TECHNICAL PUBLICATION
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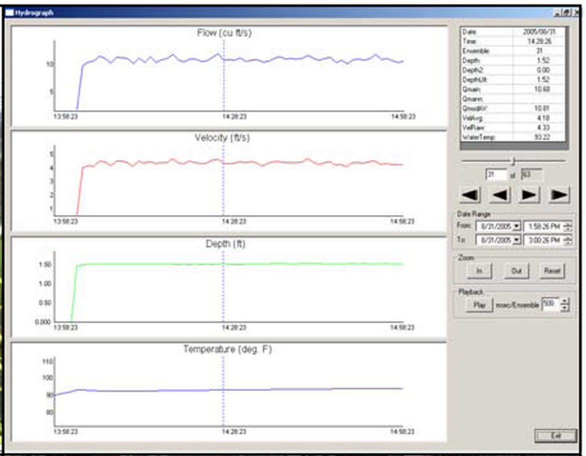
RATING DEVELOPMENT FOR FLOW THROUGH CULVERTS UNDER SR 9336 IN THE EVERGLADES NATIONAL PARK
III: FINAL REPORT



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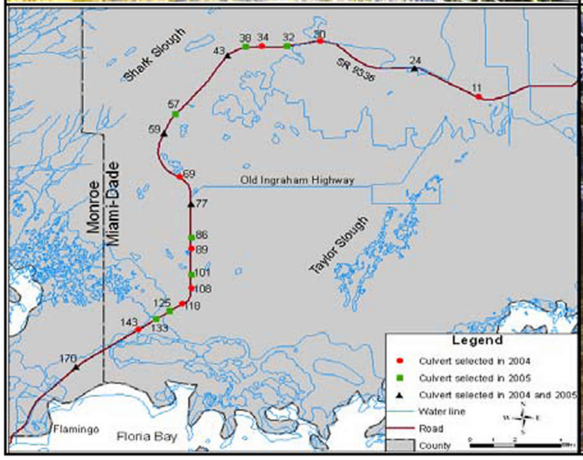

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January 2006

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EXECUTIVE SUMMARY

In this study, a total of nineteen representative sites were investigated and discharge ratings were developed for the 178 culverts underlying State Road 9336 (SR 9336) in the Everglades National Park (ENP). Field flow measurements were done at the nineteen culverts in 2004 and 2005. In 2004, a model (Model One) of discharge coefficient (C_d) as a function of the ratio of headwater depth to culvert diameter (h_1/D) was developed based on the flow measurements made at twelve representative culverts. In 2005, a second group of twelve culverts (five of them were in the first group of twelve) was selected for further analysis. By analyzing the data collected in 2005, it was possible to validate the discharge coefficient model of C_d as a function of h_1/D. An alternative model (Model Two) based on the regression of the discharge-area term on the head term was proposed and rated for individual culverts. Subsequently, a regression equation of $Q/(A_3\sqrt{2g})$ on $\sqrt{h_1 - h_4}$ was developed using all measurements of the nineteen representative culverts. The results reveal that: 1) A significant correlation exists between C_d and h_1/D; 2) In terms of the coefficient of determination between the computed and measured discharges, the two models give similar degrees of accuracy under the flow conditions in the ENP for the culverts investigated; 3) Using all measurements of the nineteen culverts, the regression of $Q/(A_3\sqrt{2g})$ on $\sqrt{h_1 - h_4}$ resulted in a simpler solution with reasonable accuracy.

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A_i = cross-sectional area of flow in the culvert barrel
A_3 = cross-sectional area of flow at culvert outlet
C_d = discharge coefficient for type 3 flow
D = diameter of culvert
g = acceleration due to gravity
h_1 = water level above datum at approach section upstream from the inlet
h_3 = water level above datum at the culvert outlet
h_4 = water level above datum downstream of the barrel
$h_{f\,2,3}$ = head loss due to friction in the culvert barrel
K_2 = conveyance of culvert inlet
K_3 = conveyance of culvert outlet
L = length of culvert barrel
n = Manning’s coefficient of roughness
Q = discharge through culvert
R = hydraulic radius

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BACKGROUND

The Florida Bay Flow Monitoring Assistance Project (C-15967-WO05) was initiated in January 2003. A total of 114 flow measurements were taken at 12 selected culverts underlying State Road 9336 (SR 9336) in the Everglades National Park (ENP) from June through November 2004. An Acoustic Doppler Flow Meter (ADFM) and an alternative Price Pygmy Current Meter (pygmy meter) were employed to measure discharge at the 12 culverts. A variable discharge coefficient model was developed based on the data of the 12 culverts (identified by number as 24, 30, 34, 43, 59, 69, 77, 89, 108, 118, 143 and 170). The results were presented in two previous reports (Wu and Imru, 2005a and 2005b) of the project.

The second phase of the project involved measuring discharge at 12 culverts (24, 32, 38, 43, 57, 59, 77, 86, 101, 125, 133, and 170) in 2005. Five of the 12 culverts were included in the original group of 12. Surveying bases were installed at the upstream and downstream ends of each of the 12 culverts to assist in accurately measuring stage. An engineering leveling instrument was used to determine the elevations of the bases and culvert inverts. The measurement scheme is presented in Appendix B. The ADFM and an alternative Acoustic Doppler Velocity (ADV) flow tracker were used to measure discharge. During the wet seasons of 2004 and 2005, a total of 219 field flow measurements were made including 105 measurements made in July through September of 2005.

The purpose of this report is to verify the previous (2004) results, and, if necessary, to improve the ratings for culvert flow in the ENP. This report presents the flow measurements, rating analysis, and the results based on the 219 measured flows. Appendix A lists responses to the reviewers' comments and recommendations for the previous two reports (i.e., Wu and Imru, 2005a and 2005b).

The rating analysis presented in this report validated the model, which relates the discharge coefficient (C_d) to the ratio of headwater depth and culvert diameter (h_1/D), as described in the previous two reports. Additional analysis in this study indicates that the discharge coefficient can be estimated from a regression of $Q/(A_3\sqrt{2g})$ on $\sqrt{h_1 - h_4}$. This estimation model gives similar results as the former model of C_d based on h_1/D, but the resulting coefficient is a constant, i.e., simpler and more straightforward to use.

DESCRIPTION OF CULVERTS

A total of 19 culverts (Table 1) were selected for this study from the 178 culverts underlying SR 9336 in the ENP. The locations of the selected culverts are shown in Figure 1.

Criteria for selection of representative culverts are (1) the ends of the culverts are not damaged or blocked by gravel; (2) the culvert outlets are not surrounded or covered by grass and/or trees so that the flow meter can be easily used; and (3) the stream channels at the farthest upstream and downstream sections are clear and not blocked by trees for accurate stage measurement.

The culverts in this study (ENP culverts) can be divided into three groups according to their shapes and site conditions. The different shapes and site conditions of ENP culverts are represented by the 19 culverts selected.

Group 1: culverts with a vertical headwall
Culverts 77, 86, 101, and 170 belong to this group. Each culvert has a circular entrance mounted flush with a vertical headwall (Figure 2).

Table 1 Culvert information

Culvert No.	Group	Period of record	Number of flow measurements	Minimum discharge (ft^3/s)	Maximum discharge (ft^3/s)	Median discharge (ft^3/s)
24	3	Aug-Oct 2004 Jun-Sep 2005	10	0.543	5.286	2.593
30	3	Aug-Oct 2004	6	0.183	0.666	0.342
32	3	Jul-Sep 2005	9	0.177	6.681	2.254
34	3	Aug-Nov 2004	11	0.236	5.603	2.856
38	3	Aug-Sep 2005	7	2.077	8.550	4.866
43	2	Jul-Oct 2004 Aug-Sep 2005	19	0.542	8.589	3.994
57	2	Jul-Sep 2005	12	0.225	10.872	2.329
59	2	Jun-Oct 2004 Jun-Sep 2005	23	0.386	13.380	5.526
69	2	Jul-Oct 2004	13	0.607	7.755	3.006
77	1	Jul-Oct 2004 Jun-Sep 2005	23	0.364	11.913	3.364
86	1	Aug-Sep 2005	7	0.798	10.863	4.138
89	1	Aug-Nov 2004	10	0.725	3.399	1.972
101	1	Jul-Sep 2005	12	0.657	10.289	2.995
108	1	Aug-Nov 2004	10	0.371	2.987	1.433
118	1	Aug-Nov 2004	10	0.209	1.692	0.888
125	2	Aug-Sep 2005	7	0.372	7.598	2.817
133	3	Jul-Sep 2005	11	0.262	7.702	2.252
143	2	Aug-Nov 2004	9	0.089	0.947	0.421
170	1	Jul-Oct 2004 Jun-Sep 2005	10	0.196	3.364	0.984

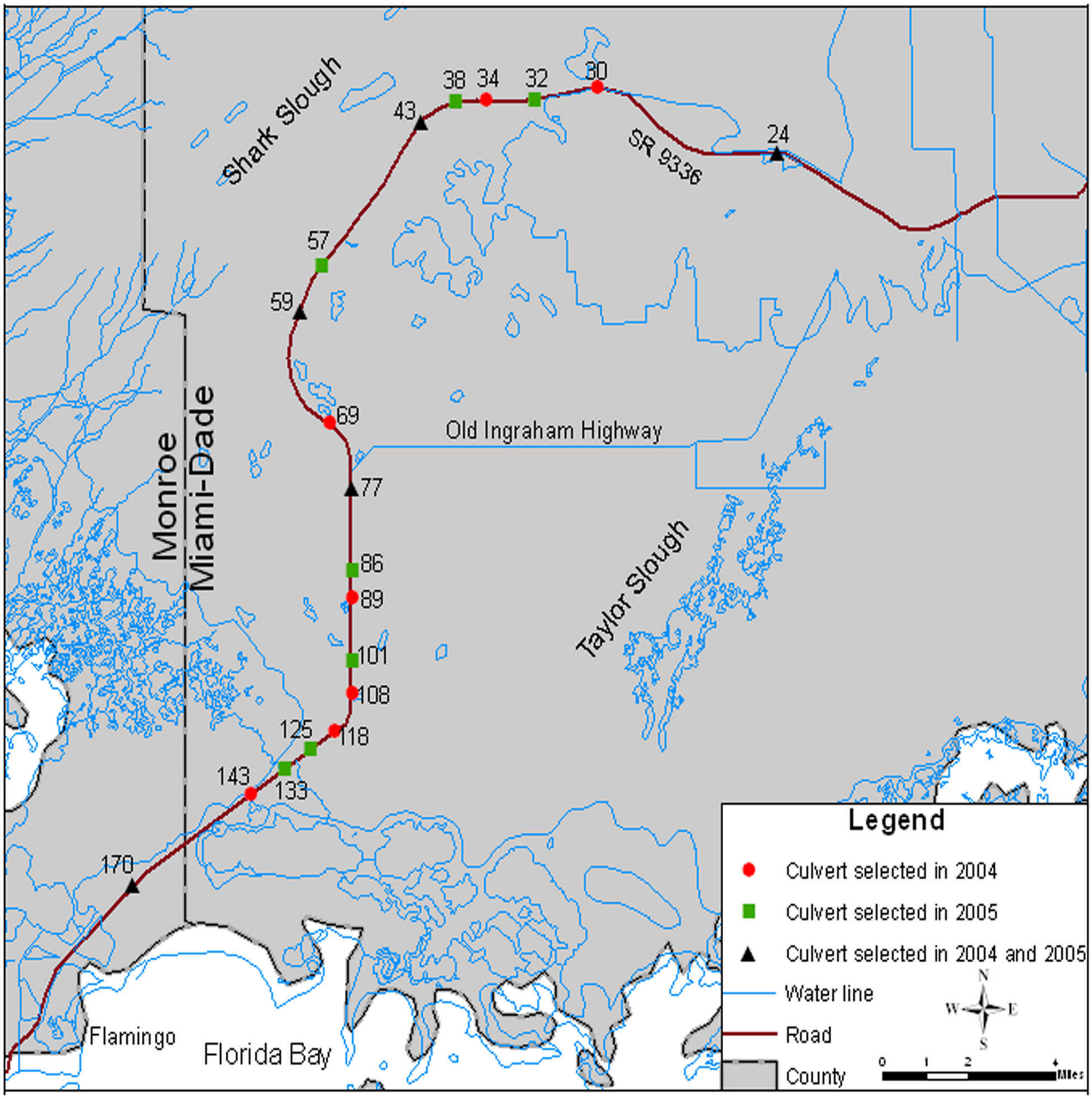

Figure 1 Locations of the selected culverts in the Everglades National Park

Figure 2 The outlet of Culvert 77 – set flush with vertical headwall

The entire floor of the culvert barrel is at the same level as the channel bottom, which allows water to flow smoothly through the culvert. However, the culvert inlet and outlet are small compared to the channel width upstream and downstream of the barrel. Hence, the water in the stream must converge at the sharp-edged flush inlet and diverge at the sharp-edged flush outlet. This flow pattern influences measurement accuracy and affects estimates of the discharge coefficient.

Group 2: culverts with beveled ends

Culverts 43, 57, 59 and 125 have beveled ends. As with Group 1, the barrel floors of Group 2 culverts are at the same level as the channel bottom (Figure 3). The culvert inlets are rounded and more open than those of culverts with the vertical headwall in Group 1.

Figure 3 The outlet of Culvert 59— beveled ends

Group 3: culverts with ends buried underground

Culverts 24, 32, 38 and 133 also have beveled ends, but both ends of the barrels are partially or even deeply buried underground (Figure 4 and Figure 5).

Figure 4 The outlet of Culvert 24 (at the center of the photograph) covered by dense grass

Figure 5 The outlet of Culvert 32

In the study, these three groups were used to represent the 178 culverts underlying SR 9336. During the rating analysis, attempts were made to watch whether the group characteristics significantly affect the flow conveyance capabilities of the culverts.

FLOW MEASUREMENTS

Flows through the 2-ft diameter culverts in the ENP are not easy to accurately measure because they are only partially full, and discharge generally is less than 4 cubic feet per second (ft^3/s). ADFM, Price pygmy current meter and ADV flow tracker, were used to measure flow in the study. ADFM was used as the primary instrument, whereas the pygmy meter and ADV were used as alternative instruments to monitor the accuracy and consistency of ADFM measurements, in 2004 and 2005, respectively, when velocities were less than 0.5 *ft/s*.

1) ADFM

The principle and operation of ADFM were presented in the second report (Wu and Imru, 2005b) of the project. ADFM records the velocity, discharge, water depth and temperature with a one-minute time interval. Discharge measurements usually take 30 to 60 minutes at each culvert depending on the ADFM stability. For velocities greater than 0.5 *ft/s*, the flow measurements are very stable.

For example, Figure 6 shows results from a flow measurement at Culvert 86 in Aug 31, 2005. The average, maximum, and minimum velocities are 4.237, 4.628 and 3.929 *ft/s*, respectively. The corresponding discharges are 10.863, 11.880 and 10.086 ft^3/s, respectively.

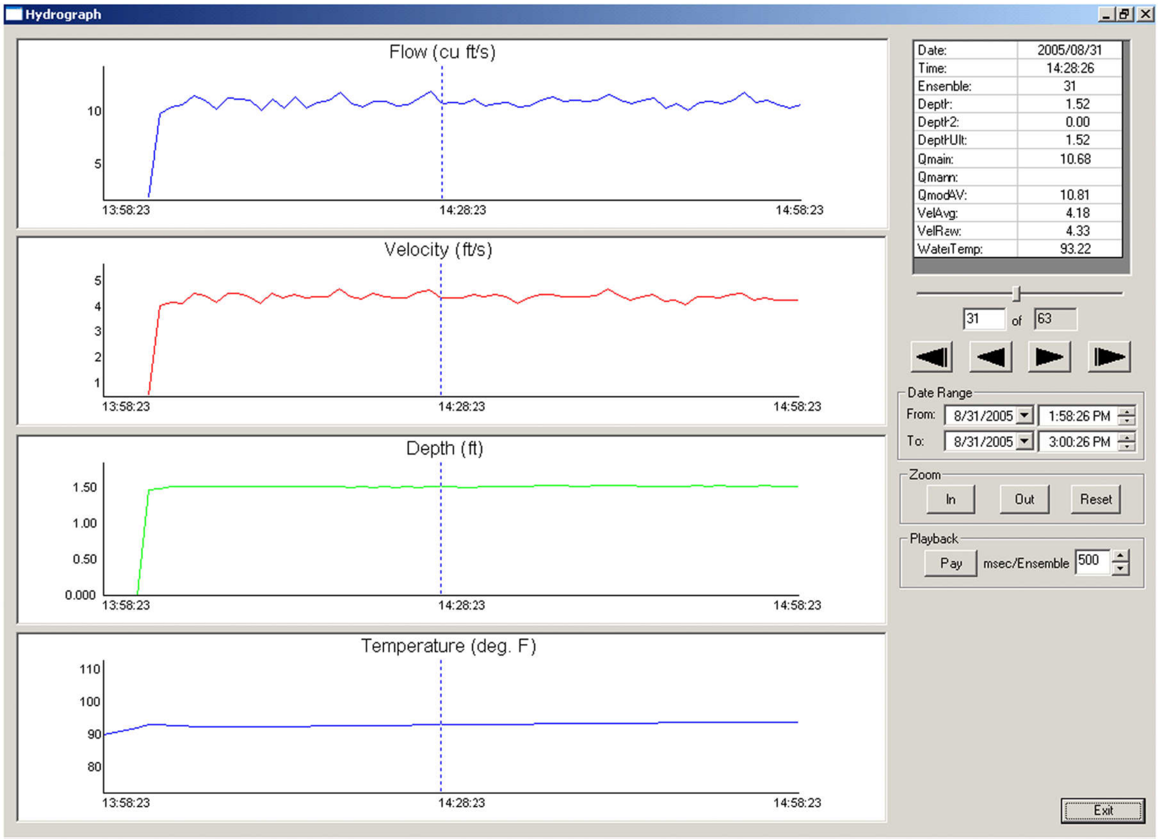

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Figure 6 ADFM flow measurement with a large discharge at Culvert 86 on 08/31/05

ADFM is less stable for measuring low velocities (less than 0.5 *ft/s*). For example, ADFM, used to measure flow at Culvert 59 on 07/27/05, indicates that velocity ranged from -0.274 to 0.809 *ft/s,* and discharge varied from -3.495 to 10.334 ft^3/s (Figure 7). Water depth remained stable during the measurement interval; hence, variations in discharge probably resulted from instability of the instrument at low velocities. Under these conditions, an alternative instrument (in this case, the ADV) was used.

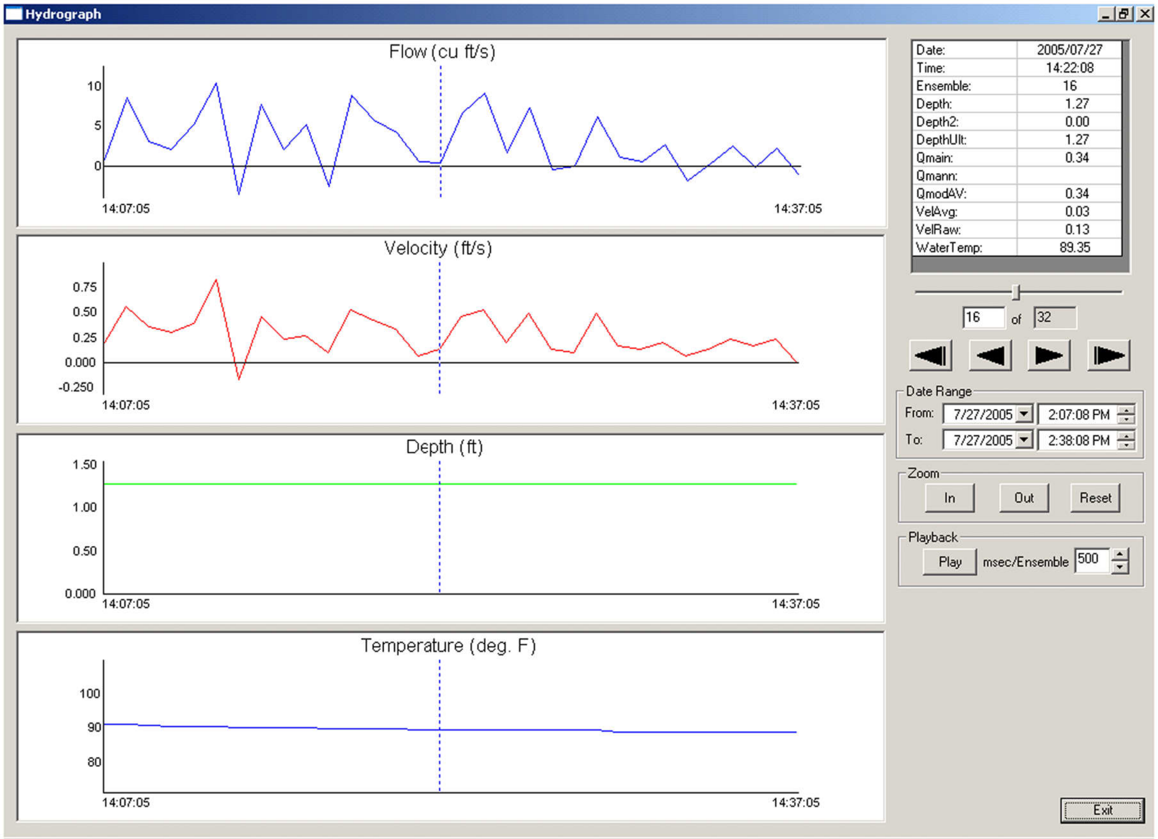

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Figure 7 ADFM discharge measurement at Culvert 59 with small flows (07/27/05)

2) Price Pygmy Meter and ADV Flow Tracker

Starting from August 2005, the pygmy meter was used to measure flow when velocities were less than 0.5 *ft/s*. A pygmy meter is a mechanical device equipped with a bucket wheel for measuring velocity. However, friction prevents the wheel from turning at very low velocities. Buchanan and Somers (1969) recommended not using pygmy meter in velocities less than 0.2 *ft/s*. Our results indicate that the pygmy meter stops working at velocities less than 0.2 *ft/s*. For this reason, the ADV was used as an alternative instrument in September 2005.

The ADV, a handheld instrument with a screen display and built-in temperature sensor, employs the same principle as that of ADFM. Velocities were measured using the ADV at 0.6 water depth, as recommended in the literature for measuring flow using index current meters (Buchanan and Somers, 1969).

The ADFM requires a minimum of 0.8 *ft* water depth, whereas the ADV can make flow measurements in water as shallow as 1 *inch* and velocities ranging from 0.003 *ft/s* to 15 *ft/s* (0.001 to 4.5 *m/s*). Velocity resolution for the ADV is 0.0003 *ft/s* (0.0001 *m/s)* with an accuracy of ±1% of actual velocity. ADV also requires less time than the ADFM in making flow measurements. Our experience indicates that measurements become stable about 40 seconds after the transmitter is put in the water. The following two features reduce the acoustic transmitter's disturbance of the flow: 1) the size of the transmitter is very small (the probe is 0.4 *inch* in diameter and 2.5 *inches* long); and 2) the tip of the transmitter probe is located about 4 *inches* away from the measuring point in the flow path, which reduces the device's effects on flow. The accuracy and stability of the ADV for field flow measurements needs further investigation, which is beyond the scope of this study.

FLOW TYPE OBSERVED IN THE EVERGLADES NATIONAL PARK

The predominant culvert flow in the ENP is Type 3, which was presented in detail in the previous two reports (Wu and Imru, 2005a and 2005b) of the project. For Type 3 flow, the discharge equation is expressed as follows (Carter, 1957; Bodhaine, 1968; Wu and Imru, 2005a):

$$Q = C_d A_3 \sqrt{2g(h_1 - h_3 - h_{f2,3})} \tag{1}$$

Where, Q — discharge (ft^3/s)

C_d — discharge coefficient

A_3 — cross-sectional area of flow at the culvert outlet (ft^2)

g — acceleration due to gravity (ft/s^2)

h_1 — headwater level at the approach section (ft)

h_3 — tailwater level at the culvert outlet (ft)

$h_{f,2-3}$ — friction loss in the culvert barrel (ft).

$h_{f,2-3}$ can be expressed as (Bodhaine, 1968)

$$h_{f,2-3} = \frac{Q^2 L}{K_2 K_3} \tag{2}$$

Where, L — culvert length (ft)

K_2, K_3 — conveyance at the culvert inlet and outlet

$K_i = \frac{1.486}{n} R_i^{2/3} A_i$

n — Manning's roughness coefficient, n=0.013 as indicated in the first report (Wu and Imru, 2005a) of the project

R_i — hydraulics radius (ft)

A_i — sectional area at the culvert inlet and outlet (ft^2)

i =2 and 3, stand for the culvert inlet and outlet, respectively

Substituting Equation (2) into Equation (1) and assuming h_3 equal to h_4 (Bodhaine, 1968), then

$$Q = C_d A_3 \sqrt{\frac{2g(h_1 - h_4)}{1 + \frac{2gC_d^{\,2} A_3^{\,2} L}{K_2 K_3}}} \tag{3}$$

and

$$C_d = \sqrt{\frac{Q^2}{2gA_3^{\,2}(h_1 - h_4 - \frac{Q^2 L}{K_2 K_3})}} \tag{4}$$

Equation (3) is applied to culvert Type 3 flow, and its criteria can be described as $(h_1 - z)/D < 1.5$, $h_4/D \leq 1.0$, $h_4/h_c > 1.0$.

FLOW RATING MODELS

Two models were developed for estimating discharge through culverts from stage data at the upstream and downstream or inlet and outlet ends of the culverts. In each model, the discharge coefficient (C_d) needs to be estimated. In Model One, C_d is estimated as a function of the ratio of upstream water level (h_1) and culvert diameter (D). In Model Two, C_d is estimated as a function of discharge, cross-sectional area, and difference in upstream and downstream water levels.

MODEL ONE--RATINGS BASED ON C_d AS A FUNCTION OF h_1/D

Carter (1957) and Bodhaine (1968) developed a relationship between discharge coefficient (C_d) and the ratio of headwater depth to culvert diameter (h_1/D). The form of the regression model is

$$C_d = a\left(\frac{h_1}{D}\right) + b \tag{5}$$

Where, *a* and *b* are coefficients determined by the least squares method.

Wu and Imru (2005a and 2005b) used this model in the first phase of the study to calculate C_d and estimate discharge through the culverts. The results indicated a significant relation between C_d and h_1/D for the 12 selected culverts in the ENP. To verify these results, rating analysis was conducted for all 219 flow measurements collected in 2004 and 2005. First, C_d values were calculated for each culvert by using field data to solve Equation (4). Subsequently, these C_d values were used in Equation (5) to determine *a* and *b* by the least squares method. The results are listed in Table 2. The table presents the regression equations, coefficient of determination (R^2), correlation coefficient (R), number of flow measurements (n) for which C_d was determined, and critical value for the Spearman Rank correlation values for the 19 culverts investigated in 2004 and 2005.

Table 2 Regression using Model One for individual culverts investigated in 2004 and 2005

Culvert No.	Group	Coefficients for Equation (5)	R^2	R	n	Critical value (α =0.05)
Culverts investigated in 2004						
30	3	$C_d = 0.50(h_1/D) - 0.36$	0.97	0.98	4	-
34	3	$C_d = 4.24(h_1/D) - 3.51$	0.94	0.97	8	0.738
69	2	$C_d = 0.89(h_1/D) + 0.06$	0.70	0.84	10	0.648
89	1	$C_d = 1.37(h_1/D) - 0.06$	0.96	0.98	4	-
108	1	$C_d = 3.15(h_1/D) - 1.29$	0.71	0.84	9	0.700
118	1	$C_d = 1.08(h_1/D) + 0.05$	0.90	0.95	5	-
143	2	$C_d = 1.61(h_1/D) - 0.12$	0.86	0.93	6	0.886
Culverts investigated in 2004 and 2005						
24	3	$C_d = 0.85(h_1/D) - 0.81$	0.30	0.55	10	0.648
43	2	$C_d = -0.32(h_1/D) + 1.09$	0.64	0.80	12	0.591
59	2	$C_d = 0.39(h_1/D) + 0.34$	0.37	0.61	20	0.450
77	1	$C_d = 0.25(h_1/D) + 0.68$	0.42	0.65	10	0.648
170	1	$C_d = 1.27(h_1/D) - 0.20$	0.53	0.73	8	0.738
Culverts investigated in 2005						
32	3	$C_d = 5.63(h_1/D) - 3.72$	0.88	0.94	5	-
38	3	$C_d = 0.50(h_1/D) + 0.28$	0.88	0.94	5	-
57	2	$C_d = 0.87(h_1/D) - 0.18$	0.88	0.94	7	0.786
86	1	$C_d = 0.21(h_1/D) + 0.63$	0.84	0.92	6	0.886
101	1	$C_d = 0.66(h_1/D) + 0.02$	0.75	0.87	10	0.648

Culvert No.	Group	Coefficients for Equation (5)	R^2	R	n	Critical value (α =0.05)
125	2	$C_d = 1.03(h_1/D) + 0.02$	0.93	0.96	4	-
133	3	$C_d = 0.89(h_1/D) - 0.48$	0.87	0.93	9	0.700

The critical value for the Spearman Rank correlation coefficient (Table 2) is used to determine the significance of correlation coefficient (R) (Larson, 2003). The fifth column n represents the number of pairs of data based on which the regression in the second column was obtained, and the sixth column represents the critical values for a level of significance $\alpha = 0.05$. The table shows that the R values are greater than the corresponding critical value for all culverts except for Culvert 24, indicating a significant correlation between C_d and h_1/D. The R^2 values for culverts 24, 43, 59, 77, and 170 are relatively lower than the R^2 values for the other 14 culverts. The relatively low R^2 value might be an artifact of data being collected in complex configuration. Culvert 24 is deeply buried underground, which results in less accurate flow measurements. Table 2 also shows considerable variability in the regression coefficients a and b. Coefficient a is positive for all culverts, except for Culvert 43, where a is negative, and thus considered unreasonable. Coefficient b can be either negative or positive. Each pair of coefficients (a and b) is culvert-specific, indicating that the model is applicable when the culverts are considered individually.

Figures 8 through 12 show the relation between actual and simulated discharges, calculated from Equation (3), where C_d is obtained from Equation (5). There are 5 culverts investigated in both 2004 and 2005, and the results of these 5 culverts are presented for the validation of the model in Figures 8 through 12.

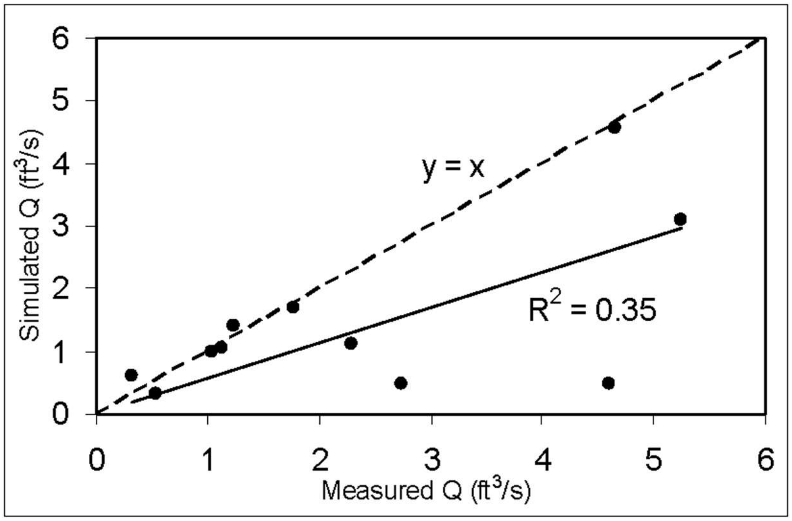

Figure 8 Simulated and measured discharges for Culvert 24 using *C_d* as a function of *h_1/D*

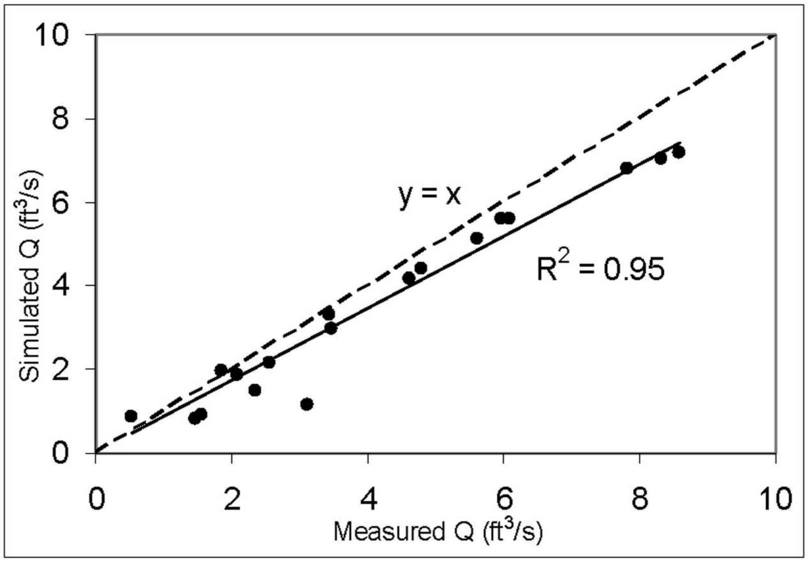

Figure 9 Simulated and measured discharges for Culvert 43 using *C_d* as a function of *h_1/D*

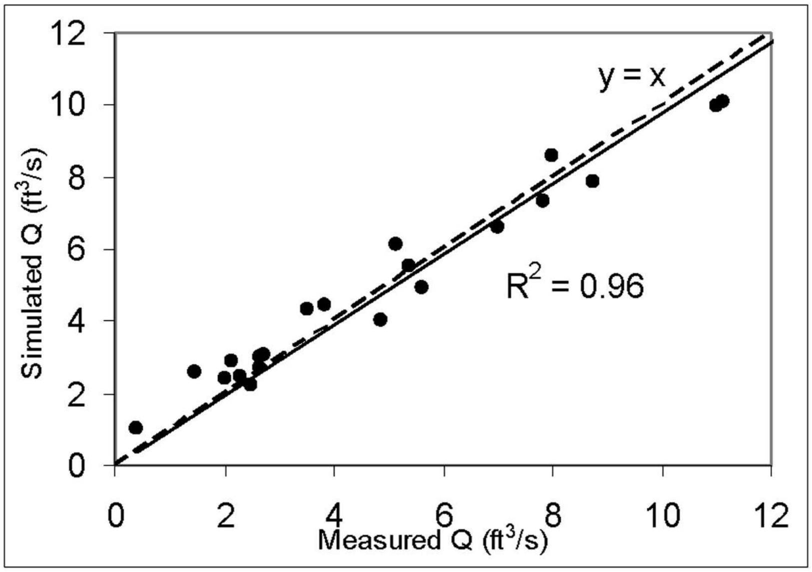

Figure 10 Simulated and measured discharges for Culvert 59 using C_d as a function of h_1/D

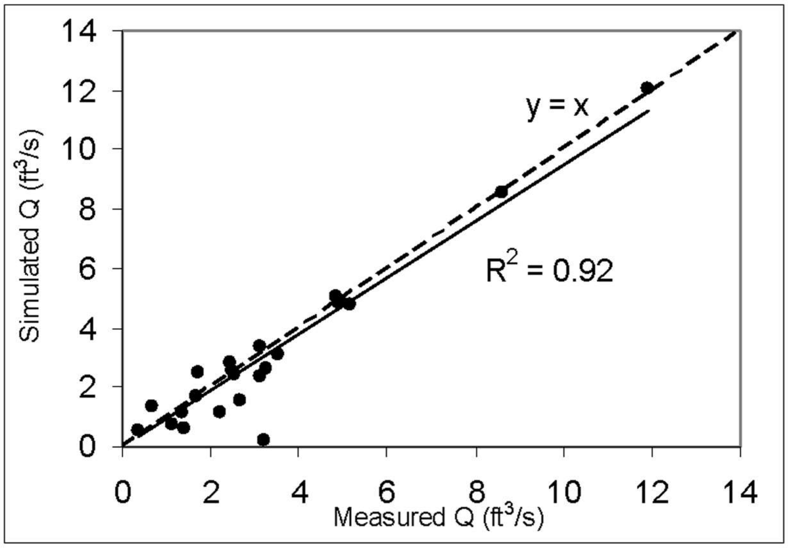

Figure 11 Simulated and measured discharges for Culvert 77 using C_d as a function of h_1/D

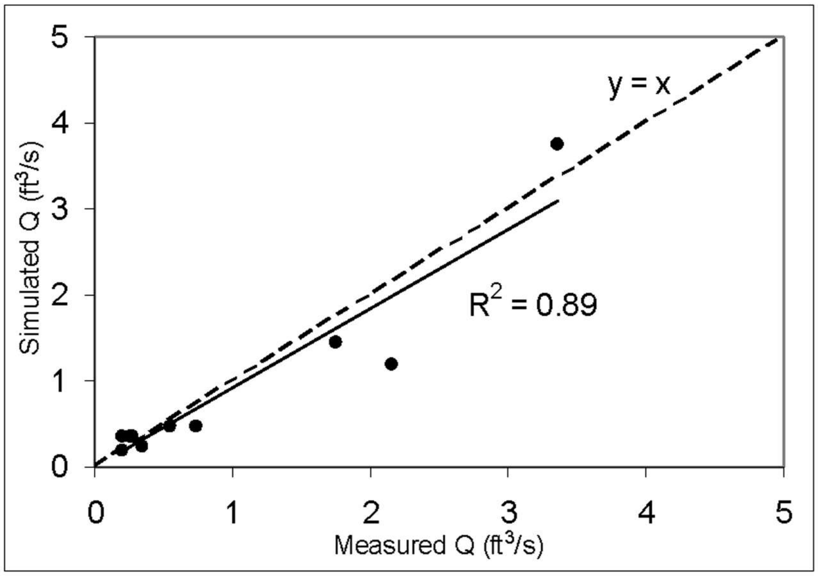

Figure 12 Simulated and measured discharges for Culvert 170 using C_d as a function of h_1/D

These results indicate the following:

1. Simulated discharge values for Culvert 24 are significantly less than measured discharge for five out of eleven data points. These five data points also happen to be the points with the largest measured discharges (greater than 2 ft^3/s). The poor agreement between measured and simulated discharge at these five data points might result from the unusual configuration of Culvert 24.

2. For most culverts, the relative errors lie within ±10%. Furthermore, as discharge increases, the relative error between measured and simulated discharges decreases.

3. The accuracy of simulated discharges decreases as the difference in the water levels decreases. Water-level differences less than the measurement error of the instruments can result in large variations of discharge coefficients. The use of ADFM can also cause errors when measuring small discharges. These factors are critical in determining the discharge coefficients.

4. The categorization of groups does not show an effect on the model. The result for Culvert 24 in Group 3 was presumably influenced by the inaccuracy of measurements due to unusual culvert configuration.

The preceding analysis demonstrated a linear relation between culvert discharge coefficient (C_d) and the ratio of headwater to culvert diameter (h_1/D). However, the regression coefficients *a* and *b* vary considerably from culvert to culvert, causing limitations when applying this model with a single C_d value to all the culverts in the ENP. For better application of Equation (3), the discharges had to be measured first and then the regression coefficients *a* and *b* had to be calibrated for each culvert individually. Furthermore, the calculations of K_2 and K_3 [Equation (3)] are complex. To simplify the calculation, a second model was applied.

MODEL TWO--RATINGS BASED ON REGRESSION OF $Q/(A_3\sqrt{2g})$ *ON* $\sqrt{h_1 - h_4}$

A second model was used in this study, and it is similar to a model used by previous investigators (Tillis and Swain, 1998). This model considers only the effect of discharge and water head difference on the flow, and the expression is given by

$$Q = C_d A_3 \sqrt{2g(h_1 - h_4)} \tag{6}$$

Where, h_1 — headwater level downstream of the barrel (*ft*)

Equation (6) can then be rewritten as

$$\frac{Q}{A_3\sqrt{2g}} = C_d \sqrt{h_1 - h_4} \tag{7}$$

First, C_d was determined individually for each of 12 culverts through regression analysis of Equation (7) with measured discharge (Q) and water-level data (h_1 and h_4). Second, discharge values were calculated using Equation (3) and the C_d values determined from Equation (7). Simulated and measured discharges were compared using the Spearman Rank correlation coefficient. Finally, a single constant C_d was estimated for all 19 culverts by regression using Equation (7). Discharges calculated using the resulting C_d were correlated to measured discharges for the 19 culverts.

Rating calibration for individual culverts

Table 3 lists the regression results for the 12 culverts investigated in 2005.

Table 3 Regression using Model Two for individual culverts investigated in 2005

Culvert No.	Group	Constant C_d for Equation (7)	R^2	R	n	Critical value (α =0.05)
24*	3	0.32	0.35	0.59	9	0.700
32	3	0.83	0.93	0.96	8	0.738
38	3	0.68	0.91	0.95	7	0.786
43*	2	0.80	0.89	0.94	13	0.566
57	2	0.59	0.88	0.94	9	0.700
59*	2	0.66	0.92	0.96	20	0.450
77*	1	0.76	0.89	0.94	13	0.566
86	1	0.68	0.95	0.97	7	0.786
101	1	0.54	0.82	0.91	12	0.591
125	2	0.77	0.76	0.87	6	0.886
133	3	0.47	0.78	0.88	10	0.648
170*	1	0.56	0.85	0.92	10	0.648

Note: 1) * includes measurement data collected in 2004 and 2005;

2) n stands for the data pairs used to obtain the regression coefficient and R^2. The total of n does not include the data collected in 7 culverts investigated in 2004.

In Table 3, the R values are greater than the critical values for all culverts except for Culvert 24. For Culvert 24, R^2 is only 0.35. As discussed previously, Culvert 24 is deeply buried, and accurately measuring flow through deeply buried culverts is difficult. C_d ranges from 0.47 to 0.83 for 11 of the 12 culverts, with an average value of 0.67.

Figures 13 through 24 show the relation between measured and simulated discharges using the values of C_d from Table 3. The corresponding data are presented in Tables C1 through C12 of Appendix C. The tables also include the relative error, standard deviation, and coefficient of variation. The R^2 value between the simulated and measured discharge is greater than 0.89 for all culverts except for 24 and 133, which have R^2 values of 0.44 and 0.77, respectively. Figures 14 through 24 also indicate that the simulated discharge is often less than the measured discharge, particularly for values greater than about 6 ft^3/s.

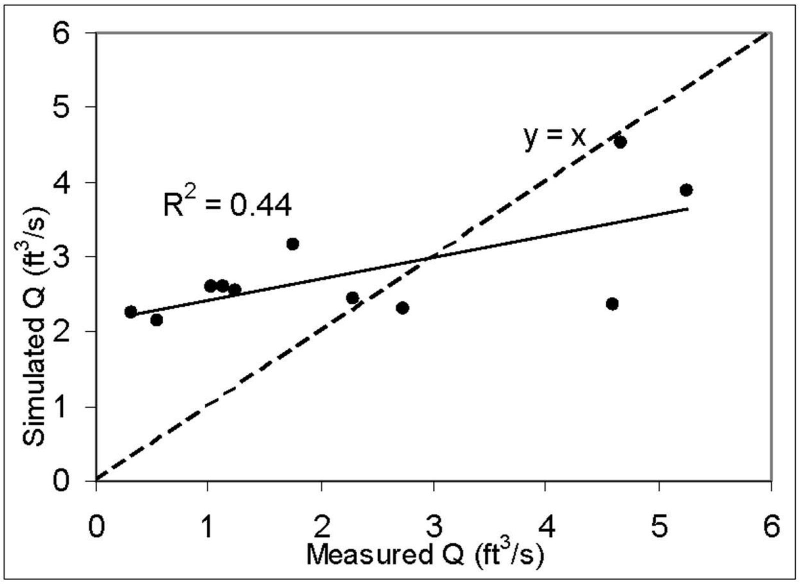

Figure 13 Simulated and measured discharges for Culvert 24 using discharge coefficient model based on $Q/(A_3\sqrt{2g})$ as a function of $\sqrt{h_1 - h_4}$

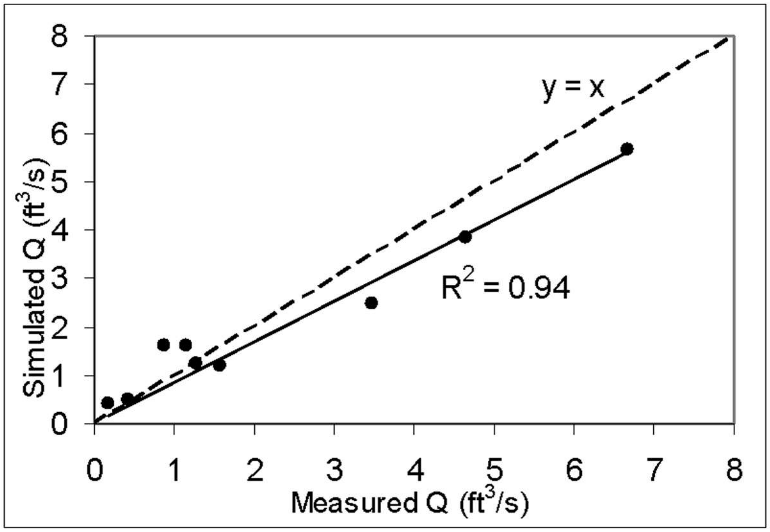

Figure 14 Simulated and measured discharges for Culvert 32 using discharge coefficient model based on $Q/(A_3\sqrt{2g})$ as a function of $\sqrt{h_1 - h_4}$

Two groups of data points, one group with a low discharge range and another group with a higher discharge range, can be observed in Figure 15.

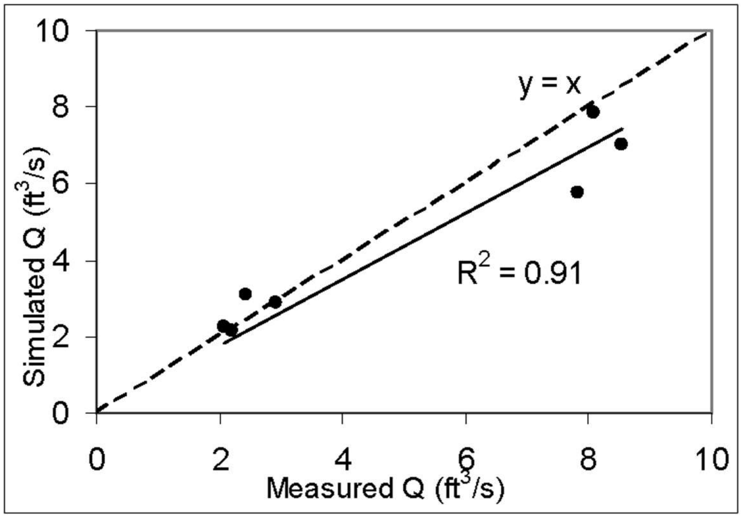

Figure 15 Simulated and measured discharges for Culvert 38 using discharge coefficient model based on $Q/(A_3\sqrt{2g})$ as a function of $\sqrt{h_1 - h_4}$

At this site (Culvert 38), a total of 7 flow measurements were made from August 3 to September 13, 2005. Between August 3 and August 23, 4 measurements were made with discharges between 2 and 3 ft^3/s which occurred as base flow. After August 23, the discharges were as high as about 8 ft^3/s. The high discharges occurred as flood and were caused by the rainfall from Hurricane Katrina which passed through the ENP area on August 25, 2005.

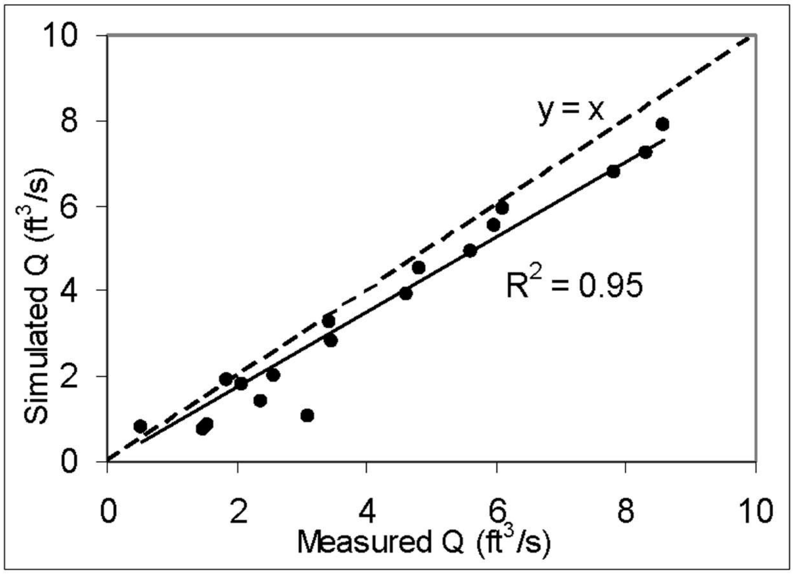

Figure 16 Simulated and measured discharges for Culvert 43 using discharge coefficient model based on $Q/(A_3\sqrt{2g})$ as a function of $\sqrt{h_1 - h_4}$

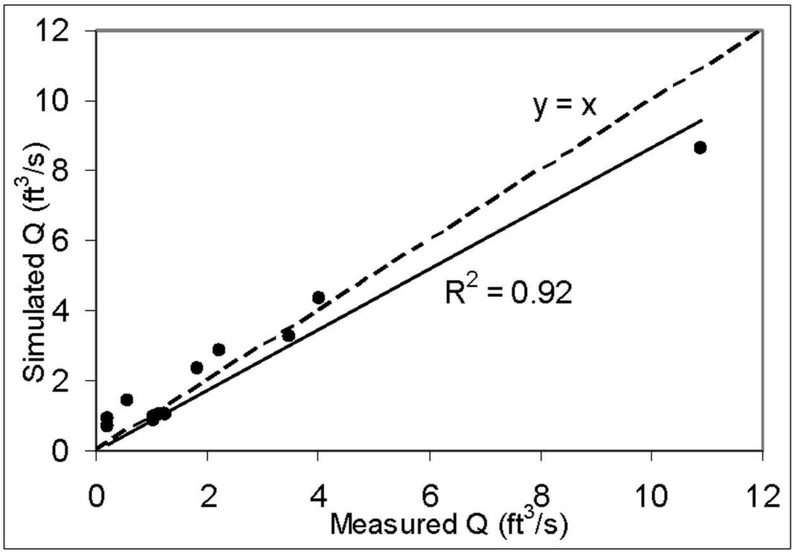

Figure 17 Simulated and measured discharges for Culvert 57 using discharge coefficient model based on $Q/(A_3\sqrt{2g})$ as a function of $\sqrt{h_1 - h_4}$

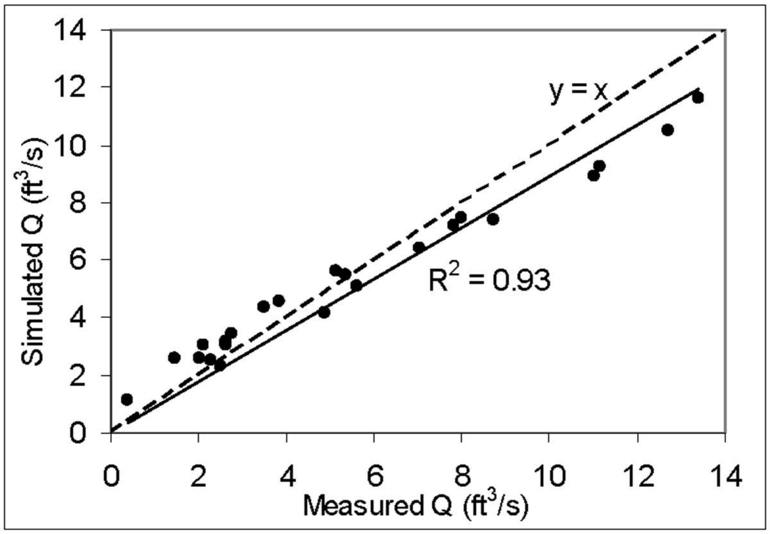

Figure 18 Simulated and measured discharges for Culvert 59 using discharge coefficient model based on $Q/(A_3\sqrt{2g})$ as a function of $\sqrt{h_1 - h_4}$

In Figure 19, one data point has a measured value of 3.223 *ft^3/s*, but a simulated discharge of close to 0.194 *ft^3/s*. Table C8 shows the result. This measurement was made on July 27, 2005, while for July 20 and August 03 2005, the measurements were 0.700 and 0.364 *ft^3/s*, respectively. During this period, there was not much rainfall in the ENP area. This suggests that the large value 3.223 *ft^3/s* may be an outlier.

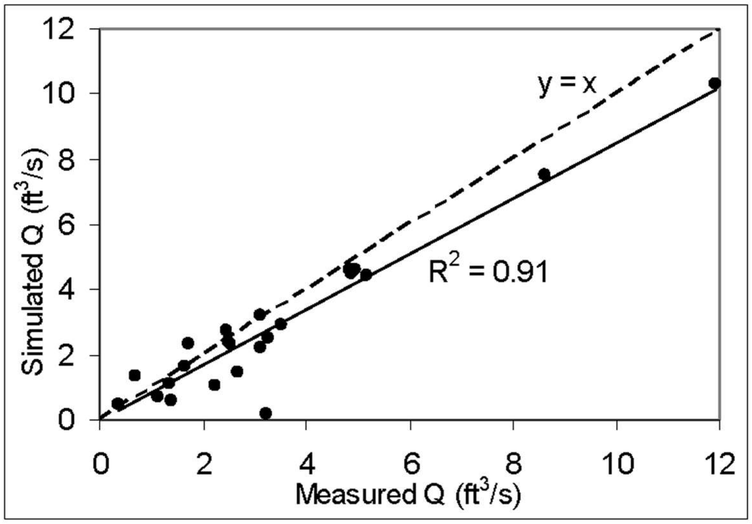

Figure 19 Simulated and measured discharges for Culvert 77 using discharge coefficient model based on $Q/(A_3\sqrt{2g})$ as a function of $\sqrt{h_1 - h_4}$

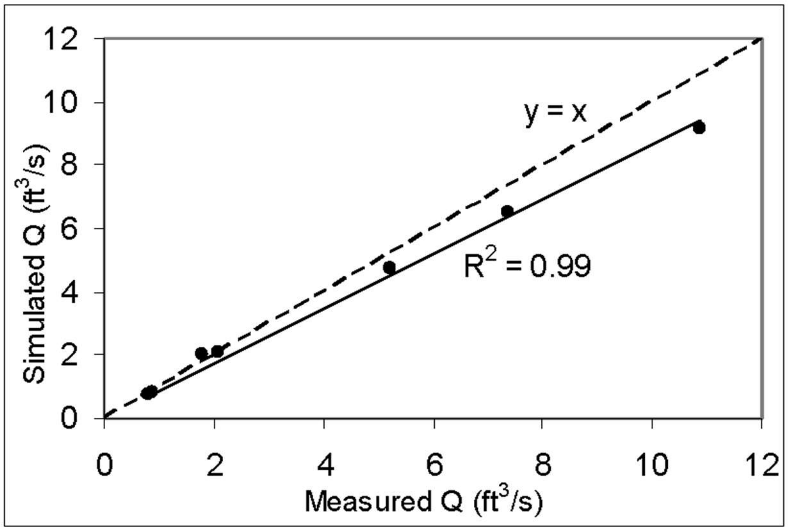

Figure 20 Simulated and measured discharges for Culvert 86 using discharge coefficient model based on $Q/(A_3\sqrt{2g})$ as a function of $\sqrt{h_1 - h_4}$

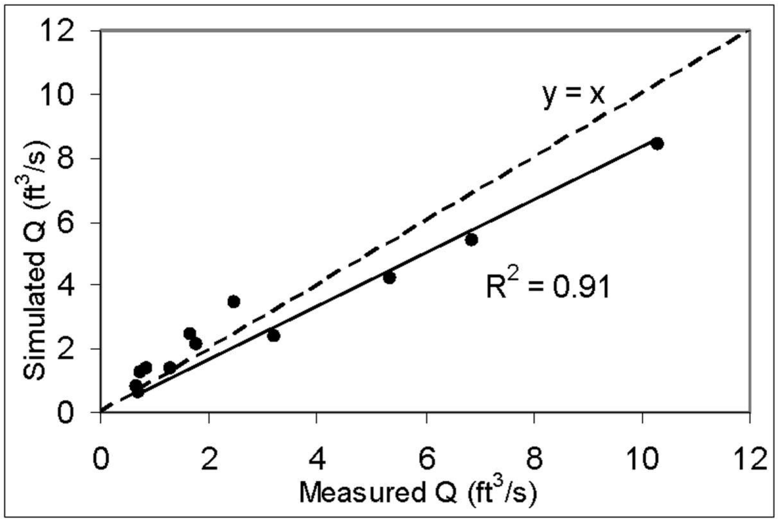

Figure 21 Simulated and measured discharges for Culvert 101 using discharge coefficient model based on $Q/(A_3\sqrt{2g})$ as a function of $\sqrt{h_1 - h_4}$

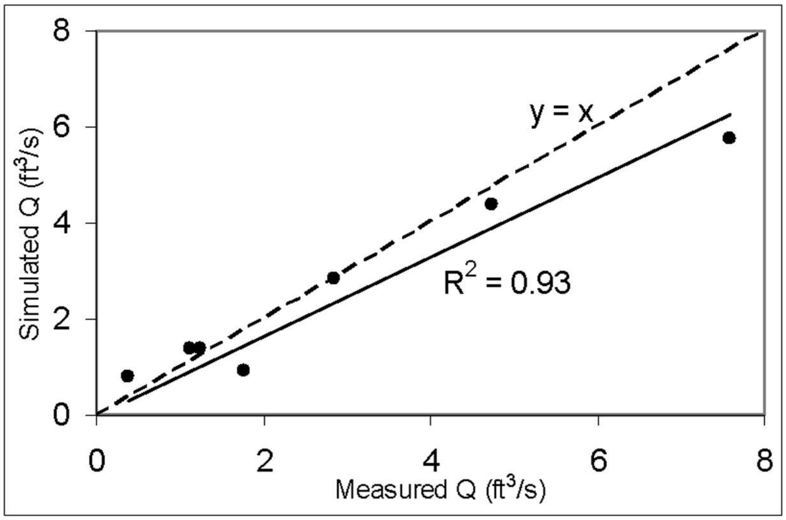

Figure 22 Simulated and measured discharges for Culvert 125 using discharge coefficient model based on $Q/(A_3\sqrt{2g})$ as a function of $\sqrt{h_1 - h_4}$

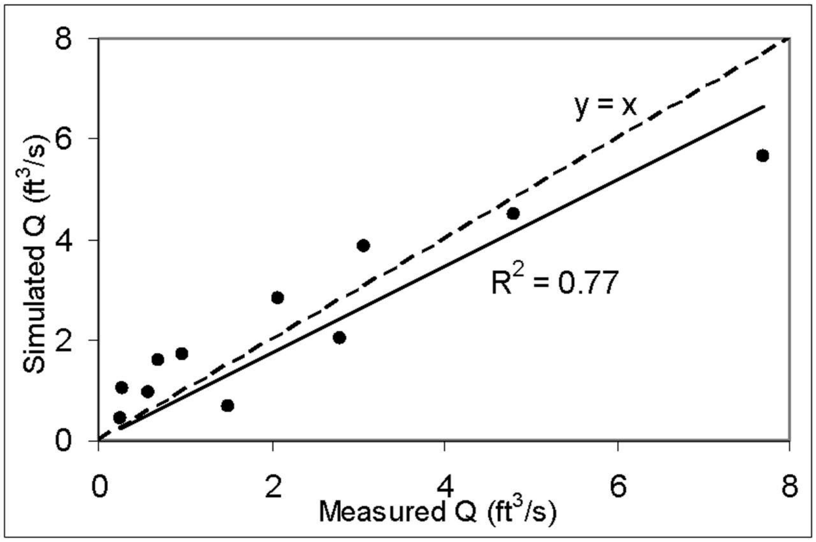

Figure 23 Simulated and measured discharges for Culvert 133 using discharge coefficient model based on $Q/(A_3\sqrt{2g})$ as a function of $\sqrt{h_1 - h_4}$

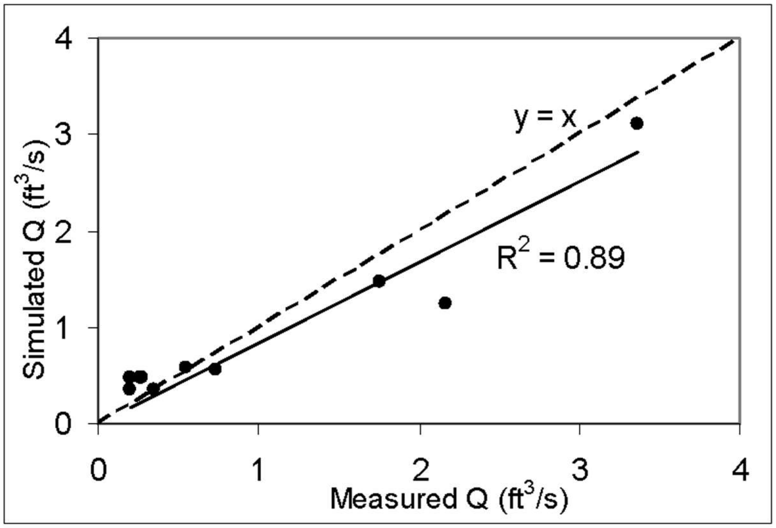

Figure 24 Simulated and measured discharges for Culvert 170 using discharge coefficient model based on $Q/(A_3\sqrt{2g})$ as a function of $\sqrt{h_1 - h_4}$

Table 4 shows the R^2 values of the two models used for calculating C_d. The R^2 values for Model Two are equal to or slightly less than the R^2 values for Model One. For Culvert 59 and 77, the C_d values obtained from Model One (Figure 10 and 11) provide a better estimate of high discharge measurements (greater than 6 ft^3/s) than do the C_d values obtained from Model Two (Figure 18 and 19).

Table 4 Coefficient of determination (R^2) for simulated and measured discharges using the two models

Culvert No.	R^2 obtained using C_d as a function of h_1/D	R^2 obtained using $Q/(A_3\sqrt{2g})$ as a function of $\sqrt{h_1 - h_4}$
24	0.35	0.44
32	0.96	0.94
38	0.93	0.91
43	0.95	0.95
57	0.95	0.92
59	0.96	0.93
77	0.92	0.91
86	0.99	0.99
101	0.97	0.91
125	0.96	0.93
133	0.91	0.77
170	0.89	0.89

Rating calibration for all culverts together using all measurements

In this section, a single constant C_d value was calculated through regression analysis based on $Q/(A_3\sqrt{2g})$ as a function of $\sqrt{h_1 - h_4}$ using data from all 19 culverts. A plot of the regression analysis and equation is shown in Figure 25. The fitted discharge coefficient C_d equals 0.69, with an R^2 value of 0.91. The final equation is

$$Q = 0.69A_3\sqrt{2g(h_1 - h_4)} \tag{8}$$

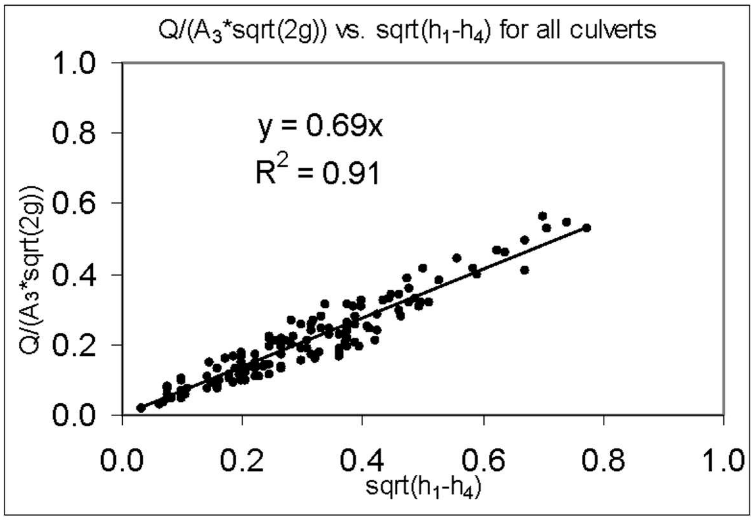

Figure 25 Regression equation derived from measurements of all 19 culverts considered together

The relation between measured discharges at the 19 culverts and simulated discharges calculated using a constant C_d value of 0.69 is shown in Figure 26. The corresponding results are presented in Table C13 of Appendix C.

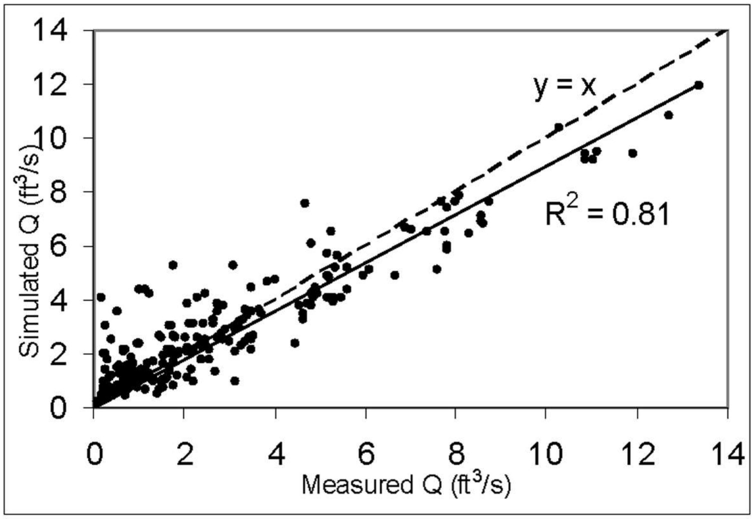

Figure 26 Simulated and measured discharges of all 19 culverts using a constant discharge coefficient

Based on reviewers' comments, one consideration was to separate the discharges into two ranges: one is below 3 ft^3/s and the other is above 3 ft^3/s. The results are shown in Figures 27 and 28. The fitted discharge coefficient C_d equals 0.57 with an R^2 value of 0.72 for discharges below 3 ft^3/s. As for the discharges above 3 ft^3/s, the C_d equals 0.72 with an R^2 value of 0.91.

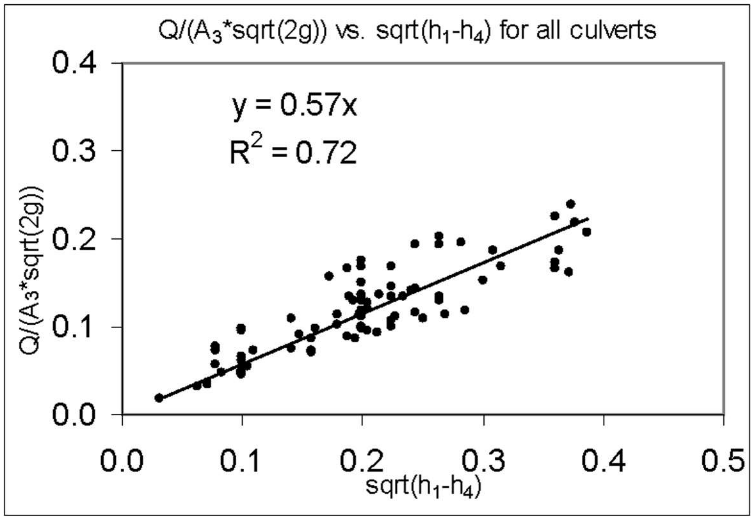

Figure 27 Regression equation derived from discharges below 3 ft^3/s

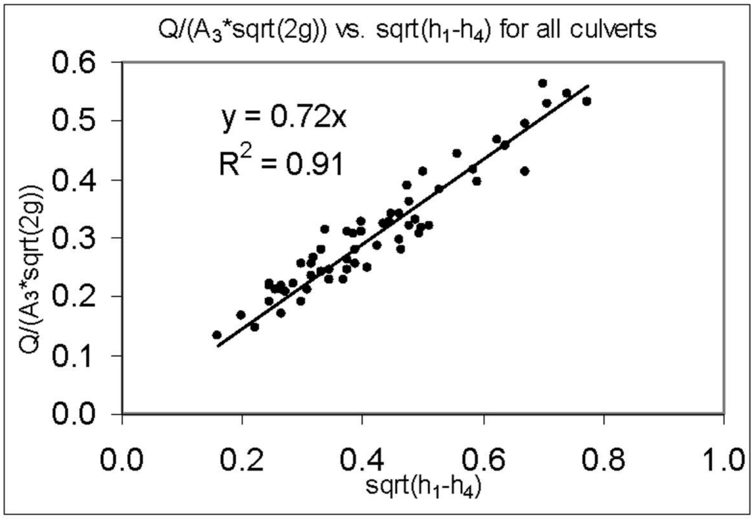

Figure 28 Regression equation derived from discharges above 3 ft^3/s

The final equations are

$$Q = 0.57 A_3 \sqrt{2g(h_1 - h_4)} \quad (Q<3\ ft^3/s) \tag{9}$$

$$Q = 0.72 A_3 \sqrt{2g(h_1 - h_4)} \quad (Q>3\ ft^3/s) \tag{10}$$

The coefficient of determination R^2 between simulated and measured discharges for constant C_d value of 0.57 and 0.72 in Equations (9) and (10) are shown in Figures 29 and 30, respectively.

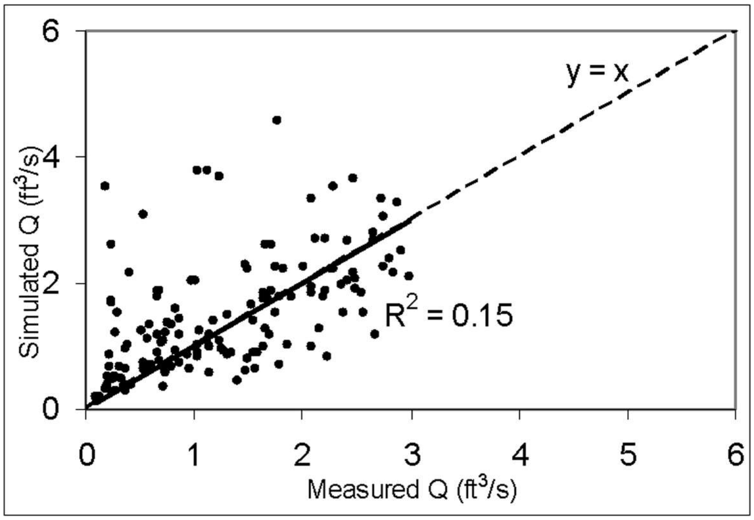

Figure 29 Simulated and measured discharges below 3 ft^3/s

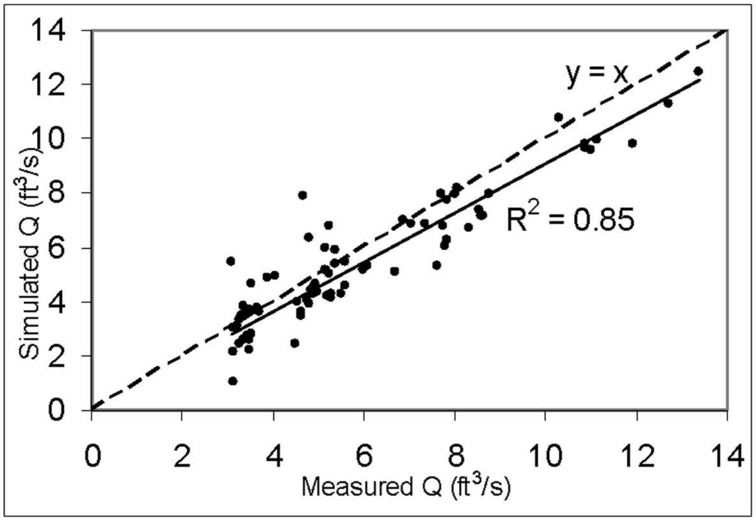

Figure 30 Simulated and measured discharges above 3 *ft³/s*

For discharge below 3 ft^3/s, the relation between simulated and measured discharges is 0.15, which is a poor regression result for the analysis. The analysis proves that result of Equation (8) is better than that of combining Equations (9) and (10).

DISCUSION AND CONCLUSIONS

Discharge data collected from 19 representative sites were used to develop flow equations for 178 culverts underlying SR 9336 in the ENP. The results of the twelve culverts investigated in 2004 were presented in two previous reports (Wu and Imru, 2005a and 2005b).

This report presents the findings from further study of discharges through twelve culverts (five of which were in the first group of twelve) in 2005. The twelve sites represent three common categories of culverts in the ENP: culverts with a vertical headwall, culverts with beveled ends, and culverts with beveled ends buried underground. During this study, we focused on: 1) confirming the variable discharge coefficient model developed on the data collected from the twelve culverts in 2004; 2) improving, if appropriate, on the models developed for culvert flow calculation in the ENP; and 3) incidentally providing a preliminary assessment of our field experience using different flow measurement equipment for the hydrodynamic conditions of the ENP.

Three types of current meters, ADFM, Price pygmy meter, and ADV have been used in flow measurement in the ENP. Our field experience shows that ADFM is a reliable instrument in measuring flows with depths greater than 0.8 *ft*. For flows less than 0.8 *ft* in depth or less than 0.5 *ft/s* in velocity, ADFM is unstable. Pygmy meter stops working when velocity is less than 0.2 *ft/s*. ADV is capable of measuring small discharges. It can measure flows as shallow as 1 *inch* and velocities as low as 0.003 *ft/s*. Due to its small size and capability of measuring points away from the transmitter, ADV has the least disturbance on the measured flow. The accuracy of ADV needs further investigation.

Rating analysis was preformed for: 1) Model One based on C_d as a function of h_1/D; the results indicate that a significant correlation exists between discharge coefficient (C_d) and the ratio of head water depth to culvert diameter (h_1/D) and that the model works well for estimating the discharges in the ENP. However, the variability of the regression coefficients makes model application limited to individual culverts only; 2) Model Two based on $Q/(A_3\sqrt{2g})$ as a function of $\sqrt{h_1 - h_4}$ applied to individual culverts; this model gives similar accuracy as that of the former. Furthermore, it assumes that C_d takes into account the head loss through the barrel of the culvert, and thus the expression is much simpler. This model is recommended for its simplicity and accuracy; 3) the model of $Q/(A_3\sqrt{2g})$ as a function of $\sqrt{h_1 - h_4}$ derived from measurements of all culverts; this application gave a constant discharge coefficient C_d= 0.69 with an R^2 value of 0.91 between the calculated and measured discharges. For culverts where flow measurements are difficult to obtain, this application provides reasonable accuracy for estimation of the culvert discharges in the ENP. Equation (8) is recommended for all the 178 culverts underlying SR 9336 of the ENP.

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Wu, Q. and Imru, M. 2005a. Rating Development for Flow through Culverts under SR9336 in the Everglades National Park I: Concepts and Methods, South Florida Water Management District, West Palm Beach, FL.

Wu, Q. and Imru, M. 2005b. Rating Development for Flow through Culverts under SR9336 in the Everglades National Park II: Rating Calibration, South Florida Water Management District, West Palm Beach, FL.

Appendix A: Responses to Reviewers' Comments on the Preceding Reports (Wu and Imru, 2005a and 2005b)

Review of Method for Development of Culvert Rating Curves for the Florida Bay/Florida Keys Feasibility Study (MSR105)

1. Introduction

The report provided to the IMC for review outlines procedures for rating analysis and flow calculations for culverts beneath SR 9336 in the Everglades National Park (ENP). The IMC, through MSR-105, was asked to provide comments and establish the suitability of the procedures documented in the report for modeling purposes.

2. General Comments

The following are general comments on the document and few corrections that should be made in order to improve the quality and readability of the report. The comments were organized according to the presentation in the report.

Introduction

Page 1 – The report should provide additional justification why the current rating analysis and flow computations in the NFLOW program cannot be used in the ENP? Is the assumption in NFLOW not valid for flow regimes in the ENP, hence, the need to develop a new procedure?

RESPONSE:

NFLOW is linked to DBHYDRO and DCVP. In NFLOW, depth of water at the culvert entrance d_2 is solved iteratively by assuming the energy difference between sections 1 and 2 being less than 2% of the energy at section 1.

Our report does not indicate or imply that the flow computation in the NFLOW program cannot be used in the ENP. What is presented in the report is a stand-alone (not linked to server/database) application of the procedure, methods and equations used in NFLOW with some improvements. These improvements consider the ENP flow conditions: the head difference (h_1- h_4) is small, the energy loss h_{f1}-$_2$ would be important to the flow computation and h_2 needs to be more accurately computed.

Two iteration methods were proposed in our study to calculate d_2: one is based on the convergence of flow (Q) and the other is based on the convergence of head (H). These methods do not impose an assumption of $h_2=0.9h_1$ and would improve the estimation on the local energy loss h_{f1}-$_2$ due to the entrance conditions.

END OF RESPONSE

Equations of Type 3 Flow

Page 3 – Under what conditions can we assume these approximations?

RESPONSE:

Type 3 Flow conditions applied in the study are based on the Bodhaine's report: "Measurement of Peak Discharge at Culverts by Indirect Methods". The Type 3 Criteria can be described as:

$$(h_1 - z)/D < 1.5,\ h_4/D \leq 1.0,\ h_4/h_c > 1.0$$

The flow criteria are indicated in page 14 of this report. Type 3 Flow (tranquil flow) is a sub-critical and open-channel flow throughout the culvert course. The downstream water level is lower than the crown elevation of the culvert, but higher than the critical depth.

END OF RESPONSE

Equations of Type 4 Flow

Page 5 – Under what conditions can we assume these approximations?

RESPONSE:

Type 4 Flow conditions applied in the study are based on the Bodhaine's report: "Measurement of Peak Discharge at Culverts by Indirect Methods". The criteria can be described as:

$$(h_1 - z)/D > 1.0, h_4/D > 1.0$$

Type 4 Flow occurs when the downstream water level is higher than the culvert's crown elevation, and the pressurized culvert flow is controlled by water head difference (h_1- h_4). The approach velocity at Section 1 and the friction loss between Sections 1 and 2 and between Sections 3 and 4 can be neglected as indicated in Bodhaine's report.

END OF RESPONSE

Page 5 – Under what conditions can we assume these approximations?

Data Used for Illustration

Page 6 – Table 1 gives the flow measurements at culvert 59. For completeness, it should also include some physical characteristics of the system such as culvert dimension and slope. Table should also indicate whether flow regime satisfies Type 3 flow based on established criteria, i.e.

$$(h_1 - z)/D < 1.5, h_4/D \leq 1.0, h_4/h_c > 1.0$$

RESPONSE:

The purpose of Table 1 in the report is mainly to list historical flow measurement records which are used for the subsequent simulations. Culvert geometric information is given where deemed appropriate in Report II: Rating Calibration. It can be found in Table 16 in Appendix II.

The simulation outputs from Table 5 through Table 8 in the report give the data for (h_1-z), h_4 and h_c. Considering the diameter of Culvert 59, the conclusion can be reached that the flow regime satisfies the Type 3 Flow criterion: $(h_1 - z)/D < 1.5, h_4/D \leq 1.0, h_4/h_c > 1.0$.

END OF RESPONSE

Procedures for Rating Development

Page 7 – Table 2 presents a calculation of the discharge coefficient assuming $h_2 = 0.9h_1$. How sensitive are these calculations to the 10% head-tail difference assumption? What would be the variability of the discharge coefficient under a different assumption?

RESPONSE:

The flow sensitivity analysis was conducted with different ratios of h_2 to h_1 as listed in Table 18 of the report of Wu and Imru, 2005a. The result shows that when h_2/h_1 ratio varies from 0.9 to 1.0, the variability of the average calculated flow is about 1.2% from 4.13ft^3/s to 4.18ft^3/s. The following table shows that with the change of assumption of h_2/h_1 from 0.85 to 0.95, the variability of the discharge coefficient is about 2.4% from 0.795 to 0.776.

		$h_2=0.85h_1$		$H_2=0.86h_1$		$h_2=0.87h_1$		$h_2=0.88h_1$		$H_2=0.89h_1$		$h_2=0.9h_1$		$H_2=0.91h_1$		$h_2=0.92h_1$		$h_2=0.93h_1$		$h_2=0.94h_1$		$h_2=0.95h_1$	
Date	Flow	h_2	C_{d3}	h_2	C_{d3}	h_2	C_{d3}	h_2	C_{d3}	H_2	C_{d3}	h_2	C_{d3}	H_2	C_{d3}	h_2	C_{d3}	h_2	C_{d3}	h_2	C_{d3}	h_2	C_{d3}
10/17/96	9.19	1.77	0.762	1.79	0.761	1.81	0.761	1.83	0.760	1.85	0.759	1.87	0.759	1.89	0.759	1.91	0.758	1.93	0.758	1.96	0.758	1.98	0.758
10/24/96	7.47	1.63	0.787	1.65	0.786	1.67	0.785	1.69	0.784	1.71	0.783	1.73	0.782	1.75	0.781	1.77	0.780	1.79	0.779	1.80	0.779	1.82	0.778
10/31/96	4.85	1.45	0.866	1.46	0.864	1.48	0.862	1.50	0.860	1.51	0.858	1.53	0.856	1.55	0.854	1.56	0.852	1.58	0.851	1.60	0.849	1.62	0.848
11/25/96	*0.47*	0.98	*0.313*	0.99	*0.313*	1.00	*0.313*	1.01	*0.313*	1.02	*0.312*	1.04	*0.312*	1.05	*0.312*	1.06	*0.312*	1.07	*0.312*	1.08	*0.312*	1.09	*0.311*
03/17/97	3.79	1.04	0.891	1.05	0.888	1.06	0.884	1.07	0.880	1.09	0.877	1.10	0.874	1.11	0.871	1.12	0.868	1.13	0.865	1.15	0.862	1.16	0.860
04/14/97	*0.59*	0.82	*0.530*	0.83	*0.529*	0.84	*0.528*	0.84	*0.527*	0.85	*0.526*	0.86	*0.525*	0.87	*0.524*	0.88	*0.523*	0.89	*0.522*	0.90	*0.521*	0.91	*0.520*
05/14/97	1.59	0.95	0.461	0.96	0.460	0.97	0.460	0.99	0.459	1.00	0.459	1.01	0.458	1.02	0.458	1.03	0.457	1.04	0.457	1.05	0.456	1.06	0.456
07/01/97	5.94	1.40	0.894	1.42	0.891	1.44	0.889	1.45	0.886	1.47	0.884	1.49	0.882	1.50	0.880	1.52	0.878	1.53	0.876	1.55	0.874	1.57	0.873
07/09/97	4.92	1.38	0.751	1.39	0.750	1.41	0.748	1.43	0.747	1.44	0.745	1.46	0.744	1.47	0.743	1.49	0.741	1.51	0.740	1.52	0.739	1.54	0.738
07/16/97	4.88	1.18	0.813	1.20	0.810	1.21	0.808	1.22	0.806	1.24	0.804	1.25	0.802	1.26	0.800	1.28	0.798	1.29	0.796	1.31	0.795	1.32	0.793
07/22/97	7.16	1.45	0.883	1.47	0.880	1.49	0.878	1.50	0.876	1.52	0.874	1.54	0.872	1.56	0.870	1.57	0.869	1.59	0.867	1.61	0.866	1.62	0.864
07/28/97	4.47	1.33	0.819	1.35	0.817	1.37	0.815	1.38	0.813	1.40	0.811	1.41	0.809	1.43	0.808	1.44	0.806	1.46	0.804	1.48	0.803	1.49	0.801
08/07/97	4.42	1.28	1.142	1.29	1.135	1.31	1.129	1.32	1.123	1.34	1.118	1.35	1.113	1.37	1.108	1.38	1.103	1.40	1.098	1.41	1.094	1.43	1.090
08/18/97	*1.10*	1.23	*0.402*	1.25	*0.402*	1.26	*0.401*	1.28	*0.401*	1.29	*0.401*	1.31	*0.401*	1.32	*0.400*	1.33	*0.400*	1.35	*0.400*	1.36	*0.400*	1.38	*0.399*
09/02/97	5.36	1.41	0.807	1.43	0.806	1.44	0.804	1.46	0.802	1.48	0.800	1.49	0.799	1.51	0.797	1.53	0.796	1.54	0.794	1.56	0.793	1.58	0.792
09/16/97	2.87	1.34	0.891	1.36	0.888	1.37	0.885	1.39	0.883	1.41	0.880	1.42	0.878	1.44	0.875	1.45	0.873	1.47	0.871	1.49	0.869	1.50	0.867
10/01/97	4.84	1.51	0.879	1.53	0.877	1.55	0.874	1.57	0.872	1.58	0.871	1.60	0.869	1.62	0.867	1.64	0.865	1.66	0.864	1.67	0.862	1.69	0.861
10/15/97	3.37	1.39	0.865	1.41	0.863	1.43	0.860	1.44	0.858	1.46	0.856	1.48	0.854	1.49	0.852	1.51	0.850	1.53	0.848	1.54	0.846	1.56	0.845
10/23/97	*2.02*	1.29	*0.768*	1.31	*0.766*	1.32	*0.764*	1.34	*0.762*	1.35	*0.760*	1.37	*0.759*	1.38	*0.757*	1.40	*0.756*	1.41	*0.754*	1.43	*0.753*	1.44	*0.752*
10/28/97	*1.60*	1.21	*0.632*	1.22	*0.631*	1.24	*0.630*	1.25	*0.628*	1.26	*0.627*	1.28	*0.626*	1.29	*0.625*	1.31	*0.624*	1.32	*0.624*	1.33	*0.623*	1.35	*0.622*
11/18/97	*2.44*	1.22	*1.110*	1.24	*1.103*	1.25	*1.097*	1.27	*1.091*	1.28	*1.086*	1.30	*1.081*	1.31	*1.076*	1.32	*1.071*	1.34	*1.067*	1.35	*1.062*	1.37	*1.058*
12/10/97	7.97	1.59	0.944	1.61	0.942	1.63	0.939	1.65	0.937	1.66	0.935	1.68	0.933	1.70	0.932	1.72	0.930	1.74	0.929	1.76	0.927	1.78	0.926
01/07/98	3.41	1.33	0.955	1.34	0.951	1.36	0.947	1.37	0.944	1.39	0.941	1.40	0.938	1.42	0.935	1.44	0.933	1.45	0.930	1.47	0.927	1.48	0.925
02/06/98	7.41	1.49	0.916	1.51	0.913	1.52	0.911	1.54	0.909	1.56	0.907	1.58	0.905	1.59	0.903	1.61	0.901	1.63	0.899	1.65	0.898	1.66	0.896
Average C_{d3}			0.795		0.793		0.791		0.788		0.786		0.785		0.783		0.781		0.779		0.778		0.776

END OF RESPONSE

Page 8 – Figure 3 shows the plot of the computed discharge coefficient as a function of head – tail water difference. There is significant variability in the computed coefficient especially within the range of a head – tail water difference (H-T) of 0.1. If a best-fit line is used, the errors in flow estimation would also be large (see Tables 5-8) especially in the H-T range of 0.1. The figure should also include the best fit line and some statistical measure.

RESPONSE:

Culvert flow of the study is mostly Type 3 Flow. In the stage measurement, errors can be from such factors as wavy water surface, equipment tolerance and head loss caused by blockage (grass, tree roots, debris and sediment). The errors may be in the same order of magnitude as water-head differences. This is the reason why the variability in the computed results is significant when the water head differences are very small.

Our study was conducted in a way to find a best fitted model as shown in subsequent figures and sections. The observation has been given in the statement following the figure:

Staff gage measurements have an error margin of ±0.02 ft. In Table 2 and Figure 3, when the head difference is small (such as around the error margin of 0.02 ft), the error of calculated discharge coefficient C_3 is expected to be high. When we conduct rating analysis, we can remove data points with small head difference (such as those below 0.02 ft). The following three figures show how rating relationships can be improved by removing data points with head difference values within the error margin and obviously unreasonable points.

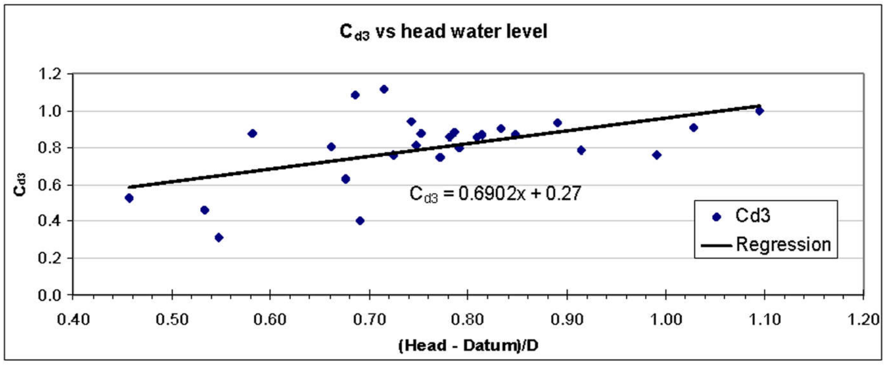


Figure A1 Rating analysis with all data points considered

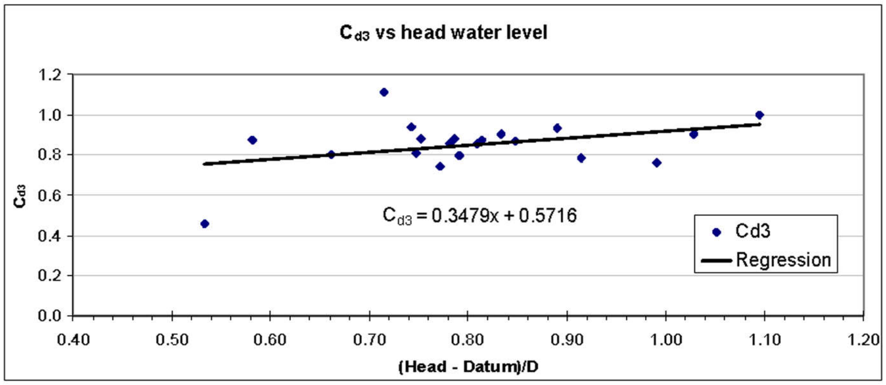


Figure A2 Rating analysis excluding data points with head difference not greater than 0.02 ft

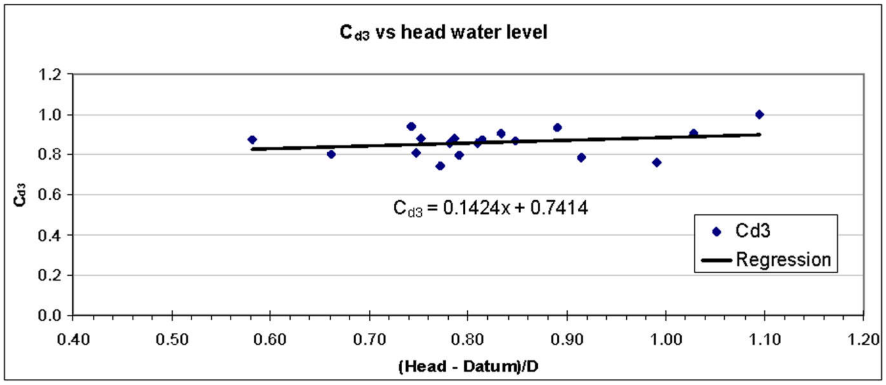


Figure A3 Rating analysis further excluding two obviously unreasonable data points

END OF RESPONSE

What does "The minimum difference is considered the best estimation of discharge coefficient" mean?

RESPONSE:

This is the "Least-Squares Method" which is a curve-fitting model determined to fit a set of measurements with the minimized sum of residuals.

END OF RESPONSE

Testing Type 3 Culvert Discharge Program

Page 14 -17 – For completeness, the discharge coefficient and roughness used in Tables 5-8 should be indicated. Is the discharge coefficient used from the linear equation in Figure 3 or is it a constant value? It is not surprising to have a close correspondence between the standard step (iteration-based method) and the flow estimation method assuming depth of water at section 2 because the calculation of discharge coefficient assumes a depth at section 2 (Table 2). Why are the two largest flows not used?

RESPONSE:

The discharge coefficient and roughness in Tables 5-8 are all the same: $C_d = 0.8$, $n = 0.013$. The purpose of Tables 5-8 is to show that the discharge simulation program can converge properly. The only change is the iteration convergence accuracy; all the other parameters are kept the same. The tables show that with the error limit changed by 10 times from 0.01 to 0.001, there is no significant difference among the simulation results.

As stated above, Figure 3 is not the purpose of the study. The discharge coefficient was not from the equation in Figure 3. It was obtained with varying ratios of h_2/h_1 in Tables 5-8.

The reason for a close correspondence can be explained from the following equation:

$$Q = C_3 A_3 \sqrt{\frac{2g(h_1 - h_3)}{1 + \frac{2g C_3{}^2 A_3{}^2 L}{K_2 K_3}}} \qquad \text{(A-1)}$$

K_2 is proportional to A_2 and A_2 is proportional to h_2. The product of K_2K_3 is large enough to make $\frac{2gC_3^2A_3^2L}{K_2K_3}$ much smaller than 1. So the accuracy in estimating h_2 does not affect the calculation of Q very much. Our study proposed iteration methods to solve the energy equation which is more theoretically sound without imposing the assumption of h_2/h_1.

As to the two largest flows, their upstream water levels were above the crown of the culvert (different from the rest of measurements) and excluded in the first stage of the discharge program.

END OF RESPONSE

Sensitivity Analysis

A more appropriate sensitivity analysis is to evaluate the sensitivity of the discharge coefficient with respect to the assumed depth at section 2 and the roughness coefficient.

RESPONSE:

From extensive experience on many District culverts, the effluence of roughness coefficient on discharge is not appreciable. This is also shown in Table 10 to Table 11 of the study.

The water depth at Section 2 is computed in the study by the iteration method based on the energy balance. Therefore, the discharge coefficient does not depend on the "assumed depth" at the Section 2. The assumption $h_2=0.9h_1$ is only used as the initial value for the iteration process. The sensitivity of flow rate on discharge coefficient is shown in Table 13 of the study.

In addition, we would recommend performing the sensitivity analysis on a physical quantity (i.e., measured flow rate) with respect to some assumed factors including regressed discharge coefficient, assumed roughness and iterated water head at Section 2. The Discharge Coefficient may not be suitable to be used as a target function since it is an intermediate approximation (regression or curve fitting) that will lead to discharge estimation (the target function).

END OF RESPONSE

Discussion

Page 23 - 24 – The equation in Table 15 is a very poor model ($R^2 = 0.10$) for estimating the discharge coefficient. In Table 14-15 and Figure 7, the largest flows were not included in the analysis.

RESPONSE:

From the following figure with confidence interval curves, it shows that some data points are out of the confidence bands. After omitting these outliers, an R-square = 0.7746 was obtained for the relationship between C_{d3} and h_1/D.

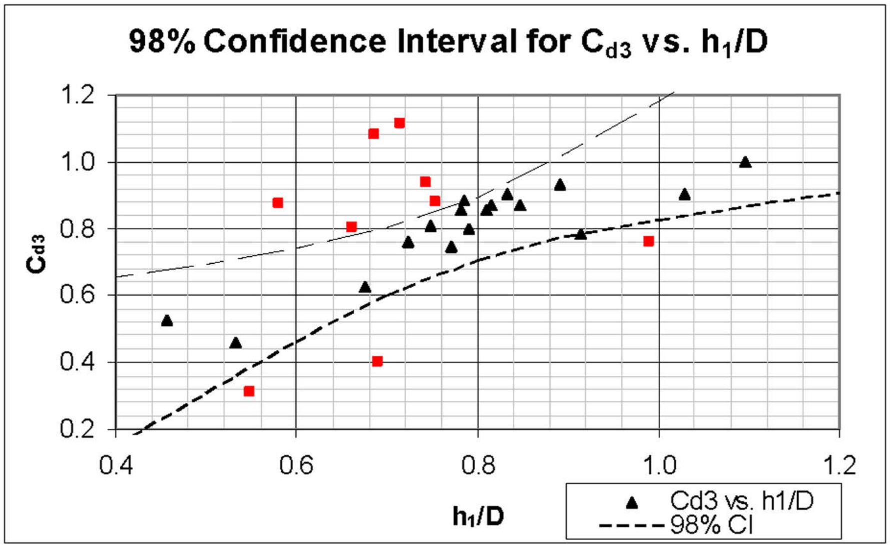


Figure A4 Outliers beyond 98% confidence interval bands for Culvert 59

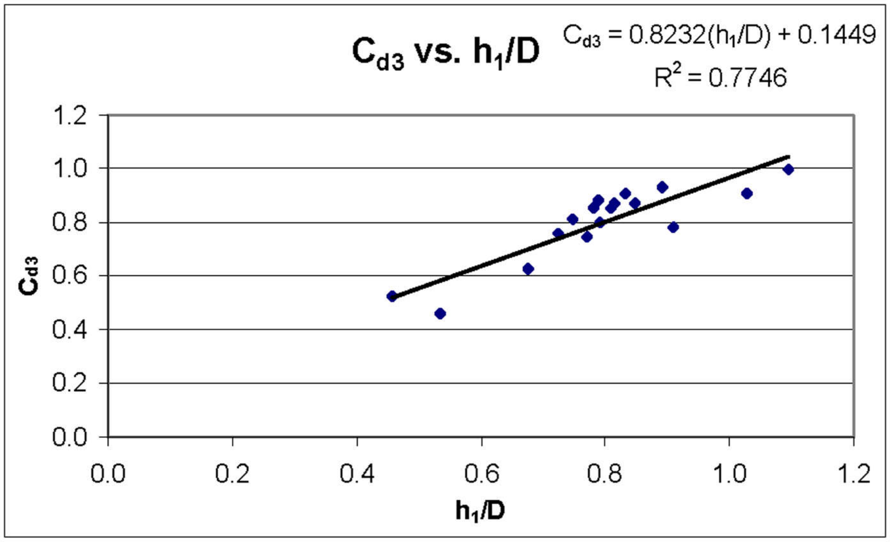


Figure A5 Regression for Culvert 59

These 9 points are listed in the following table:

Table A1 Calculation of discharge coefficients for Culvert 59 using historical data

Original Data Points				Data Points After Deleting Outliers	
Date	h_1	h_1/D	C_{d3}	h_1/D	C_{d3}
1996-10-17	2.08	0.99	0.759	Outlier	
1996-10-24	1.92	0.91	0.782	0.91	0.782
1996-10-31	1.70	0.81	0.856	0.81	0.856
1996-11-25	1.15	0.55	0.312	Outlier	
1997-03-17	1.22	0.58	0.874	Outlier	
1997-04-14	0.96	0.46	0.525	0.46	0.525
1997-05-14	1.12	0.53	0.458	0.53	0.458
1997-06-02	2.30	1.10	0.997	1.10	0.997
1997-06-23	2.16	1.03	0.905	1.03	0.905
1997-07-01	1.65	0.79	0.882	0.79	0.882
1997-07-09	1.62	0.77	0.744	0.77	0.744
1997-07-16	1.39	0.66	0.802	Outlier	
1997-07-22	1.71	0.81	0.872	0.81	0.872
1997-07-28	1.57	0.75	0.809	0.75	0.809
1997-08-07	1.50	0.71	1.113	Outlier	
1997-08-18	1.45	0.69	0.401	Outlier	
1997-09-02	1.66	0.79	0.799	0.79	0.799
1997-09-08	1.57	0.75		0.75	
1997-09-16	1.58	0.75	0.878	Outlier	
1997-10-01	1.78	0.85	0.869	0.85	0.869
1997-10-15	1.64	0.78	0.854	0.78	0.854
1997-10-23	1.52	0.72	0.759	0.72	0.759
1997-10-28	1.42	0.68	0.626	0.68	0.626

Original Data Points				Data Points After Deleting Outliers	
Date	h_1	h_1/D	C_{d3}	h_1/D	C_{d3}
1997-11-18	1.44	0.69	1.081	Outlier	
1997-12-10	1.87	0.89	0.933	0.89	0.933
1998-01-07	1.56	0.74	0.938	Outlier	
1998-02-06	1.75	0.83	0.905	0.83	0.905

The reason for a low R-square (indicated by the reviewer $R^2 = 0.1$) is:
Flow estimates are sensitive to small head differences under ENP flow conditions. When the head differences are at a similar level of errors with the stage measurement (e.g., difference < 0.1 ft), variability in flow computation becomes significant as shown in the following figure. The irregular distribution of C_{d3} in the lower range of the head differences results in a low R-square.

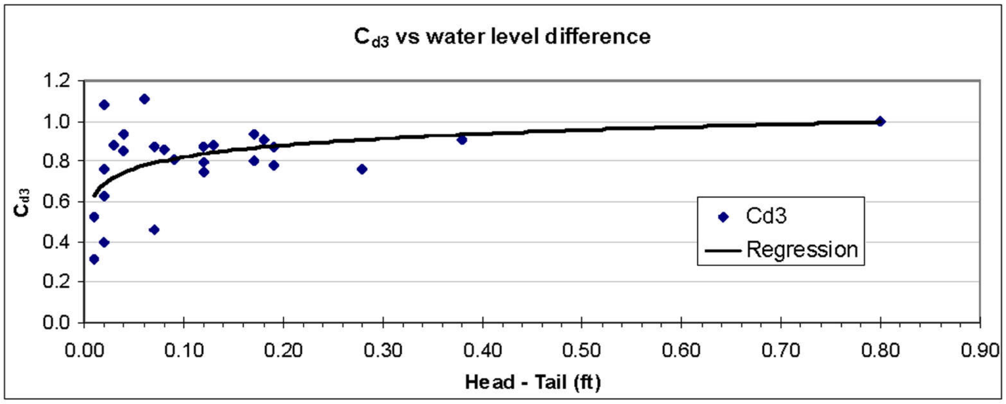


Figure A6 C_3 versus head difference corresponding to Table 2 in the report of Wu and Imru, 2005a

In the first stage of the discharge program, the flow submergence condition was excluded. The largest flows submerged the top of the culvert and were omitted for this reason.

END OF RESPONSE

Again, what is it meant by “the best estimate of discharge coefficient is obtained by minimizing the difference between the measured and calculated flows”? The discharge program in the appendices indicates the use of a linear equation to estimate the coefficient.

RESPONSE:

This sentence states the "Least-Squares Method". This method determines the best-fitting model which minimizes the sum of squares of the residuals from the measured flow to the fitted model.

Based on this method, the discharge program tries to find a linear relationship between C_{d3} and h_1/D to estimate the discharge coefficient.

END OF RESPONSE

Conclusions

Page 25 – The paper recommends that the method developed be implemented in the District's FLOW program for type 3 culvert flow. However, the report did not provide any analysis to justify that the proposed method would perform better than what is currently in the FLOW program.

RESPONSE:

The study does not recommend changing the general flow computation method implemented in the NFLOW program. However, considering the low-head culvert flow in the ENP, we proposed to improve the iteration method and the convergence criterion used to compute the water depth at section 2. In NFLOW, the iteration for computing the water depth at section 2 is considered to be convergent when the criterion $(E_1 – E_2)/ E_1 < 2\%$, where E is the total energy at section 1 or section 2, achieves. This error criterion (i.e. 2%) appears to be too large for the low water-head flow computation. For example, if the water depth at section 1 were 1.5 feet, the iteration error criterion (2% of E_1) would be 0.03 feet. This error from iteration would be significant for low-head flow computation.

In this study, the error criterion was greatly reduced to perform accurate water depth computation. In addition, the iteration algorithm is improved to achieve effective convergence. We therefore recommend implementing the developed iteration algorithm and convergence criterion in the NFLOW program.

END OF RESPONSE

3. Recommendations

(1) It was mentioned in the Introduction section that an improvement to the NFLOW method is presented, yet no comparison between what is in NFLOW and the proposed procedure was presented. The authors may consider presenting an analysis comparing the two procedures.

RESPONSE:

As stated above, the improvement is at the algorithm level for similar flow conditions as those in the ENP with very small head difference.

END OF RESPONSE

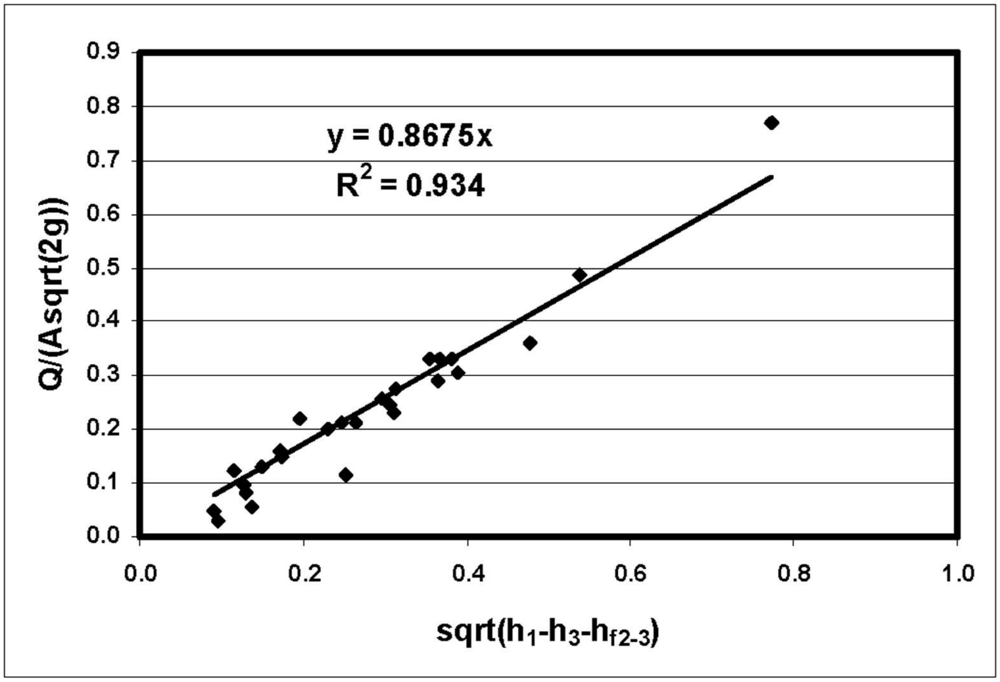
(2) The authors may consider using an independent dataset to validate the methods presented. Table 15 shows for the calibration dataset that large errors are obtained from flows within 5 cfs with head-tail difference less than 0.1. This is directly related to the estimated discharge coefficient from the best fit line in Figure 3.

RESPONSE:

Validation of the methods is part of the original project plan. An independent dataset will be obtained in the next phase depending on the adequacy of funding. This phase will be conducted in the wet season before December, 2005. In this phase, more flow and stage measurements will be made to collect independent dataset to verify and validate the equations proposed and calibrated in the study.
Our study has tried to develop a model to simulate the relationship between C_{d3} and h_1/D.

END OF RESPONSE

(3) The authors may consider an alternative way of deriving the discharge coefficient. From equation 11, C_3 can be obtained from the slope of the curve of $\frac{Q}{A_3\sqrt{2g}}$ as a function of $\sqrt{(h_1 - h_3 - h_{f2-3})}$. The Figure below shows the plot for the dataset in Table 2. As in Table 2, h_1/h_2 is assumed as 0.1. Sensitivity of the slope to various ranges of h_1/h_2 as well as the roughness coefficient can be evaluated.



The above procedure is similar to the approach used by Tillis and Swain (1998) in developing discharge coefficient for selected coastal control structures in Broward and Palm Beach counties.

RESPONSE:

The above curve fitting relates to a constant C_{d3} value though not explicit.

In our study, C_{d3} was evaluated as a function of h_1/D instead of a constant. It is because that at small water head difference, flow through culverts would be affected considerably by local physical conditions such as entrance obstructions (e.g., grass and debris), sediment deposition along the barrier, and geometries of culvert entrances. We consider it appropriate to evaluate C_{d3} as a function of h_1/D in order to represent the impact of local physical conditions on the flow rate when the water head difference is low.

The method used by Tillis and Swain and that in this study are similar. The difference between these two methods is on how C_{d3} varies (i.e., constant C_{d3} versus C_{d3} varying (in $Q = C_{d3} A_3 \sqrt{2g(h_1 - h_3 - h_{f2-3})}$) with respect to h_1/D). Both the arithmetic average of C_{d3} in Table 2 and the C_{d3} in Tables 5-8 obtained by using our method are 0.8, which is about 7.8% deviation from 0.8675 obtained in the above figure.

Regression is used to assess the relationship among a set of variables based on physical realities. Given a selected set of dependent ($\frac{Q}{A_3\sqrt{2g}}$) and independent ($\sqrt{(h_1 - h_3 - h_{f2-3})}$) variables for the C_59 culvert dataset, the T&S' method shows a high value of correlation coefficient (R^2 =0.93). However, a larger R^2 does not necessarily mean a better interpretation on hydraulics. For example, if using a cubic polynomial function to fit the same dataset, R^2 value would be higher than that for the linear fitting (0.96 vs 0.93 as shown in the figure below). Since the cubic fitting would result in a divergent C_{d3} (the asymptotic line of the fitting curve has the slope larger than 1), this fitting function would not be suitable to describe the discharge coefficient.

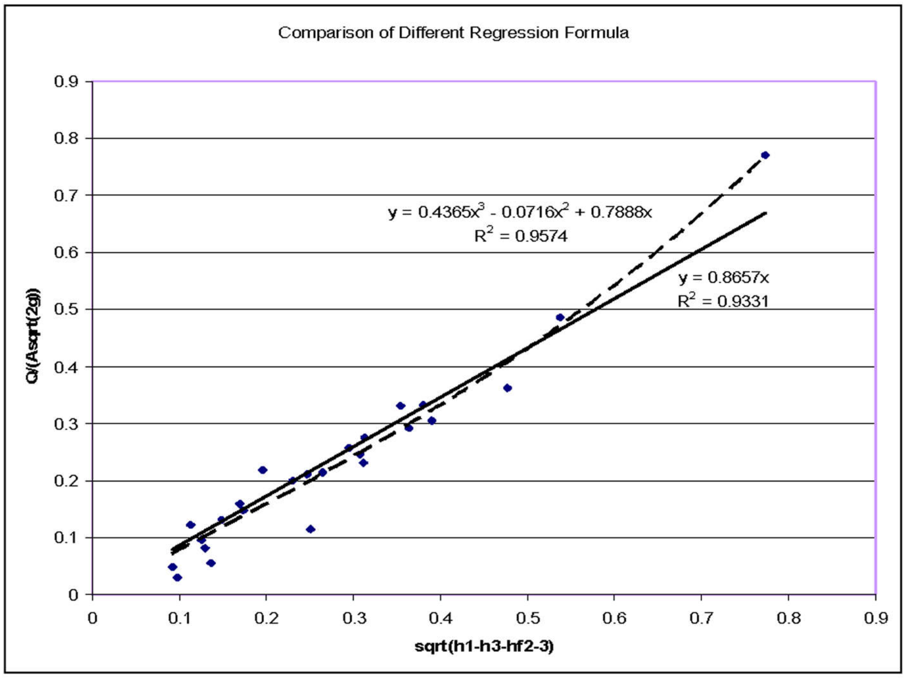


Figure A7 Comparison of different regression formula

The suggested alternative method is presented in the revised report. Users should make the selection based on applications.

END OF RESPONSE

Reference provided by the reviewers:

Tillis, G. M. and E. D. Swain, 1998. Determining Discharge-Coefficient Ratings for selected coastal control structures in Broward and Palm Beach counties, Fl. USGS Water Resources Investigation Report 98-4007.

Appendix B: Measurements of Water Levels

In order to measure the headwater and tailwater levels, two bases were installed in the upstream and downstream sections with calm water surface. These areas are within 10 feet of the ends of the culverts. An engineering level was used to measure the four elevations *a, b, c*, and *d* shown in following figure.

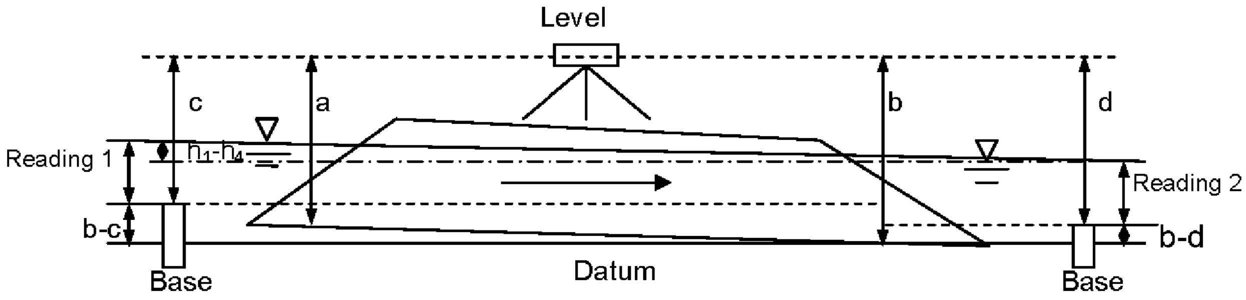


Figure B1. Installation of bases for measuring water surface elevations

Where *a, b, c, d* – elevations measured using an engineering level

Reading 1 –water depth above the base upstream

Reading 2 –water depth above the base downstream

The surveying data for *a, b, c*, and *d* are used in the subsequent field flow measurements. However, the values of Reading 1 and Reading 2 are recorded every time when measuring the flow at the site.

The values of Reading 1 and Reading 2 can be either positive or negative, depending on the water level. A positive value means that the top of the base is under the water surface, and the reading was taken from the water surface to the top of the base. A negative value means that the top of the base is above the water surface, and the reading was taken from the top of the base to the water surface.

Based on these values, the head difference can be obtained by using the following equations:

$$h_1 = (b-c) + \text{Reading } 1 \quad \text{(B1)}$$

$$h_4 = (b-d) + \text{Reading } 2 \quad \text{(B2)}$$

$$h_1 - h_4 = [(b-c) + \text{Reading } 1]-[(b-d) + \text{Reading } 2] \quad \text{(B3)}$$

Table B1 through B7 present the measured elevations for seven of the newly investigated twelve culverts. Water depths in other five culverts are measured by staff gauges.

Table B1 Survey data and head difference calculation for Culvert 32

	a	b	c	d
06-30 reading	7.156	7.229	5.802	6.073
07-06 reading	Upstream		Downstream	
	0.205		0.470	
h_1-h_4 = 0.006				

Table B2 Survey data and head difference calculation for Culvert 38

	a	b	c	d
08-03 reading	6.813	6.667	5.380	5.292
08-03 reading	Upstream		Downstream	
	0.170		0.050	
h_1-h_4 = 0.032				

Table B3 Survey data and head difference calculation for Culvert 57

	a	b	c	d
06-30 reading	6.010	6.177	4.927	5.625
07-06 reading	Upstream		Downstream	
	-0.020		0.510	
h_1-h_4 = 0.168				

Table B4 Survey data and head difference calculation for Culvert 86

	a	b	c	d
08-03 reading	6.490	6.573	6.083	6.125
08-03 reading	Upstream		Downstream	
	0.106		0.090	
h_1-h_4 = 0.058				

Table B5 Survey data and head difference calculation for Culvert 101

	a	b	c	d
06-30 reading	6.208	6.438	5.771	5.693
07-06 reading	Upstream		Downstream	
	0.604		0.430	
h_1-h_4 = 0.096				

Table B6 Survey data and head difference calculation for Culvert 125

	a	b	c	d
08-03 reading	6.380	6.620	6.052	6.417
08-03 reading	Upstream		Downstream	
	0.252		0.548	
h_1-h_4 = 0.069				

Table B7 Survey data and head difference calculation for Culvert 133

	a	b	c	d
06-30 reading	6.688	7.042	5.609	6.005
07-06 reading	Upstream		Downstream	
	0.220		0.570	
h_1-h_4 = 0.046				

Appendix C: Simulated and Measured Discharges Using Model Two

Table C1 Simulated and measured discharges for culvert 24

Date	Measured Q	Head water	Tail water	H-T	h_1	h_4	A_3	$h_{f2,3}$	C_d	Simulated Q	Relative Error
	(ft^3/s)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft^2)	(ft)		(ft^3/s)	(%)
2004-08-04	2.290	4.030	3.960	0.070	2.310	2.240	3.142	0.005	0.355	2.250	-1.7
2004-08-18	1.031	3.960	3.880	0.080	2.240	2.160	3.142	0.001	0.145	2.406	133.3
2004-08-25	0.314	3.860	3.800	0.060	2.140	2.080	3.142	0.000	0.051	*2.083*	*563.5*
2004-10-19	1.128	3.980	3.900	0.080	2.260	2.180	3.142	0.001	0.159	2.406	113.2
2005-06-29	1.234	4.108	4.032	0.076	2.388	2.312	3.142	0.001	0.179	2.345	90.0
2005-07-06	2.735	3.813	3.750	0.063	2.093	2.030	3.142	0.007	0.457	2.135	-21.9
2005-07-07	0.543	3.762	3.708	0.054	2.042	1.988	3.142	0.000	0.093	*1.976*	*264.0*
2005-07-12	4.604	3.806	3.740	0.066	2.086	2.020	3.142	0.019	0.839	2.185	-52.5
2005-08-30	4.660	4.540	4.300	0.240	2.820	2.580	3.142	0.019	0.393	4.167	-10.6
2005-09-07	5.256	4.338	4.160	0.178	2.618	2.440	3.142	0.024	0.532	3.588	-31.7
2005-09-13	1.766	4.098	3.980	0.118	2.378	2.260	3.142	0.003	0.206	2.922	65.4
						Mean				2.711	31.5
						Standard deviation				0.714	69.3
						Coefficient of Variation				0.263	2.2

Table C2 Simulated and measured discharges for culvert 32

Date	Measured Q	Head water	Tail water	H-T	h_1	h_4	A_3	$h_{f2,3}$	C_d	Simulated Q	Relative Error
	(ft^3/s)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft^2)	(ft)		(ft^3/s)	(%)
2005-07-06	1.587	0.205	0.470	0.006	1.632	1.626	2.69	0.00	1.228	1.216	-23.4
2005-07-12	1.267	0.210	0.475	0.006	1.637	1.631	2.74	0.00	0.860	1.237	-2.4
2005-07-13	0.876	0.190	0.451	0.010	1.617	1.607	2.74	0.00	0.414	1.597	82.3
2005-07-20	0.421	0.090	0.360	0.001	1.517	1.516	2.76	0.00	0.665	0.502	19.3
2005-07-27	0.177	0.030	0.300	0.001	1.457	1.456	2.25	0.00	0.317	*0.417*	*135.4*
2005-08-23	1.146	0.150	0.410	0.011	1.577	1.566	2.63	0.00	0.553	1.606	40.2
2005-08-30	6.681	0.750	0.920	0.101	2.177	2.076	3.14	0.04	1.068	5.662	-15.3
2005-09-07	4.644	0.560	0.770	0.061	1.987	1.926	2.63	0.02	1.069	3.854	-17.0
2005-09-13	3.487	0.360	0.610	0.021	1.787	1.766	2.92	0.01	1.408	2.473	-29.1
						Mean				2.268	6.8
						Standard deviation				1.701	38.4
						Coefficient of Variation				0.750	5.6

Table C3 Simulated and measured discharges for culvert 38

Date	Measured Q	Head water	Tail water	H-T	h_1	h_4	A_3	$h_{f2,3}$	C_d	Simulated Q	Relative Error
	(ft^3/s)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft^2)	(ft)		(ft^3/s)	(%)
2005-08-03	2.212	0.170	0.050	0.032	1.457	1.425	2.44	0.01	0.701	2.161	-2.3
2005-08-09	2.077	0.190	0.070	0.032	1.477	1.445	2.53	0.00	0.623	2.237	7.7
2005-08-16	2.424	0.340	0.200	0.052	1.627	1.575	2.73	0.01	0.513	3.096	27.7
2005-08-23	2.916	0.420	0.290	0.042	1.707	1.665	2.84	0.01	0.687	2.895	-0.7
2005-08-30	8.072	1.230	0.880	0.262	2.517	2.255	3.14	0.06	0.708	7.828	-3.0
2005-09-07	8.550	1.060	0.760	0.212	2.347	2.135	3.14	0.06	0.883	7.042	-17.6
2005-09-13	7.811	0.820	0.590	0.142	2.107	1.965	3.14	0.05	1.030	5.785	-25.9
						Mean				4.435	-2.0
						Standard deviation				2.391	17.3
						Coefficient of Variation				0.539	-8.5

Table C4 Simulated and measured discharges for culvert 43

Date	Measured Q	Head water	Tail water	H-T	h_1	h_4	A_3	$h_{f2,3}$	C_d	Simulated Q	Relative Error
	(ft^3/s)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft^2)	(ft)		(ft^3/s)	(%)
2004-07-28	4.622	1.690	1.580	0.110	1.500	1.390	2.07	0.03	0.841	3.896	-15.7
2004-08-06	5.613	1.860	1.700	0.160	1.670	1.510	2.14	0.04	0.816	4.923	-12.3
2004-08-12	3.481	1.700	1.640	0.060	1.510	1.450	2.00	0.02	0.886	2.794	-19.7
2004-08-20	7.831	2.090	1.840	0.250	1.900	1.650	2.36	0.06	0.828	6.780	-13.4
2004-08-26	5.984	1.990	1.830	0.160	1.800	1.640	2.41	0.04	0.774	5.520	-7.7
2004-09-15	3.117	1.580	1.570	0.010	1.390	1.380	1.91	0.02	2.039	*1.079*	*-65.4*
2004-09-16	1.478	1.550	1.545	0.005	1.360	1.355	1.93	0.00	1.351	*0.769*	*-48.0*
2004-09-22	2.565	1.690	1.660	0.030	1.500	1.470	2.05	0.01	0.902	2.017	-21.4
2004-09-29	1.550	1.630	1.640	*-0.01*	1.440	1.450	2.03	0.00	--	outlier	
2004-10-05	1.560	1.685	1.680	0.005	1.495	1.490	2.10	0.00	1.308	*0.844*	*-45.9*
2004-10-12	0.542	1.645	1.640	0.005	1.455	1.450	2.03	0.00	0.471	*0.814*	*50.2*
2004-10-19	8.310	2.245	2.020	0.225	2.055	1.830	2.67	0.06	0.816	7.217	-13.1
2005-08-03	2.365	1.760	1.750	0.010	1.570	1.560	2.53	0.01	1.167	*1.422*	*-39.9*
2005-08-09	2.085	1.790	1.770	0.020	1.600	1.580	2.23	0.01	0.825	1.795	-13.9
2005-08-16	1.863	1.900	1.880	0.020	1.710	1.690	2.37	0.00	0.694	1.910	2.5
2005-08-23	3.427	2.020	1.970	0.050	1.830	1.780	2.57	0.01	0.744	3.275	-4.4
2005-08-30	8.589	2.650	2.440	0.210	2.460	2.250	3.14	0.06	0.744	7.868	-8.4
2005-09-07	6.093	2.490	2.370	0.120	2.300	2.180	3.14	0.03	0.698	5.947	-2.4
2005-09-13	4.805	2.300	2.230	0.070	2.110	2.040	3.14	0.02	0.721	4.542	-5.5
						Mean				4.499	-10.4
						Standard deviation				2.086	6.9
						Coefficient of Variation				0.464	-0.7

Table C5 Simulated and measured discharges for culvert 57

Date	Measured Q	Head water	Tail water	H-T	h_1	h_4	A_3	$h_{f2,3}$	C_d	Simulated Q	Relative Error
	(ft^3/s)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft^2)	(ft)		(ft^3/s)	(%)
2005-07-06	3.469	-0.020	0.510	0.168	1.230	1.062	1.73	0.03	0.668	3.246	-6.4
2005-07-12	2.221	-0.070	0.490	0.138	1.180	1.042	1.71	0.01	0.459	2.879	29.6
2005-07-20	1.038	-0.370	0.302	0.026	0.880	0.854	1.33	0.01	0.695	0.947	-8.7
2005-07-27	0.225	0.228	-0.480	0.010	0.613	0.072	1.84	0.00	0.155	*0.711*	*216.2*
2005-08-02	1.138	0.350	-0.390	0.042	0.735	0.162	1.18	0.01	0.703	1.036	-9.0
2005-08-03	1.262	0.375	-0.360	0.037	0.760	0.192	1.21	0.01	0.859	1.005	-20.3
2005-08-09	0.227	-0.290	0.390	0.018	0.960	0.942	1.51	0.00	0.140	*0.901*	*297.1*
2005-08-16	0.592	-0.090	0.580	0.028	1.160	1.132	1.87	0.00	0.240	*1.409*	*138.0*
2005-08-23	1.030	0.710	0.000	0.012	1.095	0.552	1.78	0.00	0.761	0.873	-15.2
2005-08-30	10.872	0.920	1.210	0.408	2.170	1.762	2.96	0.10	0.823	8.615	-20.8
2005-09-07	4.041	0.570	1.160	0.108	1.820	1.712	2.87	0.01	0.570	4.332	7.2
2005-09-13	1.831	0.330	0.990	0.038	1.580	1.542	2.63	0.00	0.466	2.348	28.2
						Mean				2.809	-1.7
						Standard deviation				2.501	19.3
						Coefficient of Variation				0.890	-11.3

Table C6 Simulated and measured discharges for culvert 86

Date	Measured Q	Head water	Tail water	H-T	h_1	h_4	A_3	$h_{f2,3}$	C_d	Simulated Q	Relative Error
	(ft^3/s)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft^2)	(ft)		(ft^3/s)	(%)
2005-08-03	0.798	0.106	0.090	0.058	0.596	0.538	0.70	0.02	0.720	0.768	-3.8
2005-08-09	2.078	0.300	0.200	0.142	0.790	0.648	1.19	0.04	0.674	2.092	0.7
2005-08-16	1.788	0.260	0.170	0.132	0.750	0.618	1.19	0.03	0.584	2.001	11.9
2005-08-23	0.860	0.280	0.300	0.022	0.770	0.748	1.19	0.01	0.723	0.823	-4.3
2005-08-30	10.863	1.370	0.910	0.502	1.860	1.358	2.56	0.11	0.839	9.137	-15.9
2005-09-07	7.354	1.060	0.760	0.342	1.550	1.208	2.21	0.07	0.794	6.474	-12.0
2005-09-13	5.228	0.860	0.665	0.237	1.350	1.113	1.97	0.05	0.762	4.763	-8.9
							Mean			3.723	-4.6
							Standard deviation			3.182	9.1
							Coefficient of Variation			0.855	-2.0

Table C7 Simulated and measured discharges for culvert 59

Date	Measured Q	Head water	Tail water	H-T	h_1	h_4	A_3	$h_{f2,3}$	C_d	Simulated Q	Relative Error
	(ft^3/s)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft^2)	(ft)		(ft^3/s)	(%)
2004-06-16	2.748	0.400	0.270	0.130	1.240	1.110	1.98	0.02	0.511	3.445	25.3
2004-07-23	2.657	0.420	0.320	0.100	1.260	1.160	1.96	0.01	0.574	3.011	13.3
2004-08-06	7.825	0.890	0.540	0.350	1.730	1.380	2.47	0.06	0.734	7.214	-7.8
2004-08-12	5.609	0.700	0.520	0.180	1.540	1.360	2.44	0.04	0.755	5.065	-9.7
2004-08-20	11.146	1.210	0.760	0.450	2.050	1.600	2.81	0.10	0.836	9.272	-16.8
2004-08-26	8.741	1.080	0.800	0.280	1.920	1.640	2.86	0.06	0.814	7.428	-15.0
2004-09-15	4.877	0.690	0.570	0.120	1.530	1.410	2.47	0.03	0.808	4.175	-14.4
2004-09-22	3.855	0.750	0.610	0.140	1.590	1.450	2.48	0.02	0.551	4.545	17.9
2004-10-01	2.296	0.740	0.700	0.040	1.580	1.540	2.57	0.01	0.598	2.516	9.6
2004-10-06	2.487	0.620	0.580	0.040	1.460	1.420	2.40	0.01	0.718	2.339	-6.0
2004-10-12	2.015	0.600	0.550	0.050	1.440	1.390	2.34	0.01	0.507	2.551	26.6
2004-10-21	11.023	1.320	0.930	0.390	2.160	1.770	2.94	0.10	0.870	8.939	-18.9
2005-06-29	12.718	1.360	0.810	0.550	2.200	1.650	2.91	0.14	0.846	10.526	-17.2
2005-07-06	7.029	0.930	0.700	0.230	1.770	1.540	2.73	0.04	0.742	6.430	-8.5
2005-07-12	5.379	0.870	0.700	0.170	1.710	1.540	2.72	0.03	0.651	5.487	2.0
2005-07-20	2.122	0.580	0.508	0.072	1.420	1.348	2.34	0.01	0.440	*3.056*	*44.0*
2005-07-27	0.386	0.410	0.398	0.012	1.250	1.238	2.16	0.00	0.206	*1.139*	*195.0*
2005-08-09	2.657	0.640	0.570	0.070	1.480	1.410	2.46	0.01	0.541	3.175	19.5
2005-08-16	3.510	0.846	0.742	0.104	1.686	1.582	2.74	0.01	0.523	4.329	23.3
2005-08-23	1.478	0.840	0.805	0.035	1.680	1.645	2.83	0.00	0.358	*2.583*	*74.8*
2005-08-30	13.380	1.920	1.320	0.600	2.760	2.160	3.14	0.16	0.798	11.644	-13.0
2005-09-07	8.000	1.518	1.270	0.248	2.358	2.110	3.14	0.06	0.725	7.486	-6.4
2005-09-13	5.153	1.258	1.120	0.138	2.098	1.960	3.11	0.02	0.605	5.587	8.4
						Mean				5.758	0.6
						Standard deviation				2.780	15.9
						Coefficient of Variation				0.483	25.8

Table C8 Simulated and measured discharges for culvert 77

Date	Measured Q	Head water	Tail water	H-T	h_1	h_4	A_3	$h_{f2,3}$	C_d	Simulated Q	Relative Error
	(ft^3/s)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft^2)	(ft)		(ft^3/s)	(%)
2004-07-29	3.125	0.300	0.220	0.080	1.070	0.990	1.47	0.04	1.269	*2.240*	*-28.3*
2004-08-05	4.872	0.520	0.330	0.190	1.290	1.100	1.88	0.05	0.854	4.486	-7.9
2004-08-12	3.271	0.270	0.180	0.090	1.040	0.950	1.58	0.04	1.128	2.530	-22.7
2004-08-20	3.119	0.370	0.250	0.120	1.140	1.020	1.70	0.03	0.747	3.182	2.0
2004-08-26	2.468	0.305	0.210	0.095	1.075	0.980	1.65	0.02	0.679	*2.714*	*10.0*
2004-09-15	3.523	0.350	0.250	0.100	1.120	1.020	1.72	0.03	1.003	2.913	-17.3
2004-09-23	2.679	0.260	0.230	0.030	1.030	1.000	1.59	0.03	3.183	*1.466*	*-45.3*
2004-09-30	2.230	0.390	0.380	0.010	1.160	1.150	1.98	0.01	--	*1.055*	*-52.7*
2004-10-07	1.403	0.170	0.165	0.005	0.940	0.935	1.51	0.01	--	*0.557*	*-60.3*
2004-10-14	1.140	0.130	0.120	0.010	0.900	0.890	1.37	0.01	1.967	*0.714*	*-37.4*
2004-10-20	5.178	0.590	0.442	0.148	1.360	1.212	2.10	0.04	0.947	4.422	-14.6
2005-06-29	4.954	0.518	0.320	0.198	1.288	1.090	1.89	0.05	0.848	4.584	-7.5
2005-07-07	2.497	0.310	0.230	0.080	1.080	1.000	1.58	0.02	0.807	2.403	-3.8
2005-07-12	2.549	0.320	0.250	0.070	1.090	1.020	1.64	0.02	0.868	2.327	-8.7
2005-07-20	0.700	0.160	0.130	0.030	0.930	0.900	1.45	0.00	0.362	*1.312*	*87.4*
2005-07-27	3.223	0.041	0.040	0.001	0.811	0.810	1.20	0.08	--	*0.194*	*-94.0*
2005-08-03	0.364	0.182	0.178	0.004	0.952	0.948	1.47	0.00	0.529	*0.489*	*34.2*
2005-08-09	1.342	0.190	0.170	0.020	0.960	0.940	1.52	0.01	0.995	1.127	-16.0
2005-08-16	1.661	0.230	0.190	0.040	1.000	0.960	1.52	0.01	0.804	1.605	-3.3
2005-08-23	1.714	0.350	0.280	0.070	1.120	1.050	1.65	0.01	0.523	*2.352*	*37.2*
2005-08-30	11.913	1.260	0.770	0.490	2.030	1.540	2.65	0.12	0.925	10.284	-13.7
2005-09-07	8.625	0.960	0.650	0.310	1.730	1.420	2.43	0.07	0.913	7.516	-12.9
2005-09-13	4.826	0.680	0.530	0.150	1.450	1.300	2.16	0.03	0.815	4.598	-4.7
						Mean				3.998	-10.1
						Standard deviation				2.522	6.8
						Coefficient of Variation				0.631	-0.7

Table C9 Simulated and measured discharges for culvert 101

Date	Measured Q	Head water	Tail water	H-T	h_1	h_4	A_3	$h_{f2,3}$	C_d	Simulated Q	Relative Error
	(ft^3/s)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft^2)	(ft)		(ft^3/s)	(%)
2005-07-06	3.228	0.604	0.430	0.096	1.271	1.175	1.90	0.02	0.774	2.373	-26.5
2005-07-12	2.472	0.720	0.460	0.182	1.387	1.205	1.98	0.01	0.375	3.426	38.6
2005-07-20	1.754	0.550	0.390	0.082	1.217	1.135	1.85	0.01	0.430	2.133	21.6
2005-07-27	0.867	0.440	0.320	0.042	1.107	1.065	1.65	0.00	0.329	1.353	56.0
2005-08-02	0.748	0.370	0.254	0.038	1.037	0.999	1.64	0.00	0.299	1.272	70.0
2005-08-03	0.657	0.350	0.240	0.032	1.017	0.985	1.17	0.00	0.405	0.844	28.5
2005-08-09	1.669	0.500	0.310	0.112	1.167	1.055	1.83	0.01	0.350	2.457	47.2
2005-08-16	1.308	0.430	0.310	0.042	1.097	1.055	1.71	0.01	0.496	1.398	6.9
2005-08-23	0.711	0.475	0.390	0.007	1.142	1.135	1.85	0.00	0.633	0.617	-13.2
2005-08-30	10.289	1.590	1.060	0.452	2.257	1.805	3.11	0.09	0.682	8.392	-18.4
2005-09-07	6.872	1.260	0.970	0.212	1.927	1.72	2.88	0.04	0.711	5.384	-21.7
2005-09-13	5.362	1.090	0.870	0.142	1.757	1.62	2.73	0.03	0.715	4.179	-22.1
							Mean			2.819	13.9
							Standard deviation			2.256	34.3
							Coefficient of Variation			0.800	2.5

Table C10 Simulated and measured discharges for culvert 125

Date	Measured Q	Head water	Tail water	H-T	h_1	h_4	A_3	$h_{f2,3}$	C_d	Simulated Q	Relative Error
	(ft^3/s)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft^2)	(ft)		(ft^3/s)	(%)
2005-08-03	1.245	0.222	0.548	0.039	0.79	0.751	1.36	0.01	0.685	1.380	10.8
2005-08-09	1.125	0.400	0.740	0.025	0.968	0.943	1.63	0.00	0.608	1.379	22.6
2005-08-16	1.784	0.310	0.664	0.011	0.878	0.867	1.65	0.01	--	0.902	-49.4
2005-08-23	0.372	0.710	0.330	0.015	0.673	0.658	1.32	0.00	0.302	*0.787*	*111.5*
2005-08-30	7.598	1.350	1.600	0.115	1.918	1.803	3.01	0.04	1.183	5.755	-24.3
2005-09-07	4.746	1.130	1.420	0.075	1.698	1.623	2.83	0.02	0.890	4.363	-8.1
2005-09-13	2.850	1.001	1.330	0.036	1.569	1.533	2.67	0.01	0.798	2.846	-0.1
							Mean			2.771	-8.1
							Standard deviation			1.940	25.8
							Coefficient of Variation			0.700	-3.2

Table C11 Simulated and measured discharges for culvert 133

Date	Measured Q	Head water	Tail water	H-T	h_1	h_4	A_3	$h_{f2,3}$	C_d	Simulated Q	Relative Error
	(ft^3/s)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft^2)	(ft)		(ft^3/s)	(%)
2005-07-06	2.808	0.220	0.570	0.046	1.653	1.607	2.58	0.01	0.697	2.029	-27.7
2005-07-12	2.090	0.340	0.659	0.077	1.773	1.696	2.79	0.00	0.345	2.842	36.0
2005-07-20	0.975	0.205	0.569	0.032	1.638	1.606	2.63	0.00	0.262	1.730	77.4
2005-07-27	0.576	0.100	0.485	0.011	1.533	1.522	2.46	0.00	0.283	0.948	64.7
2005-08-02	0.284	0.020	0.400	0.016	1.453	1.437	2.22	0.00	0.127	*1.031*	*263.0*
2005-08-09	0.686	0.140	0.505	0.031	1.573	1.542	2.46	0.00	0.199	1.591	131.9
2005-08-16	1.501	0.050	0.440	0.006	1.483	1.477	2.40	0.00	1.365	0.681	-54.6
2005-08-23	0.262	0.490	0.090	0.004	1.923	1.127	1.87	0.00	0.279	0.441	68.3
2005-08-30	7.702	1.070	1.220	0.246	2.503	2.257	3.14	0.05	0.694	5.650	-26.6
2005-09-07	4.801	0.820	1.060	0.156	2.253	2.097	3.14	0.02	0.517	4.499	-6.3
2005-09-13	3.083	0.680	0.960	0.116	2.113	1.997	3.14	0.01	0.373	3.879	25.8
							Mean			2.429	28.9
							Standard deviation			1.658	55.1
							Coefficient of Variation			0.682	1.9

Table C12 Simulated and measured discharges for culvert 170

Date	Measured Q	Head water	Tail water	H-T	h_1	h_4	A_3	$h_{f2,3}$	C_d	Simulated Q	Relative Error
	(ft^3/s)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft^2)	(ft)		(ft^3/s)	(%)
2004-07-30	0.196	0.100	0.090	0.010	0.730	0.720	0.94	0.001	0.271	0.359	83.6
2004-09-16	0.270	0.280	0.270	0.010	0.910	0.900	1.23	0.001	0.284	0.485	79.5
2004-09-23	0.201	0.270	0.260	0.010	0.900	0.890	1.23	0.000	0.208	0.484	140.3
2004-09-30	2.165	0.520	0.485	0.035	1.150	1.115	1.64	0.021	1.413	1.234	-43.0
2004-10-06	0.259	0.280	0.270	0.010	0.910	0.900	1.21	0.001	0.276	0.478	84.5
2004-10-13	0.733	0.380	0.370	0.010	1.010	1.000	1.39	0.004	0.832	0.555	-24.3
2004-10-20	0.551	0.395	0.385	0.010	1.025	1.015	1.43	0.002	0.535	0.572	3.8
2005-06-29	0.345	0.255	0.250	0.005	0.885	0.880	1.19	0.001	0.556	0.348	0.8
2005-08-30	3.364	0.800	0.620	0.180	1.430	1.250	1.77	0.034	0.619	3.100	-7.8
2005-09-07	1.751	0.550	0.500	0.050	1.180	1.130	1.64	0.013	0.697	1.481	-15.4
							Mean			0.910	30.2
							Standard deviation			0.859	61.3
							Coefficient of Variation			0.944	2.0

Note: the italic values are outliers from Table C1 through C13.

Table C13 Simulated and Measured Discharges Derived From Measurements of All Culverts Using Model Based on $\frac{Q}{A_3\sqrt{2g}}$ as a Function of $\sqrt{h_1 - h_4}$

Culvert No.	Date	Measured Q	$h_1 - h_4$	A3	$\sqrt{h_1 - h_4}$	$\frac{Q}{A_3\sqrt{2g}}$	Simulated Q	Relative Error
		(ft^3/s)	(ft)	(ft^2)			(ft^3/s)	(%)
C_24	2004-08-04	2.290	0.070	3.14	0.265	0.09	*4.094*	*-78.8*
	2004-08-18	1.031	0.080	3.14	0.283	0.04	*4.352*	*-322.1*
	2004-10-19	1.128	0.080	3.14	0.283	0.04	*4.352*	*-285.7*
	2005-06-29	1.234	0.076	3.14	0.276	0.05	*4.242*	*-243.7*
	2005-07-06	2.735	0.063	3.14	0.251	0.11	*3.862*	*-41.2*
	2005-07-07	0.543	0.054	3.14	0.232	0.02	*3.575*	*-558.5*
	2005-07-12	5.286	0.066	3.14	0.257	0.21	3.953	25.2
	2005-08-30	4.660	0.240	3.14	0.490	0.18	*7.538*	*-61.8*
	2005-09-07	5.256	0.178	3.14	0.422	0.21	6.492	-23.5
	2005-09-13	1.766	0.118	3.14	0.344	0.07	*5.285*	*-199.3*
C_30	2004-08-04	0.183	0.070	3.10	0.265	0.01	*4.083*	*-2131.3*
	2004-08-11	0.409	0.030	2.89	0.173	0.02	*2.511*	*-514.6*
	2004-08-18	0.666	0.020	3.14	0.141	0.03	*2.176*	*-226.6*
	2004-08-27	0.245	0.020	2.80	0.141	0.01	*1.992*	*-713.0*
	2004-09-01	0.303	0.015	2.87	0.122	0.01	*1.768*	*-482.8*
	2004-10-19	0.245	0.040	3.04	0.200	0.01	*3.037*	*-1139.8*
C_32	2005-07-06	1.587	0.006	2.69	0.077	0.07	1.042	34.3
	2005-07-12	1.267	0.006	2.74	0.077	0.06	1.061	16.3
	2005-07-13	0.876	0.010	2.74	0.100	0.04	*1.369*	*-56.3*
	2005-07-20	0.421	0.001	2.76	0.032	0.02	0.432	-2.6
	2005-07-27	0.177	0.001	2.25	0.032	0.01	*0.357*	*-101.7*
	2005-08-23	1.146	0.011	2.63	0.105	0.05	1.378	-20.2
	2005-08-30	6.681	0.101	3.14	0.318	0.27	4.890	26.8
	2005-09-07	4.644	0.061	2.63	0.247	0.22	3.288	29.2
	2005-09-13	3.487	0.021	2.92	0.145	0.15	2.120	39.2
C_34	2004-08-06	5.289	0.070	3.14	0.265	0.21	4.086	22.7
	2004-08-11	3.706	0.050	3.13	0.224	0.15	3.471	6.3
	2004-08-18	5.483	0.070	3.14	0.265	0.22	4.071	25.7
	2004-08-27	3.361	0.025	3.14	0.158	0.13	2.451	27.1
	2004-09-01	2.871	0.060	3.11	0.245	0.12	3.787	-31.9
	2004-09-16	0.236	0.020	2.79	0.141	0.01	*1.972*	*-733.8*
	2004-09-23	1.490	0.030	2.99	0.173	0.06	*2.587*	*-73.6*
	2004-10-01	1.715	0.040	3.01	0.200	0.07	*3.008*	*-75.4*

Culvert No.	Date	Measured Q	$h_1 - h_4$	A_3	$\sqrt{h_1 - h_4}$	$\frac{Q}{A_3\sqrt{2g}}$	Simulated Q	Relative Error
		(ft^3/s)	(ft)	(ft^2)			(ft^3/s)	(%)
	2004-10-05	0.656	0.020	2.90	0.141	0.03	*2.051*	*-212.7*
	2004-10-19	5.603	0.082	3.14	0.286	0.22	4.406	21.4
	2004-11-05	1.007	0.025	3.01	0.158	0.04	*2.378*	*-136.2*
C_38	2005-08-03	2.212	0.032	2.44	0.179	0.11	2.175	1.7
	2005-08-09	2.077	0.032	2.53	0.179	0.10	2.251	-8.4
	2005-08-16	2.424	0.052	2.73	0.228	0.11	3.116	-28.6
	2005-08-23	2.916	0.042	2.84	0.205	0.13	2.913	0.1
	2005-08-30	8.072	0.262	3.14	0.512	0.32	7.876	2.4
	2005-09-07	8.550	0.212	3.14	0.460	0.34	7.085	17.1
	2005-09-13	7.811	0.142	3.14	0.377	0.31	5.821	25.5
C_43	2004-07-28	4.622	0.110	2.07	0.332	0.28	3.463	25.1
	2004-08-06	5.613	0.160	2.14	0.400	0.33	4.368	22.2
	2004-08-12	3.481	0.060	2.00	0.245	0.22	2.482	28.7
	2004-08-20	7.831	0.250	2.36	0.500	0.41	6.013	23.2
	2004-08-26	5.984	0.160	2.41	0.400	0.31	4.900	18.1
	2004-09-15	3.117	0.010	1.91	0.100	0.20	*0.960*	*69.2*
	2004-09-16	1.478	0.005	1.93	0.071	0.10	*0.685*	*53.7*
	2004-09-22	2.565	0.030	2.05	0.173	0.16	1.793	30.1
	2004-09-29	1.550	0.010	2.03	0.100	0.09	1.026	33.8
	2004-10-05	1.560	0.005	2.10	0.071	0.09	*0.750*	*51.9*
	2004-10-12	0.542	0.005	2.03	0.071	0.03	*0.724*	*-33.6*
	2004-10-19	8.310	0.225	2.67	0.474	0.39	6.416	22.8
	2005-08-03	2.365	0.000	2.53	0.000	0.12	*0.000*	*100.0*
	2005-08-09	2.085	0.010	2.23	0.100	0.12	*1.133*	*45.6*
	2005-08-16	1.863	0.010	2.37	0.100	0.10	1.204	35.4
	2005-08-23	3.427	0.040	2.57	0.200	0.17	2.607	23.9
	2005-08-30	8.589	0.200	3.14	0.447	0.34	6.881	19.9
	2005-09-07	6.093	0.110	3.14	0.332	0.24	5.103	16.2
	2005-09-13	4.805	0.060	3.14	0.245	0.19	3.769	21.6
C_57	2005-07-06	3.469	0.168	1.74	0.410	0.25	3.547	-2.2
	2005-07-12	2.221	0.138	1.71	0.371	0.16	*3.144*	*-41.5*
	2005-07-20	1.038	0.026	1.33	0.161	0.10	1.028	0.9
	2005-07-27	0.225	0.010	1.84	0.100	0.02	*0.757*	*-236.4*
	2005-08-02	1.138	0.042	1.18	0.205	0.12	1.119	1.7
	2005-08-03	1.262	0.037	1.21	0.192	0.13	1.087	13.9
	2005-08-09	0.227	0.018	1.51	0.134	0.02	*0.980*	*-331.6*
	2005-08-16	0.592	0.028	1.87	0.167	0.04	*1.536*	*-159.5*
	2005-08-23	1.030	0.012	1.78	0.110	0.07	0.951	7.7

Culvert No.	Date	Measured Q	$h_1 - h_4$	A$_3$	$\sqrt{h_1 - h_4}$	$\frac{Q}{A_3\sqrt{2g}}$	Simulated Q	Relative Error
		(ft^3/s)	(ft)	(ft^2)			(ft^3/s)	(%)
	2005-08-30	10.872	0.408	2.96	0.639	0.46	9.413	13.4
	2005-09-07	4.041	0.108	2.87	0.329	0.18	4.739	-17.3
	2005-09-13	1.831	0.038	2.63	0.195	0.09	*2.566*	*-40.2*
C_59	2004-06-16	2.748	0.130	1.98	0.361	0.17	3.528	-28.4
	2004-07-23	2.657	0.100	1.96	0.316	0.17	3.084	-16.1
	2004-08-06	7.825	0.350	2.47	0.592	0.39	7.396	5.5
	2004-08-12	5.609	0.180	2.44	0.424	0.29	5.191	7.5
	2004-08-20	11.146	0.450	2.81	0.671	0.49	9.503	14.7
	2004-08-26	8.741	0.280	2.86	0.529	0.38	7.612	12.9
	2004-09-15	4.877	0.120	2.47	0.346	0.25	4.278	12.3
	2004-09-22	3.855	0.140	2.48	0.374	0.19	4.658	-20.8
	2004-10-01	2.296	0.040	2.57	0.200	0.11	2.578	-12.3
	2004-10-06	2.487	0.040	2.40	0.200	0.13	2.396	3.7
	2004-10-12	2.015	0.050	2.34	0.224	0.11	2.614	-29.7
	2004-10-21	11.023	0.390	2.94	0.624	0.47	9.157	16.9
	2005-06-29	12.718	0.550	2.91	0.742	0.54	10.784	15.2
	2005-07-06	7.029	0.230	2.73	0.480	0.32	6.590	6.3
	2005-07-12	5.379	0.170	2.72	0.412	0.25	5.623	-4.5
	2005-07-20	2.122	0.072	2.34	0.268	0.11	*3.131*	*-47.5*
	2005-07-27	0.386	0.012	2.16	0.110	0.02	*1.166*	*-202.1*
	2005-08-09	2.657	0.070	2.46	0.265	0.13	3.253	-22.4
	2005-08-16	3.510	0.104	2.74	0.322	0.16	4.436	-26.4
	2005-08-23	1.478	0.035	2.83	0.187	0.07	*2.647*	*-79.1*
	2005-08-30	13.380	0.600	3.14	0.775	0.53	11.918	10.9
	2005-09-07	8.000	0.248	3.14	0.498	0.32	7.662	4.2
	2005-09-13	5.153	0.138	3.11	0.371	0.21	5.722	-11.0
C_69	2004-07-23	0.607	0.010	1.63	0.100	0.05	0.796	-31.3
	2004-07-29	4.543	0.100	2.40	0.316	0.24	3.800	16.4
	2004-08-05	4.919	0.140	2.35	0.374	0.26	4.435	9.8
	2004-08-12	4.476	0.050	2.10	0.224	0.27	*2.338*	*47.8*
	2004-08-19	5.147	0.150	2.52	0.387	0.25	4.918	4.5
	2004-08-26	3.662	0.090	2.41	0.300	0.19	3.612	1.4
	2004-09-15	1.650	0.040	2.04	0.200	0.10	2.024	-22.6
	2004-09-16	1.526	0.040	1.93	0.200	0.10	1.915	-25.5
	2004-09-22	2.201	0.040	2.10	0.200	0.13	2.082	5.4
	2004-09-30	0.832	0.030	2.16	0.173	0.05	*1.861*	*-123.7*
	2004-10-07	0.719	0.020	1.83	0.141	0.05	*1.266*	*-76.1*
	2004-10-12	1.035	0.020	1.70	0.141	0.08	1.178	-13.8

Culvert No.	Date	Measured Q	$h_1 - h_4$	A$_3$	$\sqrt{h_1 - h_4}$	$\frac{Q}{A_3\sqrt{2g}}$	Simulated Q	Relative Error
		(ft^3/s)	(ft)	(ft^2)			(ft^3/s)	(%)
	2004-10-21	7.755	0.230	2.69	0.480	0.36	6.510	16.1
C_77	2004-07-29	3.125	0.080	1.47	0.283	0.26	2.052	34.3
	2004-08-05	4.872	0.190	1.88	0.436	0.32	4.101	15.8
	2004-08-12	3.271	0.090	1.58	0.300	0.26	2.322	29.0
	2004-08-20	3.119	0.120	1.70	0.346	0.23	2.915	6.5
	2004-08-26	2.468	0.095	1.65	0.308	0.19	2.490	-0.9
	2004-09-15	3.523	0.100	1.72	0.316	0.26	2.671	24.2
	2004-09-23	2.679	0.030	1.59	0.173	0.21	*1.346*	*49.7*
	2004-09-30	2.230	0.010	1.98	0.100	0.14	*0.968*	*56.6*
	2004-10-07	1.403	0.005	1.51	0.071	0.12	*0.513*	*63.5*
	2004-10-14	1.140	0.010	1.37	0.100	0.10	0.658	42.3
	2004-10-20	5.178	0.148	2.10	0.385	0.31	4.042	21.9
	2005-06-29	4.954	0.198	1.89	0.445	0.33	4.190	15.4
	2005-07-07	2.497	0.080	1.58	0.283	0.20	2.203	11.8
	2005-07-12	2.549	0.070	1.64	0.265	0.19	2.134	16.3
	2005-07-20	0.700	0.030	1.45	0.173	0.06	*1.207*	*-72.5*
	2005-07-27	3.223	0.001	1.20	0.032	0.33	*0.209*	*93.5*
	2005-08-03	0.364	0.004	1.47	0.063	0.03	0.450	-23.5
	2005-08-09	1.342	0.020	1.52	0.141	0.11	1.037	22.7
	2005-08-16	1.661	0.040	1.52	0.200	0.14	1.475	11.2
	2005-08-23	1.714	0.070	1.65	0.265	0.13	2.155	-25.7
	2005-08-30	11.913	0.490	2.65	0.700	0.56	9.375	21.3
	2005-09-07	8.625	0.310	2.43	0.557	0.44	6.851	20.6
	2005-09-13	4.826	0.150	2.16	0.387	0.28	4.199	13.0
C_86	2005-08-03	0.798	0.058	0.70	0.241	0.14	0.773	3.2
	2005-08-09	2.078	0.142	1.19	0.377	0.22	2.107	-1.4
	2005-08-16	1.788	0.132	1.19	0.363	0.19	2.015	-12.7
	2005-08-23	0.860	0.022	1.19	0.148	0.09	0.828	3.7
	2005-08-30	10.863	0.502	2.56	0.709	0.53	9.210	15.2
	2005-09-07	7.354	0.342	2.21	0.585	0.42	6.526	11.3
	2005-09-13	5.228	0.237	1.97	0.487	0.33	4.800	8.2
C_89	2004-08-12	0.725	0.010	0.89	0.100	0.10	0.416	42.7
	2004-08-20	1.308	0.060	0.85	0.245	0.19	0.986	24.6
	2004-08-26	0.951	0.040	0.79	0.200	0.15	0.743	21.9
	2004-09-16	3.399	0.215	1.51	0.464	0.28	3.442	-1.3
	2004-09-23	2.748	0.140	1.44	0.374	0.24	2.617	4.8
	2004-09-30	1.057	0.025	1.84	0.158	0.07	*1.422*	*-34.5*
	2004-10-06	2.275	0.150	1.37	0.387	0.21	2.568	-12.9

Culvert No.	Date	Measured Q	$h_1 - h_4$	A$_3$	$\sqrt{h_1 - h_4}$	$\frac{Q}{A_3\sqrt{2g}}$	Simulated Q	Relative Error
		(ft^3/s)	(ft)	(ft^2)			(ft^3/s)	(%)
	2004-10-13	2.365	0.130	1.31	0.361	0.23	2.262	4.3
	2004-10-20	3.242	0.135	1.77	0.367	0.23	3.198	1.4
	2004-11-05	1.649	0.130	1.24	0.361	0.17	2.127	-29.0
C_101	2005-07-06	3.228	0.096	1.90	0.310	0.21	2.933	9.1
	2005-07-12	2.472	0.182	1.98	0.427	0.16	*4.247*	*-71.8*
	2005-07-20	1.754	0.082	1.85	0.286	0.12	*2.631*	*-50.0*
	2005-07-27	0.867	0.042	1.65	0.205	0.07	*1.665*	*-92.0*
	2005-08-02	0.748	0.038	1.64	0.195	0.06	*1.560*	*-108.5*
	2005-08-03	0.657	0.032	1.17	0.179	0.07	*1.042*	*-58.6*
	2005-08-09	1.669	0.112	1.83	0.335	0.11	*3.026*	*-81.3*
	2005-08-16	1.308	0.042	1.71	0.205	0.10	1.719	-31.4
	2005-08-23	0.711	0.007	1.85	0.084	0.05	0.759	-6.8
	2005-08-30	10.289	0.452	3.11	0.672	0.41	10.341	-0.5
	2005-09-07	6.872	0.212	2.88	0.460	0.30	6.675	2.9
	2005-09-13	5.362	0.142	2.73	0.377	0.24	5.182	3.4
C_108	2004-08-12	0.371	0.020	1.59	0.141	0.03	*1.086*	*-192.6*
	2004-08-19	0.803	0.040	1.57	0.200	0.06	*1.521*	*-89.5*
	2004-08-26	0.513	0.040	1.49	0.200	0.04	*1.447*	*-182.2*
	2004-09-16	2.987	0.070	1.84	0.265	0.20	2.435	18.5
	2004-09-23	2.383	0.040	1.77	0.200	0.17	1.772	25.7
	2004-09-30	0.657	0.015	2.22	0.122	0.04	*1.358*	*-106.7*
	2004-10-06	1.900	0.055	1.77	0.235	0.13	2.070	-8.9
	2004-10-13	1.544	0.040	1.64	0.200	0.12	1.635	-5.9
	2004-10-20	2.427	0.050	2.09	0.224	0.14	2.350	3.2
	2004-11-05	0.742	0.030	1.63	0.173	0.06	*1.398*	*-88.5*
C_118	2004-08-12	0.209	0.010	0.77	0.100	0.03	*0.353*	*-69.1*
	2004-08-19	0.360	0.010	0.74	0.100	0.06	0.336	6.8
	2004-08-26	0.277	0.010	0.70	0.100	0.05	0.318	-14.7
	2004-09-16	1.684	0.090	1.38	0.300	0.15	2.020	-19.9
	2004-09-23	1.692	0.050	1.26	0.224	0.17	1.360	19.6
	2004-09-30	0.307	0.010	1.59	0.100	0.02	*0.778*	*-153.5*
	2004-10-06	1.648	0.040	1.18	0.200	0.17	1.142	30.7
	2004-10-13	0.837	0.035	1.18	0.187	0.09	1.058	-26.4
	2004-10-20	1.176	0.045	1.57	0.212	0.09	*1.629*	*-38.5*
	2004-11-04	0.686	0.025	1.19	0.158	0.07	0.880	-28.2
C_125	2005-08-03	1.245	0.039	1.36	0.197	0.11	1.246	-0.1
	2005-08-09	1.125	0.025	1.63	0.158	0.09	1.237	-9.9
	2005-08-16	1.784	0.011	1.65	0.105	0.13	*0.813*	*54.4*

Culvert No.	Date	Measured Q	$h_1 - h_4$	A_3	$\sqrt{h_1 - h_4}$	$\frac{Q}{A_3\sqrt{2g}}$	Simulated Q	Relative Error
		(ft^3/s)	(ft)	(ft^2)			(ft^3/s)	(%)
	2005-08-23	0.372	0.015	1.32	0.122	0.04	*0.717*	*-92.9*
	2005-08-30	7.598	0.115	3.01	0.339	0.31	5.107	32.8
	2005-09-07	4.746	0.075	2.83	0.274	0.21	3.872	18.4
	2005-09-13	2.850	0.036	2.67	0.190	0.13	2.527	11.3
C_133	2005-07-06	2.808	0.046	2.58	0.214	0.14	2.772	1.3
	2005-07-12	2.090	0.077	2.79	0.277	0.09	*3.883*	*-85.8*
	2005-07-20	0.975	0.032	2.63	0.179	0.05	*2.363*	*-142.4*
	2005-07-27	0.576	0.011	2.46	0.105	0.03	*1.295*	*-124.8*
	2005-08-02	0.284	0.016	2.22	0.126	0.02	*1.408*	*-395.7*
	2005-08-09	0.686	0.031	2.46	0.176	0.03	*2.174*	*-216.9*
	2005-08-16	1.501	0.006	2.40	0.077	0.08	0.929	38.1
	2005-08-23	0.262	0.004	1.87	0.063	0.02	*0.610*	*-132.9*
	2005-08-30	7.702	0.246	3.14	0.496	0.31	7.631	0.9
	2005-09-07	4.801	0.156	3.14	0.395	0.19	6.077	-26.6
	2005-09-13	3.083	0.116	3.14	0.341	0.12	*5.240*	*-70.0*
C_143	2004-08-19	0.124	0.025	0.28	0.158	0.05	*0.210*	*-69.8*
	2004-08-26	0.089	0.030	0.27	0.173	0.04	*0.218*	*-145.2*
	2004-09-16	0.947	0.060	0.83	0.245	0.14	1.004	-6.0
	2004-09-23	0.583	0.050	0.72	0.224	0.10	*0.790*	*-35.7*
	2004-09-30	0.243	0.010	1.11	0.100	0.03	*0.552*	*-126.8*
	2004-10-06	0.568	0.040	0.70	0.200	0.10	0.690	-21.4
	2004-10-13	0.372	0.060	0.61	0.245	0.08	*0.740*	*-99.0*
	2004-10-20	0.527	0.030	0.98	0.173	0.07	*0.839*	*-59.4*
	2004-11-04	0.340	0.045	0.53	0.212	0.08	*0.544*	*-60.0*
C_170	2004-07-30	0.196	0.010	0.94	0.100	0.03	*0.412*	*-110.4*
	2004-09-16	0.270	0.010	1.23	0.100	0.03	*0.562*	*-107.8*
	2004-09-23	0.201	0.010	1.23	0.100	0.02	*0.560*	*-177.9*
	2004-09-30	2.165	0.035	1.64	0.187	0.16	1.440	33.5
	2004-10-06	0.259	0.010	1.21	0.100	0.03	*0.553*	*-113.7*
	2004-10-13	0.733	0.010	1.39	0.100	0.07	0.645	12.0
	2004-10-20	0.551	0.010	1.43	0.100	0.05	0.665	-20.7
	2005-06-29	0.345	0.005	1.19	0.071	0.04	0.410	-18.9
	2005-08-30	3.364	0.180	1.77	0.424	0.24	3.652	-8.6
	2005-09-07	1.751	0.050	1.64	0.224	0.13	1.732	1.1
					Mean		3.445	5.6
					Standard deviation		2.508	18.8
					Coefficient of Variation		0.728	3.3