Determining Discharge-Coefficient Ratings for Selected Coastal Control Structures in Broward and Palm Beach Counties, Florida

By Gina M. Tillis *and* Eric D. Swain

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BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY

Thomas J. Casadevall, Acting Director

For additional information write to:

District Chief
U.S. Geological Survey
Suite 3015
227 North Bronough St.
Tallahassee, FL 32301

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Abstract

Discharges through 10 selected coastal control structures in Broward and Palm Beach Counties, Florida, are presently computed using the theoretical discharge-coefficient ratings developed from scale modeling, theoretical discharge coefficients, and some field calibrations whose accuracies for specific sites are unknown. To achieve more accurate discharge-coefficient ratings for the coastal control structures, field discharge measurements were taken with an Acoustic Doppler Current Profiler at the coastal control structures under a variety of flow conditions. These measurements were used to determine computed discharge-coefficient ratings for the coastal control structures under different flow regimes: submerged orifice flow, submerged weir flow, free orifice flow, and free weir flow.

Theoretical and computed discharge-coefficient ratings for submerged orifice and weir flows were determined at seven coastal control structures, and discharge ratings for free orifice and weir flows were determined at three coastal control structures. The difference between the theoretical and computed discharge-coefficient ratings varied from structure to structure. The theoretical and computed discharge-coefficient ratings for submerged orifice flow were within 10 percent at four of seven coastal control structures; however, differences greater than 20 percent were found at two of the seven structures. The theoretical and computed discharge-coefficient ratings for submerged weir flow were within 10 percent at three of seven coastal control structures; however, differences greater than 20 percent were found at four of the seven coastal control structures. The difference between theoretical and computed discharge-coefficient ratings for free orifice and free weir flows ranged from 5 to 32 percent. Some differences between the theoretical and computed discharge-coefficient ratings could be better defined with more data collected over a greater distribution of measuring conditions.

INTRODUCTION

The hydrologic system of southern Florida has been extensively altered by man. A system of canals and levees (fig. 1) has been constructed over the last century for the purpose of draining the wetlands and for flood control. Strategically placed control structures allow water-management operators to drain water during high runoff periods and to retain water during the dry periods. Starting in the 1920's, water issues other than flood control became prominent in southern Florida. These issues included the effects of lowered ground- and surface-water levels caused by over-drainage, droughts, frequent dry-season fires in the wetlands, and saltwater intrusion in coastal areas. To address these concerns, hydraulic control structures were added to the system, regulating flows through the system to the east coast. By the late 1960's, most of the complex system of canals, levees, pump stations, and salinity-control structures was completed. Although the system has made southern Florida more suitable for urbanization and agriculture, water-management problems associated with periodic droughts, saltwater intrusion, and such continue to persist.

One of the major factors driving the development of southern Florida water controls is the need to maintain adequate water supplies to support the rapid population growth along the lower east coast. In 1990, the total population of Broward County and Palm Beach County was 1,255,488 and 863,518, respectively (University of Florida, 1991).

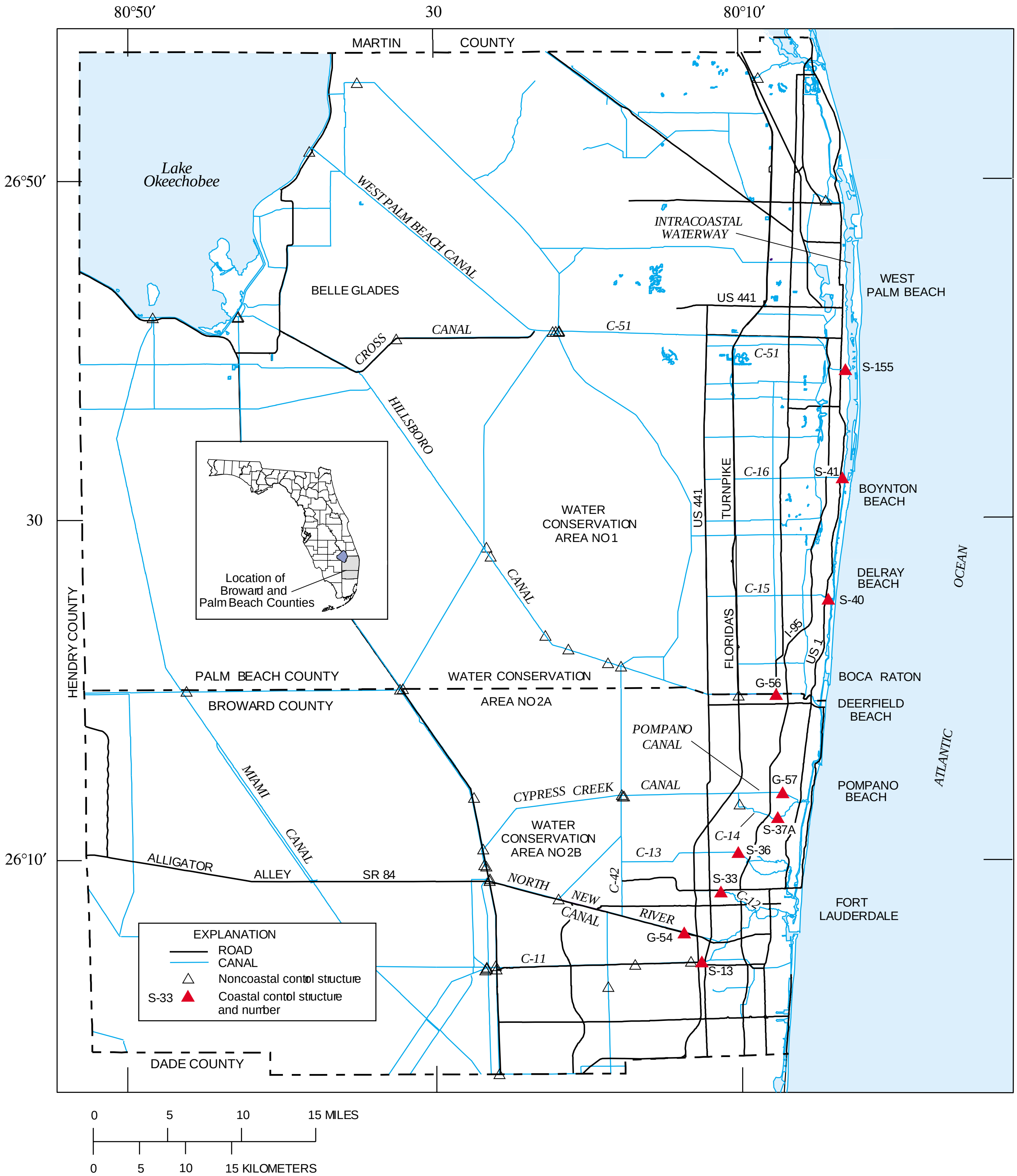

Figure 1. Location of coastal control structures in eastern Broward and Palm Beach Counties.

The largest amount of fresh ground water and surface water withdrawn in all of Florida was in Palm Beach County at a rate of 997 Mgal/d (million gallons per day). Broward County was one of the largest consumers of fresh ground water withdrawn at a rate of 245 Mgal/d (Marella, 1992).

Ground-water withdrawals from the Biscayne aquifer for public supply are threatened by saltwater intrusion induced by the lowering of inland ground-water levels. The use of surface water to replace the aquifer losses means that less water is available for the wetland areas. The salinity-control structures along the coast in eastern Broward and eastern Palm Beach Counties (fig. 1), referred to herein as coastal control structures, are used to maintain higher water levels upstream to minimize saltwater intrusion. The higher surface-water levels induce higher ground-water levels, minimizing saltwater movement inland through the aquifer.

Excess stormwater is also drained through coastal control structures. These freshwater discharges not only affect the amount of water available to the wetland areas and for water supply in the lower east coast, but also adversely affect the biota in the Intracoastal Waterway (Browder and others, 1989).

Quantifying freshwater discharges to the east coast is an important component in computing accurate water budgets for the inland and wetland areas, calibrating and applying regional water-management models, and computing nutrient loadings to the Intracoastal Waterway and associated water bodies. In southeastern Florida, discharges through the coastal control structures are computed from manual readings of gate openings, stages, and application of theoretical discharge relations by the South Florida Water Management District (SFWMD) and the U.S. Army Corps of Engineers (USACE). In order to ensure that these data used to compute discharges are accurate, flow measurements must be used to calibrate the coastal control structures. This requires accurate measurements of discharges and data on structure operations and headwater and tailwater elevations (field measurements), which must be taken under a variety of conditions to encompass all the flow regimes occurring at each coastal control structure.

The U.S. Geological Survey (USGS), in cooperation with the SFWMD, began a study in 1994 to develop procedures for measuring freshwater flows and to determine discharge-coefficient ratings for selected coastal control structures in southeastern Florida. The study was done as part of the South Florida Ecosystem Program, which is a collaborative effort by the USGS, various other Federal, State, and local agencies, and Indian Tribes to provide earth science information needed to resolve land-use and water issues in southern Florida. Two reports were generated for this study, one for Dade County (Swain and others, 1997) and the other for Broward and Palm Beach Counties (this report). Ongoing efforts are underway by the SFWMD to develop computed discharge-coefficient ratings (at other coastal control structures) similar to the ones presented in this report.

Purpose and Scope

The purpose of this report is to present procedures for determining more accurate discharge-coefficient ratings for selected coastal control structures in Broward and Palm Beach Counties than those which presently exist. Discharges through most of the coastal control structures in southeastern Florida are presently determined by theoretical discharge-coefficient ratings developed from scale modeling, theoretical discharge coefficients, and some field calibrations whose accuracies for specific sites are unknown.

Discharge measurements were taken using an Acoustic Doppler Current Profiler (ADCP) at 10 coastal control structures in Broward and Palm Beach Counties under varying flow conditions – submerged orifice flow, submerged weir flow, free orifice flow, and free weir flow. Field measurements were used to determine a computed discharge-coefficient rating for appropriate hydraulic equations at each site. Logarithmic and linear scale plots were constructed to compare computed and theoretical discharge-coefficient ratings (using flood discharge characteristics and structural data) for the coastal control structures. All concurrent water-level, gate opening, and discharge data were collated and analyzed using a spreadsheet program. A least squares regression analysis was made to determine the best estimate of the appropriate coefficients for the different flow regimes. Accuracy of the coefficient values was determined from the error in fit of the field data. Results of these analyses are presented herein.

Description of Coastal Control Structures

Discharge-coefficient ratings were determined at 10 coastal structures in Broward and Palm Beach Counties. Seven coastal control structures are located in eastern Broward County, and the remaining three are located in eastern Palm Beach County (fig. 1). Of the 10 coastal control structures, 9 are gated spillways and 1 is a combination gated spillway and pump station. The discharge rating type for each coastal control structure is given in table 1.

The northernmost coastal control structure (S-155) is a gated spillway on the C-51 canal (West Palm Beach Canal) as shown in figure 1. The C-51 canal, which is interconnected with the C-15 canal (Hidden Valley Canal) and the C-16 canal (Boynton Canal), drains an area of about 164 mi^2 (square miles). Construction on structure S-155 was completed in 1982. Management of this coastal control structure was transferred to the SFWMD on February 19, 1986.

Structure S-41 is a gated spillway on the C-16 canal (Boynton Canal) and is located south of structure S-155 and north of structure S-40 (fig. 1). The C-16 canal, which is interconnected with the C-15 canal (Hidden Valley Canal) and the C-51 canal (West Palm Beach Canal), drains an area of about 53 mi^2. Construction on structure S-41 began on April 15, 1963, and was completed on August 31, 1965. Management of this coastal control structure was transferred to the SFWMD on July 21, 1967.

Structure S-40 is a gated spillway on the C-15 canal (Hidden Valley Canal) and is located south of structure S-41 and north of structure G-56 (fig. 1). The C-15 canal, which is interconnected with the C-16 canal (Boynton Canal) and the C-51 canal (West Palm Beach Canal), drains an area of about 75 mi^2. Construction on structure S-40 began on March 26, 1963, and was completed on January 1, 1965. Management of this coastal control structure was transferred to the SFWMD on December 14, 1965.

Structure G-56 is a gated spillway on the Hillsboro Canal and is located south of structure S-40 and north of structure G-57 (fig. 1). The Hillsboro Canal, which drains an area of about 103 mi^2, was originally built as a drainage outlet from Lake Okeechobee. Structure G-56 (replacing Deerfield Lock at the same location) was constructed by the SFWMD in 1991 to control flows from the Hillsboro Canal and to regulate discharge to tidewater.

Structure G-57 is a gated spillway on the Pompano Canal and is located south of structure G-56 and north of structure S-37A (fig. 1). The Pompano Canal drains an area of about 7.2 mi^2. Construction on structure G-57 was completed in 1989. Management of this coastal control structure was transferred to the SFWMD on November 15, 1989.

Structure S-37A is a gated spillway on the C-14 canal (Cypress Creek Canal) and is located south of structure G-57 and north of structure S-36 (fig. 1). The C-14 canal drains a total area of about 59 mi^2 (25 mi^2 in the western part of the drainage basin and 34 mi^2 in the eastern part of the drainage basin). Construction on structure S-37A began on July 13, 1959, and was completed on July 18, 1961. Management of this coastal control structure was transferred to the SFWMD on August 9, 1961.

Structure S-36 is a gated spillway on the C-13 canal (Middle River Canal) and is located south of structure S-37A and north of structure S-33 (fig. 1). The C-13 canal drains a total area of about 39 mi^2 (30 mi^2 in the western part of the drainage basin and 9 mi^2 in the eastern part of the drainage basin). Construction on structure S-36 began on July 20, 1953, and was completed on October 29, 1954. Management of this coastal control structure was transferred to the SFWMD on November 1, 1954.

Table 1. Description of coastal control structures used in the study

[Structure locations are shown in figure 1. Structure type: FC, fixed-crest, gated spillway; GS, gated spillway; PS, pump station]

Structure number	Location	Structure type	Discharge rating type prior to study
G-54	Fort Lauderdale area; on the North New River Canal and about 1.5 miles west of Florida's Turnpike	FC	Theoretical
G-56	Deerfield Beach; near the mouth of the Hillsboro Canal and about halfway between Florida's Turnpike and U.S. Highway 1	FC	Theoretical
G-57	Pompano Beach; on the Pompano Canal and about 2 miles west of U.S. Highway 1	FC	Theoretical
S-13	Fort Lauderdale area; on the C-11 canal and about 0.5 mile east of Florida's Turnpike	GS/PS	Theoretical
S-33	Fort Lauderdale area; on the C-12 canal and about 1 mile east of Florida's Turnpike	GS	Theoretical
S-36	Fort Lauderdale area; on the C-13 canal and about 2 miles east of U.S. Highway 441	GS	Theoretical
S-37A	Fort Lauderdale area; on the C-14 canal and about 2 miles west of U.S. Highway 1	GS	Theoretical
S-40	South of Delray Beach; on the C-15 canal and about 500 feet east of U.S. Highway 1	GS	Theoretical
S-41	Boynton Beach; on the C-16 canal and about 200 feet east of U.S. Highway 1	GS	Theoretical
S-155	South of West Palm Beach; on the eastern end of the C-51 canal and about 400 feet east of U.S. Highway 1	GS	Discharge measurements made for calibration

Structure S-33 is a gated spillway on the C-12 canal (Plantation Canal) and is located south of structure S-36 and north of structure G-54 (fig. 1). The C-12 canal drains an area of about 19 mi^2. Structure S-33 generally passes a design discharge rate of about 620 ft^3/s (cubic feet per second), but will pass a design discharge rate of about 900 ft^3/s at slightly higher stages with the additional Plantation Drainage District pumps at the western end of the drainage basin. Construction on structure S-33 began on July 20, 1953, and was completed on October 29, 1954. Management of this coastal control structure was transferred to the SFWMD on November 1, 1954.

Structure G-54 is a gated spillway on the North New River Canal and is located south of structure S-33 and north of structure S-13 (fig. 1). The North New River Canal drains a total area of about 30 mi^2 (23 mi^2 in the western part of the drainage basin and 7 mi^2 in the eastern part of the drainage basin). Structure G-54 (replacing Sewell Lock at the same location) was constructed by the SFWMD in 1992 to control flow from the North New River Canal (which also conveys runoff from the C-42 canal) and to regulate discharge from Water Conservation Area No. 2B.

Structure S-13 is a gated spillway and pump station on the C-11 canal (South New River Canal) and is the southernmost coastal control structure in the study area (fig. 1). The C-11 canal drains a total area of about 104 mi^2 (81 mi^2 in the western part of the drainage basin and 23 mi^2 in the eastern part of the drainage basin). Construction on structure S-13 began on June 29, 1953, and was completed on November 23, 1954. Management of this coastal control structure was transferred to the SFWMD on November 1, 1954.

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METHODS OF INVESTIGATION

The subsequent sections describe the methods and procedures that were used in the development of discharge-coefficient rating equations for the four flow regimes (submerged orifice, submerged weir, free orifice, and free weir flows) and the field procedures used in collecting data at the coastal control structures in Broward and Palm Beach Counties. The first sections describe the procedures that were applied in rating gated spillways and pump stations under the different flow regimes. Diagrams of a typical gated spillway and a pump station are shown in figure 2. The latter sections describe the procedure for calculating percent standard errors for the flow regimes, the application of the ADCP and its advantages and disadvantages, and the procedures that were used in taking discharge measurements to determine the computed discharge-coefficient ratings for the coastal control structures. Methods and procedures used at these coastal control structures can be applied to other locations with similar hydrologic conditions.

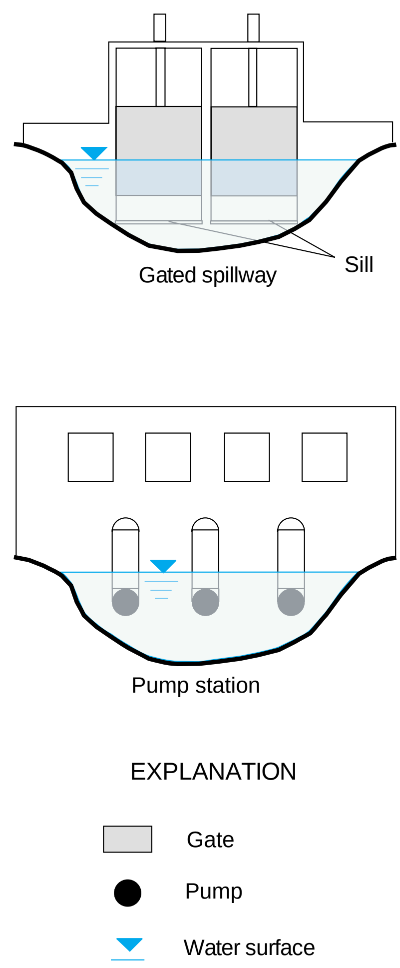

Figure 2. A typical gated spillway and a pump station.

Rating Development for Gated Spillways

During 1960-61, the USACE performed a study on a 1:16 scale physical model of a typical SFWMD gated coastal control structure (U.S. Army Corps of Engineers, 1963). The test results indicated that four possible flow regimes exist: submerged orifice flow, submerged weir flow, free orifice flow, and free weir flow (fig. 3). The USACE developed theoretical flow equations for the stage-discharge relations for the gated spillway coastal control structures under these regimes. In laboratory analyses, the USACE also determined experimental values for the discharge coefficients for the equations under these flow regimes, relating the coefficients and pertinent variables in plots (U.S. Army Corps of Engineers, 1963). Since then, the SFWMD has applied the USACE equations and calibrated them for each individual coastal control structure (Otero, 1994).

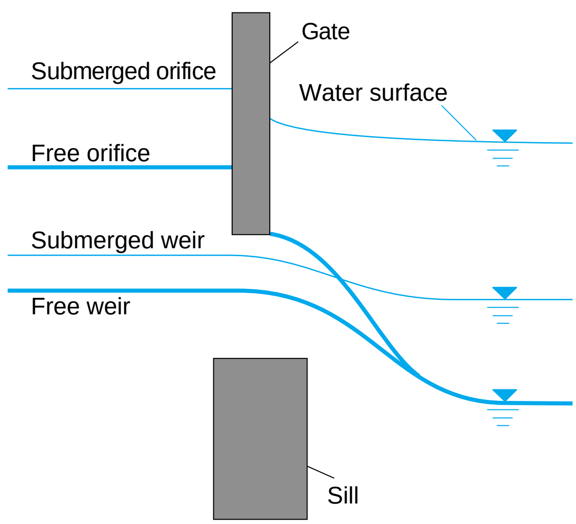

Figure 3. Flow regimes for a gated spillway.

Orifice-flow equations are used where flows are controlled by gates, and weir-flow equations are used where flows are not controlled by gates. Whether the flow is free or submerged depends on the downstream stage. Free flow occurs when the downstream stage is low enough relative to the sill that it does not affect flows through the coastal control structure. Free-orifice and free-weir flows are computed using only upstream water-surface elevations and physical characteristics of the orifice or weir. Submerged orifice and submerged weir flows are common at the coastal control structures. Free flow is more common at the northern coastal control structures because the sill elevations are high with respect to sea level.

The exact gate openings for the transition zone between orifice and weir flows are difficult to define. Collins (1977) considered submerged weir flow to exist if the gate opening were greater than two-thirds the height of the upstream water level over the gate sill. Otero (1994) considered a transition zone from gate openings three-fifths the upstream water level over the gate sill to a point where the gates were out of the water. This transition zone, which is neither orifice nor weir flow, was assumed to occur when the discharge coefficient no longer changed, in accordance with the orifice flow equation, with the gate opening. Weir flow is considered to be the flow regime when the flow is unaffected by the gate (U.S. Army Corps of Engineers, 1963; Collins, 1977).

Submerged Orifice-Flow Equation

Submerged orifice flow is expressed by the equation (Collins, 1977):

$$Q = C_{gs} L h \sqrt{2g(H-h)} \ , \qquad (1)$$

where Q is discharge, in cubic feet per second; C_{gs} is the discharge coefficient relative to the function of a gate opening and submergence; L is length of gate sill, in feet; g is acceleration of gravity, in feet per second per second; H is headwater height above sill, in feet; and h is tailwater height above sill, in feet. C_{gs} can be derived from field measurements by rearranging equation (1) as:

$$C_{gs} = \frac{Q}{Lh\sqrt{2g(H-h)}} \ . \qquad (2)$$

Because C_{gs} is considered to be both a function of gate opening and submergence, values of C_{gs} computed from field measurements are plotted against the dimensionless parameter h/G in a log-log plot and a linear scale plot, where G is the gate opening, in feet. The theoretical submerged orifice discharge coefficient most often used by the SFWMD is 0.75 times the inverse of h/G. A least squares regression analysis of available data points yields the rating curve, which is an estimate of the true relation. The sensitivity of the fit is inversely proportional to available data points.

Submerged Weir-Flow Equation

Submerged weir flow is expressed by the equation (U.S. Army Corps of Engineers, 1963):

$$Q = C_{ws}Lh\sqrt{2g(H-h)}\ , \quad (3)$$

which can be rearranged in the form:

$$\frac{Q}{Lh\sqrt{2g}} = C_{ws}\sqrt{H-h}\,, \quad (4)$$

where C_{ws} is a discharge coefficient for submerged weir flow. C_{gs} should approach C_{ws} as the gate opening approaches submerged weir flow conditions.

The standard USGS method for describing submerged weir flow is (Collins, 1977):

$$Q = C_s C_w LH\sqrt{H}\,, \quad (5)$$

which can be rearranged in the form:

$$\frac{Q}{LH} = C_s C_w\sqrt{H}\,, \quad (6)$$

where C_s is a submergence coefficient relative to the function of *h/H*, and C_w is the discharge coefficient for free weir flow. Equations (4) and (6) were applied to the field data that were collected by the ADCP. Although equations (4) and (6) adequately fit the range of field data, an attempt to extrapolate equation (6) to lower *h/H* values yielded unacceptable results because the equation is highly nonlinear. Thus, it was decided that equation (4) would be used to express submerged weir flow. The dependent and independent axes correspond to the left and right sides, respectively, of equation (4) with a slope of C_{ws}. The median C_{ws} currently used by the SFWMD is 0.9.

Free Orifice-Flow Equation

Free orifice flow is expressed by the equation (Otero, 1994):

$$Q = C_g LG\sqrt{2g(H-0.5G)}\ , \quad (7)$$

which can be rearranged in the form:

$$\frac{Q}{LG\sqrt{2g}} = C_g\sqrt{H-0.5G}\,, \quad (8)$$

where C_g, a discharge coefficient for free orifice flow, is a function of *G* and *H*.

Because C_g is considered to be a function of headwater and gate openings, values of:

$$\frac{Q}{LG\sqrt{2g}}$$

computed from field measurements are plotted against $\sqrt{H-0.5G}$ as presented in equation (8). A regression of these data points results in a linear fit having a slope of C_g. The sensitivity of the fit is inversely proportional to available data points. The existing theoretical free orifice coefficient is 0.75. The range of gate openings used to determine the computed free orifice discharge coefficient C_g varied from about 1 to 4 ft (feet).

Free Weir-Flow Equation

Free weir flow is expressed by the equation (U.S. Army Corps of Engineers, 1963; Collins, 1977):

$$Q = CLH^{1.5}\,, \quad (9)$$

where neither the gate nor the tailwater pool restricts the flow.

To be consistent with the coefficients for the other flow regimes where the $\sqrt{2g}$ term is external to the coefficient, equation (9) was manipulated to the following form:

$$\frac{Q}{LH\sqrt{2g}} = C_w\sqrt{H}\,, \quad (10)$$

where C_w is equal to:

$$\frac{C}{\sqrt{2g}}\,.$$

The discharge coefficient for free weir flow, C_w, is assumed to be a constant in this study. The dependent and independent axes of the linear scale plot are the left and right sides, respectively, of equation (10) with a slope of C_w. The existing theoretical free weir coefficient, C_w, is 0.361.

Rating Development for Pump Stations

At a pump station, water can be pumped from a lower stage to a higher stage. Most of the pump stations in southern Florida were built by the USACE, which developed pump curves that approximate the performance of the pumps. The SFWMD is in the process of recalibrating the ratings with additional discharge measurements. A third-order two-variable polynomial discharge equation was used to rate pump station S-13 (Draper and Smith, 1966):

$$Q = C_0 + C_1X + C_2Y + C_3X^2 + C_4XY + C_5Y^2 + C_6X^3 + C_7YX^2 + C_8XY^2 + C_9Y^3 \quad , \quad (11)$$

where C_0 to C_9 are pump coefficients (table 2), X is a dimensionless head parameter (H/H_{fact} in which H is the head value, in feet, and H_{fact} is the head factor), and Y is the dimensionless engine speed parameter. $Y = (N - N_{min})/N_{fact}$ where N is engine speed in revolutions per minute, N_{min} is minium speed to move water, N_{fact} is the engine speed factor ($N_{max} – N_{min}$), and N_{max} is maximum engine speed. Coefficients C_0 to C_9 were determined by solving simultaneous linear equations. The Gauss-Jordan method was chosen because the solution results in an identity matrix rather than a triangular matrix, which makes back-substitution to obtain the solution unnecessary.

The head and engine speed parameters are the dimensionless normalized values. They are normalized by subtracting the minimum value possible and dividing by the difference between the maximum and minimum values possible. By normalizing, the domain of the head and engine speed parameters is from zero to one. In this way, the use of large values for head and engine speed is avoided, the magnitude of each coefficient ranging from C_0 to C_9 is minimized, and the handling of the two-variable polynomial is simplified. The dimensionless head parameter, X, is obtained by dividing the head value, H, by the head factor, H_{fact}. For example, the maximum possible head, H_{fact}, at pump station S-13 is 9 ft. For an H of 5 ft, X is 5/9 = 0.556. To obtain the dimensionless 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}, the maximum engine speed minus the minimum engine speed. For example, N_{max} and N_{min} at pump station S-13 are 1,200 and 300 r/min (revolutions per minute), respectively, and N_{fact} is 1,200 – 300 = 900 r/min. For an N of 1,050 r/min, Y is (1,050 – 300)/900 = 0.833.

Calculating Percentage Standard Errors for the Flow Regimes

The percentage standard errors for the submerged orifice flow regime were derived using the parameter conversion from a log to a normal distribution. The normal standard error as a percentage can be calculated as follows:

$$\text{Upper } \sigma_n = (10^{+\sigma L} - 1) \times 100 \text{ percent,}$$

and

$$\text{Lower } \sigma_n = (10^{-\sigma L} - 1) \times 100 \text{ percent,}$$

where σ_n is the normal standard error as a percentage, and σ_L is the log base 10 standard error. As for the submerged weir, free orifice, and free weir flow regimes, the calculated standard deviations of residuals (SDR) can be calculated as follows:

$$SDR = \frac{STD(C_i - C_{eq})}{C_{eq}} \times 100 \text{ percent} \ ,$$

where C_i is the flow coefficient computed from the field data, and C_{eq} is the flow coefficient computed from the regression equations.

Table 2. Pump coefficient values

[Values for equation 11 are in text]

Pump coefficient	Value
C_0	0
C_1	4E+08
C_2	-4E+08
C_3	2E+08
C_4	-1E+09
C_5	1E+09
C_6	5E+07
C_7	-4E+08
C_8	1E+09
C_9	-1E+09

Acoustic Doppler Current Profiler Techniques

Existing discharge ratings using theoretical coefficients are based on varying flow regimes through idealized control structures (the 1:16 scale physical USACE model) of the same proportions as the field structures. This physical model does not take into account variations and peculiarities in the varying flow regimes of the field structures. To properly estimate discharge coefficients in equations (2), (4), (8), and (10), field measurements of varying flow regimes must be taken simultaneously as water elevations and structure operations are recorded. The use of an ADCP is ideal for taking these measurements.

Measuring discharge near coastal control structures can be a difficult process. Very slow velocities, 0.2 ft/s (foot per second) or less, can occur especially when the canal is significantly wider than the flow-way of the coastal control structure. Additionally, the spatial distribution of velocities can have a wide variation near a coastal control structure because the flow through the structure disrupts the normal flow pattern in the canal. The ADCP is capable of accurately measuring flows as slow as 0.2 ft/s and is ideal for taking reliable measurements under these conditions.

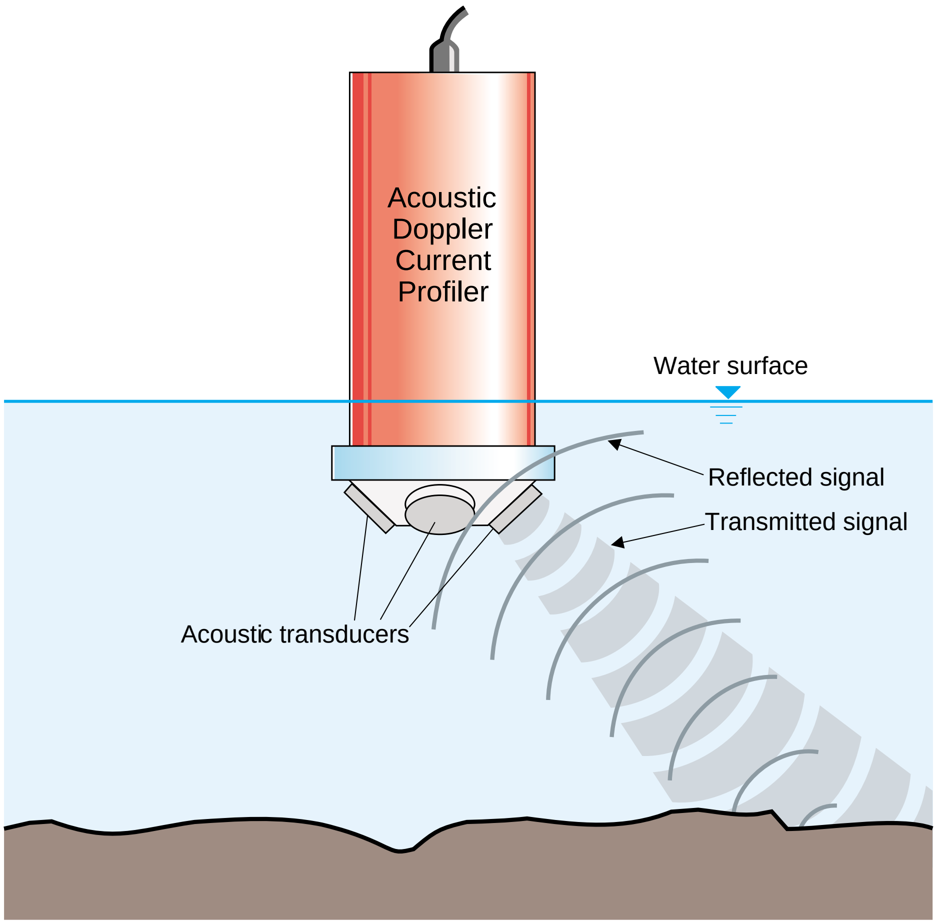

Figure 4. Signal paths of an Acoustic Doppler Current Profiler.

The ADCP uses the Doppler shift in reflected acoustic signals to determine the velocity of moving water (RD Instruments, 1989). A schematic of the acoustic transducers and the transmitted and reflected signals is shown in figure 4. The ADCP can locate the vertical position where the measured velocities occurred by the travel times of the transmitted and received signals (Simpson and Oltmann, 1991) and integrate them to find a vertically average velocity. Additionally, the Doppler shift in the signal reflected from the canal bottom is used to determine the speed and direction of boat movement. Velocity measurements can be taken from a moving boat because the ADCP automatically subtracts the boat velocity from the total measured velocity. Total discharge and direction of flow are computed from data collected with the ADCP and by the ADCP computation software. For these reasons, the ADCP was used for measuring flow at the coastal control structures in Broward and Palm Beach Counties.

Discharge measurements using an ADCP can generally be taken within 5 to 10 min (minutes), which represents a considerable reduction in the time required using the Price current meter (a mechanical point velocity meter). The ADCP allows for the more accurate collection of data in the dynamic conditions that were encountered in this study (for example, a discharge measurement could be taken before water levels changed substantially). Another advantage of the ADCP over the Price current meter is that ADCP data are collected on a continuum in the water column and cross section rather than at discrete points (Lipscomb, 1995).

One disadvantage of the older (narrowband) ADCP system is that it requires a minimum profiling depth of about 11.5 ft (Simpson and Oltmann, 1991). However, neither ADCP system (broadband nor narrowband) allows velocity-profile data to be collected very close to the banks or edges of a channel. The ADCP software uses an algorithm for estimating discharges in the shallow regions that cannot be measured (Simpson and Oltmann, 1991).

Field Protocol

Discharge measurements at five of the coastal control structure sites were taken simultaneously using two ADCP instruments (USGS and SFWMD). Access to all the sites was made upstream, using a small jonboat. A typical monitoring setup is shown at structure S-155 on the C-51 canal (West Palm Beach Canal) in figure 5. The boat used at this site is positioned upstream of the coastal control structure. The ADCP is mounted on the bow of a boat, which is pointed into the direction of flow. A tagline is stretched across the canal, and the boat is pulled by hand slowly across the water during the measurement process. The blockhouse at the coastal control structure contains the upstream and downstream stage recorders. Stages and gate openings were recorded at the beginning and end of every measurement. The gate operations for the coastal control structure are controlled from the blockhouse. Although most gate openings at the structures are controlled by telemetry, manual control can be made from the blockhouse.

Discharge measurements were taken under a variety of flow conditions at each coastal control structure. In coordination with the SFWMD, discharge measurements were scheduled (table 3) depending on the hydrologic activity (drought or flood conditions), which determined allowable gate operations. When sufficient water was available for release, the SFWMD implemented various gate openings to provide a variety of flow conditions for the discharge measurements.

Figure 5. Typical field setup for an Acoustic Doppler Current Profiler (ADCP) measurement of streamflow for structure S-15 on the C-51 canal.

DETERMINATION OF DISCHARGE-COEFFICIENT RATINGS FOR COASTAL CONTROL STRUCTURES

Discharge-coefficient ratings were determined for 10 selected coastal control structures in Broward and Palm Beach Counties, and the results are presented herein. All of the coastal control structures presented in this report regulate the total surface-water flows to the Intracoastal Waterway and associated water bodies (fig. 1). Developing accurate discharge-coefficient ratings for these coastal control structures is vital to determining the effects of these flows on nearshore areas of the Atlantic coast and determining the net loss of water from Broward and Palm Beach Counties.

Flood discharge characteristics for each coastal control structure are presented in appendix I, and structural data for each coastal control structure are presented in appendix II. Also discussed in appendix I (and on the accompanying pages) is the degree of protection from the standard project storm; that is, the most severe storm or sequence of storms considered reasonably characteristic of southeastern Florida, in terms of standard project flood (SPF). The U.S. Army Corps of Engineers (1995) defines the SPF rainfall as the 100-year storm values increased by 25 percent. The primary purpose of the canals and coastal control structures is to provide for satisfactory removal of a specific percentage of the SPF.

Table 3. Dates and number of Acoustic Doppler Current Profiler measurements taken at coastal control structures

[ADCP, Acoustic Doppler Current Profiler]

Structure	Dates of measurement	No. of ADCP's employed
G-54	06-24-96 06-25-96	1 1
G-56	06-26-96 09-12-96	2 1
G-57	03-19-96	1
S-13	11-01-95 06-25-96 09-10-96 09-12-96 10-07-96	1 1 2 1 1
S-33	10-09-96	1
S-36	10-31-95	1
S-37A	03-20-96	1
S-40	06-27-96 09-10-96	2 2
S-41	09-12-96	2
S-155	09-13-96	2

Structure S-155

Structure S-155 (fig. 6) is a reinforced-concrete gated spillway with discharge controlled by three cable-operated, vertical lift gates. This coastal control structure is located south of West Palm Beach on the eastern end of the C-51 canal (West Palm Beach Canal) and is about 400 ft east of U.S. Highway 1 (fig. 1). Structure S-155 is one of three structures in this study (the other two being structures S-40 and S-41) that experiences free flow where flows are not dependent on the downstream (tailwater) water level. Structure S-155 maintains optimum water-control stages upstream in the C-51 canal and prevents saltwater intrusion during periods of high tide. Additionally, this coastal control structure passes the design flood (60 percent of the SPF) without exceeding upstream flood design stage criteria set by water managers and restricting downstream flood stages and discharge velocities to nondamaging levels. Appendix I presents flood discharge characteristics for structure S-155, and appendix II presents structural data for S-155.

The automatic controls on structure S-155 are actuated by the headwater elevation. When the headwater elevation increases to 8.3 ft, the gates begin to open and continue to open until the headwater elevation decreases to 8.0 ft (the gates become stationary). The gates begin to close when the headwater elevation decreases to 7.8 ft. To provide room for the anticipated runoff resulting during times of heavy storm activity, the automatic operation is switched to a lower range of values from 7.5 to 7.0 ft, with the midpoint headwater elevation of 7.3 ft causing the gates to become stationary.

Two ADCP's were used to take measurements at structure S-155 on September 13, 1996 (table 3). One measurement section was about 300 ft upstream of the coastal control structure, and the other was about 400 ft upstream of the U.S. Highway 1 bridge (fig. 6). Data were collected with one gate opened at 1 and 2 ft. The other two gates remained closed for all measurements. These data (along with flow measurements taken from May 29, 1984, to September 14, 1993) were used to determine discharge-coefficient ratings for free orifice and free weir flows. Linear scale plots of the discharge-coefficient ratings for the free orifice- and free weir-flow regimes using data collected by the ADCP are shown in figure 7. A glossary of the mathematical symbols used in the linear scale plots is presented in appendix III. The SDR for the free orifice discharge coefficient is 12 percent, and the SDR for the free weir discharge coefficient is 7 percent. Using the difference in equation constants as a measure, the theoretical and computed free orifice ratings differ by 4.9 percent, and the theoretical and computed free weir ratings differ by 29.6 percent.

Figure 6. Location of structure S-155.

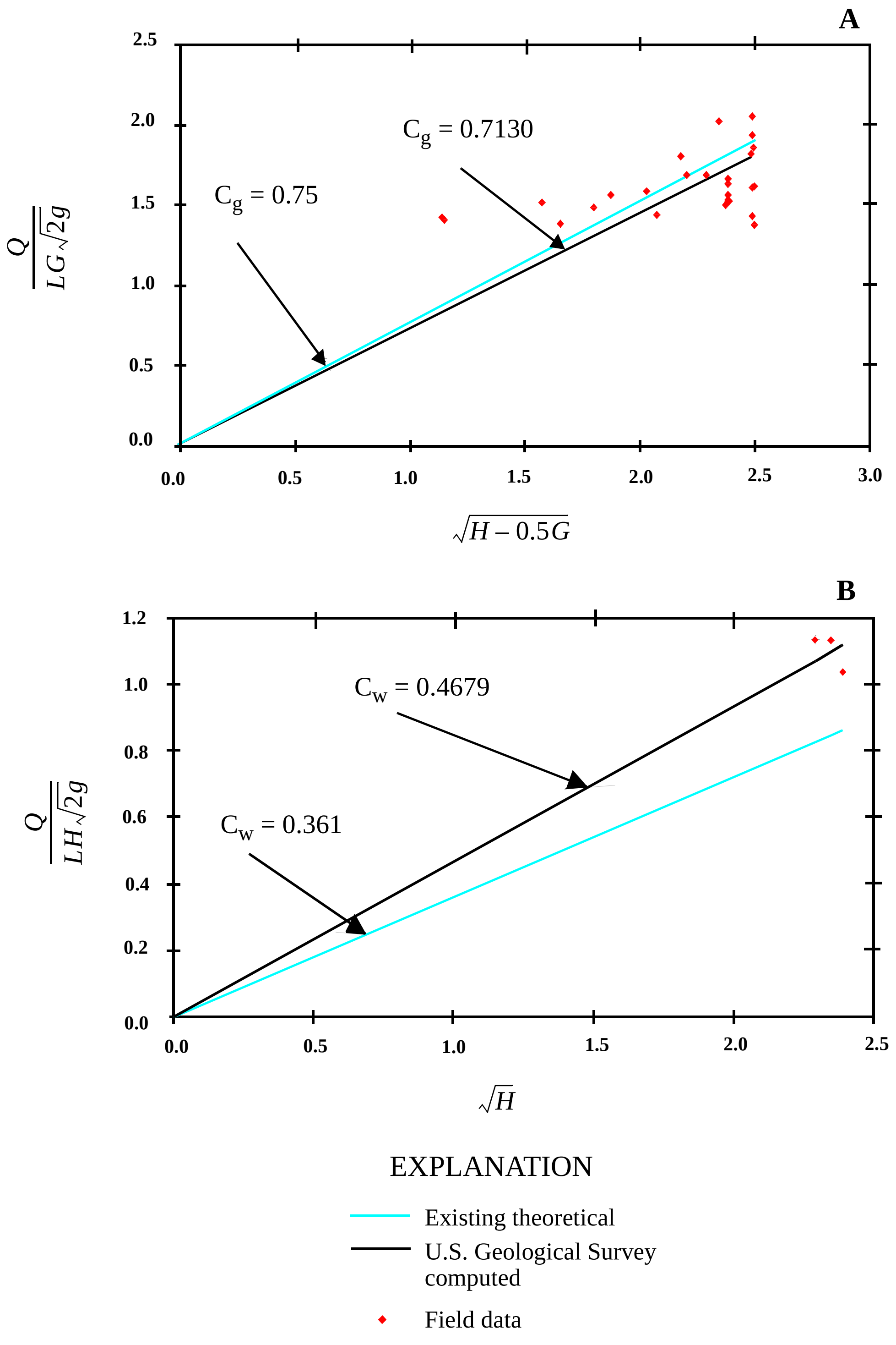

Figure 7. Linear scale plots of a comparison of the S-155 discharge coefficient for free orifice flow (graph A) and free weir flow (graph B). An explanation of the mathematical symbols is given in appendix III.

Structure S-41

Structure S-41 (fig. 8) is a reinforced-concrete gated spillway with discharge controlled by two cable-operated, vertical lift gates. This coastal control structure is located in Boynton Beach on the C-16 canal (Boynton Canal) and is about 200 ft east of U.S. Highway 1 (fig. 1). Structure S-41 is one of three structures in this study (the other two being structures S-40 and S-155) that experiences free flow where flows are not dependent on the downstream (tailwater) water level. Structure S-41 maintains optimum water-control stages upstream in the C-16 canal and prevents salt-water intrusion during periods of high tide. Additionally, this coastal control structure passes the design flood (60 percent of the SPF) without exceeding upstream flood design stage criteria set by water managers and restricting downstream flood stages and discharge velocities to nondamaging levels. Appendix I presents flood discharge characteristics for structure S-41, and appendix II presents structural data for S-41.

The automatic controls on structure S-41 are actuated by the headwater elevation. When the headwater elevation increases to 8.5 ft, the gates begin to open and continue to open until the headwater elevation decreases to 8.2 ft (the gates become stationary). The gates begin to close when the headwater elevation decreases to 7.9 ft. To provide room for the anticipated runoff resulting during times of heavy storm activity, the automatic operation is switched to a lower range of values from 8.0 to 7.3 ft, with the midpoint head-water elevation of 7.7 ft causing the gates to become stationary.

Two ADCP's were used to take measurements at structure S-41 on September 12, 1996 (table 3). One measurement section was about 60 ft upstream of the coastal control structure, and the other was about 80 ft upstream of the coastal control structure (fig. 8). Data were collected with both gates simultaneously opened at 0.8 ft. Data were also collected with one gate opened at 1.6, 2, and 4 ft and when the gate was completely out of the water, while the other gate remained closed for all measurements. Linear scale plots of the discharge-coefficient ratings for the free orifice- and free weir-flow regimes using data collected by the ADCP are shown in figure 9. A glossary of the mathematical symbols used in the linear scale plots is presented in appendix III. The SDR for the free orifice discharge coefficient is 9 percent, and the SDR for the free weir discharge coefficient is 5 percent. Using the difference in equation constants as a measure, the theoretical and computed free orifice ratings differ by 13.4 percent, and the theoretical and computed free weir ratings differ by 25.4 percent.

Figure 8. Location of structure S-41.

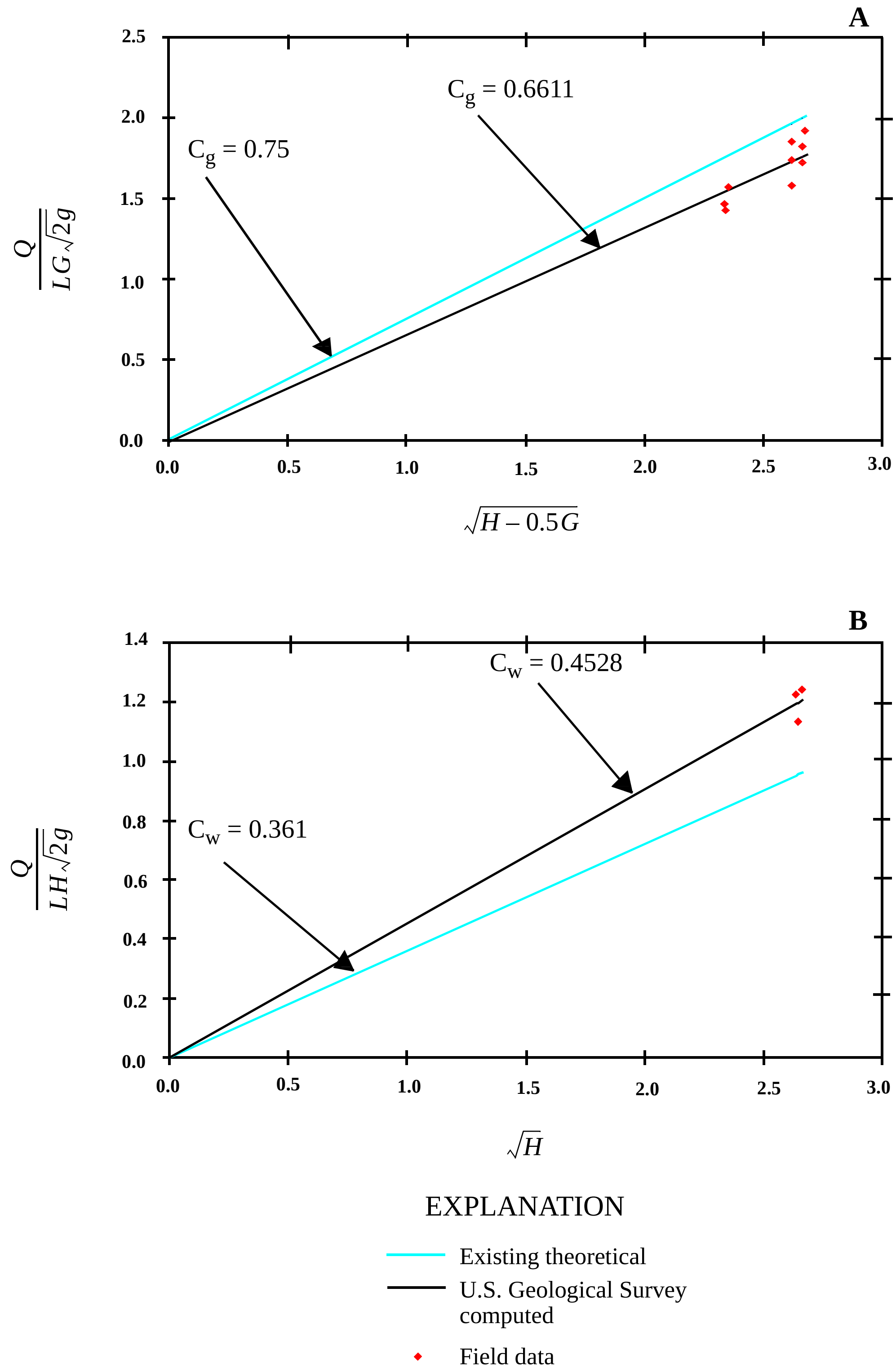

Figure 9. Linear scale plots of a comparison of the S-41 discharge coefficient for free orifice flow (graph A) and free weir flow (graph B). An explanation of the mathematical symbols is given in appendix III.

Structure S-40

Structure S-40 (fig. 10) is a reinforced-concrete gated spillway with discharge controlled by two cable-operated, vertical lift gates. This coastal control structure is located south of Delray Beach on the C-15 canal (Hidden Valley Canal) and is about 500 ft east of U.S. Highway 1 (fig. 1). Structure S-40 is one of three structures in this study (the other two being structures S-41 and S-155) that experiences free flow where flows are not dependent on the downstream (tailwater) water level. Structure S-40 maintains optimum water-control stages upstream in the C-15 canal and prevents saltwater intrusion during periods of high tide. Additionally, this coastal control structure passes the design flood (60 percent of the SPF) without exceeding upstream flood design stage criteria set by water managers and restricting downstream flood stages and discharge velocities to nondamaging levels. Appendix I presents flood discharge characteristics for structure S-40, and appendix II presents structural data for S-40.

The automatic controls on structure S-40 are actuated by the headwater elevation. When the headwater elevation increases to 8.5 ft, the gates begin to open and continue to open until the headwater elevation decreases to 8.2 ft (the gates become stationary). The gates begin to close when the headwater elevation decreases to 7.9 ft. To provide room for the anticipated runoff resulting during times of heavy storm activity, the automatic operation is switched to a lower range of values from 8.0 to 7.3 ft, with the midpoint headwater elevation of 7.7 ft causing the gates to become stationary.

Two ADCP's were used to take measurements at structure S-40 on June 27, 1996, and September 10, 1996 (table 3). All of the measurements were taken at the two measurement sections, 200 and 300 ft upstream of the coastal control structure, as shown in figure 10. On June 27, 1996, data were collected with one gate opened at 1, 2, and 4 ft and when the gate was completely out of the water. The same gate was completely out of the water for data collected on September 10, 1996. The other gate remained closed for all measurements. Linear scale plots of the discharge-coefficient ratings for the free orifice- and free weir-flow regimes using data collected by the ADCP are shown in figure 11. A glossary of the mathematical symbols used in the linear scale plots is presented in appendix III. The SDR is 5 percent for both the free orifice and free weir discharge coefficients. Using the difference in equation constants as a measure, the theoretical and computed free orifice ratings differ by 31.8 percent, and the theoretical and computed free weir ratings differ by 17.1 percent.

Figure 10. Location of structure S-40.

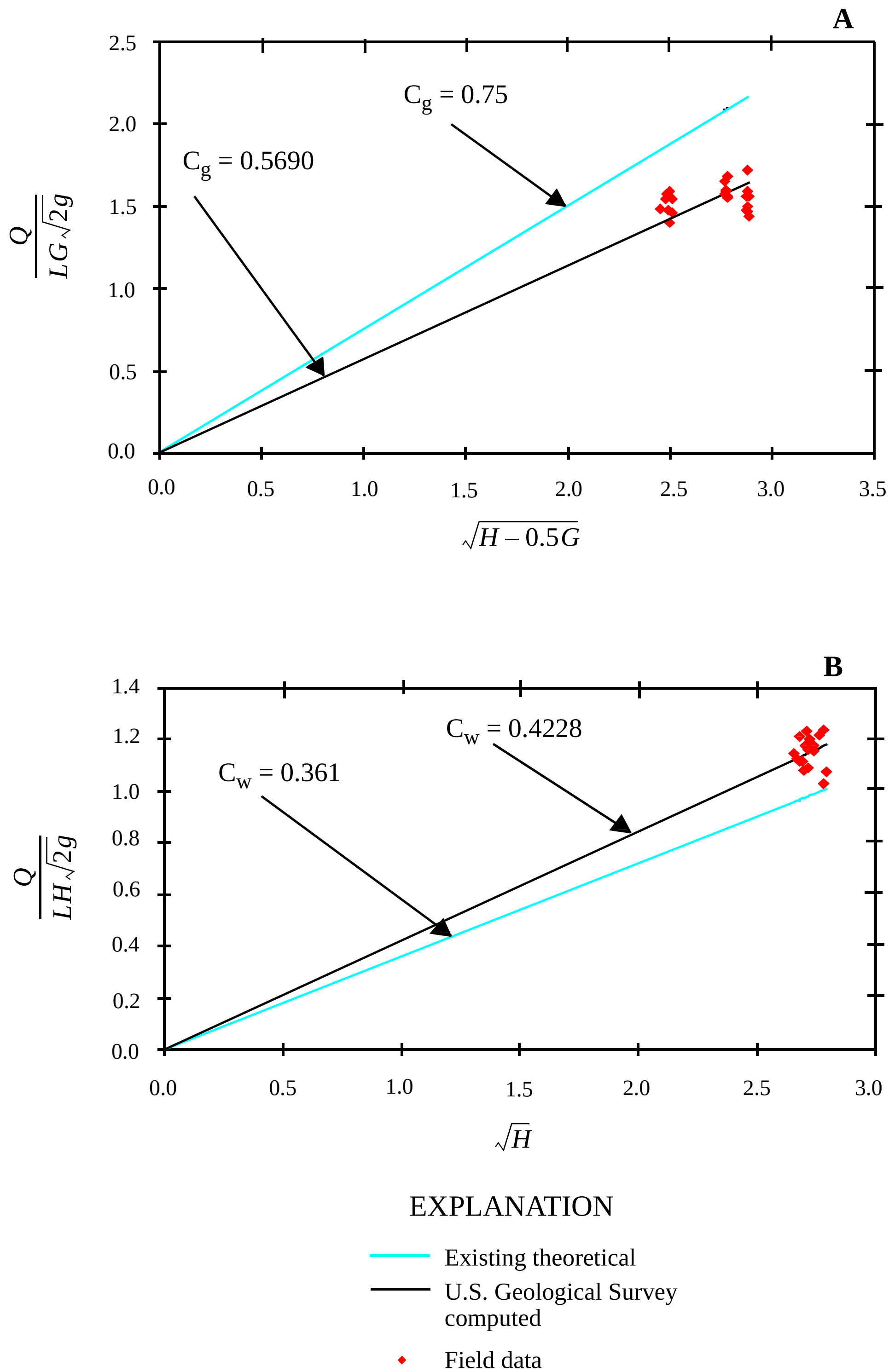

Figure 11. Linear scale plots of a comparison of the S-40 discharge coefficient for free orifice flow (graph A) and free weir flow (graph B). An explanation of the mathematical symbols is given in appendix III.

Structure G-56

Structure G-56 (fig. 12) is a fixed-crest, reinforced-concrete gated spillway with discharge controlled by three cable-operated, vertical slide gates. This coastal control structure is located in Deerfield Beach near the mouth of the Hillsboro Canal and is about halfway between Florida's Turnpike and U.S. Highway 1 (fig. 1). The submerged orifice-flow and submerged weir-flow regimes exist at this site. Structure G-56 maintains optimum water-control stages upstream in the Hillsboro Canal and prevents salt-water intrusion during periods of high tide. Additionally, this coastal control structure passes the design flood (60 percent of the SPF) without exceeding upstream flood design stage criteria set by water managers and restricting downstream flood stages and discharge velocities to nondamaging levels. Appendix I presents flood discharge characteristics for structure G-56, and appendix II presents structural data for G-56.

The automatic controls on structure G-56 are actuated by the headwater elevation. When the headwater elevation increases to 8.0 ft, the gates begin to open and continue to open until the headwater elevation decreases to 7.5 ft (the gates become stationary). The gates begin to close when the headwater elevation decreases to 7.0 ft. During dry periods, the automatic operation is switched to a higher range of values from 8.3 to 8.7 ft, with the midpoint headwater elevation of 8.5 ft causing the gates to become stationary.

Two ADCP's were used to take measurements at structure G-56 on June 26, 1996, and one ADCP was used to take measurements on September 12, 1996 (table 3). One measurement section was about 300 ft upstream of the coastal control structure, and the other was about 400 ft upstream of the coastal control structure (fig. 12). On June 26, 1996, data were collected with one gate opened at 1, 2, and 4 ft. The same gate was completely out of the water for data collected on September 12, 1996. The other two gates remained closed for all measurements. Logarithmic and linear scale plots of the discharge-coefficient ratings for the submerged orifice- and submerged weir-flow regimes using data collected by the ADCP are shown in figure 13.
A glossary of the mathematical symbols used in the logarithmic and linear scale plots is presented in appendix III. The range of percent standard error for the submerged orifice discharge coefficient is 5 to -5 percent, and the SDR for the submerged weir discharge coefficient is 13 percent. The coefficient of determination for the submerged orifice discharge coefficient is 0.9881. Using the difference in equation constants as a measure, the theoretical and computed submerged orifice ratings differ by 2.2 percent, and the theoretical and computed submerged weir ratings differ by 28.9 percent.

Figure 12. Location of structure G-56.

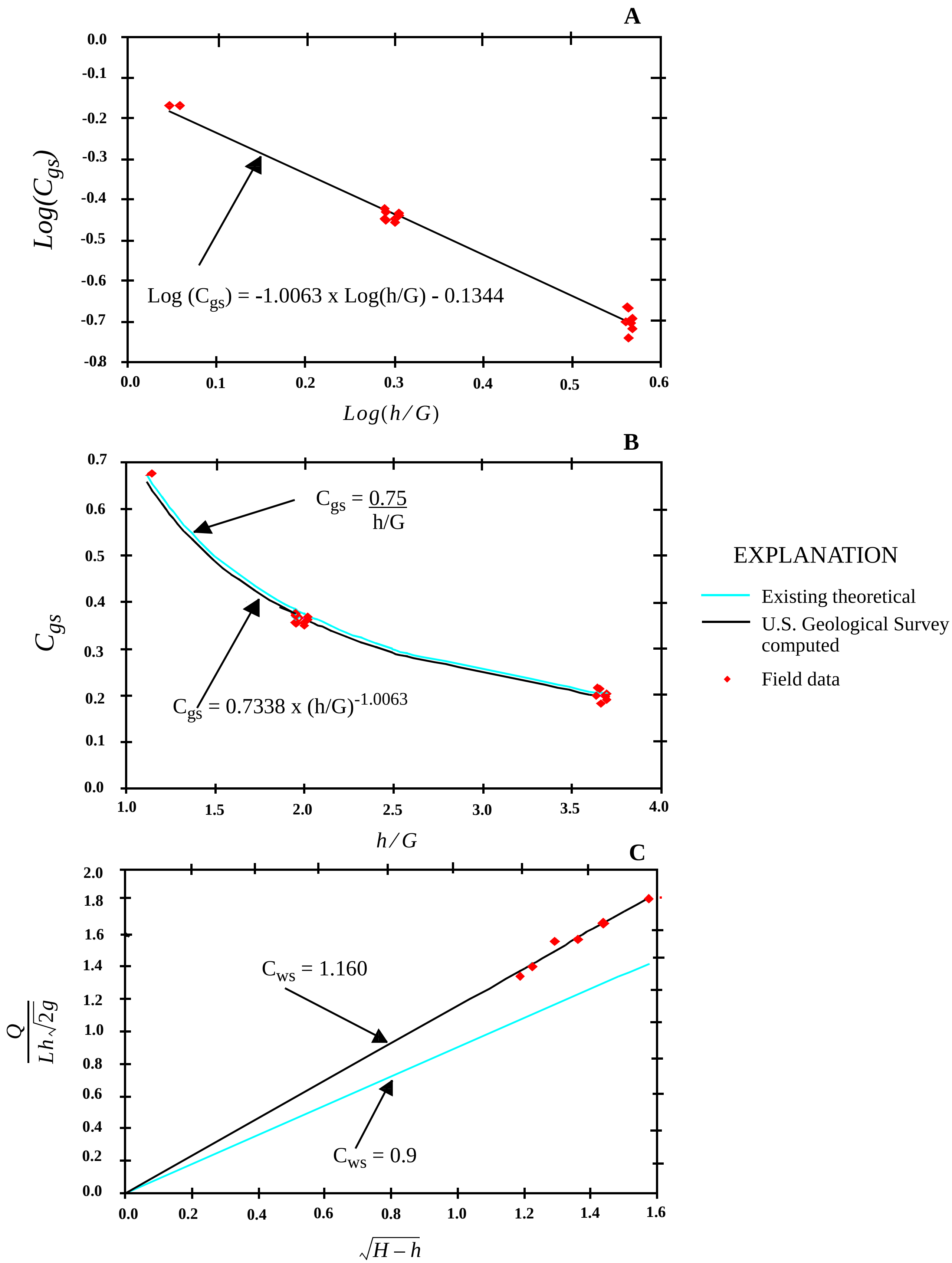

Figure 13. Logarithmic plot of the G-56 discharge coefficient for submerged orifice flow (graph A) and linear scale plots of a comparison of the G-56 discharge coefficient for submerged orifice flow (graph B) and submerged weir flow (graph C). An explanation of the mathematical symbols is given in appendix III.

Structure G-57

Structure G-57 (fig. 14) is a fixed-crest, reinforced-concrete gated spillway with discharge controlled by two cable-operated, vertical lift gates. This coastal control structure is located in Pompano Beach on the Pompano Canal and is about 2 mi west of U.S. Highway 1 (fig. 1). The submerged orifice-flow and submerged weir-flow regimes exist at this site. Structure G-57 maintains optimum water-control stages upstream in the Pompano Canal and prevents saltwater intrusion during periods of high tide. Additionally, this coastal control structure passes the design flood discharge rate of 375 ft^3/s without exceeding upstream flood design stage criteria set by water managers and restricting downstream flood stages and discharge velocities to nondamaging levels. Appendix I presents flood discharge characteristics for structure G-57, and appendix II presents structural data for G-57.

The automatic controls on structure G-57 are actuated by the headwater elevation. When the headwater elevation increases to 4.8 ft, the gates begin to open and continue to open until the headwater elevation decreases to 4.6 ft (the gates become stationary). The gates begin to close when the headwater elevation decreases to 4.3 ft. The automatic controls on this coastal control structure have an overriding mechanism that closes the gates, regardless of the upstream water level in the event of high tide, when the differential between the falling headwater and rising tailwater pool elevations reaches 0.2 ft.

An ADCP was used to take measurements at structure G-57 on March 19, 1996 (table 3). The measurement section (not shown in fig. 14) was about 1,000 ft upstream of the coastal control structure (upstream of the culvert which directed flows underground). Data were collected with one gate opened at 1 and 2 ft and when the gate was completely out of the water. The other gate remained closed for all measurements. Logarithmic and linear scale plots of the discharge-coefficient ratings for the submerged orifice- and submerged weir-flow regimes using data collected by the ADCP are shown in figure 15. A glossary of the mathematical symbols used in the logarithmic and linear scale plots is presented in appendix III. The range of percent standard error for the submerged orifice discharge coefficient is 31 to -24 percent, and the SDR for the submerged weir discharge coefficient is 34 percent. The coefficient of determination for the submerged orifice discharge coefficient is 0.4951. Using the difference in equation constants as a measure, the theoretical and computed submerged orifice ratings differ by 27.4 percent, and the theoretical and computed submerged weir ratings differ by 1.4 percent.

Figure 14. Location of structure G-57.

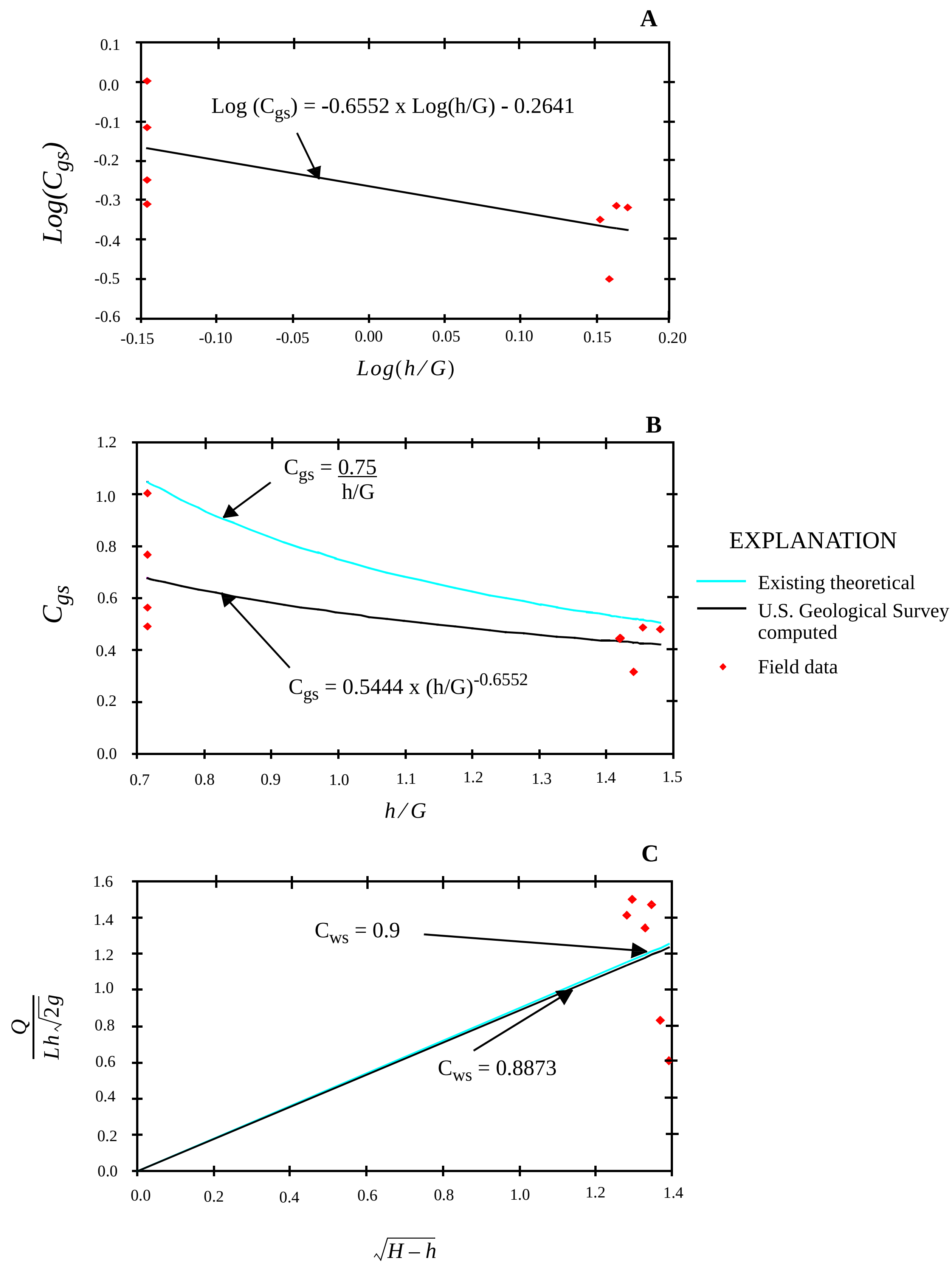

Figure 15. Logarithmic plot of the G-57 discharge coefficient for submerged orifice flow (graph A) and linear scale plots of a comparison of the G-57 discharge coefficient for submerged orifice flow (graph B) and submerged weir flow (graph C). An explanation of the mathematical symbols is given in appendix III.

Structure S-37A

Structure S-37A (fig. 16) is a reinforced-concrete gated spillway with discharge controlled by two cable-operated, vertical lift gates. This coastal control structure is located in the vicinity of Fort Lauderdale on the C-14 canal (Cypress Creek Canal) and is about 2 mi west of U.S. Highway 1 (fig. 1). The submerged orifice-flow and submerged weir-flow regimes exist at this site. Structure S-37A maintains optimum water-control stages upstream in the C-14 canal and prevents saltwater intrusion during periods of high tide. Additionally, this coastal control structure passes the design flood (100 percent of the SPF) without exceeding upstream flood design stage criteria set by water managers and restricting downstream flood stages and discharge velocities to nondamaging levels. Appendix I presents flood discharge characteristics for structure S-37A, and appendix II presents structural data for S-37A.

The automatic controls on structure S-37A are actuated by the headwater elevation. When the headwater elevation increases to 4.4 ft, the gates begin to open and continue to open until the headwater elevation decreases to 4.0 ft (the gates become stationary). The gates begin to close when the headwater elevation decreases to 3.0 ft. The automatic controls on this coastal control structure have an overriding mechanism that closes the gates, regardless of the upstream water level in the event of high tide, when the differential between the falling headwater and rising tailwater pool elevations reaches 0.2 ft.

An ADCP was used to take measurements at structure S-37A on March 20, 1996 (table 3). The measurement section was about 200 ft upstream of the coastal control structure as shown in figure 16. Data were collected with one gate opened at 1, 2, 2.5, 3, and 4 ft and when the gate was completely out of the water. The other gate remained closed for all measurements. Logarithmic and linear scale plots of the discharge-coefficient ratings for the submerged orifice- and submerged weir-flow regimes using data collected by the ADCP are shown in figure 17. A glossary of the mathematical symbols used in the logarithmic and linear scale plots is presented in appendix III. The range of percent standard error for the submerged orifice discharge coefficient is 10 to -9 percent, and the SDR for the submerged weir discharge coefficient is 3 percent. The coefficient of determination for the submerged orifice discharge coefficient is 0.9728. Using the difference in equation constants as a measure, the theoretical and computed orifice ratings differ by 7.2 percent and the theoretical and computed submerged weir ratings differ by 39.2 percent.

Figure 16. Location of structure 37A.

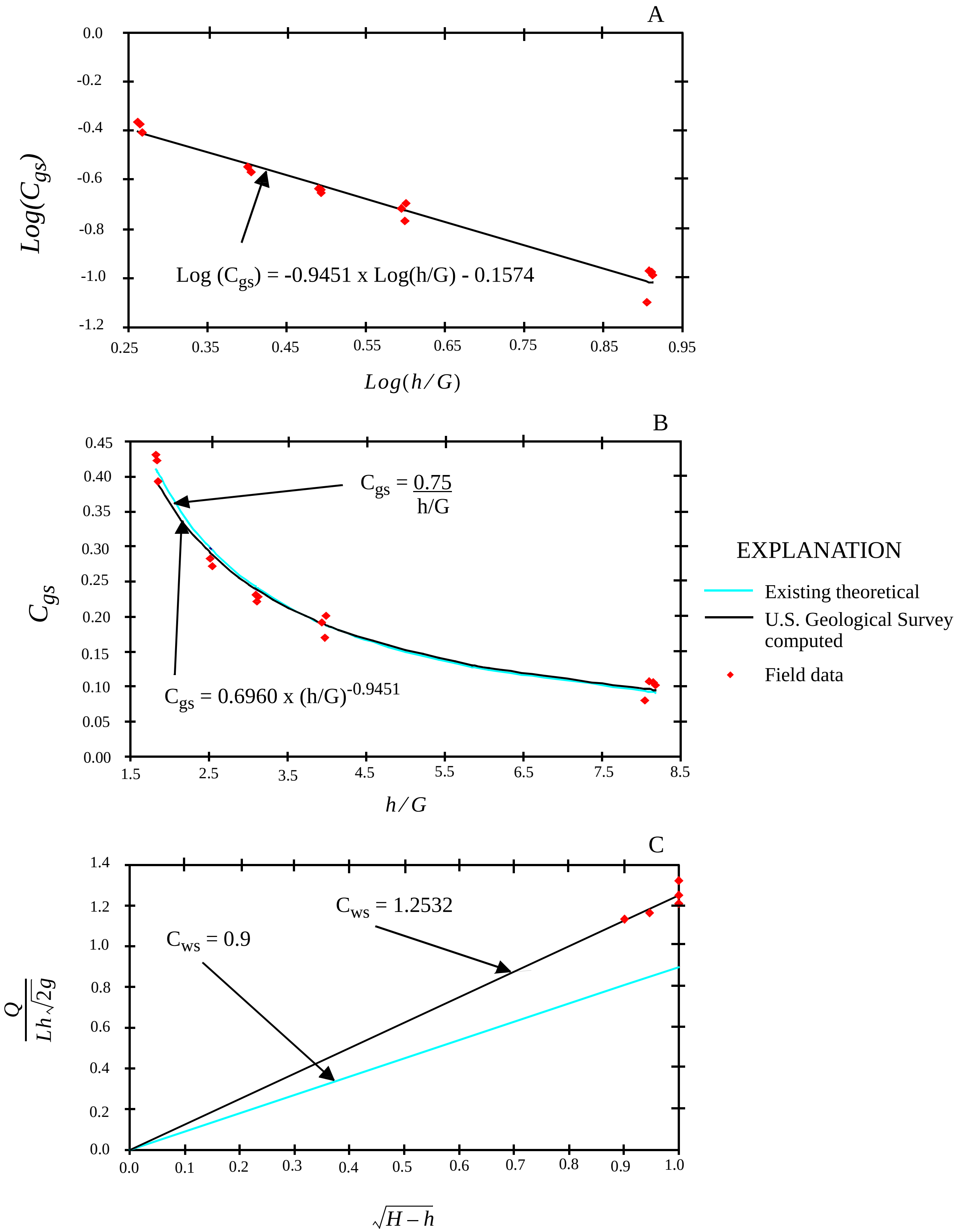

Figure 17. Logarithmic plot of the S-37A discharge coefficient for submerged orifice flow (graph A) and linear scale plots of a comparison of the S-37A discharge coefficient for submerged orifice flow (graph B) and submerged weir flow (graph C). An explanation of the mathematical symbols is given in appendix III.

Structure S-36

Structure S-36 (fig. 18) is a reinforced-concrete gated spillway with discharge controlled by one cable-operated, vertical slide gate. This coastal control structure is located in the vicinity of Fort Lauderdale on the C-13 canal (Middle River Canal) and is about 2 mi east of U.S. Highway 441 (fig. 1). The submerged orifice-flow and submerged weir-flow regimes exist at this site. Structure S-36 maintains optimum water-control stages upstream in the C-13 canal and prevents saltwater intrusion during periods of high tide. Additionally, this coastal control structure passes the design flood (50 percent of the SPF) without exceeding upstream flood design stage criteria set by water managers and restricting downstream flood stages and discharge velocities to nondamaging levels. Appendix I presents flood discharge characteristics for structure S-36, and appendix II presents structural data for S-36.

The automatic controls on structure S-36 are actuated by the headwater elevation. When the headwater elevation increases to 4.9 ft, the gate begins to open and continues to open until the headwater elevation decreases to 4.4 ft (the gate becomes stationary). The gate begins to close when the headwater elevation decreases to 4.0 ft. During times when little or no rainfall occurs (dry periods), the automatic operation is switched to a higher range of values from 4.2 to 5.5 ft, with the midpoint headwater elevation of 4.5 ft causing the gate to become stationary. The automatic controls on this coastal control structure have an overriding mechanism that closes the gate, regardless of the upstream water level in the event of high tide, when the differential between the falling headwater and rising tailwater pool elevations reaches 0.2 ft.

An ADCP was used to take measurements at structure S-36 on October 31, 1995 (table 3). The measurement section was about 50 ft upstream of the coastal control structure as shown in figure 18. Data were collected with the gate opened at 1, 2, 3, and 4 ft and when the gate was completely out of the water. Logarithmic and linear scale plots of the discharge-coefficient ratings for the submerged orifice- and submerged weir-flow regimes using data collected by the ADCP are shown in figure 19. A glossary of the mathematical symbols used in the logarithmic and linear scale plots is presented in appendix III. The range of percent standard error for the submerged orifice discharge coefficient is 8 to -8 percent, and the SDR for the submerged weir discharge coefficient is 8 percent. The coefficient of determination for the submerged orifice discharge coefficient is 0.9677. Using the difference in equation constants as a measure, the theoretical and computed submerged orifice ratings differ by 23.1 percent, and the theoretical and computed submerged weir ratings differ by 79.4 percent.

Figure 18. Location of structure S-36.

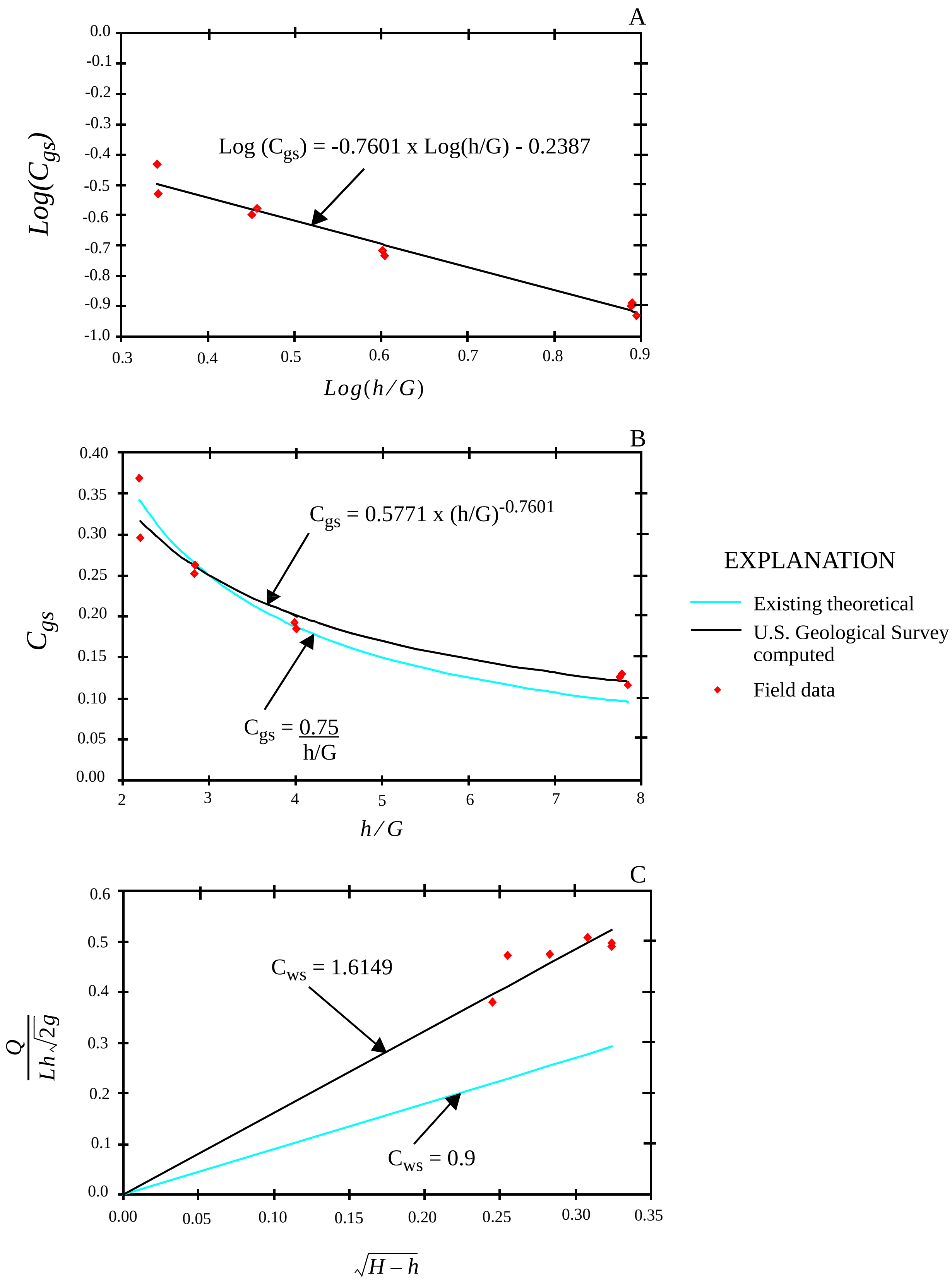

Figure 19. Logarithmic plot of the S-36 discharge coefficient for submerged orifice flow (graph A) and linear scale plots of a comparison of the S-36 discharge coefficient for submerged orifice flow (graph B) and submerged weir flow (graph C). An explanation of charge coefficient for the mathematical symbols is given in appendix III.

Structure S-33

Structure S-33 (fig. 20) is a reinforced-concrete gated spillway with discharge controlled by one cable-operated, vertical slide gate. This coastal control structure is located in the vicinity of Fort Lauderdale on the C-12 canal (Plantation Canal) and is about 1 mi east of Florida's Turnpike (fig. 1). The submerged orifice-flow and submerged weir-flow regimes exist at this site. Structure S-33 maintains optimum water-control stages upstream in the C-12 canal and prevents saltwater intrusion during periods of high tide. Additionally, this coastal control structure passes the design flood (50 percent of the SPF) without exceeding upstream flood design stage criteria set by water managers and restricting downstream flood stages and discharge velocities to nondamaging levels. Appendix I presents flood discharge characteristics for structure S-33, and appendix II presents structural data for S-33.

The automatic controls on structure S-33 are actuated by the headwater elevation. When the headwater elevation increases to 4.0 ft, the gate begins to open and continues to open until the headwater elevation decreases to 3.5 ft (the gate becomes stationary). The gate begins to close when the headwater elevation decreases to 3.0 ft. The automatic controls on this coastal control structure have an overriding mechanism that closes the gate, regardless of the upstream water level in the event of high tide, when the differential between the falling headwater and rising tailwater pool elevations reaches 0.2 ft.

An ADCP was used to take measurements at structure S-33 on October 9, 1996 (table 3). The measurement section was about 100 ft upstream of the coastal control structure as shown in figure 20. Data were collected with the gate opened at 1 and 2 ft and when the gate was completely out of the water. Logarithmic and linear scale plots of the discharge-coefficient ratings for the submerged orifice- and submerged weir-flow regimes using data collected by the ADCP are shown in figure 21. A glossary of the mathematical symbols used in the logarithmic and linear scale plots is presented in appendix III. The range of percent standard error for the submerged orifice discharge coefficient is 6 to
-6 percent, and the SDR for the submerged weir discharge coefficient is 6 percent. The coefficient of determination for the submerged orifice discharge coefficient is 0.9631. Using the difference in equation constants as a measure, the theoretical and computed submerged orifice ratings differ by 0.7

Figure 20. Location of structure S-33.

percent, and the theoretical and computed submerged weir ratings differ by 4.9 percent.

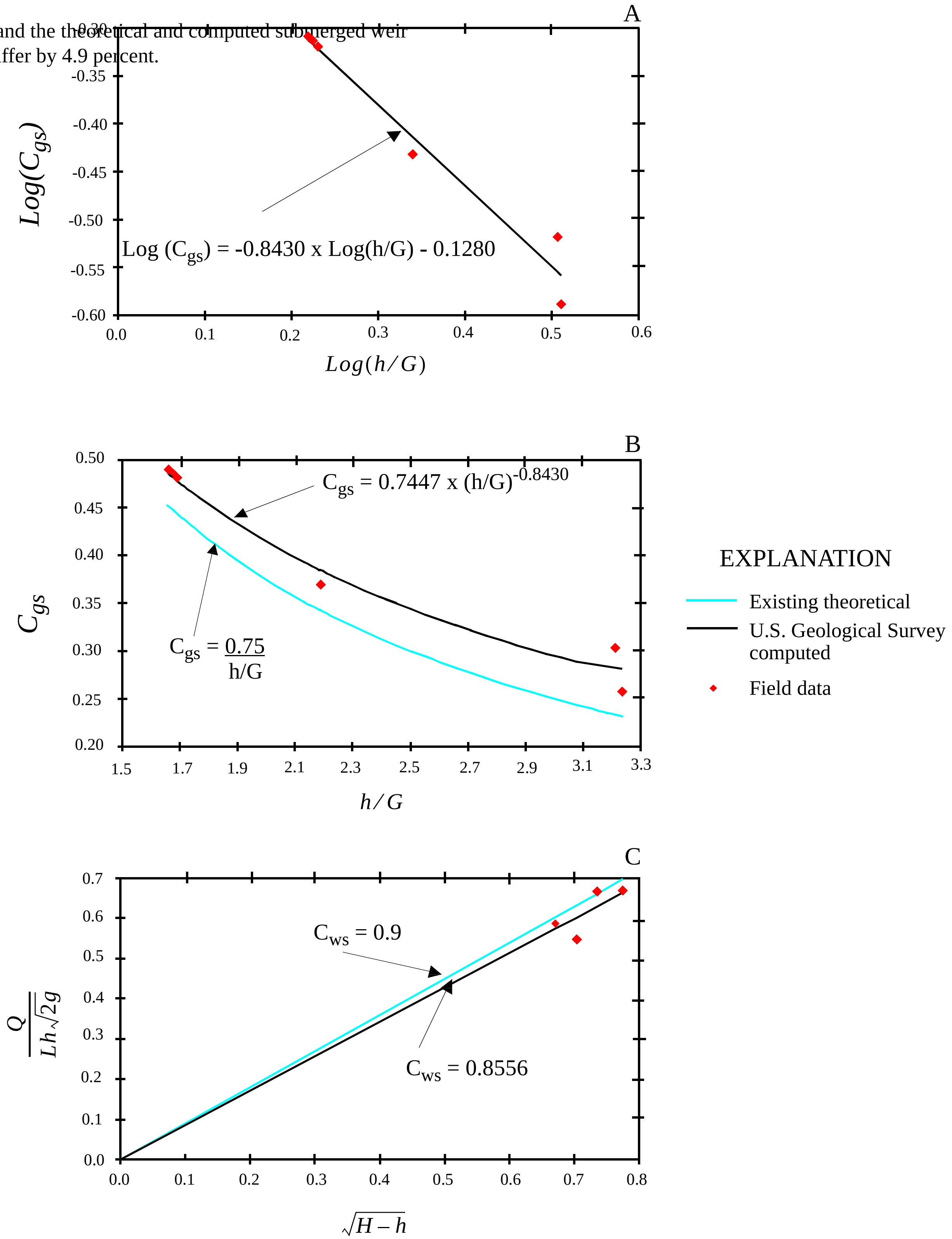

Figure 21. Logarithmic plot of the S-33 discharge coefficient for submerged orifice flow (graph A) and linear scale plots of a comparison of the S-33 discharge coefficient for submerged orifice flow (graph B) and submerged weir flow (graph C). An explanation of the mathematical symbols is given in appendix III.

Structure G-54

Structure G-54 (fig. 22) is a fixed-crest, reinforced-concrete gated spillway with discharge controlled by three cable-operated, vertical slide gates. This coastal control structure is located in the vicinity of Fort Lauderdale on the North New River Canal and is about 1.5 mi west of Florida's Turnpike (fig. 1). The submerged orifice-flow and submerged weir-flow regimes exist at this site. Structure G-54 maintains optimum water-control stages upstream in the North New River Canal and prevents saltwater intrusion during periods of high tide. Additionally, this coastal control structure passes the design flood (25-year recurrence interval) without exceeding upstream flood design stage criteria set by water managers and restricting downstream flood stages and discharge velocities to nondamaging levels. Appendix I presents flood discharge characteristics for structure G-54, and appendix II presents structural data for G-54.

The automatic controls on structure G-54 are actuated by the headwater elevation. When the headwater elevation increases to 4.5 ft, the gates begin to open and continue to open until the headwater elevation decreases to 4.0 ft (the gates become stationary). The gates begin to close when the headwater elevation decreases to 3.5 ft. During dry periods, the automatic operation is switched to a higher range of values from 4.0 to 5.0 ft, with the midpoint headwater elevation of 4.5 ft causing the gates to become stationary.

An ADCP was used to take measurements at structure G-54 on June 24, 1996, and June 25, 1996 (table 3). The measurement section was about 75 ft upstream of the coastal control structure as shown in figure 22. Data were collected with one gate opened at 1, 2, and 4 ft and when the gate was completely out of the water. The other two gates remained closed for all measurements. Logarithmic and linear scale plots of the discharge-coefficient ratings for the submerged orifice- and submerged weir-flow regimes using data collected by the ADCP are shown in figure 23. A glossary of the mathematical symbols used in the logarithmic and linear scale plots is presented in appendix III. The range of percent standard error for the submerged orifice discharge coefficient is 17 to -14 percent, and the SDR for the submerged weir discharge coefficient is 5 percent. The coefficient of determination for the submerged orifice discharge coefficient is 0.9379. Using the difference in equation constants as a measure, the theoretical and computed submerged orifice ratings differ by 17.0 percent, and the theoretical and computed submerged weir ratings differ by 7.1 percent.

Figure 22. Location of structure G-54.

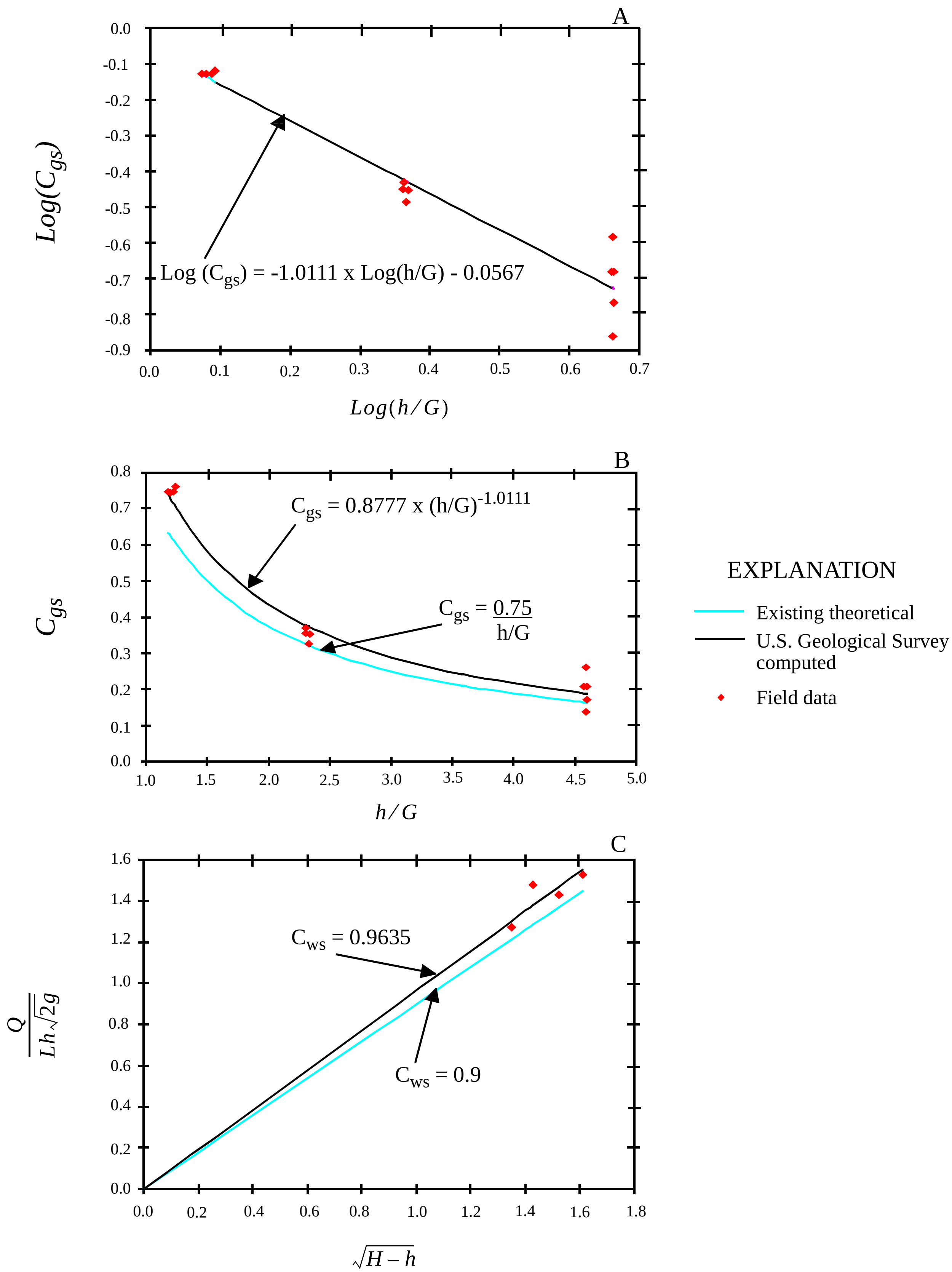

Figure 23. Logarithmic plot of the G-54 discharge coefficient for submerged orifice flow (graph A) and linear scale plots of a comparison of the G-54 discharge coefficient for submerged orifice flow (graph B) and submerged weir flow (graph C). An explanation of the mathematical symbols is given in appendix III.

Structure S-13

Structure S-13 (fig. 24) is a pump station that consists of three pumping units with a gated spillway (one cable-operated, vertical lift gate) used to control flows which bypass the pumps. This coastal control structure is located in the vicinity of Fort Lauderdale on the C-11 canal (South New River Canal) and is about 0.5 mi east of Florida's Turnpike (fig. 1). The submerged orifice-flow and submerged weir-flow regimes exist at this site. The pumping units at structure S-13 maintain optimum water-control stages upstream in the C-11 canal and prevent saltwater intrusion during periods of high tides. The automatic controls on this coastal control structure have an overriding mechanism that closes the gate, regardless of the upstream water level in the event of high tide, when the differential between the falling headwater and rising tailwater pool elevations reaches 0.2 ft. Appendix I presents flood discharge characteristics for structure S-13, and appendix II presents structural data for S-13.

The automatic controls on structure S-13 are actuated by the headwater elevation. When the headwater elevation increases to 1.8 ft, the gate begins to open and continues to open until the headwater elevation decreases to 1.6 ft (the gate becomes stationary). The gate begins to close when the headwater elevation decreases to 1.4 ft. A timing device that prevents sudden gate closing has been installed to protect manatees during automatic gate operation. During this operation, the upstream float sensor indicates when the gate should open; the gate opens a minimum of 2.5 ft. If this opening results in a headwater elevation below the gate closing level of 1.4 ft (as is often the case), the gate will begin to close and the normal operation will take control. Initial gate openings stop the gate for 30 seconds upon the first sign of water movement. The gate openings then stop at 0.05-ft increments for 30 seconds until a gate opening of 0.3 ft is obtained. The pumps are operated when the water level in the C-11 canal exceeds 2.5 ft west of structure S-13 and is less than 8 ft east of S-13.

One ADCP was used to take measurements at structure S-13 on November 1, 1995, June 25, 1996, September 12, 1996, and October 7, 1996, and two ADCP's were used to take measurements at the coastal control structure on September 10, 1996 (table 3). One measurement section was about 20 ft upstream of the coastal control structure, and the other was about 100 ft upstream of the coastal control structure (fig. 24). On November 1, 1995, data were collected with the gate opened at 1, 2, 3, and 4 ft and when the gate was completely out of the water. The same gate was opened at 3, 4, and 6 ft for data collected on June 25, 1996. Logarithmic and linear scale plots of the discharge-coefficient ratings for the submerged orifice- and submerged weir-flow regimes using data collected by the ADCP are shown in figure 25. A glossary of the mathematical symbols used in the logarithmic and linear scale plots is presented in appendix III. The range of percent standard error for the submerged orifice discharge coefficient is 29 to -23 percent, and the SDR for the submerged weir discharge coefficient is 9 percent. The coefficient of determination for the submerged orifice discharge coefficient is 0.8715. Using the difference in equation constants as a measure, the theoretical and computed submerged orifice ratings differ by 7.2 percent, and the theoretical and computed submerged weir ratings differ by 31.4 percent.

Because of the anticipated approach of several hurricanes, pumps were used round-the-clock for several days in September and October 1996. The September and October measurements were taken for three pumps operating at 1,000, 1,200, 1,500, and 1,700 r/min and two pumps at 1,700 r/min. The pump coefficient values computed using data collected by the ADCP are given in table 2. The computed pump coefficients produced erratic results for the study, and therefore, are not recommended.

Figure 24. Aerial photograph showing location of structure S-13.

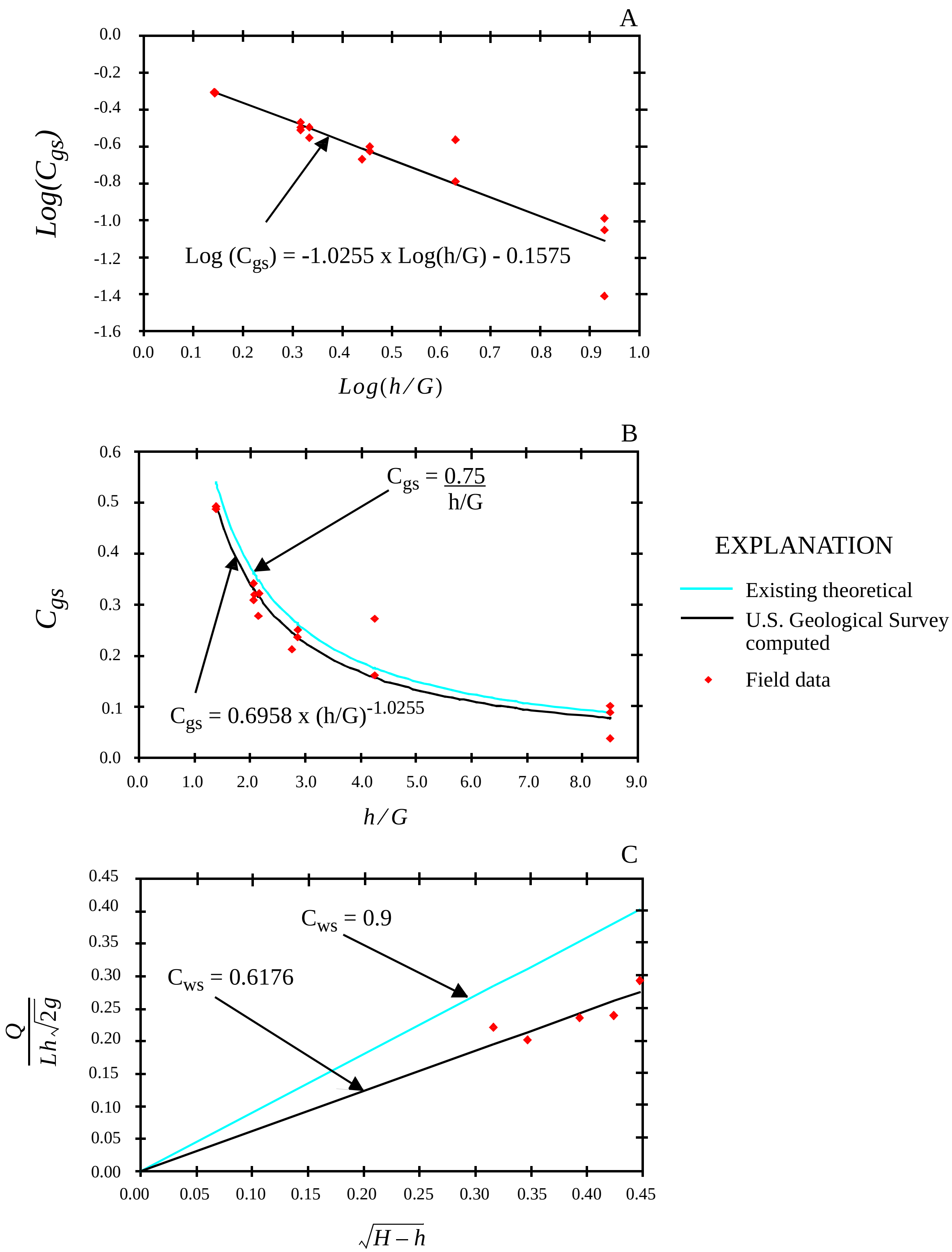

Figure 25. Logarithmic plot of the S-13 discharge coefficient for submerged orifice flow (graph A) and linear scale plots of a comparison of the S-13 discharge coefficient for submerged orifice flow (graph B) and submerged weir flow (graph C). An explanation of the mathematical symbols is given in appendix III.

EVALUATION OF DISCHARGE-COEFFICIENT RATINGS

Many factors could affect the accuracy of the theoretical discharge coefficients used in flow equations at coastal control structures even if the coefficients are calibrated by laboratory tests and Price current meter field calibrations. The application of a theoretical discharge coefficient assumes that the coastal control structure is completely controlling the flow in the channel, and the design and effectiveness of the coastal control structure are the only limiting factors in the discharge. However, in real-world situations, the upstream and downstream channel conditions affect the discharge and cannot be accurately modeled in a laboratory. Therefore, the effective flow area of the coastal control structure opening might not be what is assumed when determining the theoretical discharge coefficient. Computed discharge coefficients calculated from ADCP measurements can better quantify the actual flow conditions.

The inverse log transformation from a simple linear log-regression gives a rating curve based on the medians (not the means), and therefore, the result might be biased low. One way to correct for this bias is by using a nonparametric or "smearing" estimate of mass, which only requires the assumption that the residuals are independent and homoscedastic (the variance of the error term is constant for all values for the independent variables). This equation, shown below (Helsel and Hirsch, 1992), applies for a log transformation and can be generalized for any transformation:

$$Y_i = \frac{\sum_{i=1} f^{-1}(b_0 + b_1 X_i + e_i)}{n} \tag{12}$$

where Y_i is the response variable; f^{-1} is the inverse of the selected transformation; constants b_0 and b_1 are the coefficients of the fitted regression; e_i represents the residuals, $Y_i = b_0 + b_1 X_i + e_i$, where X_i is the specific value of X for which we want to estimate Y; and n is the total number of data points.

The smearing estimator is based on each of the residuals being equally alike and "smears" their magnitudes in the original units across the range of X, which, in the instance of the submerged orifice plot, is log h/G. The smearing estimate is accomplished by expressing the residuals, e_i, from the log-log equation into the original units and computing their mean. This mean is the "bias-correction factor" to be multiplied by the median estimate for all X_o. Application of this bias correction factor to a typical southern Florida coastal control structure shows the bias to be within 1 to 4 percent (Swain and others, 1997).

The statistics and computed discharge-coefficient ratings for submerged orifice and weir flows and free orifice and weir flows determined for the coastal control structures in Broward and Palm Beach Counties are given in table 4. The theoretical equation used by the SFWMD for the submerged orifice discharge coefficient is $C_{gs} = 0.75/(h/G)$. In table 4, this would correspond to values of A = 0.75 and B = -1.0. Values of A for submerged orifice flow ranged from 0.5444 to 0.8777, and values of B for submerged orifice flow ranged from -1.0255 to -0.6552; the average values of A were about 0.7, and the average values of B were about -0.9. The theoretical equation used by the SFWMD for the free orifice discharge coefficient is C_g = 0.75, which corresponds to a value of A = 0.75 and B = 0, because the regression analysis was forced through zero. Values of A for free orifice flow ranged from 0.5690 to 0.7130, which was lower than the theoretical equation. The theoretical equation used by the SFWMD for the submerged weir discharge coefficient is C_{ws} = 0.9, which corresponds to a value of A = 0.9. Values of A for submerged weir flow ranged from 0.6176 to 1.6149 with average values being about 1.0. The theoretical equation used by the SFWMD for the free weir discharge coefficient is C_w = 0.361 (the slope has a value of 0.361). Values of A for free weir flow were higher than the theoretical equation, ranging from 0.4228 to 0.4679, with average values being about 0.45.

SUMMARY AND CONCLUSIONS

Theoretical and computed discharge-coefficient ratings for submerged orifice and weir flows and free orifice and weir flows were determined for selected coastal control structures in Broward and Palm Beach Counties. The difference between the theoretical and computed discharge-coefficient ratings varied from structure to structure. The theoretical and computed discharge-coefficient ratings for submerged orifice flow were within 10 percent at structures G-56, S-13, S-33, and S-37A; however, differences were greater than 20 percent at structures G-57 and S-36. The theoretical and computed discharge-coefficient ratings for submerged weir flow were within 10 percent at structures G-54, G-57, and S-33; however, differences were greater than 20 percent at structures G-56, S-13, S-36, and S-37A. The difference between theoretical and computed discharge-coefficient ratings for free orifice flow ranged from 5 to 32 percent, and the difference between theoretical and computed discharge-coefficient ratings for free weir flow ranged from 17 to 30 percent. Structures S-33 and S-36 were the only coastal control structures in the study whose computed

Table 4. Summary of computed discharge-coefficient ratings for the different flow regimes

[R^2 does not apply to regression through zero, thus R^2 values only are given for the submerged orifice flow regime]

Structure	Flow regime	Coefficient of determination (R^2)	Range of percent standard error	Standard deviation of residuals (percent)	$C = A \times (X)^{B}$*	
					A	B
G-54	Submerged orifice flow	0.9379	17 to -14	--	0.8777	-1.0111
	Submerged weir flow	--	--	5	0.9635	0
G-56	Submerged orifice flow	0.9881	5 to -5	--	0.7338	-1.0063
	Submerged weir flow	--	--	13	1.1600	0
G-57	Submerged orifice flow	0.4951	31 to -24	--	0.5444	-0.6552
	Submerged weir flow	--	--	34	0.8873	0
S-13	Submerged orifice flow	0.8715	29 to -23	--	0.6958	-1.0255
	Submerged weir flow	--	--	9	0.6176	0
S-33	Submerged orifice flow	0.9631	6 to -6	--	0.7447	-0.8430
	Submerged weir flow	--	--	6	0.8556	0
S-36	Submerged orifice flow	0.9677	8 to -8	--	0.5771	-0.7601
	Submerged weir flow	--	--	8	1.6149	0
S-37A	Submerged orifice flow	0.9728	10 to -9	--	0.6960	-0.9451
	Submerged weir flow	--	--	3	1.2532	0
S-40	Free orifice flow	--	--	5	0.5690	0
	Free weir flow	--	--	5	0.4228	0
S-41	Free orifice flow	--	--	9	0.6611	0
	Free weir flow	--	--	5	0.4528	0
S-155	Free orifice flow	--	--	12	0.7130	0
	Free weir flow	--	--	7	0.4679	0

*C = flow coefficient, $X = h/G$ for submerged orifice flow at spillways, and $X = h/H$ for submerged weir flow.

discharge-coefficient ratings for both submerged orifice and submerged weir flows were within 10 percent and greater than 20 percent, respectively, of the theoretical discharge-coefficient ratings. Some differences between the theoretical and computed discharge-coefficient ratings could be better defined with more data collected over a greater distribution of measuring conditions.

The speed at which ADCP measurements can be taken was essential for the collection of data in rapidly changing conditions and slow, nonuniform velocities. Measurements were taken for a wide range of flow conditions to determine computed discharge-coefficient ratings for specified ranges at all of the coastal control structures, except for the pumps at structure S-13 (the pump coefficients produced erratic results and their use is not recommended). Ongoing efforts are being made by the SFWMD at other coastal control structures to develop computed discharge-coefficient ratings similar to the ones presented in this report. The increased certainty in these computed discharge-coefficient ratings will allow water managers to be more accurate in their determination of flows to tidewater. The techniques developed in this study can be applied to other locations with similar hydrologic conditions.

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Appendix I. Flood discharge characteristics for the coastal control structures in Broward and Palm Beach Counties

[SPF, Standard Project Flood; SWF, submerged weir flow; SOF, submerged orifice flow; FWF, free weir flow; ft, feet; ft^3/s, cubic feet per second. The SPF discharge describes the amount of rainfall runoff associated with the 100-year storm, most severe storm, or sequence of storms considered reasonably characteristic of southeastern Florida, increased by 25 percent]

Structure	Design Flood					Structure Protection Design				
	Discharge rate (ft^3/s)	Degree of protection (SPF in percent)	Headwater elevation (ft)	Tailwater elevation (ft)	Flow regime	Discharge rate (ft^3/s)	Degree of protection (SPF in percent)	Headwater elevation (ft)	Tailwater elevation (ft)	Flow regime
G-54	1,600	--	4.6	4.3	SWF	--	--	--	--	--
G-56	3,760	60	7.6	6.9	SOF	5,000	80	7.2	6.0	--
G-57	375	--	5.0	4.5	SOF	--	--	--	--	--
S-13*	540 540	--	2.2–2.5 1.2	6.2–6.5 1.0	Pumped SWF	--	--	--	--	--
S-33	620	50	5.9	4.9	SWF	1,080	88	7.1	7.1	SWF
S-36	1,090	50	5.3	4.8	SWF	1,640	75	7.7	6.9	SWF
S-37A	3,890	100	3.0	-0.4–2.0	SOF	3,890	100	5.4	-0.4–2.0	SOF
S-40	4,800	60	8.2	1.2–2.7	FWF	5,500	70	9.0	1.3–2.7	FWF
S-41	4,600	60	8.1	1.8	FWF	5,300	70	8.8	1.9	FWF
S-155	4,800	60	8.5	-1.0–2.0	FWF	8,000	100	11.0	2.0	FWF

*For structure S-13, the upper set represents pump design and the lower set represents gravity design.

Appendix II. Structural data for the coastal control structures in Broward and Palm Beach Counties

Structure number	Weir Crest		Service bridge elevation (feet)	Water-surface elevation[1] (feet)	Number and type of gates	Size of gates, in feet (height x width)
	Net length (feet)	Elevation (feet below land surface)				
G-54	48	4.0	10.0	8.0	Three vertical slide gates	9.5 x 16.0
G-56	60	3.5	14.0	12.0	Three vertical slide gates	12.2 x 20.0
G-57	28	1.0	17.0	9.0	Two vertical lift gates	6.0 x 14.0
S-13[2]	16	8.0	8.0	8.0	One vertical lift gate	11.3 x 17.3
S-33	20	2.0	11.5	10.0	One vertical slide gate	9.0 x 20.0
S-36	25	7.0	11.5	11.5	One vertical slide gate	14.0 x 25.0
S-37A	50	7.7	8.0	8.0	Two vertical lift gates	12.8 x 25.8
S-40	50	.4	11.5	11.5	Two vertical lift gates	9.0 x 25.8
S-41	50	.4	11.5	11.5	Two vertical lift gates	9.0 x 25.8
S-155	75	1.8	16.0		Three vertical lift gates	7.7 x 25.8

[1] Water-surface elevation which will bypass structure.

[2] Structure S-13 contains three pumping units (60-inch vertical lift propeller type). The design rating is 180 cubic feet per second for each, and the propeller speed is 191 revolutions per minute.

Appendix III. Glossary of mathematical symbols used in report

Symbol	Definition
b_0, b_1	Coefficients for the regression equation
C_{eq}	C from the regression equation
C_g	Discharge coefficient for free orifice flow
C_{gs}	Discharge coefficient for submerged orifice flow
C_i	C from the field data
C_s	Submergence coefficient relative to the function of H/h
C_w	Discharge coefficient for free weir flow
C_{ws}	Discharge coefficient for submerged weir flow
C_0 to C_9	Pump coefficients
e_i	Residuals
f^{-1}	Inverse of the selected transformation
G	Gate opening, in feet
g	Acceleration of gravity, in feet per second per second
H	Headwater height above sill or head value, in feet
H_{fact}	Head factor
h	Tailwater height above sill or downstream stage, in feet
L	Length of gate sill, in feet
N	Engine speed value
N_{fact}	Engine speed factor
N_{max}	Maximum engine speed
N_{min}	Minimum engine speed
n	Total number of data points
σ_n	Normal standard error, in percent
σ_L	Log base 10 standard error, in log units
Q	Discharge, in cubic feet per second
X	Dimensionless head parameter
Y	Dimensionless engine speed parameter
Y_i	Response variable