Technical Publication

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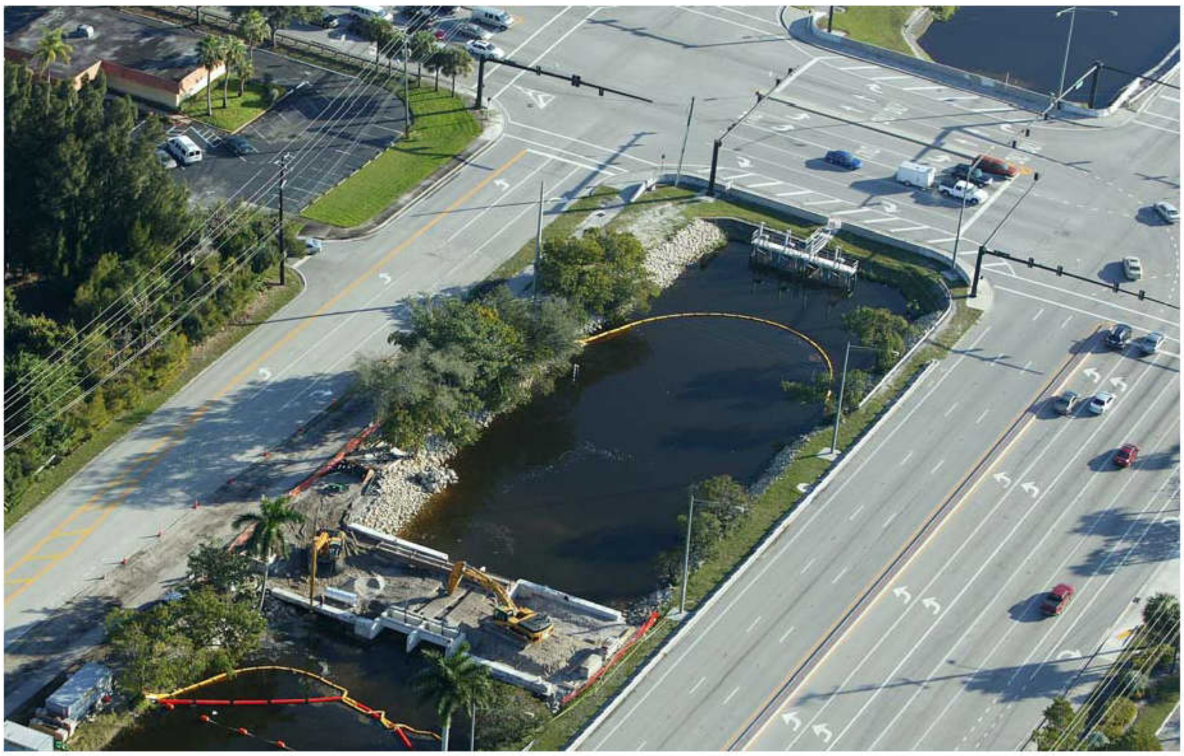
S-13A Structure Improvements and Hydraulic Design



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Executive Summary

The existing S-13A Structure is located in the C-11 Canal (South New River Canal) approximately five miles west from the S-13 Structure (pump and spillway). It is a four-barrel, corrugated metal pipe culvert, 6-foot diameter with upstream sluice gates (in their western side). The structure was originally designed to maintain optimum stages in the western reach of the C-11 Canal and to provide supply (dry season) releases to the eastern reach of the C-11 Canal with a design capacity of 120 cubic feet per second (cfs) under submerged conditions with a head difference of 0.50 ft.

A different flood control operation was initiated in July 2003, when S-13A began releasing flows from the western C-11 Basin to be discharged to tide through the S-13 structure. Those flood releases would have previously been released to WCA-3A though the S-9 Pump Station. In light of these operational changes and because the four original gates were extremely deteriorated, a replacement structure with a preferred gated concrete box culvert was proposed. This structure will be located approximately 260 feet upstream (to the west) from the gates of the existing S-13A.

This publication contains the detailed hydraulic design of the new S-13A Structure, which is a double-box, concrete culvert with sluice gates mounted in the upstream (western side) end. The appropriate flow discharge for the new flood control operation was selected based on existing wet season records since 2003 and considering the fact that the existing four barrels will remain in place after removal of their damaged gates. Also, the discharge capacity of the S-13 Structure (1,080 cfs) was taken into consideration (combined capacity for spillway and pump station, 540 cfs each). Appendix A includes the detailed flow regulation of the new S-13A Structure for a range of flows (from 500 cfs for both boxes to 125 cfs for one box closed) under several headwater and tailwater stage conditions. The new S-13A Structure is currently under construction.

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Introduction

The existing S-13A Structure is located in the C-11 Canal (South New River Canal) approximately five miles west from the S-13 Pump Station in Broward County (Figure 1). The structure is at the canal crossing of S.W. 100th Avenue (Nob Hill Road) between S.W. 45th Street (Orange Drive) to the north and Griffin Road (State Road 818), to the south. It is a four-barrel corrugated metal pipe (CMP) culvert with upstream sluice gates (on their western side) which control the flow. Each 6-ft barrel is 200 ft long with invert elevation at -4.1 ft National Geodetic Vertical Datum (NGVD). This structure was originally designed to control optimum stages in the western reach of the C-11 Canal and provide supply (dry season) releases to the eastern reach of the C-11 Canal (east of the structure). The design discharge is 120 cubic feet per second (cfs) for submerged conditions with headwater stage at 2.5 ft NGVD and tailwater at 2.0 ft NGVD.

As shown on Figure 1, the C-11 Impoundment is a proposed 1,490-acre, above-ground reservoir capable of holding a water depth up to 4.3 ft. It is located within the City of Weston and is one of the Broward County Water Preserve components identified in the Comprehensive Everglades Restoration Plan (CERP), incorporated into Acceler8, and recently transferred to the U.S. Army Corps of Engineers for design and construction. This impoundment will receive stormwater from the western C-11 Basin which would otherwise have been discharged into Water Conservation Area 3A (WCA-3A) by the S-9 Pump Station to provide flood protection to the urban areas. The C-11 Impoundment will also assist in providing groundwater recharge which will eventually improve urban water supply and prevent salt water intrusion. If water is not available in the impoundment to meet the water supply demands, the seepage divide structure, S-381 (Obermeyer-type gate), will be opened to make the deliveries. Flood control releases to tide from the western C-11 Basin will also be done through S-13A to recapture storage capacity in the C-11 Impoundment. Releases to the eastern C-11 Basin will occur only after flood protection in this basin is not impacted. This scenario will impose a substantial change to the original design of the S-13A Structure.

Beginning in July 2003, wet season flood control releases from the western C-11 Basin, which were originally pumped to WCA-3A by the S-9 Pump Station, were discharged to tide by the S-13 Structure (Pump Station and Spillway). Although unnecessary prior to July 2003, this flood control operation scheme now allows wet season flows through the S-13A Structure by means of its sluice gates. The sluice gates have shown a significant deterioration lately, therefore a new structure was proposed upstream (a short distance to the west) of the existing S-13A Structure. There is currently a preference at the District toward the use of gated concrete box culverts, which will be more appropriate for the proposed regulation during the wet seasons, as well as for the continuing water supply releases during the dry seasons. The sluice gates of the existing S-13A Structure will be dismantled when the new S-13A is built. The four CMP culverts could be eventually replaced by a bridge.

Recent Wet Season Operation of Existing S-13A Structure

S-13A Structure's flow records indicate that this structure began its wet season operation releasing flows on a consistent basis from the western C-11 Basin in July 2003. These flows, which were typically discharged to WCA-3A through the S-9 Pump Station, were thus released to tide by the S-13 Structure. Figures 2A through 2C depict the flows and headwater and tailwater stages for S-13A and also the flows being released to tide by the S-13 Structure, all of them as mean daily values. S-13 Structure flows represent the combined discharges for the Pump Station (Q_{design}= 540 cfs) and for the Spillway (Q_{design}= 540 cfs). However, releases to tide are mostly done through the spillway and sporadically using the pump (i.e., large flows associated with extreme events and/or high tide).

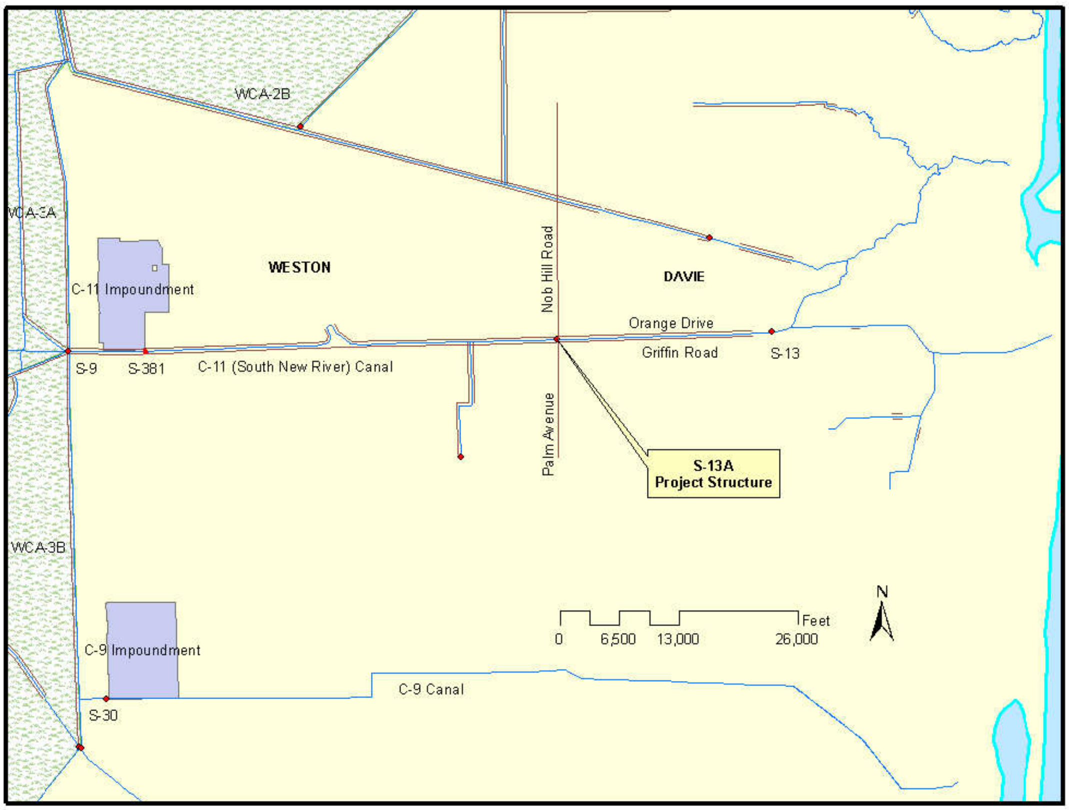
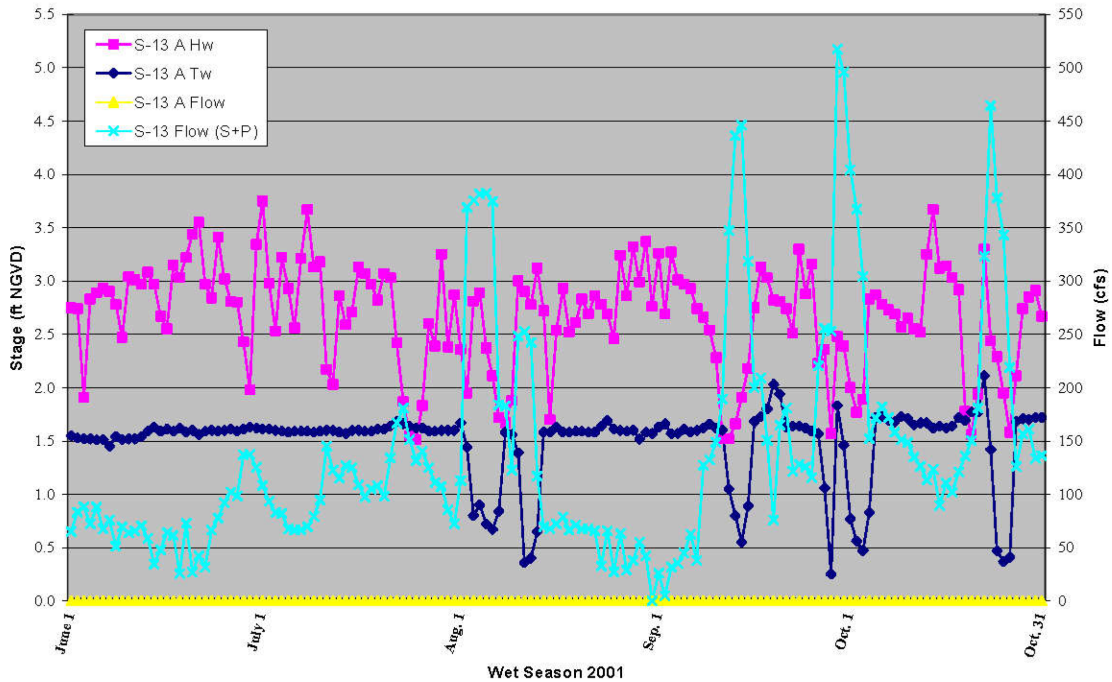


Figure 1. Location of S-13A Structure in the C-11 (South New River) Canal

As shown in Figure 2B, the operation of the S-13A Structure during the wet season began on July 2, 2003. This operation, which is characterized by larger flows at S-13 Structure than those at S-13A (Figures 2B and 2C), indicates flood control conditions consistently during the 2004 through 2006 wet seasons. However, it is observed during the 2003 wet season that the flows through the S-13A and S-13 structures were not strictly representative of flood control operation (i.e., as the S-13A Structure remained open, its flows were larger than those through S-13 Structure). This may be an indication of the relatively dry conditions of 2003 in the C-11 Basin. There was almost a 25 percent rainfall deficit for the five months of the 2003 wet season based on historic conditions (37.41 in), which yielded a shortage of 9.32 in. The monthly rainfall range (deficit and surplus) was -77 percent and 29.7 percent in October and August, respectively.



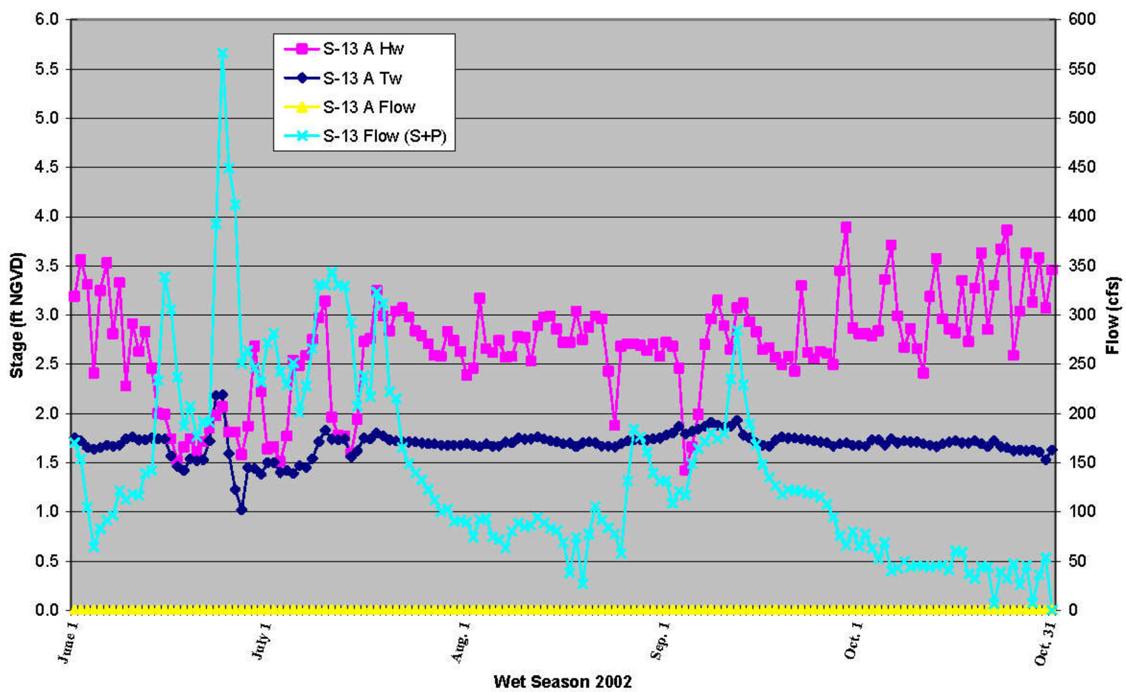
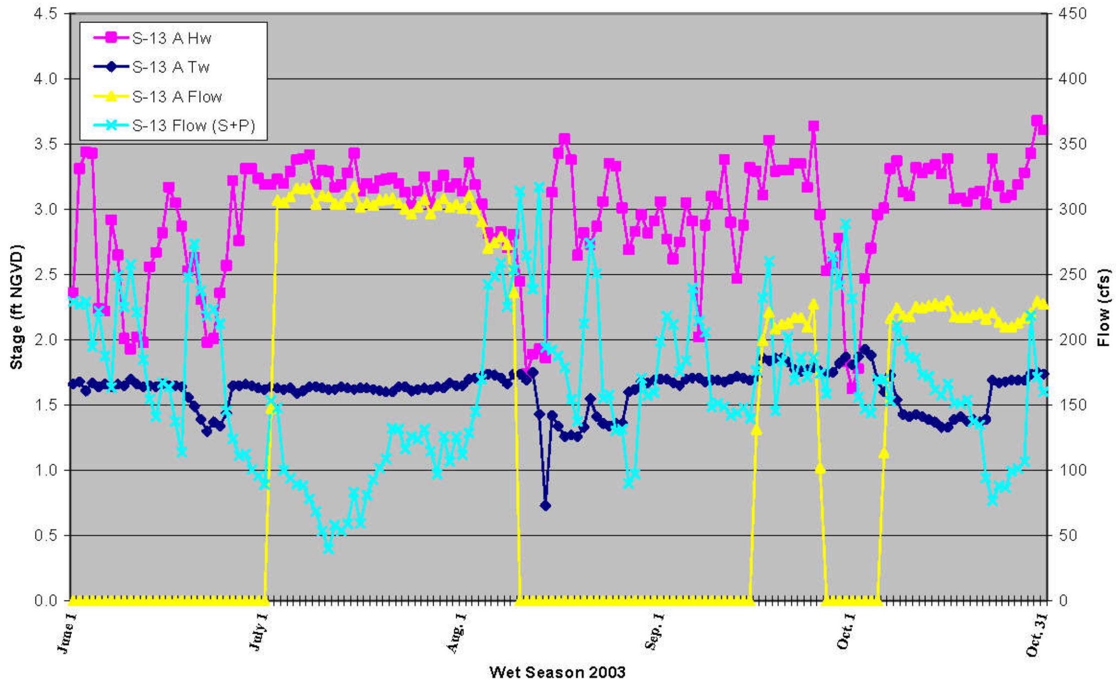


Figure 2A. Stage and flow records for S-13A and flow records for S-13 (mean daily values) for the 2001 and 2002 wet seasons



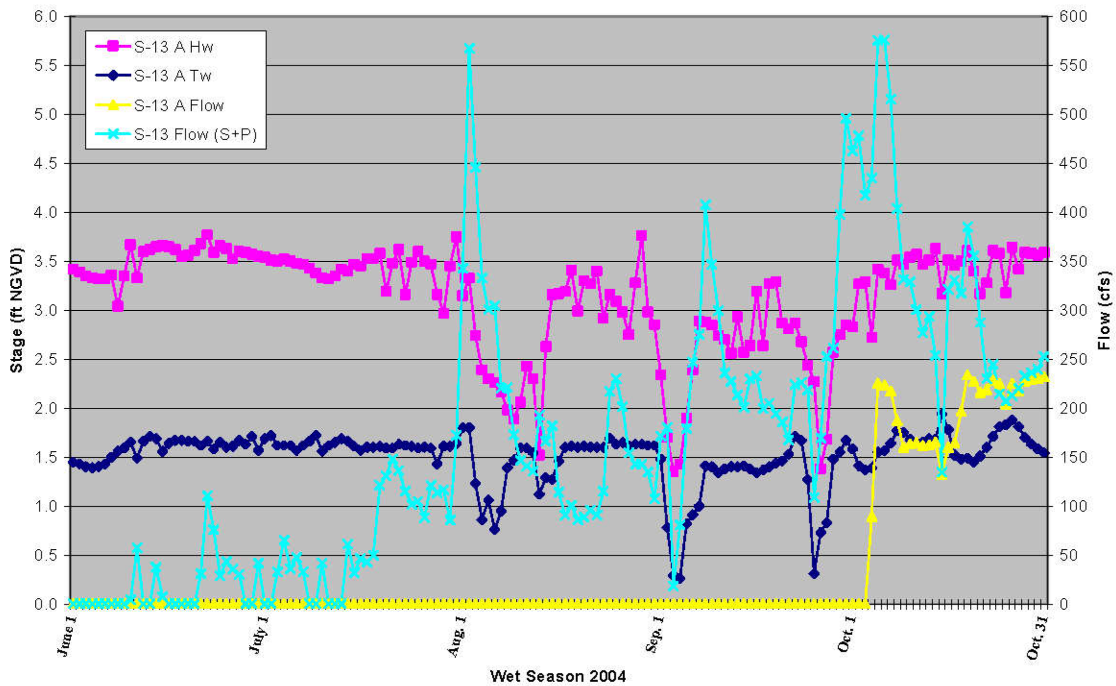
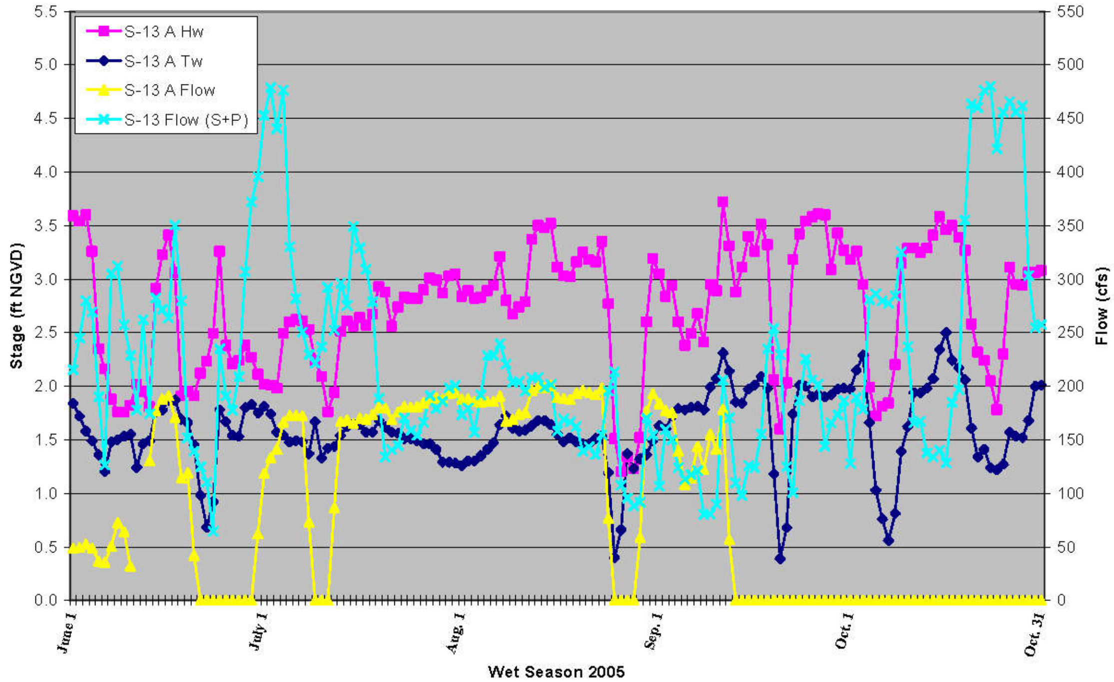


Figure 2B. Stage and flow records for S-13A and flow records for S-13 (mean daily values) for the 2003 and 2004 wet seasons



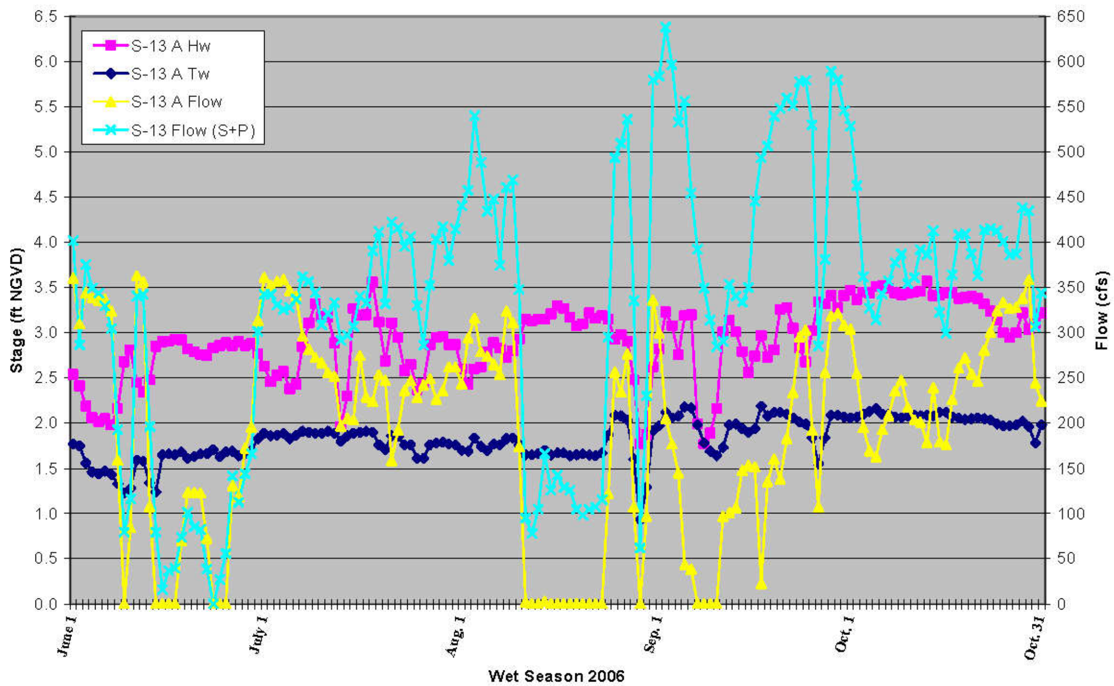


Figure 2C. Stage and flow records for S-13A and flow records for S-13 (mean daily values) for the 2005 and 2006 wet seasons

Table 1 shows statistical results based on mean daily stage records during the last six wet seasons (2001 to 2006) for the S-13A Structure. Table 2 shows similar results based on mean daily flows for both structures, S-13A and S-13.

Table 1. Stage data analysis for existing S-13A Structure

Wet Season	Value	Upstream (west side)		Downstream (east side)	
		Headwater (ft NGVD)	Occurrence	Tailwater (ft NGVD)	Occurrence
2001	Max.	3.75	July 01	2.11	Oct. 22
	Min.	1.51	July 25	0.25	Sep. 28
	Mean	2.67	n/a	1.49	1.18[1]
2002	Max.	3.89	Sep. 29	2.19	June 24
	Min.	1.42	Sep. 04	1.02	June 27
	Mean	2.68	n/a	1.69	0.99[1]
2003	Max.	3.68	Oct. 30	1.93	Oct. 03
	Min.	1.63	Oct. 01	0.73	Aug. 14
	Mean	2.96	n/a	1.61	1.35[1]
2004	Max.	3.77	June 22	1.94	Oct. 15
	Min.	1.35	Sep. 03	0.26	Sep. 04
	Mean	3.14	n/a	1.51	1.63[1]
2005	Max.	3.72	Sep. 11	2.50	Oct. 16
	Min.	1.20	Aug. 26	0.39	Sep. 20
	Mean	2.72	n/a	1.58	1.14[1]
2006	Max.	3.57	Oct. 13	2.19	Sep. 17
	Min.	1.77	Sep. 08	0.93	Aug. 29
	Mean	2.91	n/a	1.83	1.08[1]

[1] average head difference obtained from mean headwater and tailwater stages

Table 2. Flow data analysis for S-13A and S-13 Structures

Wet Season	Value	S-13A Structure		S-13 Structure (S+P)	
		Flow (cfs)	Occurrence	Flow (cfs)	Occurrence
2001	Max.	0	[1] No operation	517	Sep. 29
	Mean	0	n/a	141	n/a
2002	Max.	0	[1] No operation	567	June 24
	Mean	0	n/a	142	n/a
2003	Max.	317	July 15	317	Aug. 13
	Mean	126	n/a	163	n/a
2004	Max.	234	Oct. 19	576	Oct. 06
	Mean	36	n/a	166	n/a
2005	Max.	201	Aug. 15	480	Oct. 23
	Mean	85	n/a	222	n/a
2006	Max.	363	June 11	638	Sep. 02
	Mean	193	n/a	334	n/a

[1] S-13A Structure remained closed during the entire wet season

For a better understanding of the operation of the two structures during the wet season, it would be more appropriate to analyze their flows considering only the days of operation of the S-13A Structure. The results are provided in Table 3.

Table 3. Flow characteristics of S-13A and S-13 Structures during the days when S-13A was in operation

Wet Season	Value	S-13A Structure		S-13 Structure (S+P)	
		Flow (cfs)	Occurrence	Flow (cfs)	Occurrence
2003	Max.	317	July 15	260[2]	Sep. 18
	Min.	102	Sep. 26	40	July 11
	Mean	255	n/a	141	76[1]
2004	Max.	234	Oct. 19	576	Oct. 06
	Min.	89	Oct. 04	135	Oct. 15
	Mean	196	n/a	311	28[1]
2005	Max.	201	Aug. 15	479[2]	July 02
	Min.	32	June 10	80	Sep. 08
	Mean	149	n/a	214	86[1]
2006	Max.	363	June 11	638	Sep. 02
	Min.	2	Aug. 11	39	June 22
	Mean	230	n/a	375	128[1]

[1] number of days of S-13A operation out of the 153 days in the wet season
[2] maximum flow does not coincide with that in Table 2 (S-13A didn't operate)

S-13A mean flow during the five months of the 2003 wet season (June through October) exceeded that released to tide from S-13 by nearly 81 percent (Table 3). This does not agree with flood control operation, which predominantly occurs during wet seasons (S-13 flow will tend to be larger than S-13A flow). As previously discussed, this occurred due to dry conditions associated with a lower-than-normal rainfall during the 2003 wet season.

Design Operation of the Existing S-13A Structure

S-13A was originally designed as a water supply structure to release dry season flows to the eastern C-11 Basin and to maintain optimum upstream water control stages at approximately 2.2 ft NGVD. Control is achieved by electrically operated sluice gates mounted on steel frames erected on the upstream end of each culvert (CMP). Design description and characteristics of the hydraulic structure are provided in Table 4.

Table 4. Design characteristics and description of existing S-13A Structure

Flow Discharge, Q (cfs)	120
Headwater Stage, Hw (ft NGVD)	2.5
Tailwater Stage, Tw (ft NGVD)	2.0
Discharge Type	Submerged
Number of Barrels	4
Barrel Diameter, d (ft)	6.0
Barrel Length (ft), L (ft)	200
Invert Elevation (ft NGVD)	-4.1
Service Bridge Elevation (ft NGVD)	9.25

The maximum flow (mean daily value) during the dry season was 400.66 cfs recorded on January 14, 2000. The peak flow for that day was 408.89 cfs, which represents an increase of 2.05 percent over the mean daily value. Figure 3 depicts mean daily flows and headwater and tailwater mean daily stages for S-13A Structure during these extreme flow releases for a period of four days. Flow records during dry season indicate that S-13A is able to release larger flows than 120 cfs even though the gates were partially opened, as shown in Figure 4. However, the head difference (head loss) was considerably greater than 0.50 ft (design) as it can be observed in Figure 3.

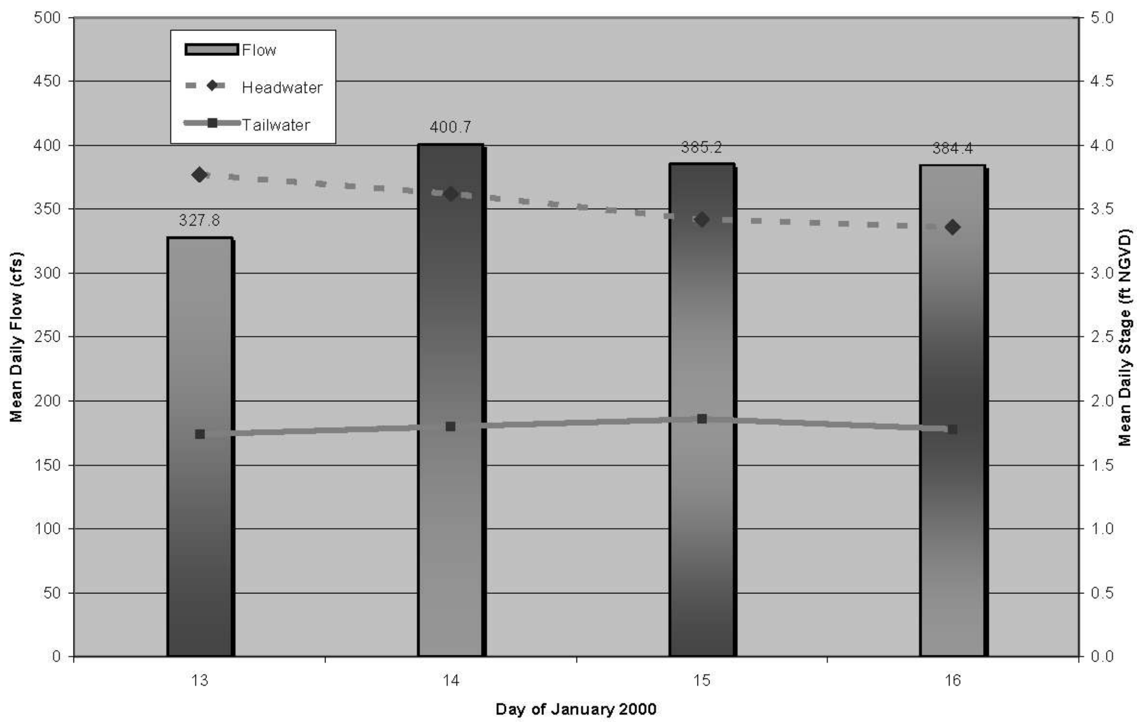


Figure 3. Mean daily flow and stages for S-13A Structure during the January 2000 event

The larger flow on January 14, 2000 than that on January 13 (in spite of a much larger head difference as shown in Figure 3) was due to the operation of the four gates. As seen in Figure 4, the gate opening was increased from one foot to 2-ft for the four barrels at 11:20 am on January 13, 2000, and remained the same during the following days.

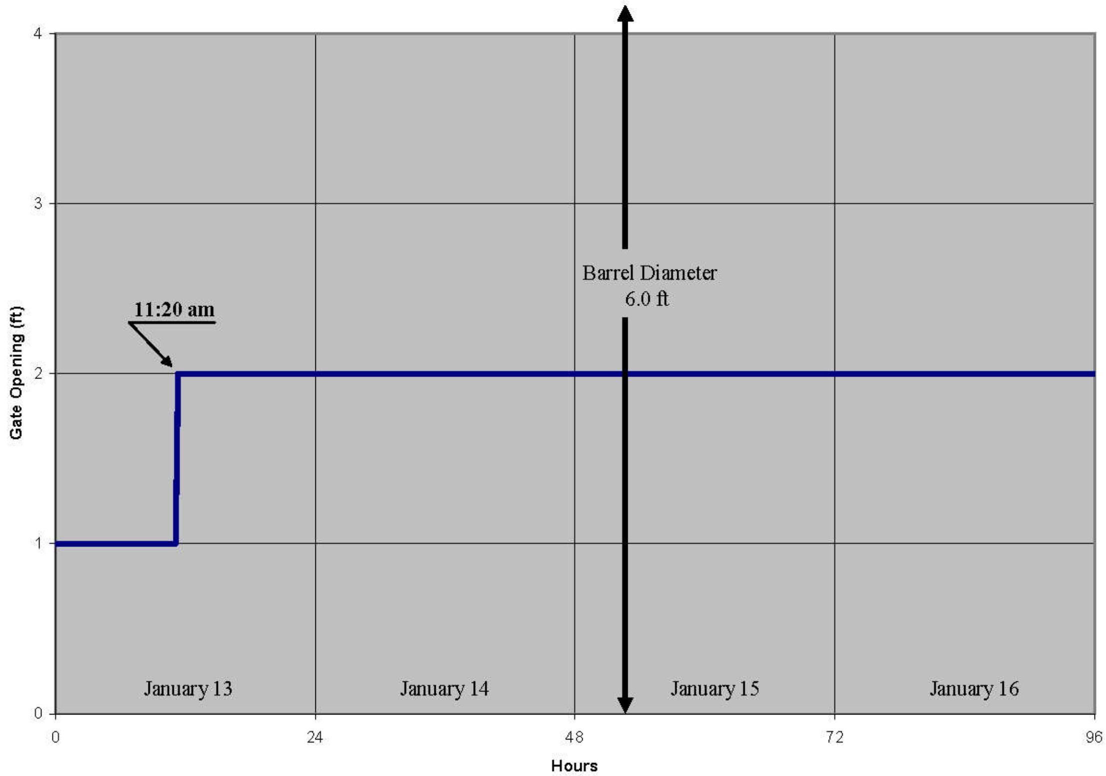


Figure 4. Operation of the four gates of S-13A Structure during the occurrence of the dry season peak flow (408.9 cfs) on January 14, 2000

A discharge equation for the S-13A Structure as a function of its head loss (Hw stage – Tw stage) was developed with its four gates fully open and the structure totally submerged (full flow). The total head loss across the culvert was estimated as the sum of the entrance (h_e), friction (h_f) and exit losses (h_o). Local head losses include entrance and exit losses and they are calculated as follows

$$h_e = K_e \times \frac{v^2}{2g} \tag{1}$$

$$h_o = K_o \times \frac{v^2}{2g} \tag{2}$$

where K_e and K_o = entrance and exit loss coefficients, respectively and are provided in Table 5, and $v^2/2g$ = velocity head (ft) with v = full flow velocity = Q/A (ft/sec) and g = gravity acceleration = 32.2 ft/sec^2.

Using the appropriate geometry values in Table 4 and Manning's n included in Table 5, friction head losses, h_f (ft), were estimated from the Manning equation as follows,

$$h_f = \left[\frac{Q \times n}{1.49 \times A \times R_h^{2/3}} \right]^2 \times L \tag{3}$$

where Q = discharge (cfs), n = Manning's roughness coefficient (sec/ft$^{1/3}$), A = area (ft^2), R_h = hydraulic radius = A/P_w (ft), L = barrel length (ft), 1.49 = conversion factor for English units.

Table 5. Hydraulic parameters and coefficients of existing S-13A Structure

[1] Full Flow Area, A (ft^2)	28.27
[1] Full Flow Wetted Perimeter, P_w (ft)	18.85
[1] Full Flow Hydraulic Radius, R_h (ft)	1.50
n (sec/ft$^{1/3}$)	0.024
K_e (entrance loss coefficient)	0.5
K_o (exit loss coefficient)	1.0

[1] value for each barrel

For comparison purposes, the orifice equation was also used,

$$Q = C_o \times A \times \sqrt{2g \times \Delta H} \tag{4}$$

where C_o = orifice coefficient and ΔH = head difference (ft). The term (ΔH) is equivalent to the total head loss (entrance + friction + exit) when a culvert equation is used.

The orifice coefficient (C_o) was computed using the following equation (Brater and King: Handbook of Hydraulics, 4-35) for CMP,

$$C_o = \left[1 + 0.16 \times d^{0.6} + \frac{0.106 \times L}{d^{1.2}} \right]^{-1/2} \tag{5}$$

where d = barrel diameter (ft). C_o for each barrel of existing S-13A Structure fully open is 0.504. The results are depicted in Figure 5. The orifice equation underestimates the discharge by 6.45 percent compared to the culvert equation.

Figure 5 shows that the existing S-13A Structure is capable of discharging 346 cfs (323 cfs from orifice equation) under a head difference (total head loss) of 0.50 ft when the four gates are removed.

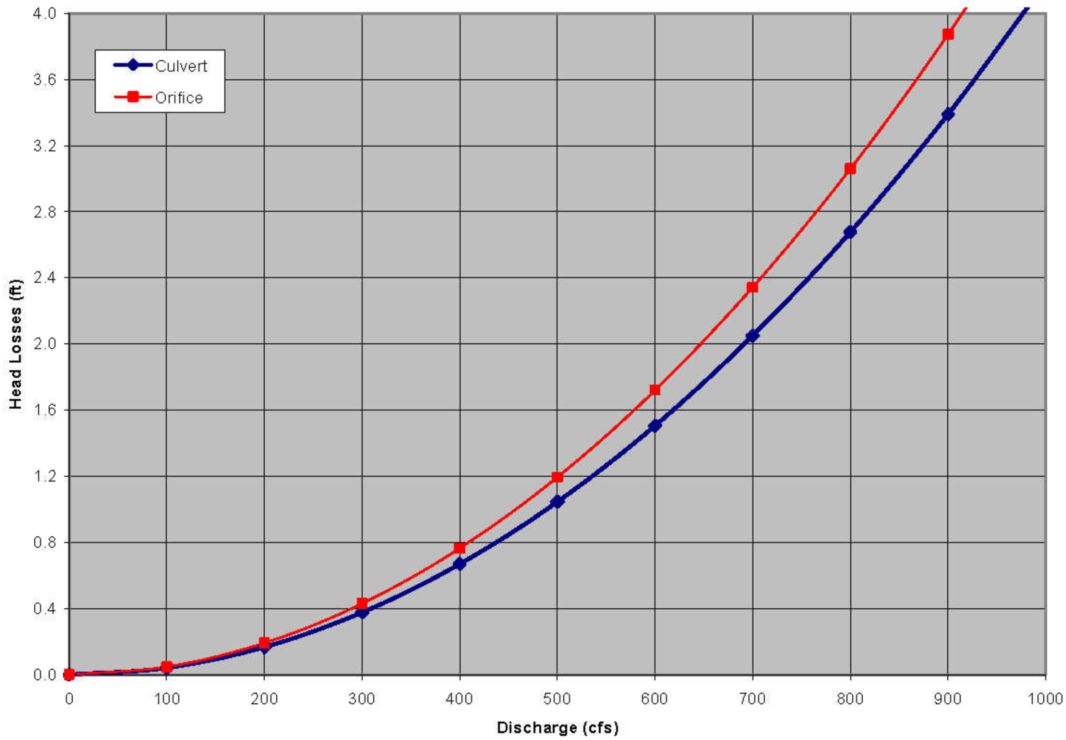


Figure 5. Discharge function for existing S-13A Structure totally submerged

S-13A Structure stage records of the last six years were used to analyze their seasonal variation. Results are shown in Table 6.

Table 6. Seasonal headwater and tailwater stages and mean head difference (Hw-Tw) at existing S-13A Structure from November 2000 through October 2006

From	To	Season	Year	Hw Stage (ft NGVD)			Tw Stage (ft NGVD)			Mean Head Diff. (ft)
				Max.	Min.	Mean	Max.	Min.	Mean	
Nov. 00	May 01	Dry	2001	4.05	2.03	3.62	2.07	1.53	1.76	1.86
June 01	Oct. 01	Wet	2001	3.75	1.51	2.67	2.11	0.25[W]	1.49	1.18
Nov. 01	May 02	Dry	2002	4.04	1.21[D]	3.28	1.83	0.16[D]	1.62	1.66
June 02	Oct. 02	Wet	2002	3.89[W]	1.42	2.68	2.19	1.02	1.69	0.99
Nov. 02	May 03	Dry	2003	4.42[D]	1.79	3.21	2.42[D]	0.55	1.64	1.57
June 03	Oct. 03	Wet	2003	3.68	1.63	2.96	1.93	0.73	1.61	1.35
Nov. 03	May 04	Dry	2004	4.10	1.85	3.30	2.12	1.00	1.51	1.79
June 04	Oct. 04	Wet	2004	3.77	1.35	3.14	1.94	0.26	1.51	1.63
Nov. 04	May 05	Dry	2005	3.84	2.30	3.51	1.95	1.23	1.52	1.98
June 05	Oct. 05	Wet	2005	3.72	1.20[W]	2.72	2.50[W]	0.39	1.58	1.14
Nov. 05	May 06	Dry	2006	3.56	1.65	2.98	2.18	0.91	1.67	1.31
June 06	Oct. 06	Wet	2006	3.57	1.77	2.91	2.19	0.93	1.83	1.08
			Average for Dry Season			3.31			1.62	**1.69**
			Average for Wet Season			2.85			1.62	**1.23**

[D] and [W] denote extreme stage values for dry season and wet season, respectively

Table 6 shows relevant information about the seasonal stages and head difference (head losses) across the existing S-13A Structure for the last six years based on mean daily values. Headwater stages have a range of 3.21 and 2.69 ft for dry and wet seasons, respectively. Tailwater stages have a range 2.26 and 2.25 ft for dry and wet seasons, respectively. These ranges were estimated from the extreme stages in Table 6 in which the superscripts D and W represent dry season and wet season, respectively. The average head differences across the existing S-13A Structure were 1.69 ft for dry season and 1.23 ft for wet season. Results show that the head difference across the existing S-13A Structure is larger during the dry season than during the wet season.

Table 7 presents the maximum head differences and their occurrences for each of the six seasons. The maximum head difference during a dry season, based on mean daily stages, was 2.84 ft (January 23, 2003). The maximum head difference during a wet season was 2.54 ft (August 11, 2001), as shown in Table 7. However, as previously mentioned, the S-13A Structure remained closed at that time (Figure 2A). As observed from Figure 5, for the average head difference of 1.69 ft during the dry season (Table 6), the existing S-13A Structure (fully open) can discharge approximately 636 cfs (595 cfs from the orifice equation), and for the maximum head difference of 2.84 ft (Table 7) the discharge can be up to 824 cfs (771 cfs from the orifice equation).

Table 7. Seasonal headwater and tailwater stages yielding maximum head differences (Hw-Tw) at existing S-13A Structure and their occurrences

From	To	Season	Year	Hw (ft NGVD)	Tw (ft NGVD)	Max. Head Diff. (ft)	Occurrence
Nov. 00	May 01	Dry	2001	4.05	1.64	2.41	Jan. 09, 2001
June 01	Oct. 01	Wet	2001	2.90	0.36	2.54^{W}	Aug. 11, 2001
Nov. 01	May 02	Dry	2002	3.84	1.38	2.46	Dec. 12, 2001
June 02	Oct. 02	Wet	2002	3.86	1.65	2.21	Oct. 24, 2002
Nov. 02	May 03	Dry	2003	4.42	1.58	2.84^{D}	Jan. 23, 2003
June 03	Oct. 03	Wet	2003	3.54	1.26	2.28	Aug. 17, 2003
Nov. 03	May 04	Dry	2004	3.78	1.26	2.52	Dec. 07, 2003
June 04	Oct. 04	Wet	2004	3.76	1.63	2.13	Aug. 29, 2004
Nov. 04	May 05	Dry	2005	3.78	1.28	2.50	Jan. 20, 2005
June 05	Oct. 05	Wet	2005	3.60	1.58	2.02	June 03, 2005
Nov. 05	May 06	Dry	2006	3.56	1.65	1.91	Jan. 09, 2006
June 06	Oct. 06	Wet	2006	3.34	1.55	1.79	Sep. 26, 2006

^{D} and ^{W} denote the maximum values for dry season and wet season, respectively

Design of the Replacement S-13A Structure

The replacement of the S-13A Structure will be a double-box, concrete culvert with the control sluice gates mounted on the upstream end (west side of the structure). The new structure will be located approximately 260 ft upstream (to the west) of the four gates of the existing S-13A. Once the new structure is built, the four sluice gates will be dismantled.

With all previous considerations on historical operation, it was determined that the new S-13A Structure would be designed for an average discharge of 500 cfs under a head difference (total head loss) of approximately 0.50 ft. As shown in Table 6, the average head difference during wet season was 1.23 ft (including the last four seasons during which flood control releases occurred from the western C-11 Basin to the eastern C-11 Basin). During the dry season, the average head difference was 1.69 ft. The lower wet season head difference across the S-13A Structure is due to lower stages maintained in the western reach of C-11 Canal in anticipation of flood control operations. On the contrary, stages in the eastern reach of the C-11 Canal (i.e., S-13A tailwater stage) are maintained throughout the year at approximately 1.6 ft NGVD as shown in Figures 2A through 2C and in Table 6. A discharge of 500 cfs across the four barrels of the existing S-13A Structure requires a head difference of one foot (Figure 5). The remaining four barrels of the existing S-13A Structure will produce roughly 2/3 of the total losses when the new, double-box culvert begins operation during flood control. Even though the 1.5 ft head difference (0.50 ft for the new structure plus one-foot for the existing structures without the gates) slightly exceeds the average value of 1.23 ft (Table 6), the design conditions are reasonable due to the presence of the S-13 Structure. This structure releases flows to tide by gravity and pumping (each spillway and pump station have a design capacity of 540 cfs each). If in the future, the existing S-13A Structure (four barrels) is replaced by a bridge, the discharge of the new, double-box culvert structure could increase considerably by the reduction in losses (four barrels compared with a bridge).

After several trials, a 10 by 5-ft, double-box culvert was selected as a design cross section of the new S-13A Structure. The detailed information for the new S-13A Structure (designed based on flood control releases) is included in Table 8. The design hydraulic parameters are shown in Table 9.

Table 8. Design characteristics and description of the new S-13A Structure

Flow Discharge (cfs)	500
Headwater Stage, Hw (ft NGVD)	2.75
Tailwater Stage, Tw (ft NGVD)	2.25
Discharge Type	Submerged
Number of Boxes	2
Box Width, B (ft)	10.0
Box Height, H (ft)	5.0
Box Length, L (ft)	50.0
Invert Elevation (ft NGVD)	-4.0

Table 9. Hydraulic parameters and coefficients of the new S-13A Structure

[1] Full Flow Area, A (ft^2)	50.0
[1] Full Flow Wetted Perimeter, P_w (ft)	30.0
[1] Full Flow Hydraulic Radius, R_h (ft)	1.67
n ($sec/ft^{1/3}$)	0.012
K_e (entrance loss coefficient)	0.28
K_o (exit loss coefficient)	1.0

[1] value for each box

A discharge equation for the new S-13A Structure as a function of its head difference (Hw – Tw) was developed assuming fully open gates and conditions of total submergence. Head difference represents the total head loss across the culvert which was estimated as the sum of the entrance, friction and exit losses. Local losses were calculated using Equations 1 and 2 with entrance and exit loss coefficients from Table 9 and a velocity head for a 10 by 5-ft box section. Using the appropriate geometry values from Table 8 and Manning's n from Table 9, friction losses were estimated from the Manning equation (Equation 3). Also the orifice equation (4) was used for comparison purposes.

The orifice coefficient (C_o) was computed using the following equation (Brater and King: Handbook of Hydraulics, 4-37) for concrete-box culverts with square-cornered entrance,

$$C_o = \left[1 + 0.4 \times R_h^{\ 0.3} + \frac{0.0045 \times L}{R_h^{\ 1.25}}\right]^{-1/2} \tag{6}$$

where R_h = box culvert hydraulic radius (ft) and L = box culvert length (ft). C_o for each box of the new S-13A Structure fully open is 0.794. Results from the two equations are shown in Figure 6. The orifice equation underestimates the discharge by 6.50 percent compared to the culvert equation. The new S-13A Structure is schematically illustrated in Figure 7.

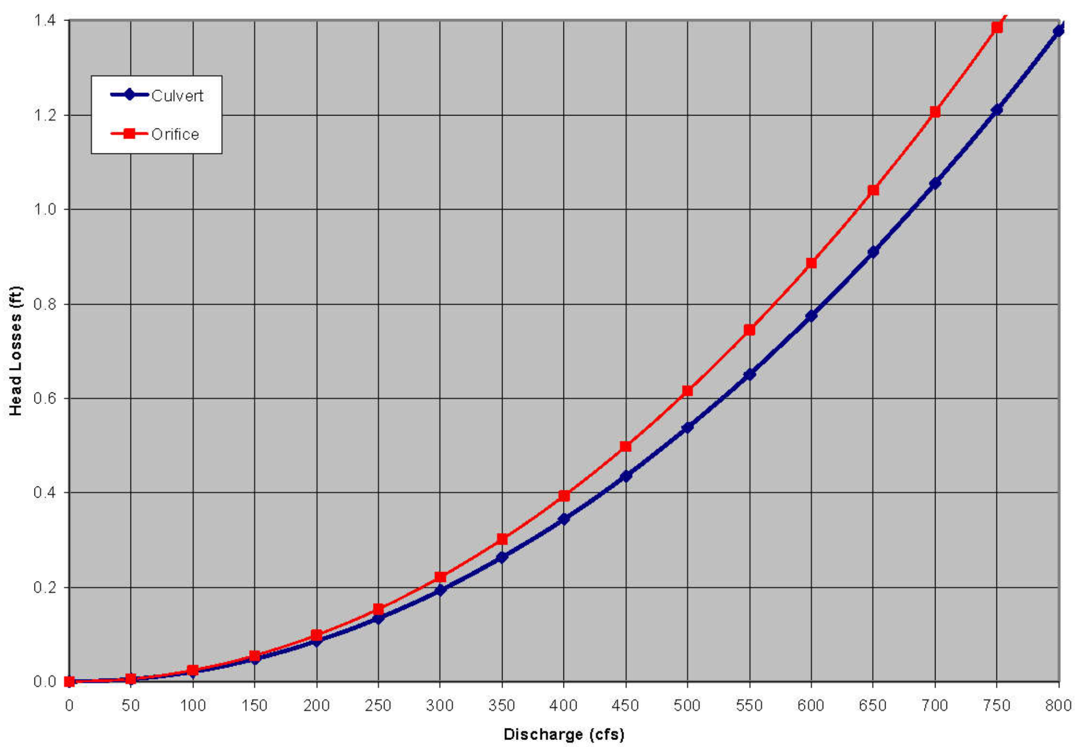


Figure 6. Discharge function for the new S-13A Structure with two gates fully open and totally submerged

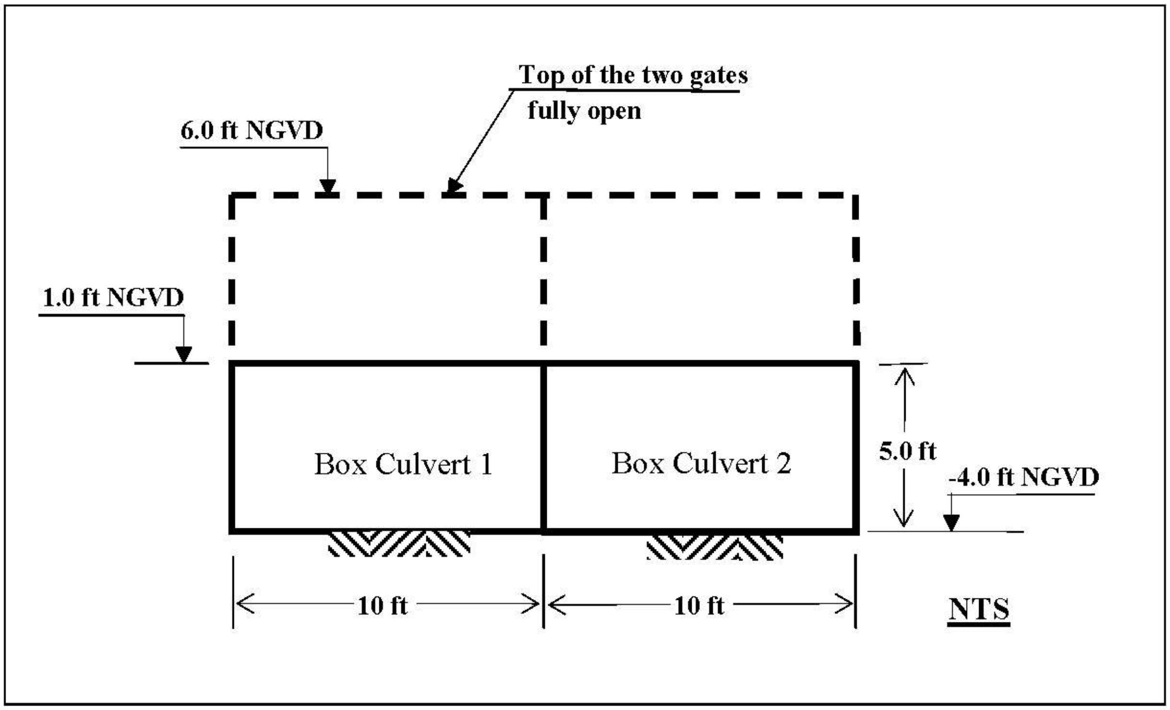


Figure 7. Schematic representation and dimensions of the new S-13A Structure

Discharge Regulation for the Replacement S-13A Structure

Generally the flow discharges through the new structure during the dry season (water supply operation) should be smaller than those during the wet season (flood control operation). The proposed flood control operation will consist of releases to tide through the S-13 Structure from the western C-11 Basin, which were previously pumped to WCA-3A by S-9 Pump Station. Also, as previously mentioned, headwater stages tend to be higher during the dry season than those during the wet season. Therefore, water supply releases should be controlled by the gates operation depending on headwater and tailwater stages.

Using a Microsoft Excel® spreadsheet, a model has been developed to simulate several scenarios for a reasonable range of stages and gate openings. The simulation results will be use to evaluate the flow control capabilities of the new S-13A Structure. The model and the complete description of the hydraulic computations are included in Appendix A.

Appendix A

Hydraulic Model for Flow Regulation through the S-13A Structure

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Introduction

This appendix includes the hydraulic model developed for flow control through the sluice gates of the new S-13A double-box concrete culvert. Programmed in a Microsoft Excel® spreadsheet, the model computes the three possible flow conditions (i.e., free, drowned and full flow), as shown in Figure A1. The detailed model is presented in Table A1 and contains the simulation for a flow discharge (Q) of 500 cfs and Hw stage of 3.0 ft NGVD (Y_1 = 7.0 ft). Supporting information is presented in Tables A1 through A13 at the end of this appendix.

Hydraulic Model

The model determines the three possible flow conditions for a selected upstream flow depth (Y_1), flow discharge (Q) and a range of downstream flow depths (Y_3) as seen in Figure A1. All the Y_3 selected have to be reasonable values expected during the normal operation of the culvert. The model computes the required gate opening to pass the selected flow discharge (Q) with the selected upstream flow depth (Y_1) and downstream flow depths (Y_3) depending on the flow condition. Free flow occurs for relatively small gate openings (GO) able to generate flow depths downstream of the gate (Y_2) smaller than the critical depth (y_c). For such a flow regime, the specific energy at the headwater matches that just downstream of the gate ($E_1 = E_2$) as seen in Table A1, y_c and specific energy are computed as follows,

$$y_c = \sqrt[3]{\frac{q^2}{g}} \qquad \text{(A1)}$$

where q = unit flow discharge = Q/B (ft^2/sec), B = box culvert width (ft) and g = gravity acceleration (32.2 ft/sec^2), and

$$E = Y + \frac{v^2}{2g} \qquad \text{(A2)}$$

where Y = flow depth (ft) and $v^2/2g$ = velocity head (ft).

For free flow conditions, the flow just downstream of the gate is supercritical which corresponds to a Froude Number (Fr) larger than one. Fr for a rectangular section can be calculated from the following equation,

$$Fr = \frac{v}{\sqrt{g \times Y}} \qquad \text{(A3)}$$

Free flow conditions will exist until the downstream flow depth (Y_3) at the tailwater of the culvert is less than the sequent depth (y_S). When the downstream flow depth (Y_3)

matches the sequent depth (y_s), a hydraulic jump will occur just downstream of the gate. Sequent depth, y_s, is estimated from the following equation,

$$y_s = \frac{Y_2}{2}\left(\sqrt{1 + 8Fr_2^{\ 2}} - 1\right) \tag{A4}$$

where Y_2 = flow depth (ft) and Fr_2 = Froude Number (supercritical flow) both just downstream of the gate and for free flow conditions.

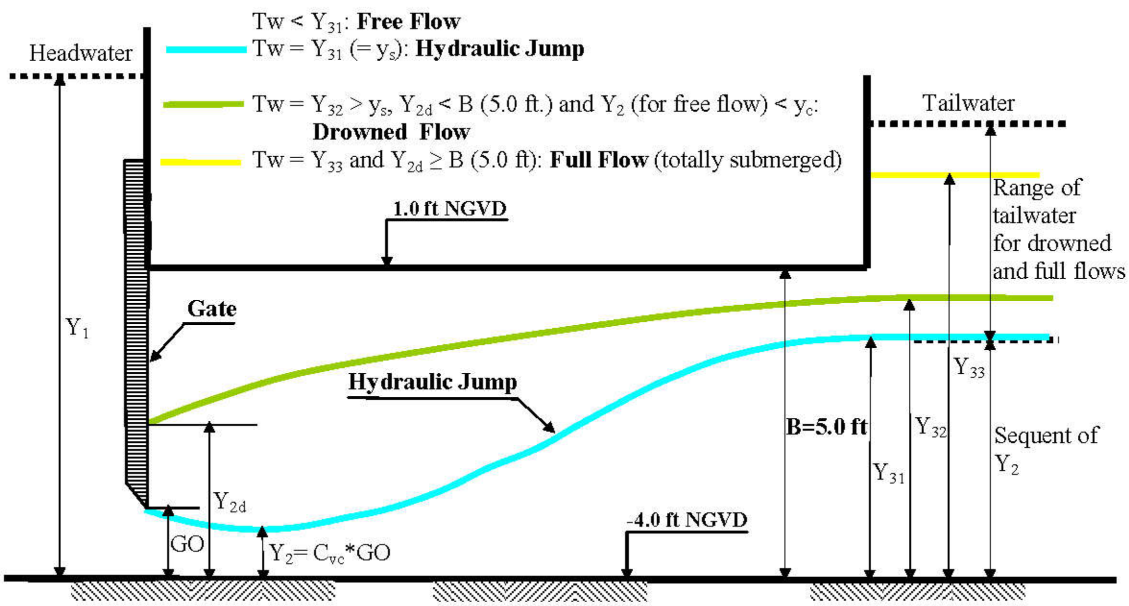

Figure A1. Schematic representation of the three flow regimes which may occur during flow regulation through the sluice gates

For the hydraulic jump occurrence as well as for drowned flow, flow depths downstream of the gate computed from energy basis (specific energy) and momentum basis have to be equal (Table A1). Flow depth Y_{2d} for drowned flow (Table A1) based on momentum basis is calculated as follows,

$$Y_{2d} = Y_3\sqrt{1 + 2Fr_3^{\ 2}\left(1 - \frac{Y_3}{Y_2}\right)} \tag{A5}$$

where Y_2 = flow depth (ft) just downstream of the gate and for free flow conditions and Fr_3 = Froude Number (subcritical flow) at the tailwater.

The length of the hydraulic jump (L_j) on a horizontal surface can be estimated as follows,

$$L_j = Y_2 \times 9.75 \times (Fr_2 - 1)^{1.01} \tag{A6}$$

where Y_2 and Fr_2 = flow depth (ft) and Froude Number, respectively, both for free flow conditions and just downstream of the gate. The L_j value indicates whether the hydraulic jump is contained within the culvert (as it compares with the box culvert length).

Energy head loss (ΔE) in a horizontal hydraulic jump can be estimated as follows,

$$\Delta E = \frac{(Y_3 - Y_2)^3}{4Y_2Y_3} \tag{A7}$$

where Y_3 = downstream or tailwater flow depth (ft) which is equal to the sequent depth (y_s), in this case. As shown in Table A1 (bold numbers), the hydraulic jump losses computed from Equation A7 are the same as those estimated as the difference between the specific energies upstream and downstream of the hydraulic jump (i.e., $E_2 = E_3 + \Delta E$).

As Y_2 exceeds the critical depth (y_c), the flow regime changes to full flow conditions. This condition occurs as Y_2 exceeds y_c and Fr_2 becomes less than one (columns 6 and 11 in Tables A1). Subsequent to drowned flow conditions, Y_{2d} will exceed the box culvert height (H=5.0 ft) and full flow conditions will begin with both GO and Y_3 (Tw stage) increasing. This regime is characterized by total submergence.

For full flow conditions the total head loss in the culvert has to match exactly the available head represented as the difference between Headwater and Tailwater stages (Hw–Tw) at the upstream and downstream of the culvert, respectively. There are friction and local head losses in a culvert. Entrance, expansion, and exit are all local head losses created by geometrical changes in the path of the flow as well as characteristics and material of the box culvert.

Entrance head loss, h_e (ft), is estimated as follows,

$$h_e = K_e \times \frac{v_G^{\,2}}{2g} \tag{A8}$$

where K_e = entrance loss coefficient and v_G = average flow velocity (ft/sec) through the gate opening (GO). This head loss depends on the shape and characteristics of the inlet.

Expansion head loss, h_{exp} (ft), is produced by the transition from the gate opening (GO) to the box culvert section, and is computed by the following equation,

$$h_{exp} = K_{exp} \times \frac{v_G^{\ 2} - v_C^{\ 2}}{2g} \qquad \text{(A9)}$$

where K_{exp} = expansion loss coefficient and v_C = average flow velocity (ft/sec) through the full box culvert. This equation shows that the smaller the GO is, the larger the expansion head loss becomes. This head loss, evidently, becomes null when the gate is fully open (i.e., $v_G = v_C$).

Exit head loss, h_o, is created at the culvert outlet and computed as follows,

$$h_o = K_o \times \frac{v_C^{\ 2}}{2g} \qquad \text{(A10)}$$

where K_o = exit loss coefficient and is generally equal to one.

Friction head loss, h_f (ft), is estimated from Manning equation as follows,

$$h_f = \left[\frac{Q \times n}{1.49 \times A \times R^{2/3}} \right]^2 \times L \qquad \text{(A11)}$$

where Q = discharge (cfs), n = Manning's roughness coefficient (sec/ft$^{1/3}$), A = full flow box culvert area (ft^2), R_h = full flow box culvert hydraulic radius (ft), L = box culvert length (ft), and 1.49 = conversion factor for English units.

The K_e, K_o and Manning's n coefficients are 0.28, 1.0 and 0.012 sec/ft$^{1/3}$, respectively, and coincide with those used for design (Table 5). The selected value for K_{exp} was 0.60.

Model Simulations

The first simulation was performed for Q equal to 500 cfs (Table A1). The two boxes of the S-13A culvert are equally operated and each box discharges 250 cfs. Headwater stage was maintained at 3.0 ft NGVD (Y_1 = 7.0 ft) and the tailwater ranged from 0.0 to 2.46 ft NGVD (Y_3 from 4.0 to 6.46 ft).

Free flow was obtained for a GO of 1.52 ft from the minimum tailwater stage of 0.0 ft NGVD (Y_3 = 4.0 ft) to 0.88 ft NGVD (Y_3 = 4.88 ft) which corresponds to the sequent depth (y_s) of the hydraulic jump. From then on, Y_3 and GO begin to increase up to 6.05 and 2.51 ft (y_c = 2.69 ft), respectively to yield drowned flow conditions. For drowned flow condition, the drowned flow depths (Y_{2d}) downstream of the gate computed from the specific energy (A2) and momentum (A5) equations are equal (columns 15 and 16, respectively). The free flow depth (Y_2) downstream of the gate is smaller than the critical depth (y_c), and therefore Fr_2 will be greater than one (columns 6 and 11). However drowned flow tends to be subcritical (Fr smaller than one) at least for conditions apart from the transition zone with the free flow regime. Additional increases to Y_3 and GO will create eventually the transition to full flow regime. The GO should be greater than y_c (2.69 ft), which indicates the transition to subcritical flow downstream of the gate ($Fr_2 < 1$). For full flow, total submergence will exist and the total head loss will match the available head (columns 27 and 28) imposed by the upstream and downstream stages at the culvert (Hw – Tw). When the two gates are fully open, the total head loss of 0.54 ft matches exactly the result obtained from the design using the culvert equation (Figure 6).

Additional simulations were performed for discharges from 450 to 250 cfs in increments of 50 cfs (Tables A2 through A6) and Hw stage at 3.0 ft NGVD (Y_1 = 7.0 ft). Tables A7 through A12 contain the simulations for discharges from 500 to 250 cfs also in increments of 50 cfs and Hw stage at 2.5 ft NGVD (Y_1 = 6.5 ft). The last row in each table contains the simulation for the gates fully open. Total head loss values equal those values computed for design from the culvert equation as depicted in Figure 6.

Figures A2 and A3 depict the flow regulation results through the gates from the simulations with Hw stages at 3.0 and 2.5 ft NGVD (Y_1 = 7.0 and 6.5 ft, respectively). The three flow regimes are represented by the downstream flow depth (Y_3) as a function of the gate opening (GO) expressed as a percent of the box culvert height (H) which is 5.0 ft.

Discharge coefficient (C_d) for the gates under free flow conditions were computed from the following equation,

$$Q = C_d \times GO \times B \times \sqrt{2g \times Y_1} \qquad \text{(A12)}$$

Table A13 contains the discharge coefficients computed from Equation A12 for free flow conditions simulations with the two Hw stages selected (3.0 and 2.5 ft NGVD). For free flow conditions under constant inlet control, the discharge coefficient (C_d) increases as the flow (Q), gate opening (GO), and downstream flow depth (Y_3) decrease. Free flow conditions cannot occur for flow smaller than 350 cfs (175 cfs through each box) because their sequent depths (y_s) are smaller than $Y_{3\,min}$ of 4.0 ft which corresponds to a minimum Tailwater stage of 0 ft NGVD imposed to the simulations (Tables A5, A6, A11, and A12).

Finally, for inlet control (i.e., no influence of the tailwater stage) under constant flow, the Hw stage decreases as C_d decreases. Decreases in C_d will become smaller as the flows diminish.

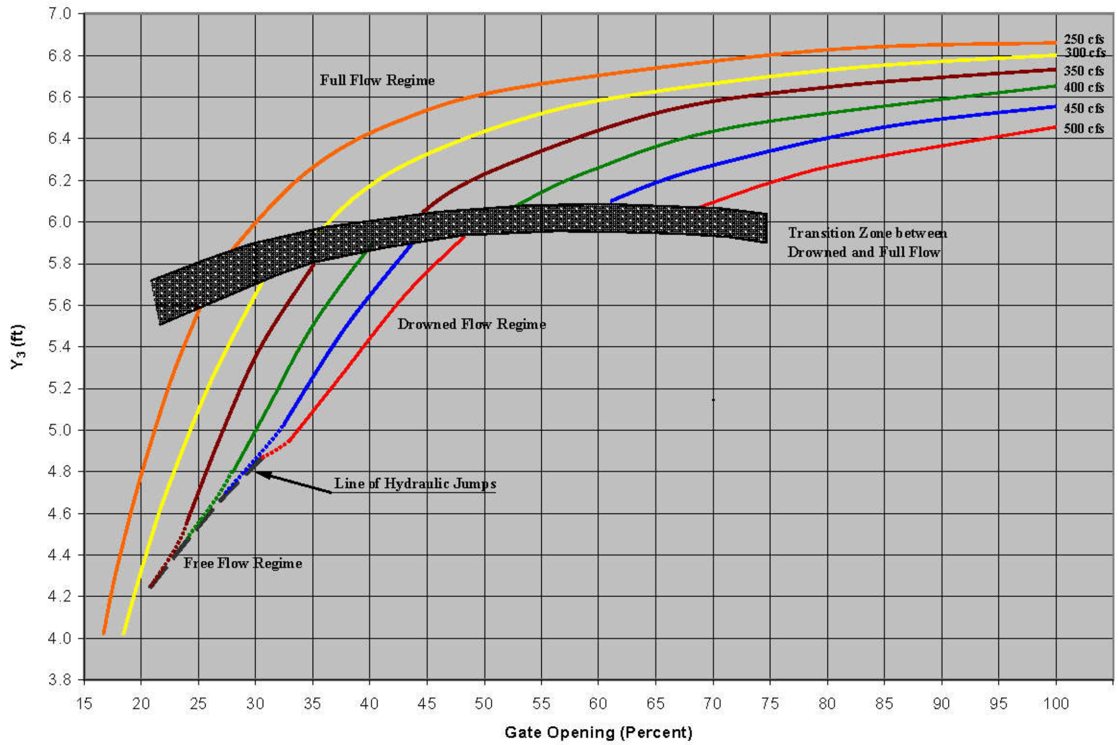

Figure A2. Flow results from simulations for Hw stage at 3.0 ft NGVD (Y_1=7.0 ft)

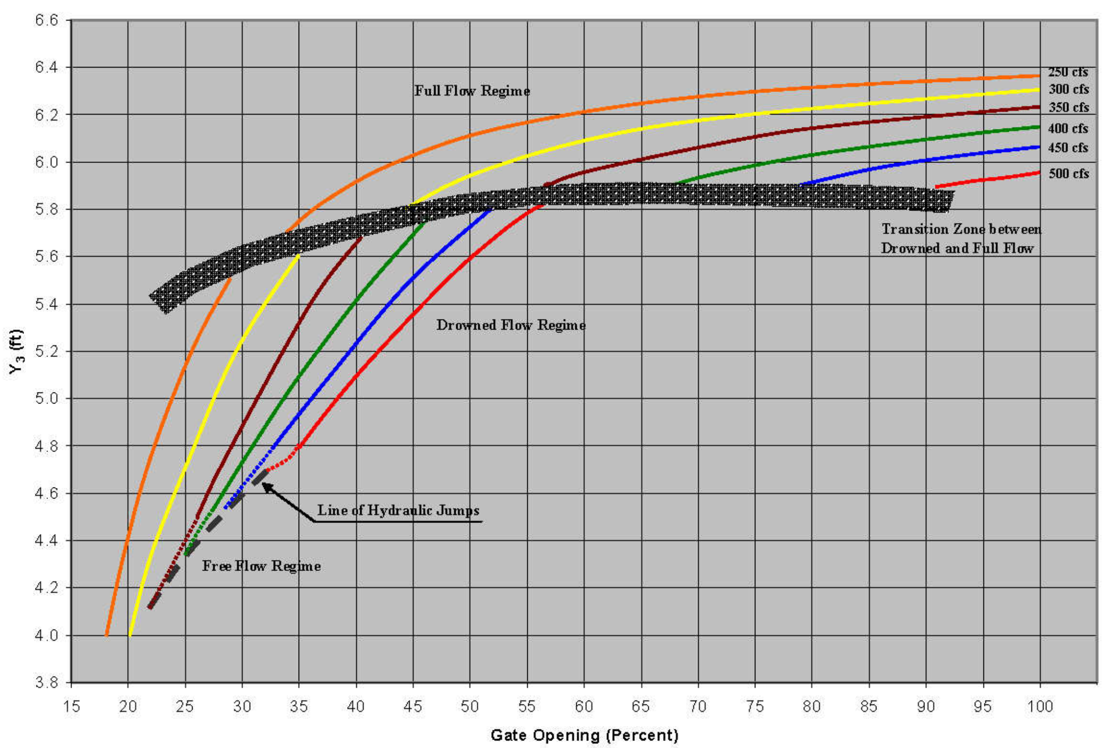

Figure A3. Flow results from simulations for Hw stage at 2.5 ft NGVD (Y_1=6.5 ft)

Tables

Table A1. Hydraulic model for flow regulation through the sluice gates of the new S-13A Structure (double-box concrete culvert, each box 250 cfs) in the C-11 Canal.
Q = 500 cfs and Hw Stage = 3.0 ft NGVD (Y_1 = 7.0 ft)

Invert Elevation (ft NGVD)	**-4.00**
No. of Boxes	**2**
Box Culvert Height, H (ft)	**5.00**
Box Culvert Width, B (ft)	**10.00**
Inlet Width (ft)	**13.00**
Box Culvert Length, L (ft)	**50.00**
$^*y_c$ = 2.69 ft	

Entrance loss coefficient, K_e	**0.28**	
Expansion loss coefficient, K_{exp}	**0.60**	
Exit loss coefficient, K_o	**1.00**	
Manning's n coefficient ($sec/ft^{1/3}$)	**0.012**	
Vena Contracta Coefficient, C_{vc}	**0.85**	Flow depth D/S of gate (Y_2) for free flow conditions (C_{vc}*GO)

Full Flow Culvert Computations

Box Flow Area, A (ft^2)	**50.00**
Box Wetted Perimeter, P_w (ft)	**30.00**
Box Hydraulic Radius, R_h (ft)	**1.67**

Hydraulic Jump Computations

13	**Sequent Depth, y_s (ft)**	**4.88**	It is the maximum Tw for free flow conditions (=Y_{3max})
17	**H. J. Length, L_j (ft)**	**25.41**	
18	**H. J. Loss, ΔE (ft)**	**1.83**	Loss must match the difference between Specific Energy U/S and D/S of Hydraulic Jump (=E_2-E_3)

Flow Regime	Flow Q (cfs)	Stage Hw (ft NGVD)	Stage Tw (ft NGVD)	Opening GO (ft)	Flow Depth Hw Y_1 (ft)	Flow Depth D/S of G Y_2 (ft)	Flow Depth Tw Y_3 (ft)	Specific Energy E_1 (ft)	Specific Energy E_2 (ft)	Specific Energy E_3 (ft)	Froude Number Fr_2 Free Flow	Froude Number Fr_3 Tw	Max TW Free Flow Y_{3max} (ft)	Drowned Flow? Yes/No	Drowned Depth Y_{2d} D/S of Gate Energy (ft)	Drowned Depth Y_{2d} D/S of Gate Momentum (ft)	Specific Energy E_{2d} (ft)	Box Full? Yes/No	Full Flow Conditions Velocity Head Gate (ft)	Velocity Head Box (ft)	Culvert Head Losses Entrance (ft)	Expans. (ft)	Exit (ft)	Friction (ft)	Total (ft)	Available Head (ft)	Comments
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	19	20	21	22	23	24	25	26	27	28	
Free Flow D/S Gate	500	3.00	0.00	1.52	7.00	1.29	4.00	7.12	7.12	4.61	3.01	0.55	4.88	No	1.29	#NUM!	N/A	No	4.21	0.39						3.000	
	500	3.00	0.20	1.52	7.00	1.29	4.20	7.12	7.12	4.75	3.01	0.51	4.88	No	1.29	#NUM!	N/A	No	4.21	0.39						2.800	
	500	3.00	0.40	1.52	7.00	1.29	4.40	7.12	7.12	4.90	3.01	0.48	4.88	No	1.29	#NUM!	N/A	No	4.21	0.39						2.600	
	500	3.00	0.60	1.52	7.00	1.29	4.60	7.12	7.12	5.06	3.01	0.45	4.88	No	1.29	#NUM!	N/A	No	4.21	0.39						2.400	
	500	3.00	0.88	1.52	7.00	1.29	4.88	7.12	**7.12**	**5.29**	3.01	0.41	4.88	No	1.29	1.29	N/A	No	4.21	0.39						2.122	Hydraulic Jump for 250 cfs
Drowned Flow	500	3.00	0.95	1.64	7.00	1.39	4.95	7.12	6.40	5.35	2.68	0.40	4.63	Yes	2.11	2.11	4.29	No	3.62	0.39	1.01	1.94	0.39	0.04	3.379	2.050	Drowned flow for Y_{2s} up to
	500	3.00	1.15	1.79	7.00	1.52	5.15	7.12	5.71	5.52	2.35	0.38	4.35	Yes	2.92	2.92	4.06	No	3.03	0.39	0.85	1.58	0.39	0.04	2.862	1.850	5.0 ft (Box Culvert Height)
	500	3.00	1.25	1.86	7.00	1.58	5.25	7.12	5.46	5.60	2.22	0.37	4.23	Yes	3.23	3.23	4.16	No	2.81	0.39	0.79	1.45	0.39	0.04	2.665	1.750	and GO < y_c
	500	3.00	1.45	1.99	7.00	1.69	5.45	7.12	5.09	5.78	2.01	0.35	4.02	Yes	3.72	3.72	4.42	No	2.46	0.39	0.69	1.24	0.39	0.04	2.357	1.550	
	500	3.00	1.65	2.14	7.00	1.82	5.65	7.12	4.75	5.95	1.80	0.33	3.80	Yes	4.18	4.18	4.73	No	2.12	0.39	0.59	1.04	0.39	0.04	2.061	1.350	
	500	3.00	1.85	2.30	7.00	1.96	5.85	7.12	4.49	6.13	1.61	0.31	3.58	Yes	4.58	4.58	5.04	No	1.83	0.39	0.51	0.87	0.39	0.04	1.811	1.150	
	500	3.00	2.05	2.51	7.00	2.13	6.05	7.12	4.27	6.32	1.42	0.30	3.33	Yes	4.98	4.98	5.37	No	1.55	0.39	0.43	0.69	0.39	0.04	1.556	0.950	
Full Flow	500	3.00	2.07	3.41	7.00	2.90	6.07	7.12	4.05	6.33	0.89	0.29	2.49	Yes	5.96	5.46	N/A	Yes	0.83	0.39	0.23	0.27	0.39	0.04	0.930	0.930	Full flow Q = 250 cfs by
	500	3.00	2.10	3.48	7.00	2.96	6.10	7.12	4.07	6.36	0.86	0.29	2.43	Yes	6.01	5.52	N/A	Yes	0.80	0.39	0.22	0.25	0.39	0.04	0.900	0.900	increasing GO.
	500	3.00	2.20	3.76	7.00	3.20	6.20	7.12	4.15	6.45	0.77	0.29	2.23	Yes	6.17	5.71	N/A	Yes	0.69	0.39	0.19	0.18	0.39	0.04	0.800	0.800	Flow totally submerged
	500	3.00	2.30	4.12	7.00	3.50	6.30	7.12	4.29	6.54	0.67	0.28	2.01	Yes	6.33	5.90	N/A	Yes	0.57	0.39	0.16	0.11	0.39	0.04	0.700	0.700	
	500	3.00	2.40	4.60	7.00	3.91	6.40	7.12	4.54	6.64	0.57	0.27	1.75	Yes	6.48	6.09	N/A	Yes	0.46	0.39	0.13	0.04	0.39	0.04	0.600	0.600	
	500	3.00	2.46	5.00	7.00	4.25	6.46	7.12	4.50	6.69	0.50	0.27	1.57	Yes	6.58	6.22	N/A	Yes	0.39	0.39	0.11	0.00	0.39	0.04	**0.538**	**0.538**	Gates fully open

*. Critical Depth for box culvert computed from Eq. A1

Y_2>y_c → Fr_2<1.0

It doesn't correspond with drowned flow

It matches Culvert Equation in Figure 6

1. Flow Discharge
2. Headwater Stage (west side of structure)
3. Tailwater Stage (east side of structure)
4. Gate Opening from invert elevation of -4.0 ft NGVD
5. Upstream (Hw) Flow Depth (west side of structure)
6. Flow Depth (Free Flow) just downstream of gate based on assumed Vena Contracta Coefficient (C_c)
7. Downstream (Tw) Flow Depth (west side of structure)
8. Specific Energy upstream of structure computed from Eq. A2 with Inlet Width (Refer to Fig. A1)
9. Specific Energy just downstream of gate (contracted jet only) computed from Eq. A2 (Refer to Fig. A1)
10. Specific Energy downstream of structure computed from Eq. A2 (Refer to Fig. A1)
11. Froude Number of contracted jet under free flow conditions computed from Eq. A3
12. Froude Number for flow downstream of structure (Tw) computed from Eq. A3
13. Sequent Depth of hydraulic jump downstream of gate computed from Eq. A4
14. Is jet drowned by Hydraulic Jump downstream of gate? If Y_3 is greater than Y_{3max} (=y_s), Yes
15. Drowned Flow Depth computed (Energy basis) from Specific Energy (Eq. A2)
16. Drowned Flow Depth computed (Momentum basis) from Eq. A5
17. Length of the Hydraulic Jump (only for free flow conditions) computed from Eq. A6
18. Energy losses in a horizontal Hydraulic Jump computed from Eq. A7
19. Specific Energy just downstream of gate for drowning conditions (TW=Y_3>Sequent Depth [13]) computed from Eq. A2
20. Is the culvert flowing full? Both boxes are equally operated and carry the same flow, in this case
21. Velocity Head at gate entrance [$v^2/(2g)$], through GO
22. Velocity Head in culvert box (full flow conditions)
23. Entrance Head Loss considering full flow through the gate opening (GO) from Eq. A8
24. Expansion Head Loss D/S of gate to account for GO from Eq. A9
25. Exit Head Loss at the culvert outlet from Eq. A10
26. Friction Head Loss under full flow conditions (using Manning Equation) from Eq. A11
27. Total Head Loss under full flow conditions ([23]+[24]+[25]+[26])
28. Available Head as the difference between Hw and Tw ([2]-[3])

Criteria to Estimate the Required GO

A. Free Flow

If free flow conditions exist D/S of the gate (Y_2 < y_c), then Specific Energy just U/S and D/S of the gate must be equal, so **[8] = [9]**

B. Drowned Flow

If jet downstream of gate is drowned (Y_3 greater than Sequent Depth of Hydraulic Jump), then the Flow Depth (Y_{2d}) computed from Energy basis must be equal to that computed from Momentum basis, therefore **[15] = [16]**

C. Full Flow

If culvert is flowing full (Y_{2d} greater than or equal to 5.0 ft the Box Culvert Height), then the Total Head Loss must match the Available Head, thus **[27] = [28]**

Table A2. Hydraulic model simulation for Q = 450 cfs and Hw Stage = 3.0 ft NGVD (Y_1 = 7.0 ft). Two-box culvert under same operation, 225 cfs each

Invert Elevation (ft NGVD)	-4.00
No. of Boxes	2
Box Culvert Height, H (ft)	5.00
Box Culvert Width, B (ft)	10.00
Inlet Width (ft)	13.00
Box Culvert Length, L (ft)	50.00

Entrance loss coefficient, K_e	0.28
Expansion loss coefficient, K_{exp}	0.60
Exit loss coefficient, K_o	1.00
Manning's n coefficient (sec/ft$^{1/3}$)	0.012
Vena contracta coefficient, C_{vc}	0.85

Full Flow Culvert Computations

Box Flow Area, A (ft^2)	50.00
Box Wetted Perimeter, P_w (ft)	30.00
Box Hydraulic Radius, R_h (ft)	1.67

Hydraulic Jump Computations

13	Sequent Depth, y_s (ft)	4.69
17	H. J. Length, L_j (ft)	25.04
18	H. J. Loss, ΔE (ft)	**2.05**

y_c = **2.51 ft**					Flow Depth								Max TW		Drowned Depth Y_{2d}		Specific		Full Flow Conditions							
Flow Regime	Flow Q (cfs)	Stage Hw (ft NGVD)	Stage Tw (ft NGVD)	Opening GO (ft)	Hw Y_1 (ft)	D/S of G Y_2 (ft)	Tw Y_3 (ft)	Specific Energy E_1 (ft)	Specific Energy E_2 (ft)	Specific Energy E_3 (ft)	Froude Number Fr_2 Free Flow	Froude Number Fr_3	Free Flow $Y_{3\,max}$ (ft)	Drowned Flow? Yes/No	D/S of Gate Energy (ft)	D/S of Gate Momentum (ft)	Energy E_{2d} (ft)	Box Full? Yes/No	Velocity Head Gate (ft)	Velocity Head Box (ft)	Culvert Head Losses Entrance (ft)	Expans. (ft)	Exit (ft)	Friction (ft)	Total (ft)	Available Head (ft)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	19	20	21	22	23	24	24	26	27	28
Free Flow	450	3.00	0.00	1.35	7.00	1.15	4.00	7.09	7.09	4.49	3.22	0.50	4.69	No	1.15	#NUM!	N/A	No	4.30	0.31						3.00
D/S Gate	450	3.00	0.10	1.35	7.00	1.15	4.10	7.09	7.09	4.57	3.22	0.48	4.69	No	1.15	#NUM!	N/A	No	4.30	0.31						2.90
	450	3.00	0.20	1.35	7.00	1.15	4.20	7.09	7.09	4.65	3.22	0.46	4.69	No	1.15	#NUM!	N/A	No	4.30	0.31						2.80
	450	3.00	0.30	1.35	7.00	1.15	4.30	7.09	7.09	4.73	3.22	0.44	4.69	No	1.15	#NUM!	N/A	No	4.30	0.31						2.70
	450	3.00	0.50	1.35	7.00	1.15	4.50	7.09	7.09	4.89	3.22	0.42	4.69	No	1.15	#NUM!	N/A	No	4.30	0.31						2.50
	450	3.00	0.68	1.35	7.00	1.15	4.68	7.09	**7.09**	**5.04**	3.22	0.39	4.69	No	**1.15**	**1.14**	N/A	No	4.30	0.31						2.32
Drowned	450	3.00	0.80	1.49	7.00	1.26	4.80	7.09	6.19	5.14	2.79	0.38	4.40	Yes	2.17	2.17	3.84	No	3.56	0.31	1.00	1.95	0.31	0.03	3.29	2.20
Flow	450	3.00	0.85	1.52	7.00	1.29	4.85	7.09	6.01	5.18	2.71	0.37	4.33	Yes	2.37	2.37	3.77	No	3.41	0.31	0.96	1.86	0.31	0.03	3.16	2.15
	450	3.00	1.10	1.66	7.00	1.41	5.10	7.09	5.37	5.40	2.37	0.34	4.07	Yes	3.14	3.14	3.94	No	2.86	0.31	0.80	1.53	0.31	0.03	2.68	1.90
	450	3.00	1.30	1.77	7.00	1.51	5.30	7.09	4.97	5.58	2.15	0.32	3.88	Yes	3.63	3.63	4.22	No	2.50	0.31	0.70	1.31	0.31	0.03	2.36	1.70
	450	3.00	1.50	1.89	7.00	1.61	5.50	7.09	4.65	5.76	1.95	0.31	3.69	Yes	4.05	4.05	4.53	No	2.20	0.31	0.62	1.13	0.31	0.03	2.10	1.50
	450	3.00	1.70	2.02	7.00	1.72	5.70	7.09	4.38	5.94	1.76	0.29	3.50	Yes	4.44	4.44	4.84	No	1.92	0.31	0.54	0.96	0.31	0.03	1.85	1.30
	450	3.00	1.90	2.18	7.00	1.85	5.90	7.09	4.14	6.13	1.57	0.28	3.30	Yes	4.81	4.81	5.15	No	1.65	0.31	0.46	0.80	0.31	0.03	1.61	1.10
Full Flow	450	3.00	2.10	3.05	7.00	2.59	6.10	7.09	3.76	6.31	0.95	0.26	2.42	Yes	5.92	5.50	5.76	Yes	0.85	0.31	0.24	0.32	0.31	0.03	0.90	0.90
	450	3.00	2.15	3.17	7.00	2.69	6.15	7.09	3.78	6.36	0.90	0.26	2.32	Yes	6.01	5.59	5.84	Yes	0.78	0.31	0.22	0.28	0.31	0.03	0.85	0.85
	450	3.00	2.25	3.42	7.00	2.91	6.25	7.09	3.84	6.45	0.80	0.25	2.14	Yes	6.16	5.77	6.00	Yes	0.67	0.31	0.19	0.21	0.31	0.03	0.75	0.75
	450	3.00	2.35	3.75	7.00	3.19	6.35	7.09	3.96	6.54	0.70	0.25	1.93	Yes	6.32	5.95	6.17	Yes	0.56	0.31	0.16	0.15	0.31	0.03	0.65	0.65
	450	3.00	2.45	4.21	7.00	3.58	6.45	7.09	4.19	6.64	0.59	0.24	1.67	Yes	6.48	6.14	6.35	Yes	0.44	0.31	0.12	0.08	0.31	0.03	0.55	0.55
Gates Open	450	3.00	2.56	5.00	7.00	4.25	6.56	7.09	4.50	6.75	0.45	0.24	1.33	Yes	6.66	6.36	6.56	Yes	0.31	0.31	0.09	0.00	0.31	0.03	**0.44**	**0.44**

$Y_2 > y_c \rightarrow Fr_2 < 1.0$

It doesn't correspond with drowned flow

It matches culvert Eq. (Figure 6)

Table A3. Hydraulic model simulation for Q = 400 cfs and Hw Stage = 3.0 ft NGVD (Y_1 = 7.0 ft). Two-box culvert under same operation, 200 cfs each

Invert Elevation (ft NGVD)	-4.00
No. of Boxes	2
Box Culvert Height, H (ft)	5.00
Box Culvert Width, B (ft)	10.00
Inlet Width (ft)	13.00
Box Culvert Length, L (ft)	50.00

Entrance loss coefficient, K_e	0.28
Expansion loss coefficient, K_{exp}	0.60
Exit loss coefficient, K_o	1.00
Manning's n coefficient (sec/ft$^{1/3}$)	0.012
Vena contracta coefficient, C_{vc}	0.85

Full Flow Culvert Computations

Box Flow Area, A (ft^2)	50.00
Box Wetted Perimeter, P_w (ft)	30.00
Box Hydraulic Radius, R_h (ft)	1.67

Hydraulic Jump Computations

13	Sequent Depth, y_s (ft)	4.47
17	H. J. Length, L_j (ft)	24.51
18	H. J. Loss, ΔE (ft)	**2.29**

y_c = 2.32 ft					Flow Depth								Max TW		Drowned Depth Y_{2d}		Specific		Full Flow Conditions							
Flow Regime	Flow Q (cfs)	Stage Hw (ft NGVD)	Stage Tw (ft NGVD)	Opening GO (ft)	Hw Y_1 (ft)	D/S of G Y_2 (ft)	Tw Y_3 (ft)	Specific Energy E_1 (ft)	Specific Energy E_2 (ft)	Specific Energy E_3 (ft)	Froude Number Fr_2 Free Flow	Froude Number Fr_3	Free Flow $Y_{3\,max}$ (ft)	Drowned Flow? Yes/No	D/S of Gate Energy (ft)	D/S of Gate Momentum (ft)	Energy E_{2d} (ft)	Box Full? Yes/No	Velocity Head Gate (ft)	Velocity Head Box (ft)	Culvert Head Losses Entrance (ft)	Culvert Head Losses Expans. (ft)	Culvert Head Losses Exit (ft)	Culvert Head Losses Friction (ft)	Culvert Head Losses Total (ft)	Available Head (ft)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	19	20	21	22	23	24	24	26	27	28
Free Flow	400	3.00	0.00	1.19	7.00	1.01	4.00	7.08	7.08	4.39	3.46	0.44	4.47	No	1.01	#NUM!	N/A	No	4.38	0.25						3.00
D/S Gate	400	3.00	0.10	1.19	7.00	1.01	4.10	7.08	7.08	4.47	3.46	0.42	4.47	No	1.01	#NUM!	N/A	No	4.38	0.25						2.90
	400	3.00	0.20	1.19	7.00	1.01	4.20	7.08	7.08	4.55	3.46	0.41	4.47	No	1.01	#NUM!	N/A	No	4.38	0.25						2.80
	400	3.00	0.30	1.19	7.00	1.01	4.30	7.08	7.08	4.64	3.46	0.40	4.47	No	1.01	#NUM!	N/A	No	4.38	0.25						2.70
	400	3.00	0.47	1.19	7.00	1.01	4.47	7.08	**7.08**	**4.78**	3.46	0.37	4.47	No	**1.01**	**1.01**	N/A	No	4.38	0.25						2.53
Drowned	400	3.00	0.65	1.33	7.00	1.13	4.65	7.08	5.97	4.94	2.92	0.35	4.15	Yes	2.24	2.24	3.48	No	3.50	0.25	0.98	1.95	0.25	0.03	3.20	2.35
Flow	400	3.00	0.85	1.43	7.00	1.21	4.85	7.08	5.43	5.11	2.64	0.33	3.96	Yes	2.86	2.86	3.62	No	3.05	0.25	0.85	1.68	0.25	0.03	2.81	2.15
	400	3.00	1.10	1.54	7.00	1.31	5.10	7.08	4.93	5.34	2.35	0.31	3.75	Yes	3.45	3.45	3.97	No	2.62	0.25	0.73	1.42	0.25	0.03	2.43	1.90
	400	3.00	1.30	1.63	7.00	1.39	5.30	7.08	4.61	5.52	2.15	0.29	3.59	Yes	3.86	3.86	4.28	No	2.33	0.25	0.65	1.25	0.25	0.03	2.17	1.70
	400	3.00	1.50	1.74	7.00	1.48	5.50	7.08	4.31	5.71	1.96	0.27	3.42	Yes	4.24	4.24	4.59	No	2.05	0.25	0.57	1.08	0.25	0.03	1.93	1.50
	400	3.00	1.70	1.86	7.00	1.58	5.70	7.08	4.06	5.89	1.77	0.26	3.25	Yes	4.60	4.60	4.89	No	1.79	0.25	0.50	0.92	0.25	0.03	1.70	1.30
	400	3.00	1.90	2.01	7.00	1.71	5.90	7.08	3.84	6.08	1.58	0.25	3.05	Yes	4.95	4.95	5.20	No	1.54	0.25	0.43	0.77	0.25	0.03	1.48	1.10
Full Flow	400	3.00	2.05	2.58	7.00	2.33	6.05	7.08	3.47	6.22	0.99	0.24	2.30	Yes	5.93	5.48	5.69	Yes	0.93	0.25	0.26	0.41	0.25	0.03	0.95	0.95
	400	3.00	2.15	2.74	7.00	2.52	6.15	7.08	3.50	6.31	0.88	0.23	2.13	Yes	6.09	5.66	5.85	Yes	0.83	0.25	0.23	0.35	0.25	0.03	0.85	0.85
	400	3.00	2.25	2.96	7.00	2.74	6.25	7.08	3.57	6.41	0.78	0.23	1.94	Yes	6.25	5.83	6.01	Yes	0.71	0.25	0.20	0.28	0.25	0.03	0.75	0.75
	400	3.00	2.35	3.22	7.00	3.06	6.35	7.08	3.72	6.50	0.66	0.22	1.70	Yes	6.41	6.01	6.18	Yes	0.60	0.25	0.17	0.21	0.25	0.03	0.65	0.65
	400	3.00	2.45	3.60	7.00	4.25	6.45	7.08	4.59	6.60	0.40	0.22	1.09	Yes	6.73	6.29	6.45	Yes	0.48	0.25	0.13	0.14	0.25	0.03	0.55	0.55
Gates Open	400	3.00	2.66	5.00	7.00	4.25	6.66	7.08	4.50	6.80	0.40	0.21	1.09	Yes	6.73	6.50	6.64	Yes	0.25	0.25	0.07	0.00	0.25	0.03	**0.34**	**0.34**

$Y_2 > y_c \rightarrow Fr_2 < 1.0$

It doesn't correspond with drowned flow

It matches culvert Eq. (Figure 6)

Table A4. Hydraulic model simulation for Q = 350 cfs and Hw Stage = 3.0 ft NGVD (Y_1 = 7.0 ft). Two-box culvert under same operation, 175 cfs each

Invert Elevation (ft NGVD)	-4.00
No. of Boxes	2
Box Culvert Height, H (ft)	5.00
Box Culvert Width, B (ft)	10.00
Inlet Width (ft)	13.00
Box Culvert Length, L (ft)	50.00

Entrance loss coefficient, K_e	0.28
Expansion loss coefficient, K_{exp}	0.60
Exit loss coefficient, K_o	1.00
Manning's n coefficient (sec/ft$^{1/3}$)	0.012
Vena contracta coefficient, C_{vc}	0.85

Full Flow Culvert Computations

Box Flow Area, A (ft^2)	50.00
Box Wetted Perimeter, P_w (ft)	30.00
Box Hydraulic Radius, R_h (ft)	1.67

Hydraulic Jump Computations

13	Sequent Depth, y_s (ft)	4.24
17	H. J. Length, L_j (ft)	23.79
18	H. J. Loss, ΔE (ft)	**2.56**

y_c = 2.12 ft					Flow Depth								Max TW		Drowned Depth Y_{2d}		Specific		Full Flow Conditions							
Flow Regime	Flow Q (cfs)	Stage Hw (ft NGVD)	Stage Tw (ft NGVD)	Opening GO (ft)	Hw Y_1 (ft)	D/S of G Y_2 (ft)	Tw Y_3 (ft)	Specific Energy E_1 (ft)	Specific Energy E_2 (ft)	Specific Energy E_3 (ft)	Froude Number Fr_2 Free Flow	Froude Number Fr_3	Free Flow $Y_{3\,max}$ (ft)	Drowned Flow? Yes/No	D/S of Gate Energy (ft)	D/S of Gate Momentum (ft)	Energy E_{2d} (ft)	Box Full? Yes/No	Velocity Head Gate (ft)	Velocity Head Box (ft)	Culvert Head Losses Entrance (ft)	Culvert Head Losses Expans. (ft)	Culvert Head Losses Exit (ft)	Culvert Head Losses Friction (ft)	Culvert Head Losses Total (ft)	Available Head (ft)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	19	20	21	22	23	24	24	26	27	28
Free Flow	350	3.00	0.00	1.03	7.00	0.88	4.00	7.06	7.06	4.30	3.75	0.39	4.24	No	0.88	#NUM!	N/A	No	4.47	0.19						3.00
D/S Gate	350	3.00	0.05	1.03	7.00	0.88	4.05	7.06	7.06	4.34	3.75	0.38	4.24	No	0.88	#NUM!	N/A	No	4.47	0.19						2.95
	350	3.00	0.10	1.03	7.00	0.88	4.10	7.06	7.06	4.38	3.75	0.37	4.24	No	0.88	#NUM!	N/A	No	4.47	0.19						2.90
	350	3.00	0.15	1.03	7.00	0.88	4.15	7.06	7.06	4.43	3.75	0.36	4.24	No	0.88	0.35	N/A	No	4.47	0.19						2.85
	350	3.00	0.20	1.03	7.00	0.88	4.20	7.06	7.06	4.47	3.75	0.36	4.24	No	0.88	0.70	N/A	No	4.47	0.19						2.80
	350	3.00	0.24	1.03	7.00	0.88	4.24	7.06	**7.06**	**4.50**	3.75	0.35	4.24	No	**0.88**	**0.88**	N/A	No	4.47	0.19						2.76
Drowned	350	3.00	0.50	1.18	7.00	1.01	4.50	7.06	5.70	4.73	3.05	0.32	3.87	Yes	2.36	2.36	3.21	No	3.39	0.19	0.95	1.92	0.19	0.02	3.08	2.50
Flow	350	3.00	0.75	1.27	7.00	1.08	4.75	7.06	5.14	4.96	2.74	0.30	3.69	Yes	3.00	3.00	3.53	No	2.93	0.19	0.82	1.65	0.19	0.02	2.68	2.25
	350	3.00	1.00	1.37	7.00	1.16	5.00	7.06	4.69	5.19	2.47	0.28	3.51	Yes	3.52	3.52	3.91	No	2.55	0.19	0.71	1.42	0.19	0.02	2.34	2.00
	350	3.00	1.20	1.44	7.00	1.23	5.20	7.06	4.39	5.38	2.27	0.26	3.37	Yes	3.90	3.90	4.21	No	2.28	0.19	0.64	1.26	0.19	0.02	2.11	1.80
	350	3.00	1.40	1.53	7.00	1.30	5.40	7.06	4.11	5.56	2.08	0.25	3.23	Yes	4.25	4.25	4.51	No	2.03	0.19	0.57	1.10	0.19	0.02	1.88	1.60
	350	3.00	1.60	1.63	7.00	1.39	5.60	7.06	3.86	5.75	1.89	0.23	3.07	Yes	4.59	4.59	4.81	No	1.79	0.19	0.50	0.96	0.19	0.02	1.67	1.40
	350	3.00	1.80	1.75	7.00	1.49	5.80	7.06	3.64	5.94	1.70	0.22	2.91	Yes	4.91	4.91	5.11	No	1.55	0.19	0.44	0.82	0.19	0.02	1.46	1.20
Full Flow	350	3.00	2.05	2.22	7.00	1.89	6.05	7.06	3.22	6.18	1.19	0.21	2.37	Yes	5.72	5.45	5.61	Yes	0.96	0.19	0.27	0.46	0.19	0.02	0.95	0.95
	350	3.00	2.25	2.53	7.00	2.15	6.25	7.06	3.18	6.37	0.98	0.20	2.09	Yes	6.03	5.77	5.91	Yes	0.74	0.19	0.21	0.33	0.19	0.02	0.75	0.75
	350	3.00	2.45	3.03	7.00	2.58	6.45	7.06	3.29	6.56	0.75	0.19	1.72	Yes	6.34	6.10	6.22	Yes	0.52	0.19	0.15	0.20	0.19	0.02	0.55	0.55
	350	3.00	2.65	4.03	7.00	3.43	6.65	7.06	3.83	6.76	0.49	0.18	1.20	Yes	6.65	6.44	6.56	Yes	0.29	0.19	0.08	0.06	0.19	0.02	0.35	0.35
Gates Open	350	3.00	2.74	5.00	7.00	4.25	6.74	7.06	4.50	6.84	0.35	0.18	0.87	Yes	6.79	6.61	6.72	Yes	0.19	0.19	0.05	0.00	0.19	0.02	**0.26**	**0.26**

$Y_2 > y_c \rightarrow Fr_2 < 1.0$

It doesn't correspond with drowned flow

It matches culvert Eq. (Figure 6)

Table A5. Hydraulic model simulation for Q = 300 cfs and Hw Stage = 3.0 ft NGVD (Y_1 = 7.0 ft). Two-box culvert under same operation, 150 cfs each

Invert Elevation (ft NGVD)	-4.00
No. of Boxes	2
Box Culvert Height, H (ft)	5.00
Box Culvert Width, B (ft)	10.00
Inlet Width (ft)	13.00
Box Culvert Length, L (ft)	50.00

Entrance loss coefficient, K_e	0.28
Expansion loss coefficient, K_{exp}	0.60
Exit loss coefficient, K_o	1.00
Manning's n coefficient (sec/ft$^{1/3}$)	0.012
Vena contracta coefficient, C_{vc}	0.85

Full Flow Culvert Computations

Box Flow Area, A (ft^2)	50.00
Box Wetted Perimeter, P_w (ft)	30.00
Box Hydraulic Radius, R_h (ft)	1.67

Hydraulic Jump Computations

13	Sequent Depth, y_s (ft)	3.98
17	H. J. Length, L_j (ft)	N/A
18	H. J. Loss, ΔE (ft)	N/A

Free flow cannot occur since y_s<$Y_{3\,min}$ (4.0 ft)

y_c = 1.91 ft					Flow Depth								Max TW		Drowned Depth Y_{2d}		Specific		Full Flow Conditions							
Flow	Flow	Stage		Opening	Hw	D/S of G	Tw	Specific Energy			Froude Number		Free Flow	Drowned	D/S of Gate		Energy	Box	Velocity Head		Culvert Head Losses					Available
Regime	Q	Hw	Tw	GO	Y_1	Y_2	Y_3	E_1	E_2	E_3	Fr_2	Fr_3	$Y_{3\,max}$	Flow?	Energy	Momentum	E_{2d}	Full?	Gate	Box	Entrance	Expans.	Exit	Friction	Total	Head
	(cfs)	(ft NGVD)		(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	Free Flow		(ft)	Yes/No	(ft)	(ft)	(ft)	Yes/No	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	19	20	21	22	23	24	24	26	27	28
Free Flow	300	3.00	0.00	0.88	7.00	0.74	4.00	7.04	7.04	4.22	4.11	0.33	3.98	No	0.74	0.85	N/A	No	4.55	0.14						3.00
Drowned	300	3.00	0.00	0.91	7.00	0.77	4.00	7.04	6.64	4.22	3.90	0.33	3.89	Yes	1.18	1.18	3.70	No	4.24	0.14	1.19	2.46	0.14	0.01	3.80	3.00
Flow	300	3.00	0.50	1.07	7.00	0.91	4.50	7.04	5.12	4.67	3.04	0.28	3.49	Yes	2.83	2.83	3.27	No	3.04	0.14	0.85	1.74	0.14	0.01	2.75	2.50
	300	3.00	0.75	1.14	7.00	0.97	4.75	7.04	4.68	4.90	2.76	0.26	3.34	Yes	3.33	3.33	3.65	No	2.68	0.14	0.75	1.52	0.14	0.01	2.43	2.25
	300	3.00	1.00	1.22	7.00	1.03	5.00	7.04	4.30	5.14	2.51	0.24	3.19	Yes	3.78	3.78	4.02	No	2.36	0.14	0.66	1.33	0.14	0.01	2.15	2.00
	300	3.00	1.25	1.30	7.00	1.11	5.25	7.04	3.96	5.38	2.27	0.22	3.04	Yes	4.19	4.19	4.39	No	2.06	0.14	0.58	1.15	0.14	0.01	1.88	1.75
	300	3.00	1.50	1.40	7.00	1.19	5.50	7.04	3.65	5.62	2.03	0.20	2.88	Yes	4.59	4.59	4.76	No	1.77	0.14	0.50	0.98	0.14	0.01	1.63	1.50
	300	3.00	1.70	1.50	7.00	1.28	5.70	7.04	3.42	5.81	1.83	0.19	2.73	Yes	4.90	4.90	5.05	No	1.54	0.14	0.43	0.84	0.14	0.01	1.43	1.30
Full Flow	300	3.00	1.90	1.73	7.00	1.47	5.90	7.04	3.09	6.00	1.48	0.18	2.43	Yes	5.43	5.26	5.39	Yes	1.17	0.14	0.33	0.62	0.14	0.01	1.10	1.10
	300	3.00	2.10	1.92	7.00	1.63	6.10	7.04	2.94	6.19	1.27	0.18	2.22	Yes	5.73	5.56	5.68	Yes	0.95	0.14	0.27	0.48	0.14	0.01	0.90	0.90
	300	3.00	2.30	2.21	7.00	1.88	6.30	7.04	2.87	6.39	1.03	0.17	1.95	Yes	6.05	5.87	5.97	Yes	0.72	0.14	0.20	0.35	0.14	0.01	0.70	0.70
	300	3.00	2.40	2.42	7.00	2.06	6.40	7.04	2.88	6.49	0.90	0.16	1.77	Yes	6.22	6.03	6.13	Yes	0.60	0.14	0.17	0.27	0.14	0.01	0.60	0.60
	300	3.00	2.60	3.08	7.00	2.62	6.60	7.04	3.13	6.68	0.62	0.16	1.35	Yes	6.53	6.35	6.44	Yes	0.37	0.14	0.10	0.14	0.14	0.01	0.40	0.40
Gates Open	300	3.00	2.81	5.00	7.00	4.25	6.81	7.04	4.50	6.88	0.30	0.15	0.67	Yes	6.85	6.72	6.79	Yes	0.14	0.14	0.04	0.00	0.14	0.01	0.19	0.19

Y_2>y_c → Fr_2<1.0

It matches culvert Eq. (Figure 6)

Table A6. Hydraulic model simulation for Q = 250 cfs and Hw Stage = 3.0 ft NGVD (Y_1 = 7.0 ft). Two-box culvert Under same operation, 125 cfs each

Invert Elevation (ft NGVD)	-4.00
No. of Boxes	2
Box Culvert Height, H (ft)	5.00
Box Culvert Width, B (ft)	10.00
Inlet Width (ft)	13.00
Box Culvert Length, L (ft)	50.00

Entrance loss coefficient, K_e	0.28
Expansion loss coefficient, K_{exp}	0.60
Exit loss coefficient, K_o	1.00
Manning's n coefficient (sec/ft$^{1/3}$)	0.012
Vena contracta coefficient, C_{vc}	0.85

Full Flow Culvert Computations

Box Flow Area, A (ft^2)	50.00
Box Wetted Perimeter, P_w (ft)	30.00
Box Hydraulic Radius, R_h (ft)	1.67

Hydraulic Jump Computations

13	Sequent Depth, y_s (ft)	3.68
17	H. J. Length, L_j (ft)	N/A
18	H. J. Loss, ΔE (ft)	N/A

Free flow cannot occur since y_s<$Y_{3\,min}$ (4.0 ft)

y_c = 1.69 ft

Flow Regime	Flow Q (cfs)	Stage Hw (ft NGVD)	Stage Tw (ft NGVD)	Opening GO (ft)	Flow Depth Hw Y_1 (ft)	Flow Depth D/S of G Y_2 (ft)	Flow Depth Tw Y_3 (ft)	Specific Energy E_1 (ft)	Specific Energy E_2 (ft)	Specific Energy E_3 (ft)	Froude Number Fr_2 Free Flow	Froude Number Fr_3	Max TW Free Flow $Y_{3\,max}$ (ft)	Drowned Flow? Yes/No	Drowned Depth Y_{2d} D/S of Gate Energy (ft)	Drowned Depth Y_{2d} D/S of Gate Momentum (ft)	Specific Energy E_{2d} (ft)	Box Full? Yes/No	Full Flow Velocity Head Gate (ft)	Full Flow Velocity Head Box (ft)	Culvert Head Losses Entrance (ft)	Culvert Head Losses Expans. (ft)	Culvert Head Losses Exit (ft)	Culvert Head Losses Friction (ft)	Culvert Head Losses Total (ft)	Available Head (ft)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	19	20	21	22	23	24	24	26	27	28
Free Flow	250	3.00	0.00	0.72	7.00	0.61	4.00	7.03	7.03	4.15	4.57	0.28	3.68	No	0.61	1.63	N/A	No	4.64	0.10						3.00
Drowned	250	3.00	0.00	0.83	7.00	0.71	4.00	7.03	5.57	4.15	3.71	0.28	3.37	Yes	2.16	2.16	2.68	No	3.52	0.10	0.98	2.05	0.10	0.01	3.14	3.00
Flow	250	3.00	0.50	0.94	7.00	0.79	4.50	7.03	4.64	4.62	3.11	0.23	3.12	Yes	3.19	3.19	3.43	No	2.78	0.10	0.78	1.61	0.10	0.01	2.49	2.50
	250	3.00	0.75	0.99	7.00	0.84	4.75	7.03	4.25	4.86	2.84	0.21	3.00	Yes	3.62	3.62	3.81	No	2.46	0.10	0.69	1.42	0.10	0.01	2.21	2.25
	250	3.00	1.00	1.06	7.00	0.90	5.00	7.03	3.91	5.10	2.59	0.20	2.87	Yes	4.01	4.01	4.17	No	2.18	0.10	0.61	1.25	0.10	0.01	1.97	2.00
	250	3.00	1.25	1.13	7.00	0.96	5.25	7.03	3.60	5.34	2.35	0.18	2.74	Yes	4.39	4.39	4.52	No	1.91	0.10	0.53	1.09	0.10	0.01	1.73	1.75
	250	3.00	1.50	1.22	7.00	1.03	5.50	7.03	3.30	5.58	2.09	0.17	2.59	Yes	4.76	4.76	4.86	No	1.64	0.10	0.46	0.92	0.10	0.01	1.49	1.50
	250	3.00	1.60	1.26	7.00	1.07	5.60	7.03	3.20	5.68	2.00	0.17	2.53	Yes	4.90	4.90	5.00	No	1.54	0.10	0.43	0.86	0.10	0.01	1.40	1.40
Full Flow	250	3.00	1.85	1.39	7.00	1.18	5.85	7.03	2.91	5.92	1.71	0.16	2.33	Yes	5.30	5.26	5.35	Yes	1.25	0.10	0.35	0.69	0.10	0.01	1.15	1.15
	250	3.00	2.05	1.54	7.00	1.31	6.05	7.03	2.73	6.12	1.47	0.15	2.15	Yes	5.61	5.55	5.63	Yes	1.03	0.10	0.29	0.56	0.10	0.01	0.95	0.95
	250	3.00	2.25	1.74	7.00	1.48	6.25	7.03	2.59	6.31	1.22	0.14	1.93	Yes	5.92	5.84	5.91	Yes	0.80	0.10	0.22	0.42	0.10	0.01	0.75	0.75
	250	3.00	2.45	2.06	7.00	1.75	6.45	7.03	2.54	6.51	0.95	0.13	1.64	Yes	6.24	6.13	6.19	Yes	0.57	0.10	0.16	0.28	0.10	0.01	0.55	0.55
	250	3.00	2.65	2.68	7.00	2.28	6.65	7.03	2.75	6.70	0.64	0.13	1.22	Yes	6.56	6.44	6.49	Yes	0.34	0.10	0.09	0.14	0.10	0.01	0.35	0.35
Gates Open	250	3.00	2.87	5.00	7.00	4.25	6.87	7.03	4.38	6.92	0.25	0.12	0.48	Yes	6.89	6.80	6.85	Yes	0.10	0.10	0.03	0.00	0.10	0.01	0.13	0.13

Y_2>y_c → Fr_2<1.0

It matches culvert Eq. (Figure 6)

Table A7. Hydraulic model simulation for Q = 500 cfs and Hw Stage = 2.5 ft NGVD (Y_1 = 6.5 ft). Two-box culvert under same operation, 250 cfs each

Invert Elevation (ft NGVD)	-4.00
No. of Boxes	2
Box Culvert Height, H (ft)	5.00
Box Culvert Width, B (ft)	10.00
Inlet Width (ft)	13.00
Box Culvert Length, L (ft)	50.00

Entrance loss coefficient, K_e	0.28
Expansion loss coefficient, K_{exp}	0.60
Exit loss coefficient, K_o	1.00
Manning's n coefficient (sec/ft$^{1/3}$)	0.012
Vena contracta coefficient, C_{vc}	0.85

Full Flow Culvert Computations

Box Flow Area, A (ft^2)	50.00
Box Wetted Perimeter, P_w (ft)	30.00
Box Hydraulic Radius, R_h (ft)	1.67

Hydraulic Jump Computations

13	Sequent Depth, y_s (ft)	4.72
17	H. J. Length, L_j (ft)	23.81
18	H. J. Loss, ΔE (ft)	**1.49**

y_c = 2.69 ft					Flow Depth								Max TW		Drowned Depth Y_{2d}		Specific		Full Flow Conditions							
Flow	Flow	Stage		Opening	Hw	D/S of G	Tw	Specific Energy			Froude Number		Free Flow	Drowned	D/S of Gate		Energy	Box	Velocity Head		Culvert Head Losses					Available
Regime	Q	Hw	Tw	GO	Y_1	Y_2	Y_3	E_1	E_2	E_3	Fr_2	Fr_3	$Y_{3\,max}$	Flow?	Energy	Momentum	E_{2d}	Full?	Gate	Box	Entrance	Expans.	Exit	Friction	Total	Head
	(cfs)	(ft NGVD)		(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	Free Flow		(ft)	Yes/No	(ft)	(ft)	(ft)	Yes/No	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	19	20	21	22	23	24	24	26	27	28
Free Flow	500	2.50	0.00	1.60	6.50	1.36	4.00	6.64	6.64	4.61	2.79	0.55	4.72	No	1.36	#NUM!	N/A	No	3.81	0.39						2.50
D/S Gate	500	2.50	0.10	1.60	6.50	1.36	4.10	6.64	6.64	4.68	2.79	0.53	4.72	No	1.36	#NUM!	N/A	No	3.81	0.39						2.40
	500	2.50	0.20	1.60	6.50	1.36	4.20	6.64	6.64	4.75	2.79	0.51	4.72	No	1.36	#NUM!	N/A	No	3.81	0.39						2.30
	500	2.50	0.30	1.60	6.50	1.36	4.30	6.64	6.64	4.82	2.79	0.49	4.72	No	1.36	#NUM!	N/A	No	3.81	0.39						2.20
	500	2.50	0.50	1.60	6.50	1.36	4.50	6.64	6.64	4.98	2.79	0.46	4.72	No	1.36	0.49	N/A	No	3.81	0.39						2.00
	500	2.50	0.72	1.60	6.50	1.36	4.72	6.64	**6.64**	**5.15**	2.79	0.43	4.72	No	1.36	1.36	N/A	No	3.81	0.39						1.78
Drowned	500	2.50	0.80	1.74	6.50	1.48	4.80	6.64	5.90	5.22	2.44	0.42	4.43	Yes	2.22	2.22	4.19	No	3.19	0.39	0.89	1.68	0.39	0.04	3.00	1.70
Flow	500	2.50	0.85	1.79	6.50	1.52	4.85	6.64	5.70	5.26	2.34	0.41	4.34	Yes	2.46	2.46	4.06	No	3.02	0.39	0.85	1.58	0.39	0.04	2.85	1.65
	500	2.50	1.10	2.00	6.50	1.70	5.10	6.64	5.06	5.47	1.99	0.38	4.00	Yes	3.28	3.28	4.18	No	2.43	0.39	0.68	1.22	0.39	0.04	2.33	1.40
	500	2.50	1.30	2.18	6.50	1.85	5.30	6.64	4.69	5.65	1.75	0.36	3.75	Yes	3.80	3.80	4.47	No	2.05	0.39	0.57	1.00	0.39	0.04	2.00	1.20
	500	2.50	1.50	2.38	6.50	2.02	5.50	6.64	4.40	5.82	1.53	0.34	3.49	Yes	4.26	4.26	4.79	No	1.71	0.39	0.48	0.80	0.39	0.04	1.71	1.00
	500	2.50	1.70	2.61	6.50	2.22	5.70	6.64	4.19	6.00	1.33	0.32	3.22	Yes	4.67	4.67	5.12	No	1.42	0.39	0.40	0.62	0.39	0.04	1.45	0.80
	500	2.50	1.85	2.84	6.50	2.42	5.85	6.64	4.08	6.13	1.17	0.31	2.98	Yes	4.98	4.98	5.37	No	1.20	0.39	0.34	0.49	0.39	0.04	1.25	0.65
Full Flow	500	2.50	1.90	4.57	6.50	3.89	5.90	6.64	4.53	6.18	0.58	0.31	1.77	Yes	5.99	5.60	5.91	Yes	0.46	0.39	0.13	0.05	0.39	0.04	0.60	0.60
	500	2.50	1.92	4.72	6.50	4.01	5.92	6.64	4.61	6.20	0.55	0.31	1.70	Yes	6.03	5.65	5.95	Yes	0.44	0.39	0.12	0.03	0.39	0.04	0.58	0.58
	500	2.50	1.94	4.84	6.50	4.12	5.94	6.64	4.69	6.22	0.53	0.30	1.64	Yes	6.06	5.69	5.99	Yes	0.41	0.39	0.12	0.02	0.39	0.04	0.56	0.56
Gates Open	500	2.50	1.96	5.00	6.50	4.25	5.96	6.64	4.50	6.24	0.50	0.30	1.57	Yes	6.10	5.74	6.03	Yes	0.39	0.39	0.11	0.00	0.39	0.04	**0.54**	**0.54**

$Y_2 > y_c \rightarrow Fr_2 < 1.0$

It doesn't correspond with drowned flow

It matches culvert Eq. (Figure 6)

Table A8. Hydraulic model simulation for Q = 450 cfs and Hw Stage = 2.5 ft NGVD (Y_1 = 6.5 ft). Two-box culvert under same operation, 225 cfs each

Invert Elevation (ft NGVD)	-4.00
No. of Boxes	2
Box Culvert Height, H (ft)	5.00
Box Culvert Width, B (ft)	10.00
Inlet Width (ft)	13.00
Box Culvert Length, L (ft)	50.00

Entrance loss coefficient, K_e	0.28
Expansion loss coefficient, K_{exp}	0.60
Exit loss coefficient, K_o	1.00
Manning's n coefficient (sec/$ft^{1/3}$)	0.012
Vena contracta coefficient, C_{vc}	0.85

Full Flow Culvert Computations

Box Flow Area, A (ft^2)	50.00
Box Wetted Perimeter, P_w (ft)	30.00
Box Hydraulic Radius, R_h (ft)	1.67

Hydraulic Jump Computations

13	Sequent Depth, y_s (ft)	4.54
17	H. J. Length, L_j (ft)	23.60
18	H. J. Loss, ΔE (ft)	**1.69**

y_c = 2.51 ft					Flow Depth								Max TW		Drowned Depth Y_{2d}		Specific		Full Flow Conditions							
Flow Regime	Flow Q (cfs)	Stage Hw (ft NGVD)	Stage Tw (ft NGVD)	Opening GO (ft)	Hw Y_1 (ft)	D/S of G Y_2 (ft)	Tw Y_3 (ft)	Specific Energy E_1 (ft)	Specific Energy E_2 (ft)	Specific Energy E_3 (ft)	Froude Number Fr_2 Free Flow	Froude Number Fr_3	Free Flow $Y_{3\,max}$ (ft)	Drowned Flow? Yes/No	D/S of Gate Energy (ft)	D/S of Gate Momentum (ft)	Energy E_{2d} (ft)	Box Full? Yes/No	Velocity Head Gate (ft)	Velocity Head Box (ft)	Culvert Head Losses Entrance (ft)	Expans. (ft)	Exit (ft)	Friction (ft)	Total (ft)	Available Head (ft)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	19	20	21	22	23	24	24	26	27	28
Free Flow	450	2.50	0.00	1.42	6.50	1.21	4.00	6.61	6.61	4.49	2.99	0.50	4.54	No	1.21	#NUM!	N/A	No	3.90	0.31						2.50
D/S Gate	450	2.50	0.10	1.42	6.50	1.21	4.10	6.61	6.61	4.57	2.99	0.48	4.54	No	1.21	#NUM!	N/A	No	3.90	0.31						2.40
	450	2.50	0.20	1.42	6.50	1.21	4.20	6.61	6.61	4.65	2.99	0.46	4.54	No	1.21	#NUM!	N/A	No	3.90	0.31						2.30
	450	2.50	0.30	1.42	6.50	1.21	4.30	6.61	6.61	4.73	2.99	0.44	4.54	No	1.21	#NUM!	N/A	No	3.90	0.31						2.20
	450	2.50	0.40	1.42	6.50	1.21	4.40	6.61	6.61	4.81	2.99	0.43	4.54	No	1.21	0.66	N/A	No	3.90	0.31						2.10
	450	2.50	0.54	1.42	6.50	1.21	4.54	6.61	**6.61**	**4.92**	2.99	0.41	4.54	No	1.21	1.21	N/A	No	3.90	0.31						1.96
Drowned	450	2.50	0.65	1.57	6.50	1.33	4.65	6.61	5.75	5.01	2.57	0.40	4.23	Yes	2.20	2.20	3.83	No	3.19	0.31	0.89	1.72	0.31	0.03	2.97	1.85
Flow	450	2.50	0.85	1.71	6.50	1.45	4.85	6.61	5.17	5.18	2.26	0.37	3.98	Yes	2.89	2.89	3.83	No	2.69	0.31	0.75	1.42	0.31	0.03	2.52	1.65
	450	2.50	1.10	1.89	6.50	1.60	5.10	6.61	4.66	5.40	1.95	0.34	3.70	Yes	3.55	3.55	4.17	No	2.21	0.31	0.62	1.14	0.31	0.03	2.10	1.40
	450	2.50	1.30	2.03	6.50	1.73	5.30	6.61	4.36	5.58	1.74	0.32	3.49	Yes	3.98	3.98	4.48	No	1.90	0.31	0.53	0.95	0.31	0.03	1.83	1.20
	450	2.50	1.50	2.21	6.50	1.88	5.50	6.61	4.11	5.76	1.54	0.31	3.26	Yes	4.38	4.38	4.79	No	1.61	0.31	0.45	0.78	0.31	0.03	1.58	1.00
	450	2.50	1.70	2.43	6.50	2.06	5.70	6.61	3.91	5.94	1.34	0.29	3.00	Yes	4.77	4.77	5.12	No	1.33	0.31	0.37	0.61	0.31	0.03	1.33	0.80
	450	2.50	1.80	2.57	6.50	2.19	5.80	6.61	3.83	6.03	1.23	0.28	2.85	Yes	4.97	4.97	5.29	No	1.19	0.31	0.33	0.52	0.31	0.03	1.20	0.70
Full Flow	450	2.50	1.90	3.94	6.50	3.47	5.90	6.61	4.12	6.13	0.61	0.28	1.74	Yes	5.96	5.57	5.83	Yes	0.51	0.31	0.14	0.12	0.31	0.03	0.60	0.60
	450	2.50	1.93	4.08	6.50	3.60	5.93	6.61	4.21	6.15	0.58	0.27	1.66	Yes	6.00	5.63	5.88	Yes	0.47	0.31	0.13	0.09	0.31	0.03	0.57	0.57
	450	2.50	1.96	4.23	6.50	3.81	5.96	6.61	4.35	6.18	0.53	0.27	1.54	Yes	6.07	5.70	5.95	Yes	0.44	0.31	0.12	0.07	0.31	0.03	0.54	0.54
	450	2.50	2.00	4.48	7.00	4.00	6.00	7.09	4.49	6.22	0.49	0.27	1.44	Yes	6.60	5.78	6.01	Yes	0.39	0.31	0.11	0.05	0.31	0.03	0.50	0.50
	450	2.50	2.03	4.71	6.50	4.25	6.03	6.61	4.69	6.25	0.45	0.27	1.33	Yes	6.17	5.85	6.08	Yes	0.35	0.31	0.10	0.02	0.31	0.03	0.47	0.47
Gates Open	450	2.50	2.06	5.00	6.50	4.25	6.06	6.61	4.50	6.28	0.45	0.27	1.33	Yes	6.17	5.88	6.11	Yes	0.31	0.31	0.09	0.00	0.31	0.03	**0.44**	**0.44**

$Y_2 > y_c \rightarrow Fr_2 < 1.0$

It doesn't correspond with drowned flow

It matches culvert Eq. (Figure 6)

Table A9. Hydraulic model simulation for Q = 400 cfs and Hw Stage = 2.5 ft NGVD (Y_1 = 6.5 ft). Two-box culvert under same operation, 200 cfs each

Invert Elevation (ft NGVD)	-4.00
No. of Boxes	2
Box Culvert Height, H (ft)	5.00
Box Culvert Width, B (ft)	10.00
Inlet Width (ft)	13.00
Box Culvert Length, L (ft)	50.00

Entrance loss coefficient, K_e	0.28
Expansion loss coefficient, K_{exp}	0.60
Exit loss coefficient, K_o	1.00
Manning's n coefficient (sec/ft$^{1/3}$)	0.012
Vena contracta coefficient, C_{vc}	0.85

Full Flow Culvert Computations

Box Flow Area, A (ft^2)	50.00
Box Wetted Perimeter, P_w (ft)	30.00
Box Hydraulic Radius, R_h (ft)	1.67

Hydraulic Jump Computations

13	Sequent Depth, y_s (ft)	4.34
17	H. J. Length, L_j (ft)	23.23
18	H. J. Loss, ΔE (ft)	**1.92**

y_c = 2.32 ft					Flow Depth								Max TW		Drowned Depth Y_{2d}		Specific		Full Flow Conditions							
Flow Regime	Flow	Stage		Opening	Hw	D/S of G	Tw	Specific Energy			Froude Number		Free Flow	Drowned	D/S of Gate		Energy	Box	Velocity Head		Culvert Head Losses					Available
	Q	Hw	Tw	GO	Y_1	Y_2	Y_3	E_1	E_2	E_3	Fr_2	Fr_3	$Y_{3\,max}$	Flow?	Energy	Momentum	E_{2d}	Full?	Gate	Box	Entrance	Expans.	Exit	Friction	Total	Head
	(cfs)	(ft NGVD)		(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	Free Flow		(ft)	Yes/No	(ft)	(ft)	(ft)	Yes/No	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	19	20	21	22	23	24	24	26	27	28
Free Flow	400	2.50	0.00	1.25	6.50	1.06	4.00	6.59	6.59	4.39	3.23	0.44	4.34	No	1.06	#NUM!	N/A	No	3.99	0.25						2.50
D/S Gate	400	2.50	0.05	1.25	6.50	1.06	4.05	6.59	6.59	4.43	3.23	0.43	4.34	No	1.06	#NUM!	N/A	No	3.99	0.25						2.45
	400	2.50	0.10	1.25	6.50	1.06	4.10	6.59	6.59	4.47	3.23	0.42	4.34	No	1.06	#NUM!	N/A	No	3.99	0.25						2.40
	400	2.50	0.15	1.25	6.50	1.06	4.15	6.59	6.59	4.51	3.23	0.42	4.34	No	1.06	#NUM!	N/A	No	3.99	0.25						2.35
	400	2.50	0.20	1.25	6.50	1.06	4.20	6.59	6.59	4.55	3.23	0.41	4.34	No	1.06	0.35	N/A	No	3.99	0.25						2.30
	400	2.50	0.34	1.25	6.50	1.06	4.34	6.59	**6.59**	**4.67**	3.23	0.39	4.34	No	**1.06**	**1.06**	N/A	No	3.99	0.25						2.16
Drowned	400	2.50	0.50	1.40	6.50	1.19	4.50	6.59	5.56	4.81	2.71	0.37	4.01	Yes	2.22	2.22	3.48	No	3.16	0.25	0.88	1.74	0.25	0.03	2.90	2.00
Flow	400	2.50	0.75	1.54	6.50	1.31	4.75	6.59	4.93	5.03	2.35	0.34	3.75	Yes	2.97	2.97	3.67	No	2.62	0.25	0.73	1.42	0.25	0.03	2.43	1.75
	400	2.50	1.00	1.68	6.50	1.43	5.00	6.59	4.47	5.25	2.06	0.32	3.51	Yes	3.55	3.55	4.04	No	2.20	0.25	0.61	1.17	0.25	0.03	2.06	1.50
	400	2.50	1.20	1.81	6.50	1.54	5.20	6.59	4.17	5.43	1.85	0.30	3.33	Yes	3.95	3.95	4.35	No	1.90	0.25	0.53	0.99	0.25	0.03	1.80	1.30
	400	2.50	1.40	1.95	6.50	1.66	5.40	6.59	3.92	5.61	1.65	0.28	3.13	Yes	4.33	4.33	4.66	No	1.63	0.25	0.46	0.83	0.25	0.03	1.56	1.10
	400	2.50	1.60	2.14	6.50	1.82	5.60	6.59	3.70	5.80	1.44	0.27	2.90	Yes	4.71	4.71	4.99	No	1.36	0.25	0.38	0.66	0.25	0.03	1.32	0.90
	400	2.50	1.70	2.25	6.50	1.91	5.70	6.59	3.61	5.89	1.34	0.26	2.78	Yes	4.88	4.88	5.14	No	1.23	0.25	0.35	0.59	0.25	0.03	1.21	0.80
Full Flow	400	2.50	1.90	3.40	6.50	2.89	5.90	6.59	3.64	6.08	0.72	0.25	1.82	Yes	5.85	5.52	5.72	Yes	0.54	0.25	0.15	0.17	0.25	0.03	0.60	0.60
	400	2.50	1.94	3.56	6.50	3.03	5.94	6.59	3.70	6.12	0.67	0.24	1.73	Yes	5.91	5.59	5.79	Yes	0.49	0.25	0.14	0.14	0.25	0.03	0.56	0.56
	400	2.50	1.98	3.74	6.50	3.18	5.98	6.59	3.79	6.15	0.62	0.24	1.63	Yes	5.97	5.67	5.86	Yes	0.44	0.25	0.12	0.12	0.25	0.03	0.52	0.52
	400	2.50	2.12	4.66	6.50	3.96	6.12	6.59	4.36	6.29	0.45	0.23	1.21	Yes	6.19	5.94	6.11	Yes	0.29	0.25	0.08	0.02	0.25	0.03	0.38	0.38
Gates Open	400	2.50	2.16	5.00	6.50	4.25	6.16	6.59	4.50	6.32	0.40	0.23	1.09	Yes	6.24	6.01	6.18	Yes	0.25	0.25	0.07	0.00	0.25	0.03	**0.34**	**0.34**

$Y_2 > y_c \rightarrow Fr_2 < 1.0$

It doesn't correspond with drowned flow

It matches culvert Eq. (Figure 6)

Table A10. Hydraulic model simulation for Q = 350 cfs and Hw Stage = 2.5 ft NGVD (Y_1 = 6.5 ft). Two-box culvert under same operation, 175 cfs each

Invert Elevation (ft NGVD)	-4.00
No. of Boxes	2
Box Culvert Height, H (ft)	5.00
Box Culvert Width, B (ft)	10.00
Inlet Width (ft)	13.00
Box Culvert Length, L (ft)	50.00

Entrance loss coefficient, K_e	0.28
Expansion loss coefficient, K_{exp}	0.60
Exit loss coefficient, K_o	1.00
Manning's n coefficient (sec/ft$^{1/3}$)	0.012
Vena contracta coefficient, C_{vc}	0.85

Full Flow Culvert Computations

Box Flow Area, A (ft^2)	50.00
Box Wetted Perimeter, P_w (ft)	30.00
Box Hydraulic Radius, R_h (ft)	1.67

Hydraulic Jump Computations

13	Sequent Depth, y_s (ft)	4.12
17	H. J. Length, L_j (ft)	22.65
18	H. J. Loss, ΔE (ft)	**2.17**

4.117562

y_c = **2.12 ft**					Flow Depth								Max TW		Drowned Depth Y_{2d}		Specific		Full Flow Conditions							
Flow Regime	Flow Q (cfs)	Stage Hw (ft NGVD)	Stage Tw (ft NGVD)	Opening GO (ft)	Hw Y_1 (ft)	D/S of G Y_2 (ft)	Tw Y_3 (ft)	Specific Energy E_1 (ft)	Specific Energy E_2 (ft)	Specific Energy E_3 (ft)	Froude Number Fr_2 Free Flow	Froude Number Fr_3	Free Flow $Y_{3\,max}$ (ft)	Drowned Flow? Yes/No	D/S of Gate Energy (ft)	D/S of Gate Momentum (ft)	Energy E_{2d} (ft)	Box Full? Yes/No	Velocity Head Gate (ft)	Velocity Head Box (ft)	Culvert Head Losses Entrance (ft)	Expans. (ft)	Exit (ft)	Friction (ft)	Total (ft)	Available Head (ft)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	19	20	21	22	23	24	24	26	27	28
Free Flow	350	2.50	0.00	1.08	6.50	0.92	4.00	6.57	6.57	4.30	3.51	0.39	4.12	No	0.92	0.15	N/A	No	4.08	0.19						2.50
D/S Gate	350	2.50	0.05	1.08	6.50	0.92	4.05	6.57	6.57	4.34	3.51	0.38	4.12	No	0.92	0.61	N/A	No	4.08	0.19						2.45
	350	2.50	0.10	1.08	6.50	0.92	4.10	6.57	6.57	4.38	3.51	0.37	4.12	No	0.92	0.85	N/A	No	4.08	0.19						2.40
	350	2.50	0.12	1.08	6.50	0.92	4.12	6.57	**6.57**	**4.40**	3.51	0.37	4.12	No	**0.92**	**0.92**	N/A	No	4.08	0.19						2.38
Drowned	350	2.50	0.50	1.31	6.50	1.11	4.50	6.57	4.96	4.73	2.63	0.32	3.62	Yes	2.71	2.71	3.36	No	2.78	0.19	0.78	1.56	0.19	0.02	2.55	2.00
Flow	350	2.50	0.75	1.42	6.50	1.20	4.75	6.57	4.49	4.96	2.34	0.30	3.42	Yes	3.28	3.28	3.72	No	2.37	0.19	0.66	1.31	0.19	0.02	2.18	1.75
	350	2.50	1.00	1.53	6.50	1.30	5.00	6.57	4.10	5.19	2.07	0.28	3.22	Yes	3.77	3.77	4.10	No	2.02	0.19	0.57	1.10	0.19	0.02	1.88	1.50
	350	2.50	1.20	1.64	6.50	1.40	5.20	6.57	3.83	5.38	1.87	0.26	3.06	Yes	4.13	4.13	4.41	No	1.76	0.19	0.49	0.94	0.19	0.02	1.65	1.30
	350	2.50	1.40	1.78	6.50	1.51	5.40	6.57	3.59	5.56	1.66	0.25	2.87	Yes	4.48	4.48	4.72	No	1.51	0.19	0.42	0.79	0.19	0.02	1.42	1.10
	350	2.50	1.60	1.93	6.50	1.64	5.60	6.57	3.40	5.75	1.46	0.23	2.68	Yes	4.81	4.81	5.02	No	1.27	0.19	0.36	0.65	0.19	0.02	1.22	0.90
	350	2.50	1.65	1.99	6.50	1.69	5.65	6.57	3.36	5.80	1.40	0.23	2.61	Yes	4.90	4.90	5.10	No	1.20	0.19	0.34	0.61	0.19	0.02	1.16	0.85
Full Flow	350	2.50	1.85	2.74	6.50	2.33	5.85	6.57	3.21	5.99	0.87	0.22	1.92	Yes	5.69	5.41	5.58	Yes	0.63	0.19	0.18	0.27	0.19	0.02	0.65	0.65
	350	2.50	1.95	3.03	6.50	2.58	5.95	6.57	3.29	6.08	0.75	0.21	1.72	Yes	5.85	5.59	5.74	Yes	0.52	0.19	0.15	0.20	0.19	0.02	0.55	0.55
	350	2.50	2.05	3.44	6.50	2.92	6.05	6.57	3.48	6.18	0.62	0.21	1.48	Yes	6.01	5.77	5.91	Yes	0.40	0.19	0.11	0.13	0.19	0.02	0.45	0.45
	350	2.50	2.15	4.09	6.50	3.48	6.15	6.57	3.87	6.28	0.48	0.20	1.18	Yes	6.17	5.95	6.09	Yes	0.28	0.19	0.08	0.06	0.19	0.02	0.35	0.35
Gates Open	350	2.50	2.24	5.00	6.50	4.25	6.24	6.57	4.50	6.36	0.35	0.20	0.87	Yes	6.30	6.12	6.25	Yes	0.19	0.19	0.05	0.00	0.19	0.02	**0.26**	**0.26**

$Y_2 > y_c \rightarrow Fr_2 < 1.0$

It doesn't correspond with drowned flow

It matches culvert Eq. (Figure 6)

Table A11. Hydraulic model simulation for Q = 300 cfs and Hw Stage = 2.5 ft NGVD (Y_1 = 6.5 ft). Two-box culvert under same operation, 150 cfs each

Invert Elevation (ft NGVD)	-4.00
No. of Boxes	2
Box Culvert Height, H (ft)	5.00
Box Culvert Width, B (ft)	10.00
Inlet Width (ft)	13.00
Box Culvert Length, L (ft)	50.00

Entrance loss coefficient, K_e	0.28
Expansion loss coefficient, K_{exp}	0.60
Exit loss coefficient, K_o	1.00
Manning's n coefficient (sec/ft$^{1/3}$)	0.012
Vena contracta coefficient, C_{vc}	0.85

Full Flow Culvert Computations

Box Flow Area, A (ft^2)	50.00
Box Wetted Perimeter, P_w (ft)	30.00
Box Hydraulic Radius, R_h (ft)	1.67

Hydraulic Jump Computations

13	Sequent Depth, y_s (ft)	3.87
17	H. J. Length, L_j (ft)	N/A
18	H. J. Loss, ΔE (ft)	N/A

Free flow cannot occur since y_s<$Y_{3\,min}$ (4.0 ft)

y_c = **1.91 ft**

Flow Regime	Flow Q (cfs)	Stage Hw (ft NGVD)	Stage Tw (ft NGVD)	Opening GO (ft)	Flow Depth Hw Y_1 (ft)	Flow Depth D/S of G Y_2 (ft)	Flow Depth Tw Y_3 (ft)	Specific Energy E_1 (ft)	Specific Energy E_2 (ft)	Specific Energy E_3 (ft)	Froude Number Fr_2 Free Flow	Froude Number Fr_3	Max TW Free Flow $Y_{3\,max}$ (ft)	Drowned Flow? Yes/No	Drowned Depth Y_{2d} D/S of Gate Energy (ft)	Drowned Depth Y_{2d} D/S of Gate Momentum (ft)	Specific Energy E_{2d} (ft)	Box Full? Yes/No	Full Flow Conditions Velocity Head Gate (ft)	Velocity Head Box (ft)	Culvert Head Losses Entrance (ft)	Expans. (ft)	Exit (ft)	Friction (ft)	Total (ft)	Available Head (ft)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	19	20	21	22	23	24	24	26	27	28
Free Flow	300	2.50	0.00	0.92	6.50	0.78	4.00	6.55	6.55	4.22	3.85	0.33	3.87	No	0.78	1.24	N/A	No	4.17	0.14						2.50
Drowned	300	2.50	0.00	1.01	6.50	0.86	4.00	6.55	5.63	4.22	3.34	0.33	3.64	Yes	1.77	1.77	2.88	No	3.45	0.14	0.97	1.99	0.14	0.01	3.11	2.50
Flow	300	2.50	0.50	1.18	6.50	1.00	4.50	6.55	4.49	4.67	2.64	0.28	3.27	Yes	3.06	3.06	3.44	No	2.52	0.14	0.71	1.43	0.14	0.01	2.29	2.00
	300	2.50	0.75	1.27	6.50	1.08	4.75	6.55	4.09	4.90	2.37	0.26	3.10	Yes	3.54	3.54	3.82	No	2.18	0.14	0.61	1.22	0.14	0.01	1.99	1.75
	300	2.50	1.00	1.37	6.50	1.17	5.00	6.55	3.73	5.14	2.10	0.24	2.93	Yes	3.98	3.98	4.20	No	1.85	0.14	0.52	1.03	0.14	0.01	1.70	1.50
	300	2.50	1.20	1.47	6.50	1.25	5.20	6.55	3.50	5.33	1.90	0.22	2.78	Yes	4.30	4.30	4.49	No	1.63	0.14	0.46	0.89	0.14	0.01	1.50	1.30
	300	2.50	1.40	1.58	6.50	1.35	5.40	6.55	3.28	5.52	1.69	0.21	2.62	Yes	4.62	4.62	4.79	No	1.39	0.14	0.39	0.75	0.14	0.01	1.30	1.10
	300	2.50	1.60	1.73	6.50	1.47	5.60	6.55	3.09	5.71	1.48	0.20	2.43	Yes	4.93	4.93	5.08	No	1.17	0.14	0.33	0.62	0.14	0.01	1.10	0.90
Full Flow	300	2.50	1.80	2.21	6.50	1.88	5.80	6.55	2.87	5.90	1.03	0.19	1.95	Yes	5.56	5.35	5.47	Yes	0.72	0.14	0.20	0.35	0.14	0.01	0.70	0.70
	300	2.50	1.95	2.54	6.50	2.16	5.95	6.55	2.91	6.05	0.83	0.18	1.68	Yes	5.80	5.59	5.70	Yes	0.54	0.14	0.15	0.24	0.14	0.01	0.55	0.55
	300	2.50	2.10	3.06	6.50	2.60	6.10	6.55	3.12	6.19	0.63	0.18	1.36	Yes	6.03	5.84	5.94	Yes	0.37	0.14	0.10	0.14	0.14	0.01	0.40	0.40
	300	2.50	2.20	3.70	6.50	3.15	6.20	6.55	3.50	6.29	0.47	0.17	1.06	Yes	6.20	6.02	6.12	Yes	0.26	0.14	0.07	0.07	0.14	0.01	0.30	0.30
Gates Open	300	2.50	2.31	5.00	6.50	4.25	6.31	6.55	4.50	6.39	0.30	0.17	0.67	Yes	6.36	6.22	6.31	Yes	0.14	0.14	0.04	0.00	0.14	0.01	**0.19**	**0.19**

Y_2>y_c → Fr_2<1.0

It matches culvert Eq. (Figure 6)

Table A12. Hydraulic model simulation for Q = 250 cfs and Hw Stage = 2.5 ft NGVD (Y_1 = 6.5 ft). Two-box culvert under same operation, 125 cfs each

Invert Elevation (ft NGVD)	-4.00
No. of Boxes	2
Box Culvert Height, H (ft)	5.00
Box Culvert Width, B (ft)	10.00
Inlet Width (ft)	13.00
Box Culvert Length, L (ft)	50.00

Entrance loss coefficient, K_e	0.28
Expansion loss coefficient, K_{exp}	0.60
Exit loss coefficient, K_o	1.00
Manning's n coefficient (sec/ft$^{1/3}$)	0.012
Vena contracta coefficient, C_{vc}	0.85

Full Flow Culvert Computations

Box Flow Area, A (ft^2)	50.00
Box Wetted Perimeter, P_w (ft)	30.00
Box Hydraulic Radius, R_h (ft)	1.67

Hydraulic Jump Computations

13	Sequent Depth, y_s (ft)	3.58
17	H. J. Length, L_j (ft)	N/A
18	H. J. Loss, ΔE (ft)	N/A

Free flow cannot occur since y_s<$Y_{3\,min}$ (4.0 ft)

y_c = 1.69 ft					Flow Depth								Max TW		Drowned Depth Y_{2d}		Specific		Full Flow Conditions							
Flow	Flow	Stage		Opening	Hw	D/S of G	Tw	Specific Energy			Froude Number		Free Flow	Drowned	D/S of Gate		Energy	Box	Velocity Head		Culvert Head Losses					Available
Regime	Q	Hw	Tw	GO	Y_1	Y_2	Y_3	E_1	E_2	E_3	Fr_2	Fr_3	$Y_{3\,max}$	Flow?	Energy	Momentum	E_{2d}	Full?	Gate	Box	Entrance	Expans.	Exit	Friction	Total	Head
	(cfs)	(ft NGVD)		(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	Free Flow		(ft)	Yes/No	(ft)	(ft)	(ft)	Yes/No	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)	(ft)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	19	20	21	22	23	24	24	26	27	28
Free Flow	250	2.50	0.00	0.75	6.50	0.64	4.00	6.53	6.53	4.15	4.29	0.28	3.58	No	0.64	1.82	N/A	No	4.26	0.10						2.50
Drowned	250	2.50	0.00	0.90	6.50	0.77	4.00	6.53	4.90	4.15	3.29	0.28	3.20	Yes	2.40	2.40	2.82	No	2.99	0.10	0.84	1.73	0.10	0.01	2.68	2.50
Flow	250	2.50	0.50	1.03	6.50	0.87	4.50	6.53	4.05	4.62	2.70	0.23	2.92	Yes	3.36	3.36	3.58	No	2.30	0.10	0.64	1.32	0.10	0.01	2.07	2.00
	250	2.50	0.75	1.10	6.50	0.94	4.75	6.53	3.70	4.86	2.43	0.21	2.78	Yes	3.77	3.77	3.94	No	2.00	0.10	0.56	1.14	0.10	0.01	1.81	1.75
	250	2.50	1.00	1.19	6.50	1.01	5.00	6.53	3.38	5.10	2.17	0.20	2.63	Yes	4.16	4.16	4.30	No	1.71	0.10	0.48	0.97	0.10	0.01	1.56	1.50
	250	2.50	1.20	1.28	6.50	1.09	5.20	6.53	3.14	5.29	1.95	0.19	2.50	Yes	4.47	4.47	4.59	No	1.49	0.10	0.42	0.83	0.10	0.01	1.36	1.30
	250	2.50	1.40	1.37	6.50	1.17	5.40	6.53	2.95	5.48	1.75	0.18	2.36	Yes	4.76	4.76	4.87	No	1.29	0.10	0.36	0.71	0.10	0.01	1.18	1.10
	250	2.50	1.50	1.44	6.50	1.22	5.50	6.53	2.84	5.58	1.63	0.17	2.27	Yes	4.91	4.91	5.01	No	1.17	0.10	0.33	0.64	0.10	0.01	1.08	1.00
Full Flow	250	2.50	1.70	1.69	6.50	1.44	5.70	6.53	2.61	5.77	1.28	0.16	1.98	Yes	5.36	5.24	5.33	Yes	0.85	0.10	0.24	0.45	0.10	0.01	0.80	0.80
	250	2.50	1.85	1.89	6.50	1.61	5.85	6.53	2.55	5.92	1.08	0.16	1.78	Yes	5.59	5.46	5.54	Yes	0.68	0.10	0.19	0.35	0.10	0.01	0.65	0.65
	250	2.50	2.00	2.17	6.50	1.84	6.00	6.53	2.56	6.07	0.88	0.15	1.55	Yes	5.82	5.69	5.76	Yes	0.52	0.10	0.14	0.25	0.10	0.01	0.50	0.50
	250	2.50	2.15	2.66	6.50	2.26	6.15	6.53	2.74	6.21	0.65	0.14	1.23	Yes	6.06	5.93	5.99	Yes	0.34	0.10	0.10	0.15	0.10	0.01	0.35	0.35
Gates Open	250	2.50	2.37	5.00	6.50	4.25	6.37	6.53	4.50	6.43	0.25	0.14	0.48	Yes	6.40	6.31	6.37	Yes	0.10	0.10	0.03	0.00	0.10	0.01	0.13	0.13

Y_2>y_c → Fr_2<1.0

It matches culvert Eq. (Figure 6)

Table A13. Estimates of C_d for free flow regime (inlet control) from simulations

[1] Flow Q (cfs)	Stage (ft NGVD) Hw	Tw	Gate Opening GO (ft)	Flow Depth (ft) Y_1	Y_2	[2] $Y_{3\ max}$	C_d
500	3.0	0.88	1.52	7.0	1.29	4.88	0.776
450	3.0	0.68	1.35	7.0	1.15	4.69	0.783
400	3.0	0.47	1.19	7.0	1.01	4.47	0.791
350	3.0	0.24	1.03	7.0	0.88	4.24	0.799
500	2.5	0.72	1.60	6.5	1.36	4.72	0.766
450	2.5	0.54	1.42	6.5	1.21	4.54	0.775
400	2.5	0.34	1.25	6.5	1.06	4.34	0.784
350	2.5	0.12	1.08	6.5	0.92	4.12	0.792

[1] total flow through the two boxes
[2] maximum downstream (Tw) flow depth to achieve free flow conditions