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RATING DEVELOPMENT FOR FLOW THROUGH CULVERTS UNDER SR9336 IN THE EVERGLADES NATIONAL PARK
I: CONCEPTS AND METHODS

BY

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EXECUTIVE SUMMARY

This report describes theoretical principles governing the rating analysis and flow calculation for culverts in the Everglades National Park (ENP). It presents steps to conduct rating analysis using flow data collected from ENP.

The dominant flow types across the main park road (SR 9336) are type 3 and type 4, based on USGS (Bodhaine's) classification of flow through culverts. For type 3, two methods are employed to simulate the culvert flow. One method is based on convergence of calculated flow values; the other is based on convergence of calculated head values. While these two methods give the same results, the head based method is simpler. For type 4 flow, no iteration is required. Simulation of culvert flow for this type is a direct application of the flow equation.

A FORTRAN program is written for each of these two flow types. The programs developed in this study determine depth of water at the culvert entrance for type 3 flow and calculate flow for both type 3 and type 4. By applying the programs developed, we get calculated flows. By comparing calculated flows with measured flows, we examine the appropriateness of discharge coefficients obtained from rating analyses.

It is recommended that the algorithm to simulate depth of water h_2 developed in this study be implemented in the District's FLOW program for type 3 culvert flow. It is further recommended that similar approaches be used to model other types of culvert flow and flows with gate control in the FLOW program.

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LIST OF ACRONYMS AND ABBREVATIONS

CERP	Comprehensive Everglades Restoration Project
ENP	Everglades National Park
RECOVER	REstoration, COordination, and VERification

NOTATIONS FOR PRINCIPLE ILLUSTRATION

A	flow cross section
A_0	area of culvert barrel (area of section of full flow)
A_3	area of flow at section 3
C_3	discharge coefficient for type 3 culvert flow
C_4	discharge coefficient for type 4 culvert flow
D	diameter of culvert
d	depth of water inside culvert
d_2	depth of water at section 2
d_c	maximum depth of water in the critical flow section
g	acceleration of gravity
h_1	water level above datum at section 1
h_3	water level above datum at section 3
$h_{f\,1\text{-}2}$	head loss due to friction between sections 1 and 2
$h_{f\,2\text{-}3}$	head loss due to friction in the culvert barrel
$h_{f\,3\text{-}4}$	head loss due to friction between sections 3 and 4
h_e	head loss due to entrance contraction
h_{v1}	velocity head of section 1
h_{v3}	velocity head of section 3
h_{v4}	velocity head of section 4
K	conveyance of section
K_0	conveyance of full culvert barrel
K_2	conveyance of section 2
K_3	conveyance of section 3
L	length of culvert barrel
n	Manning's roughness coefficient
P	wetted perimeter
Q	discharge through culvert
R	hydraulic radius
T	width of the section at the water surface
V_2	mean velocity at section 2
z	Elevation of culvert inlet above datum. If datum is selected as the elevation of culvert outlet invert, then z = inlet invert elevation - outlet invert elevation
Θ	one half of the central angle of the circular segment intercepted by the free water surface in a partially filled culvert

NOTATIONS FOR PROGRAM IMPLEMENTATION

A2	Area of flow at section 2 (culvert entrance)
A3	Area of flow at section 3 (culvert outlet)
DC	Maximum depth of water in the critical flow section
ERROR1	Relative difference of QRES versus QOBS
ERROR2	Relative difference of QEST versus QOBS
ERROR3	Relative difference of QEST versus QRES
H1	Head water depth above outlet invert
H2	Water level above outlet invert at culvert entrance (Section 2)
H2/H1	Ratio of depth of water (H2) to depth of head water (H1)
H3	Water level above invert at culvert outlet (Section 3)
H4	Tail water depth above outlet invert
HW	Head water level (measured)
K2	Conveyance of section 2
K3	Conveyance of section 3
P2	Wetted perimeter of section 2
P3	Wetted perimeter of section 3
QEST	Flow estimated using assumed depth of water at section 2 without iteration
QOBS	Flow measured from field
QRES	Flow calculated by solving energy equation iteratively using the standard step method
R2	Hydraulic radius of section 2
R3	Hydraulic radius of section 3
TW	Tail water level (measured)
ε_F	Error limit of function value to determine if convergence has been reached
ε_Q	Error limit of flow value to determine if convergence has been reached for the flow based iteration method
ε_R	Error limit of root sought to determine if convergence has been reached
$\Theta 2$	One half of the central angle of the circular segment intercepted by the free water surface at section 2
$\Theta 3$	One half of the central angle of the circular segment intercepted by the free water surface at section 3

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INTRODUCTION

In the Everglades National Park (ENP), a 40 mile main park road SR 9336, running from the visitor center to Flamingo, divides the park into two major parts: Shark Slough on the north and west side, Taylor Slough on the south and east side. Under the road, 178 culverts connect the water flow between the two sides. To support RECOVER (REstoration, COordination, and VERification) and CERP (Comprehensive Everglades Restoration Project) efforts, accurate flow computations through the culverts under SR 9336 are needed for regional water balance and flow modeling studies, as well as for evaluating the hydrological well-being of the Everglades.

Simulation of culvert flow was originally conducted in the South Florida Water Management District (the District) by Andrew Fan in 1985, who was then an employee of the District. Fan's method and algorithm were based on the concept of entrance loss coefficient. Application of Fan's methods resulted in relatively large differences from actual measurements (Damisse, et al, 1997). The discrepancy is especially large for the condition of open channel flow, which is the dominant flow type in the Everglades culverts. To overcome the problem of Fan's method, Damisse et al (1997) presented a discharge coefficient based method to calculate culvert flow. The method presented by Damisse at al (NFLOW) was based on the principles presented in Bodhaine (1968). This method is more physically based compared to Fan's, is easier to use, and gives better results.

For the flow calculation, the principles used in this study are those presented in Bodhaine's report. Compared with NFLOW, one improvement resulting from this study relates to how depth of water at culvert entrance (d_2) is calculated. In NFLOW, 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; whereas in this report, d_2 is solved iteratively without imposing such an assumption.

OBJECTIVE AND SCOPE

The objective of this report is to examine principles for conducting rating analysis to determine discharge coefficients for type 3 and 4 culvert flows based on field measured data, as well as to provide ways to model type 3 and 4 culvert flows. The scope of this effort includes developing algorithms to implement numerical simulation of type 3 culvert flow, and presenting computer programs (also called the discharge program all across this report) for both type 3 and 4 culvert flows. Putting discharge coefficients into the computer models, we calculate flows. By comparing calculated and measured flows, we examine the appropriateness of discharge coefficients obtained from rating analyses.

DOMINANT CULVERT FLOW TYPES IN ENP

According to Bodhaine, six types of flow can occur through a culvert. Under ENP conditions (flat topography), two types of flow are likely to occur. They are type 3 (tranquil flow throughout) and type 4 flow (submerged outlet), as illustrated in Figure 1**Error! Reference source not found.** and Figure 2**Error! Reference source not found.**. For these two types of

flow, backwater is the controlling factor in the culvert flow. Type 3 flows partly full inside the culvert; whereas type 4 flows full, with both ends completely submerged. To describe the flow, we choose four sections along the flow path. Section 1 is the approach section, at the location of the head water level. This section is assumed the same as where the upstream staff gauge is located. Section 2 is the culvert entrance. Section 3 is the culvert outlet. Section 4 is the location of the tail water level. This is where the downstream staff gauge is located. As a simplification in this study, water level in Section 3 is assumed the same as that in Section 4.

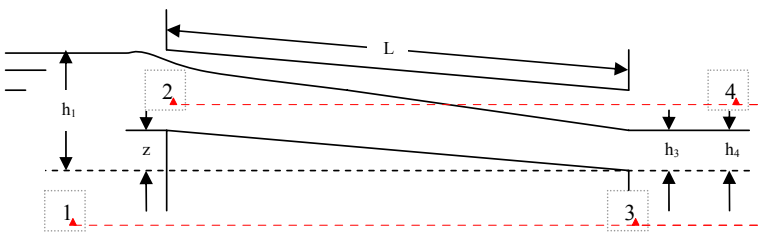

Figure 1. Type 3 culvert flow (Tranquil Flow Throughout)

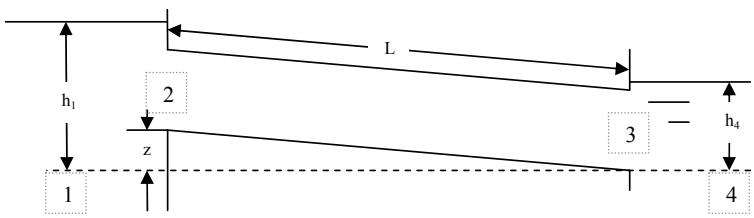

Figure 2. Type 4 culvert flow (Submerged Outlet)

BASIC GEOMETRIC AND HYDRAULIC PROPERTIES

The following equations are used to determine basic parameters related to culvert flow.

$$\Theta = \arccos(1 - 2\frac{d}{D}) \tag{1}$$

$$A = \frac{D^2}{4}(\Theta - \frac{1}{2}\sin 2\Theta) \tag{2}$$

$$P = \Theta D \tag{3}$$

$$R = A / P \tag{4}$$

$$T = D \sin \Theta \tag{5}$$

$$K = \frac{1.486}{n} R^{2/3} A \tag{6}$$

Where
Θ = one half of the central angle of the circular segment intercepted by the free water surface in a partially filled culvert,
d = depth of water inside culvert,
D = diameter of culvert,
A = area of section of flow in the culvert,
P = wetted perimeter of cross section of flow,
R = hydraulic radius,
T = width of the section at the water surface,
n = Manning's roughness coefficient,
K = conveyance of section

Head loss due to friction in the culvert barrel $h_{f\,2\text{-}3}$ can be estimated by:

$$h_{f\,2-3} = L \frac{Q^2}{K_2 K_3} \tag{7}$$

Where
K_2, K_3 = conveyances of sections 2 and 3 respectively,
L = length of culvert barrel,
Q = discharge through culvert

EQUATIONS OF TYPE 3 FLOW

For type 3, the depth of water d_2 at section 2 is an important quantity to estimate the flow. The complete energy equation for determining d_2 is given by Bodhaine as:

$$h_1 - z = d_2 + \frac{V_2^2}{2g} + (\frac{1}{C^2} - 1)\frac{V_3^2}{2g} + h_{f\,1\text{-}2} - \frac{\alpha_1 V_1^2}{2g} \tag{8}$$

As an approximation, assuming the approach friction and the approach velocity head are compensating and $V_2 = V_3$, the above equation can be simplified as:

$$h_1 - z = d_2 + \frac{V_2^2}{2gC_3^2} \tag{9}$$

The discharge equation given by Bodhaine is:

$$Q = C_3 A_3 \sqrt{2g(h_1 + \frac{\alpha_1 V_1^2}{2g} - h_3 - h_{f1-2} - h_{f2-3})} \tag{10}$$

Similarly assuming that $\frac{\alpha_1 V_1^2}{2g}$ is compensating for h_{f1-2}, Equation (10) is simplified as:

$$Q = C_3 A_3 \sqrt{2g(h_1 - h_3 - h_{f2-3})} \tag{11}$$

Where
h_1 = water level above datum at section 1,
z = elevation of inlet invert above datum. If datum is selected as the elevation of outlet invert, then z = inlet invert elevation - outlet invert elevation,
d_2 = depth of water at section 2,
V_2 = mean velocity at section 2,
g = acceleration of gravity,
C_3 = coefficient of discharge for type 3 flow,
A_3 = area of section of flow at section 3,
h_3 = water level above datum at section 3,
h_{f2-3} = head loss due to friction in the culvert barrel.

Putting Equation (7) of head loss h_{f2-3} into Equation (11) and rearranging, we have:

$$Q = C_3 A_3 \sqrt{\frac{2g(h_1 - h_3)}{1 + \frac{2gC_3^2 A_3^2 L}{K_2 K_3}}} \tag{12}$$

When conducting rating analysis, head water, tail water and flow data are used to determine discharge coefficient C_3. From the above equation, C_3 can be represented as:

$$C_3 = \sqrt{\frac{Q^2}{2gA_3^2(h_1 - h_3 - \frac{Q^2 L}{K_2 K_3})}} \tag{13}$$

EQUATIONS OF TYPE 4 FLOW

Type 4 is full pipe flow. Depth of water at culvert inlet d_2 is the culvert diameter. The energy equation given by Bodhaine is:

$$h_1 + h_{v1} = h_4 + h_{v4} + h_{f\,1\text{-}2} + h_e + h_{f\,2\text{-}3} + h_{f\,3\text{-}4} + (h_{v3} - h_{v4}) \tag{14}$$

Where
h_{v1}, h_{v3}, h_{v4} = velocity head of sections 1, 3 and 4 respectively. The quantity (h_{v3} - h_{v4}) represents the energy loss due to section expansion from 3 to 4.
$h_{f\,1\text{-}2}$, $h_{f\,2\text{-}3}$, $h_{f\,3\text{-}4}$ = head loss due to friction between corresponding sections,
h_e = head loss due to entrance contraction.

Assuming h_{v1} is compensating $h_{f\,1-2}$ and ignoring $h_{f\,3\text{-}4}$, Equation (14) can be simplified as:

$$h_1 = h_4 + h_e + h_{f\,2\text{-}3} + h_{v3} \tag{15}$$

Assuming that h_e and h_{v3} are included into the discharge coefficient, the discharge equation can be written as:

$$Q = C_4 A_0 \sqrt{2g(h_1 - h_4 - h_{f\,2-3})} \tag{16}$$

Where,
A_0 = area of culvert barrel,
C_4 = discharge coefficient for type 4 culvert flow.

Putting Equation (7) of head loss $h_{f\,2\text{-}3}$ into Equation (16) and rearranging, we have:

$$Q = C_4 A_0 \sqrt{\frac{2g(h_1 - h_4)}{1 + \frac{2gC_4^2 A_0^2 L}{K_0^2}}} \tag{17}$$

Where, K_0 = conveyance of full culvert barrel.

Equation (17) can be used to calculate Q given head water, tail water and discharge coefficient C_4. The following equation can be used to obtain C_4.

$$C_4 = \sqrt{\frac{Q^2}{2gA_0^2(h_1 - h_4 - \frac{Q^2 L}{K_0^2})}} \tag{18}$$

DATA USED FOR ILLUSTRATION

To illustrate rating development and culvert flow simulation, historical flow measurement data is used in this report. Table 1 contains some flow measurement records obtained at culvert site 59 in the Everglades National Park.

Table 1. Historical flow measurement records at culvert 59 along SR 9336 in ENP

No.	Date	Flow	Head water	Tail water	No.	Date	Flow	Head water	Tail water
		(ft^3/s)	(ft)	(ft)			(ft^3/s)	(ft)	(ft)
1	1996-10-17	9.19	2.78	2.50	15	1997-08-07	4.42	2.20	2.14
2	1996-10-24	7.47	2.62	2.43	16	1997-08-18	1.10	2.15	2.13
3	1996-10-31	4.85	2.40	2.32	17	1997-09-02	5.36	2.36	2.24
4	1996-11-25	0.47	1.85	1.84	18	1997-09-08	6.74	2.27	2.24
5	1997-03-17	3.79	1.92	1.80	19	1997-09-16	2.87	2.28	2.25
6	1997-04-14	0.59	1.66	1.65	20	1997-10-01	4.84	2.48	2.41
7	1997-05-14	1.59	1.82	1.75	21	1997-10-15	3.37	2.34	2.30
8	1997-06-02	16.38	3.00	2.20	22	1997-10-23	2.02	2.22	2.20
9	1997-06-23	12.21	2.86	2.48	23	1997-10-28	1.60	2.12	2.10
10	1997-07-01	5.94	2.35	2.22	24	1997-11-18	2.44	2.14	2.12
11	1997-07-09	4.92	2.32	2.20	25	1997-12-10	7.97	2.57	2.40
12	1997-07-16	4.88	2.09	1.92	26	1998-01-07	3.41	2.26	2.22
13	1997-07-22	7.16	2.41	2.22	27	1998-02-06	7.41	2.45	2.27
14	1997-07-28	4.47	2.27	2.18					

Flow type (type 3 or 4) is determined from field flow measurements based on submergence of culvert entrance and exit. If there is no record on the submergence of a culvert, then some analysis and estimation is required. This is done by assuming a relationship between h_1 and h_2, h_3 and h_4.

ESTIMATION OF DISCHARGE COEFFICIENT

For a set of field flow measurements (flow, head water and tail water), Equations (13) and (18) are used to calculate C_3 of type 3 flow and C_4 of type 4 flow respectively. Table 2 is an example showing how C_3 is determined. The data in the first 4 columns is from field flow measurements. Figure 3 is a graphical representation of the discharge coefficients in Table 2.

When using Equation (13) to estimate C_3, we need to know the depth of water at section 2. By assuming h_2 as a ratio of h_1, parameters in section 2 are estimated. When conducting field flow measurement, we notice contraction of flow at the culvert entrance. According to what is presented in Damisse (Damisse, et al, 1997), h_2 is assumed to be 0.9 of h_1 in Table 2 below. This assumed ratio is close to the simulated value (see Table 5).

Determination of coefficient of discharge based on a set of observation data collected from culvert 59 in ENP
(Depth of water above the datum in section 2 is assumed to be 0.9 that in section 1)

Date	Flow	Head water	Tail water	Head – Tail	h_1	h_4	$h_2 - z$ ($h_2 = 0.9\ h_1$)	Θ_2	A_2	P_2	R_2	K_2	Θ_3	A_3	P_3	R_3	K_3	$h_1 - h_4$	$h_{f\,2,3}$	$h_1 - h_4 - h_{f2,3}$	C_{d3}
	(ft^3/s)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(rad)	(ft^2)	(ft)	(ft)	(ft^3/s)	(rad)	(ft^2)	(ft)	(ft)	(ft^3/s)	(ft)	(ft)	(ft)	
1996-10-17	9.19	2.78	2.50	0.28	2.08	1.80	1.87	2.470	3.260	5.187	0.629	273.449	2.366	3.160	4.969	0.636	267.118	0.280	0.052	0.228	0.759
1996-10-24	7.47	2.62	2.43	0.19	1.92	1.73	1.73	2.273	3.049	4.773	0.639	258.560	2.275	3.053	4.778	0.639	258.824	0.190	0.038	0.152	0.782
1996-10-31	4.85	2.40	2.32	0.08	1.70	1.62	1.53	2.046	2.704	4.296	0.629	226.950	2.145	2.867	4.504	0.637	242.529	0.080	0.019	0.061	0.856
1996-11-25	0.47	1.85	1.84	0.01	1.15	1.14	1.04	1.557	1.700	3.269	0.520	125.711	1.657	1.921	3.479	0.552	147.740	0.010	0.001	0.009	0.312
1997-03-17	3.79	1.92	1.80	0.12	1.22	1.10	1.10	1.617	1.833	3.395	0.540	138.880	1.618	1.837	3.399	0.540	139.301	0.120	0.033	0.087	0.874
1997-04-14	0.59	1.66	1.65	0.01	0.96	0.95	0.86	1.393	1.343	2.925	0.459	91.401	1.475	1.522	3.098	0.491	108.327	0.010	0.002	0.008	0.525
1997-05-14	1.59	1.82	1.75	0.07	1.12	1.05	1.01	1.531	1.644	3.215	0.511	120.132	1.571	1.732	3.299	0.525	128.829	0.070	0.007	0.063	0.458
1997-06-02	16.38	3.00	2.20	0.80	2.30	1.50	2.07	2.902	3.454	6.094	0.567	270.347	2.014	2.647	4.229	0.626	221.408	0.800	0.202	0.598	0.997
1997-06-23	12.21	2.86	2.48	0.38	2.16	1.78	1.94	2.589	3.347	5.438	0.616	276.863	2.340	3.130	4.913	0.637	264.942	0.380	0.091	0.289	0.905
1997-07-01	5.94	2.35	2.22	0.13	1.65	1.52	1.49	1.998	2.618	4.196	0.624	218.582	2.035	2.685	4.273	0.628	225.120	0.130	0.032	0.098	0.882
1997-07-09	4.92	2.32	2.20	0.12	1.62	1.50	1.46	1.970	2.567	4.137	0.620	213.409	2.014	2.647	4.229	0.626	221.408	0.120	0.023	0.097	0.744
1997-07-16	4.88	2.09	1.92	0.17	1.39	1.22	1.25	1.763	2.151	3.703	0.581	171.211	1.733	2.087	3.640	0.573	164.670	0.170	0.038	0.132	0.802
1997-07-22	7.16	2.41	2.22	0.19	1.71	1.52	1.54	2.055	2.720	4.316	0.630	228.582	2.035	2.685	4.273	0.628	225.120	0.190	0.045	0.145	0.872
1997-07-28	4.47	2.27	2.18	0.09	1.57	1.48	1.41	1.924	2.479	4.040	0.614	204.571	1.993	2.609	4.185	0.623	217.632	0.090	0.020	0.070	0.809
1997-08-07	4.42	2.20	2.14	0.06	1.50	1.44	1.35	1.861	2.353	3.907	0.602	191.827	1.951	2.532	4.098	0.618	209.904	0.060	0.022	0.038	1.113
1997-08-18	1.10	2.15	2.13	0.02	1.45	1.43	1.31	1.816	2.262	3.814	0.593	182.524	1.941	2.512	4.076	0.616	207.939	0.020	0.001	0.019	0.401
1997-09-02	5.36	2.36	2.24	0.12	1.66	1.54	1.49	2.007	2.636	4.216	0.625	220.282	2.056	2.722	4.318	0.630	228.762	0.120	0.026	0.094	0.799
1997-09-08	6.74	2.27	2.24	0.03	1.57	1.54	1.41	1.924	2.479	4.040	0.614	204.571	2.056	2.722	4.318	0.630	228.762	0.030	0.044	-0.014	
1997-09-16	2.87	2.28	2.25	0.03	1.58	1.55	1.42	1.933	2.496	4.059	0.615	206.358	2.067	2.741	4.341	0.631	230.555	0.030	0.008	0.022	0.878
1997-10-01	4.84	2.48	2.41	0.07	1.78	1.71	1.60	2.124	2.835	4.461	0.636	239.554	2.251	3.020	4.726	0.639	256.130	0.070	0.017	0.053	0.869
1997-10-15	3.37	2.34	2.30	0.04	1.64	1.60	1.48	1.989	2.601	4.176	0.623	216.869	2.122	2.832	4.456	0.635	239.218	0.040	0.010	0.030	0.854
1997-10-23	2.02	2.22	2.20	0.02	1.52	1.50	1.37	1.878	2.389	3.945	0.606	195.506	2.014	2.647	4.229	0.626	221.408	0.020	0.004	0.016	0.759
1997-10-28	1.60	2.12	2.10	0.02	1.42	1.40	1.28	1.790	2.207	3.758	0.587	176.884	1.911	2.453	4.012	0.611	201.973	0.020	0.003	0.017	0.626
1997-11-18	2.44	2.14	2.12	0.02	1.44	1.42	1.30	1.807	2.244	3.795	0.591	180.648	1.931	2.492	4.055	0.615	205.962	0.020	0.007	0.013	1.081
1997-12-10	7.97	2.57	2.40	0.17	1.87	1.70	1.68	2.218	2.975	4.658	0.639	252.292	2.238	3.004	4.700	0.639	254.735	0.170	0.044	0.126	0.933
1998-01-07	3.41	2.26	2.22	0.04	1.56	1.52	1.40	1.915	2.461	4.021	0.612	202.774	2.035	2.685	4.273	0.628	225.120	0.040	0.011	0.029	0.938
1998-02-06	7.41	2.45	2.27	0.18	1.75	1.57	1.58	2.094	2.786	4.398	0.634	234.952	2.089	2.777	4.387	0.633	234.083	0.180	0.045	0.135	0.905

Table 2. Worksheet to estimate coefficient of discharge

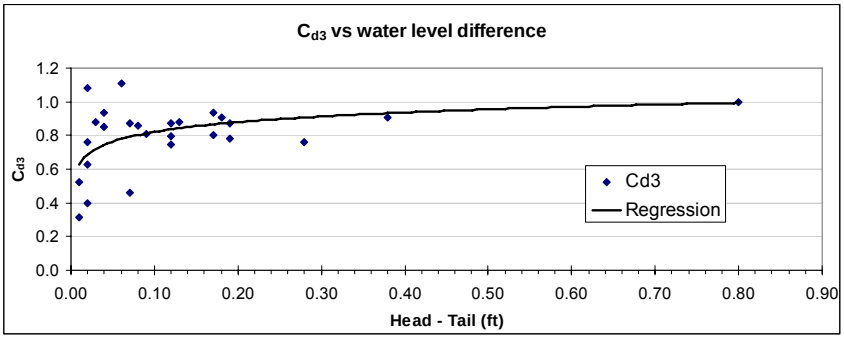

Figure 3. C_3 versus head difference corresponding to Table 2

Staff gauge 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. If there are enough measurements when we conduct rating analysis, we can remove data points with small head difference (such as those below 0.02 ft). This will generally result in the improvement of rating relationships. 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.

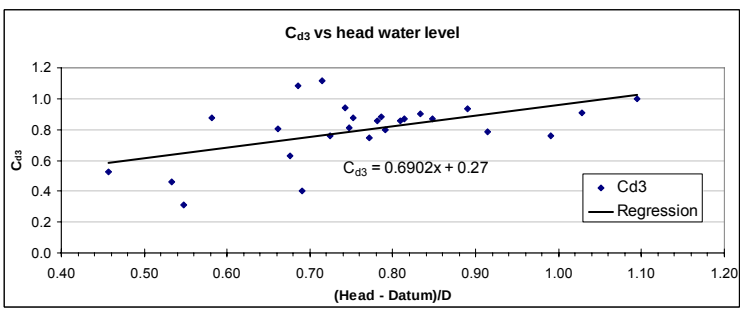

Figure 4. Rating analysis with all data points considered

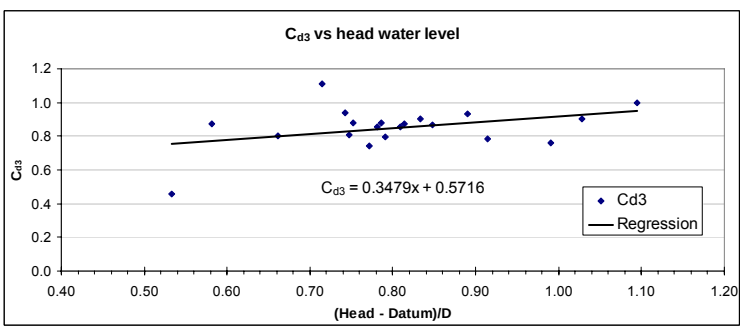

Figure 5. Rating analysis excluding data points with head difference not greater than 0.02 ft

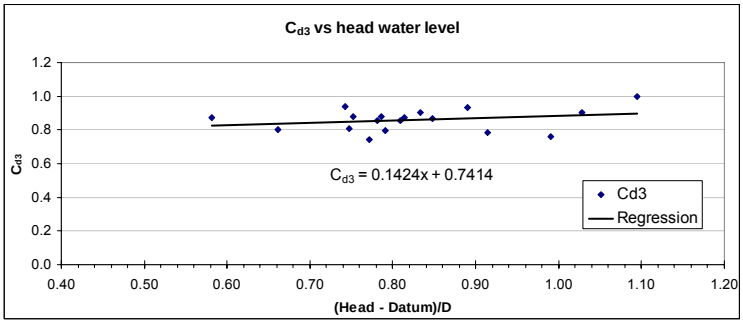

Figure 6. Rating analysis further excluding two obviously unreasonable data points

By putting discharge coefficient into the discharge program developed for this project, we calculate flow through culvert and other hydraulic quantities. The difference between calculated and measured flows can be shown by drawing a y=x line on a plot of calculated and observed flow points. Various estimates of discharge coefficient will result in corresponding differences between calculated and measured flows. The minimum difference is considered the best estimation of discharge coefficient.

SIMULATION OF TYPE 3 CULVERT FLOW

Two methods are developed in this study to simulate type 3 culvert flow. One is iteration based on convergence of flow; the other is based on convergence of head. While both methods give similar results, the head based method is more straight forward and simpler to use. To show how culvert flow can be solved in different ways, these two methods are illustrated.

Iteration Method Based on Convergence of Flow (Q)

This method is introduced by Bodhaine. This project implements the method in a computer program to automate the whole calculation.

Figure 7, in conjunction with Figure 8, are diagrams showing how the flow based iteration method is used to estimate type 3 flow through a culvert.

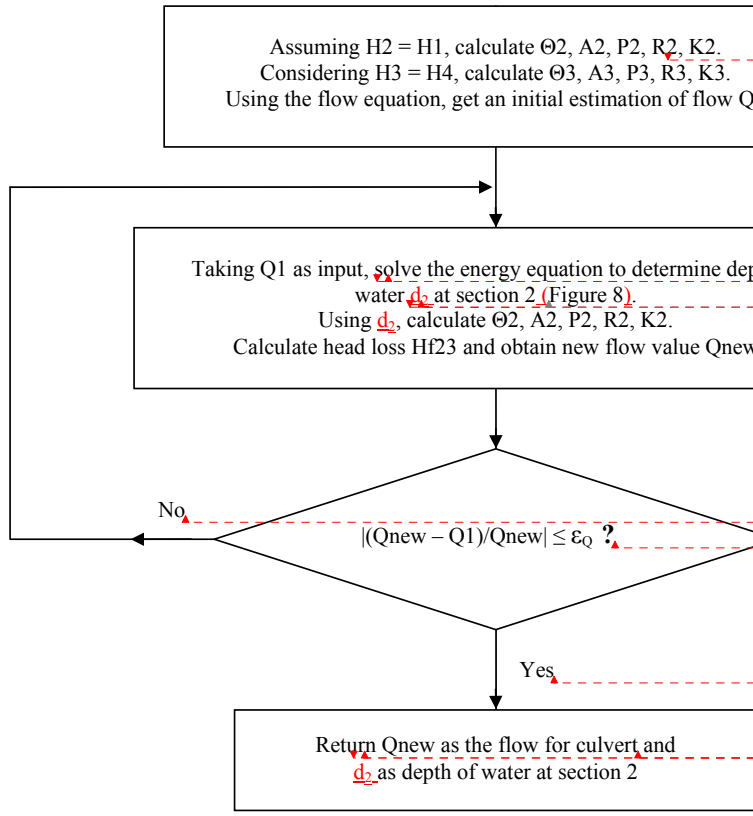

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Figure 7. Flow chart of iteration method based on convergence of flow

Given Q, solving the energy equation to determine depth of water d_2 at section 2 is a critical part of the flow simulation program. To find the root d_2, the energy equation is rearranged to the following form. Due to the non-linearity of the equation, the bisection method is employed to find the root.

$$f(d_2) = d_2 + \frac{V_2^2}{2gC_3^2} - (h_1 - z) = 0 \tag{19}$$

Figure 8 shows the steps to solve the above equation.

The program code is listed in Appendix I.

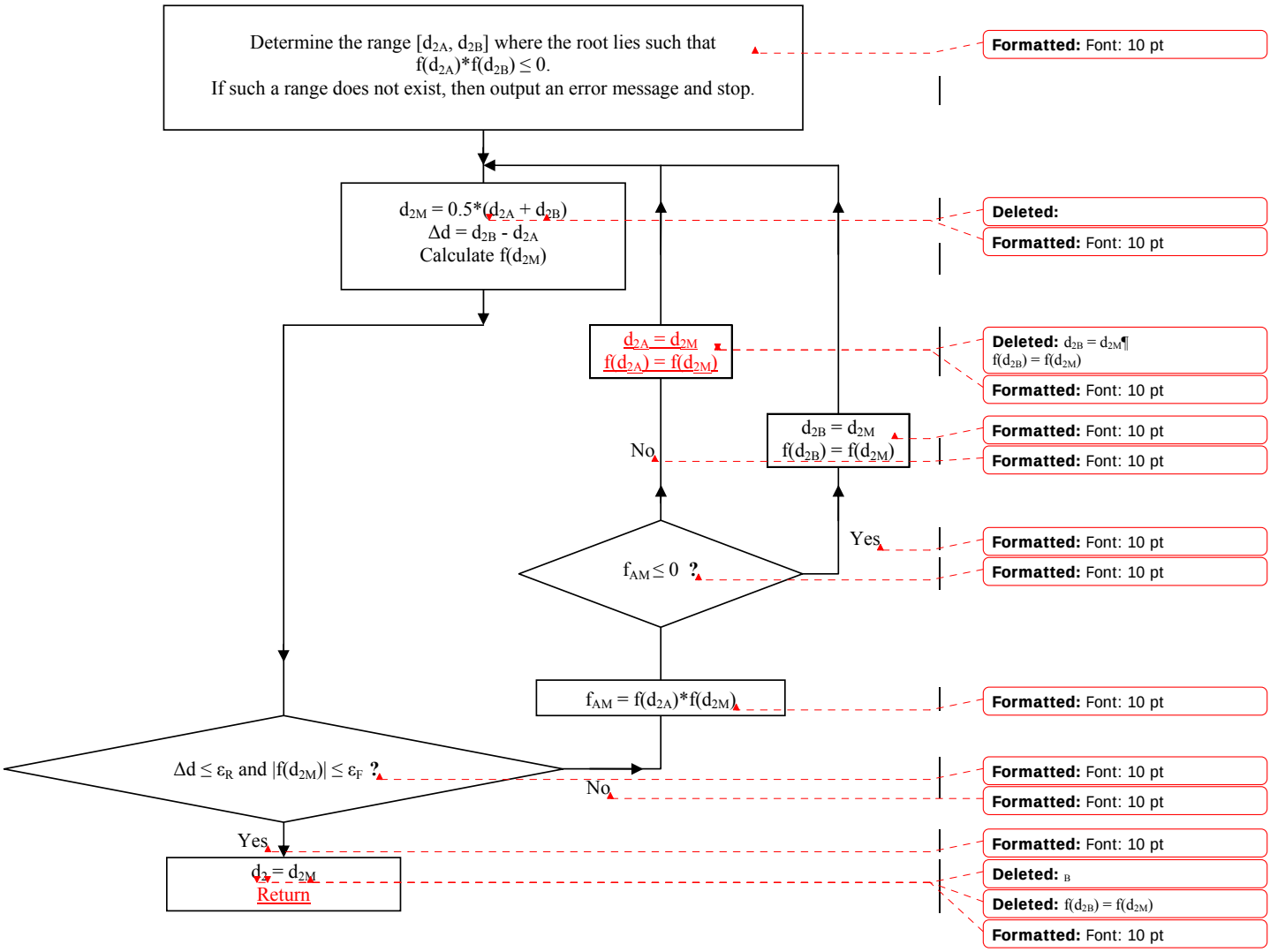

Figure 8. Flow chart to get depth of water d_2 for a given flow Q

Iteration Method Based on Convergence of Head (H)

This method is the outcome of this project. Figure 9 is a diagram showing how the head based iteration method is used to solve type 3 flow for a culvert.

Program code listing is included in Appendix II.

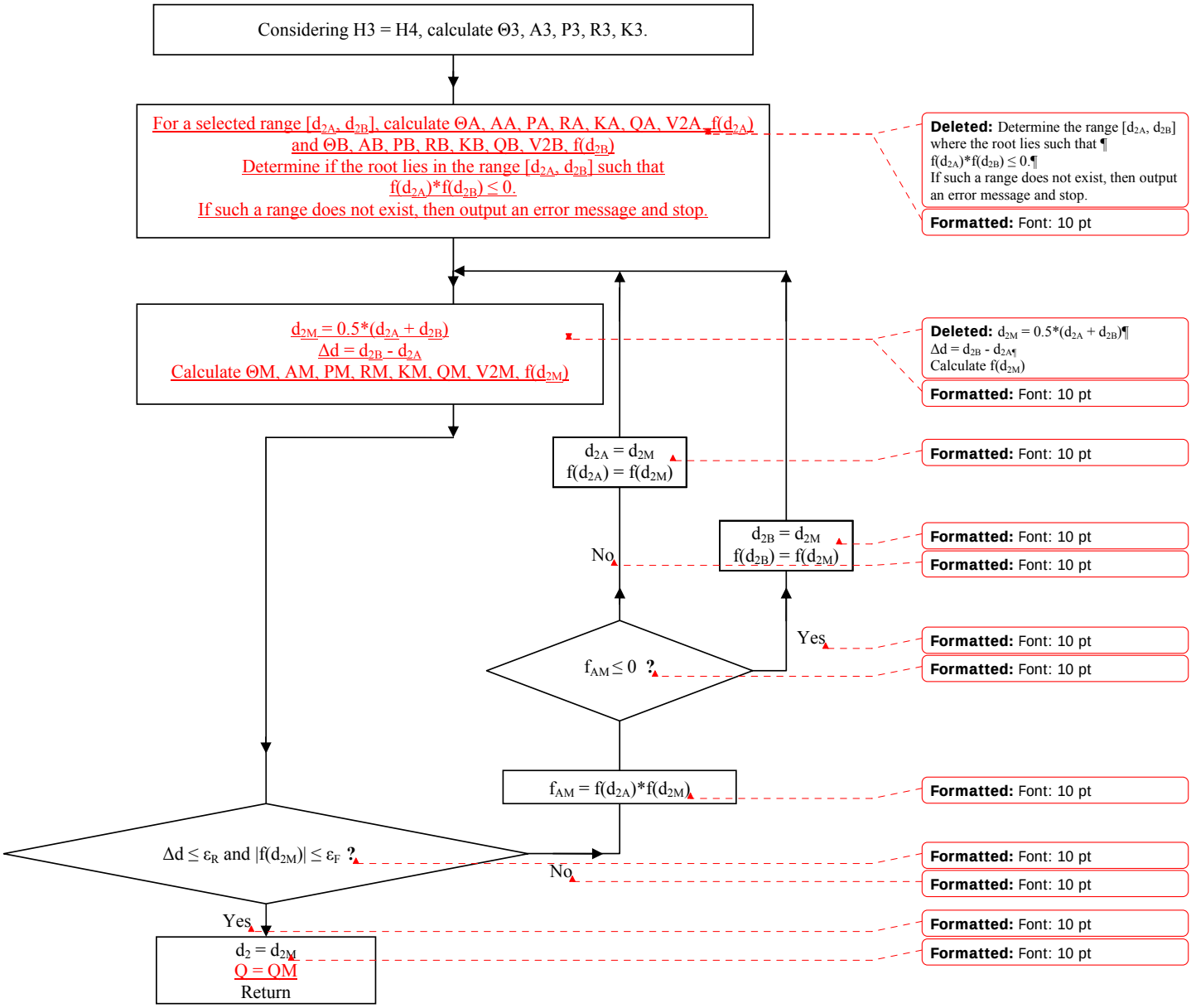

Figure 9. Flow chart of iteration method based on convergence of head

CRITICAL DEPTH

For each measured flow, there is a critical depth of water corresponding to it. For type 3 culvert flow, the downstream water level h_4 and the critical depth d_c satisfy the following relationship:

$$\frac{h_4}{d_c} > 1 \tag{20}$$

Where
h_4 = water level above datum at section 4,
d_c = depth of water for critical flow.

By comparing observed tail water depth h_4 with calculated critical depth d_c, we examine if the observed flow is type 3. Type 4 is full pipe flow all the way from entrance to outlet. The flow type is determined by observing h_1 and h_4 values. So critical depth d_c is not calculated and comparison of h_4 with d_c is not needed for this case.

To determine critical depth d_c, the following equation is used:

$$f(d_c) = Q - A_C^{3/2}\sqrt{\frac{g}{T}} = 0 \tag{21}$$

Where
A_C = the area of section at critical water depth,
T = width of the section at the water surface.

The method used to solve d_c is the same as that listed in Figure 8 - Flow chart to get depth of water d_2 for a given flow Q.

SIMULATION OF TYPE 4 CULVERT FLOW

Type 4 is full pipe flow. The depth of water at sections 2 and 3 in Figure 2 is the same as the culvert diameter, which is different from type 3 flow. No iteration is needed to calculate depth of water h_2 and h_3. Calculation of type 4 culvert flow is a direct application of Equation (17) given head water h_1, tail water h_4 and discharge coefficient C_4. Program code to calculate this type of flow is listed in Appendix III.

TESTING TYPE 3 CULVERT DISCHARGE PROGRAM

Iteration Method Based on Convergence of Flow (Q)

To prove the flow based iteration method of the discharge program, the following tests were conducted:

All small subroutines such as calculating one half of the central angle of the circular segment, flow cross sectional area, wetted perimeter, width of water surface, hydraulic radius, conveyance of section, etc. are called and the results are compared with manual calculation results, showing they are the same.

The following 2 tables are simulation results of using the standard step method to calculate flow across the culvert and depth of water in section 2. Scenario 1 finds the flow rate by one iteration (M=1). Scenario 2 finds the flow rate by two iterations (M=2. For M=1, $|E_Q|$ exceeds the limit of $\varepsilon_Q = 0.01$). In these 2 tables, the computer simulation results are the same as manual calculations.

Table 3. Solving flow across culvert and depth of water in section 2 (scenario 1)
($H_1 = 1.5$, $H_4 = 1.44$, $\varepsilon_Q = \varepsilon_R = \varepsilon_F = 0.01$)

M	Q	K	A	F(A)	B	F(B)	Δd = A-B	R	F(R)
1	3.552								
		1	1.452	-.108338E-02	1.488	0.324720E-01	0.036	1.470	0.156648E-01
		2	1.452	-.108338E-02	1.470	0.156648E-01	0.018	1.461	0.728306E-02
		3	1.452	-.108338E-02	1.461	0.728306E-02	0.009	1.457	0.309796E-02
	3.534	$E_Q = 0.0051 < 0.01$, $\Delta d = 0.009 < 0.01$, $\lvert F(R)\rvert = 0.0031 < 0.01$. Solution Found !							

Table 4. Solving flow across culvert and depth of water in section 2 (scenario 2)
($H_1 = 1.75$, $H_4 = 1.57$, $\varepsilon_Q = \varepsilon_R = \varepsilon_F = 0.01$)

M	Q	K	A	F(A)	B	F(B)	Δd = A-B	R	F(R)
1	6.809								
		1	1.606	-.468423E-02	1.714	0.868561E-01	0.108	1.660	0.405127E-01
		2	1.606	-.468423E-02	1.660	0.405127E-01	0.054	1.633	0.177610E-01
		3	1.606	-.468423E-02	1.633	0.177610E-01	0.027	1.619	0.649877E-02
		4	1.606	-.468423E-02	1.619	0.649877E-02	0.0135	1.613	0.897205E-03
		5	1.606	-.468423E-02	1.613	0.897205E-03	0.00675	1.609	-.189602E-02
	6.740	$\lvert E_Q\rvert = 0.0102 > 0.01$, $\Delta d = 0.00675 < 0.01$, $\lvert F(R)\rvert = 0.0019 < 0.01$. Solution Not Found !							
2	6.775								
		1	1.606	-.608032E-02	1.714	0.856249E-01	0.108	1.660	0.392048E-01
		2	1.606	-.608032E-02	1.660	0.392048E-01	0.054	1.633	0.164106E-01
		3	1.606	-.608032E-02	1.633	0.164106E-01	0.027	1.619	0.512588E-02
		4	1.606	-.608032E-02	1.619	0.512588E-02	0.0135	1.613	-.487178E-03
		5	1.613	-.487178E-03	1.619	0.512588E-02	0.00675	1.616	0.231685E-02
	6.753	$\lvert E_Q\rvert = 0.0033 < 0.01$, $\Delta d = 0.00675 < 0.01$, $\lvert F(R)\rvert = 0.0023 < 0.01$. Solution Found !							

By changing the error limit for the standard step method, we run the discharge program to compare the model results. Table 5 and Table 6 are two scenarios with the error limit changed by a factor of 10. We see the results are very close to each other. This means the program is stable and converges to the theoretical values satisfactorily.

By comparing critical depth d_c with tail water depth, we know all $h_4/h_c > 1.0$, which meets the criteria for type 3 flow stipulated by Bodhaine.

Table 5. A result using iteration method based on convergence of flow (iteration accuracy $\varepsilon_Q = \varepsilon_R = \varepsilon_F = 0.01$)

*** Calculation of Flow through Culverts ***

When Estimating Flow Directly Using Flow Equation, Depth Of Water At Section 2 Versus That At Section 1 Is Considered To Be: 0.90. $\varepsilon_Q = \varepsilon_R = \varepsilon_F = 0.01$

QOBS	HW	TW	H1	H4	H2	H2/H1	DC	QRES	ERROR1	QEST	ERROR2	ERROR3
FT**3/S	(FT)	(FT)	(FT)	(FT)	(FT)		(FT)	FT**3/S		FT**3/S		
9.187	2.78	2.5	2.08	1.8	1.869	0.899	1.091	9.59	0.044	9.586	0.043	0
7.474	2.62	2.43	1.92	1.73	1.772	0.923	0.966	7.621	0.02	7.613	0.019	-0.001
4.852	2.4	2.32	1.7	1.62	1.639	0.964	0.747	4.64	-0.044	4.606	-0.051	-0.007
0.468	1.85	1.84	1.15	1.14	1.145	0.996	0.352	1.076	1.3	1.054	1.252	-0.021
3.789	1.92	1.8	1.22	1.1	1.137	0.932	0.652	3.571	-0.058	3.55	-0.063	-0.006
0.588	1.66	1.65	0.96	0.95	0.955	0.995	0.312	0.837	0.423	0.816	0.388	-0.025
1.593	1.82	1.75	1.12	1.05	1.072	0.957	0.548	2.554	0.603	2.522	0.583	-0.013
5.939	2.35	2.22	1.65	1.52	1.551	0.94	0.817	5.531	-0.069	5.51	-0.072	-0.004
4.919	2.32	2.2	1.62	1.5	1.528	0.944	0.795	5.236	0.064	5.212	0.06	-0.005
4.878	2.09	1.92	1.39	1.22	1.27	0.914	0.767	4.876	0	4.87	-0.002	-0.001
7.158	2.41	2.22	1.71	1.52	1.569	0.917	0.904	6.703	-0.064	6.692	-0.065	-0.002
4.474	2.27	2.18	1.57	1.48	1.501	0.956	0.732	4.466	-0.002	4.434	-0.009	-0.007
4.416	2.2	2.14	1.5	1.44	1.457	0.971	0.649	3.534	-0.2	3.497	-0.208	-0.01
1.1	2.15	2.13	1.45	1.43	1.437	0.991	0.488	2.023	0.84	1.993	0.812	-0.015
5.358	2.36	2.24	1.66	1.54	1.568	0.945	0.807	5.39	0.006	5.365	0.001	-0.005
6.736	2.27	2.24	1.57	1.54	1.55	0.988	0.564	2.694	-0.6	2.661	-0.605	-0.013
2.874	2.28	2.25	1.58	1.55	1.56	0.988	0.566	2.713	-0.056	2.68	-0.068	-0.012
4.838	2.48	2.41	1.78	1.71	1.727	0.97	0.741	4.574	-0.055	4.541	-0.061	-0.007
3.368	2.34	2.3	1.64	1.6	1.611	0.982	0.62	3.239	-0.038	3.204	-0.049	-0.011
2.022	2.22	2.2	1.52	1.5	1.507	0.991	0.501	2.137	0.057	2.107	0.042	-0.014
1.597	2.12	2.1	1.42	1.4	1.407	0.991	0.481	1.974	0.236	1.944	0.217	-0.015
2.443	2.14	2.12	1.44	1.42	1.427	0.991	0.485	2.007	-0.178	1.977	-0.191	-0.015
7.969	2.57	2.4	1.87	1.7	1.737	0.929	0.931	7.093	-0.11	7.08	-0.111	-0.002
3.412	2.26	2.22	1.56	1.52	1.531	0.981	0.603	3.067	-0.101	3.031	-0.112	-0.012
7.409	2.45	2.27	1.75	1.57	1.616	0.923	0.908	6.753	-0.089	6.737	-0.091	-0.002
Absolute Average						0.959			0.21		0.207	0.009
Arithmetic Average						0.959			0.077		0.066	-0.009

Notes for the variables used in the table:
QOBS: Flow measured from field
HW: Head water level
TW: Tail water level
H1: Head water depth above outlet invert
H4: Tail water depth above outlet invert
H2: Water level above outlet invert at culvert entrance (Section 2)
H2/H1: Ratio of depth of water (H2) to depth of head water (H1)
DC: Maximum depth of water in the critical flow section
QRES: Flow calculated by solving energy equation using the standard step method
ERROR1: Relative difference of QRES versus QOBS
QEST: Flow estimated using assumed depth of water at section 2
ERROR2: Relative difference of QEST versus QOBS
ERROR3: Relative difference of QEST versus QRES

Table 6. A result using iteration method based on convergence of flow (iteration accuracy $\varepsilon_Q = \varepsilon_R = \varepsilon_F = 0.001$)

*** Calculation of Flow through Culverts ***

When Estimating Flow Directly Using Flow Equation, Depth Of Water At Section 2 Versus That At Section 1 Is Considered To Be: 0.90. $\varepsilon_Q = \varepsilon_R = \varepsilon_F = 0.001$

QOBS	HW	TW	H1	H4	H2	H2/H1	DC	QRES	ERROR1	QEST	ERROR2	ERROR3
FT**3/S	(FT)	(FT)	(FT)	(FT)	(FT)		(FT)	FT**3/S		FT**3/S		
9.187	2.78	2.5	2.08	1.8	1.87	0.899	1.09	9.587	0.044	9.586	0.043	0
7.474	2.62	2.43	1.92	1.73	1.775	0.924	0.968	7.629	0.021	7.613	0.019	-0.002
4.852	2.4	2.32	1.7	1.62	1.638	0.963	0.747	4.643	-0.043	4.606	-0.051	-0.008
0.468	1.85	1.84	1.15	1.14	1.142	0.993	0.353	1.076	1.299	1.054	1.252	-0.021
3.789	1.92	1.8	1.22	1.1	1.135	0.93	0.652	3.573	-0.057	3.55	-0.063	-0.006
0.588	1.66	1.65	0.96	0.95	0.952	0.992	0.31	0.836	0.422	0.816	0.388	-0.024
1.593	1.82	1.75	1.12	1.05	1.07	0.955	0.549	2.555	0.604	2.522	0.583	-0.013
5.939	2.35	2.22	1.65	1.52	1.551	0.94	0.819	5.54	-0.067	5.51	-0.072	-0.006
4.919	2.32	2.2	1.62	1.5	1.528	0.943	0.796	5.245	0.066	5.212	0.06	-0.006
4.878	2.09	1.92	1.39	1.22	1.269	0.913	0.767	4.881	0.001	4.87	-0.002	-0.002
7.158	2.41	2.22	1.71	1.52	1.568	0.917	0.904	6.707	-0.063	6.692	-0.065	-0.002
4.474	2.27	2.18	1.57	1.48	1.501	0.956	0.733	4.471	-0.001	4.434	-0.009	-0.008
4.416	2.2	2.14	1.5	1.44	1.453	0.969	0.649	3.536	-0.199	3.497	-0.208	-0.011
1.1	2.15	2.13	1.45	1.43	1.434	0.989	0.487	2.023	0.839	1.993	0.812	-0.015
5.358	2.36	2.24	1.66	1.54	1.568	0.945	0.808	5.398	0.007	5.365	0.001	-0.006
6.736	2.27	2.24	1.57	1.54	1.546	0.985	0.564	2.694	-0.6	2.661	-0.605	-0.012
2.874	2.28	2.25	1.58	1.55	1.556	0.985	0.566	2.713	-0.056	2.68	-0.068	-0.012
4.838	2.48	2.41	1.78	1.71	1.725	0.969	0.741	4.576	-0.054	4.541	-0.061	-0.008
3.368	2.34	2.3	1.64	1.6	1.608	0.981	0.62	3.24	-0.038	3.204	-0.049	-0.011
2.022	2.22	2.2	1.52	1.5	1.504	0.99	0.501	2.137	0.057	2.107	0.042	-0.014
1.597	2.12	2.1	1.42	1.4	1.404	0.989	0.481	1.974	0.236	1.944	0.217	-0.015
2.443	2.14	2.12	1.44	1.42	1.424	0.989	0.485	2.007	-0.179	1.977	-0.191	-0.015
7.969	2.57	2.4	1.87	1.7	1.74	0.93	0.932	7.101	-0.109	7.08	-0.111	-0.003
3.412	2.26	2.22	1.56	1.52	1.528	0.98	0.603	3.068	-0.101	3.031	-0.112	-0.012
7.409	2.45	2.27	1.75	1.57	1.614	0.922	0.908	6.756	-0.088	6.737	-0.091	-0.003
Absolute Average						0.958			0.21		0.207	0.009
Arithmetic Average						0.958			0.078		0.066	-0.009

Iteration Method Based on Convergence of Head (H)

We run the discharge program to examine iteration method based on convergence of head. Table 7 and Table 8 are two scenarios with the error limit changed by a factor of 10. The results are very close to each other. This means the program is stable and converges to the solution well.

Table 9 lists the simulation results on depth of water H_2 and flow Q from using head based and flow based iteration methods. Both methods generate the same simulation results.

Both methods of iteration, i.e. the one based on convergence of flow and that on convergence of head give good results.

Table 7. A result using iteration method based on convergence of head (iteration accuracy $\varepsilon_R = \varepsilon_F = 0.01$)

*** Calculation of Flow through Culverts ***

When Estimating Flow Directly Using Flow Equation, Depth Of Water At Section 2 Versus That At Section 1 Is Considered To Be: 0.90. $\varepsilon_R = \varepsilon_F = 0.01$

QOBS	HW	TW	H1	H4	H2	H2/H1	DC	QRES	ERROR1	QEST	ERROR2	ERROR3
FT**3/S	(FT)	(FT)	(FT)	(FT)	(FT)		(FT)	FT**3/S		FT**3/S		
9.187	2.78	2.5	2.08	1.8	1.869	0.898	1.09	9.585	0.043	9.586	0.043	0
7.474	2.62	2.43	1.92	1.73	1.773	0.923	0.968	7.63	0.021	7.613	0.019	-0.002
4.852	2.4	2.32	1.7	1.62	1.64	0.965	0.747	4.645	-0.043	4.606	-0.051	-0.008
0.468	1.85	1.84	1.15	1.14	1.142	0.993	0.352	1.076	1.299	1.054	1.252	-0.021
3.789	1.92	1.8	1.22	1.1	1.132	0.928	0.652	3.572	-0.057	3.55	-0.063	-0.006
0.588	1.66	1.65	0.96	0.95	0.956	0.995	0.312	0.837	0.423	0.816	0.388	-0.025
1.593	1.82	1.75	1.12	1.05	1.07	0.955	0.548	2.555	0.604	2.522	0.583	-0.013
5.939	2.35	2.22	1.65	1.52	1.549	0.939	0.819	5.54	-0.067	5.51	-0.072	-0.006
4.919	2.32	2.2	1.62	1.5	1.526	0.942	0.796	5.244	0.066	5.212	0.06	-0.006
4.878	2.09	1.92	1.39	1.22	1.273	0.916	0.767	4.884	0.001	4.87	-0.002	-0.003
7.158	2.41	2.22	1.71	1.52	1.568	0.917	0.904	6.708	-0.063	6.692	-0.065	-0.002
4.474	2.27	2.18	1.57	1.48	1.5	0.955	0.732	4.472	-0.001	4.434	-0.009	-0.008
4.416	2.2	2.14	1.5	1.44	1.454	0.97	0.649	3.537	-0.199	3.497	-0.208	-0.011
1.1	2.15	2.13	1.45	1.43	1.433	0.988	0.488	2.023	0.839	1.993	0.812	-0.015
5.358	2.36	2.24	1.66	1.54	1.569	0.945	0.808	5.399	0.008	5.365	0.001	-0.006
6.736	2.27	2.24	1.57	1.54	1.544	0.984	0.564	2.694	-0.6	2.661	-0.605	-0.012
2.874	2.28	2.25	1.58	1.55	1.554	0.984	0.566	2.713	-0.056	2.68	-0.068	-0.012
4.838	2.48	2.41	1.78	1.71	1.726	0.97	0.741	4.577	-0.054	4.541	-0.061	-0.008
3.368	2.34	2.3	1.64	1.6	1.605	0.979	0.62	3.24	-0.038	3.204	-0.049	-0.011
2.022	2.22	2.2	1.52	1.5	1.502	0.988	0.501	2.137	0.057	2.107	0.042	-0.014
1.597	2.12	2.1	1.42	1.4	1.403	0.988	0.481	1.974	0.236	1.944	0.217	-0.015
2.443	2.14	2.12	1.44	1.42	1.423	0.988	0.485	2.007	-0.179	1.977	-0.191	-0.015
7.969	2.57	2.4	1.87	1.7	1.739	0.93	0.931	7.102	-0.109	7.08	-0.111	-0.003
3.412	2.26	2.22	1.56	1.52	1.527	0.979	0.603	3.068	-0.101	3.031	-0.112	-0.012
7.409	2.45	2.27	1.75	1.57	1.616	0.923	0.908	6.757	-0.088	6.737	-0.091	-0.003
Absolute Average						0.958			0.21		0.207	0.01
Arithmetic Average						0.958			0.078		0.066	-0.01

Table 8. A result using iteration method based on convergence of head (iteration accuracy $\varepsilon_R = \varepsilon_F = 0.001$)

*** Calculation of Flow through Culverts ***

When Estimating Flow Directly Using Flow Equation, Depth Of Water At Section 2 Versus That At Section 1 Is Considered To Be: 0.90. $\varepsilon_R = \varepsilon_F = 0.001$

QOBS FT**3/S	HW (FT)	TW (FT)	H1 (FT)	H4 (FT)	H2 (FT)	H2/H1	DC (FT)	QRES FT**3/S	ERROR1	QEST FT**3/S	ERROR2	ERROR3
9.187	2.78	2.5	2.08	1.8	1.87	0.899	1.09	9.585	0.043	9.586	0.043	0
7.474	2.62	2.43	1.92	1.73	1.775	0.924	0.968	7.631	0.021	7.613	0.019	-0.002
4.852	2.4	2.32	1.7	1.62	1.638	0.963	0.747	4.644	-0.043	4.606	-0.051	-0.008
0.468	1.85	1.84	1.15	1.14	1.142	0.993	0.353	1.076	1.299	1.054	1.252	-0.021
3.789	1.92	1.8	1.22	1.1	1.135	0.93	0.652	3.573	-0.057	3.55	-0.063	-0.006
0.588	1.66	1.65	0.96	0.95	0.953	0.993	0.31	0.836	0.423	0.816	0.388	-0.025
1.593	1.82	1.75	1.12	1.05	1.07	0.955	0.549	2.555	0.604	2.522	0.583	-0.013
5.939	2.35	2.22	1.65	1.52	1.551	0.94	0.819	5.541	-0.067	5.51	-0.072	-0.006
4.919	2.32	2.2	1.62	1.5	1.529	0.944	0.796	5.245	0.066	5.212	0.06	-0.006
4.878	2.09	1.92	1.39	1.22	1.269	0.913	0.767	4.882	0.001	4.87	-0.002	-0.002
7.158	2.41	2.22	1.71	1.52	1.568	0.917	0.904	6.707	-0.063	6.692	-0.065	-0.002
4.474	2.27	2.18	1.57	1.48	1.501	0.956	0.733	4.472	0	4.434	-0.009	-0.008
4.416	2.2	2.14	1.5	1.44	1.454	0.969	0.649	3.537	-0.199	3.497	-0.208	-0.011
1.1	2.15	2.13	1.45	1.43	1.434	0.989	0.487	2.024	0.84	1.993	0.812	-0.015
5.358	2.36	2.24	1.66	1.54	1.568	0.945	0.808	5.398	0.008	5.365	0.001	-0.006
6.736	2.27	2.24	1.57	1.54	1.547	0.985	0.564	2.695	-0.6	2.661	-0.605	-0.013
2.874	2.28	2.25	1.58	1.55	1.556	0.985	0.566	2.713	-0.056	2.68	-0.068	-0.012
4.838	2.48	2.41	1.78	1.71	1.725	0.969	0.741	4.577	-0.054	4.541	-0.061	-0.008
3.368	2.34	2.3	1.64	1.6	1.609	0.981	0.62	3.24	-0.038	3.204	-0.049	-0.011
2.022	2.22	2.2	1.52	1.5	1.504	0.99	0.501	2.137	0.057	2.107	0.042	-0.014
1.597	2.12	2.1	1.42	1.4	1.405	0.989	0.481	1.974	0.236	1.944	0.217	-0.015
2.443	2.14	2.12	1.44	1.42	1.424	0.989	0.485	2.007	-0.178	1.977	-0.191	-0.015
7.969	2.57	2.4	1.87	1.7	1.74	0.93	0.932	7.102	-0.109	7.08	-0.111	-0.003
3.412	2.26	2.22	1.56	1.52	1.528	0.98	0.603	3.068	-0.101	3.031	-0.112	-0.012
7.409	2.45	2.27	1.75	1.57	1.614	0.922	0.908	6.757	-0.088	6.737	-0.091	-0.003
Absolute Average						0.958			0.21		0.207	0.01
Arithmetic Average						0.958			0.078		0.066	-0.01

Table 9. Comparison between head based iteration method and flow based iteration method
(C_3 = 0.85, n = 0.013, $\varepsilon_Q = \varepsilon_R = \varepsilon_F$ = 0.001)

QOBS	HW	TW	H1	H4	H2	H2/H1	Q	H2(M1)	Q(M1)	|H2(M1) – H2| / H2	|Q(M1) – Q| / Q
FT**3/S	(FT)	(FT)	(FT)	(FT)	(FT)		FT**3/S	(FT)	FT**3/S		
					Head based iteration			Flow based iteration			
9.187	2.78	2.5	2.08	1.8	1.876	0.902	10.056	1.876	10.057	0.000	0.000
7.474	2.62	2.43	1.92	1.73	1.779	0.927	8.006	1.779	8.005	0.000	0.000
4.852	2.4	2.32	1.7	1.62	1.64	0.965	4.871	1.639	4.87	-0.001	0.000
0.468	1.85	1.84	1.15	1.14	1.143	0.994	1.126	1.142	1.126	-0.001	0.000
3.789	1.92	1.8	1.22	1.1	1.138	0.932	3.742	1.138	3.742	0.000	0.000
0.588	1.66	1.65	0.96	0.95	0.953	0.993	0.874	0.953	0.874	0.000	0.000
1.593	1.82	1.75	1.12	1.05	1.071	0.956	2.674	1.071	2.674	0.000	0.000
5.939	2.35	2.22	1.65	1.52	1.554	0.942	5.812	1.554	5.812	0.000	0.000
4.919	2.32	2.2	1.62	1.5	1.531	0.945	5.502	1.531	5.502	0.000	0.000
4.878	2.09	1.92	1.39	1.22	1.274	0.916	5.118	1.273	5.117	-0.001	0.000
7.158	2.41	2.22	1.71	1.52	1.572	0.919	7.038	1.572	7.037	0.000	0.000
4.474	2.27	2.18	1.57	1.48	1.502	0.957	4.69	1.503	4.689	0.001	0.000
4.416	2.2	2.14	1.5	1.44	1.455	0.97	3.708	1.455	3.708	0.000	0.000
1.1	2.15	2.13	1.45	1.43	1.435	0.99	2.121	1.435	2.121	0.000	0.000
5.358	2.36	2.24	1.66	1.54	1.571	0.946	5.663	1.57	5.662	-0.001	0.000
6.736	2.27	2.24	1.57	1.54	1.547	0.986	2.826	1.547	2.825	0.000	0.000
2.874	2.28	2.25	1.58	1.55	1.557	0.986	2.846	1.557	2.845	0.000	0.000
4.838	2.48	2.41	1.78	1.71	1.727	0.97	4.8	1.726	4.8	-0.001	0.000
3.368	2.34	2.3	1.64	1.6	1.61	0.982	3.398	1.609	3.398	-0.001	0.000
2.022	2.22	2.2	1.52	1.5	1.504	0.99	2.241	1.504	2.24	0.000	0.000
1.597	2.12	2.1	1.42	1.4	1.405	0.989	2.069	1.405	2.069	0.000	0.000
2.443	2.14	2.12	1.44	1.42	1.424	0.989	2.104	1.425	2.104	0.001	0.000
7.969	2.57	2.4	1.87	1.7	1.744	0.933	7.452	1.743	7.45	-0.001	0.000
3.412	2.26	2.22	1.56	1.52	1.529	0.98	3.217	1.53	3.217	0.001	0.000
7.409	2.45	2.27	1.75	1.57	1.618	0.925	7.089	1.618	7.089	0.000	0.000
Absolute Average						0.959				0.000	0.000
Arithmetic Average						0.959				0.000	0.000

SENSITIVITY ANALYSIS AND DISCUSSIONS

Conclusions of this section apply to both type 3 and type 4 culvert flows.

Roughness Coefficient

The sensitivity of flow estimates to variation of Manning's roughness coefficient n is evaluated. By increasing n by 50% to n=0.0195 and decreasing it by 25% to n=0.01, two discharges are calculated. Table 10 and Table 11 are the simulation results. The results show that the flow increases with the decrease of roughness coefficient and vice versa. This is reasonable since n represents the smoothness of the culvert.

Table 10. Effect of increasing roughness coefficient by 50% to n = 0.0195

*** Calculation of Flow through Culverts ***

When Estimating Flow Directly Using Flow Equation, Depth Of Water At Section 2 Versus That At Section 1 Is Considered To Be: 0.90. $\varepsilon_Q = \varepsilon_R = \varepsilon_F = 0.001$

QOBS	HW	TW	H1	H4	H2	H2/H1	DC	QRES	ERROR1	QEST	ERROR2	ERROR3
FT**3/S	(FT)	(FT)	(FT)	(FT)	(FT)		(FT)	FT**3/S		FT**3/S		
9.187	2.78	2.5	2.08	1.8	1.918	0.922	1.029	8.58	-0.066	8.564	-0.068	-0.002
7.474	2.62	2.43	1.92	1.73	1.807	0.941	0.913	6.835	-0.086	6.792	-0.091	-0.006
4.852	2.4	2.32	1.7	1.62	1.651	0.971	0.705	4.151	-0.144	4.086	-0.158	-0.016
0.468	1.85	1.84	1.15	1.14	1.144	0.995	0.33	0.945	1.019	0.912	0.948	-0.035
3.789	1.92	1.8	1.22	1.1	1.157	0.948	0.612	3.162	-0.166	3.107	-0.18	-0.017
0.588	1.66	1.65	0.96	0.95	0.954	0.994	0.288	0.725	0.232	0.695	0.182	-0.041
1.593	1.82	1.75	1.12	1.05	1.082	0.966	0.514	2.244	0.409	2.187	0.373	-0.026
5.939	2.35	2.22	1.65	1.52	1.573	0.953	0.773	4.959	-0.165	4.895	-0.176	-0.013
4.919	2.32	2.2	1.62	1.5	1.548	0.956	0.751	4.691	-0.046	4.626	-0.06	-0.014
4.878	2.09	1.92	1.39	1.22	1.299	0.934	0.722	4.353	-0.108	4.307	-0.117	-0.011
7.158	2.41	2.22	1.71	1.52	1.6	0.936	0.855	6.016	-0.16	5.967	-0.166	-0.008
4.474	2.27	2.18	1.57	1.48	1.516	0.965	0.691	3.994	-0.107	3.925	-0.123	-0.017
4.416	2.2	2.14	1.5	1.44	1.464	0.976	0.611	3.152	-0.286	3.085	-0.301	-0.021
1.1	2.15	2.13	1.45	1.43	1.438	0.992	0.458	1.8	0.636	1.752	0.593	-0.026
5.358	2.36	2.24	1.66	1.54	1.588	0.957	0.762	4.83	-0.099	4.765	-0.111	-0.013
6.736	2.27	2.24	1.57	1.54	1.552	0.988	0.532	2.403	-0.643	2.348	-0.651	-0.023
2.874	2.28	2.25	1.58	1.55	1.562	0.988	0.534	2.42	-0.158	2.366	-0.177	-0.022
4.838	2.48	2.41	1.78	1.71	1.737	0.976	0.699	4.09	-0.155	4.029	-0.167	-0.015
3.368	2.34	2.3	1.64	1.6	1.615	0.985	0.585	2.892	-0.141	2.834	-0.158	-0.02
2.022	2.22	2.2	1.52	1.5	1.508	0.992	0.472	1.904	-0.059	1.856	-0.082	-0.025
1.597	2.12	2.1	1.42	1.4	1.408	0.991	0.452	1.754	0.098	1.706	0.068	-0.027
2.443	2.14	2.12	1.44	1.42	1.428	0.991	0.457	1.785	-0.27	1.737	-0.289	-0.027
7.969	2.57	2.4	1.87	1.7	1.768	0.946	0.88	6.362	-0.202	6.313	-0.208	-0.008
3.412	2.26	2.22	1.56	1.52	1.535	0.984	0.568	2.736	-0.198	2.676	-0.216	-0.022
7.409	2.45	2.27	1.75	1.57	1.645	0.94	0.858	6.058	-0.182	6.007	-0.189	-0.008
Absolute Average						0.968			0.233		0.234	0.019
Arithmetic Average						0.968			-0.042		-0.061	-0.019

Table 11. Effect of decreasing roughness coefficient by about 25% to n = 0.01

*** Calculation of Flow through Culverts ***

When Estimating Flow Directly Using Flow Equation, Depth Of Water At Section 2 Versus That At Section 1 Is Considered To Be: 0.90. $\varepsilon_Q = \varepsilon_R = \varepsilon_F = 0.001$

QOBS	HW	TW	H1	H4	H2	H2/H1	DC	QRES	ERROR1	QEST	ERROR2	ERROR3
FT**3/S	(FT)	(FT)	(FT)	(FT)	(FT)		(FT)	FT**3/S		FT**3/S		
9.187	2.78	2.5	2.08	1.8	1.847	0.888	1.115	10.004	0.089	10.008	0.089	0
7.474	2.62	2.43	1.92	1.73	1.759	0.916	0.989	7.961	0.065	7.954	0.064	-0.001
4.852	2.4	2.32	1.7	1.62	1.631	0.96	0.764	4.848	-0.001	4.824	-0.006	-0.005
0.468	1.85	1.84	1.15	1.14	1.142	0.993	0.362	1.132	1.419	1.117	1.387	-0.014
3.789	1.92	1.8	1.22	1.1	1.124	0.921	0.669	3.752	-0.01	3.741	-0.013	-0.003
0.588	1.66	1.65	0.96	0.95	0.951	0.991	0.319	0.886	0.506	0.871	0.482	-0.016
1.593	1.82	1.75	1.12	1.05	1.064	0.95	0.564	2.691	0.689	2.671	0.676	-0.008
5.939	2.35	2.22	1.65	1.52	1.541	0.934	0.837	5.784	-0.026	5.767	-0.029	-0.003
4.919	2.32	2.2	1.62	1.5	1.518	0.937	0.814	5.477	0.113	5.458	0.11	-0.004
4.878	2.09	1.92	1.39	1.22	1.254	0.902	0.785	5.108	0.047	5.107	0.047	0
7.158	2.41	2.22	1.71	1.52	1.552	0.907	0.925	6.997	-0.023	6.993	-0.023	-0.001
4.474	2.27	2.18	1.57	1.48	1.494	0.951	0.749	4.672	0.044	4.649	0.039	-0.005
4.416	2.2	2.14	1.5	1.44	1.449	0.966	0.664	3.698	-0.163	3.672	-0.168	-0.007
1.1	2.15	2.13	1.45	1.43	1.433	0.988	0.498	2.117	0.925	2.097	0.906	-0.01
5.358	2.36	2.24	1.66	1.54	1.558	0.939	0.826	5.635	0.052	5.616	0.048	-0.003
6.736	2.27	2.24	1.57	1.54	1.544	0.984	0.577	2.816	-0.582	2.793	-0.585	-0.008
2.874	2.28	2.25	1.58	1.55	1.554	0.984	0.579	2.835	-0.014	2.813	-0.021	-0.008
4.838	2.48	2.41	1.78	1.71	1.72	0.966	0.758	4.778	-0.012	4.755	-0.017	-0.005
3.368	2.34	2.3	1.64	1.6	1.606	0.979	0.634	3.384	0.005	3.361	-0.002	-0.007
2.022	2.22	2.2	1.52	1.5	1.503	0.989	0.512	2.234	0.105	2.214	0.095	-0.009
1.597	2.12	2.1	1.42	1.4	1.403	0.988	0.492	2.066	0.294	2.045	0.281	-0.01
2.443	2.14	2.12	1.44	1.42	1.423	0.988	0.496	2.1	-0.14	2.08	-0.149	-0.01
7.969	2.57	2.4	1.87	1.7	1.726	0.923	0.953	7.41	-0.07	7.399	-0.071	-0.001
3.412	2.26	2.22	1.56	1.52	1.526	0.978	0.617	3.206	-0.06	3.182	-0.068	-0.008
7.409	2.45	2.27	1.75	1.57	1.6	0.914	0.928	7.048	-0.049	7.04	-0.05	-0.001
Absolute Average						0.953			0.22		0.217	0.006
Arithmetic Average						0.953			0.128		0.121	-0.006

Table 12 lists the results of increasing and decreasing n by 25%. It can be seen that the flows decrease and increase by about 5%, which is significant.

Table 12. Variation of Manning's roughness coefficient n and its effect on flow calculation ($C_3 = 0.8$, $\varepsilon_Q = \varepsilon_R = \varepsilon_F = 0.001$, H_2/H_1 assumed to be 0.9 to calculate flow by flow equation)

Program+	Equation&	Program	Equation	Program	Equation	Program	Equation	Program	Equation
(ft^3/s)	(ft^3/s)	(ft^3/s)	(ft^3/s)	Relative Difference#		(ft^3/s)	(ft^3/s)	Relative Difference#	
n = 0.013		n = 0.01625				n = 0.01			
9.587	9.586	9.091	9.083	-0.052	-0.052	10.004	10.008	0.043	0.044
7.629	7.613	7.237	7.209	-0.051	-0.053	7.961	7.954	0.044	0.045
4.643	4.606	4.4	4.348	-0.052	-0.056	4.848	4.824	0.044	0.047
1.076	1.054	1.011	0.982	-0.060	-0.068	1.132	1.117	0.052	0.060
3.573	3.55	3.367	3.329	-0.058	-0.062	3.752	3.741	0.050	0.054
0.836	0.816	0.78	0.754	-0.067	-0.076	0.886	0.871	0.060	0.067
2.555	2.522	2.398	2.353	-0.061	-0.067	2.691	2.671	0.053	0.059
5.54	5.51	5.253	5.206	-0.052	-0.055	5.784	5.767	0.044	0.047
5.245	5.212	4.97	4.922	-0.052	-0.056	5.477	5.458	0.044	0.047
4.881	4.87	4.619	4.591	-0.054	-0.057	5.108	5.107	0.047	0.049
6.707	6.692	6.366	6.335	-0.051	-0.053	6.997	6.993	0.043	0.045
4.471	4.434	4.235	4.182	-0.053	-0.057	4.672	4.649	0.045	0.048
3.536	3.497	3.346	3.293	-0.054	-0.058	3.698	3.672	0.046	0.050
2.023	1.993	1.913	1.873	-0.054	-0.060	2.117	2.097	0.046	0.052
5.398	5.365	5.117	5.068	-0.052	-0.055	5.635	5.616	0.044	0.047
2.694	2.661	2.55	2.506	-0.053	-0.058	2.816	2.793	0.045	0.050
2.713	2.68	2.568	2.524	-0.053	-0.058	2.835	2.813	0.045	0.050
4.576	4.541	4.337	4.288	-0.052	-0.056	4.778	4.755	0.044	0.047
3.24	3.204	3.069	3.021	-0.053	-0.057	3.384	3.361	0.044	0.049
2.137	2.107	2.022	1.982	-0.054	-0.059	2.234	2.214	0.045	0.051
1.974	1.944	1.865	1.825	-0.055	-0.061	2.066	2.045	0.047	0.052
2.007	1.977	1.897	1.857	-0.055	-0.061	2.1	2.08	0.046	0.052
7.101	7.08	6.737	6.702	-0.051	-0.053	7.41	7.399	0.044	0.045
3.068	3.031	2.904	2.855	-0.053	-0.058	3.206	3.182	0.045	0.050
6.756	6.737	6.412	6.377	-0.051	-0.053	7.048	7.04	0.043	0.045
Average				-0.054	-0.059			0.046	0.050

Notes:
+: Program means flow is obtained using standard step method
&: Equation means flow is obtained by using flow Equation (12) with assumed depth of water h_2
#: Relative Difference is obtained by comparing scenario of n = 0.013

Discharge Coefficient

Increasing and decreasing coefficient of discharge C, we calculate flow rates for three scenarios in Table 13. It can be seen that both flow rates calculated by the discharge program and that

using Equation (12) are closely related to C. The results suggest that the coefficient of discharge influences the accuracy of flow calculation significantly.

Table 13. Variation of discharge coefficient and its effect on flow calculation
($n = 0.013$, $\varepsilon_Q = \varepsilon_R = \varepsilon_F = 0.01$, H_2/H_1 assumed to be 0.9 to calculate flow by flow equation)

Program	Equation	Program	Equation	Program	Equation	Program	Equation	Program	Equation
(ft^3/s)	(ft^3/s)	(ft^3/s)	(ft^3/s)	Relative Difference+		(ft^3/s)	(ft^3/s)	Relative Difference+	
$C_3 = 0.8$		$C_3 = 0.85$				$C_3 = 0.75$			
9.59	9.586	10.064	10.055	0.049	0.049	9.1	9.099	-0.051	-0.051
7.621	7.613	7.995	7.984	0.049	0.049	7.235	7.228	-0.051	-0.051
4.64	4.606	4.865	4.827	0.048	0.048	4.403	4.376	-0.051	-0.050
1.076	1.054	1.126	1.101	0.046	0.045	1.024	1.004	-0.048	-0.047
3.571	3.55	3.738	3.714	0.047	0.046	3.391	3.378	-0.050	-0.048
0.837	0.816	0.874	0.85	0.044	0.042	0.797	0.779	-0.048	-0.045
2.554	2.522	2.671	2.635	0.046	0.045	2.428	2.403	-0.049	-0.047
5.531	5.51	5.798	5.775	0.048	0.048	5.253	5.233	-0.050	-0.050
5.236	5.212	5.489	5.462	0.048	0.048	4.973	4.951	-0.050	-0.050
4.876	4.87	5.112	5.101	0.048	0.047	4.63	4.628	-0.050	-0.050
6.703	6.692	7.029	7.018	0.049	0.049	6.359	6.354	-0.051	-0.051
4.466	4.434	4.681	4.646	0.048	0.048	4.238	4.214	-0.051	-0.050
3.534	3.497	3.704	3.662	0.048	0.047	3.354	3.325	-0.051	-0.049
2.023	1.993	2.121	2.087	0.048	0.047	1.922	1.896	-0.050	-0.049
5.39	5.365	5.65	5.623	0.048	0.048	5.118	5.096	-0.050	-0.050
2.694	2.661	2.825	2.786	0.049	0.047	2.557	2.529	-0.051	-0.050
2.713	2.68	2.845	2.806	0.049	0.047	2.575	2.547	-0.051	-0.050
4.574	4.541	4.797	4.759	0.049	0.048	4.341	4.314	-0.051	-0.050
3.239	3.204	3.397	3.357	0.049	0.048	3.075	3.046	-0.051	-0.049
2.137	2.107	2.24	2.206	0.048	0.047	2.029	2.004	-0.051	-0.049
1.974	1.944	2.069	2.034	0.048	0.046	1.875	1.849	-0.050	-0.049
2.007	1.977	2.104	2.069	0.048	0.047	1.906	1.88	-0.050	-0.049
7.093	7.08	7.441	7.425	0.049	0.049	6.734	6.723	-0.051	-0.050
3.067	3.031	3.215	3.174	0.048	0.047	2.911	2.881	-0.051	-0.049
6.753	6.737	7.082	7.065	0.049	0.049	6.401	6.397	-0.052	-0.050
Average				0.048	0.047			-0.050	-0.049

Notes:
+: Relative Difference is obtained by comparing scenario of $C_3 = 0.8$

Culvert Length

In practice, there are errors with the length of culverts. By decreasing and increasing the culvert length by 5 ft, two discharges are calculated. Table 14 and Table 15 are the simulation results.

The results show that the flow increases with the decrease of culvert length and vice versa. This is expected since head loss due to friction in the culvert barrel h_{f2-3} is proportional to the length of culvert.

Table 16 shows the effect on flow of decreasing and increasing the culvert length by 5 ft. These results show that errors in estimating culvert length do not affect the calculated flow significantly.

Table 14. Flow estimates by decreasing culvert length by 5 ft from 45 to 40 ft

*** Calculation of Flow through Culverts ***

When Estimating Flow Directly Using Flow Equation, Depth Of Water At Section 2 Versus That At Section 1 Is Considered To Be: 0.90. $\varepsilon_R = \varepsilon_F = 0.01$

QOBS	HW	TW	H1	H4	H2	H2/H1	DC	QRES	ERROR1	QEST	ERROR2	ERROR3
FT**3/S	(FT)	(FT)	(FT)	(FT)	(FT)		(FT)	FT**3/S		FT**3/S		
9.187	2.78	2.5	2.08	1.8	1.862	0.895	1.097	9.693	0.055	9.695	0.055	0
7.474	2.62	2.43	1.92	1.73	1.773	0.923	0.973	7.717	0.032	7.702	0.03	-0.002
4.852	2.4	2.32	1.7	1.62	1.632	0.96	0.752	4.696	-0.032	4.662	-0.039	-0.007
0.468	1.85	1.84	1.15	1.14	1.142	0.993	0.354	1.09	1.33	1.07	1.286	-0.019
3.789	1.92	1.8	1.22	1.1	1.132	0.928	0.656	3.619	-0.045	3.599	-0.05	-0.006
0.588	1.66	1.65	0.96	0.95	0.956	0.995	0.313	0.85	0.445	0.83	0.411	-0.023
1.593	1.82	1.75	1.12	1.05	1.07	0.955	0.553	2.591	0.626	2.56	0.607	-0.012
5.939	2.35	2.22	1.65	1.52	1.549	0.939	0.824	5.604	-0.056	5.576	-0.061	-0.005
4.919	2.32	2.2	1.62	1.5	1.526	0.942	0.8	5.305	0.079	5.276	0.073	-0.006
4.878	2.09	1.92	1.39	1.22	1.264	0.909	0.772	4.939	0.013	4.931	0.011	-0.002
7.158	2.41	2.22	1.71	1.52	1.563	0.914	0.909	6.782	-0.053	6.77	-0.054	-0.002
4.474	2.27	2.18	1.57	1.48	1.5	0.955	0.737	4.524	0.011	4.489	0.003	-0.008
4.416	2.2	2.14	1.5	1.44	1.454	0.97	0.654	3.579	-0.19	3.542	-0.198	-0.01
1.1	2.15	2.13	1.45	1.43	1.433	0.988	0.489	2.048	0.862	2.02	0.836	-0.014
5.358	2.36	2.24	1.66	1.54	1.564	0.942	0.813	5.459	0.019	5.43	0.013	-0.005
6.736	2.27	2.24	1.57	1.54	1.544	0.984	0.567	2.726	-0.595	2.695	-0.6	-0.011
2.874	2.28	2.25	1.58	1.55	1.554	0.984	0.57	2.745	-0.045	2.714	-0.056	-0.011
4.838	2.48	2.41	1.78	1.71	1.726	0.97	0.745	4.629	-0.043	4.596	-0.05	-0.007
3.368	2.34	2.3	1.64	1.6	1.605	0.979	0.624	3.277	-0.027	3.245	-0.037	-0.01
2.022	2.22	2.2	1.52	1.5	1.502	0.988	0.505	2.162	0.069	2.135	0.056	-0.013
1.597	2.12	2.1	1.42	1.4	1.403	0.988	0.483	1.998	0.251	1.97	0.233	-0.014
2.443	2.14	2.12	1.44	1.42	1.423	0.988	0.488	2.031	-0.169	2.003	-0.18	-0.014
7.969	2.57	2.4	1.87	1.7	1.739	0.93	0.937	7.183	-0.099	7.163	-0.101	-0.003
3.412	2.26	2.22	1.56	1.52	1.527	0.979	0.607	3.104	-0.09	3.07	-0.1	-0.011
7.409	2.45	2.27	1.75	1.57	1.611	0.92	0.913	6.832	-0.078	6.816	-0.08	-0.002
Absolute Average						0.957			0.213		0.209	0.009
Arithmetic Average						0.957			0.091		0.08	-0.009

Table 15. Flow estimates by increasing culvert length by 5 ft from 45 to 50 ft

*** Calculation of Flow through Culverts ***

When Estimating Flow Directly Using Flow Equation, Depth Of Water At Section 2 Versus That At Section 1 Is Considered To Be: 0.90. $\varepsilon_R = \varepsilon_F = 0.01$

QOBS	HW	TW	H1	H4	H2	H2/H1	DC	QRES	ERROR1	QEST	ERROR2	ERROR3
FT**3/S	(FT)	(FT)	(FT)	(FT)	(FT)		(FT)	FT**3/S		FT**3/S		
9.187	2.78	2.5	2.08	1.8	1.875	0.902	1.084	9.481	0.032	9.48	0.032	0
7.474	2.62	2.43	1.92	1.73	1.779	0.927	0.962	7.548	0.01	7.528	0.007	-0.003
4.852	2.4	2.32	1.7	1.62	1.64	0.965	0.743	4.593	-0.053	4.551	-0.062	-0.009
0.468	1.85	1.84	1.15	1.14	1.142	0.993	0.351	1.062	1.269	1.038	1.219	-0.022
3.789	1.92	1.8	1.22	1.1	1.14	0.934	0.649	3.531	-0.068	3.503	-0.076	-0.008
0.588	1.66	1.65	0.96	0.95	0.956	0.995	0.307	0.825	0.403	0.802	0.365	-0.027
1.593	1.82	1.75	1.12	1.05	1.07	0.955	0.544	2.521	0.583	2.486	0.561	-0.014
5.939	2.35	2.22	1.65	1.52	1.555	0.942	0.813	5.481	-0.077	5.445	-0.083	-0.006
4.919	2.32	2.2	1.62	1.5	1.531	0.945	0.791	5.188	0.055	5.151	0.047	-0.007
4.878	2.09	1.92	1.39	1.22	1.273	0.916	0.763	4.826	-0.011	4.811	-0.014	-0.003
7.158	2.41	2.22	1.71	1.52	1.574	0.92	0.9	6.636	-0.073	6.617	-0.076	-0.003
4.474	2.27	2.18	1.57	1.48	1.5	0.955	0.727	4.421	-0.012	4.381	-0.021	-0.009
4.416	2.2	2.14	1.5	1.44	1.454	0.97	0.646	3.496	-0.208	3.454	-0.218	-0.012
1.1	2.15	2.13	1.45	1.43	1.433	0.988	0.485	2	0.818	1.968	0.789	-0.016
5.358	2.36	2.24	1.66	1.54	1.569	0.945	0.803	5.338	-0.004	5.302	-0.01	-0.007
6.736	2.27	2.24	1.57	1.54	1.544	0.984	0.561	2.664	-0.605	2.628	-0.61	-0.013
2.874	2.28	2.25	1.58	1.55	1.554	0.984	0.564	2.682	-0.067	2.647	-0.079	-0.013
4.838	2.48	2.41	1.78	1.71	1.726	0.97	0.737	4.526	-0.065	4.487	-0.073	-0.009
3.368	2.34	2.3	1.64	1.6	1.613	0.984	0.617	3.205	-0.048	3.166	-0.06	-0.012
2.022	2.22	2.2	1.52	1.5	1.502	0.988	0.497	2.112	0.045	2.081	0.029	-0.015
1.597	2.12	2.1	1.42	1.4	1.403	0.988	0.478	1.951	0.221	1.918	0.201	-0.017
2.443	2.14	2.12	1.44	1.42	1.423	0.988	0.483	1.984	-0.188	1.951	-0.201	-0.016
7.969	2.57	2.4	1.87	1.7	1.744	0.933	0.927	7.026	-0.118	7.001	-0.122	-0.004
3.412	2.26	2.22	1.56	1.52	1.527	0.979	0.599	3.033	-0.111	2.994	-0.123	-0.013
7.409	2.45	2.27	1.75	1.57	1.616	0.923	0.903	6.683	-0.098	6.661	-0.101	-0.003
Absolute Average						0.959			0.21		0.207	0.01
Arithmetic Average						0.959			0.065		0.053	-0.01

Table 16. Variation of culvert length and its effect on flow calculation
($n = 0.013$, $\varepsilon_R = \varepsilon_F = 0.01$, H_2/H_1 assumed to be 0.9 to calculate flow by flow equation)

Program	Equation	Program	Equation	Program	Equation	Program	Equation	Program	Equation
(ft^3/s)	(ft^3/s)	(ft^3/s)	(ft^3/s)	Relative Difference+		(ft^3/s)	(ft^3/s)	Relative Difference+	
L = 45 ft		L = 40 ft				L = 50 ft			
9.585	9.586	9.693	9.695	0.011	0.011	9.481	9.48	-0.011	-0.011
7.63	7.613	7.717	7.702	0.011	0.012	7.548	7.528	-0.011	-0.011
4.645	4.606	4.696	4.662	0.011	0.012	4.593	4.551	-0.011	-0.012
1.076	1.054	1.09	1.07	0.013	0.015	1.062	1.038	-0.013	-0.015
3.572	3.55	3.619	3.599	0.013	0.014	3.531	3.503	-0.011	-0.013
0.837	0.816	0.85	0.83	0.016	0.017	0.825	0.802	-0.014	-0.017
2.555	2.522	2.591	2.56	0.014	0.015	2.521	2.486	-0.013	-0.014
5.54	5.51	5.604	5.576	0.012	0.012	5.481	5.445	-0.011	-0.012
5.244	5.212	5.305	5.276	0.012	0.012	5.188	5.151	-0.011	-0.012
4.884	4.87	4.939	4.931	0.011	0.013	4.826	4.811	-0.012	-0.012
6.708	6.692	6.782	6.77	0.011	0.012	6.636	6.617	-0.011	-0.011
4.472	4.434	4.524	4.489	0.012	0.012	4.421	4.381	-0.011	-0.012
3.537	3.497	3.579	3.542	0.012	0.013	3.496	3.454	-0.012	-0.012
2.023	1.993	2.048	2.02	0.012	0.014	2	1.968	-0.011	-0.013
5.399	5.365	5.459	5.43	0.011	0.012	5.338	5.302	-0.011	-0.012
2.694	2.661	2.726	2.695	0.012	0.013	2.664	2.628	-0.011	-0.012
2.713	2.68	2.745	2.714	0.012	0.013	2.682	2.647	-0.011	-0.012
4.577	4.541	4.629	4.596	0.011	0.012	4.526	4.487	-0.011	-0.012
3.24	3.204	3.277	3.245	0.011	0.013	3.205	3.166	-0.011	-0.012
2.137	2.107	2.162	2.135	0.012	0.013	2.112	2.081	-0.012	-0.012
1.974	1.944	1.998	1.97	0.012	0.013	1.951	1.918	-0.012	-0.013
2.007	1.977	2.031	2.003	0.012	0.013	1.984	1.951	-0.011	-0.013
7.102	7.08	7.183	7.163	0.011	0.012	7.026	7.001	-0.011	-0.011
3.068	3.031	3.104	3.07	0.012	0.013	3.033	2.994	-0.011	-0.012
6.757	6.737	6.832	6.816	0.011	0.012	6.683	6.661	-0.011	-0.011
Average				0.012	0.013			-0.011	-0.012

Notes:
+: Relative Difference is obtained by comparing scenario of L = 45 ft

Culvert Diameter

Table 17 shows the relative difference of flow by decreasing and increasing the culvert diameter by 5%. The results show considerable flow decrease or increase. So the culvert diameter is a critical parameter and needs to be determined as accurately as possible.

Table 17. Variation of culvert diameter and its effect on flow calculation
($n = 0.013$, $\varepsilon_R = \varepsilon_F = 0.01$, H_2/H_1 assumed to be 0.9 to calculate flow by flow equation)

Program	Equation	Program	Equation	Program	Equation	Program	Equation	Program	Equation
(ft^3/s)	(ft^3/s)	(ft^3/s)	(ft^3/s)	Relative Difference+		(ft^3/s)	(ft^3/s)	Relative Difference+	
D = 2.0 ft		D = 1.9 ft				D = 2.1 ft			
8.939	8.939	8.192	8.194	-0.084	-0.083	9.585	9.586	0.072	0.072
7.16	7.147	6.64	6.636	-0.073	-0.071	7.63	7.613	0.066	0.065
4.388	4.354	4.111	4.083	-0.063	-0.062	4.645	4.606	0.059	0.058
1.033	1.012	0.988	0.968	-0.044	-0.043	1.076	1.054	0.042	0.042
3.431	3.411	3.289	3.265	-0.041	-0.043	3.572	3.55	0.041	0.041
0.806	0.786	0.775	0.755	-0.038	-0.039	0.837	0.816	0.038	0.038
2.458	2.426	2.356	2.325	-0.041	-0.042	2.555	2.522	0.039	0.040
5.257	5.23	4.957	4.932	-0.057	-0.057	5.54	5.51	0.054	0.054
4.983	4.951	4.702	4.674	-0.056	-0.056	5.244	5.212	0.052	0.053
4.679	4.665	4.464	4.451	-0.046	-0.046	4.884	4.87	0.044	0.044
6.364	6.351	5.998	5.987	-0.058	-0.057	6.708	6.692	0.054	0.054
4.25	4.216	4.015	3.984	-0.055	-0.055	4.472	4.434	0.052	0.052
3.367	3.33	3.186	3.153	-0.054	-0.053	3.537	3.497	0.050	0.050
1.927	1.899	1.824	1.799	-0.053	-0.053	2.023	1.993	0.050	0.049
5.119	5.089	4.82	4.794	-0.058	-0.058	5.399	5.365	0.055	0.054
2.555	2.524	2.406	2.379	-0.058	-0.057	2.694	2.661	0.054	0.054
2.571	2.541	2.42	2.394	-0.059	-0.058	2.713	2.68	0.055	0.055
4.301	4.272	4	3.98	-0.070	-0.068	4.577	4.541	0.064	0.063
3.064	3.032	2.876	2.848	-0.061	-0.061	3.24	3.204	0.057	0.057
2.029	2.002	1.915	1.891	-0.056	-0.055	2.137	2.107	0.053	0.052
1.881	1.853	1.784	1.758	-0.052	-0.051	1.974	1.944	0.049	0.049
1.912	1.884	1.811	1.785	-0.053	-0.053	2.007	1.977	0.050	0.049
6.679	6.661	6.213	6.203	-0.070	-0.069	7.102	7.08	0.063	0.063
2.911	2.878	2.745	2.715	-0.057	-0.057	3.068	3.031	0.054	0.053
6.398	6.38	6.012	5.998	-0.060	-0.060	6.757	6.737	0.056	0.056
Average				-0.057	-0.056			0.053	0.053

Notes:
+: Relative Difference is obtained by comparing scenario of D = 2.0 ft

Flow calculated by iterative methods versus flow calculated with assumed depth of water h_2

When Equation (12) is used to calculate flow, water level at section 2 above the culvert outlet invert is assumed to be a ratio of that at section 1, with a factor such as 0.9, 0.95. Table 18 lists the flow rate calculated by using Equation (12) for 3 scenarios and the comparison with that by the discharge program. The results of Equation (12) are very close to the discharge program results. This gives us enough confidence to use Equation (12) to estimate flow by assuming

H_2/H_1 to be 0.9. Table 18 also shows that most accurate results are obtained when assuming H_2/H_1 to be 0.95. This is true since this assumed ratio is the closest to the modeled ratio of 0.959 (see Table 18) resulting from the model.

After conducting rating analysis for a data set, we apply the calculated discharge coefficient to the model to calculate flow based on head water and tail water readings. Table 19 is one simulation result using discharge coefficients obtained from Figure 3. Figure 10 shows the difference between measured and calculated flows. Except one point being significantly away from the y = x line, the rest of the points are within a reasonable range along the line. The best estimate of discharge coefficient is obtained by minimizing the difference between the measured and calculated flows.

Table 18. Flow calculated by discharge program with iterations versus flow calculated with assumed h_2 without iteration
($C_3 = 0.8$, $n = 0.013$, $\varepsilon_Q = \varepsilon_R = \varepsilon_F = 0.01$)

Flow calculated by standard step method	Flow calculated simply by using flow Equation (12)					
	H_2/H_1 assumed to be 0.9		H_2/H_1 assumed to be 0.95		H_2/H_1 assumed to be 1.0	
	Q	ERROR	Q	ERROR	Q	ERROR
(ft^3/s)	(ft^3/s)		(ft^3/s)		(ft^3/s)	
9.59	9.586	0	9.599	0.001	9.567	-0.002
7.621	7.613	-0.001	7.645	0.003	7.663	0.006
4.64	4.606	-0.007	4.637	-0.001	4.661	0.005
1.076	1.054	-0.021	1.066	-0.009	1.077	0.001
3.571	3.55	-0.006	3.587	0.005	3.62	0.014
0.837	0.816	-0.025	0.828	-0.011	0.838	0.002
2.554	2.522	-0.013	2.552	-0.001	2.578	0.009
5.531	5.51	-0.004	5.548	0.003	5.579	0.009
5.236	5.212	-0.005	5.25	0.003	5.281	0.009
4.876	4.87	-0.001	4.913	0.008	4.95	0.015
6.703	6.692	-0.002	6.734	0.005	6.767	0.01
4.466	4.434	-0.007	4.468	0.001	4.497	0.007
3.534	3.497	-0.01	3.527	-0.002	3.552	0.005
2.023	1.993	-0.015	2.011	-0.006	2.027	0.002
5.39	5.365	-0.005	5.402	0.002	5.432	0.008
2.694	2.661	-0.013	2.682	-0.005	2.7	0.002
2.713	2.68	-0.012	2.701	-0.005	2.718	0.002
4.574	4.541	-0.007	4.568	-0.001	4.589	0.003
3.239	3.204	-0.011	3.228	-0.003	3.247	0.002
2.137	2.107	-0.014	2.125	-0.006	2.14	0.001
1.974	1.944	-0.015	1.962	-0.006	1.977	0.002
2.007	1.977	-0.015	1.995	-0.006	2.01	0.002
7.093	7.08	-0.002	7.115	0.003	7.137	0.006
3.067	3.031	-0.012	3.055	-0.004	3.076	0.003
6.753	6.737	-0.002	6.777	0.004	6.809	0.008
Absolute Average		0.009		0.004		0.005
Arithmetic Average		-0.009		-0.001		0.005

Table 19. Examining the coefficient of discharge
(Discharge coefficient C_3 used = 0.7458 + 0.3912 * (Head water – Tail water))

*** Calculation of Flow through Culverts ***

When Estimating Flow Directly Using Flow Equation, Depth Of Water At Section 2 Versus That At Section 1 Is Considered To Be: 0.90, n = 0.013, $\varepsilon_Q = \varepsilon_R = \varepsilon_F = 0.01$

QOBS	HW	TW	H1	H4	H2	H2/H1	DC	QRES	ERROR1	QEST	ERROR2	ERROR3
FT**3/S	(FT)	(FT)	(FT)	(FT)	(FT)		(FT)	FT**3/S		FT**3/S		
9.187	2.78	2.5	2.08	1.8	1.88	0.904	1.121	10.113	0.101	10.104	0.1	-0.001
7.474	2.62	2.43	1.92	1.73	1.779	0.926	0.977	7.775	0.04	7.764	0.039	-0.001
4.852	2.4	2.32	1.7	1.62	1.639	0.964	0.737	4.534	-0.066	4.502	-0.072	-0.007
0.468	1.85	1.84	1.15	1.14	1.145	0.996	0.344	1.024	1.187	1.004	1.146	-0.019
3.789	1.92	1.8	1.22	1.1	1.137	0.932	0.649	3.546	-0.064	3.526	-0.07	-0.006
0.588	1.66	1.65	0.96	0.95	0.955	0.995	0.302	0.797	0.355	0.779	0.325	-0.023
1.593	1.82	1.75	1.12	1.05	1.067	0.952	0.542	2.486	0.56	2.459	0.544	-0.011
5.939	2.35	2.22	1.65	1.52	1.551	0.94	0.816	5.513	-0.072	5.491	-0.075	-0.004
4.919	2.32	2.2	1.62	1.5	1.528	0.944	0.792	5.199	0.057	5.175	0.052	-0.005
4.878	2.09	1.92	1.39	1.22	1.27	0.914	0.772	4.934	0.011	4.928	0.01	-0.001
7.158	2.41	2.22	1.71	1.52	1.569	0.917	0.914	6.835	-0.045	6.825	-0.047	-0.002
4.474	2.27	2.18	1.57	1.48	1.501	0.956	0.724	4.382	-0.021	4.351	-0.027	-0.007
4.416	2.2	2.14	1.5	1.44	1.457	0.971	0.639	3.426	-0.224	3.392	-0.232	-0.01
1.1	2.15	2.13	1.45	1.43	1.436	0.99	0.475	1.929	0.754	1.903	0.73	-0.013
5.358	2.36	2.24	1.66	1.54	1.568	0.945	0.804	5.351	-0.001	5.327	-0.006	-0.005
6.736	2.27	2.24	1.57	1.54	1.546	0.985	0.551	2.578	-0.617	2.549	-0.622	-0.011
2.874	2.28	2.25	1.58	1.55	1.556	0.985	0.554	2.596	-0.097	2.568	-0.107	-0.011
4.838	2.48	2.41	1.78	1.71	1.727	0.97	0.731	4.451	-0.08	4.42	-0.086	-0.007
3.368	2.34	2.3	1.64	1.6	1.608	0.98	0.607	3.113	-0.076	3.082	-0.085	-0.01
2.022	2.22	2.2	1.52	1.5	1.506	0.991	0.488	2.037	0.007	2.011	-0.005	-0.013
1.597	2.12	2.1	1.42	1.4	1.406	0.99	0.468	1.882	0.178	1.856	0.162	-0.014
2.443	2.14	2.12	1.44	1.42	1.426	0.99	0.473	1.914	-0.217	1.888	-0.227	-0.014
7.969	2.57	2.4	1.87	1.7	1.737	0.929	0.937	7.179	-0.099	7.166	-0.101	-0.002
3.412	2.26	2.22	1.56	1.52	1.528	0.979	0.591	2.947	-0.136	2.916	-0.145	-0.011
7.409	2.45	2.27	1.75	1.57	1.616	0.923	0.914	6.852	-0.075	6.845	-0.076	-0.001
Absolute average						0.959			0.206		0.204	0.008
Arithmetic average						0.959			0.054		0.045	-0.008

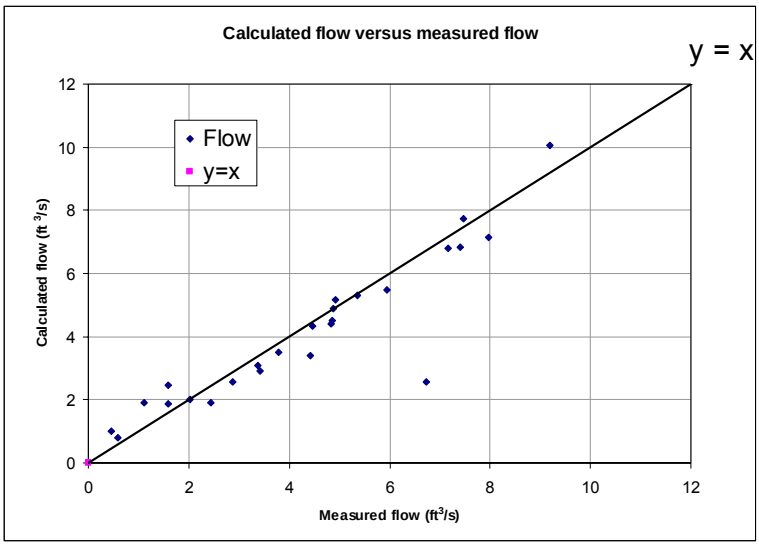

Figure 10. Calculated and measured flows

CONCLUSIONS

In this study, principles governing rating analyses for culvert flow in the Everglades National Park are illustrated. A FORTRAN program is developed to model type 3 and type 4 culvert flows, for which type 3 is solved by an iterative process while type 4 is a direct application of the flow equation. By solving the energy equation iteratively, both the iteration method based on convergence of flow and that based on convergence of head give the depth of water h_2 at the culvert entrance, which in turn determines the contraction of flow at the entrance. Factors affecting flow calculation such as roughness coefficient, discharge coefficient, culvert length and culvert diameter are demonstrated. Discharge coefficient varies over a large range. Flow calculation is mostly sensitive to the discharge coefficient and thus it is the key parameter to be determined when we conduct rating analysis. Processes used to obtain the best estimate of discharge coefficient are also demonstrated.

It is recommended that the algorithm to simulate depth of water h_2 developed in this study be implemented in the District's FLOW program for type 3 culvert flow. It is further recommended that similar approaches be used to model other types of culvert flow and flows with gate control in the FLOW program.

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APPENDIX I – TYPE 3 FLOW CALCULATION SOURCE CODE FOR ITERATION BASED ON FLOW

```
C
C       FILE NAME: CULFLOW3_F.FOR
C       SIMULATE TYPE 3 FLOW (OPEN CHANNEL FLOW) ACROSS CULVERT USING AN
C       ITERATION METHOD BASED ON CONVERGENCE OF FLOW
C
C       THIS PROGRAM CALCULATES THE FLOW ACROSS CULVERT USING THE STANDARD STEP
C       METHOD
C
        PARAMETER(NA1=200)
        DIMENSION QOBS(NA1), HW(NA1), TW(NA1), QFINAL(NA1)
        DIMENSION H1(NA1), H4(NA1), H2(NA1), DC(NA1)
        DIMENSION ERROR1(NA1), QEST(NA1), ERROR2(NA1), ERROR3(NA1)
        DIMENSION RAH2H1(NA1)
        CHARACTER OUTNAME*10

        REAL K2, K3, N, LEN, INEL
        LOGICAL DEBUG
C
C       ***** VARIABLES *****
C
C       NA1: ARRAY SIZE
C       HW: HEAD WATER LEVEL (FT)
C       TW: TAIL WATER LEVEL (FT)
C       DC: MAXIMUM DEPTH OF WATER IN THE CRITICAL FLOW SECTION (FT)
C       INEL: CULVERT INLET INVERT ELEVATION (FT)
C       OUTEL: CULVERT OUTLET INVERT ELEVATION (FT)
C       Z2: DIFFERENCE BETWEEN INLET INVERT AND OUTLET INVERT ELEVATION
C           Z2 = INEL - OUTEL (FT)
C       H1: HEAD WATER DEPTH ABOVE OUTLET INVERT (FT)
C       H4: TAIL WATER DEPTH ABOVE OUTLET INVERT (FT)
C       H2: WATER LEVEL ABOVE OUTLET INVERT (FT)
C       D: DIAMETER OF THE CULVERT (FT)
c       LEN: LENGTH OF THE CULVERT (FT)
C       N: MANNING ROUGHNESS OF COEFFICIENT (FT**(1/6))
C       G: ACCELERATION OF GRAVITY (G = 32.18 FT/S**2)
C       C3: DISCHARGE COEFFICIENT FOR TYPE 3 FLOW
C
C       THETA2: HALF OF THE CENTRAL ANGLE OF THE CIRCULAR SEGMENT INTERCEPTED
C               BY THE FREE WATER SURFACE IN A PARTIALLY FILLED CULVERT (RAD)
C       A2: AREA OF SECTION OF FLOW AT SECTION 2 (FT**2)
C       P2: WETTED PERIMETER OF CROSS SECTION OF FLOW AT SECTION 2 (FT)
C       R2: HYDRAULIC RADIUS AT SECTION 2 (FT)
C       K2: CONVEYANCE OF SECTION 2 (FT**3/S)
C       D2: DEPTH OF WATER ABOVE INLET INVERT (FT)
C       THETA3: HALF OF THE CENTRAL ANGLE OF THE CIRCULAR SEGMENT INTERCEPTED
C               BY THE FREE WATER SURFACE FOR SECTION 3 (RAD)
C       A3: AREA OF SECTION OF FLOW AT SECTION 3 (FT**2)
C       P3: WETTED PERIMETER OF CROSS SECTION OF FLOW AT SECTION 3 (FT)
C       R3: HYDRAULIC RADIUS AT SECTION 3 (FT)
C       K3: CONVEYANCE OF SECTION 3 (FT**3/S)
C       HF23: HEAD LOSS DUE TO FRICTION IN THE CULVERT BARREL (FT)
C
C       RLIM: ALLOWED ERROR RANGE OF ROOT (D2, DC) WHEN SEEKING IT BY
C             BISECTION METHOD
C        FLIM: ALLOWED MAXIMUM ABSOLUTE VALUE OF THE ROOT FUNCTION. WHEN ABSOLUTE
C              VALUE OF THE ROOT FUNCTION IS LESS THAN FLIM, IT IS REGARDED AS
c             ZERO
C       QACCU: ALLOWED ERROR RANGE OF FLOW WHEN SEEKING IT BY ITERATION METHOD
C       D2VSD1: ESTIMATED RATIO OF DEPTH OF WATER AT SECTION 2 (D2) TO THAT AT
C               SECTION 1 (D1). THE VALUE IS USED TO APPROXIMATELY CALCULATE FLOW
C               USING TYPE 3 FLOW EQUATION
C       OUTNAME: OUTPUT DATA FILE NAME
C       DEBUG: LOGICAL VARIABLE TO CONTROL IF ANY INTERMEDIATE SIMULATION RESULTS
C              ARE TO BE PRINTED
C
C       QOBS: FLOW MEASURED FROM FIELD
C       QFINAL: FLOW CALCULATED BY SOLVING THE ENERGY EQUATION
C       ERROR1: RELATIVE DIFFERENCE OF QFINAL VERSUS QOBS
C       QEST: FLOW CALCULATED USING ASSUMED DEPTH OF WATER AT SECTION 2
C       ERROR2: RELATIVE DIFFERENCE OF QEST VERSUS QOBS
C       ERROR3: RELATIVE DIFFERENCE OF QEST VERSUS QFINAL
C
C       ***** SUBROUTINE *****
C
C       HALFANG: CALCULATING HALF OF THE CENTRAL ANGLE OF THE CIRCULAR SEGMENT
```

```
C               INTERCEPTED BY THE FREE WATER SURFACE IN A PARTIALLY FILLED CULVERT
C       AREA: CALCULATING AREA OF SECTION OF FLOW
C       PERIMET: CALCULATING WETTED PERIMETER OF CROSS SECTION OF FLOW
C       WIDTH: CALCULATING WIDTH OF THE SECTION AT THE WATER SURFACE
C       HYDRAD: CALCULATING HYDRAULIC RADIUS
C       CONVEY: CALCULATING CONVEYANCE OF A SECTION
C       GETC3: CALCULATING THE DISCHARGE COEFFICIENT FOR THE FLOW
C       GETQ: CALCULATING CULVERT FLOW USING THE DISCHARGE EQUATION FOR TYPE 3 FLOW
C       QSOLVE: SOLVING THE ENERGY EQUATION TO CALCULATE FLOW GIVEN HEAD WATER,
C               TAIL WATER AND DISCHARGE COEFFICIENT
C       SEEKD2: CALCULATING DEPTH OF WATER ABOVE INLET INVERT D2 BY SOLVING ENERGY
C               EQUATION BETWEEN SECTION 1 AND 2, GIVEN FLOW, HEAD WATER AND
C               TAIL WATER
C       SEEKDC: DETERMINING MAXIMUM DEPTH OF WATER IN THE CRITICAL FLOW SECTION
C               BY SOLVING THE DISCHARGE EQUATION
C
C       READ NECESSARY DATA FROM A DATA FILE
C
        OPEN(3, FILE='DATA3C_F.TXT')
        READ(3,*) C3CON, C3COE, G
        READ(3,*) LEN, D, INEL, OUTEL, N
        READ(3,*) RLIM, FLIM, QACCU
        READ(3,*) D2VSD1
        READ(3,*) OUTNAME, DEBUG
        READ(3,*) NARRAY
        READ(3,*) (QOBS(I), HW(I), TW(I), I=1,NARRAY)
        CLOSE(3)

        Z2 = INEL - OUTEL

        DO 100 I=1, NARRAY

        H1(I) = HW(I) - OUTEL
        H4(I) = TW(I) - OUTEL

        CALL QSOLVE(C3CON, C3COE, H1(I), H4(I), G, LEN, D,
     * Z2, N, RLIM, FLIM, QACCU, D2, DEBUG, QFINAL(I))
C
C       CALCULATE WATER LEVEL ABOVE OUTLET INVERT FOR SECTION 2 AND MODELED
C       RATIO OF H2 TO H1
C
        H2(I) = D2 + Z2
        RAH2H1(I) = H2(I)/H1(I)

100     CONTINUE

C
C       ASSUMING WATER LEVEL IN SECTION 2 (H2) IS A FIXED RATIO OF HEAD WATER LEVEL,
C       ESTIMATE FLOW USING ENERGY EQUATION FOR TYPE 3 FLOW.
C
        DO 120 I=1, NARRAY

        CALL HALFANG(D2VSD1 * H1(I) - Z2, D, THETA2)
        CALL AREA(D, THETA2, A2)
        CALL PERIMET(D, THETA2, P2)
        CALL HYDRAD(A2, P2, R2)
        CALL CONVEY(R2, A2, N, K2)

        CALL HALFANG(H4(I), D, THETA3)
        CALL AREA(D, THETA3, A3)
        CALL PERIMET(D, THETA3, P3)
        CALL HYDRAD(A3, P3, R3)
        CALL CONVEY(R3, A3, N, K3)

        CALL GETC3(C3CON, C3COE, H1(I), H4(I), C3)

        CALL GETQ(C3, A3, H1(I), H4(I), G, K2, K3, LEN, QEST(I))

120     CONTINUE
C
C       INITIALIZATION FOR ABSOLUTE SUM
C
        H2H1S = 0.0
        E1SUM = 0.0
        E2SUM = 0.0
        E3SUM = 0.0
C
C       INITIALIZATION FOR ARITHMETIC SUM
C
        H2H1BS = 0.0
        E1BSUM = 0.0
```

```
      E2BSUM = 0.0
      E3BSUM = 0.0

      OPEN(4, FILE=OUTNAME)
      WRITE(4,122)
122   FORMAT(/1X, 110(1H-)/1X, 35X,40H*** FLOW CALCULATION ACROSS CULVERTS ***/)
      WRITE(4,124) D2VSD1
124   FORMAT(1X, 2X,'WHEN ESTIMATING FLOW DIRECTLY USING FLOW EQUATION, DEPTH OF'/
     * 3X, 'WATER AT SECTION 2 VERSUS THAT AT SECTION 1 IS CONSIDERED TO BE: ',
     * F4.2)

      WRITE(4,126) C3CON, C3COE, N
126   FORMAT(1X,2X, 24HDISCHARGE COEFFICIENT = ,F5.2, 3H + , F5.2, 4H * X, 5X,
     * 24HROUGHNESS COEFFICIENT = , F6.4)

      WRITE(4,128) RLIM, FLIM, QACCU
128   FORMAT(1X,2X, 35HITERATION ACCURACY CONTROL: RLIM = , F6.4, 2X, 7HFLIM = ,
     *  F6.4, 2X, 8HQACCU = , F6.4)

      WRITE(4,130)
130   FORMAT(/1X,2X,4HQOBS,1X, 2X,3X,2HHW,1X, 2X,3X,2HTW,1X, 2X,3X,2HH1,1X,
     * 2X,3X,2HH4,1X, 2X,3X,2HH2,1X, 2X,5HH2/H1,
     *  2X,3X,2HDC,1X, 2X,1X,6HQFINAL, 2X,2X,6HERROR1,
     * 2X,2X,4HQEST,1X, 2X,2X,6HERROR2, 2X,2X,6HERROR3)

      WRITE(4,135)
135   FORMAT(1X,7HFT**3/S, 2X,2X,4H(FT), 2X,2X,4H(FT), 2X,2X,4H(FT),
     * 2X,2X,4H(FT), 2X,2X,4H(FT), 2X,5X,
     *  2X,2X,4H(FT), 2X,7HFT**3/S, 2X,8X, 2X,7HFT**3/S,
     *  2X,8X, 2X,8X)

      WRITE(4,*)
C
C     DETERMINE THE CRITICAL DEPTH IN ORDER TO VERIFY THE TYPE OF FLOW
C
      DO 140 I=1, NARRAY
      CALL SEEKDC(D, G, QFINAL(I), RLIM, FLIM, DC(I))
140   CONTINUE

      DO 150 I=1, NARRAY

      H2H1S = H2H1S + ABS(RAH2H1(I))
      H2H1BS = H2H1BS + RAH2H1(I)

      ERROR1(I) = (QFINAL(I) - QOBS(I)) / QOBS(I)
      E1SUM = E1SUM + ABS(ERROR1(I))
      E1BSUM = E1BSUM + ERROR1(I)

      ERROR2(I) = (QEST(I) - QOBS(I)) / QOBS(I)
      E2SUM = E2SUM + ABS(ERROR2(I))
      E2BSUM = E2BSUM + ERROR2(I)

      ERROR3(I) = (QEST(I) - QFINAL(I)) / QFINAL(I)
      E3SUM = E3SUM + ABS(ERROR3(I))
      E3BSUM = E3BSUM + ERROR3(I)

      WRITE(4,200) QOBS(I), HW(I), TW(I), H1(I), H4(I), H2(I), RAH2H1(I),
     *  DC(I), QFINAL(I), ERROR1(I), QEST(I), ERROR2(I), ERROR3(I)

200   FORMAT(1X,F7.3, 2X,F6.2, 2X,F6.2, 2X,F6.2, 2X,F6.2, 2X,F6.2, 2X,F5.2,
     *  2X,F6.2, 2X,F7.2, 2X,F8.2, 2X,F7.2, 2X,F8.2, 2X,F8.2)

150   CONTINUE

      H2H1AVG = H2H1S / FLOAT(NARRAY)
      E1AVG = E1SUM / FLOAT(NARRAY)
      E2AVG = E2SUM / FLOAT(NARRAY)
      E3AVG = E3SUM / FLOAT(NARRAY)

      H2H1BAVG = H2H1BS / FLOAT(NARRAY)
      E1BAVG = E1BSUM / FLOAT(NARRAY)
      E2BAVG = E2BSUM / FLOAT(NARRAY)
      E3BAVG = E3BSUM / FLOAT(NARRAY)

      WRITE(4,210) H2H1AVG, E1AVG, E2AVG, E3AVG
210   FORMAT(/1X, 16HABSOLUTE AVERAGE,7X, 2X,6X, 2X,6X, 2X,6X, 2X,F5.2, 2X,6X,
     *  2X,7X, 2X,F8.2, 2X,7X, 2X,F8.2, 2X,F8.2)

      WRITE(4,215) H2H1BAVG, E1BAVG, E2BAVG, E3BAVG
215   FORMAT(/1X,18HARITHMETIC AVERAGE,5X, 2X,6X, 2X,6X, 2X,6X, 2X,F5.2, 2X,6X,
     *  2X,7X, 2X,F8.2, 2X,7X, 2X,F8.2, 2X,F8.2)
```

```
      CLOSE(4)
      STOP
      END


C
C     FILE NAME: QSOLVE.FOR
C
C     CALCULATE THE CULVERT FLOW BY SOLVING THE ENERGY EQUATION
C
      SUBROUTINE QSOLVE(C3CON, C3COE, H1, H4, G, LEN, D,
     * Z2, N, RLIM, FLIM, QACCU, D2, DEBUG, QFINAL)

      REAL K2, K3, N, LEN, INEL
      LOGICAL DEBUG
C
C     TO START THE ITERATION PROCESS, WE NEED AN INITIAL VALUE OF FLOW Q. BY
C     ASSUMING WATER LEVEL IN SECTION 2 IS THE SAME AS HEAD WATER LEVEL, WE CAN
C     GET SUCH AN INITIAL VALUE OF FLOW Q.
C
C     CALCULATE THETA2
C
      CALL HALFANG(H1 - Z2, D, THETA2)
C
C     CALCULATE A2
C
      CALL AREA(D, THETA2, A2)
C
C     CALCULATE P2
C
      CALL PERIMET(D, THETA2, P2)
C
C     CALCULATE R2
C
      CALL HYDRAD(A2, P2, R2)
C
C     CALCULATE CONVEYANCE K2
C
      CALL CONVEY(R2, A2, N, K2)

      IF (DEBUG) THEN

      WRITE(*,10) A2, P2, R2, K2
10     FORMAT(/4HA2= ,F7.3,3X,
     *  4HP2= ,F7.3,3X, 4HR2= ,F7.3,3X, 4HK2= ,F9.5,3X)

      END IF
C
C
C     CALCULATE THETA3
C
      CALL HALFANG(H4, D, THETA3)
C
C     CALCULATE A3
C
      CALL AREA(D, THETA3, A3)
C
C     CALCULATE P3
C
      CALL PERIMET(D, THETA3, P3)
C
C     CALCULATE R3
C
      CALL HYDRAD(A3, P3, R3)
C
C     CALCULATE CONVEYANCE K3
C
      CALL CONVEY(R3, A3, N, K3)

      IF (DEBUG) THEN

      WRITE(*,15) A3, P3, R3, K3
15     FORMAT(/4HA3= ,F7.3,3X,
     *  4HP3= ,F7.3,3X, 4HR3= ,F7.3,3X, 4HK3= ,F9.5,3X)

      END IF
C
C     CALCULATE DISCHARGE COEFFICIENT
C
      CALL GETC3(C3CON, C3COE, H1, H4, C3)
```

```
C
C       ESTIMATE FLOW Q
C
        CALL GETQ(C3, A3, H1, H4, G, K2, K3, LEN, Q1)

        IF (DEBUG) THEN

        WRITE(*,20) C3, Q1
20       FORMAT(/4HC3= ,F7.3,3X, 4HQ1= ,F7.3,3X)

        END IF
C
C       USE ITERATION TO DETERMINE WATER DEPTH D2
C
        M=0
50       M=M+1
        CALL SEEKD2(D, C3, G, Q1, RLIM, FLIM, H1, H4, Z2, DEBUG, D2)
C
C       UPDATE ALL VALUES IN SECTION 2 USING D2
C
        CALL HALFANG(D2, D, THETA2)

        CALL AREA(D, THETA2, A2)

        CALL PERIMET(D, THETA2, P2)

        CALL HYDRAD(A2, P2, R2)

        CALL CONVEY(R2, A2, N, K2)
C
C       CALCULATE HEAD LOSS DUE TO FRICTION FROM SECTION 2 TO 3
C
        HF23 = Q1 * Q1 * LEN / (K2 * K3)
C
        QNEW = C3 * A3 * SQRT(2.0 * G * (H1 - H4 - HF23))

        IF (DEBUG) THEN

        WRITE(*,80) M, Q1, QNEW, HF23
80       FORMAT(/3HM= ,I2,3X,
     *   4HQ1= ,F7.3,3X, 6HQNEW= ,F7.3,3X, 6HHF23= ,F9.5,3X)

        END IF

        IF (ABS((QNEW - Q1) / QNEW) .LE. QACCU) THEN
C
C         ROOT FOUND
C
          QFINAL = QNEW
C
           WRITE(*,90) M, Q1, QNEW, HF23
90         FORMAT(/18H*** ROOT FOUND ***/3HM= ,I2,3X,
     *     4HQ1= ,F7.3,3X, 6HQNEW= ,F7.3,3X, 6HHF23= ,F9.5,3X)

        ELSE
           IF(M .GT. 50) THEN
C
C            ROOT SEEKING FAILED
C
             WRITE(*,100) M, Q1, QNEW, HF23
100          FORMAT(/31HITERATION NUMBER LIMIT EXCEEDED/3HM= ,I2,3X,
     *       4HQ1= ,F7.3,3X, 6HQNEW= ,F7.3,3X, 6HHF23= ,F9.5,3X)

             STOP
           END IF

          Q1 = 0.5 * (Q1 + QNEW)
          GO TO 50
        END IF

        RETURN
        END


C
C       FILE NAME: SEEKD2.FOR
C
C       SEEK ROOT D2 BY BISECTION METHOD
C
        SUBROUTINE SEEKD2(D, C3, G, QEST, RLIM, FLIM, H1, H4, Z2, DEBUG, D2)
        LOGICAL DEBUG
```

```
C
C       DIVIDE (H1, H4) INTO 10 EQUAL INTERVALS
C
        HAVE = 0.5 * (H1 + H4)
        DELTH = 0.1 * (H1 - H4)
C
C       FIND THE RANGE WHERE THE ROOT LIES
C
        DO 100 I = 1, 5
        XA = HAVE - FLOAT(I) * DELTH
        XB = HAVE + FLOAT(I) * DELTH
C
        CALL HALFANG(XA, D, THETAA)
        CALL AREA(D, THETAA, AA)
        V2A = QEST/AA

        YA = XA + V2A * V2A / (2.0 * G * C3 * C3) - (H1 - Z2)
C
        CALL HALFANG(XB, D, THETAB)
        CALL AREA(D, THETAB, AB)
        V2B = QEST/AB

        YB = XB + V2B * V2B / (2.0 * G * C3 * C3) - (H1 - Z2)
C
C       TEST IF THE ROOT LIES IN THIS RANGE
C
        FABMU = YA * YB
C
C       IF THE FOLLOWING SATISFIES, THEN THE RANGE WHERE ROOT LIES IS FOUND
C
         IF(FABMU.LE.0.0) GO TO 110

         IF(FABMU.GT.0.0 .AND. I.EQ.5) THEN
C
C          THE RANGE WHERE ROOT LIES CAN NOT BE FOUND. ROOT SEEKING FAILS
C
           WRITE(*,105) I, HAVE, XA, YA, XB, YB
105        FORMAT(/33HERROR OCCURS IN SEEKING ROOT (D2)/3HI= ,I2,3X,
     *     6HHAVE= ,F7.3,3X, 4HXA= ,F7.3,3X, 4HYA= ,E12.6,3X,
     *     4HXB= ,F7.3,3X, 4HYB= ,E12.6)
           STOP
         END IF
C
100      CONTINUE
C
C        THE CENTRAL PART OF BISECTION METHOD
C
110      CONTINUE
C
        K=0
130      K=K+1
         XAVE = 0.5 * (XA + XB)
         WIDAB = XB - XA
C
        CALL HALFANG(XAVE, D, THETAM)
        CALL AREA(D, THETAM, AM)
        V2M = QEST/AM
C
        FXAVE = XAVE + V2M * V2M / (2.0 * G * C3 * C3) - (H1 - Z2)
C
        IF (DEBUG) THEN

        WRITE(*,132) K, XA, YA, XB, YB, WIDAB, XAVE, FXAVE
132      FORMAT(/30HOUTPUT FOR TESTING THE PROGRAM/3HK= ,I2,3X,
     *   4HXA= ,F7.3,3X, 4HYA= ,E12.6,3X, 4HXB= ,F7.3,3X,
     *   4HYB= ,E12.6,3X/1X, 7HWIDAB= ,F9.7,3X, 6HXAVE= ,F7.3,3X,
     *  7HFXAVE= ,E12.6)

        END IF

         IF(WIDAB.LT.RLIM .AND. ABS(FXAVE).LT.FLIM) THEN
C
C          PRECISION FOR CONVERGENCE HAS BEEN ACHIEVED. ROOT FOUND
C
           D2 = XAVE
           WRITE(*,135) H1, H4, K, WIDAB, FXAVE, D2
135        FORMAT(/4HH1= ,F7.3,3X, 4HH4= ,F6.4,3X, 3HK= ,I2,3X,
     *     7HWIDAB= ,F9.7,3X, 7HFXAVE= ,E12.6,3X, 4HD2= ,F8.4)

         ELSE IF(WIDAB.GE.RLIM .OR. ABS(FXAVE).GT.FLIM) THEN
C
```

```
C         PRECISION FOR CONVERGENCE HAS NOT BEEN ACHIEVED YET
C
          IF(K .GT. 50) THEN
C
C           ROOT SEEKING FAILS
C
            WRITE(*,140) K, XA, YA, XB, YB, XAVE, FXAVE
140         FORMAT(/31HITERATION NUMBER LIMIT EXCEEDED/3HK= ,I2,3X,
     *      4HXA= ,F7.3,3X, 4HYA= ,E12.6,3X, 4HXB= ,F7.3,3X,
     *      4HYB= ,E12.6,3X, 6HXAVE= ,F7.3,3X, 7HFXAVE= ,E12.6)
            STOP
          END IF
C
         FABMU = YA * FXAVE

          IF(FABMU .LE. 0.0) THEN
C
C           THE ROOT LIES IN THE RANGE [XA, XAVE]
C
            XB = XAVE
            YB = FXAVE
            GO TO 130

          ELSE IF(FABMU .GT. 0.0) THEN
C
C           THE ROOT LIES IN THE RANGE [XAVE, XB]
C
            XA = XAVE
            YA = FXAVE
            GO TO 130
          END IF
        END IF

       RETURN
       END


C
C      FILE NAME: HALFANG.FOR
C
C      CALCULATE THE ANGLE THETA FOR A CIRCULAR CROSS SECTION BASED ON WATER DEPTH
C
       SUBROUTINE HALFANG(DEPTH, D, THETA)
C
       IF (DEPTH .LE. D) THEN
         THETA = ACOS(1.0 - 2.0* DEPTH/D)
       ELSE
         THETA = ACOS(-1.0)
       END IF

        RETURN
        END


C
C      FILE NAME: AREA.FOR
C
C      CALCULATE THE CROSS SECTIONAL AREA OF THE CHANNEL
C
       SUBROUTINE AREA(D, THETA, S)
C
       S = 0.25 * D * D * (THETA - 0.5 * SIN(2.0 * THETA))
       RETURN
       END


C
C      FILE NAME: PERIMET.FOR
C
C      CALCULATE THE WETTED PERIMETER OF THE CHANNEL
C
       SUBROUTINE PERIMET(D, THETA, P)
C
       P = THETA * D
       RETURN
       END


C
C      FILE NAME: WIDTH.FOR
C
```

```
C       CALCULATE THE WIDTH OF THE SECTION AT THE WATER SURFACE OF THE CHANNEL
C
        SUBROUTINE WIDTH(D, THETA, T)
C
        T = D * SIN(THETA)
        RETURN
        END


C
C       FILE NAME: HYDRAD.FOR
C
C       CALCULATE THE HYDRAULIC RADIUS OF A SECTION
C
        SUBROUTINE HYDRAD(S, P, HYDR)
C
        HYDR = S/P
        RETURN
        END


C
C       FILE NAME: CONVEY.FOR
C
C       CALCULATE THE CONVEYANCE OF THE CULVERT AT THE INLET AND OUTLET SECTION
C       (UNIT: FT^3/S)
C
        SUBROUTINE CONVEY(R, A, N, CONV)
        REAL N
C
        CONV = 1.486/N * R**(2.0/3.0) * A
        RETURN
        END


C
C       FILE NAME: GETC3.FOR
C
C       ESTIMATE THE DISCHARGE COEFFICIENT FOR THE FLOW
C
        SUBROUTINE GETC3(C3CON, COEFF, H1, H4, C3)
C
        C3 = C3CON + COEFF * (H1 - H4)
        RETURN
        END


C
C       FILE NAME: GETQ.FOR
C
C       CALCULATE THE CULVERT FLOW USING DISCHARGE EQUATION
C
        SUBROUTINE GETQ(C3, A3, H1, H4, G, K2, K3, LEN, Q)
        REAL K2, K3, LEN
C
        Q = C3 * A3 * SQRT(2.0 * G * (H1 - H4) / (1.0 +
     *      2.0 * G * C3 * C3 * A3 * A3 * LEN / (K2 * K3)))
        RETURN
        END


C
C       FILE NAME: SEEKDC.FOR
C
C       SEEK CRITICAL WATER DEPTH DC BY BISECTION METHOD
C
        SUBROUTINE SEEKDC(D, G, Q, RLIM, FLIM, DC)
C
C       DIVIDE THE POSSIBLE RANGE OF CRITICAL DEPTH INTO 10 EQUAL INTERVALS
C
        HAVE = 0.5 * (0.001 * D + 0.999 * D)
        DELTH = 0.1 * (0.999 * D - 0.001 * D)
C
C       FIND THE RANGE WHERE THE ROOT LIES
C
        DO 100 I = 1, 5
        XA = HAVE - FLOAT(I) * DELTH
        XB = HAVE + FLOAT(I) * DELTH
C
        CALL HALFANG(XA, D, THETAA)
        CALL AREA(D, THETAA, AA)
```

```
      CALL WIDTH(D, THETAA, TA)

      YA = AA**1.5 * SQRT(G/TA) - Q
C
      CALL HALFANG(XB, D, THETAB)
      CALL AREA(D, THETAB, AB)
      CALL WIDTH(D, THETAB, TB)

      YB = AB**1.5 * SQRT(G/TB) - Q
C
C     TEST IF THE ROOT LIES IN THIS RANGE
C
      FABMU = YA * YB
C
C     IF THE FOLLOWING SATISFIES, THEN THE RANGE WHERE ROOT LIES IS FOUND
C
       IF(FABMU.LE.0.0) GO TO 110

       IF(FABMU.GT.0.0 .AND. I.EQ.5) THEN
C
C        THE RANGE WHERE ROOT LIES CAN NOT BE FOUND. ROOT SEEKING FAILS
C
         WRITE(*,105) I, HAVE, XA, YA, XB, YB
105      FORMAT(/33HERROR OCCURS IN SEEKING ROOT (DC)/3HI= ,I2,3X,
     *   6HHAVE= ,F7.3,3X, 4HXA= ,F7.3,3X, 4HYA= ,E12.6,3X,
     *   4HXB= ,F7.3,3X, 4HYB= ,E12.6)
         STOP
       END IF
C
100    CONTINUE
C
C      THE CENTRAL PART OF BISECTION METHOD
C
110    CONTINUE
C
      K=0
130    K=K+1
       XAVE = 0.5 * (XA + XB)
       WIDAB = XB - XA
C
      CALL HALFANG(XAVE, D, THETAM)
      CALL AREA(D, THETAM, AM)
      CALL WIDTH(D, THETAM, TM)
C
      FXAVE = AM**1.5 * SQRT(G/TM) - Q

       IF(WIDAB.LT.RLIM .AND. ABS(FXAVE).LT.FLIM) THEN
C
C        PRECISION FOR CONVERGENCE HAS BEEN ACHIEVED. ROOT FOUND
C
         DC = XAVE
         WRITE(*,135) XA, XB, K, WIDAB, FXAVE, DC
135      FORMAT(/4HXA= ,F7.3,3X, 4HXB= ,F6.4,3X, 3HK= ,I2,3X,
     *   7HWIDAB= ,F9.7,3X, 7HFXAVE= ,E12.6,3X, 4HDC= ,F8.4)

       ELSE IF(WIDAB.GE.RLIM .OR. ABS(FXAVE).GT.FLIM) THEN
C
C        PRECISION FOR CONVERGENCE HAS NOT BEEN ACHIEVED YET
C
         IF(K .GT. 50) THEN
C
C          ROOT SEEKING FAILS
C
           WRITE(*,140) K, XA, YA, XB, YB, XAVE, FXAVE
140        FORMAT(/31HITERATION NUMBER LIMIT EXCEEDED/3HK= ,I2,3X,
     *     4HXA= ,F7.3,3X, 4HYA= ,E12.6,3X, 4HXB= ,F7.3,3X,
     *     4HYB= ,E12.6,3X, 6HXAVE= ,F7.3,3X, 7HFXAVE= ,E12.6)
           STOP
         END IF
C
        FABMU = YA * FXAVE

         IF(FABMU .LE. 0.0) THEN
C
C          THE ROOT LIES IN THE RANGE [XA, XAVE]
C
           XB = XAVE
           YB = FXAVE
           GO TO 130

         ELSE IF(FABMU .GT. 0.0) THEN
```

```
C
C           THE ROOT LIES IN THE RANGE [XAVE, XB]
C
            XA = XAVE
            YA = FXAVE
            GO TO 130
          END IF
        END IF

       RETURN
       END
```

APPENDIX II – TYPE 3 FLOW CALCULATION SOURCE CODE FOR ITERATION BASED ON HEAD

```
C
C       FILE NAME: CULFLOW.FOR
C       SIMULATE TYPE 3 FLOW (OPEN CHANNEL FLOW) ACROSS CULVERT USING AN
C       ITERATION METHOD BASED ON CONVERGENCE OF HEAD
C
C       THIS PROGRAM CALCULATES THE FLOW ACROSS CULVERT USING THE STANDARD STEP
C       METHOD
C
        PARAMETER(NA1=200)
        DIMENSION QOBS(NA1), HW(NA1), TW(NA1), QFINAL(NA1)
        DIMENSION H1(NA1), H4(NA1), H2(NA1), DC(NA1)
        DIMENSION ERROR1(NA1), QEST(NA1), ERROR2(NA1), ERROR3(NA1)
        DIMENSION RAH2H1(NA1)

        CHARACTER OUTNAME*10
        REAL K2, K3, N, LEN, INEL
        LOGICAL DEBUG
C
C       ***** VARIABLES *****
C
C       NA1: ARRAY SIZE
C       HW: HEAD WATER LEVEL (FT)
C       TW: TAIL WATER LEVEL (FT)
C       DC: MAXIMUM DEPTH OF WATER IN THE CRITICAL FLOW SECTION (FT)
C       INEL: CULVERT INLET INVERT ELEVATION (FT)
C       OUTEL: CULVERT OUTLET INVERT ELEVATION (FT)
C       Z2: DIFFERENCE BETWEEN INLET INVERT AND OUTLET INVERT ELEVATION
C           Z2 = INEL - OUTEL (FT)
C       H1: HEAD WATER DEPTH ABOVE OUTLET INVERT (FT)
C       H4: TAIL WATER DEPTH ABOVE OUTLET INVERT (FT)
C       H2: WATER LEVEL OF SECTION 2 ABOVE OUTLET INVERT (FT)
C       D: DIAMETER OF THE CULVERT (FT)
c       LEN: LENGTH OF THE CULVERT (FT)
C       N: MANNING ROUGHNESS OF COEFFICIENT (FT**(1/6))
C       G: ACCELERATION OF GRAVITY (G = 32.18 FT/S**2)
C       C3: DISCHARGE COEFFICIENT FOR TYPE 3 FLOW
C
C       THETA2: HALF OF THE CENTRAL ANGLE OF THE CIRCULAR SEGMENT INTERCEPTED
C               BY THE FREE WATER SURFACE IN A PARTIALLY FILLED CULVERT (RAD)
C       A2: AREA OF SECTION OF FLOW AT SECTION 2 (FT**2)
C       P2: WETTED PERIMETER OF CROSS SECTION OF FLOW AT SECTION 2 (FT)
C       R2: HYDRAULIC RADIUS AT SECTION 2 (FT)
C       K2: CONVEYANCE OF SECTION 2 (FT**3/S)
C       D2: DEPTH OF WATER ABOVE INLET INVERT (FT)
C       THETA3: HALF OF THE CENTRAL ANGLE OF THE CIRCULAR SEGMENT INTERCEPTED
C               BY THE FREE WATER SURFACE FOR SECTION 3 (RAD)
C       A3: AREA OF SECTION OF FLOW AT SECTION 3 (FT**2)
C       P3: WETTED PERIMETER OF CROSS SECTION OF FLOW AT SECTION 3 (FT)
C       R3: HYDRAULIC RADIUS AT SECTION 3 (FT)
C       K3: CONVEYANCE OF SECTION 3 (FT**3/S)
C
C       RLIM: ALLOWED ERROR RANGE OF ROOT (D2, DC) WHEN SEEKING IT BY
C             BISECTION METHOD
C       FLIM: ALLOWED MAXIMUM ABSOLUTE VALUE OF THE ROOT FUNCTION. WHEN ABSOLUTE
C             VALUE OF THE ROOT FUNCTION IS LESS THAN FLIM, IT IS REGARDED AS
C             ZERO
C       D2VSD1: ESTIMATED RATIO OF DEPTH OF WATER AT SECTION 2 (D2) TO THAT AT
C               SECTION 1 (D1). THE VALUE IS USED TO APPROXIMATELY CALCULATE FLOW
C               USING TYPE 3 FLOW EQUATION
C       OUTNAME: OUTPUT DATA FILE NAME
C       DEBUG: LOGICAL VARIABLE TO CONTROL IF ANY INTERMEDIATE SIMULATION RESULTS
C              ARE TO BE PRINTED
C
C       QOBS: FLOW MEASURED FROM FIELD
C       QFINAL: FLOW CALCULATED BY SOLVING THE ENERGY EQUATION
C       ERROR1: RELATIVE DIFFERENCE OF QFINAL VERSUS QOBS
C       QEST: FLOW CALCULATED USING ASSUMED DEPTH OF WATER AT SECTION 2
C       ERROR2: RELATIVE DIFFERENCE OF QEST VERSUS QOBS
C       ERROR3: RELATIVE DIFFERENCE OF QEST VERSUS QFINAL
C
C       ***** SUBROUTINES *****
C
C       HALFANG: CALCULATING HALF OF THE CENTRAL ANGLE OF THE CIRCULAR SEGMENT
C                INTERCEPTED BY THE FREE WATER SURFACE IN A PARTIALLY FILLED CULVERT
C       AREA: CALCULATING AREA OF SECTION OF FLOW
```

```
C       PERIMET: CALCULATING WETTED PERIMETER OF CROSS SECTION OF FLOW
C       WIDTH: CALCULATING WIDTH OF THE SECTION AT THE WATER SURFACE
C       HYDRAD: CALCULATING HYDRAULIC RADIUS
C       CONVEY: CALCULATING CONVEYANCE OF A SECTION
C       GETC3: CALCULATING THE DISCHARGE COEFFICIENT FOR THE FLOW
C       GETQ: CALCULATING CULVERT FLOW USING THE DISCHARGE EQUATION FOR TYPE 3 FLOW
C       D2SOLVE: DETERMINING DEPTH OF WATER ABOVE INLET INVERT D2 AND FLOW THROUGH
C               CULVERT BY SOLVING ENERGY EQUATION BETWEEN SECTION 1 AND 2 GIVEN
C               STAGE AT SECTION 1
C       SEEKDC: DETERMINING MAXIMUM DEPTH OF WATER IN THE CRITICAL FLOW SECTION
C              BY SOLVING THE DISCHARGE EQUATION
C
C       READ NECESSARY DATA FROM A DATA FILE
C
        OPEN(3, FILE='DATA2.TXT')
        READ(3,*) C3CON, C3COE, G
        READ(3,*) LEN, D, INEL, OUTEL, N
        READ(3,*) RLIM, FLIM
        READ(3,*) D2VSD1
        READ(3,*) OUTNAME, DEBUG
        READ(3,*) NARRAY
        READ(3,*) (QOBS(I), HW(I), TW(I), I=1,NARRAY)
        CLOSE(3)

        Z2 = INEL - OUTEL

        DO 100 I=1, NARRAY

        H1(I) = HW(I) - OUTEL
        H4(I) = TW(I) - OUTEL

100     CONTINUE

        DO 120 I=1, NARRAY
C
C       ASSUMING WATER LEVEL IN SECTION 2 (H2) IS A FIXED RATIO OF HEAD WATER LEVEL,
C       ESTIMATE FLOW USING ENERGY EQUATION FOR TYPE 3 FLOW.
C
        CALL HALFANG(D2VSD1 * H1(I) - Z2, D, THETA2)
        CALL AREA(D, THETA2, A2)
        CALL PERIMET(D, THETA2, P2)
        CALL HYDRAD(A2, P2, R2)
        CALL CONVEY(R2, A2, N, K2)

        CALL HALFANG(H4(I), D, THETA3)
        CALL AREA(D, THETA3, A3)
        CALL PERIMET(D, THETA3, P3)
        CALL HYDRAD(A3, P3, R3)
        CALL CONVEY(R3, A3, N, K3)

        CALL GETC3(C3CON, C3COE, H1(I), H4(I), C3)

        CALL GETQ(C3, A3, H1(I), H4(I), G, K2, K3, LEN, QEST(I))
C
C       WITHOUT IMPOSING ANY ASSUMPTION ON H2, DETERMINE H2 AND FLOW BY SOLVING
C       THE ENERGY EQUATION ITERATIVELY
C
        CALL D2SOLVE(D, LEN, C3, G, N, RLIM, FLIM, H1(I), H4(I), Z2, D2,
     *               DEBUG, QFINAL(I))
        H2(I) = D2 + Z2
        RAH2H1(I) = H2(I)/H1(I)

120     CONTINUE
C
C       INITIALIZATION FOR ABSOLUTE SUM
C
        H2H1S = 0.0
        E1SUM = 0.0
        E2SUM = 0.0
        E3SUM = 0.0
C
C       INITIALIZATION FOR ARITHMETIC SUM
C
        H2H1BS = 0.0
        E1BSUM = 0.0
        E2BSUM = 0.0
        E3BSUM = 0.0

        OPEN(4, FILE=OUTNAME)
        WRITE(4,122)
122     FORMAT(/1X, 110(1H-)/1X, 35X,40H*** FLOW CALCULATION ACROSS CULVERTS ***/)
```

```
      WRITE(4,124) D2VSD1
124   FORMAT(1X, 2X,'WHEN ESTIMATING FLOW DIRECTLY USING FLOW EQUATION, DEPTH OF'/
     * 3X, 'WATER AT SECTION 2 VERSUS THAT AT SECTION 1 IS CONSIDERED TO BE: ',
     * F4.2)

      WRITE(4,126) C3CON, C3COE, N
126   FORMAT(1X,2X, 24HDISCHARGE COEFFICIENT = ,F5.2, 3H + , F5.2, 4H * X, 5X,
     * 24HROUGHNESS COEFFICIENT = , F6.4)

      WRITE(4,128) RLIM, FLIM
128   FORMAT(1X,2X, 35HITERATION ACCURACY CONTROL: RLIM = , F6.4, 2X, 7HFLIM = ,
     *  F6.4)

      WRITE(4,130)
130   FORMAT(/1X,2X,4HQOBS,1X, 1X,3X,2HHW,1X, 1X,3X,2HTW,1X, 1X,3X,2HH1,1X,
     * 1X,3X,2HH4,1X, 1X,3X,2HH2,1X, 1X,5HH2/H1,
     *  1X,3X,2HDC,1X, 1X,1X,6HQFINAL, 1X,1X,6HERROR1,1X,
     * 1X,2X,4HQEST,1X, 1X,1X,6HERROR2,1X, 1X,1X,6HERROR3,1X)

      WRITE(4,135)
135   FORMAT(1X,7HFT**3/S, 1X,2X,4H(FT), 1X,2X,4H(FT), 1X,2X,4H(FT),
     * 1X,2X,4H(FT), 1X,2X,4H(FT), 1X,5X,
     *  1X,2X,4H(FT), 1X,7HFT**3/S, 1X,8X, 1X,7HFT**3/S,
     *  1X,8X, 1X,8X)

      WRITE(4,*)
C
C     DETERMINE THE CRITICAL DEPTH IN ORDER TO VERIFY THE TYPE OF FLOW
C
      DO 140 I=1, NARRAY
      CALL SEEKDC(D, G, QFINAL(I), RLIM, FLIM, DC(I))
140   CONTINUE

      DO 150 I=1, NARRAY

      H2H1S = H2H1S + ABS(RAH2H1(I))
      H2H1BS = H2H1BS + RAH2H1(I)

      ERROR1(I) = (QFINAL(I) - QOBS(I)) / QOBS(I)
      E1SUM = E1SUM + ABS(ERROR1(I))
      E1BSUM = E1BSUM + ERROR1(I)

      ERROR2(I) = (QEST(I) - QOBS(I)) / QOBS(I)
      E2SUM = E2SUM + ABS(ERROR2(I))
      E2BSUM = E2BSUM + ERROR2(I)

      ERROR3(I) = (QEST(I) - QFINAL(I)) / QFINAL(I)
      E3SUM = E3SUM + ABS(ERROR3(I))
      E3BSUM = E3BSUM + ERROR3(I)

      WRITE(4,200) QOBS(I), HW(I), TW(I), H1(I), H4(I), H2(I), RAH2H1(I),
     *  DC(I), QFINAL(I), ERROR1(I), QEST(I), ERROR2(I), ERROR3(I)

200   FORMAT(1X,F7.2, 1X,F6.2, 1X,F6.2, 1X,F6.2, 1X,F6.2, 1X,F6.2, 1X,F5.2,
     *  1X,F6.2, 1X,F7.2, 1X,F7.2,1X, 1X,F7.2, 1X,F7.2,1X, 1X,F7.2,1X)

150   CONTINUE

      H2H1AVG = H2H1S / FLOAT(NARRAY)
      E1AVG = E1SUM / FLOAT(NARRAY)
      E2AVG = E2SUM / FLOAT(NARRAY)
      E3AVG = E3SUM / FLOAT(NARRAY)

      H2H1BAVG = H2H1BS / FLOAT(NARRAY)
      E1BAVG = E1BSUM / FLOAT(NARRAY)
      E2BAVG = E2BSUM / FLOAT(NARRAY)
      E3BAVG = E3BSUM / FLOAT(NARRAY)

      WRITE(4,210) H2H1AVG, E1AVG, E2AVG, E3AVG
210   FORMAT(/1X, 16HABSOLUTE AVERAGE,5X, 1X,6X, 1X,6X, 1X,6X, 1X,F5.2, 1X,6X,
     *  1X,7X, 1X,F7.2,1X, 1X,7X, 1X,F7.2,1X, 1X,F7.2,1X)

      WRITE(4,215) H2H1BAVG, E1BAVG, E2BAVG, E3BAVG
215   FORMAT(/1X,18HARITHMETIC AVERAGE,3X, 1X,6X, 1X,6X, 1X,6X, 1X,F5.2, 1X,6X,
     *  1X,7X, 1X,F7.2,1X, 1X,7X, 1X,F7.2,1X, 1X,F7.2,1X)

      CLOSE(4)
      STOP
      END
```

```
C
C       FILE NAME: D2SOLVE.FOR
C
C       SEEK ROOT D2 AND FLOW Q ALTOGETHER BY BISECTION METHOD
C
        SUBROUTINE D2SOLVE(D, LEN, C3, G, N, RLIM, FLIM, H1, H4, Z2, D2,
     *                     DEBUG, QFINAL)

        REAL K2, K3, N, LEN
        LOGICAL DEBUG

C
C       SET UP AN INITIAL VALUE AND INCREMENT TO SEARCH THE ROOT RANGE
C
        D2AVE = 0.85 * (H1 - Z2)
        D2DELT = 0.05 * (H1 - Z2)

        CALL HALFANG(H4, D, THETA3)
        CALL AREA(D, THETA3, A3)
        CALL PERIMET(D, THETA3, P3)
        CALL HYDRAD(A3, P3, R3)
        CALL CONVEY(R3, A3, N, K3)
C
C       FIND THE RANGE WHERE THE ROOT LIES
C
        DO 100 I = 1, 5
        XA = D2AVE - FLOAT(I) * D2DELT
        XB = D2AVE + FLOAT(I) * D2DELT

        CALL HALFANG(XA, D, THETAA)
        CALL AREA(D, THETAA, AA)
        CALL PERIMET(D, THETAA, PA)
        CALL HYDRAD(AA, PA, RA)
        CALL CONVEY(RA, AA, N, RKA)

        CALL GETQ(C3, A3, H1, H4, G, RKA, K3, LEN, QA)
        V2A = QA/AA

        YA = XA + V2A * V2A / (2.0 * G * C3 * C3) - (H1 - Z2)

        CALL HALFANG(XB, D, THETAB)
        CALL AREA(D, THETAB, AB)
        CALL PERIMET(D, THETAB, PB)
        CALL HYDRAD(AB, PB, RB)
        CALL CONVEY(RB, AB, N, RKB)

        CALL GETQ(C3, A3, H1, H4, G, RKB, K3, LEN, QB)
        V2B = QB/AB

        YB = XB + V2B * V2B / (2.0 * G * C3 * C3) - (H1 - Z2)
C
C       TEST IF THE ROOT LIES IN THIS RANGE
C
        FABMU = YA * YB
C
C       IF THE FOLLOWING SATISFIES, THEN THE RANGE WHERE ROOT LIES IS FOUND
C
         IF(FABMU.LE.0.0) GO TO 110

         IF(FABMU.GT.0.0 .AND. I.EQ.5) THEN
C
C          THE RANGE WHERE ROOT LIES CAN NOT BE FOUND. ROOT SEEKING FAILS
C
           WRITE(*,105) I, D2AVE, XA, YA, XB, YB
105        FORMAT(/33HERROR OCCURS IN SEEKING ROOT (D2)/3HI= ,I2,3X,
     *     7HD2AVE= ,F7.3,3X, 4HXA= ,F7.3,3X, 4HYA= ,E12.6,3X,
     *     4HXB= ,F7.3,3X, 4HYB= ,E12.6)
           STOP
         END IF
C
100      CONTINUE
C
C        THE CENTRAL PART OF BISECTION METHOD
C
110      CONTINUE
C
        K=0
130      K=K+1
         XAVE = 0.5 * (XA + XB)
         WIDAB = XB - XA
C
```

```
      CALL HALFANG(XAVE, D, THETAM)
      CALL AREA(D, THETAM, AM)
      CALL PERIMET(D, THETAM, PM)
      CALL HYDRAD(AM, PM, RM)
      CALL CONVEY(RM, AM, N, RKM)

      CALL GETQ(C3, A3, H1, H4, G, RKM, K3, LEN, QM)
      V2M = QM/AM
C
      FXAVE = XAVE + V2M * V2M / (2.0 * G * C3 * C3) - (H1 - Z2)
C
      IF (DEBUG) THEN

      WRITE(*,132) K, XA, YA, XB, YB, WIDAB, XAVE, FXAVE
132    FORMAT(/30HOUTPUT FOR TESTING THE PROGRAM/3HK= ,I2,3X,
     *  4HXA= ,F7.3,3X, 4HYA= ,E12.6,3X, 4HXB= ,F7.3,3X,
     *  4HYB= ,E12.6,3X/1X, 7HWIDAB= ,F9.7,3X, 6HXAVE= ,F7.3,3X,
     * 7HFXAVE= ,E12.6)

      END IF

       IF(WIDAB.LT.RLIM .AND. ABS(FXAVE).LT.FLIM) THEN
C
C        PRECISION FOR CONVERGENCE HAS BEEN ACHIEVED. ROOT FOUND
C
         D2 = XAVE
        QFINAL = QM

         WRITE(*,135) H1, H4, K, WIDAB, FXAVE, D2
135      FORMAT(/4HH1= ,F7.3,3X, 4HH4= ,F6.4,3X, 3HK= ,I2,3X,
     *   7HWIDAB= ,F9.7,3X, 7HFXAVE= ,E12.6,3X, 4HD2= ,F8.4)

       ELSE IF(WIDAB.GE.RLIM .OR. ABS(FXAVE).GT.FLIM) THEN
C
C        PRECISION FOR CONVERGENCE HAS NOT BEEN ACHIEVED YET
C
         IF(K .GT. 50) THEN
C
C          ROOT SEEKING FAILS
C
           WRITE(*,140) K, XA, YA, XB, YB, XAVE, FXAVE
140        FORMAT(/31HITERATION NUMBER LIMIT EXCEEDED/3HK= ,I2,3X,
     *     4HXA= ,F7.3,3X, 4HYA= ,E12.6,3X, 4HXB= ,F7.3,3X,
     *     4HYB= ,E12.6,3X, 6HXAVE= ,F7.3,3X, 7HFXAVE= ,E12.6)
           STOP
         END IF
C
        FABMU = YA * FXAVE

         IF(FABMU .LE. 0.0) THEN
C
C          THE ROOT LIES IN THE RANGE [XA, XAVE]
C
           XB = XAVE
           YB = FXAVE
           GO TO 130

         ELSE IF(FABMU .GT. 0.0) THEN
C
C          THE ROOT LIES IN THE RANGE [XAVE, XB]
C
           XA = XAVE
           YA = FXAVE
           GO TO 130
         END IF
       END IF

      RETURN
      END


C
C     FILE NAME: HALFANG.FOR
C
C     CALCULATE THE ANGLE THETA FOR A CIRCULAR CROSS SECTION BASED ON WATER DEPTH
C
      SUBROUTINE HALFANG(DEPTH, D, THETA)
C
      IF (DEPTH .LE. D) THEN
        THETA = ACOS(1.0 - 2.0* DEPTH/D)
      ELSE
```

```
          THETA = ACOS(-1.0)
        END IF

        RETURN
        END

C
C       FILE NAME: AREA.FOR
C
C       CALCULATE THE CROSS SECTIONAL AREA OF THE CHANNEL
C
        SUBROUTINE AREA(D, THETA, S)
C
        S = 0.25 * D * D * (THETA - 0.5 * SIN(2.0 * THETA))
        RETURN
        END

C
C       FILE NAME: PERIMET.FOR
C
C       CALCULATE THE WETTED PERIMETER OF THE CHANNEL
C
        SUBROUTINE PERIMET(D, THETA, P)
C
        P = THETA * D
        RETURN
        END

C
C       FILE NAME: WIDTH.FOR
C
C       CALCULATE THE WIDTH OF THE SECTION AT THE WATER SURFACE OF THE CHANNEL
C
        SUBROUTINE WIDTH(D, THETA, T)
C
        T = D * SIN(THETA)
        RETURN
        END

C
C       FILE NAME: HYDRAD.FOR
C
C       CALCULATE THE HYDRAULIC RADIUS OF A SECTION
C
        SUBROUTINE HYDRAD(S, P, HYDR)
C
        HYDR = S/P
        RETURN
        END

C
C       FILE NAME: CONVEY.FOR
C
C       CALCULATE THE CONVEYANCE OF THE CULVERT AT THE INLET AND OUTLET SECTION
C       (UNIT: FT^3/S)
C
        SUBROUTINE CONVEY(R, A, N, CONV)
        REAL N
C
        CONV = 1.486/N * R**(2.0/3.0) * A
        RETURN
        END

C
C       FILE NAME: GETC3.FOR
C
C       ESTIMATE THE DISCHARGE COEFFICIENT FOR THE FLOW
C
        SUBROUTINE GETC3(C3CON, COEFF, H1, H4, C3)
C
        C3 = C3CON + COEFF * (H1 - H4)
        RETURN
        END
```

```
C
C       FILE NAME: GETQ.FOR
C
C       CALCULATE THE CULVERT FLOW USING DISCHARGE EQUATION
C
        SUBROUTINE GETQ(C3, A3, H1, H4, G, K2, K3, LEN, Q)
        REAL K2, K3, LEN
C
        Q = C3 * A3 * SQRT(2.0 * G * (H1 - H4) / (1.0 +
     *      2.0 * G * C3 * C3 * A3 * A3 * LEN / (K2 * K3)))
        RETURN
        END


C
C       FILE NAME: SEEKDC.FOR
C
C       SEEK CRITICAL WATER DEPTH DC BY BISECTION METHOD
C
        SUBROUTINE SEEKDC(D, G, Q, RLIM, FLIM, DC)
C
C       DIVIDE THE POSSIBLE RANGE OF CRITICAL DEPTH INTO 10 EQUAL INTERVALS
C
        HAVE = 0.5 * (0.001 * D + 0.999 * D)
        DELTH = 0.1 * (0.999 * D - 0.001 * D)
C
C       FIND THE RANGE WHERE THE ROOT LIES
C
        DO 100 I = 1, 5
        XA = HAVE - FLOAT(I) * DELTH
        XB = HAVE + FLOAT(I) * DELTH
C
        CALL HALFANG(XA, D, THETAA)
        CALL AREA(D, THETAA, AA)
        CALL WIDTH(D, THETAA, TA)

        YA = AA**1.5 * SQRT(G/TA) - Q
C
        CALL HALFANG(XB, D, THETAB)
        CALL AREA(D, THETAB, AB)
        CALL WIDTH(D, THETAB, TB)

        YB = AB**1.5 * SQRT(G/TB) - Q
C
C       TEST IF THE ROOT LIES IN THIS RANGE
C
        FABMU = YA * YB
C
C       IF THE FOLLOWING SATISFIES, THEN THE RANGE WHERE ROOT LIES IS FOUND
C
         IF(FABMU.LE.0.0) GO TO 110

         IF(FABMU.GT.0.0 .AND. I.EQ.5) THEN
C
C          THE RANGE WHERE ROOT LIES CAN NOT BE FOUND. ROOT SEEKING FAILS
C
           WRITE(*,105) I, HAVE, XA, YA, XB, YB
105        FORMAT(/33HERROR OCCURS IN SEEKING ROOT (DC)/3HI= ,I2,3X,
     *     6HHAVE= ,F7.3,3X, 4HXA= ,F7.3,3X, 4HYA= ,E12.6,3X,
     *     4HXB= ,F7.3,3X, 4HYB= ,E12.6)
           STOP
         END IF
C
100      CONTINUE
C
C        THE CENTRAL PART OF BISECTION METHOD
C
110      CONTINUE
C
        K=0
130      K=K+1
         XAVE = 0.5 * (XA + XB)
         WIDAB = XB - XA
C
        CALL HALFANG(XAVE, D, THETAM)
        CALL AREA(D, THETAM, AM)
        CALL WIDTH(D, THETAM, TM)
C
        FXAVE = AM**1.5 * SQRT(G/TM) - Q

         IF(WIDAB.LT.RLIM .AND. ABS(FXAVE).LT.FLIM) THEN
```

```
C
C         PRECISION FOR CONVERGENCE HAS BEEN ACHIEVED. ROOT FOUND
C
          DC = XAVE
          WRITE(*,135) XA, XB, K, WIDAB, FXAVE, DC
135       FORMAT(/4HXA= ,F7.3,3X, 4HXB= ,F6.4,3X, 3HK= ,I2,3X,
     *    7HWIDAB= ,F9.7,3X, 7HFXAVE= ,E12.6,3X, 4HDC= ,F8.4)

        ELSE IF(WIDAB.GE.RLIM .OR. ABS(FXAVE).GT.FLIM) THEN
C
C         PRECISION FOR CONVERGENCE HAS NOT BEEN ACHIEVED YET
C
          IF(K .GT. 50) THEN
C
C           ROOT SEEKING FAILS
C
            WRITE(*,140) K, XA, YA, XB, YB, XAVE, FXAVE
140         FORMAT(/31HITERATION NUMBER LIMIT EXCEEDED/3HK= ,I2,3X,
     *      4HXA= ,F7.3,3X, 4HYA= ,E12.6,3X, 4HXB= ,F7.3,3X,
     *      4HYB= ,E12.6,3X, 6HXAVE= ,F7.3,3X, 7HFXAVE= ,E12.6)
            STOP
          END IF
C
         FABMU = YA * FXAVE

          IF(FABMU .LE. 0.0) THEN
C
C           THE ROOT LIES IN THE RANGE [XA, XAVE]
C
            XB = XAVE
            YB = FXAVE
            GO TO 130

          ELSE IF(FABMU .GT. 0.0) THEN
C
C           THE ROOT LIES IN THE RANGE [XAVE, XB]
C
            XA = XAVE
            YA = FXAVE
            GO TO 130
          END IF
        END IF

       RETURN
       END
```

APPENDIX III – TYPE 4 FLOW CALCULATION SOURCE CODE

```
C
C       FILE NAME: CULTYPE4.FOR
C       SIMULATE TYPE 4 FLOW (FULL PIPE FLOW) ACROSS CULVERT
C
C
        PARAMETER(NA1=200)
        DIMENSION QOBS(NA1), HW(NA1), TW(NA1), QFINAL(NA1)
        DIMENSION H1(NA1), H4(NA1)
        DIMENSION ERROR1(NA1), QEST(NA1)

        CHARACTER OUTNAME*10
        REAL K2, K3, N, LEN, INEL
C
C       ***** VARIABLES *****
C
C       NA1: ARRAY SIZE
C       HW: HEAD WATER LEVEL (FT)
C       TW: TAIL WATER LEVEL (FT)
C       INEL: CULVERT INLET INVERT ELEVATION (FT)
C       OUTEL: CULVERT OUTLET INVERT ELEVATION (FT)
C       Z2: DIFFERENCE BETWEEN INLET INVERT AND OUTLET INVERT ELEVATION
C           Z2 = INEL - OUTEL (FT)
C       H1: HEAD WATER DEPTH ABOVE OUTLET INVERT (FT)
C       H4: TAIL WATER DEPTH ABOVE OUTLET INVERT (FT)
C       D: DIAMETER OF THE CULVERT (FT)
c       LEN: LENGTH OF THE CULVERT (FT)
C       N: MANNING ROUGHNESS OF COEFFICIENT (FT**(1/6))
C       G: ACCELERATION OF GRAVITY (G = 32.18 FT/S**2)
C       C4: DISCHARGE COEFFICIENT FOR TYPE 4 FLOW
C
C       THETA2: HALF OF THE CENTRAL ANGLE OF THE CIRCULAR SEGMENT INTERCEPTED
C               BY THE FREE WATER SURFACE IN A PARTIALLY FILLED CULVERT (RAD)
C       A2: AREA OF SECTION OF FLOW AT SECTION 2 (FT**2)
C       P2: WETTED PERIMETER OF CROSS SECTION OF FLOW AT SECTION 2 (FT)
C       R2: HYDRAULIC RADIUS AT SECTION 2 (FT)
C       K2: CONVEYANCE OF SECTION 2 (FT**3/S)
C       D2: DEPTH OF WATER ABOVE INLET INVERT (FT)
C       THETA3: HALF OF THE CENTRAL ANGLE OF THE CIRCULAR SEGMENT INTERCEPTED
C               BY THE FREE WATER SURFACE FOR SECTION 3 (RAD)
C       A3: AREA OF SECTION OF FLOW AT SECTION 3 (FT**2)
C       P3: WETTED PERIMETER OF CROSS SECTION OF FLOW AT SECTION 3 (FT)
C       R3: HYDRAULIC RADIUS AT SECTION 3 (FT)
C       K3: CONVEYANCE OF SECTION 3 (FT**3/S)
C
C       OUTNAME: OUTPUT DATA FILE NAME
C
C       QOBS: FLOW MEASURED FROM FIELD
C       QFINAL: FLOW CALCULATED BY SOLVING THE ENERGY EQUATION
C       ERROR1: RELATIVE DIFFERENCE OF QFINAL VERSUS QOBS
C       QEST: FLOW CALCULATED USING ASSUMED DEPTH OF WATER AT SECTION 2

C
C       ***** SUBROUTINES *****
C
C       HALFANG: CALCULATING HALF OF THE CENTRAL ANGLE OF THE CIRCULAR SEGMENT
C                INTERCEPTED BY THE FREE WATER SURFACE IN A PARTIALLY FILLED CULVERT
C       AREA: CALCULATING AREA OF SECTION OF FLOW
C       PERIMET: CALCULATING WETTED PERIMETER OF CROSS SECTION OF FLOW
C       WIDTH: CALCULATING WIDTH OF THE SECTION AT THE WATER SURFACE
C       HYDRAD: CALCULATING HYDRAULIC RADIUS
C       CONVEY: CALCULATING CONVEYANCE OF A SECTION
C       GETC4: CALCULATING THE DISCHARGE COEFFICIENT FOR THE FLOW
C       GETQ: CALCULATING CULVERT FLOW USING THE DISCHARGE EQUATION FOR TYPE 4 FLOW
C
C       READ NECESSARY DATA FROM A DATA FILE
C
        OPEN(3, FILE='DATA_T4.TXT')
        READ(3,*) C4CON, C4COE, G
        READ(3,*) LEN, D, INEL, OUTEL, N
        READ(3,*) OUTNAME
        READ(3,*) NARRAY
        READ(3,*) (QOBS(I), HW(I), TW(I), I=1,NARRAY)
        CLOSE(3)

        Z2 = INEL - OUTEL

        DO 100 I=1, NARRAY
```

```
      H1(I) = HW(I) - OUTEL
      H4(I) = TW(I) - OUTEL

100   CONTINUE

      DO 120 I=1, NARRAY
C
C     ASSUMING WATER LEVEL IN SECTION 2 (H2) IS THE SAME AS HEAD WATER LEVEL (H1).
C
      CALL HALFANG(H1(I) - Z2, D, THETA2)
      CALL AREA(D, THETA2, A2)
      CALL PERIMET(D, THETA2, P2)
      CALL HYDRAD(A2, P2, R2)
      CALL CONVEY(R2, A2, N, K2)

      CALL HALFANG(H4(I), D, THETA3)
      CALL AREA(D, THETA3, A3)
      CALL PERIMET(D, THETA3, P3)
      CALL HYDRAD(A3, P3, R3)
      CALL CONVEY(R3, A3, N, K3)

      CALL GETC4(C4CON, C4COE, H1(I), H4(I), C4)

      CALL GETQ(C4, A3, H1(I), H4(I), G, K2, K3, LEN, QFINAL(I))

120   CONTINUE
C
C     INITIALIZATION FOR ABSOLUTE SUM
C
      E1SUM = 0.0
C
C     INITIALIZATION FOR ARITHMETIC SUM
C
      E1BSUM = 0.0

      OPEN(4, FILE=OUTNAME)
      WRITE(4,122)
122   FORMAT(/1X, 110(1H-)/1X, 35X,40H*** FLOW CALCULATION ACROSS CULVERTS ***/)

      WRITE(4,126) C4CON, C4COE, N
126   FORMAT(1X,2X, 24HDISCHARGE COEFFICIENT = ,F5.2, 3H + , F5.2, 4H * X, 5X,
     * 24HROUGHNESS COEFFICIENT = , F6.4)

      WRITE(4,130)
130   FORMAT(/1X,2X,4HQOBS,1X, 1X,3X,2HHW,1X, 1X,3X,2HTW,1X, 1X,3X,2HH1,1X,
     * 1X,3X,2HH4,1X,
     *  1X,1X,6HQFINAL, 1X,1X,6HERROR1,1X)

      WRITE(4,135)
135   FORMAT(1X,7HFT**3/S, 1X,2X,4H(FT), 1X,2X,4H(FT), 1X,2X,4H(FT),
     * 1X,2X,4H(FT), 1X,7HFT**3/S, 1X,8X)

      WRITE(4,*)

      DO 150 I=1, NARRAY

      ERROR1(I) = (QFINAL(I) - QOBS(I)) / QOBS(I)
      E1SUM = E1SUM + ABS(ERROR1(I))
      E1BSUM = E1BSUM + ERROR1(I)

      WRITE(4,200) QOBS(I), HW(I), TW(I), H1(I), H4(I),
     *  QFINAL(I), ERROR1(I)

200   FORMAT(1X,F7.2, 1X,F6.2, 1X,F6.2, 1X,F6.2, 1X,F6.2,
     *  1X,F7.2, 1X,F7.2,1X)

150   CONTINUE

      E1AVG = E1SUM / FLOAT(NARRAY)

      E1BAVG = E1BSUM / FLOAT(NARRAY)

      WRITE(4,210) E1AVG
210   FORMAT(/1X, 16HABSOLUTE AVERAGE,5X, 1X,6X, 1X,6X, 1X,7X, 1X,F7.2,1X)

      WRITE(4,215) E1BAVG
215   FORMAT(/1X,18HARITHMETIC AVERAGE,3X, 1X,6X, 1X,6X, 1X,7X, 1X,F7.2,1X)

      CLOSE(4)
      STOP
```

```
      END

C
C     FILE NAME: HALFANG.FOR
C
C     CALCULATE THE ANGLE THETA FOR A CIRCULAR CROSS SECTION BASED ON WATER DEPTH
C
      SUBROUTINE HALFANG(DEPTH, D, THETA)
C
      IF (DEPTH .LE. D) THEN
        THETA = ACOS(1.0 - 2.0* DEPTH/D)
      ELSE
        THETA = ACOS(-1.0)
      END IF

       RETURN
       END

C
C     FILE NAME: AREA.FOR
C
C     CALCULATE THE CROSS SECTIONAL AREA OF THE CHANNEL
C
      SUBROUTINE AREA(D, THETA, S)
C
      S = 0.25 * D * D * (THETA - 0.5 * SIN(2.0 * THETA))
      RETURN
      END

C
C     FILE NAME: PERIMET.FOR
C
C     CALCULATE THE WETTED PERIMETER OF THE CHANNEL
C
      SUBROUTINE PERIMET(D, THETA, P)
C
      P = THETA * D
      RETURN
      END

C
C     FILE NAME: WIDTH.FOR
C
C     CALCULATE THE WIDTH OF THE SECTION AT THE WATER SURFACE OF THE CHANNEL
C
      SUBROUTINE WIDTH(D, THETA, T)
C
      T = D * SIN(THETA)
      RETURN
      END

C
C     FILE NAME: HYDRAD.FOR
C
C     CALCULATE THE HYDRAULIC RADIUS OF A SECTION
C
      SUBROUTINE HYDRAD(S, P, HYDR)
C
      HYDR = S/P
      RETURN
      END

C
C     FILE NAME: CONVEY.FOR
C
C     CALCULATE THE CONVEYANCE OF THE CULVERT AT THE INLET AND OUTLET SECTION
C     (UNIT: FT^3/S)
C
      SUBROUTINE CONVEY(R, A, N, CONV)
      REAL N
C
      CONV = 1.486/N * R**(2.0/3.0) * A
      RETURN
      END
```

```
C
C       FILE NAME: GETC4.FOR
C
C       ESTIMATE THE DISCHARGE COEFFICIENT FOR THE FLOW
C
        SUBROUTINE GETC4(C4CON, COEFF, H1, H4, C4)
C
        C4 = C4CON + COEFF * (H1 - H4)
        RETURN
        END


C
C       FILE NAME: GETQ.FOR
C
C       CALCULATE THE CULVERT FLOW USING DISCHARGE EQUATION
C
        SUBROUTINE GETQ(C4, A3, H1, H4, G, K2, K3, LEN, Q)
        REAL K2, K3, LEN
C
        Q = C4 * A3 * SQRT(2.0 * G * (H1 - H4) / (1.0 +
     *      2.0 * G * C4 * C4 * A3 * A3 * LEN / (K2 * K3)))
        RETURN
        END
```