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Hydraulic Laboratory Technical Memorandum PAP-1105

Physical Modeling of Overflow Outlets for Extended Detention Stormwater Basins

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Hydraulic Investigations and Laboratory Services Group
Denver, Colorado

September 2014

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U.S. Department of the Interior
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Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Hydraulic Laboratory and PAP Reports

The Hydraulic Laboratory Report and PAP series is produced by the Bureau of Reclamation's Hydraulic Investigations and Laboratory Services Group (Mail Code 85-846000), PO Box 25007, Denver, Colorado 80225-0007. At the time of publication, this report was also made available online at **http://www.usbr.gov/pmts/hydraulics_lab/pubs/**.

Disclaimer

Funding for this project was provided by Urban Drainage and Flood Control District

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Background

The Urban Drainage and Flood Control District (UDFCD) was established by the Colorado legislature in 1969 for the purpose of assisting local governments in the Denver metropolitan area to address multi-jurisdictional drainage and flood control challenges in order to protect people, property, and the environment. The District covers an area of 1608 square miles and includes Denver, parts of the 6 surrounding counties, and all or parts of 32 incorporated cities and towns. There are about 1600 miles of "major drainage ways" which are defined as draining at least 1000 acres (Urban Drainage, 2014).

The UDFCD provides design guidance on many different types of stormwater and water quality infrastructure that are used throughout the District. One of these structures is the extended detention basin (EDB), which is a sedimentation basin designed to detain stormwater for many hours after the end of storm runoff events. EDBs utilize a small outlet that extends the emptying time of the more frequently occurring runoff events to facilitate pollutant removal and reduce the peak runoff that would enter a storm water system. Figure 1 provides an overview of some of the main features of an EDB (UDFCD, 2010) which include:

- a <u>basin length to width ratio</u> of at least 2:1
- <u>side slopes</u> not steeper than 3:1
- <u>inlet structure</u> that can dissipate flow energy at the concentrated points of inflow
- <u>forebay</u> to allow larger particles to settle quickly
- <u>trickle channel</u> which conveys low flows from the forebay to the micropool
- <u>micropool</u> which creates a small permanent defined pool directly upstream from the basin outlet. The micropool prevents large shallow puddles that produce unwanted mosquito habitat.
- <u>outlet structure</u> (Figure 2) located in the embankment containing water quality orifices, a 10-yr orifice, a sloped weir overflow with trash rack, and a 100-yr orifice downstream from the trash rack.

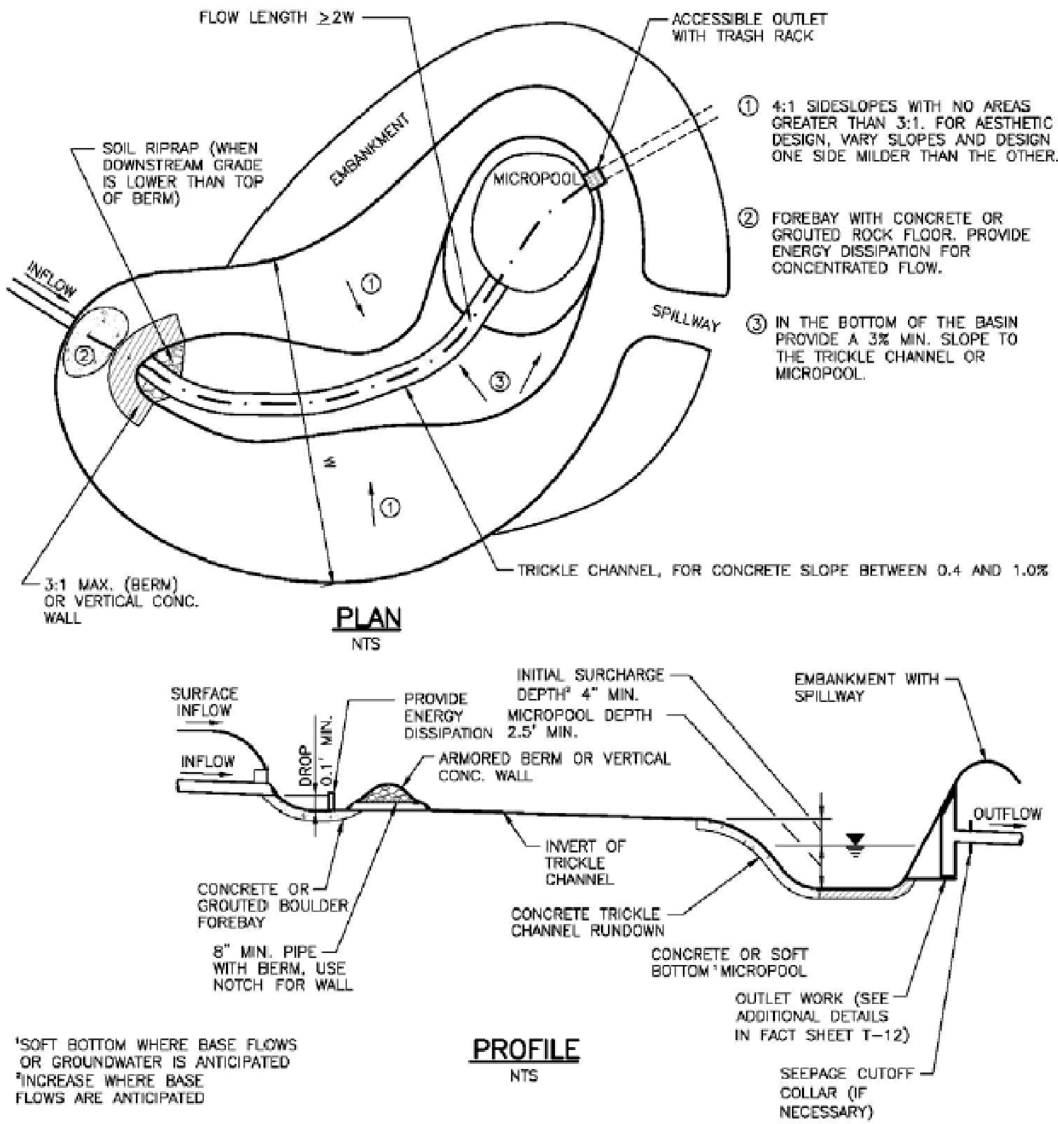

Figure 1 - Basic description of an extended detention basin (EDB) (UDFCD, 2010)

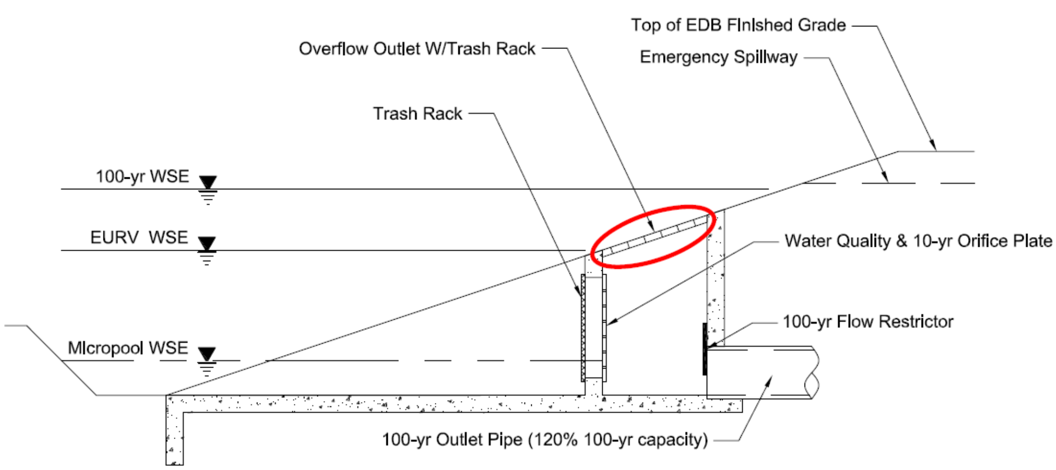

Figure 2 - Typical outlet structure for an extended detention basin (EDB)

The Urban Drainage and Flood Control District contacted the Bureau of Reclamation (Reclamation) in March 2012 to request assistance in resolving some questions regarding the calculation of flow passing through the overflow outlet portion of the outlet structure (circled in red in Figure 2). The flow through the outlet structure is used to regulate storm runoff events through detention basins. An accurate estimate of the flow passing through the overflow outlet portion of the structure will provide better regulation of extreme storm runoff events. UDFCD requested that Reclamation build and test a 1:3 scale physical model of the sloped overflow outlet (not the water quality or 10-yr orifice plate portion) in Reclamation's hydraulics laboratory to determine the head-discharge rating of the structure and evaluate previously developed rating equations.

Previous Work and Provided Information

Dr. James Guo at the University of Colorado Denver campus derived equations to represent flow through the overflow outlet based on a physical model of roadway median inlets (Guo, 2012). Guo collected data from 96 configurations of a 1:3 (model:prototype) scale physical model at the Colorado State University Hydraulics Laboratory. Two types of grates were tested at slopes varying from 0 to 30 degrees. Table 1 provides the equations to calculate flow through the median inlets based on discharge coefficients (C_d) determined from the physical model (Guo, 2012). Variables used in the equations in Table 1 are as follows (see Figure 3):

Q = Flow (ft^3/sec)
C_d = Discharge coefficient (Typically 0.62)
n = Open area ratio for the grate (typically between 0.3 and 0.7)
H = Headwater depth above bottom weir crest
H_b = Depth from bottom weir crest to the top of the upper edge of the grate
B = Bottom weir crest length
L = Horizontal grate length (not parallel to the inclined grate)
θ = Angle of inclined grate

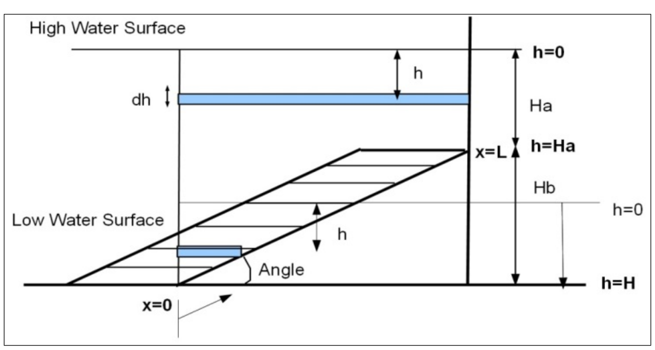

Figure 3 - Diagram of inclined grate with some variables specified (Guo, 2012)

Table 1 - Dr. Guo's equations for calculating discharge through median inlets (Guo, 2012).

Flow Type	Flow Overtopping Two Sides of Inclined Grate	Flow overtopping the Lower Base Width	Condition
Orifice	$Q_o = \frac{2}{3} n C_d BHCot\ \theta \sqrt{2gH} = \frac{2}{3} n C_d BXCos\ \theta \sqrt{2gH}$ Subject to: $X = \frac{H}{Sin\theta} < L$		$H<H_b$ Un-submerged
Weir	$Q_{WS} = \frac{4}{15} nC_d \sqrt{2g} Cot\theta H^{\frac{5}{2}} = \frac{4}{15} nC_d XCos\theta \sqrt{2g} H^{\frac{3}{2}}$ subject to: $X = \frac{H}{Sin\theta} < L$ $Q_W = 2Q_{WS} + Q_{WB}$	$Q_{WB} = \frac{2}{3} nC_d \sqrt{2g} BH^{3/2}$	$H<H_b$ Un-submerged
Orifice	$Q_o = \frac{2}{3} nC_d BLCos\theta \sqrt{2gH} [\frac{H^{\frac{3}{2}}}{H_b \sqrt{H}} - \frac{(H-H_b)^{\frac{3}{2}}}{H_b \sqrt{H}}]$ In case of θ=0 and Hb=0, then $Q_o = \frac{2}{3} nC_d BL \sqrt{2gH}\ if\ \theta = 0$		$H \geq H_b$ Submerged
Weir	$Q_{WS} = \frac{4}{15} nC_d \sqrt{2g} LCos\theta\, H^{\frac{3}{2}} [\frac{H^{\frac{5}{2}}}{H^{\frac{3}{2}} H_b} - \frac{(H-H_b)^{\frac{5}{2}}}{H^{\frac{3}{2}} H_b}]$ In case of θ=0 and Hb=0, then $Q_{WS} = \frac{2}{3} nC_d L \sqrt{2g} H^{\frac{3}{2}}$ $Q_W = 2Q_{WS} + Q_{WB}$	$Q_{WB} = \frac{2}{3} nC_d \sqrt{2g} BH^{3/2}$	$H \geq H_b$ Submerged

Jim Wulliman from Muller Engineering developed the equations in Table 2 for calculating flow through the inclined grate by deriving weir equations across a side sloping weir. Variables used in the equations contained in Table 2 are as follows:

Q = Flow (ft^3/sec)
C_W = Weir Coefficient (Muller used 2.8)
n = Open area ratio for the grate (typically between 0.3 and 0.7)
H = Headwater depth above bottom weir crest
H_b = Depth from bottom weir crest to the top of the upper edge of the grate
B = Bottom weir crest length
L = Horizontal grate length (not parallel to the inclined grate)
Z = Side slope (Z:1 = H:V)

Table 2- Equations developed by Jim Wulliman from Muller Engineering for an inclined weir

Flow Type	Two Sides of Grate	Lower Base and Top of Grate
Un-Submerged Weir ($H < H_b$)	$Q_{WS} = \frac{2}{5} C_w Z n \left(H^{\frac{5}{2}} \right)$ $\boldsymbol{Q_W = 2Q_{WS} + Q_{WB}}$	$Q_{BW} = C_w B n \left(H^{\frac{3}{2}} \right)$
Submerged Weir ($H \geq H_b$)	$Q_{WS} = \frac{2}{5} C_w Z n \left(H^{\frac{5}{2}} - (H - H_b)^{\frac{5}{2}} \right)$ $\boldsymbol{Q_W = Q_{WB} + 2Q_{WS} + Q_{TOP}}$	$Q_{WB} = \frac{2}{3} n C_w \sqrt{2g} B H^{\frac{3}{2}}$ $Q_{TOP} = C_w B n (H - H_b)^{\frac{3}{2}}$

ARCADIS Engineering performed an analysis of flow through the overflow outlet using computational fluid dynamics (CFD) modeling (Figure 4). They modeled the structure with a 3:1 (Horizontal:Vertical) slope and did not include any reduction for grate clogging.

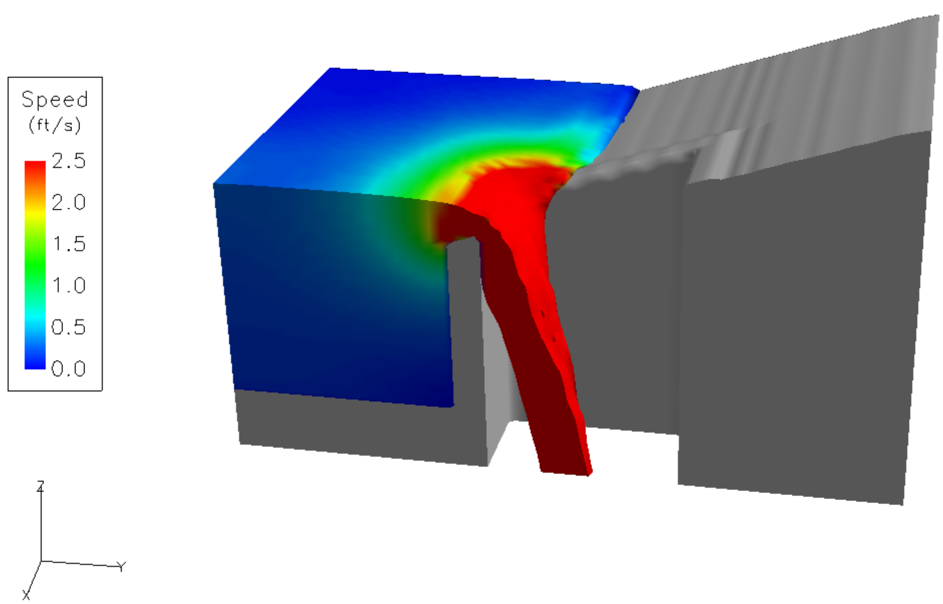

Figure 4 - ARCADIS Engineering CFD model of a 3:1 sloped overflow outlet structure

Figure 5 compares each of the previously mentioned equations and methods to each other. No two methods align very well across the full spectrum. Due to the large disagreement between each of the methods, UDFCD requested that Reclamation conduct a 1:3 scale physical model study to determine which equation best represents the flow through the overflow outlet structure.

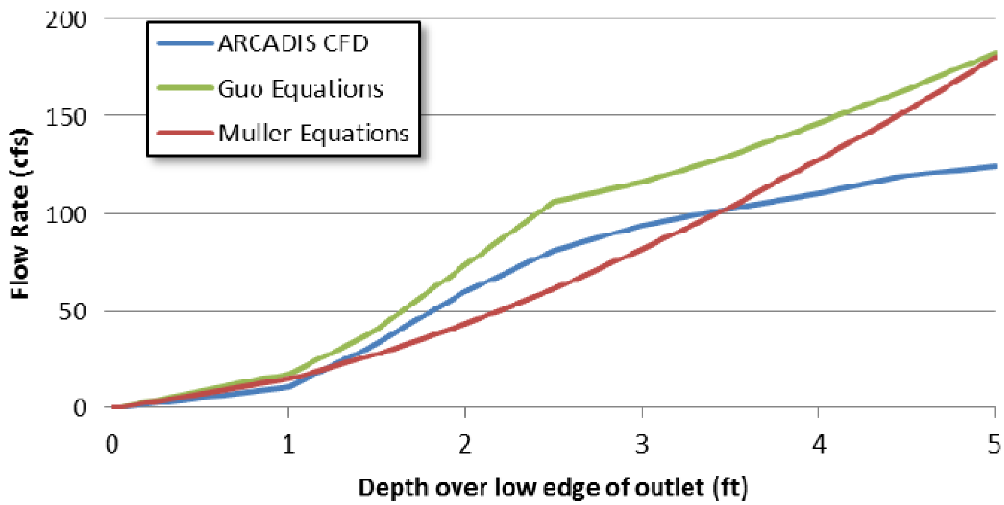

Figure 5 - Comparison of the three different methods to calculate flow through an overflow outlet structure with a 3:1 (H:V) slope (no reduction for grating or debris)

MODEL SETUP

The physical model was constructed in the Bureau of Reclamation's Hydraulics Laboratory in Denver CO, USA. A model box approximately 25-ft wide, 45-ft long and 4-ft deep was configured to simulate an extended detention basin (EDB) (Figure 6). One end of the box contained a 12-in. diameter inlet pipe and a 6-in. thick rock baffle to evenly distribute the flow entering the model. The opposite end of the box contained several configurations of the overflow outlet structure with and without grating.

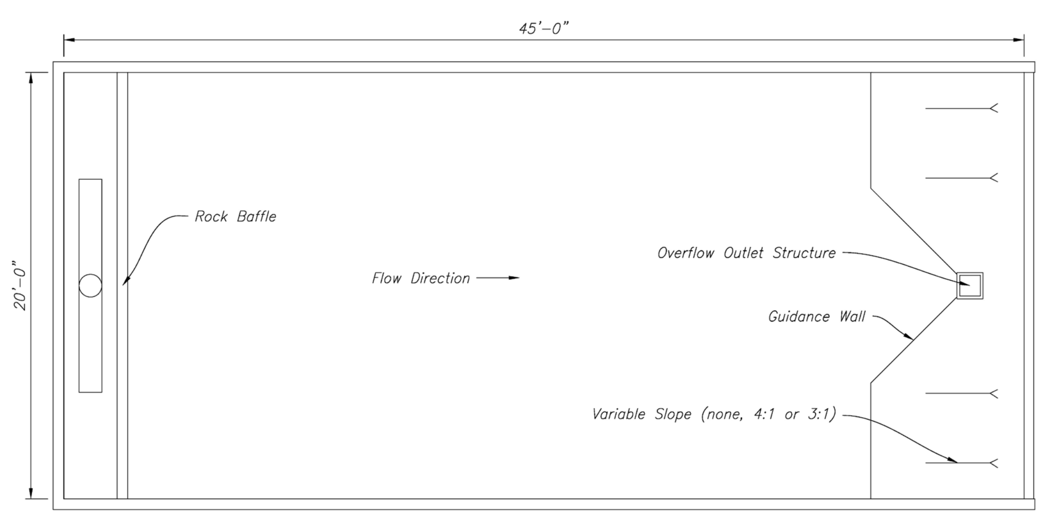

Figure 6 - Physical model layout of an extended detention basin (EDB) (model scale)

The outlet structure was modeled at a geometric scale of 1:3, which means model dimensions are one-third of the prototype dimensions. Since hydraulic performance for open channel flow depends primarily on gravitational and inertial forces, Froude law scaling was used to establish a relationship between the model and prototype. Froude law scaling causes the ratio of gravitational to inertial forces to be equal in the model and prototype; stated in another way, the Froude numbers of the model and prototype are kept equal to one another. Froude law similitude produces the following relationships between model (m) and prototype (p):

Length Ratio: $L_r = L_m/L_p = 1:3$
Velocity Ratio: $V_r = V_m/V_p = L_r^{1/2} = 1:1.732$
Discharge Ratio: $Q_r = Q_m/Q_p = L_r^{5/2} = 1:15.59$

Three different grates were tested (Colorado Department of Transportation Standard Plan No. M-604-10): a Standard CDOT Type C (Figure 7) grate which is approximately 40.5-in. by 26.75-in. with four 2.67-in. wide members on 8-in. centers creating an open area of 68.6 percent, a CDOT close-mesh (Figure 8) grate which is approximately 40.4-in. by 33.5-in. with 0.375-in. wide members on 2.375-in. centers creating an open area of 79.8 percent, and None (Figure 9) or no grate which is a rectangular opening approximately 41-in. by 35-in. and has a 3-in. lip on two edges to hold each grate in position. Each grate was tested at slopes of 3:1 (H:V)(Figure 10), 4:1 (Figure 11), and 1:0 horizontal (no slope).

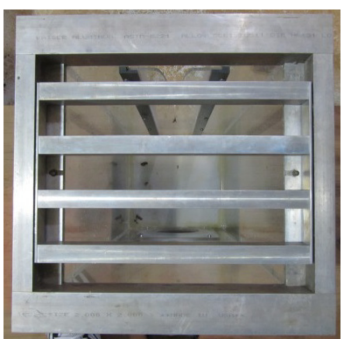

Figure 7 - Plan view of CDOT Type C grate

Figure 8 - Plan view of CDOT close-mesh grate

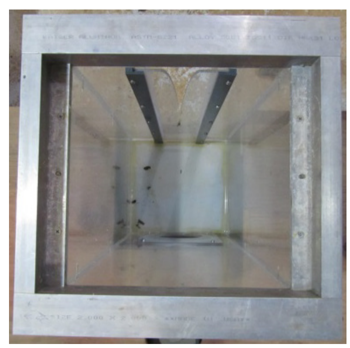

Figure 9 - Plan view of no grate

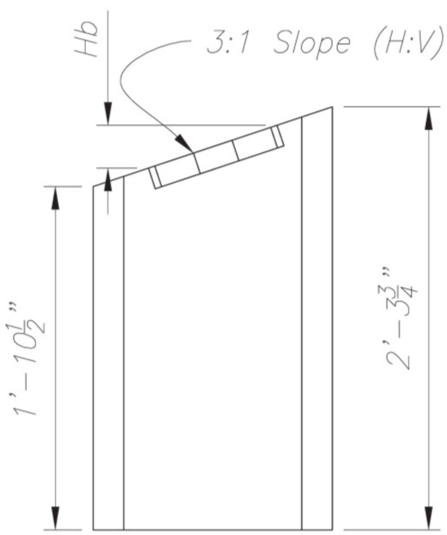

Figure 10 - 3:1 sloped weir box with grate H_b= 0.307 ft (model scale)

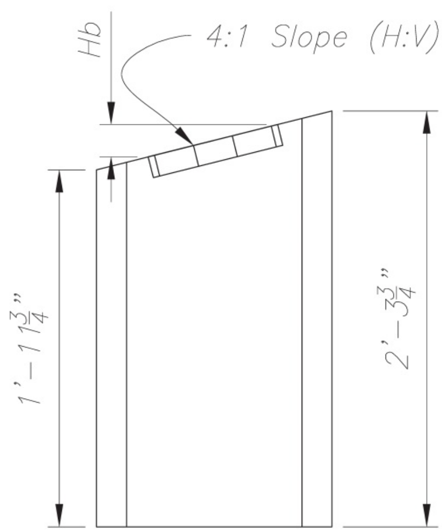

Figure 11 - 4:1 sloped weir box with grate H_b= 0.236 ft (model scale)

Table 3 contains a summary of the test configurations modeled and indicates where surrounding topography was set at the same slope as the overflow outlet structure and grate (Figure 12).

Table 3 - Summary of test configurations that were modeled

Slope	Grate	Surrounding Topography
3:1 (H:V)	Standard CDOT Type C	YES
3:1 (H:V)	CDOT Close Mesh	YES
3:1 (H:V)	None	YES
4:1 (H:V)	Standard CDOT Type C	YES
4:1 (H:V)	CDOT Close Mesh	YES
4:1 (H:V)	None	YES
None	Standard CDOT Type C	NO
None	CDOT Close Mesh	NO
None	None	NO

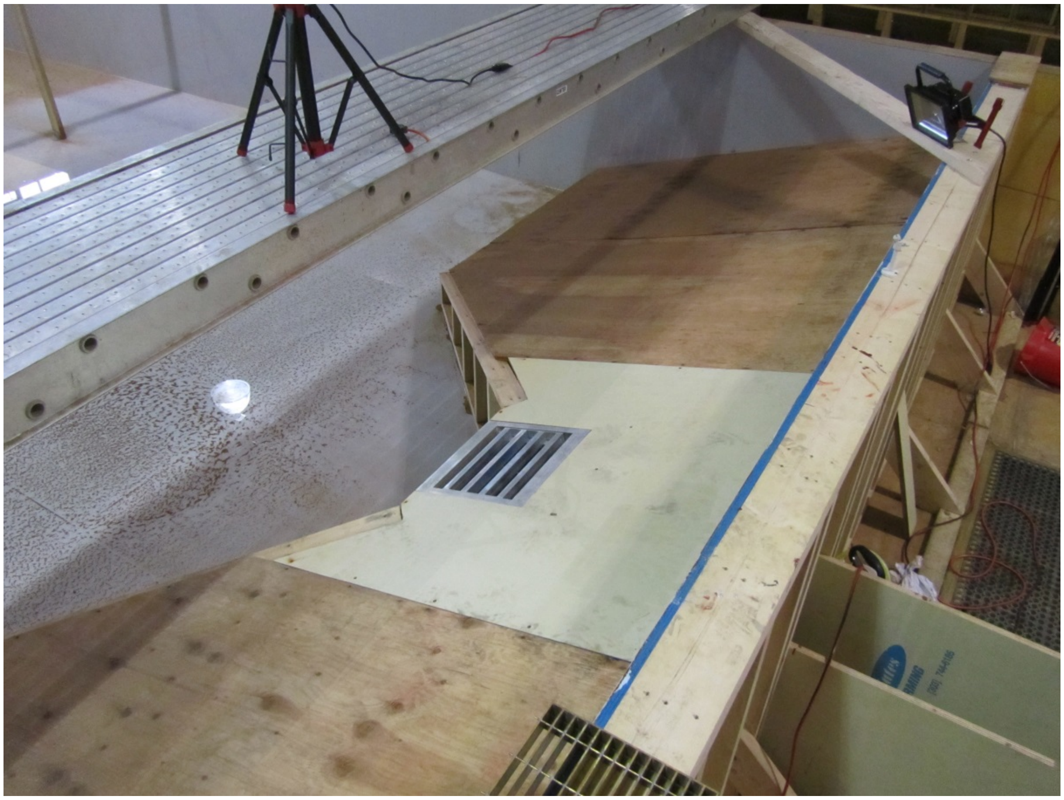

Figure 12 - 3:1 (H:V) slope showing the surrounding topography set at the same slope as the inlet grate

Most test configurations modeled the flow passing through the overflow outlet portion of the outlet works. One final configuration was modeled that tested no slope with no topography and included a complete outlet structure with micropool (Figure 13), water quality orifice plate and 100-yr orifice (Figure 14) restricting flow downstream of the overflow outlet. The water quality orifice plate was modeled as both the standard configuration with a series of orifice holes and as an alternative elliptical weir (Figure 15).

Figure 13 - Complete outlet structure including micropool, water quality orifice plate, horizontal overflow outlet and 100 year controlling orifice

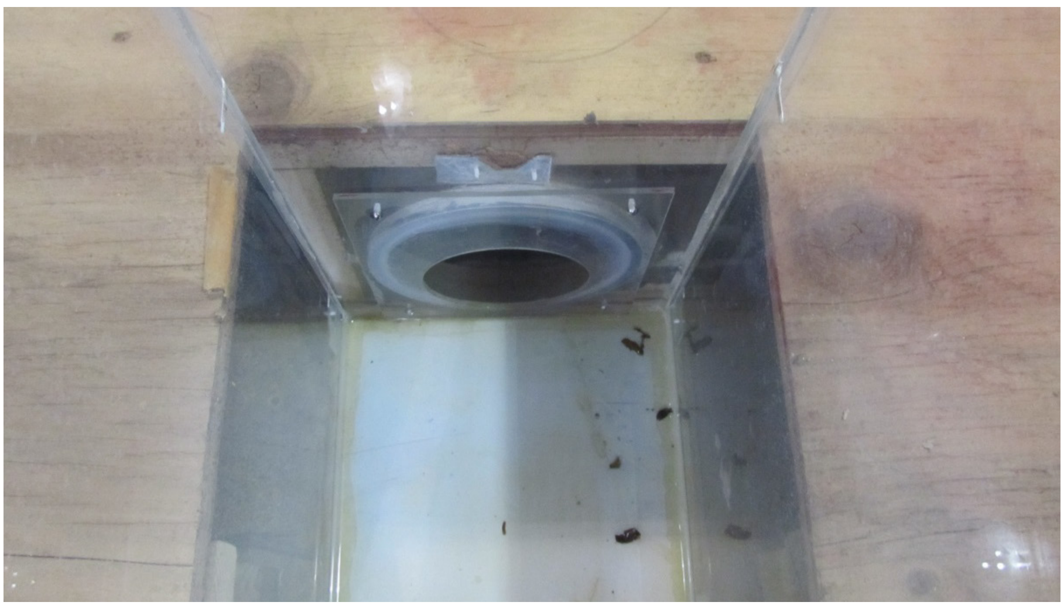

Figure 14 - 100 year controlling outlet orifice (inside outlet structure downstream of overflow)

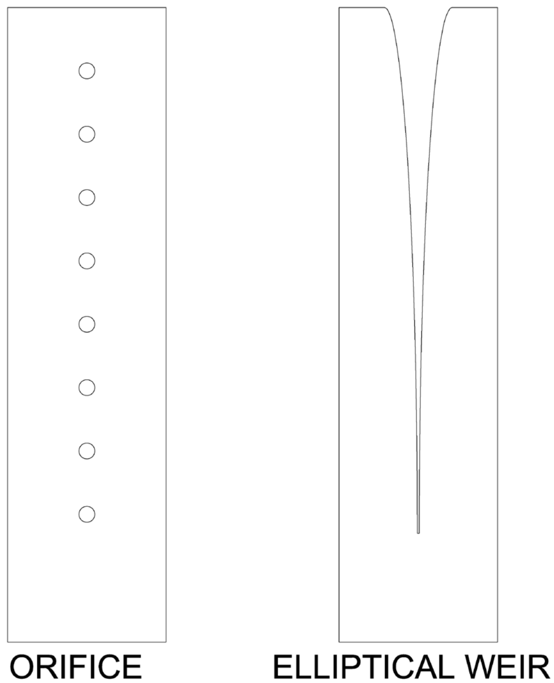

Figure 15 - Water quality orifice plate configurations tested in the complete EDB model

Test Procedure

Each model configuration was tested by completing the following steps:

1. Establish a specific flow rate measured by a calibrated venturi meter accurate to ±0.25 percent (USBR 1989) into the model box.
2. Allow the flow to stabilize for the necessary amount of time so that no change in water surface in the EDB is noticed for at least 5 minutes.
3. Obtain the water surface elevation (stage) above the lower edge of the inlet using both a calibrated laboratory ultrasonic sensor and a point gauge (redundant measurements for consistency).
4. Record both the stage and flow.
5. Repeat steps 1-4 to create a complete rating curve that identifies any transitions between weir and orifice flow.

Inflow and stage were recorded and plotted to generate stage-discharge relationships for each configuration. Collected data were then compared to the provided rating equations in Table 1 and Table 2.

RESULTS

All results presented in this section are reported in prototype dimensions. Figure 17 shows data collected at the 1:0 (H:V) (no slope) configuration for each of the three tested grates. Figure 18 shows data collected at the 4:1 (H:V) slope configuration for each of the three tested grates. Figure 18 shows data collected at the 3:1 (H:V) slope configuration for each of the three tested grates. Each figure plots stage above the lowest edge of the overflow outlet structure in ft on the x-axis and discharge through the overflow outlet in ft^3/sec on the y-axis.

Figure 19 provides data collected on the complete EDB with micropool, water quality orifice, horizontal overflow outlet and 100-year controlling orifice. This plot also shows stage (ft) above the lowest edge of the overflow outlet structure on the x-axis and discharge through the overflow outlet in ft^3/sec on the y-axis. All three grates were tested with a series of orifice holes in the water quality plate. One test was conducted with the orifice holes being replaced with an elliptical weir which releases a significantly larger discharge for a given head.

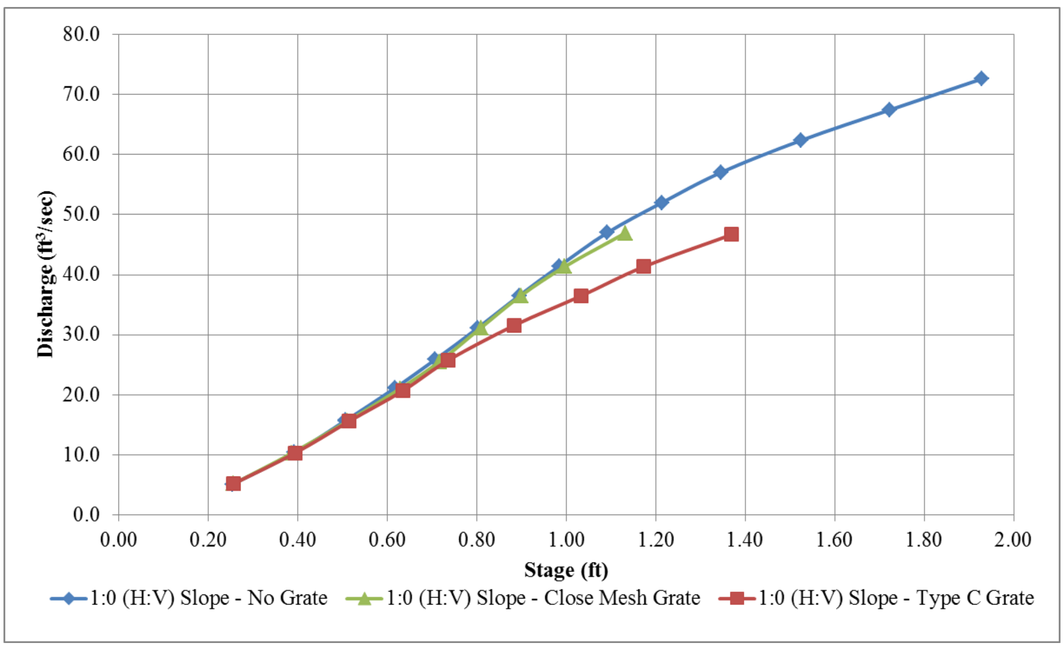

Figure 16 - Data collected in the 1:0 (H:V) slope configuration for each grate (prototype dimensions)

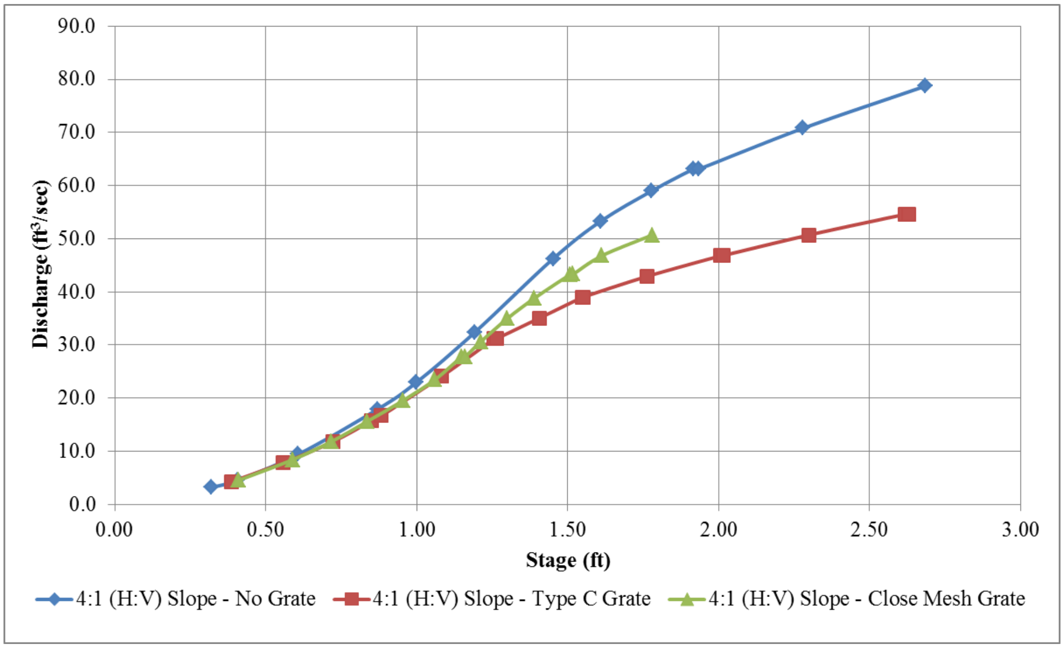

Figure 17 - Data collected in the 4:1 (H:V) slope configuration for each grate (prototype dimensions)

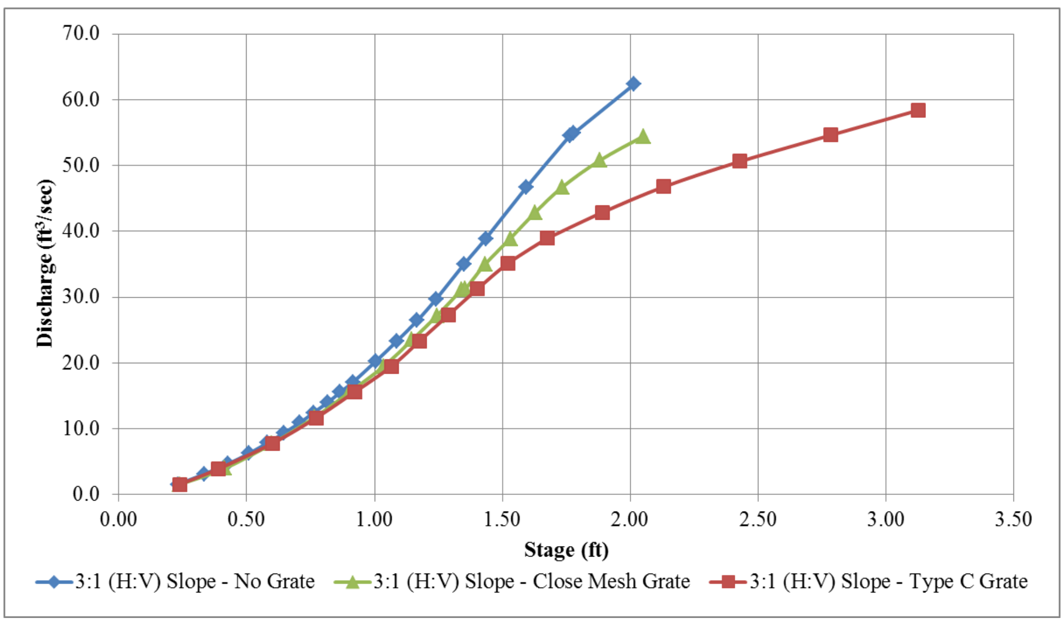

Figure 18 - Data collected in the 3:1 (H:V) slope configuration for each grate (prototype dimensions)

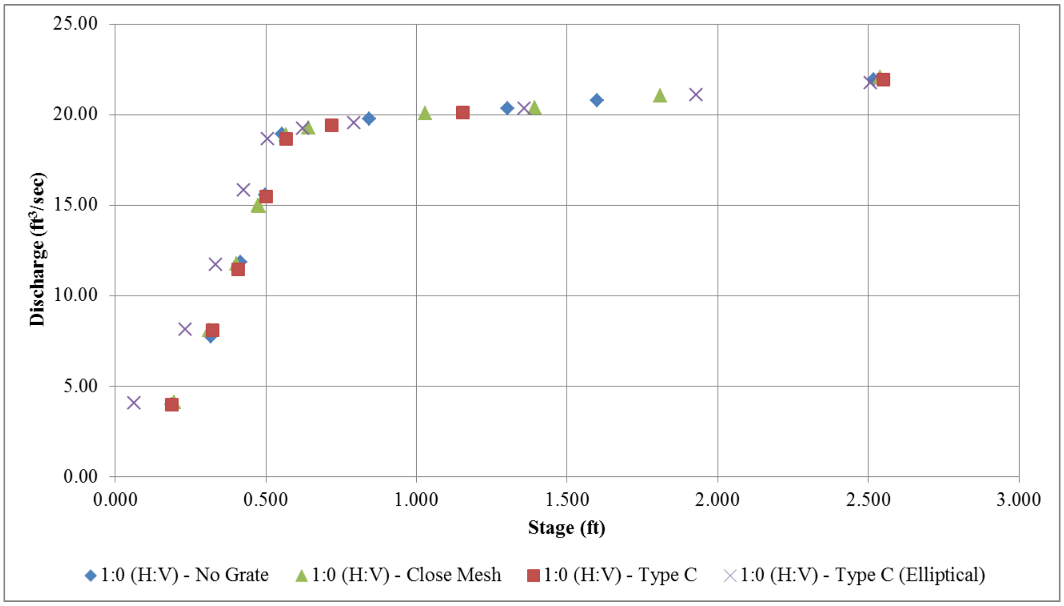

Figure 19 - Data collected on the complete EDB with micropool and 1:0 (H:V) slope overflow outlet structure. Water quality plates and the 100-year controlling orifice were installed for each configuration tested.

ANALYSIS

Each scenario was compared to the equations provided in Table 1 and Table 2 to determine if any of the equations generated rating curves consistent with the physical model. Figure 20 provides a sample plot with all of the equations and the laboratory data. These plots were created for each of the model configurations. Only one plot (4:1 (H:V) slope with a Type C grate installed) is presented in this report to give a representative sample of the data comparisons. Minor differences between generated plots occurred, but all looked similar, with inconsistencies existing between the model data and computed equations.

Two lines to pay particular attention to in Figure 20 are the “Model Data” and the “UDFCD ss” lines. The “Model Data” line is the model data taken in the laboratory. The “UDFCD ss” line is the set of equations adopted by the UDFCD for design purposes, which uses simple logic to determine which flow regime the overflow outlet structure is in and then uses the respective equations developed by Guo to calculate the flow. Table 4 shows tabulated values from Figure 20. The absolute difference was calculated by subtracting the model value from the equation value and the percent difference was determined by dividing the absolute difference by the model value and multiplying by 100. Equation values ranged from -26% to 493% different from the model data, and this was typical across all configurations tested. Values of NA in the table were not calculated because the equations were unable to calculate flows at those stages.

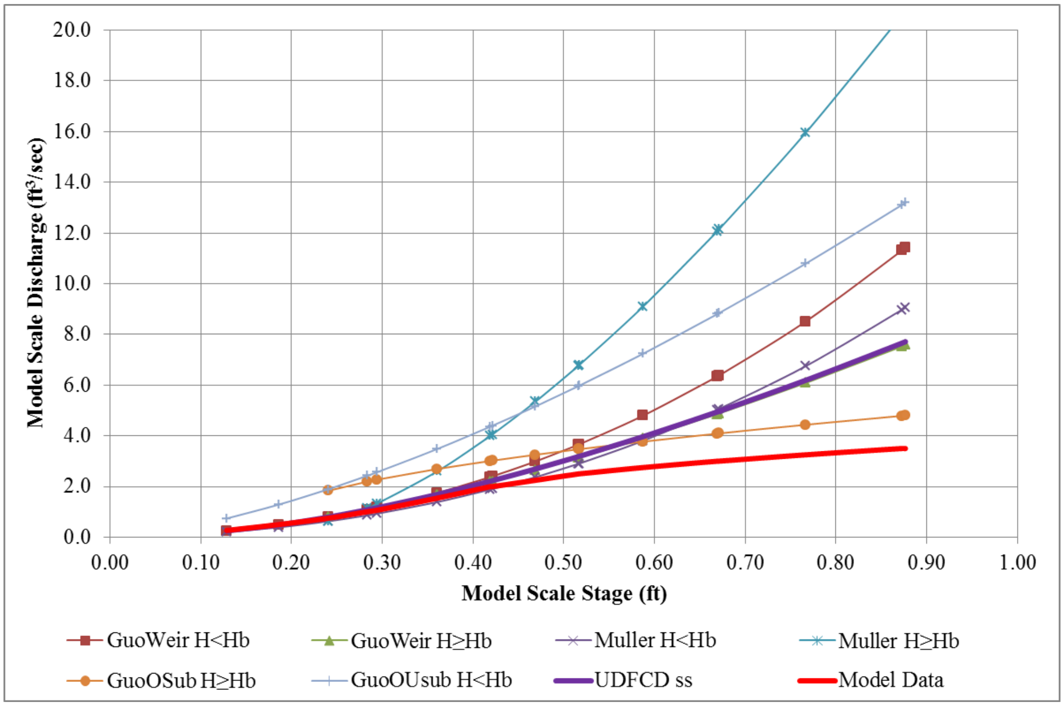

Figure 20 - 4:1 (H:V) slope with Type C grate model data compared to all equations presented in Tables 1 and 2 calculated using the same configuration information.

Table 4 - Data comparison between equation and model data presented in absolute difference [equation data - model data] and percent difference [absolute difference/model data X 100].

GuoWeir $_{H<Hb}$	GuoWeir $_{H\geq Hb}$	Muller $_{H<Hb}$	Muller $_{H\geq Hb}$	GuoOSub $_{H\geq Hb}$	GuoOUsub $_{H<Hb}$	UDFCD $_{ss}$
-0.02 (-7%)	NA	-0.07 (-26%)	NA	NA	0.47 (174%)	-0.02 (-7%)
-0.01 (-2%)	NA	-0.11 (-22%)	NA	NA	0.79 (158%)	-0.01 (-2%)
0.04 (6%)	0.03 (4%)	-0.12 (-16%)	-0.11 (-15%)	1.08 (144%)	1.14 (152%)	0.04 (6%)
0.08 (8%)	0.06 (6%)	-0.14 (-14%)	0.14 (14%)	1.18 (118%)	1.42 (141%)	0.08 (8%)
0.1 (10%)	0.08 (7%)	-0.14 (-13%)	0.26 (24%)	1.2 (112%)	1.5 (140%)	0.1 (9%)
0.21 (14%)	0.12 (8%)	-0.15 (-10%)	1.05 (68%)	1.15 (74%)	1.94 (126%)	0.15 (10%)
0.38 (19%)	0.18 (9%)	-0.12 (-6%)	1.99 (100%)	1.01 (51%)	2.36 (118%)	0.21 (11%)
0.4 (20%)	0.2 (10%)	-0.09 (-5%)	2.06 (103%)	1.02 (51%)	2.4 (120%)	0.24 (12%)
0.74 (33%)	0.41 (18%)	0.12 (6%)	3.1 (138%)	1.01 (45%)	2.92 (130%)	0.45 (20%)
1.15 (46%)	0.63 (25%)	0.4 (16%)	4.26 (170%)	0.97 (39%)	3.46 (138%)	0.68 (27%)
1.16 (46%)	0.64 (26%)	0.4 (16%)	4.29 (171%)	0.97 (39%)	3.48 (139%)	0.69 (28%)
2.05 (74%)	1.15 (42%)	1.05 (38%)	6.35 (231%)	1.02 (37%)	4.49 (163%)	1.22 (44%)
3.33 (111%)	1.86 (62%)	2.02 (67%)	9.06 (302%)	1.09 (36%)	5.8 (193%)	1.94 (65%)
3.38 (113%)	1.89 (63%)	2.06 (69%)	9.15 (305%)	1.1 (36%)	5.85 (195%)	1.97 (66%)
5.26 (162%)	2.84 (87%)	3.5 (107%)	12.7 (391%)	1.19 (36%)	7.54 (232%)	2.94 (90%)
7.81 (223%)	4.02 (115%)	5.47 (156%)	17.08 (488%)	1.29 (37%)	9.61 (274%)	4.15 (119%)
7.92 (226%)	4.08 (117%)	5.56 (159%)	17.26 (493%)	1.3 (37%)	9.7 (277%)	4.21 (120%)

The shape of the head-discharge curve observed in the model makes it apparent that flow control varies from weir flow at low heads to transitional (mixed flow) at intermediate heads, and finally orifice flow at high heads. Approximate bounds of these zones are illustrated in Figure 21. Zones will change slightly depending on the geometry and configuration of the outlet structure and overflow weir.

When flows were in the mixed flow zone they became unstable and the stage in the EDB would fluctuate significantly with a constant inflow. Figure 22 shows this phenomenon, which was present at all configurations. Data was collected for each configuration until the stage oscillations were noticed. As can be seen in Figure 16 through Figure 18 oscillations occurred at different head and discharge for each configuration.

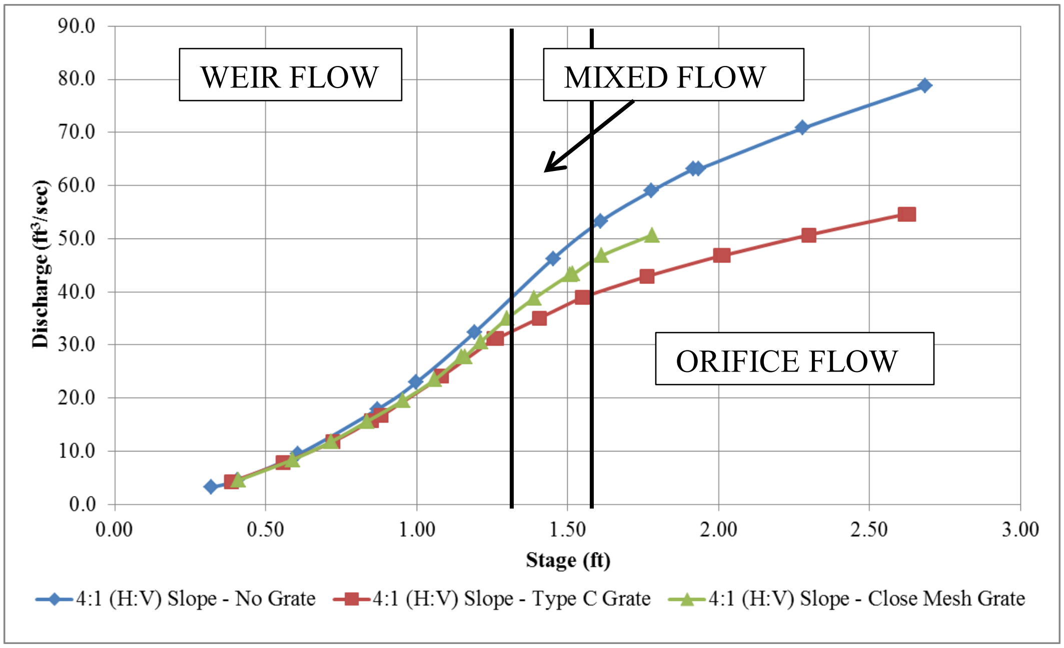

Figure 21 - Approximate boundary zones for weir flow, mixed flow and orifice flow

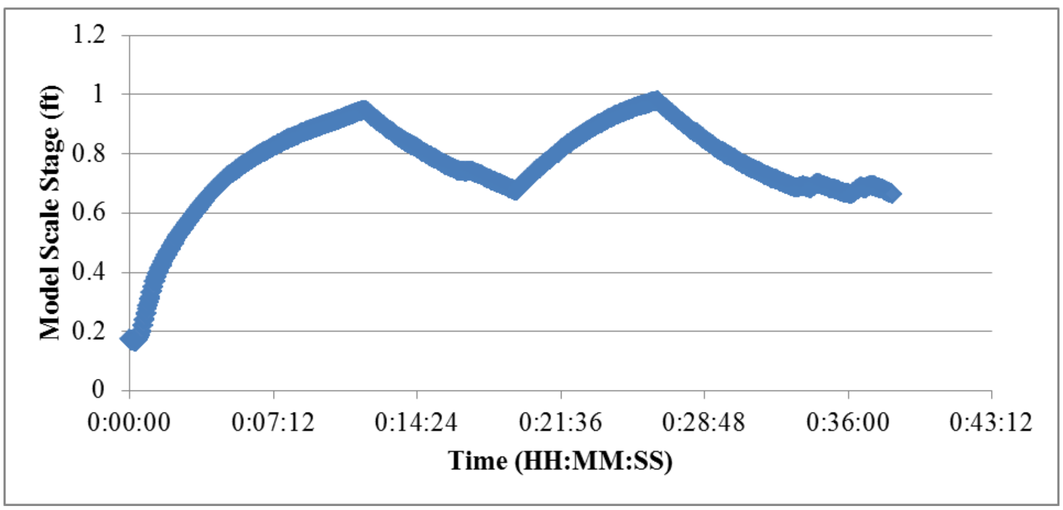

Figure 22 - Sample flow oscillations that occurred when flows entered mixed zone for the 4:1 case with standard type c grate.

Reclamation analyzed the data to determine if a single new equation or set of equations of consistent form could be generated that would accurately describe the flow through the overflow outlet works for all structure configurations. Reclamation plotted the data in TableCurve 2D and TableCurve 3D utilizing different dependent and independent variables. No single relationship was found that accurately described the overflow outlet discharge for all configurations tested. Reclamation determined that it would be difficult to develop a new equation that would accurately describe the flow through the overflow outlet in all zones (weir, mixed and orifice) for any slope, especially with the limited amount of data that was collected during this modeling effort. If more slopes and flows were tested it may be possible to generate a more uniform equation.

Reclamation determined that calculating the discharge through the overflow outlet in all three zones (weir, mixed and orifice) was unnecessary from a practical perspective, because when installed, the outlet works is required to have a 100-yr orifice that restricts the flow through the overflow outlet and prevents the outlet from ever functioning as the flow control in the transitional or orifice mode. After discussing this with UDFCD it was determined that modeling a complete EDB would verify how the 100-yr orifice controls the flow. As shown in Figure 19, the complete model of the EDB confirmed that flow would be restricted by the 100-yr orifice prior to the overflow outlet entering the mixed flow or orifice flow zones; the overflow outlet is in the weir flow zone for the entire range in which it controls the flow.

The 100-yr orifice installed downstream of the overflow outlet performs several valuable functions for the EDB. First, the flow rate from the EDB must be limited to the 100-yr flow so that piping systems downstream of the EDB outlet are not overwhelmed. Second, the 100-yr orifice makes calculating the flow from the overflow outlet less complicated because the flow would remain primarily in the weir flow zone. Discharge calculations from the EDB would transfer to using the 100-yr orifice before utilizing the overflow outlet as an orifice. Third, the 100-yr orifice would prevent the overflow outlet from reaching an unstable oscillating water surface with associated unstable outflows that could not be accurately calculated from the EDB stage.

Flows entering the outlet structure become very turbulent between the overflow outlet and the 100-yr orifice. Reclamation questioned if using a standard orifice discharge coefficient of 0.61 would yield accurate discharge calculations from the 100-yr orifice. Data from the physical model were used to determine that the coefficient in the model was 0.60. When calculating flow from the 100-yr orifice, head relative to the center of the orifice was used.

When calculating flow through an overflow outlet, UDFCD was utilizing a clogging factor which was a reduction factor to represent typical clogging plus the reduction in area caused by the grates. Reclamation determined that it would be more appropriate to use a discharge coefficient to account for the reduction in flow caused by the grate and have a separate clogging factor to account for debris clogging. By creating custom discharge coefficients from the physical model data for each grate and slope, Reclamation was able to match the physical model data utilizing the weir equations provided by Guo in Table 1. Discharge coefficients for each slope and grate can be found in Table 5. These discharge coefficients are used in the equations presented in Table 6 (adapted from Guo's) to calculate the flow from the overflow outlet structure; variable locations are shown in Figure 23.

Table 5 - Discharge coefficients for each slope and grate

100-yr Orifice Coefficient	
0.60	100-yr orifice
Overflow Outlet Coefficient, C_d	
0.64	1:0 (H:V) Slope - No Grate
0.62	1:0 (H:V) Slope - Close Mesh
0.60	1:0 (H:V) Slope - Type C
0.68	4:1 (H:V) Slope - No Grate
0.63	4:1 (H:V) Slope - Close Mesh
0.62	4:1 (H:V) Slope - Type C
0.68	3:1 (H:V) Slope - No Grate
0.60	3:1 (H:V) Slope - Close Mesh
0.58	3:1 (H:V) Slope - Type C

Table 6 - Equations to determine discharge from the overflow section of an extended detention basin.

Flow Type	**Equation**
100-yr orifice	$Q_O = C_o A_o \sqrt{2gH}$
Flat Weir	$Q_{Flat} = \frac{2}{3} n C_d (2B + 2L) \sqrt{2g} H^{\frac{3}{2}}$
Sloped Un-Submerged Weir ($H < H_b$)	$Q_{WS} = \frac{4}{15} n C_d \sqrt{2g} \cot(\theta)\, H^{\frac{5}{2}}$ $Q_{WB} = \frac{2}{3} n C_d \sqrt{2g} B H^{\frac{3}{2}}$ $\boldsymbol{Q_W = 2Q_{WS} + Q_{WB}}$
Sloped Submerged Weir ($H \geq H_b$)	$Q_{WS} = \frac{4}{15} n C_d \sqrt{2g} L \cos(\theta) \left[\frac{H^{\frac{5}{2}} - (H - H_b)^{\frac{5}{2}}}{H_b}\right]$ $Q_{WB} = \frac{2}{3} n C_d \sqrt{2g} B H^{\frac{3}{2}}$ $\boldsymbol{Q_W = 2Q_{WS} + Q_{WB}}$

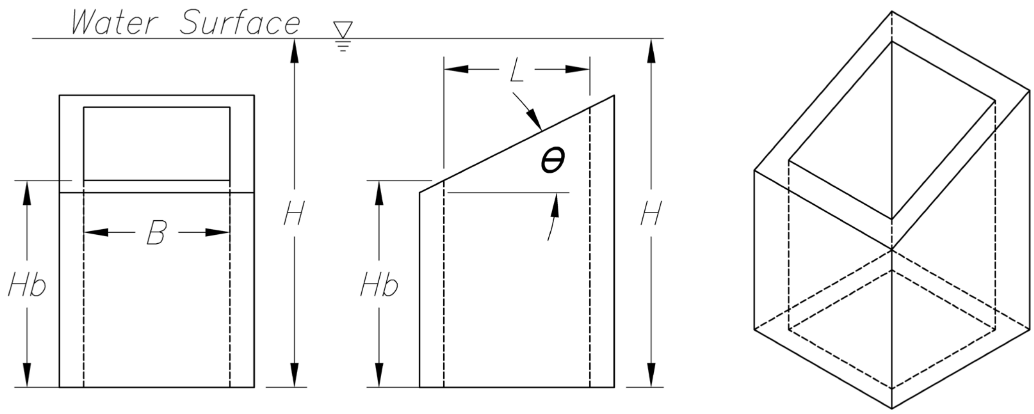

Figure 23 - Variable Locations for Equations in Table 6

Guo’s weir-flow equations calculate flow into only three sides of the overflow outlet (flow over the top edge is considered negligible because the head acting on this section is limited by the overland flow across the ground surface). For the 1:0 (H:V) no slope case, this is not realistic because flow can enter equally from all four sides since these outlets typically are not installed in the bank of the EDB and do not have surrounding topography.

Reclamation used the information gathered from the physical model to develop a new spreadsheet for UDFCD to utilize when calculating the discharge from the overflow outlet. Visual Basic programming was used to logically determine, based on the outlet configuration and the stage, which equations should be used to determine the flow. The entire Visual Basic program can be found in Appendix A. The spreadsheet calculations were compared to all physical model data to verify that it accurately calculates the flow through the discharge structure. Figure 24 is a plot directly from the spreadsheet that shows the physical model data overlaid on top of the spreadsheet stage discharge relationship. The stage sharply increases where the 100-yr orifice begins controlling the flow through the outlet structure.

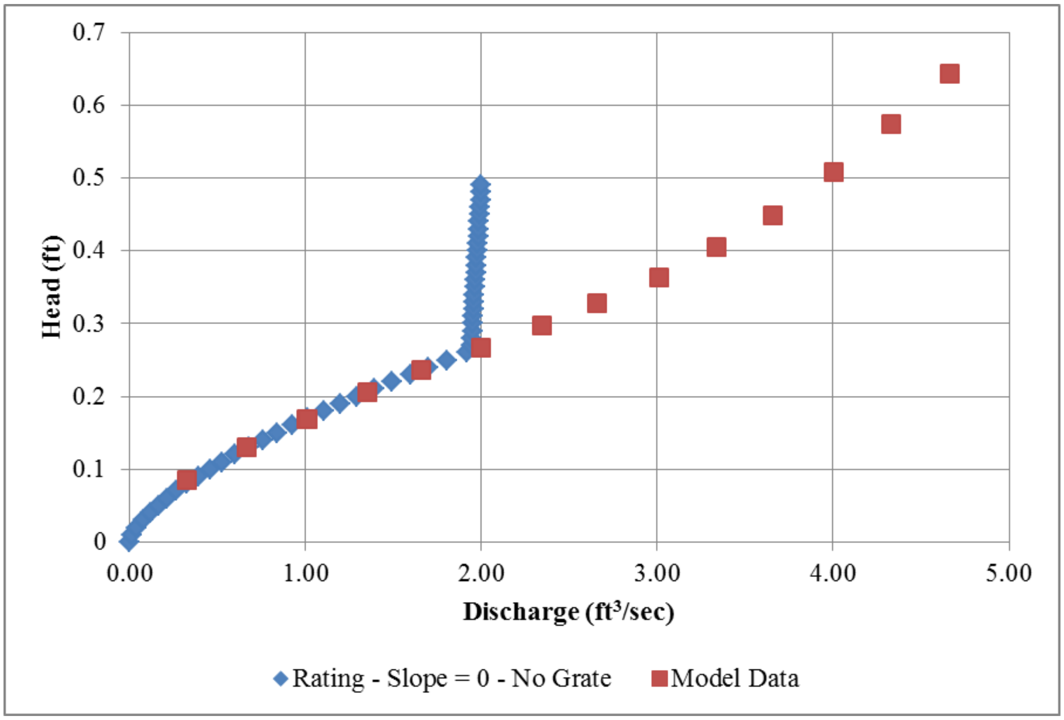

Figure 24 - Final spreadsheet stage discharge plot showing the rating calculated from the spreadsheet in blue and the model data for a 1:0 (H:V) slope with no grate in red.

When modeling the complete EDB, two different water quality orifice options were tested, a series of orifice holes and an elliptical weir configuration. The elliptical weir configuration is desirable from a debris standpoint because the orifice holes have a tendency to clog when floating debris enters the EDB. Given the same stage, Figure 19 shows that the elliptical weir will release more flow from the EDB than the orifice configuration.

UDFCD wished to know if the Flow-3D commercially available computational fluid dynamics (CFD) software package was capable of accurately determining the discharge through the overflow outlet. FLOW-3D is developed by Flow Science Inc. and was chosen because of its ability to accurately model free-surface flows. FLOW-3D utilizes the Reynolds-averaged Navier-Stokes (RANS) equations to solve for fluid flow. Reclamation modeled a single configuration using Flow-3D at a 4:1 (H:V) slope with no grate. Figure 25 confirms that Flow-3D can be used to accurately model the discharge through the overflow section of the outlet works. The CFD model was set up and run at multiple discharges and differences between the physical and numerical model were only compared graphically. Differences between the physical and CFD model were minimal and could most likely be improved by doing a mesh resolution analysis on the CFD model to determine if the resolution of the model was as accurate as possible. This type of analysis was not pursued.

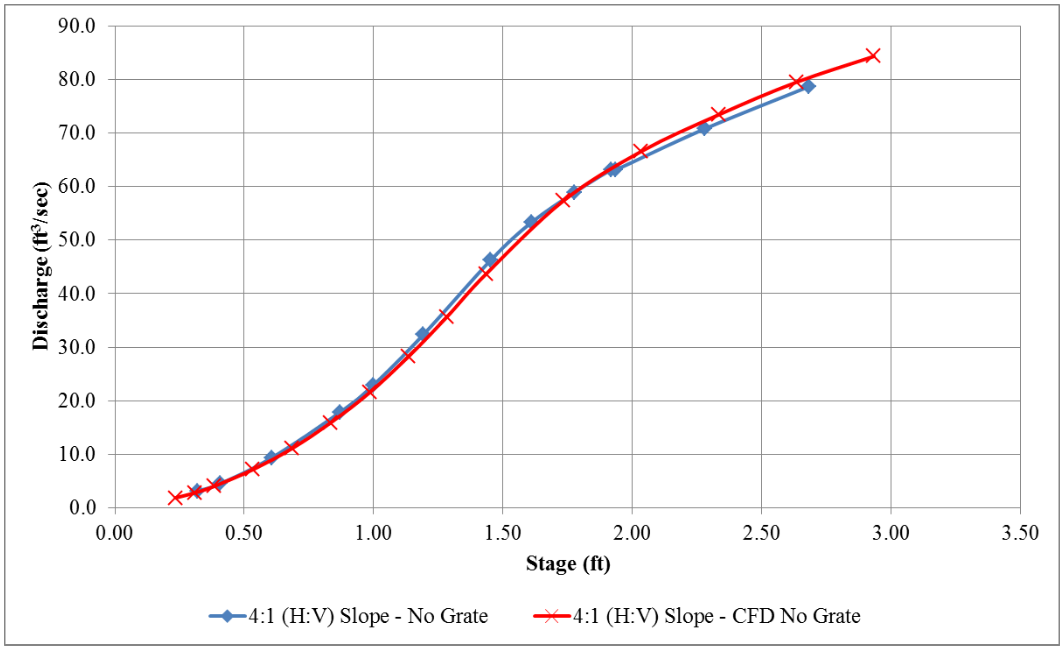

Figure 25 - Computational Fluid Dynamics (CFD) and physical model comparison of the 4:1 (H:V) slope configuration with no grate.

RECOMMENDATIONS

Reclamation recommends utilizing the spreadsheet created in conjunction with this study to calculate the flow through extended detention basin overflow outlets (EDBs). The results of the spreadsheet were compared to the physical model data and good agreement was confirmed between model data and spreadsheet results for all configurations tested.

The spreadsheet has some limitations.

- It has only been verified against the data collected in the physical model, which was limited to three slopes and three grate configurations.
- If grates are used in parallel (side by side or end to end to increase area) the spreadsheet calculations may not be accurate.
- The spreadsheet does not calculate the flow through the water quality orifice plates at the front of the outlet structure. This calculation could be added if desired.
- Results of the spreadsheet are dependent on accurately inputting the correct dimensions and discharge coefficients from Table 5.

If no 100-yr orifice is installed in the EDB outlet structure, calculating flow from the overflow outlet based on stage is difficult because oscillating stage with a constant inflow is possible when the weir flow limit is exceeded. Flow through the 100-yr orifice should be calculated using an orifice discharge coefficient of 0.60 and a head referenced from the center of the orifice.

Designs that are unique and push the limits of what was tested in the physical model can likely be modeled successfully using computational fluid dynamics. Reclamation successfully matched model test data using Flow-3D, and other CFD modeling programs might render similar results.

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APPENDIX A

The following Visual Basic Program was implemented.

```
'Urban Drainage Flood Control District Equation - Flat Top
Function QWeirFlat(Clog, Cw, W, HorzL, H)
        QWeirFlat = 2 / 3 * Clog * Cw * Sqr(64.4) * (2 * W + 2 * HorzL) * (H) ^
        1.5
End Function

'Front
Function Qfront(Clog, Cw, W, H)
        Qfront = 2 / 3 * Clog * Cw * Sqr(64.4) * (W) * (H) ^ 1.5
End Function

'Side Un-Submerged
Function QsideUN(Clog, Cw, W, Angle, H)
        QsideUN = 4 / 15 * Clog * Cw * Sqr(64.4) * ((H) / Tan(Angle)) * (H) ^
        1.5
End Function

'Side Submerged
Function QsideSUB(Clog, Cw, W, HorzL, Angle, H, Ho, Ht)
        QsideSUB = 4 / 15 * Clog * Cw * Sqr(64.4) * HorzL * Cos(Angle) *
        (((H) ^ 2.5 - (H - (Ht - Ho)) ^ 2.5) / (Ht - Ho))
End Function

‘100-yr Orifice
Function Q100yr(Co, AreaO, Stage, CenterO)
        Q100yr = Co * AreaO * Sqr(64.4 * (Stage - CenterO))
End Function

Sub Calculate()
Dim Qw, Qo, Qmin, H, i, Step, NumStep As Double

'Clear Old Data
Range("B23:D200").Select
Selection.ClearContents

'Define Variables
W = Range("W").Value
Ho = Range("Ho").Value
Ht = Range("Ht").Value
HorzL = Range("HorzL").Value
AligL = Range("AligL").Value
Clog = Range("Clog").Value
Cw = Range("Cw").Value
Co = Range("Co").Value
```

```
S = Range("S").Value
Angle = Range("Angle").Value
AreaO = Range("AreaO").Value
CenterO = Range("CenterO").Value
StepSiz = Range("StepSiz").Value
StepNum = Range("StepNum").Value

H = 0
i = 0

Do Until i = StepNum
   Stage = Ho + H
   Cells(23 + i, 2) = H
   Cells(23 + i, 3) = Stage
   If S >= 0 Then
   Qw = QWeirFlat(Clog, Cw, W, HorzL, H)
   Qo = Q100yr(Co, AreaO, Stage, CenterO)
      If Qw < Qo Then
      Qmin = Qw
      Else
      Qmin = Qo
      End If
   Else
      If H < Ht Then
      Qw = Qfront(Clog, Cw, W, H) + 2 * QsideUN(Clog, Cw, W, Angle, H)
      Qo = Q100yr(Co, AreaO, Stage, CenterO)
         If Qw < Qo Then
         Qmin = Qw
         Else
         Qmin = Qo
         End If
      Else
      Qw = Qfront(Clog, Cw, W, H) + 2 * QsideSUB(Clog, Cw, W, HorzL,
Angle, H, Ho, Ht)
      Qo = Q100yr(Co, AreaO, Stage, CenterO)
         If Qw < Qo Then
         Qmin = Qw
         Else
         Qmin = Qo
         End If
      End If
   End If

   Cells(23 + i, 4) = Qmin
   i = i + 1
   H = H + StepSiz
```

```
Loop

End Sub
```