GUIDELINES FOR HYDRAULIC RATING ANALYSES OF STANDARD CULVERTS

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EXECUTIVE SUMMARY

Guidelines for the hydraulic rating analyses of culverts are presented in this report. The tasks described herein have been applied in whole or part to a number of standard culverts that vary in size and functionality. The general procedure is comprised of the following steps:

1. Review the facility layout and site conditions.
2. Acquire engineering data and drawings.
3. Evaluate the engineering data and culvert properties.
4. Determine the relationship between flow and head loss.
5. Determine the rating equation parameters.
6. Evaluate the accuracy and quality of the rating equation calibration.
7. Perform an uncertainty analysis.
8. Perform an impact analysis.
9. Document the rating analysis in an appropriate format.

Depending on the characteristics of the culvert and the available information, not all of the above steps will necessarily need to be performed. Nonetheless, they should serve as comprehensive guidelines to ensure that the required facets of a rating analysis are accounted for.

ACKNOWLEDGEMENTS

The authors wish to express appreciation to Kwaku Oben-Nyarko who played a key role in successfully applying the flow rating analysis procedures discussed in this report to many culverts throughout the District.

DEFINITIONS

Acronyms

ACCELER8	*Accelerated* Everglades restoration projects
CERP	Comprehensive Everglades Restoration Plan
ECP	Everglades Construction Project
SOP	Standard Operating Procedure
STA	Stormwater Treatment Area
STRIVE	Structure Information Verification
TSH	Total Static Head
USACE	US Army Corps of Engineers

PREFACE

The trade names of various products and software are used at certain places within this document for illustrative purposes or as examples only. Their use does not imply endorsement by the South Florida Water Management District nor does it imply criticism of similar products or software not mentioned.

1.0 INTRODUCTION

1.1 General Characteristics of SFWMD Culverts

Most of the culverts installed at District water control structures are divided into standard culverts and compound culverts. Standard culverts include gated box and circular culverts. A compound culvert consists of both a special inlet and culvert barrel(s). Culverts with weir-box, weir-gate and flashboard-riser inlet structures are the most common compound culverts in the District. Schematics depicting a standard gated culvert and a weir-box culvert are shown in Figure 1a and Figure 1b, respectively.

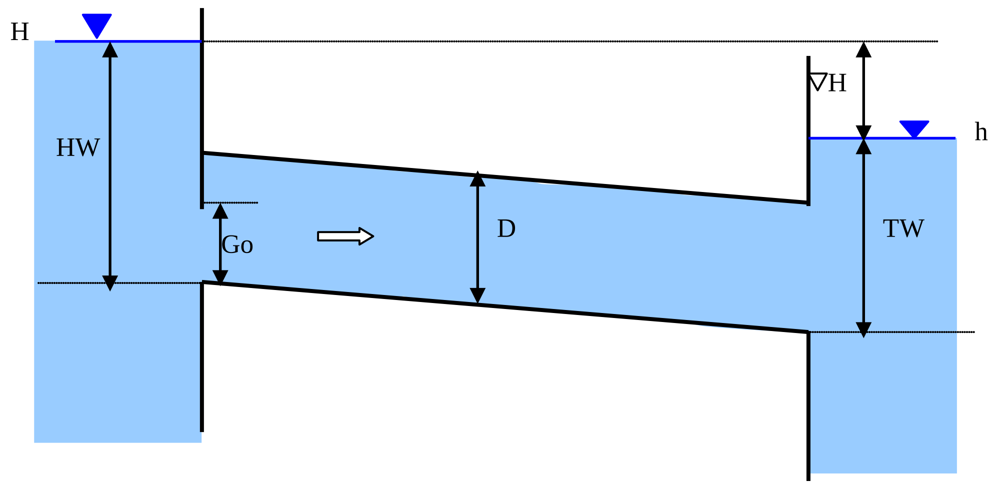

Figure 1a. Illustration sketch of a standard culvert

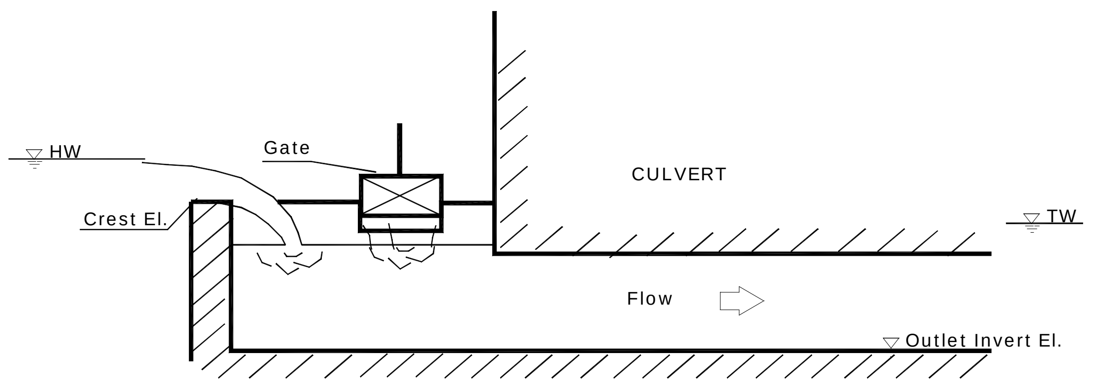

Figure 1b. Schematic of a weir-box culvert with a sluice gate at the sidewall of inlet weir box

There are three general flow conditions within standard culverts: full pipe flow, orifice flow, and open channel flow. These flow types depend on the levels of headwater and tailwater relative to the gate opening and culvert height. Open channel flow is further divided into inlet control, outlet control, and tailwater control flows, depending on the tailwater elevation and whether flow is supercritical or sub-critical throughout the culvert.

Compound culverts have complex shapes which require a combination of equations to solve for discharge. Weir-box culverts, for example, have intricate inlet geometries and multiple control points; hence, both barrel control and weir equations are used to compute flow. Flow equations are derived separately for each type of culvert flow based on the principle of conservation of mass and energy. The rating analysis of compound culverts is not discussed in these guidelines because the relevant flow algorithms are not well developed and are subject to improvement in the near future.

1.2 Purpose of These Guidelines

The purpose of these guidelines is to: (i) provide a framework for conducting rating analyses of standard culverts by outlining the primary tasks involved; (ii) help ensure consistency (to the extent warranted) in the overall approach as well as in the specific methodologies employed to complete the various tasks; and (iii) establish minimum expectations for the quality of the results. It should be emphasized that these guidelines are not to be construed as a cook book for carrying out rating analyses of culverts. In carrying out any rating analysis, the hydraulic engineer may likely encounter circumstances or issues not addressed in this document. For example, an unusual design may either necessitate the use of methodologies or procedures not included here or render invalid those that are. Sound engineering judgment should always be exercised throughout the entire effort since deviations from the guidelines may sometimes be necessary.

2.0 PRIMARY TASKS

There are essentially nine primary tasks associated with a rating analysis of a culvert. They can be stated as follows:

1. Review the facility layout and site conditions.
2. Acquire engineering data and drawings.
3. Evaluate the engineering data and culvert properties.
4. Determine the relationship between flow and head loss.
5. Determine the rating equation parameters.
6. Evaluate the accuracy and quality of the rating equation calibration.
7. Perform an uncertainty analysis.
8. Perform an impact analysis.
9. Document the rating analysis in an appropriate format.

Not all of these tasks will necessarily need to be performed during a rating analysis. For example, a new culvert will not have an existing rating equation, so in this case task 8 would not be carried out.

2.1 Task 1. Review the Facility Layout and Site Conditions

The first step is to become familiar with the configuration of the culvert facilities and general site conditions. The engineer performing the rating analysis should first review any aerial images or site photographs that provide a clear view of the source and receiving water bodies, the characteristics of the inlets and barrels, and the locations of all relevant stage monitoring stations. Afterward, a field visit to the facility is recommended. In particular, one should identify any potential problems with or limitations of flow measurements taken at this site. Also noted should be any flow obstructions between the location of the headwater monitoring station and the inlet or between the outlet and the tailwater monitoring location. Finally, the engineer must judge whether or not the stage of the receiving water body may be sensitive to the discharge rate. All of this will help in anticipating the design data that will need to be acquired.

2.2 Task 2. Acquire Engineering Data and Drawings

2.2.1 As-Built Drawings

The as-built drawings may be located in variety of places. Unfortunately, as of date, there is no central repository for structure as-built drawings. The storage location and format will depend on the age, purpose and initial ownership of the structure. When attempting to locate as-built drawings, past experiences of OHDM engineers with numerous rating analyses suggest that the following sources be considered in the order listed:

1. *The Map File Room*. Numerous as-built drawings are cataloged and stored here in either electronic or hard copy format. When contacting their staff for assistance, it is helpful to first determine the contract or project (CERP, ACCELER8, ECP or other) number pertaining to the culvert under consideration.

2. *STA Management Division.* This organization may have electronic copies of the drawings or know the Documentum path to the culvert records if the culvert is a relatively new part of a STA.

3. *Off-site Storage.* Sometimes hard copies of the drawings may be located at off-site storage facilities leased by the District or the USACOE.

If as-built drawings for a culvert are not available, the next best alternative is to obtain and use the construction drawings. A separate survey of the facility that adheres to the standards and objectives of the STRIVE project (Pathak and Chen, 2005) should then be initiated, if possible.

2.2.2 Material and Component Specifications

Certain specifications used in the culvert construction should be obtained if available. These are generally needed to accurately compute hydraulic energy losses within the culvert inlet and barrel. Specifications for the following components should be obtained:

1. *Discharge conduit*. In particular, specifications related to barrel materials may be useful.

2. *Gates and appurtenances*. Obtain properties of the gate and other appurtenances where significant energy losses may occur.

3. *Operational protocol*. The *Structure Information Site* on the IWEB, the OHDM publication entitled, “Atlas of Flow Computations at District Hydraulic Structures” and STA operational master plans are sometimes useful sources of operational protocols.

2.2.3 Flow Measurements

Stream flow measurements that may be useful for rating purposes should be available in the QMEAS tables of the DBHYDRO database. Additionally, field notes and other files associated with the flow measurements may be stored in folders located under the following server directories:

\\dataserv\570\5730\5733\Streamgauging\Field Notes

\\dataserv\570\5730\5733\Streamgauging\Measurements

2.2.4 Repair and Maintenance Records

A culvert structure may undergo modifications that can affect its rating. For example, a culvert barrel may have had its joints sealed after its sections experienced differential setting (this would affect barrel roughness). If it is suspected that the structure may have undergone such modifications, it is best to contact the project engineer who oversaw the work and/or the field station in whose jurisdiction the structure is located.

2.2.5 STRIVE Database

As-built drawings often contain errors in dimensions and elevations. The STRIVE effort (Pathak and Chen, 2005) was carried out to partially rectify this problem. The resultant database contains resurveyed elevations for a number of culverts. Hence, after acquiring the as-built or construction drawings, it is best that the pertinent elevations be verified against those in the STRIVE database, if available. The STRIVE project results can be accessed and queried at the following District web site:

http://apps.sfwmd.gov/pls/portal/url/page/PG_GRP_DISTRICT/PG_SFWMD_RPT_STRIVE

2.3 Task 3. Evaluate the Engineering Data and Culvert Properties

Once the information discussed in section 2.2 has been acquired and assembled, the tasks listed below should be performed.

2.3.1 Obtain Characteristics and Dimensions of the Inlet Structure

The flow rating algorithm is dependent on the geometric characteristics of a culvert. For example, a rectangular inlet should cause a larger entrance loss than a rounded inlet. Therefore, it is necessary to acquire all relevant dimensions.

2.3.2 Acquire the Dimensions and Properties of the Culvert Barrel

Review the as-built drawings, the Flow Atlas (Wilsnack and Zeng, 2009), and the Structure Information IWEB site to obtain the number of barrels, the barrel dimensions, and the number of controls (sluice gate and/or flap gate). In particular, the barrel length and geometry are important for estimating friction head losses. Most culvert barrels are constructed of either concrete or corrugated metal. The barrel materials must be considered when estimating the Manning' roughness coefficient.

2.3.3 Estimate the Range of Hydraulic Roughness for the Culvert Barrel

The hydraulic roughness of the culvert barrel is needed to account for energy losses in the rating analysis. This is usually specified in terms of the Manning roughness coefficient. The value of Manning roughness for a given material can be obtained from Lindeburg (2008) or other related references. A range of roughness values is needed to account for variations in both manufactured pipe and field conditions. By default, a Manning roughness coefficient of 0.012 is usually assigned to concrete barrels, while 0.024 is assigned to corrugated metal barrels with annular corrugations.

2.3.4 Estimate the Ranges of the Local Head Loss Coefficients

The range of the entrance loss coefficient K_{ent} should be estimated if entrance losses are expected to be significant. Entrance loss coefficients can be obtained from Table 12 of FHWA HDS 5 (2005) or Table 19.10 of Lindeburg (2008). The exit loss coefficient K_{exit}, on the other hand, is taken to be 1.0.

Local head losses due to the sudden contraction and expansion of the flow upstream and downstream of the gate are also incurred. Local loss coefficients for this circumstance can be obtained from references such as Daugherty and Franzini (1977), Zipparro and Hasen (1993), and Miller (1990).

2.3.5 Review the Flow Measurement Data

Each candidate measurement should be subject to a rigorous technical review that reveals the reliability and uncertainty of the measurement. Many flow measurements have been reviewed in such a manner through a quality assurance process developed by the District under contract with ECT and Sutron Corporation (2008). It is highly recommended that all flow measurements considered for use in the rating analysis be reviewed accordingly.

There are essentially two goals of the flow measurement review process, namely (i) to estimate the uncertainty of each measurement, and (ii) to categorize the potential use of each measurement in the rating process. In regard to the latter goal, measurements can be generally categorized as follows, in order of decreasing quality:

1. Measurements that can be used for rating analysis directly to calibrate the coefficients ("excellent" or "good" quality level);

2. Measurements that can be used for rating verification ("fair" quality level);

3. Measurements that should not be used at all in the rating analysis ("bad" or "poor" quality level).

Exceptions to these categories can sometimes exist. For example, if a measurement is deemed "bad" or "poor" due to a significant bias inherent to it, it may still have some use for rating verification since one would expect the rating equation to produce a flow rate that is either higher or lower (depending on the direction of the bias) than the measured flow rate. In the event that this is not the case, the data point would signify a problem with the rating equation and could therefore be considered useful.

2.4 Task 4. Determine the Relationship between Flow Rate and Head Loss

The goal of this task is to use the engineering properties of the culvert to determine the relationship between discharge, upstream (headwater) stage, downstream (tailwater) stage, and gate opening. This is accomplished by performing the subtasks given below in the order listed.

2.4.1 Compute the Head Losses Associated with Various Discharge Rates

Determining the head losses associated with a range of flow rates requires some familiarity with the fundamental types of flow that can occur in gated culverts. Damisse and Fru (2006) identified 5 basic flow regimes (hereafter designated as Types 1 – 5) that can occur within a gated culvert. Additionally, Zeng et al (2009) identified a sixth type (i.e. Type 6) that can occur under certain conditions. Each type of discharge condition is discussed here only briefly. Additional details can be found in the references cited.

In the formulations presented in this section, the following variable definitions apply unless stated otherwise:

H	=	the headwater elevation
h	=	the tailwater elevation
Q	=	the discharge rate
Y_c	=	critical depth
θ	=	water surface flow angle within a circular cross section (see, for example, Chow, 1959)

2.4.1.1 Supercritical Open-Channel Flow (Type 1)

This flow condition occurs when supercritical open-channel flow exists throughout the barrel except at the inlet, where critical depth occurs. Denoting Q_c and A_c as the corresponding critical flow and wetted area, respectively, Damisse and Fru (2006) specify the following set of equations for computing flow at critical depth in a circular culvert of diameter D:

$$F(\theta) = H - \frac{Q_c^2}{2gA_c^2} - (Y_c + z) = 0 \tag{1a}$$

$$Q_c = 0.7093 \frac{\left(\theta - \frac{1}{2}\sin 2\theta\right)^{1.5}}{(\sin\theta)^{0.5}} D^{2.5} \tag{1b}$$

where *z* is the upstream barrel invert elevation. For critical flow in a box culvert with a span of *B*, Damisse and Fru (2006) developed the following equations:

$$Q_c = 5.67 * B * Y_c^{1.5} \tag{2a}$$

$$Y_c = \frac{2}{3}(H - z) \tag{2b}$$

Once Q_c is computed, the actual discharge is given by

$$Q = C_d * Q_c \tag{3}$$

where C_d is a discharge coefficient that reflects the head losses that occur between the headwater location and the upstream face of the culvert barrel. Damisse and Fru (2006) indicate that no data are available for the parameter C_d since this flow condition rarely ever occurs in south Florida.

2.4.1.2 Subcritical Open Channel Flow with Critical Depth at the Outlet (Type 2)

This flow condition occurs when subcritical open-channel flow occurs throughout the barrel length except at its outlet, where flow passes through critical depth just before entering the downstream water body. When these conditions occur, Damisse and Fru (2006) indicate that the headwater/gate-opening ratio does not exceed 1.5, the slope of the culvert is less than the critical slope and the tail-water elevation is less than the critical depth elevation inside the barrel at its outlet. The discharge is computed using the same procedure that is used when subcritical flow occurs everywhere within the barrel (Type 3 flow). This is explained in the next section. Type 2 flow occurs infrequently in southern Florida.

2.4.1.3 Subcritical Open Channel Flow Throughout (Type 3)

This flow condition occurs when subcritical, open-channel flow occurs throughout the culvert barrel. The associated flow equation developed by Damisse and Fru (2006) is:

$$Q = C_{do} A_2 \sqrt{\frac{2g(H-h)}{1+\frac{2gA_d^2 L C_{do}^2}{K_u K_d}}} \quad (4)$$

where

A_d = the downstream water area within the culvert

$K_u = \frac{1.49}{n} R_u^{\frac{2}{3}} A_u$ (upstream water conveyance within the culvert)

A_u = the upstream water area within the culvert

R_u = the upstream hydraulic radius within the culvert

$K_d = \frac{1.49}{n} R_d^{\frac{2}{3}} A_d$ (downstream water conveyance within the culvert)

R_d = the downstream hydraulic radius within the culvert

C_{do} = the coefficient of discharge for open-channel flow conditions

Equation 4 provides the relationship between static head (H-h) and discharge (Q). At the downstream end of the culvert, the depth y_d is known since, by conservation of energy, $(y_d + V_d^2 / 2g) - V_d^2 / 2g = h = y_d$, where the variable V designates velocity. However, the upstream depth y_u and Q are implicitly related. This can be seen through conservation of energy, which implies that

$$y_u + V_u^2 / 2g = H - K_{ent} V_u^2 / 2g \quad (5)$$

By applying the relationship $K_{ent} = 1/C_d^2 - 1$ for full flow conditions to the partially full conditions encountered here, Equation (5) can be restated as

$$H = y_u + Q^2 /[2gC_{do}^2]/[A_u(y_u)]^2 \quad (6)$$

where $A_u(y_u)$ denotes A_u as a function of y_u. Equation (6) has two unknowns: Q and y_u. To determine Q based on specified values of H and h, an iterative approach is needed. One would first guess a value of y_u and then compute K_u. Damisse and Fru (2006) recommend $y_u \approx 0.9H$ as an initial guess. Subsequently, Q could be computed using Equation (4). Then, knowing Q, Equation 6 can be solved for y_u. If agreement between the successive values of y_u was not obtained within an accepted tolerance, the process would be repeated until subsequent values of y_u converged. The final result would then provide a value of Q corresponding to (H – h) under the stated conditions.

As was the case for the previous flow types, prior knowledge of the rating parameter C_{do} is needed. Unfortunately, Damisse and Fru (2006) indicate that culverts with similar physical properties can have different values of C_{do}. Consequently, a larger number of C_{do} values for similar culverts will have to be compiled to establish a reasonable range for this parameter.

2.4.1.4 Full Pipe Flow (Type 4)

When the barrel flows full throughout its length, the flow equation specified by Damisse and Fru (2006) is:

$$Q = C_d A_0 \sqrt{\frac{2g(H-h)}{\left(\frac{A_0}{A_G}\right)^2 + 2C_d{}^2\left(1 - \frac{A_0}{A_G} + \frac{gn^2L}{(1.49)^2 R_0^{4/3}}\right)}} \tag{7}$$

where A_o is the full barrel water area, A_G is the area of the gate opening, L is the culvert length, g is gravitational acceleration, R_o is the full barrel hydraulic radius, C_d is the discharge coefficient, and n is the Manning's roughness coefficient. Using energy principles, it can be easily demonstrated that the term (H – h) in Equation 1 is equal to the total head loss incurred by the flow Q through the culvert. Hence, Equation 1 can be used to develop the relationship between head loss and discharge rate for various gate openings. However, this requires prior knowledge of C_d and n. Until Equation 1 is calibrated to measured values of Q, H, h, and Go, for the culvert in question (as explained in section 2.5 below), site specific values of these parameters won't be available. However, calibrated values of C_d and n should be available for similar culverts with existing flow ratings. Using this and any other available information, the engineer should be able to estimate plausible ranges of C_d and n that can be used to compute Q versus (H – h) relationships as described in section 2.4.2 below.

2.4.1.5 Orifice Flow (Type 5)

Damisse and Fru (2006) indicate that the Type 5 flow regime is comprised of the following conditions:

- the headwater/gate-opening ratio is greater than 1.5
- the tailwater depth is below the crown at the outlet.
- the gate contracts the flow, acting similar to a sluice gate.
- the culvert flows partly full.

This flow type is also known as orifice flow. For a circular culvert of diameter D, the rating model for orifice flow through a gate opening of G_o can be stated in terms of critical depth as follows (Damisse and Fru, 2006):

$$Q = \sqrt{gD^5 \frac{(\beta - \sin\beta\cos\beta)^3}{64\sin\beta}} \tag{8a}$$

where

$$\beta = \cos^{-1}\left[1 - 2\left(\frac{Y_c}{D}\right)\right] \quad (8b)$$

$$Y_c = G_o * a\left[\frac{(H-h)}{G_o}\right]^b \quad (8c)$$

and β = θ / 2. For a box culvert,

$$Q = \left[Y_c B^{2/3} g^{1/3}\right]^{\frac{3}{2}} \quad (9)$$

where B is the barrel span and Y_c is given by Equation (8c). In either case, the rating parameters *a* and *b* have a nonlinear and complex relationship with discharge. These parameters can be estimated initially by "borrowing" values from a culvert with similar hydraulic properties. Equations 8 or Equation 9 can then be used to relate *Q* to various values of (*H* – *h*) and *Go*.

A unique problem arises when Equations (8a-c) are applied to Type 5 flow through a circular culvert barrel. From Equation (8c), it can be seen that as Y_c approaches D (i.e. the critical water surface approaches the barrel crown), β approaches π and, consequently, sin(β) approaches 0. Under this condition, the discharge given by Equation (8a) becomes infinitely large. This is physically unrealistic and leads to the following question: at what maximum value of critical depth will Equations (8a) and (8b) provide a realistic value of Type 5 discharge? Zeng et al (2009) performed a detailed evaluation of this flow condition and found that the limiting value of Y_c is about 0.8D. When critical depth exceeds this value, a different flow condition designated Type 6 exists. Type 6 flow will be discussed in the next section.

2.4.1.6 Orifice Flow with Partial Barrel Control (Type 6)

This flow condition is somewhat unique and was identified by Zeng et al (2009). In Type 6 flow, the barrel flows full over part of its length even though the inlet conditions resemble those of Type 5. This is due to the fact that the flow depth just downstream of the hydraulic jump expands to the point where it equals or exceeds the limiting depth of 0.8D discussed in the previous section. When this occurs, Zeng et al (2009) determined that the Type 4 flow equation can be used to determine the discharge. However, an effective barrel length should be used in Equation (7) to account for the portion of the total length that is flowing full. Determining this effective length is a topic that is currently under investigation.

2.4.2 Determine the Theoretical Relationship between Discharge, Head Differential and Gate Opening

Using the equations presented in section 2.4.1, construct a family of theoretical rating curves that depict discharge vs. head differential for various gate openings. Figure 2 provides an example of a theoretical rating curve for a culvert flowing full with specified gate openings. These are depicted along with measured flows to gain initial insight into the hydraulic nature of the culvert. Note that Figure 2 provides a range of Q for a given value of TSH. The rating curves represented by dotted lines should reflect the uncertainty inherent to C_d and n that was established previously.

2.5 Task 5. Determine the Rating Equation Parameters

Perhaps the most important step in a culvert flow rating analysis is to fit the rating model to measured flows by adjusting the model parameters. It is sometimes possible to determine the rating parameters in Excel manually. However, in most cases nonlinear regression or parameter estimation techniques should be used. Equation (7), for example, can be fit directly to the measured flow data, which involves two rating parameters - C_d and n. C_d , in particular, is highly dependent on the local head losses and plays an important role in culvert rating. The determination of n and C_d through nonlinear regression techniques can be accomplished using software such as ExcelSolver, Matlab, SAS, or Mathmetica. The inverse parameter estimation techniques afforded by PEST (Doherty, 2004) provide a more rigorous approach since they can account for the uncertainties inherent to measured flows, stages and gate openings. Regardless of the parameter estimation methodology used, the resultant parameter values should be compared with the ranges established in step 2.4 to verify agreement.

In the case of orifice flow, Equations (8) or Equation (9), where Q is expressed directly as a function of H – h, can be fit to the measured flow data, where a and b are the parameters. However, given the nonlinear (and somewhat convoluted when dealing with circular culverts) relationship between Q and TSH, it is usually advantageous to first convert the measured Q values to Y_c values using equations (8) and (9) as appropriate. Equation (8c) then becomes the rating equation used to determine a and b.

Under open channel flow conditions, fitting Equation (4) to measured flow data is much more complicated since the discharge and critical depth are implicitly related and acceptable ranges of C_{do} are difficult to establish. Usually, Newton-Raphson iteration is applied to determine the critical depth along with the subtypes of open channel flow encountered.

2.6 Task 6. Evaluate the Accuracy and Quality of the Rating Equation Calibration

The procedures outlined in this section are for assessing the quality of the rating equation calibration process performed in Task 5. This primarily addresses the quality of fit between the rating equation and the measured or synthetic flow data. Depending on the quantity and quality of the data used for history matching, the calibration quality indicators described here may not be a reliable indicator of the predictive accuracy inherent to the rating equation. The accuracy and reliability of the flows computed with the rating equation is best assessed through an uncertainty analysis (Task 7).

First, one should qualitatively review the computed versus measured flow plot for each flow condition. Errors should appear randomly distributed around the computed = measured reference line with no apparent bias. To examine this quantitatively, a list of model errors (computed – measured) should be constructed and statistical tests should be applied to this error set to test (i) whether or not it is a random sample from a normal distribution and, if so, (ii) the null hypothesis that the mean error is zero. This will help to reveal any biases inherent to the rating equation.

The quality of fit between a rating equation and the flow data can be evaluated in more detail by examining the Mean Square Error (MSE) and the Linear Correlation Coefficient (R). The former is simply the sum of squared values of model error while the latter is a non-dimensional measure of covariation between measured and computed flows. Although these measures have had widespread use, Weglarczyk (1998) indicates that the former can be inconvenient due to its dimensionality while the latter can be misleading in certain cases due to its lack of sensitivity to scale. Furthermore, Weglarczyk (1998) demonstrates that these measures are related while neither reflects bias. Consequently, it is suggested that that a dimensionless transformation of MSE that reflects bias be used to evaluate the agreement

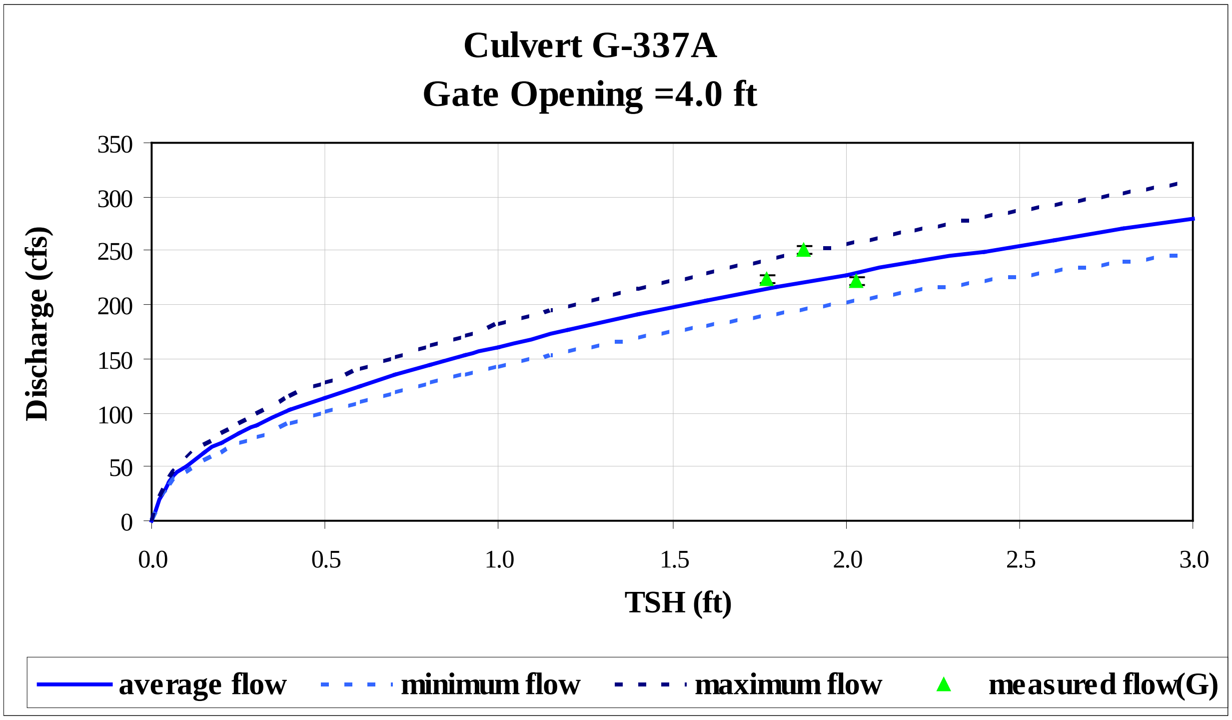

Figure 2. Example of a theoretical relationship between Q and TSH at a specified gate opening

between computed and measured flows. Nash and Sutcliffe (1970) proposed such a transformation as follows:

$$E = 1 - MSE / s_o^2 = R^2 - C^2 - B'^2 \quad (7)$$

where

E = the Nash-Sutcliffe efficiency coefficient
s_o^2 = the variance of the measured flow data set
C = a non-dimensional measure of conditional model bias
B' = a non-dimensional measure of unconditional model bias

The value of E can range from minus infinity to one. A value of E = 1 implies that the measured flows can be perfectly replicated by the rating equation. In contrast, E = 0 would indicate that the rating equation is no better a predictor of culvert flows that the mean (i.e. expected) measured flow value. A value of E less than 0 would suggest that the rating equation is so poor that the mean measured flow value is actually a better predictor of flow than the rating equation. Hence, a value as close to 1 as possible is desirable.

Given these principles, the following calibration quality indicators are suggested:

- If $0.9 \le E \le 1$, the rating calibration should be considered "excellent"
- If $0.8 \le E < 0.9$, the rating calibration should be considered "good"
- If $0.7 \le E < 0.8$, the rating calibration should be considered "fair"
- If $0.6 \le E < 0.7$, the rating calibration should be considered "poor"
- If $E < 0.6$, the rating calibration should be considered "bad"

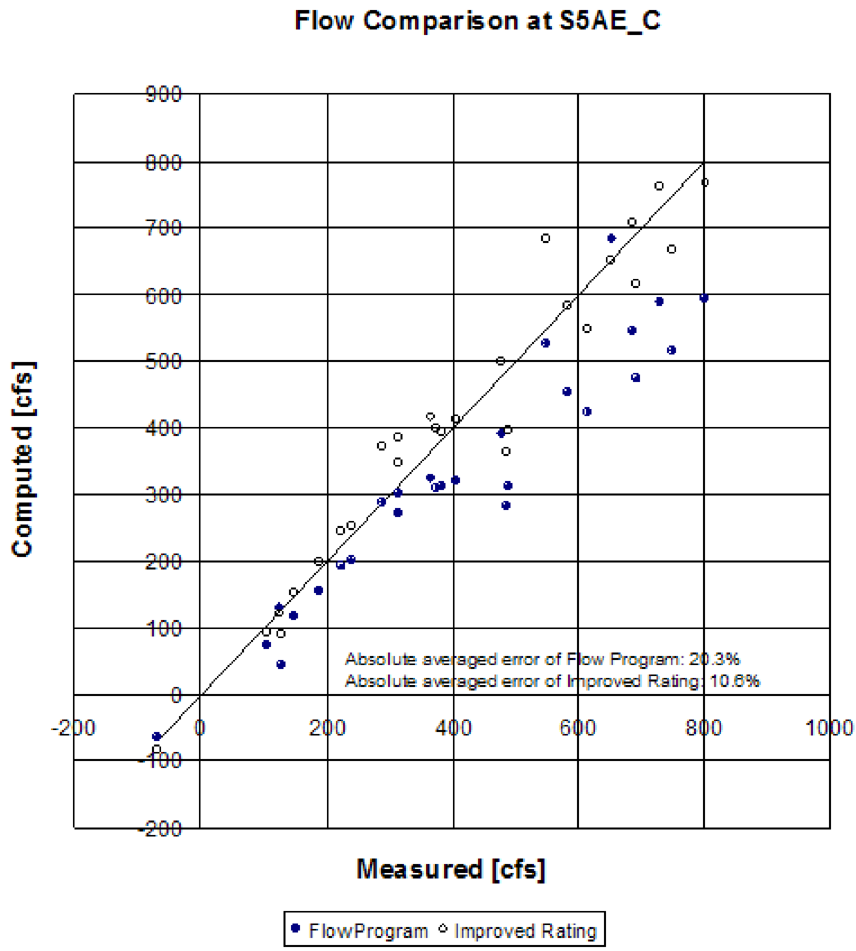

Figure 3. Rating results for S5AE comparing computed flows to measured flows

Expressions for R, C and B' are provided by Weglarczyk (1998). However, for rating analysis purposes, it should usually not be necessary to compute these quantities in addition to the Nash-Sutcliffe efficiency coefficient E. In most cases the evaluation of the computed versus measured flow plot as discussed previously should provide enough insight into the computed value of E.

2.7 Task 7. Uncertainty Analysis

Estimating the uncertainties inherent to structure flow rating is an important and challenging task. Many sources contribute to the uncertainties of flows computed with rating equations (Gonzalez et al., 1996 and 2000). These sources include measurement errors as well as the inability of these rating equations to accurately reproduce the complex nature of culvert hydraulics. Uncertainty analysis of culvert flow computation is a topic that is still under investigation. The first order Taylor approximation was used by Wilsnack (2008) to estimate the uncertainties of computed flows through spillway G-311. In that study, the uncertainties inherent to computed flows due to uncertainties in rating parameters and spillway properties were investigated. In addition, Damisse et al (2008) have developed a method based on Monte Carlo simulations to evaluate the uncertainties of computed flows through the S-65E spillway. An uncertainty analysis of computed culvert flows was performed by Zhang et al (2009), who applied the first order Taylor estimation and Monte Carlo simulation methods to the G-92 and G-342 box culverts.

If the rating equation was calibrated to measured flows using the inverse parameter estimation techniques mentioned earlier, Predictive Analysis (Doherty, 2004) or the Subspace Monte Carlo technique (Tonkin and Doherty, 2009) can be very effective in evaluating the uncertainties of computed flows under a variety of conditions. Initial applications of Predictive Analysis by OHDM staff, however, revealed that it does not work well when applied to submerged culvert flows. This may be due to the fact that the nonlinear nature of computed culvert flows results in many local maxima and minima throughout the parameter subspace of interest. Obviously, predicting a maximum or minimum discharge rate within a given parameter space under these conditions can be very problematic. Additional investigations are needed to determine if Predictive Analysis can be adapted to these conditions, or if these difficulties can be circumvented through linearization of Equation (4). Doherty (personal communication) recommends that Subspace Monte Carlo techniques be used for nonlinear models.

Additional research is needed before any specific recommendations can be made regarding the selection of an uncertainty analysis methodology for assessing the uncertainty of computed culvert flows. In the interim, the aforementioned methodologies can be implemented on a case-by-case basis to gain additional insight into their ranges of application in flow rating analysis.

2.8 Task 8. Impact Analysis

An impact analysis is performed to evaluate the need to re-compute historical flows with the new rating equation. If the culvert is new or has been structurally modified, then the new rating equation would obviously not apply to the historical period of record (if one exists) and no impact analysis would be necessary. Otherwise, the period of record over which the new rating equation is applicable should be identified. The SOP No. Q117 (SFWMD, 2009) provides guidelines for modifying historical flow data.

After the appropriate period of record has been identified, the next step is to locate all of the static data in the *production* version (WREP) of the structure database that pertain to the culvert in question. These should initially match the corresponding data fields in the *development* version (WRED) of the database. If not, change the data values in the development database so that they all match those of the production database. Examples of relevant data fields include culvert barrel diameter, upstream and downstream invert elevations, etc. At this point, the parameters of the new rating equation should then be entered into the appropriate fields of the development database only.

The final step is to use the new rating equation to re-compute the break point flows over the established period of record or as otherwise indicated in the aforementioned SOP. This involves running the production version of the FLOW program while reading all static data and parameters from the development database WRED. A set of scripts that performs this task is available. The output from these scripts can be converted to mean daily flows using the RUNIVG program. This set of mean daily flows should be compared to the corresponding set of flows currently in DBHYDRO. The comparison should be made in accordance with SOP No. Q117.

2.9 Task 9. Document the Rating Analysis

The final task is to document the results of Tasks 1 – 8. The scope and extent of the documentation will vary depending on the size, function and complexity of the culvert. For example, the rating analysis for a small, standard culvert of simple design can be adequately documented in a Technical Note. In contrast, a large, STA outflow culvert with an unusual or complex design that requires an innovative rating analysis should have its rating analysis documented in a SHDM Technical Publication. Moreover, an intermediate facility should have its rating analysis documented in an OHDM Technical Bulletin. At the current time, there are no hard and fast policies dictating what the documentation scope and format should be for a given culvert rating.

3.0 SUMMARY

The rating analysis procedures and tasks outlined below are intended to provide general guidance and direction in conducting rating analyses of District culverts:

1. Review the facility layout and site conditions.
2. Acquire engineering data and drawings.
3. Evaluate the engineering data and culvert properties.
4. Determine the relationship between flow and head loss.
5. Determine the rating equation parameters.
6. Evaluate the accuracy and quality of the rating equation calibration.
7. Perform an uncertainty analysis.
8. Perform an impact analysis.
9. Document the rating analysis in an appropriate format.

The procedures presented in this report cannot (nor are they intended to) address all issues and situations that may arise in any given rating analysis. One must bear in mind that sound engineering judgment, experience, and familiarity with the culvert under consideration are essential for developing a defendable and accurate rating equation.

4.0 FUTURE EFFORTS

It is possible that a comprehensive approach to addressing the uncertainties inherent to computed flows can be formulated through the use of inverse parameter estimation techniques (e.g., PEST) or Monte Carlo based methods. This subject is currently under investigation. Additionally, synthetic flow data for flow regimes with rare occurrences, (e.g., type 3 of open channel flow) can be generated with CFD. This may be useful for filling in measured flow data gaps while also providing culvert flow data under conditions that are not conductive to accurate flow measurements.

5.0 REFERENCES

Brater, E. F. and H. W. King. 1976. *Handbook of Hydraulics.* McGraw-Hill, New York.

Chow, V. T. 1959. *Open-Channel Hydraulics*. McGraw-Hill, New York.

Damisse, E., and Fru, W., 2006. Improved Flow Computation at District Culverts. Technical Publication, Operation and Hydrodata Management Division, South Florida Water Management District, West Palm Beach, Florida, 7pp.

Damisse E., Gonzalez, J., Wang, F., Miralles, W. F., and Tang, W. Z. 2008. Uncertainty Analysis of a Flow Rating Equation for Uncontrolled Submerged Flow over a Spillway. OHDM Draft Report, SFWMD. West Palm Beach, FL. 18 pp

Daugherty, R. L. and Franzini, J. B. 1977. *Fluid Mechanics with Engineering Applications, 7th Ed.* McGraw-Hill, New York.

Doherty, J. E. 2004. PEST Model-Independent Parameter Estimation, User's Manual: 5th edition. Watermark Numerical Computing, Brisbane, Australia, 336 pp.

ECT and Sutron Corporation. 2008. Quality Assurance of Field Flow Measurements at SFWMD Structures. Deliverable 7.0, Contract No. ST060588-WO01, 50 pp.

FHWA., 2005. Hydraulic Design Series Number 5., Techinique Publication No. FHWA-NHI-01-020, Federal Highway Administration, U.S. Department of Transportation, McLean, Virginia, 368 pp.

Gonzalez, J. A., Melching, C. S., and Oberg, K.A. 1996. Analysis of open-channel velocity measurements collected with an acoustic doppler current profiler. Proceedings from the 1st International Conference on New/Emerging Concepts for Rivers, Organized by the International Water Resources Association, Chicago. Illinois. September 22-26, 1996.

Gonzalez, J. A., Oberg, K., Duncker, James J. 2000. Effects of Temporal Resolution on the Accuracy of ADCP measurements. Presented at the Joint ASCE Conference on Water Resources Engineering, Planning and Management, Minneapolis. July 30-Aug 3, 2000.

Lindeburg, R.M., 2008. Civil Engineering Reference Manual for the PE Exam (11th edition). Professional Publications Inc., Belmont, CA, p. A-36

Miller, D. S. 1990. *Internal Flow Systems, 2nd Edition*. Gulf Publishing Company, Houston, TX.

Nash, J. E. and J. V. Sutcliffe. 1970. River flow forcasting through conceptual models. Part I: A discussion of principles. *Journal of Hydrology*, 10, 282-290.

Pathak, C., and M. J. Chen. 2005. Evaluating and Improving Flow Data Quality Using STRIVE Data at Water Control Structures. Volume One, Technical Publication ERA # 428, Operations and Hydro Data Management Division, South Florida Water Management District, West Palm Beach, Florida, 30 pp.

SFWMD, 2009. Change Management Procedures for Hydrometeorological Data - *Draft*. South Florida Water Management District, West Palm Beach, Florida, 41 pp.

Tonkin, M., and J. Doherty. 2009. Calibration-constrained Monte Carlo analysis of highly parameterized models using subspace techniques, *Water Resour. Res.*, 45, W00B10, doi: 10.1029/ 2007WR006678.

Weglarczyk, S. 1998. The interdependence and applicability of some statistical quality measures for hydrological models. *Journal of Hydrology*, 206, 98-103.

Wilsnack, M. M. 2008. Flow Rating Analysis for Spillway G311, Stormwater Treatment Area 1 East. Technical Publication # EMA 2008-007, South Florida Water Management District, West Palm Beach, Florida, 32 pp.

Wilsnack, M. M. and J. Zeng. 2009. Atlas of Flow Computations at District Hydraulic Structures- *Draft*. South Florida Water Management District, West Palm Beach, Florida, 136 pp.

Zipparro, V. J. and Hasen, H., 1993. *Davis' Handbook of Applied Hydraulics.* McGraw-Hill, New York.

Zhang, L. Q., Damisse, E. Zeng, J. and Chen, Z. M. 2009. Uncertainty Analysis of Non Dimensional Analysis-Based Rating for Box-Culverts. OHDM Draft Report, South Florida Water Management District, West Palm Beach, FL.