downstream Base. Same as the previous case. However, the downstream stage has a wider range of stages. The base elevation E_0 is taken downstream. The rating equation is given by:

$$Q = C_{dwn}\,(E_{dwn} - E_{dwn_0})^{n3}\,(E_{up} - E_{dwn} + A)^{n4} \tag{36}$$

in which: C_{dwn} = regression coefficient for upstream base
E_{dwn_0} = base stage for upstream stage, in feet
n_3, n_4 = regression exponents

Overbank Flow. The stage is higher than the bank, flow is computed for a stage equal to the bank elevation and a tag of " > " is attached to the discharge value.

FLOW CALCULATION NOT CONTEMPLATED

There are several flow conditions which are not contemplated due to the lack of methods for estimation or because the estimation method is not implemented in the Flow program. These include:

1. Water discharged through navigational locks during lock operation.
2. Leakage of water through the separation between a closed gate, a flashboard, or a set of stop logs and the fixed parts of a control structure. Also, leakage through the separation between stop logs stacked on top of each other. Gate leakage computation is addressed by Collins (1977) and could be implemented in the Flow program.
3. Flow through slot gates. In the past, gates in some spillway structures were fitted with smaller slot gates which enabled the release of a relatively small discharge while the main gates remained closed. At present, all slot gates are permanently closed.
4. Flow through weirs equipped with a multiple-width notch. The width of the notch increases in a stepwise fashion as the stage rises.

CONCLUSIONS AND RECOMMENDATIONS

Calculation of surface water discharge rates for water control structures in the South Florida Water Management District is performed using the Flow program. The routine data processing activities of the Hydrologic Data Management Division use the Flow program to calculate instantaneous flow values. Instantaneous values computed by Flow are time-averaged by the Interval Value Generation program to obtain daily mean flow values. The daily mean flows are stored in DBHYDRO.

The Flow rprogram equires a text file as input. The length of the input and output files are only limited by the available mass storage. It is convenient to arrange the records in the input file chronologically, although this is not a requirement. The Flow program can be used with archived or simulated data. Simulated data may be used for modeling or calibration purposes.

Currently, the discharge at any structure may be computed from several established combinations of stage and control data. Therefore, DBHYDRO contains one or more time series of daily mean flow data for each structure. Seldom is any one time series complete nor is any particular time series always the best estimate of flow. A decision-making system is being developed by the Hydrologic Data Management Division to produce a single time series of flow, called *preferred flow*, from the most accurate combination of stage and control data available for each structure. This system will eliminate redundant or contradictory flow data, while improving the quality and consistency of the resulting flow time series.

Certain changes specific to topic areas are suggested below:

PROGRAMMING. The database access subroutine, ORADBAS, should connect to the database only once for the duration of the Flow program's execution.

The culvert subroutine should be rewritten to conform to the principles of structured programming and modular programming, to provide far easier methods of debugging and fine-tuning this major subroutine.

The principles of modular programming should be implemented throughout the program. COMMON blocks should be eliminated and all variables should be passed as arguments. Subroutines larger than 100 lines of code should be identified and further subdivided, if warranted, so that the size of each resulting subprogram is no more than 100 lines of code. (Ageloff, 1981)

PUMP SUBROUTINE. In the QPUMP subroutine, when the downstream stage is below the outlet invert elevation, the downstream elevation used for discharge computations should be the outlet invert elevation.

Care should be exercised when applying the interpolation equation (Eq. 9). If N is outside the range between N_{lwr} and N_{upr}, application of this equation will result in extrapolation. Extrapolation does not necessarily result in less accurate estimates than interpolation. However, if the minimum or maximum pump speeds are well outside the interpolation range, extrapolation should be checked for accuracy.

As an alternative to the current approach for estimating the head loss due to the flap gate, it is suggested to account for this loss in the discharge rating curve(s), which is how the head losses due to all other appurtenances are accounted for.

GATED SPILLWAY SUBROUTINE. The use of a transition zone for spillway flow regimes should be avoided. Instead, the implementation of the USCOE criteria, as shown in the flow diagram in Figure 7, should be studied (U.S. Army Corps of Engineers, 1963).

It is suggested that a reverse flow estimate (negative flow) at a spillway be interpreted as an indicator of flow direction or as a warning of a possible gauge datum error, rather than an estimate of reverse flow quantity.

GATED CULVERT SUBROUTINE. It is recommended that a study be performed to evaluate the entrance loss coefficient for the three main inlet shapes found in the District: (1) projecting inlet, (2) flush headwall, and (3) wingwall. The coefficients should be evaluated for the following flow regimes: (1) full pipe flow, (2) open channel flow, and (3) orifice flow. In addition, the entrance loss coefficient should be evaluated for small inlet gate restrictions where the flow regime is not shifted but the coefficient is adjusted.

The study may involve model testing, or it may use the discharge measurements available from the Hydrologic Data Management Division through its Stream Gaging Project. Another source of discharge measurement data is the U.S. Geological Survey. The entrance loss coefficient should be correlated with dimensionless variables, plotted, and expressed in mathematical terms.

It is suggested to assign appropriate enhance loss properties to the outlet and to use these when reverse flow is completed.

TRAPEZOIDAL WEIR. It is suggested that reverse flow computation be checked with discharge measurements, as weir coefficients may not be applicable in reverse flow.

VARIABLE WEIR SUBROUTINE. The variable weir subroutine, QVARWEI, should be modified to limit the value of the discharge coefficient, for transition between sharp- and broad-crested weirs, to a maximum value of 3.32, which is the discharge coefficient for a sharp-crested weir.

FLOW CALCULATIONS NOT CONTEMPLATED. Gate leakage computation is addressed by Collins (1977) and could be implemented in the Flow program.

CHECK TAGS SUBROUTINE. The CHKTAGS subroutine should be modified as follows:

Three matrices for tag computation are necessary. The configuration of these matrices should be developed in close cooperation between computer programmers, engineering technicians, and users. The computer programmers developed the data processing software which tags the data. The senior engineering technicians and engineering technician supervisors are intimately familiar with the data processing techniques which result in tagged data. The users ultimately interpret the tags. The proposed matrices are: (1) device tag matrix, (2) stage tag matrix, and (3) discharge tag matrix.

Device Tag Matrix. The device tag matrix would be used to obtain a resulting device tag from all of the device tags in an input record. Since the matrix is a two-dimensional array, it can be used only for two devices at a time. Therefore, an iterative approach is necessary for control structures with more than two devices (e.g., a spillway with four bays).

Initially, a resulting tag is obtained through the matrix from the first and second device tags. Consequently, another resulting tag is obtained from the third tag and the result of the first two tags. Yet another resulting tag is obtained from the fourth tag, if available, and the resulting tag of the first three tags. This is done until all device tags are processed through the matrix producing one final resulting device tag for all devices in an input record.

TABLE 7. Device Tag Matrix

Tag for Device i	Accumulated Device Tag						
	null	>	<	L	E	M	N
null	null	<	>	L	E	M	N
>	>	>					
<	<		<				
L	L			L			
E	E				E		
M	M					M	
N	N						M

Stage Tag Matrix. Used when both the upstream and the downstream stages are required. The structure of this matrix is the same as the one currently used in the Flow program and presented in Table 3. The configuration of this matrix should be reevaluated to insure the proper resulting tag is being assigned. The direction of flow should be checked before the tags are entered into the matrix. Reverse flow requires the stage tags to be reversed before they are entered into the tag matrix.

Discharge Tag Matrix. Used when both stage and control activity are required for flow computation. Table 8 shows the structure of the proposed matrix.

TABLE 8. Discharge Tag Matrix

Resulting Stage Tag	Resulting Device Tag						
	null	>	<	L	E	M	N
null	null	<	>	L	E	M	N
>	>						
<	<						
L	L						
E	E						
M	M						
N	N						

CHKZEROFLOW SUBROUTINE. This subroutine currently checks whether the input data alone indicates zero flow, without performing any discharge computations. To correctly check for zero flow, the hydrologic database must be queried first to assess the input data in conjunction with the type of structure, the bypass stage of the structure, and the height for overtopping the gates. Therefore, zero flow may be predetermined in the following manner:

1. For a pump station, the flow is zero if all control values are zero and the structure is not bypassed.
2. For a gated spillway, the flow is zero if all control values are zero, the gates are not overtopped, and the structure is not bypassed.
3. For a gated culvert equipped with sluice gates, the flow is zero if all control values are zero and the structure is not bypassed.

DOCUMENTATION. The Reference Center should keep a copy of this document. A copy of the Structure Information Binders should also be kept by the Reference Center. The information in these Binders should be routinely updated by the Hydrologic Data Management Division, the Operations Division, and the Construction Division.

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APPENDIX A

SAMPLES OF CONTROL STRUCTURES DURING OPERATION

Figure A-1. Pump Station S-332 in Everglades National Park

Figure A-2. Gated Spillway S-49 on the C-24 Canal

Figure A-3. Weir S-48 on the C-23 Canal

APPENDIX B

USCOE PLATES FOR FLOW REGIMES

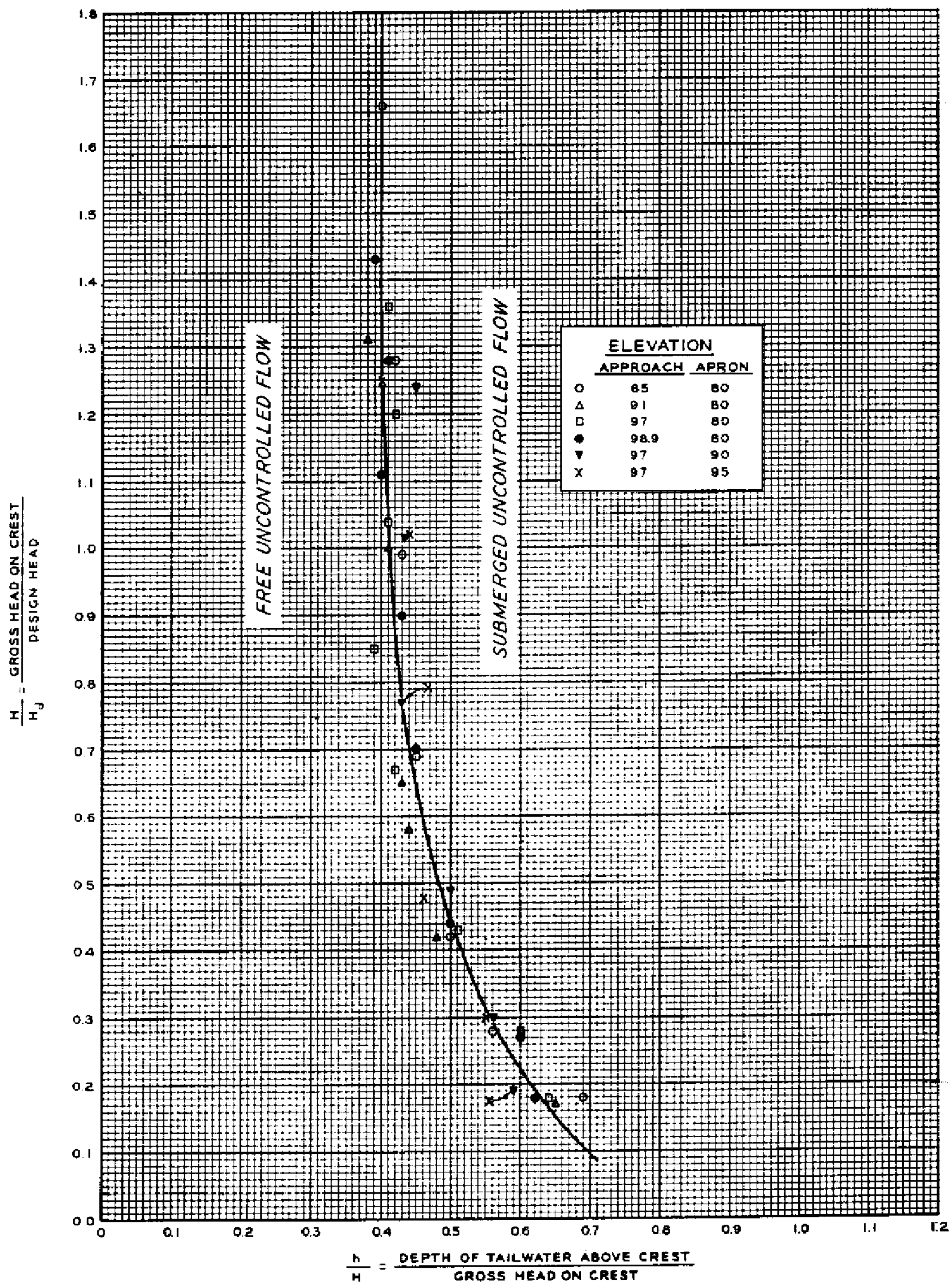

Figure B-1. Plate 41, Uncontrolled Flow Regimes (USCOE, 1963)

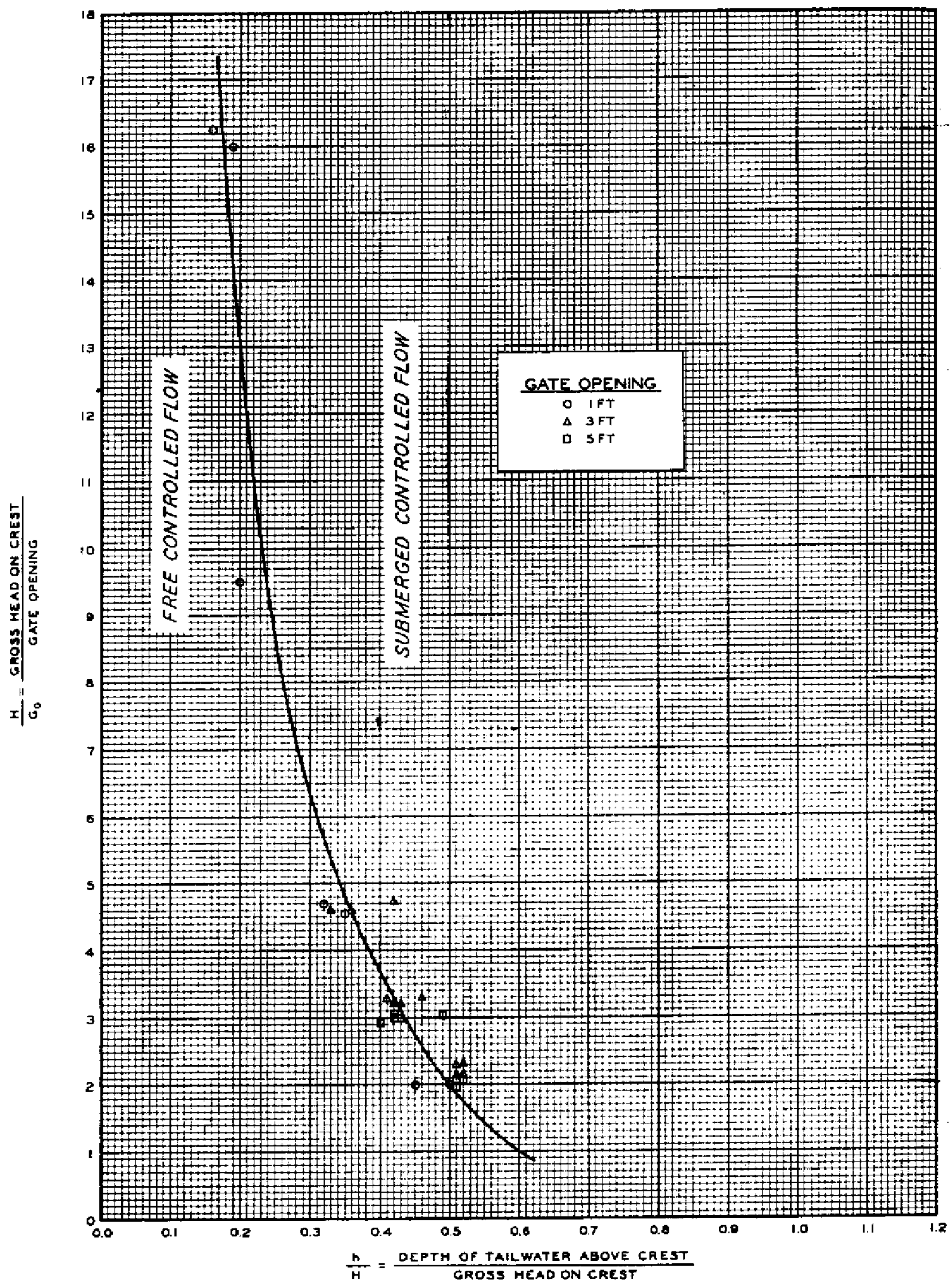

Figure B-2. Plate 42, Controlled Flow Regimes (USCOE, 1963)

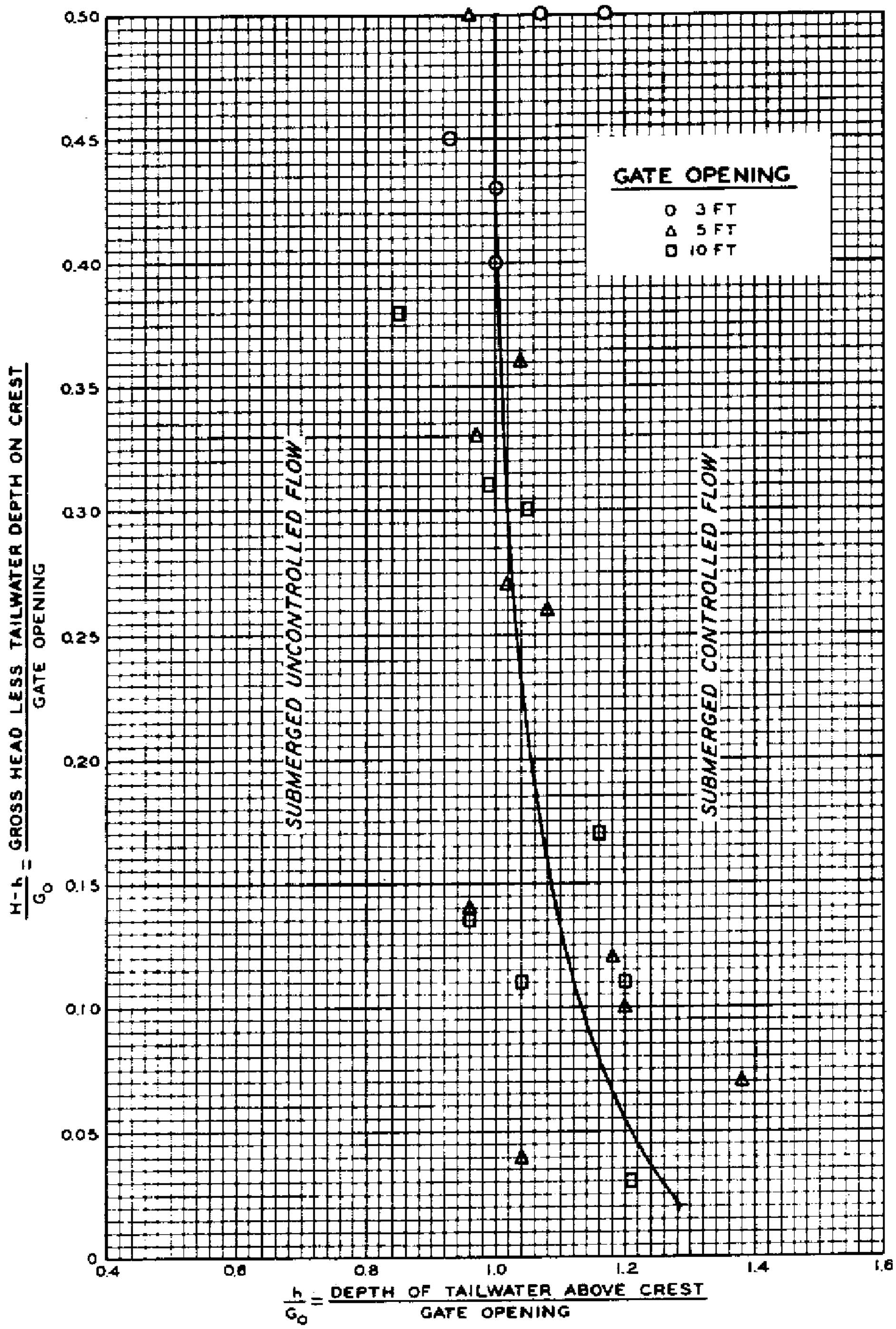

Figure B-3. Plate 43, Submerged Flow Regimes (USCOE, 1963)

APPENDIX C

MEMORANDA

ADM 12-04-02

MEMORANDUM

TO: Davies Mtundu, Supv. Prof., Civil Engineer, DTA

THROUGH: Brian Turcotte, Supv. Prof., Civil Engineer, DTA BT

FROM: José Otero, Staff Civil Engineer, DTA JMO

DATE: January 6, 1992

SUBJECT: Incorrect zero flows for flashboard culverts in DBHYDRO

It has been found that the culvert subroutine in the flow computation (FLOW) program incorrectly assigned zero flow values for culverts with flashboards. The error pertains to two cases of free flow over a culvert flashboard: (1) The flow over the flashboard is free flow and the area of flow over the flashboard is less than or equal to 20% of the area of flow in the culvert, and (2) the flow over the flashboard is free flow and the head on the inlet invert is greater than or equal to 130% of the height of the culvert. In the first case the culvert flow, Q_c, is not computed and is zero. In the second case the culvert flow is recognized as orifice flow, but the orifice subroutine does not work for flashboard culverts, and Q_c is zero. In both cases, the actual flow, Q_a, is the minimum of the weir flow, Q_w, and Q_c. Therefore, Q_a is zero for both cases. These problems have been corrected in the production version of the FLOW program as of January 4, 1991.

Attachments 1 and 2 show the program input, the incorrect program output, and the correct program output for different types of culvert flow. Attachment 3 shows breakpoint flow computed from the DCVP archive with incorrect and correct zero values. Attachment 4 shows the defective portion of the source code of the original culvert subroutine written by A. Fan in 1985. Attachment 5 shows the changes made to the portion of the source code in attachment 4 to account for free weir flow correctly.

Attachment 6 is a list of the DBHYDRO flow stations which need to be reloaded; including the suggested STATION_ID for use with the DBHY_RELOAD application, and the start and end dates. Please make arrangements to reload these daily flows to DBHYDRO.

Attachments (6)

c: Shawn Sculley

ATTACHMENT 1 - G-136 CULVERT STAGE AND OPERATIONS DATA, FLASHBOARDS EXERT FULL CONTROL, CULVERT FLOW LIKE OPEN CHANNEL FLOW AND ORIFICE FLOW

61744342	19920101	0000	16.500	12.000	3	16.000	16.000	16.000
61744342	19920101	0000	17.000	12.000	3	16.000	16.000	16.000
61744342	19920101	0000	17.500	12.000	3	16.000	16.000	16.000
61744342	19920101	0000	18.000	12.000	3	16.000	16.000	16.000
61744342	19920101	0000	18.500	12.000	3	16.000	16.000	16.000
61744342	19920101	0000	19.000	12.000	3	16.000	16.000	16.000
61744342	19920101	0000	19.500	12.000	3	16.000	16.000	16.000
61744342	19920101	0000	20.000	12.000	3	16.000	16.000	16.000

G136 FLOW DATA, INCORRECT ZERO VALUES FOR WEIR FLOW

6174434219920101	0000	**0.000**	¦ --> Problem 1
6174434219920101	0000	87.120	
6174434219920101	0000	**0.000**	¦
6174434219920101	0000	**0.000**	¦
6174434219920101	0000	**0.000**	¦ --> Problem 2
6174434219920101	0000	**0.000**	¦
6174434219920101	0000	**0.000**	¦
6174434219920101	0000	**0.000**	¦

G136 FLOW DATA, CORRECT VALUES FOR WEIR FLOW

6174434219920101	0000	30.802
6174434219920101	0000	87.120
6174434219920101	0000	160.050
6174434219920101	0000	246.413
6174434219920101	0000	344.372
6174434219920101	0000	452.689
6174434219920101	0000	570.453
6174434219920101	0000	696.960

ATTACHMENT 2 - G-136 CULVERT STAGE AND OPERATIONS DATA, FLASHBOARDS EXERT FULL CONTROL, CULVERT FLOW LIKE PIPE FLOW

61744342	19920101	0000	16.500	15.500	3	16.000	16.000	16.000
61744342	19920101	0000	17.000	15.500	3	16.000	16.000	16.000
61744342	19920101	0000	17.500	15.500	3	16.000	16.000	16.000
61744342	19920101	0000	18.000	15.500	3	16.000	16.000	16.000
61744342	19920101	0000	18.500	15.500	3	16.000	16.000	16.000
61744342	19920101	0000	19.000	15.500	3	16.000	16.000	16.000
61744342	19920101	0000	19.500	15.500	3	16.000	16.000	16.000
61744342	19920101	0000	20.000	15.500	3	16.000	16.000	16.000

G136 FLOW DATA, INCORRECT ZERO VALUE FOR SMALL WEIR FLOW

6174434219920101	0000	**0.000**	| --> Problem 1
6174434219920101	0000	87.120	
6174434219920101	0000	160.050	
6174434219920101	0000	246.413	
6174434219920101	0000	344.372	
6174434219920101	0000	452.689	
6174434219920101	0000	570.453	
6174434219920101	0000	696.960	

G136 FLOW DATA, CORRECT VALUES FOR ALL WEIR FLOWS

6174434219920101	0000	30.802
6174434219920101	0000	87.120
6174434219920101	0000	160.050
6174434219920101	0000	246.413
6174434219920101	0000	344.372
6174434219920101	0000	452.689
6174434219920101	0000	570.453
6174434219920101	0000	696.960

ATTACHMENT 3 - DCVP ARCHIVE BREAKPOINT FLOW FOR G-136 CULVERT

SITE ID	YYYYMMDD	HHMM	INCORRECT FLOW	CORRECT FLOW
51744342	19910114	1126	0.000E	0.000E
51744342	19910115	1155	0.000E	0.000E
51744342	19910116	1140	0.000E	0.000E
51744342	19910116	1141	0.000E	0.000E
51744342	19910117	1110	149.477E	149.477E
51744342	19910118	1010	135.137	135.137
51744342	19910122	1125	0.000	10.243
51744342	19910123	1130	0.000	6.653
51744342	19910124	1100	0.000	6.653
51744342	19910125	1100	0.000	1.280
51744342	19910128	1110	0.000	5.576
51744342	19910129	1145	0.000	4.564
51744342	19910130	0935	0.000	1.971
51744342	19910131	1110	0.000	1.280
51744342	19910131	1115	0.000	1.280
51744342	19910131	1116	0.000	1.280
51744342	19910131	2359	0.000	0.000
51744342	19910201	0000	0.000	0.000
51744342	19910201	1105	0.000	0.000
51744342	19910204	1125	0.000	0.000
51744342	19910205	1150	0.000	0.000
51744342	19910206	1150	0.000	0.000
51744342	19910207	1155	0.000	0.246
51744342	19910208	1105	0.000	0.697
51744342	19910211	1140	0.000	0.000
51744342	19910228	0950	N	N

ATTACHMENT 4 - DEFECTIVE PORTION OF FAN'S CULVERT SUBROUTINE

```
      IF(GTYPE.EQ.2)THEN
         CALL QCULWEI(QW,CODE,
     1            HWE,TWE,GGAP,BARREL,GTYPE,INEL(IQ), OUTEL(IQ), L(IQ),
     +            D,W, N(IQ), K(IQ), C(IQ),
     2            HW,TW,KE,ICOUNT,
     3            WB(IQ), WE, SWB(IQ), SWE(IQ), CW(IQ), A,AW)
         IF(AW/A .LT. 0.2) GO TO 100
      ENDIF
      IF(TW.GE.D)THEN
         CALL QCULPIP(QC,CODE,
     1            HWE,TWE,GGAP,BARREL,GTYPE,INEL(IQ), OUTEL(IQ), L(IQ),
     +            D,W, N(IQ), K(IQ), C(IQ),
     2            HW,TW,KE,ICOUNT)
      ELSE IF(HW.GE.1.3*D .OR. HW.GE.2.0*GGAP)THEN
             CALL QCULORI(QC,CODE,
     1                HWE,TWE,GGAP,BARREL,GTYPE,INEL(IQ), OUTEL(IQ),
     +                L(IQ), D,W, N(IQ),
     +                K(IQ), C(IQ),
     2                HW,TW,KE,ICOUNT)
          ELSE
             CALL QCULDIT(QC,CODE,
     1                HWE,TWE,GGAP,BARREL,GTYPE,INEL(IQ), OUTEL(IQ),
     +                L(IQ), D,W, N(IQ),
     +                K(IQ), C(IQ),
     2                HW,TW,KE,ICOUNT)
      ENDIF
  100 IF(GTYPE.EQ.2.AND.QW.LE.QC)THEN
         QA=QW*SIGN
         CODE(1:1) = 'W'
      ELSE
         QA=QC*SIGN
      ENDIF
```

ATTACHMENT 5 - CORRECTED PORTION OF FAN'S CULVERT SUBROUTINE

```
C
C --- Set weir control flag. (JMO 1/4/92)
C
      WEIRCTRL = .FALSE.
C
      IF(GTYPE.EQ.2)THEN
         CALL QCULWEI(QW,CODE,
     1             HWE,TWE,GGAP,BARREL,GTYPE,INEL(IQ), OUTEL(IQ), L(IQ),
     +             D,W, N(IQ), K(IQ), C(IQ),
     2             HW,TW,KE,ICOUNT,
     3             WB(IQ), WE, SWB(IQ), SWE(IQ), CW(IQ), A,AW)
C
C        IF(AW/A .LT. 0.2) GO TO 100
C
C ------ Flow through culvert with flashboard is weir flow if flashboard control
C        is significant; or if flow is free, not submerged.  (JMO 1/4/92)
C
         IF (AW/A .LT. 0.2 .OR. TWE .LT. BOARD) THEN
            WEIRCTRL = .TRUE.
            GO TO 100
         ENDIF
C
      ENDIF
      IF(TW.GE.D)THEN
         CALL QCULPIP(QC,CODE,
     1             HWE,TWE,GGAP,BARREL,GTYPE,INEL(IQ), OUTEL(IQ), L(IQ),
     +             D,W, N(IQ), K(IQ), C(IQ),
     2             HW,TW,KE,ICOUNT)
      ELSE IF(HW.GE.1.3*D .OR. HW.GE.2.0*GGAP)THEN
            CALL QCULORI(QC,CODE,
     1                  HWE,TWE,GGAP,BARREL,GTYPE,INEL(IQ), OUTEL(IQ),
     +                  L(IQ), D,W, N(IQ),
     +                  K(IQ), C(IQ),
     2                  HW,TW,KE,ICOUNT)
         ELSE
            CALL QCULDIT(QC,CODE,
     1                  HWE,TWE,GGAP,BARREL,GTYPE,INEL(IQ), OUTEL(IQ),
     +                  L(IQ), D,W, N(IQ),
     +                  K(IQ), C(IQ),
     2                  HW,TW,KE,ICOUNT)
      ENDIF
C
C 100 IF(GTYPE.EQ.2.AND.QW.LE.QC)THEN
C
C --- Flow through culvert is weir flow if flow is controlled by flashboard
C     either completely or primarily.  (JMO 1/4/92)
C                                 (GTYPE .EQ.2 .AND. QW .LE. QC)
  100 IF (WEIRCTRL .OR. ~~QW. LE. QC~~) THEN
C
         QA=QW*SIGN
         CODE(1:1) = 'W'
      ELSE
         QA=QC*SIGN
      ENDIF
```

ADM 02-06

MEMORANDUM

To: All Sr. and Engineering Technicians

From: Duane Dunn, Engineering Technician Supervisor
Trudy Morris, Engineering Technician Supervisor Trudy

Date: July 9,1992

Subject: Processing Data for Gate Operations

As you are aware, the gate activity at some sites throughout the District is recorded solely by manual notes on an operation log. Our present instrumentation efforts are set to place a monitor or sensor on all gates wherever possible. However, at those sites where only manual records are available, these records must be entered in the SG3 application manually.

Our past procedures have allowed technicians to process only gate #1 records whenever the log reflected the secondary gates had the same activity. The flow equations simply assumed all gates to be operating the same as gate one when no records were found. The secondary gates were only processed when the log reflected a change in the activity which was different from gate #1.

With the advanced processing programs, processing manual records is now easier. Operations can be entered simultaneously for all gates, etc., from the log. Therefore, we are mandating the following procedures for processing all gate, pump, or flashboard data;

1. **A data set will be processed for all gates, pumps, and flashboards at all sites.**

2. All operation logs will be maintained in neat order.

3. Any errors or questionable data should be investigated and the proper notes placed on the log, initialled and dated.

4. Keep only the current year records at your desk. All previous years should be permanently filed in the proper cabinet.

This processing procedure will be in effect beginning with June, 1992 data. Should you have any questions, please see your supervisor.

c: Davies Mtundu
Nagendra Khanal
Robb Startzman
Brian Turcotte

MEMORANDUM

TO: Jose Otero

THROUGH: Nagendra Khanal NK

FROM: Emile Damisse
Luis G. Cadavid LGC

DATE: April 12, 1993

RE: Flow Computation - Technical Publication

Thanks for the opportunity to review your technical publication. You have been assigned the not easy task of putting together what many people and many organizations have done in the past, perhaps without any connection among them, and give coherence and organization to those materials. We certainly enjoyed reading your document. It is going to be a valuable asset for the District. Congratulations on a well done job.

We would like to offer some comments and suggestions. They are aimed to improving the information the document conveys. Many of the points we discuss below are not included in your original scope of work. They are results from previous works. A fundamental basis to the flow computation program is the research work conducted by the COE. Many of the coefficients used by the algorithm appear to be derived from this study, like for instance the values of 1.7 and 2.0 given in Table 5. It will be a good idea to mention the source of these coefficients as they appear in the text, along with notes on whether the derivation is theoretical or empirical. We believe that the issues we present below should be emphasized or at least mentioned in the report so that they can be reexamined and probably modified in the future.

1 - Stastical and Physical Sigificance of Equations

First, we would like to address the statistical and physical significance of some of the equations and procedures presented in the text. The first example covers equation (3) which is used to compute discharge as function of pump speed and available head. The equation is extremely heavy, with ten coefficients which were probably determined using regression analysis. In order for equation (3) to convey any significance, a total of 50 points would be required, i.e. an average of 5 points per coefficient. In case regression analysis was used, what was the sample size ? We see the model in equation (3) as a difficult one to justify from a practical and physical point of view. In our opinion, a simpler and more attractive approach in this case would be to work with a double entry table, head and speed versus discharge, formed with the experimental data points.

Some other models, like equation (2), applicable to pumps with constant speed engines, are simpler, although they still present a relatively high number of coefficients. It will be an improvement for the document if an example of this type of model were presented. The graph should show both the data points and the resulting fitted cubic equation. Where the coefficients statistically tested for significance ? For instance, was the possibility of C_3=0 checked against the possibility of not being zero ? How different is the third order polynomial from the second order polynomial ? We believe all these are important questions which should be referred in the document. If these questions have not been addressed in the past, they should be investigated by the Data Management Division, within the general objective of improving hydrologic data quality.

Most of the discharge equations used by the flow computation program are amenable of physical derivation. General coefficients and exponents are introduced to increase generality, to account for unknown factors and to ease presentation. Values for these coefficients and exponents are derived from regression analysis. We have found difficult to justify the generalization of exponents which appear as one (1) or as zero (0) into a value n. Cases like these are observed in equation (18), where G_o is risen to a power

n_1 and h is risen to a power n_2. We would leave the gate opening as a linear term and leave h out of the equation, unless it can be shown, through an adequate set of data points, that the discharge coefficient is a function of these two variables. In this case, a more appropriate approach would be to present C_{cs} as function of G_o and h. In case it is decided to leave and calibrate, for instance, the exponent n_1, a measure of the benefit in doing so should be provided.

2 - Transition Zone Definition

The definition of the transition zone as stated in page 36, marking the change from controlled to uncontrolled flow and vice versa could be modified. Under free and uncontrolled flow conditions, we can expect the maximum discharge over a spillway for a given approach head. The transition zone or more precisely the transition point is reached when the operating condition is such that the gate is lowered to the extent that the maximum discharge is maintained. The gate opening (Go) is such that any decrease in Go would create the backwater effect upstream of the control structure. Hence, the flow is controlled by the gate and the actual discharge is less than that (Qmax) computed from the uncontrolled flow equation.

Strictly speaking, the transition point would be reached when the gate opening Go approaches the critical depth Ycr = 2/3H (or H = 1.5 Go). Because of energy loss through the control structures, the studies conducted by the COE seem to indicate that the critical point would be reached when H = 1.7Go. Hence, the criteria for level of gate restriction summarized in table 4, page 37, could be simplified. For H >= 1.7Go, the flow would be considered as controlled by the gate and uncontrolled otherwise. From this discussion, it looks that the transition criterion H/Go = 1.7 is the most appropriate, as compared to 2.0.

3 - Controlled Free Flow Equation

When the gate opening is relatively small, equation (15), page 39, would provide accurate discharges. However, when the gate opening is relatively large, we can no longer assume the approach head H is constant for every streamline in the cross sectional area of the orifice. A more appropriate flow equation for this case, as recommended by Lencastre and Valembois (Manuel d'Hydraulique generale, Editions Eyrolles, Paris 1976), is determined as follows :

$$dQ = Lvdh$$
$$v = \sqrt{2gh}$$
$$Q = L\sqrt{2g}\int_{H-Go}^{H} h^{\frac{1}{2}}\,dh$$
$$Q = \frac{2}{3}C_{cf}L\sqrt{2g}\,[H^{\frac{3}{2}} - (H-Go)^{\frac{3}{2}}] \quad (1)$$

Where :

H = the approach head over the sill of the spillway crest

Go = the gate opening

C_d = the discharge Coefficient for controlled free flow condition

This discharge equation indicates that when Go approaches H the discharge approaches the maximum discharge calculated from the uncontrolled free flow equation. In addition to being more realistic, the latter equation is consistent with the physical nature of the problem at hand. Its application would prevent cases of inconsistency with the fluid Mechanics principles as those described on the last paragraph, on page 36, and illustrated in figures 5 and 6 of the document. Furthermore, with proper calibration of the discharge coefficient (C_d), there would be no need to use the harmonic curve-fitting formula (equation 14) presented on page 37. The discharge coeficient C_d should be calibrated in such a way, that the discharge given by the controlled free flow equation approaches the discharge calculated from the uncontrolled free flow equation, as Go approaches H.

4 - Controlled Submerged Flow Equation

Equation (17) proposed by the COE to calculate discharges under controlled submerged flow conditions appears incorrect, if the parameter h is referred to as the downstream head above the sill of the spillway crest. Assuming that the equation is derived from the principle of energy conservation, applied between two sections, one upstream and the other downstream of the gate, the factor Lh would be considered as the flow cross sectional area at a downstream section. If that is the case, the downstream flow sectional area would be underestimated. This is particularly incorrect when the height of the spillway crest above the bottom of the downstream waterway is relatively important. Furthermore, energy losses through spillways are large and make difficult the application of the energy equation between the upstream and the downstream sections.

When the flow is fully submerged, in other words, when the downstream head above the crest of the spillway is larger than the gate opening, the following equation, derived from the energy principle applied between two sections, one upstream and another at the gate above the spillway crest, would be recommended :

$$Q=C_s\sqrt{2g}LGo\sqrt{H-h} \quad (2)$$

where :

C_s = discharge coefficient for fully submerged flow

The other parameters have the same meaning as described above.

When the flow is partially submerged, i.e when the downstream head above the crest of the spillway is less than gate opening, Lencastre and Valembois (Manuel d'hydraulique Generale, Editions Eyrolles, Paris 1976) suggest that such flow can be considered as divided into two parts : free and fully submerged. Therefore, they propose the following equation :

$$Q=\frac{2}{3}CL\sqrt{2g}\,[(H-h)^{\frac{3}{2}}-(H-Go)^{\frac{3}{2}}]+CsLh\sqrt{2g(H-h)} \quad (3)$$

According to some studies conducted by Weisbach, reported by Lencastre and Valembois, the discharge coefficient for free flow equation (C) and the discharge coefficient for fully submerged flow (C_s) are linked by the following relation : C_s=0.986C. Both coefficients vary with the ratio H/Go. Lencastre and Valembois suggest that the value of 0.60 is a good approximation for both coefficients.

The application of the above flow equation does not require that the transition submergence be known. The discharge coefficients (C and C_s) are the only parameters that must be calibrated.

5 - Uncontrolled Submerged Flow Equation

Equation 21, proposed by the COE is used to compute discharges for uncontrolled submerged flow. However, the accuracy of the flows computed from this equation depends upon the estimation of the discharge coefficient (C_s) and the criterion adopted for estimating the transition submergence. A transition submergence St = h/H = 0.50 has been proposed by the COE and seems to be used for all control structures in the flow computation program. The transition submergence could be defined as the value St for which the discharge given by the free-flow equation is approximately the same as that given by the submerged-flow equation.

The value of St computed from the application of the above definition is highly sensitive to errors in the discharge coefficients or exponents of either equation. Therefore, a generalized value for St would not be recommended. In some cases, the calibration approach proposed by the COE or used by the District may generate inconsistent results. The case of Spillway S-63 is a typical illustration . A value of $C_{cs} = 0.646$ is suggested for this spillway (page 43) and a free discharge coefficient of C = 2.9 is generally adopted by the District. To examine what would happen when the transition submergence point (H= 2h as proposed by the COE) is reached, let H = 6 ft and h = 3 ft. The free discharge would be q = 42.6 cfs / ft of the spillway crest width and submerged discharge qs = 26.9 cfs / ft of the spillway crest width. Hence, the submerged discharge is only 63% of that given by the free-flow equation at the transition point. This is not satisfactory.

We would like to illustrate a procedure that could be used to compute the transition submergence. The following approach is developped for the case where the flow equtions for both, uncontrolled free and uncontrolled submerged flow conditions, are derived from the energy conservation principle. The approach is still valid for general flow equations. But, when n is different from n1 + n2, where n, n1 and n2 are the exponent of H in the uncontrolled free flow equation, and the exponents of the terms (H-h) and h in the uncontrolled submerged flow equation, respectively, the value of St is dertermined by trial and error.

If discharge equations are known for both the free-flow and the submerged-flow conditions, a definite value of the transition submergence can be obtained by setting the equations equal to one another and solve for St. With S = h/H or h = SH, equation 21, becomes :

$$Q_s = C_s L (2g)^{.5} (1-S)^{.5} S H^{1.5} \quad (4)$$

Taking into account the fact that the discharge coefficient C_s is a function of the submergence, S = h/H, and by equating the above equation to equation 19, we obtain the following function that can be solved for St :

$$C_s(S_t)\,(2g)^{.5}(1-S_t)^{.5}S_t - C = 0 \quad (5)$$

Where :

Cs(St) = Discharge coefficient for submerged flow at the transition submergence point.
St = The transition submergence

For C_s constant the above equation would take the following form :

$$S_t^3 - S_t^2 + \frac{C^2}{64.4C_s^2} = 0 \quad (6)$$

For C = 2.90 and C_s = 1.23 - 0.43h/H (discharge coefficients for spillway S-5AS),and using equation (5) above, the transition submergence would be St = 0.68. For S= St = 0.68, the discharge coefficient for submerged flow condition, for spillway S-5AS would be C_s = 0.94 and the submerged discharge equation Qs becomes :

$$Q_s = 2.899 L H^{1.5} \quad (7)$$

With the assumption made regarding spillway S- 5AS, for any value of the approach head H and the downstream head h, such that S= h/H = .68, the discharge given by the submerged-flow equation would practically the same as that derived from the free-flow equation :

$$Q=2.90LH^{1.5} \quad (8)$$

It follows that the transition submergence is directly related to the discharge coefficients for both free and submerged flow conditions. Since those coefficients are not the same for all control structures, the transition submergence may vary from one structure to another. If the discharge coefficients are properly calibrated and the transition submergence carefully estimated, the continuity or more precisely the equality between discharges computed from the submerged and free flow equations at the submergence point would no longer be a concern. Depending on the values assigned to the discharge coefficients C and C_s, equations (5) and (6) above may not have positive real roots.

c. Dr. Leslie Wedderburn
Robb Startzman
Brian Turcotte