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AIR VENT SIZING IN LOW-LEVEL OUTLET WORKS FOR SMALL-TO-MEDIUM SIZED DAMS

by

Nathan W. Wright

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

Approved:

Blake P. Tullis Major Professor	Gilberto E. Urroz Committee Member
Joseph A. Caliendo Committee Member	Mark R. McLellan Vice President for Research and Dean of the School of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2013

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ABSTRACT

Air Vent Sizing in Low-Level Outlet Works for Small- to Medium-Sized Dams

by

Nathan W. Wright, Master of Science

Utah State University, 2013

Major Professor: Blake P. Tullis
Department: Civil and Environmental Engineering

The majority of dams contain low-level outlet works, which typically consist of closed conduits that run through the dam, and are used to release water from the reservoir when the water level is below the level of the surface spillways. It is also used to flush the reservoir of sediments and to control the elevation of the reservoir. Low-level outlet works typically consist of a gate that controls the flow within a closed conduit that runs through the dam and an air vent that supplies air behind the gate. In the absence of properly designed air vents, negative pressures may develop downstream of the gate. These negative pressures could potentially lead to cavitation and vibration damage. Properly sized air vents help maintain the downstream air pressure at or near atmospheric pressure and/or provide air to absorb the energy generated by cavitation, reducing the potential for damage.

The majority of research done on air vent sizing is for dams having large dam geometry, which consist of a pressurized conduit leading to a vertical slide gate that is followed by a discharge tunnel. The typical air vent design for these large dams uses the water flow rate and the Froude number measured at the vena contracta downstream of the gate. The low-level outlet works for small-to-medium-sized embankment dam geometries typically have an inclined slide gate, installed at the inlet on the upstream face of the dam slope, followed by an elbow that connects to a conduit that passes through the dam and discharges downstream. This type of outlet geometry does not produce the typical vena contracta. Consequently, the use of the Froude number, at the vena contracta , as a characteristic parameter for characterizing airflow demand is not practical.

Recently a laboratory study was performed calculating the head-discharge characteristics of low-level outlets for small-to-medium sized dam geometries. In addition to validating some of the previous laboratory-scale air venting research, the objective of this study was field verification of air-demand/air vent sizing predicted by the laboratory-based method. The influence of conduit slope, air port location, and hydraulic jumps on air demand was also evaluated in the laboratory. The findings of this study can be found within this thesis.

(61 pages)

PUBLIC ABSTRACT

Air Vent Sizing in Low-Level Outlet Works for Small- to Medium-Sized Dams

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Nathan W. Wright, Master of Science

Utah State University, 2013

The majority of dams contain low-level outlet works, which typically consist of closed conduits that run through the dam, and are used to release water from the reservoir when the water level is below the level of the surface spillways. It is also used to flush the reservoir of sediments and to control the elevation of the reservoir. Low-level outlet works typically consist of a gate that controls the flow within a closed conduit that runs through the dam and an air vent that supplies air behind the gate. In the absence of properly designed air vents, negative pressures may develop downstream of the gate. These negative pressures could potentially lead to cavitation and vibration damage. Properly sized air vents help maintain the downstream air pressure at or near atmospheric pressure and/or provide air to absorb the energy generated by cavitation, reducing the potential for damage.

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downstream of the gate. The low-level outlet works for small-to-medium-sized embankment dam geometries typically have an inclined slide gate, installed at the inlet on the upstream face of the dam slope, followed by an elbow that connects to a conduit that passes through the dam and discharges downstream. This type of outlet geometry does not produce the typical vena contracta. Consequently, the use of the Froude number, at the vena contracta , as a characteristic parameter for characterizing airflow demand is not practical.

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I am grateful to all those who have assisted me in my research project. Special thanks to the following: Blake Tullis for the opportunity to work at the Utah Water Research Laboratory and his guidance throughout the project; my committee members Gilberto E. Urroz and Joseph A. Caliendo for their advice; Mitch Dabling who assisted in the data collection; and Daryl Devey of the Central Utah Water Conservancy District who allowed the use of the three dams used for this study. Also, special thanks to the Division of Dam Safety and the Utah Water Research Laboratory for the funding needed to complete this project. Lastly, I'm especially grateful to my wife, Kaylee, and my family for their continued support and encouragement as I've pursued my master's degree.

Nathan W. Wright

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LIST OF ACRONYMS AND ABBREVIATIONS

cfs	cubic feet per second
fpm	feet per minute
fps	feet per second
ft	feet
lb	pound force
s	seconds
UWRL	Utah Water Research Laboratory
USBR	United States Bureau of Reclamation

LIST OF SYMBOLS

A_o	Area of Orifice (ft^2)
C_d	Valve/Orifice discharge coefficient
d	Diameter of Orifice (ft)
D	Diameter of low-level outlet conduit (ft)
Fr	Froude Number
g	Acceleration of Gravity (ft/s^2)
h_a	Upstream Head (ft)
Δh	Differential across the orifice plate (ft)
ΔH	Reservoir head to centerline of low-level outlet conduit (ft)
K_l	Valve loss coefficient
Q_a	Air flow rate in air vent (cfs)
Q_w	Water flow rate in low-level outlet conduit (cfs)
V	Water Velocity past Gate (ft/s)
W	Flume width (ft)
β	Dimensionless Air Demand: Air flow rate versus water flow rate ratio (Q_a/Q_w)

CHAPTER I

INTRODUCTION

Dams usually have a low-level outlet works that consists of a closed conduit through the dam with a slide gate to control the flow rate. The main purpose of the low-level outlets has been described by (Speerli and Hager, 2000): (a) first impounding control, (b) sedimentation flushing, (c) release and monitoring of irrigation waters, and (d) draw down of the reservoir for maintenance. As water flows through the conduit a pressure drop occurs as it reaches the downstream side of the gate. This pressure drop is caused as a region of streamlines begins to separate. If the pressure drop continues below atmospheric it can lead to the damaging effects of cavitation and vibration. Vents are installed on the downstream side of the gate to alleviate the negative pressures by connecting the conduit to the atmosphere outside. A properly designed air vent will allow for the pressure on the downstream side of the gate to be approximately atmospheric. This allows for safe and efficient flow through the conduit. If the air vent is undersized, problems associated with cavitation, noise, and vibration may still occur.

Background

Many previous studies have been performed regarding air demand in low-level outlet works. The volumetric flow rate of air (Q_a) has been referred to as air demand. The ratio of air demand to the volumetric flow rate of water (Q_w) in the low-level outlet works is often used in the design of air vents. This ratio is referred to as the dimensionless air demand (β).

Most of the previous work regarding air vent sizing for low-level outlet works has been specific to relatively large dam geometries which feature a vertical slide gate located near the center of the dam separating a pressurized upstream conduit and a non-or-low-pressurized downstream conduit (see Figure 1). More recently, air vents for small-to-medium sized embankment dams have been evaluated by Tullis and Larcher (2011). These dams consist of an inclined slide gate located on the upstream face of the embankment, followed by an inlet, an elbow, and a sloping non-pressurized or low-pressure conduit through the dam (see Figure 2).

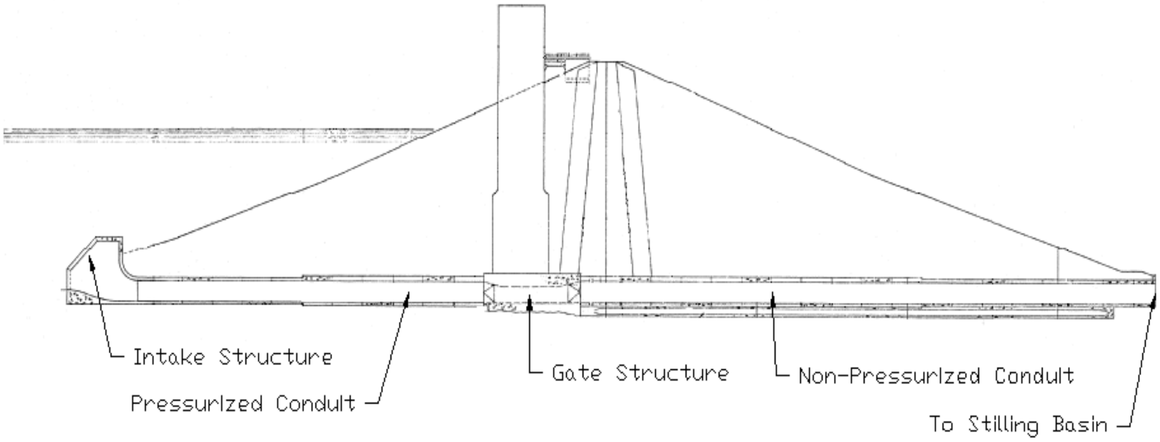

Figure 1: Large dam geometry outlet works (Larchar, 2011)

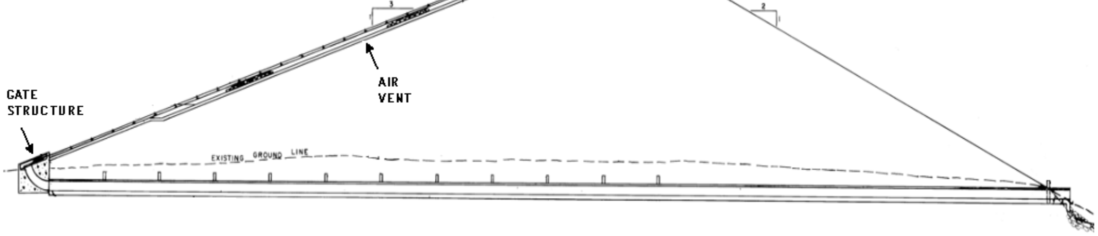

Figure 2: Small-to-medium dam geometry outlet works (Larchar, 2011)

These variations in low-level outlet geometry lead to changes in the location of flow control point and corresponding flow characteristics. Large dams are controlled downstream of the intake at the location of the gate. This geometry's limiting factors are the hydraulic characteristics of the conduit (length, roughness, slope, shape, and area), headwater depth, and tailwater depth. The low-level outlets for small dams are typically controlled by the gate at the inlet. Small dam low-level outlet works, under fully-vented conditions, are comparable to culverts operating under inlet control. This means that the conduit flow rate of water is dependent upon the ability of the inlet to pass water. For inlet control the limiting factors are headwater depth (measured from centerline of conduit to reservoir surface), cross sectional area, and inlet edge. Under inlet control, the capacity of the conduit is independent of the conduit characteristics and the outlet condition. When the conduit outlet is sufficiently submerged to create a fully pressurized flow in the conduit (i.e., outlet control), the tailwater elevation and flow resistance characteristics of the conduit also influence the discharge capacity. The flow conditions of water have a large impact on the air demand in the conduit. Both methods use dimensionless air demand to design air vents, but the differences discussed show the need for the new method for small-to-medium dam geometry.

Research Objectives

There is a need to properly size air vents in low-level outlet works in order to minimize the risks of cavitation and vibration. The objective of the research is to verify the laboratory data that were collected for small-to-medium sized dams. This study will accomplish the following objectives to better understand air vent sizing techniques.

1. Compare and contrast large dams to those of small-to-medium dams and show how the limiting factors change between the two dam geometries.
2. Measure the flow rate of air and water in the low-level outlet works of 3 dams located on the Wasatch National Forest near Kamas, Utah.
3. Evaluate the presence of size scale effects between the prototype and laboratory air demand data.
4. Investigate the effects of conduit slope on air demand in low-level outlet works by performing a lab study having a 4.5 percent and 0 percent slope for the low-level outlet works.
5. Investigate the effect of air vent positioning around the circumference of the pipe.
6. Look at the impact of a hydraulic jump on the air demand of the system.

Literature Review

Since the early 1940's people have done studies to estimate the necessary air demand in low-level outlet works. The majority of these studies have been done on dams having large-dam geometry, although a recent study was performed for small-to-medium dam geometry.

Kalinske and Robertson (1943) performed one of the first model studies on air demand in closed conduits. Their study was concerned with the effect a hydraulic jump has on air demand in circular conduits. They concluded that air demand was a function of the Froude number upstream of the jump (i.e, vena contracta).

Subsequent studies by Campbell and Guyton (1953) and the United States Army Corps of Engineers (USACE, 1964) looked at air demand for several large-dam prototypes. They found a relationship between gate opening and air demand. They noted that two maxima in air demand occurred. The first occurred at small openings (~5%) and was thought to be associated with spray flow effects. Spray flow occurs as large driving heads force water through small openings causing water to be dispersed into small droplets which entrain relatively large amounts of air. The second and larger maximum occurred when gate openings were around 80%. This maximum is due to the drag forces along the air-water interface.

Sharma (1976) performed a study that discussed possible closed-conduit flow types consistent with large-dam low-level outlet geometries, and their effect on the air-flow. He found that two maximum occurred in the air demand for free/spray flow while only one maxima occurred for flows having a hydraulic jump followed by pressurized pipe flow. For both free and spray flow he states that conduit roughness has a negligible effect on air demand. The gate opening corresponding to the maximum air demand varied with upstream head.

Mura et al. (1959) gathered data from prototype structures and found that there were two locations where airflow could potentially enter the conduit. The air vent located just downstream of the gate supplied the most air, while air flow also entered the conduit through the downstream end of the conduit (pipe exit) for flow conditions that featured a non-submerged outlet and/or non-pressurized conduit flow downstream of the control gate. He discovered that it was difficult for air to enter the conduit outlet even at small gate openings. He observed that the outlet conduit began to flow full for gate openings greater than 15% and stated that the max air demand generally occurs when the outlet flows full. He concluded that the max air flow is dependent on the properties of the gate, air vent, and conduit. It was also found that the velocity of the air column (non-pressurized flow) flowing above the water surface tended to be less than that of water.

Speerli (1999) performed a laboratory study, similar to Mura, on rectangular conduits having open channel flow with a free flowing outlet. He found that air demand remained relatively constant, independent of the driving head and tunnel length. It was found that the length of the tunnel had a large effect on the air entering at the conduit outlet due to friction losses. The United States Bureau of Reclamation (USBR, 1961) reported similar findings in their study of the Trinity Dam. They also found that as the water surface in the conduit rose, the amount of air entering at the exit decreased, as would be expected.

Sharma (1976) cites Dettmers (1953) for his study on the Lumiei Dam, which states that the gate opening for max air demand was found to be dependent on the gate structure. He also found that the airflow-to-water flow ratio (β) was dependent on the features of the gate structure, while being independent of head (Sharma, 1976).

Tullis and Larcher (2011) performed one of the first studies for air demand in small-dam low-level outlet works. The study evaluated circular conduits with round or rectangular inclined slide gates located in the upstream reservoir. They noted that due to turbulent mixing caused by water passing under the inclined gate and through the elbow, no classical vena contracta formed. Therefore, the results of the previous large-dam geometry low-level outlet air demand studies were not directly applicable to the small-dam geometries. They found that gate shape has an effect on air demand as the gate shape significantly influenced the flow characteristics immediately downstream (e.g., turbulence, spray, flow convergence, etc.). They also concluded that air demand was dependent upon the reservoir head above the inlet centerline, which was nondimensionalized using the conduit diameter (i.e., ΔH/D). A family of curves was developed for the corresponding discharge coefficient (C_d) and β values for certain gate openings. C_d values are the relationship between the pressure drop across the gate and the corresponding flow. C_d values are important in determining the water flow rate when there is no meter for calculating the flow. Valve C_d values fall within the range of 0 to 1.0. C_d=0 represents a closed valve; C_d=1.0 represents a zero energy loss valve. C_d values were calculated by using the Energy Equation applied between top of the reservoir and just downstream of the gate to calculate the minor loss coefficient (see Equation 1). C_d values were calculated using Equation 2 which was presented by Tullis (1989).

$$K_l = \frac{2*g*\Delta H}{V\text{^}2} \tag{1}$$

$$C_d = \left(\frac{1}{K_l+1}\right)^{0.5} \tag{2}$$

Tullis and Larchar (2011) concluded that the maximum air demand occurred near gate openings of 50%. Their data also showed that free flow produced a greater air demand than submerged outlet flow. This is due to the absence of air flowing above the air-water interface allowing only air that is entrained in submerged flow to exit the conduit. For this reason they recommended that free flow conditions be used in the air vent sizing process. Their data are limited to ΔH/D ≤ 22, and they recommended that further research be done for larger ΔH/D values.

A few similarities were found for estimating air demand for the large and small-to-medium dam geometries. First, the location of the air vent is the same, just downstream of the gate. Second, the submerged flow conditions yield an air demand less than that of free flow conditions for both dam geometries.

Large dams have a reservoir intake followed by a pressurized pipe and then a vertical gate structure. As flow passes under the gate it becomes supercritical and forms a vena contracta (if a submerged hydraulic jump does not exist on the downstream side of the gate) and then the varying flow types, based on the downstream conditions. Studies regarding large dams have compared air flow/water flow (β) to the Froude number at the vena contracta. The vena contracta forms as streamlines become parallel just downstream of the gate. For small dams, non-parallel streamlines converge as they pass under the gate and through the elbow. These non-parallel converging streamlines cause turbulent mixing which hinders the formation of a classical vena contracta. The vena contracta is a convenient location for measuring the Froude number for large dams (1-D hydraulics); the 3-D nature of the flow through the gate and elbow of the small-dam low-level outlet works make the identification of a characteristic Froude number impractical. It was therefore proposed by Tullis and Larchar (2011), that the air demand in small-to-medium dams be compared to $\Delta H/D$.

Comparing results from studies done on each of the two dam geometries shows major differences in the air demand related to gate opening. The USACE (1964) collected data on several large dams having free flow conditions. It is evident from Figure 3 that two maxima occur in the air flow.

Tullis and Larchar (2011) evaluated air demand for free flowing small-to-medium sized dams in a laboratory study. It is the assumption that the elbow in the small dams’ outlet works eliminates or at least greatly reduces the effects of spray flow. This can be seen in Figure 4 as only one maximum occurred under free flow conditions. The comparison of these two figures shows two very distinct maxima for the USACE (1964) study, whereas only one maximum is evident on the laboratory study for small dams. The location of the maxima also occurs at different gate openings showing the need of both methods.

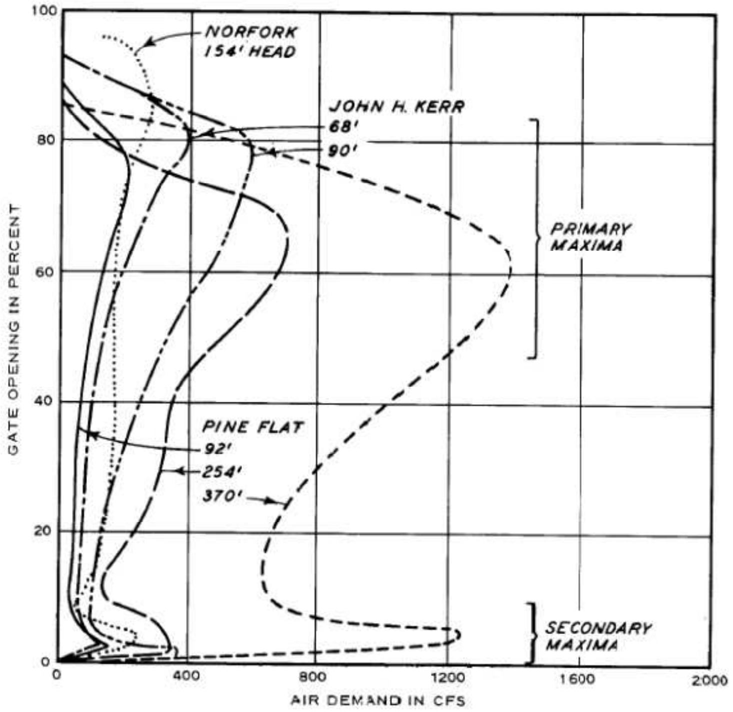

Figure 3: Large dam air demand versus gate opening data (USACE, 1964)

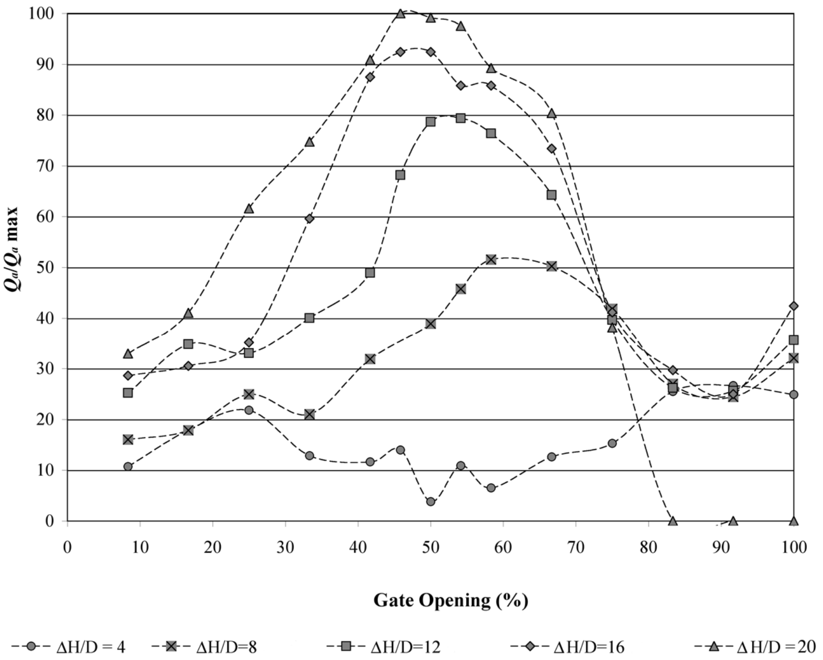

Figure 4: Small dam air demand versus gate opening (Tullis and Larchar, 2011)

CHAPTER II

EXPERIMENTAL METHODS

Prototype Experimental Setup and Measurements

To complete the given objectives, three dams were selected which are of similar geometry to the geometries studied by Tullis and Larcher (2011). Similar gate openings and ΔH/D ratios were used in order to properly compare the results. The elevation, gate opening, air flow rate, and water flow rate was measured. For each test ran it was verified that the condition at the outlet was either free flow or submerged flow. The geometry of each of the three dams can be seen in Table 1.

As the slopes of the prototypes were all much less than the 4.5 percent slope tested by Tullis and Larchar (2011) and the β results did not correlate well with their β results, a zero-sloping laboratory study was undertaken in order to better compare the results.

Table 1: Geometry of each prototype

	Gate Shape	Outlet Slope	Outlet Diameter	Elbow Angle	Outlet Length	Air Vent Diameter	Air Vent Type
Lost Lake	Rectangular	0.32%	2.5 ft.	70°	141.5 ft.	6 in.	Manifold
Trial Lake	Rectangular	0.78%	2.5 ft.	70°	192 ft.	4 in.	Tee
Washington Lake	Rectangular	0.09%	2.5 ft.	70°	180 ft.	6 in.	Manifold

The setup for the field tests consisted of attaching a PVC pipe to the end of the air vent intake and then sealing it with duct tape to assure that all air entering the system passed through the PVC pipe (see Figure 5). A 5/8-inch hole was made in the side of the PVC pipe, near the center of its length, for air velocity probe insertion. Two identical velocity probes were used during data collection to assure instrument accuracy. Once the velocity probe was installed, a target gate was established and the resulting flow was allowed to stabilize. The air velocity was then measured at the centerline of the vent. The flow rate was determined via a 5-foot wide Parshall flume, located downstream of the outlet, that was calibrated using the USBR's Water Measurement Manual. The discharge was calculated using Equation 3 (USBR, 2001). The dimensionless air demand (β) was then calculated by dividing the air demand by the water flow rate.

$$Q_w = 4 * W * {h_a}^{1.522 * W^{0.026}} \tag{3}$$

Figure 5: Air probe setup for prototype study

This process was repeated at four different reservoir elevations and at gate openings ranging from 10 to 80 percent. The gate openings were determined using the computerized data collection system used by the Central Utah Water Conservancy District (CUWCD). The reservoir elevation was taken from a Staff gauge installed at each reservoir. The reservoir elevation was made dimensionless by dividing by the low-level outlet works conduit diameter ($\Delta H/D$). The dimensionless air demand was then plotted verses the dimensionless reservoir head to develop a family of curves. This was done in order to properly compare the prototype data to the laboratory data for vented free discharging flow.

Laboratory Model Setup

A laboratory model was also tested at the Utah Water Research Laboratory. A 6’x3’x6’ (length x width x height) steel tank was used to simulate a reservoir. An acrylic floor was set to approximately a 3:1 (horizontal-to-vertical) slope to represent the upstream face of an earthen dam (see Figure 6).

Water was supplied to the tank from 1-inch and 4-inch diameter pipes depending on the necessary flow rates. A 1-inch gate valve and a 4-inch butterfly valve were used to control the flow within the respective water supply pipes. Flow rates were measured using a 1-inch diameter Siemens MAG6000 in the 1-inch pipe and a calibrated orifice plate was used in the 4-inch pipe. A pressure transducer was used to measure the pressure difference across the orifice plate. Water was supplied to the tank through a 4-inch diffuser and then passed through a plastic screen followed by a vertical baffle to eliminate source flow effects.

The low-level outlet works conduit consisted of a 3-inch diameter mitered elbow that connected to the acrylic bottom of the tank. A 5-foot long, 3-inch diameter, acrylic pipe was attached to the downstream side of the acrylic elbow using a flexible coupler. The pipe slope was tested at both 0 and 4.5 percent during the test program in order to better compare the effect of conduit slope on air demand. The outlet works setup can be seen in Figure 7. A 1-inch thick flange was installed between the elbow and the acrylic floor containing four air supply ports. Two of the air supply ports were located on the inside of the elbow directly behind the gate, while the other two air supply ports were located on the outside of the elbow. Figure 8 shows the configuration of the air vents with regards to the outlet works. A 1-inch supply line split into four separate lines that connected the four air supply ports.

A square machined gate was constructed to resemble the Hydro Gate type slide gate and was mounted on the sloped floor such that it covered the three-inch discharge opening. A crank that extended to the outside of the tank was used to change the gate opening. To increase stability, acrylic gussets were added to the floor of the tank. A picture of the gate setup can be seen in Figure 9.

Laboratory Measurements

Conduit free flow conditions were tested at various gate openings and various upstream heads. These conditions were tested for both a zero percent and 4.5 percent conduit slopes. Gate openings of 10, 30, 50, 60, 70, 90, and 100 percent were initially tested. To better understand the gate opening at which the max air demand occurred, gate openings of 45 and 55 percent were also tested. Gate openings are related to the linear

Figure 6: General laboratory setup

Figure 7: Low-level outlet works setup

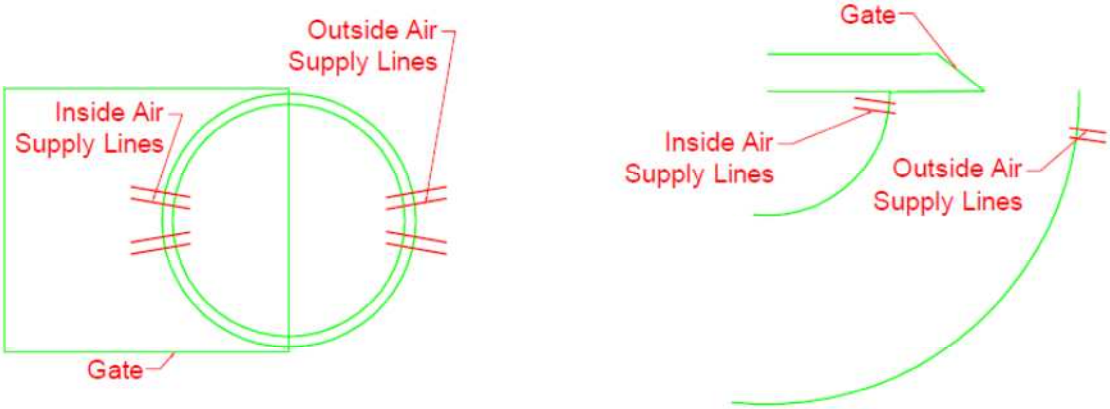

Figure 8: Air supply line terminology

Figure 9: Rectangular gate setup

travel distance of the gate not the percent of the available area. For each gate opening, ΔH values ranged from 6 to 66-inches, incremented in 12 inches elevation changes.

Reservoir vortices, associated with the low-level outlet works operation, were observed in both the Tullis and Larchar (2011) study and during the field testing. Consequently, special attention was paid to the vortex activity in this laboratory study. Vortices would form at the surface and the vortices would sometimes be drawn in to the low-level outlet intake. Other times the vortices would form at the water surface but never reach the outlet during the testing period. Both cases were recorded, as the vortex would sometimes go back and forth between the two cases. Vortices can influence the discharge efficiency as they increase the head loss, as well as reducing the amount of air needed from the air vent as vortices add air to the system.

Water flow rate

A 1-inch Siemens MAG6000 flow meter was inserted in the 1-inch line to measure flow rates. A calibrated orifice plate, installed in the 4-inch line, was used for water flow rate measurements. A pressure transducer was used to measure the pressure differential across the orifice plate. Using Equation 4 the differential was used for calculating the water flow rate in the 4-inch line.

$$Q_w = C_d * A_o * \frac{\sqrt{2*g*\Delta h}}{1-\left({}^{d}/_{D}\right)^4} \tag{4}$$

where:

Q_w	Discharge or flow rate, cfs
C_d	Orifice discharge coefficient
A_o	Cross-sectional area of the orifice throat, ft^2
g	Acceleration due to gravity, ft/s^2
Δh	Differential across the orifice plate, ft
d	Diameter of orifice throat, ft
D	Diameter of pipe, ft

Reservoir head

The reservoir head (ΔH) was measured from the centerline of the outlet works intake on the floor of the tank to the water surface. This was done by installing a pressure tap that connects to a piezometric tube mounted on the side of the tank. The tube was referenced to the centerline of the outlet using a survey level. As velocity heads in the tank were minimal, the reservoir piezometric and total head values were the same.

Air flow rate

A Kanomax thermal anemometer (Model A031) was used to measure the air velocities. Two identical thermal anemometers were used to assure that the probes were working as expected. Of the four air supply lines, two air supply ports located on the outside of the elbow filled with water and did not supply air to the system. For this reason the two outside air supply ports were only opened when comparing how the location of the air supply port affects air demand. The air velocities were measured in a 1-inch pipe which bifurcated into two ¾-inch supply lines that supplied air to the ports located on the inside of the elbow in the wake of the gate. It was verified that an abundance of air was being supplied. This was done by testing the system with the air valves in the two ¾-inch lines fully open and then closing them partially and retesting. The results were found to be comparable showing that enough air was supplied to the system.

The elevation in the tank was allowed to stabilize before air velocity measurements were taken. Air velocity data were measured and recorded in 1-second increments for a minimum of 3 minutes for each test.

CHAPTER III

RESULTS

The prototype data was collected in order to compare to the results presented by Tullis and Larchar (2011). When the prototype data did not correlate to the laboratory data from Tullis and Larchar (2011), it was anticipated that slope played a significant role in the air demand. A laboratory study similar to that of Tullis and Larchar (2011) was undertaken for a zero-sloping low-level outlet works conduit. The following results compare the prototype data to the laboratory data for zero sloping low-level outlet works unless otherwise stated.

Max Air Demand Versus Gate Opening

As the maximum air demand is of importance in the design of air vents it is important to understand when this will occur. Tests were run for several gate openings and it was found that the max air demand occurred at gate openings near 50 percent. Figure 10 shows the results found from both the 4.5 percent and 0 percent slopes tested in the laboratory. Similar results were found in the prototype study of Washington and Lost Lakes (see Figure 11). Trial Lake isn't shown as the range of gate openings was below 50 percent for most heads. It is important to note that the outlet conditions could not be controlled in the prototype as a concrete baffle was located just downstream of the outlet. The baffle caused water to back up around the outlet causing the conduit to flow full at the outlet for larger flows. Tullis and Larchar (2011) concluded that the max air demand occurs near 50% gate openings for both free and submerged conditions. This was verified for the prototype data.

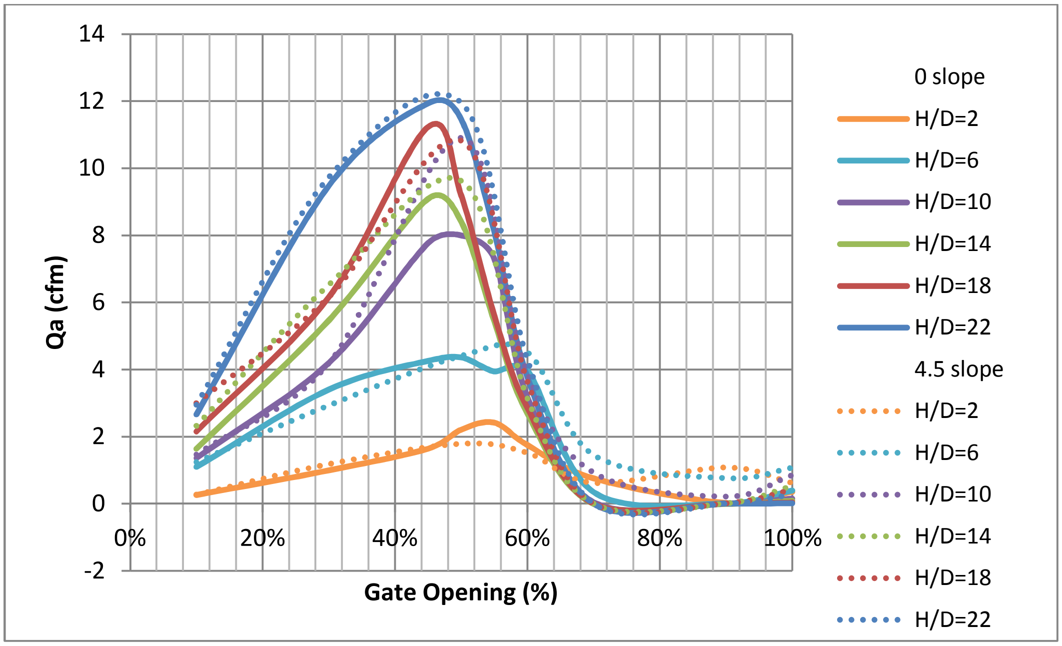

Figure 10: Laboratory air demand (ave.) vs. gate opening

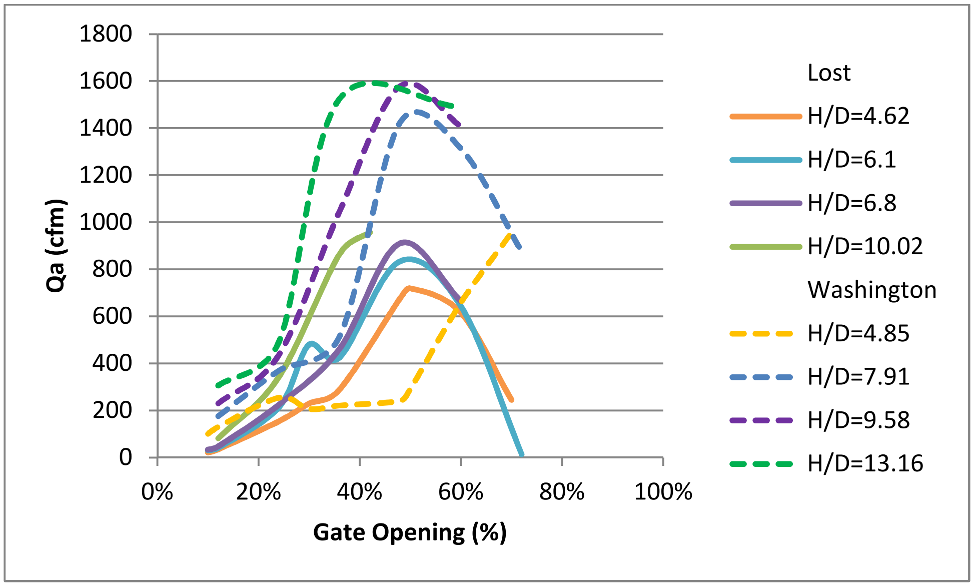

Figure 11: Prototype air demand (ave.) vs. gate opening for Lost and Washington Lakes

It was also confirmed that major fluctuations in air velocities exist. For the purpose of comparing the results to the laboratory study the average and maximum

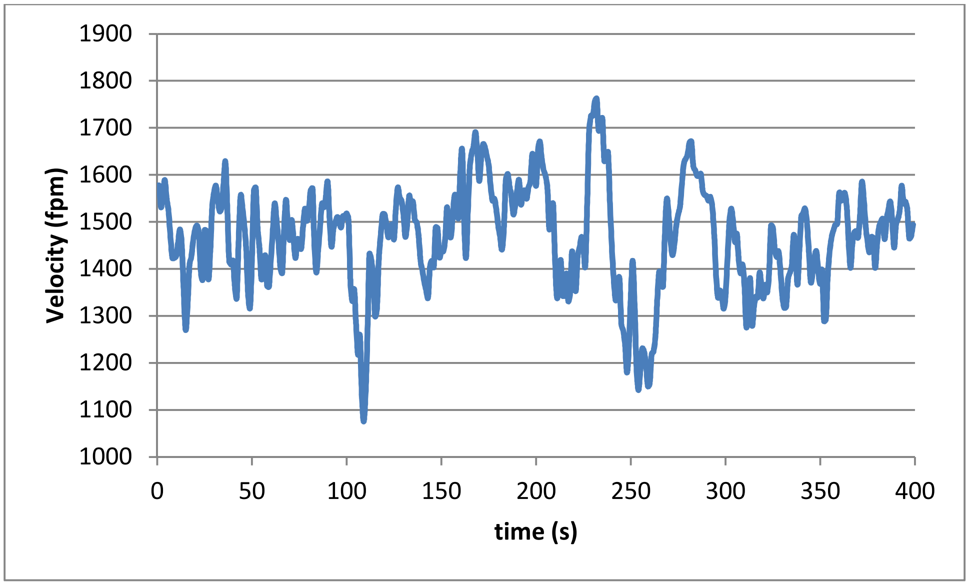

Figure 12: Air velocity fluctuations-laboratory study zero-sloping

values were used to compare the results. The fluctuation in air velocity can be seen in Figure 12, which shows the laboratory results for a gate opening of 50 percent and a $\Delta H/D = 42$. Similar fluctuations occurred at different gate openings and heads for both the laboratory and prototype studies.

The Occurrence of Vortices

It was also found that vortices formed at low reservoir heads. From the laboratory study it was found that vortices formed at $\Delta H/D \leq 10$ and gate openings$\geq$30 percent. This phenomenon was also found to be true for the three prototypes tested. Figure 13 shows flow rates and $\Delta H/D$ values where vortices were found in the laboratory. The formation of all vortices seen in the prototype study fell within the range found in the laboratory.

Vortices tended to reduce the amount of air demand as air supply to the system is being supplemented by the vortex.

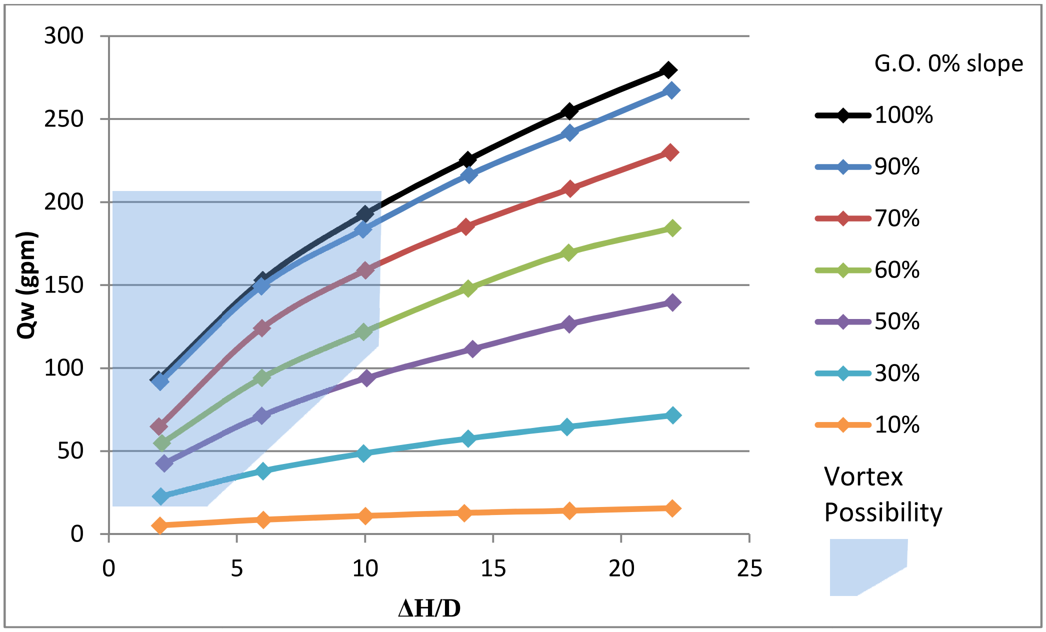

Figure 13: Probability of vortices formation

C_d Curve Comparison

Another similarity was that the C_d curves found in the laboratory fit the data collected for the prototype structures well. The same methods used by Tullis and Larchar (2011) were used in calculating C_d for both the laboratory and prototype studies. C_d values are significant in the design of low-level outlet works as they allow for the water flow rate to be calculated. This is significant as the design method proposed by Tullis and Larcher (2011) uses the dimensionless air demand in calculating the necessary diameter of the air vent. Figures 14-16 show how the three prototype data compares to the data measured in the Laboratory study having a zero-sloping conduit.

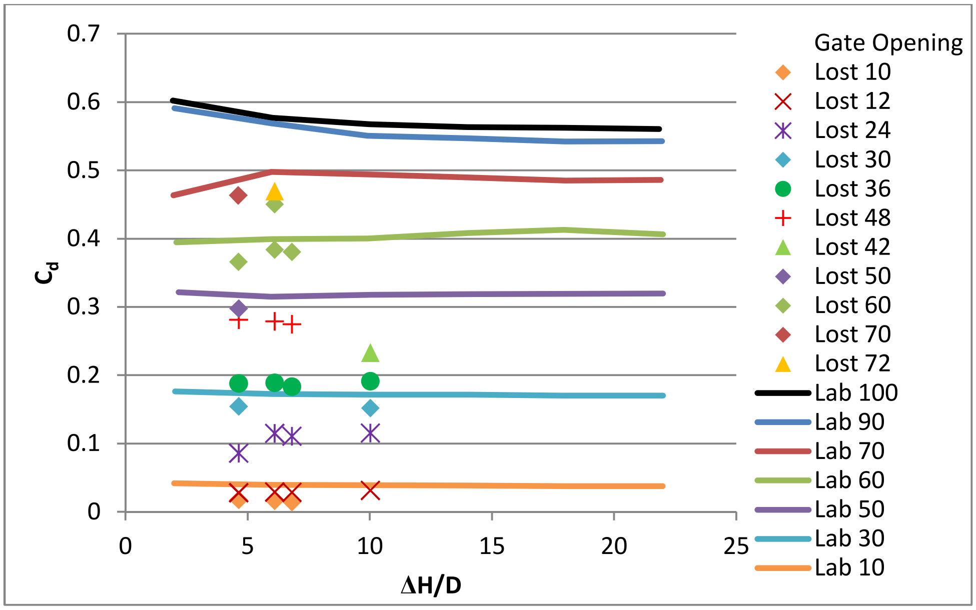

Figure 14: Lost Lake vs. zero-slope conduit laboratory C_d data

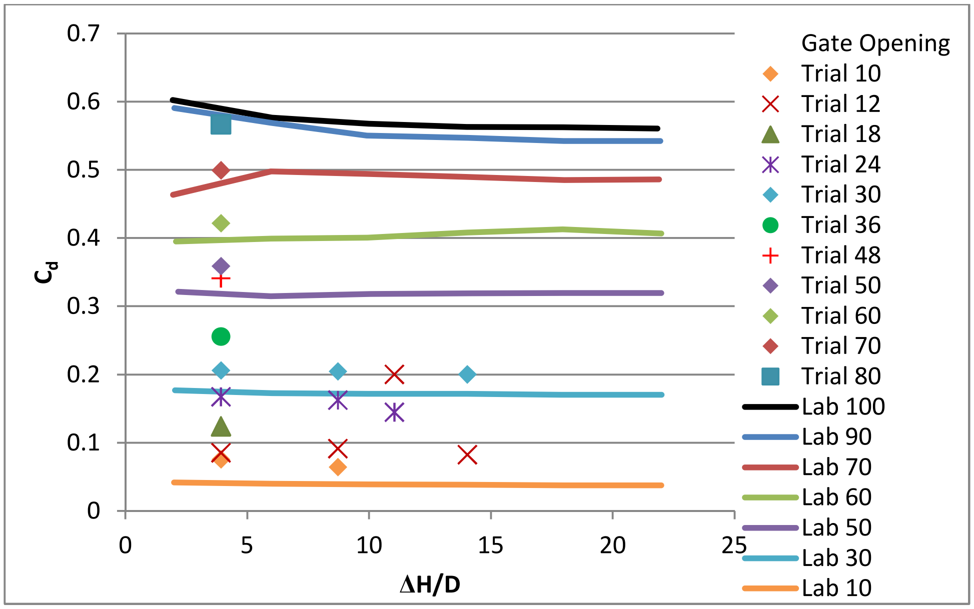

Figure 15: Trial Lake vs. zero-slope conduit laboratory C_d data

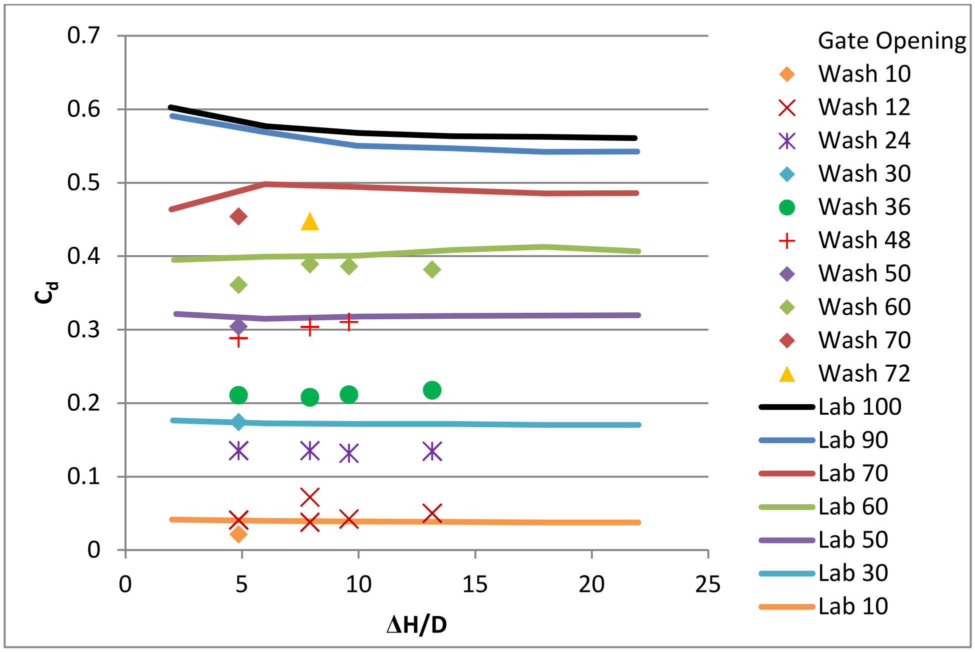

Figure 16: Washington Lake vs. zero-slope conduit laboratory C_d data

The Effect of Submergence on Dimensionless Air Demand

As the outlet condition for the prototype data could not be controlled, both submerged and free flowing outlet conditions were encountered. Tullis and Larchar (2011) found that submerged outlets had a lower air demand. However, the submerged conditions for the prototype data will be compared to the laboratory study performed by Tullis and Larchar (2011). The submerged conditions from the prototype study, shows modest correlation for the β values as compared to the laboratory study for Tullis and Larchar (2011). This may not be the best comparison as the laboratory study performed by Tullis and Larchar (2011) was for a 4.5 percent slope. It is expected that submerged flow would correlate very well. Figures 17-22 show a modest agreement between β values for the prototype study compared to the results by Tullis and Larchar (2011).

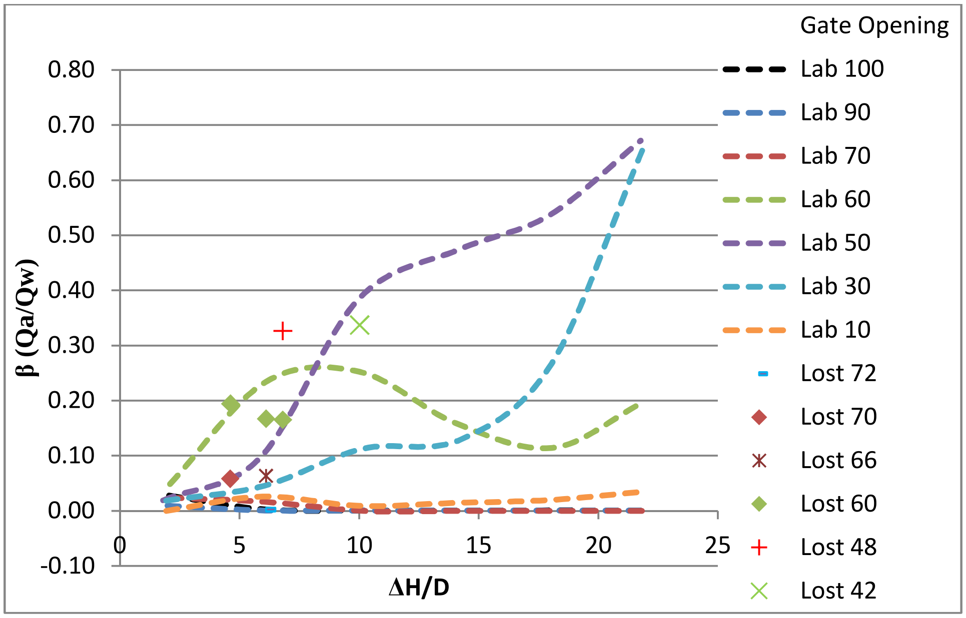

Figure 17: Dimensionless air demand (β average) vs. ΔH/D for Lost Lake field data (submerged outlet, 0.32% conduit slope) and Tullis and Larchar (2011) laboratory data (submerged outlet 4.5% conduit slope)

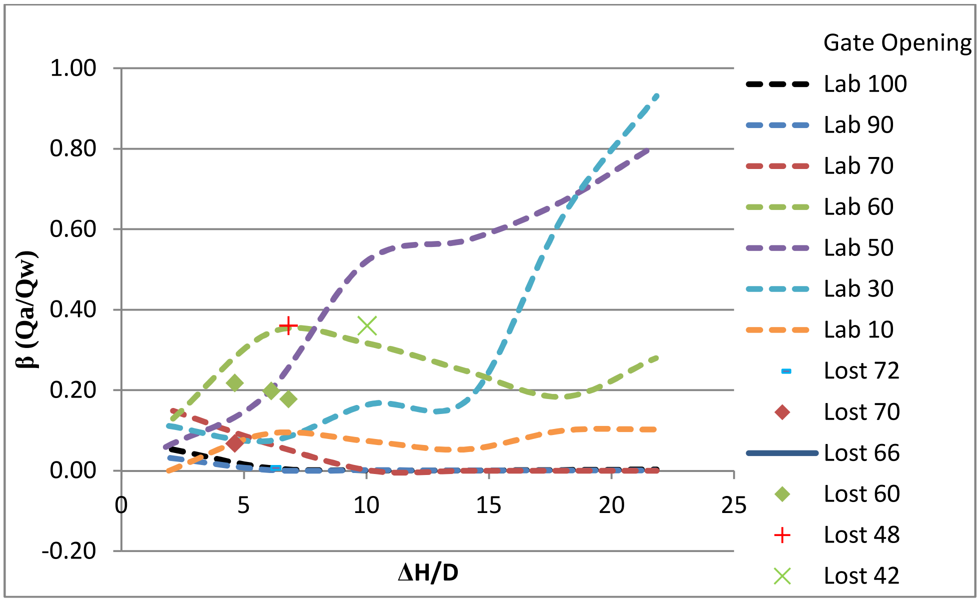

Figure 18: Dimensionless air demand (β max) vs. ΔH/D for Lost Lake field data (submerged outlet, 0.32% conduit slope) and Tullis and Larchar (2011) laboratory data (submerged outlet 4.5% conduit slope)

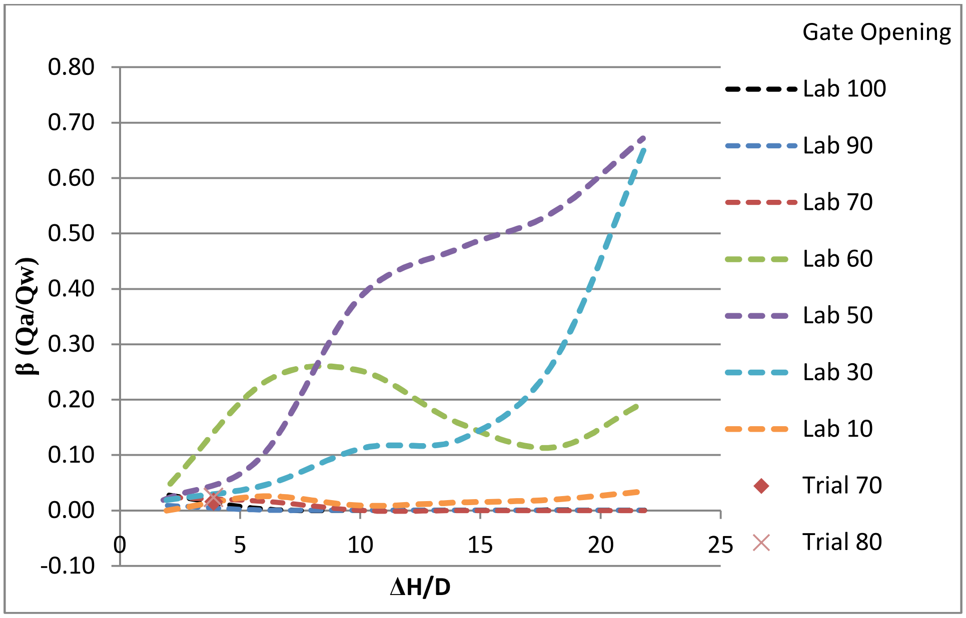

Figure 19: Dimensionless air demand (β average) vs. ΔH/D for Trial Lake field data (submerged outlet, 0.78% conduit slope) and Tullis and Larchar (2011) laboratory data (submerged outlet 4.5% conduit slope)

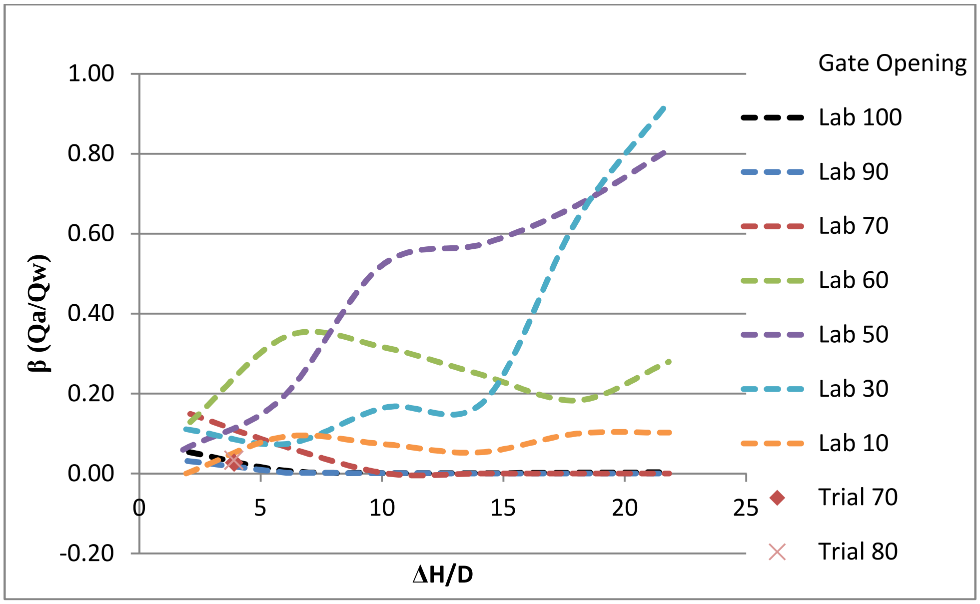

Figure 20: Dimensionless air demand (β max) vs. ΔH/D for Trial Lake field data (submerged outlet, 0.78% conduit slope) and Tullis and Larchar (2011) laboratory data (submerged outlet 4.5% conduit slope)

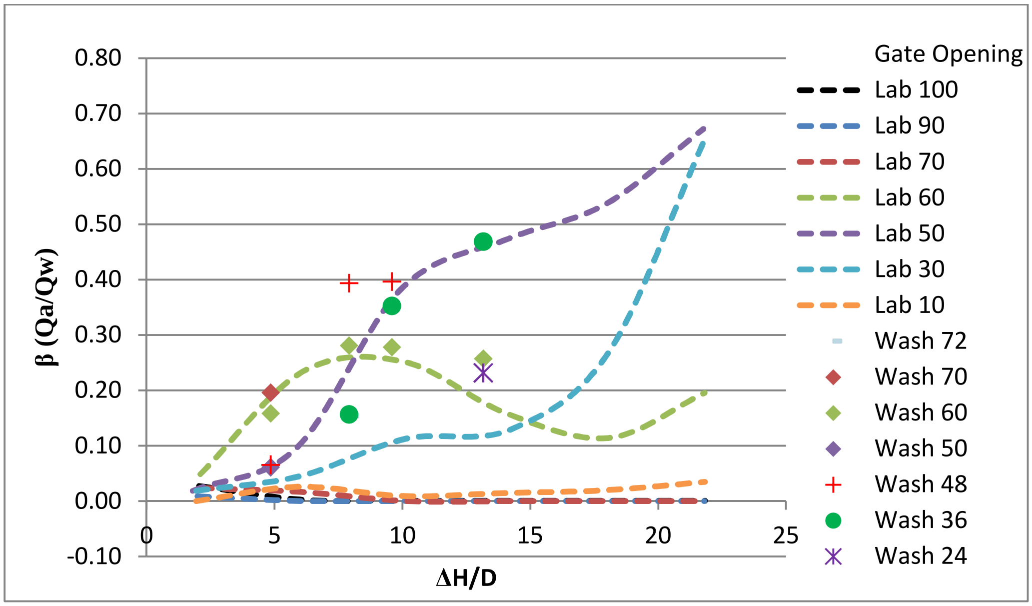

Figure 21: Dimensionless air demand (β average) vs. ΔH/D for Washington Lake field data (submerged outlet, 0.089% conduit slope) and Tullis and Larchar (2011) laboratory data (submerged outlet 4.5% conduit slope)

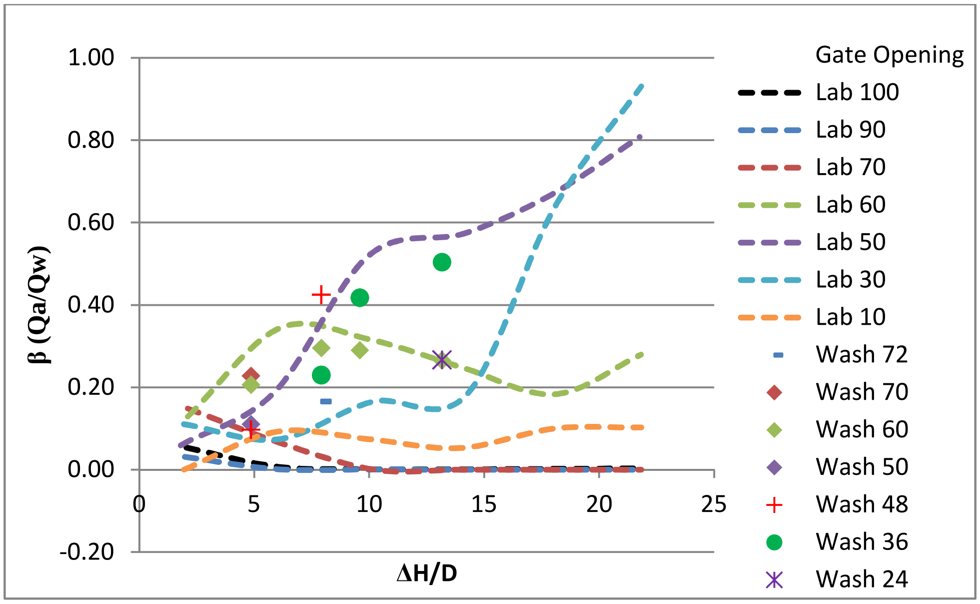

Figure 22: Dimensionless air demand (β max) vs. ΔH/D for Washington Lake field data (submerged outlet, 0.089% conduit slope) and Tullis and Larchar (2011) laboratory data (submerged outlet 4.5% conduit slope)

Differences in Laboratory and Field Results

In contrast to the submerged outlet conditions, β vs. ΔH/D data for free flowing outlet conditions did not correlate well in comparing the prototype data to the zero slope conduit laboratory data. The discrepancies for both the average and max β values can be seen in Figures 23-28, where the prototype data is compared to the zero sloping lab data.

The β vs. ΔH/D comparison in Figures 23-28 show a poor correlation between field and prototype free-flow air demand requirements. This suggests that size-scale effects related to air entrainment may exist, despite the good agreement in C_d data. At the field sites evaluated in this study, free-flow outlet conditions were limited to a small range of gate openings and upstream heads due to the presence of a baffle block in the stilling basin immediately downstream of the outlet. It is, therefore, recommended that a larger range of reservoir heads and gate openings be tested.

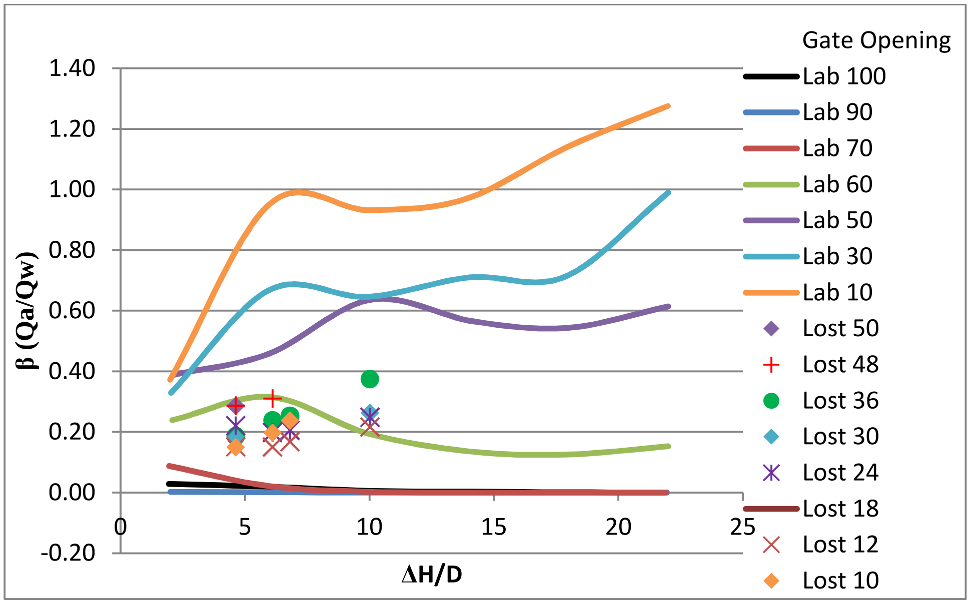

Figure 23: Dimensionless air demand (β average) vs. ΔH/D for Lost Lake field data (free flow outlet, 0.32% conduit slope) and laboratory data (free flow outlet 0% conduit slope)

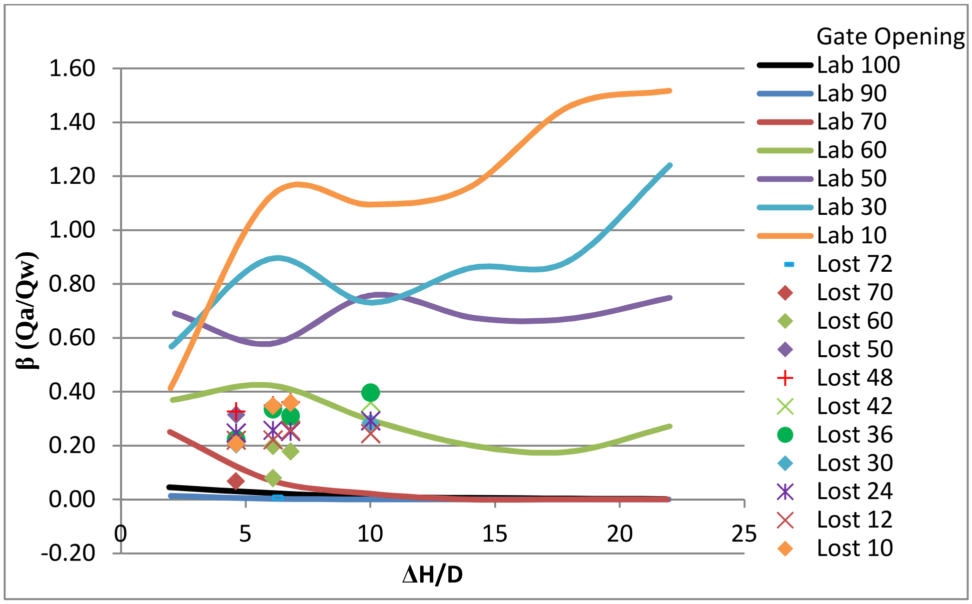

Figure 24: Dimensionless air demand (β max) vs. ΔH/D for Lost Lake field data (free flow outlet, 0.32% conduit slope) and laboratory data (free flow outlet 0% conduit slope)

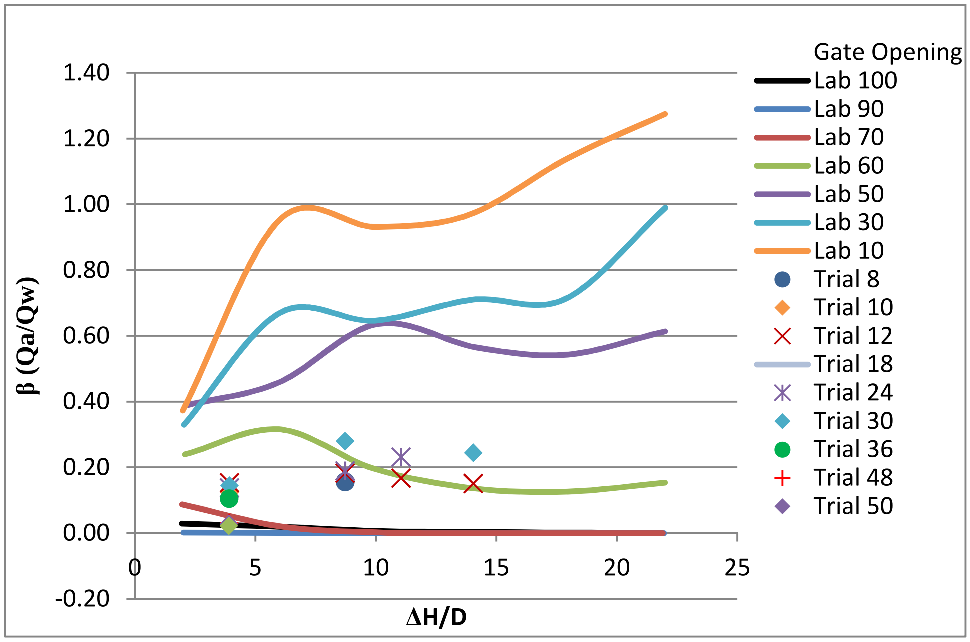

Figure 25: Dimensionless air aemand (β average) vs. ΔH/D for Trial Lake field data (free flow outlet, 0.78% conduit slope) and laboratory data (free flow outlet 0% conduit slope)

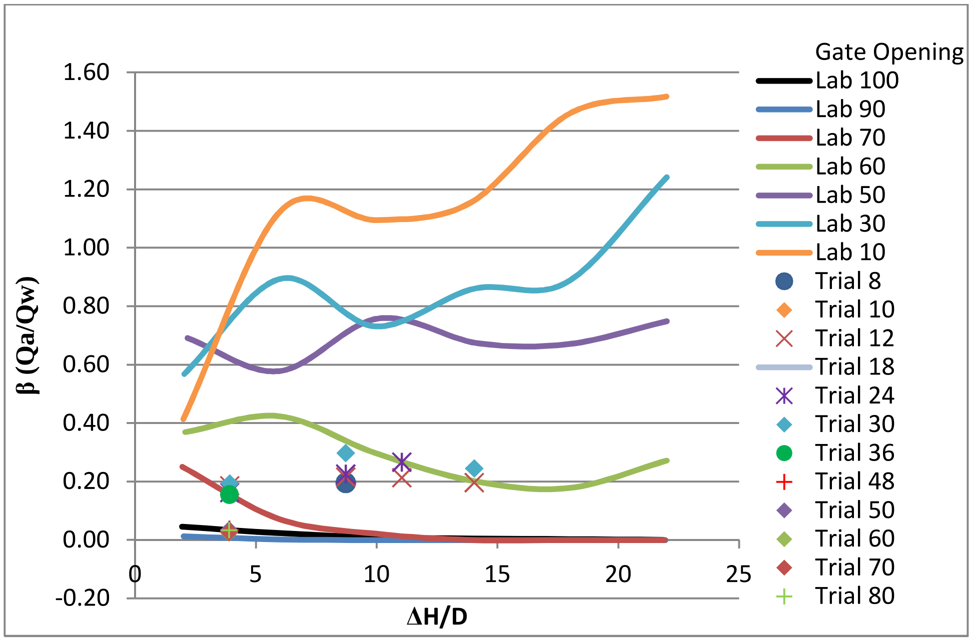

Figure 26: Dimensionless air demand (β max) vs. ΔH/D for Trial Lake field data (free flow outlet, 0.78% conduit slope) and laboratory data (free flow outlet 0% conduit slope)

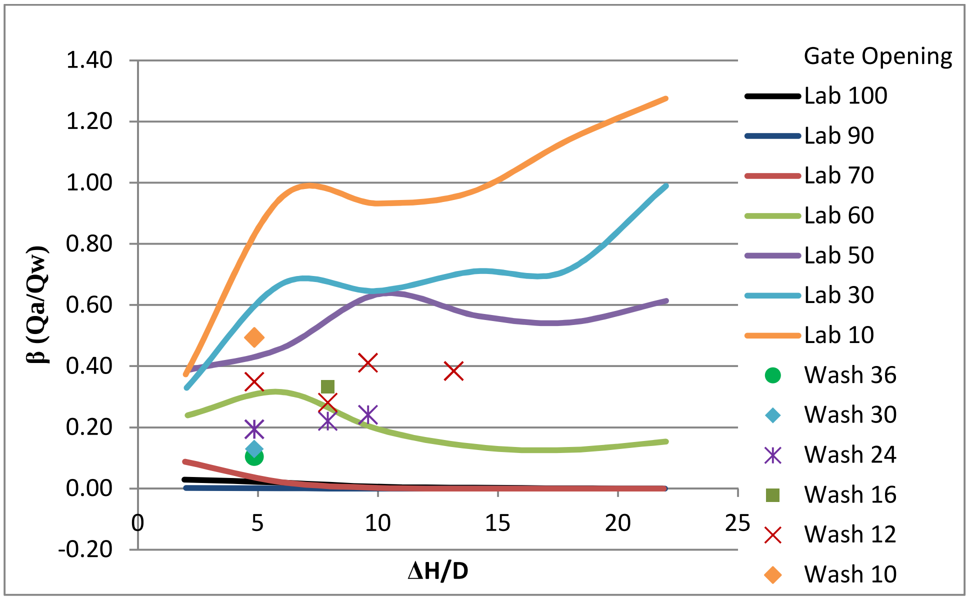

Figure 27: Dimensionless air demand (β average) vs. ΔH/D for Washington Lake field data (free flow outlet, 0.089% conduit slope) and laboratory data (free flow outlet 0% conduit slope)

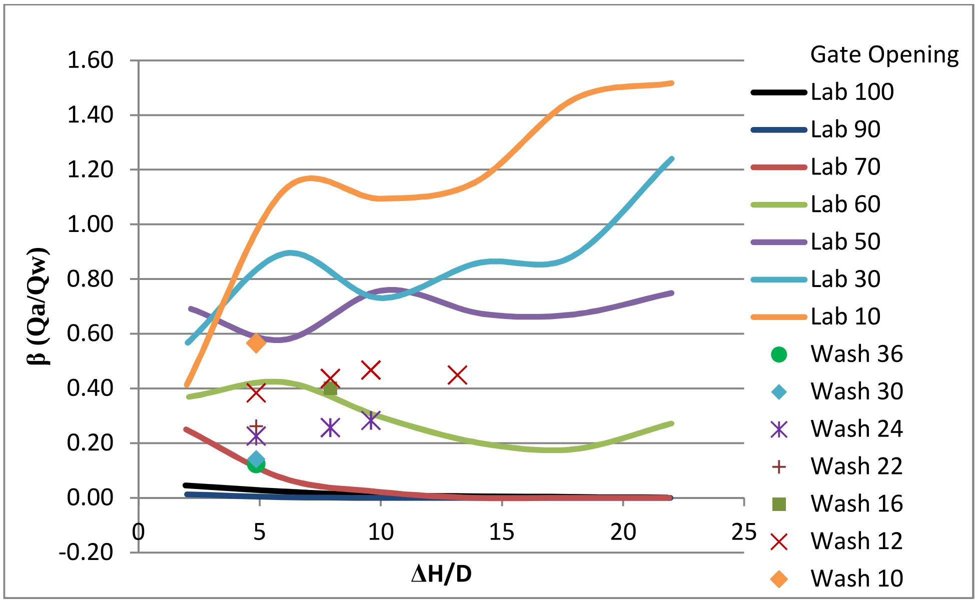

Figure 28: Dimensionless air Demand (β max) vs. ΔH/D for Washington Lake field data (free flow outlet, 0.089% conduit slope) and laboratory data (free flow outlet 0% conduit slope)

A few reasons are proposed as to why these discrepancies may have occurred. A concrete baffle was located just downstream of the outlet works for all three dams. The baffle controlled the outlet condition causing the water to back up especially for large gate openings and reservoir heads. Different venting conditions also existed. Two of the prototypes had a ring manifold air delivery system while the other air vent consisted of a tee located near the crown of the pipe. These particular air vent geometries were implemented in an effort to reduce the occurrences of “gun-shot” type noises produced by the air vent system with a single port under certain flow conditions. The loud noises occurred as a result of water in the conduit entering the vent pipe and then being rapidly sucked back out of the vent pipe. All three prototype air vents were also undersized according to the Tullis and Larcher’s (2011) method. During prototype data collection loud rushing of air could be heard as air velocities were exceptionally high, especially for gate openings near 50 percent. Under certain conditions the velocity probe reached its limit. This may be acceptable for the given prototypes as they do not operate at large gate openings, but for larger discharges, the air vent system may not meet the full air demand requirement of the system. Additionally, the total area of all the holes in the manifold was approximately ½ of the total area of the vent pipe.

Conduit Slope and Air Demand

Identical laboratory tests were ran with the exception that the conduit slope of the low-level outlet works; slopes of 0 percent and 4.5 percent were evaluated. Figure 29 shows resulting conduits slope-dependent β vs. $\Delta H/D$ data for both laboratory slopes compared to the data from Washington Lake. The 4.5 percent conduit slope geometry produced higher β values relative to the zero slope conduit geometry for most gate openings. Although there is still a discrepancy between the laboratory and prototype data, the 0 sloping condition shows better results. As the C_d values between the prototype and laboratory studies were similar it can be assumed that there is decrease in the air demand as the slope decreases. This may be due partially to the variation in mean conduit flow velocity and the shear stress that is imparted and corresponding velocity imparted to the air column above the open channel flow.

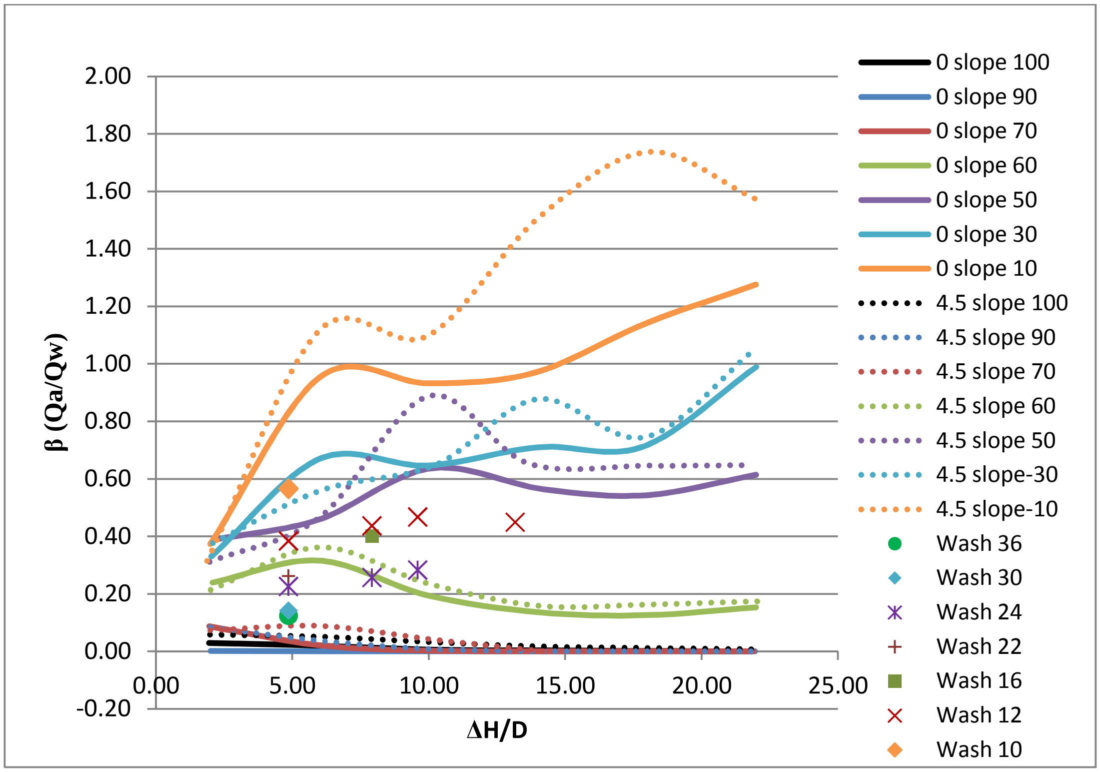

Figure 29: β vs. ΔH/D Laboratory comparison of 0 vs. 4.5 percent slope low-level outlet works conduits

The Effect of a Hydraulic Jump on Air Demand

With mild-sloping conduits and/or tailwater submergence at the outlet, hydraulic jumps will often form in the conduit of the low-level outlet. Consequently, it is important to understand how the presence of a hydraulic jump affects the air demand. The same setup was used for testing that was performed on the low-level outlet works having a 0 slope. In order to cause a hydraulic jump, the tail water was raised, submerging the outlet until a jump formed in the conduit (see Figure 30).

Figure 30: Hydraulic jump forming in the outlet works

The maximum air demand for free flowing conditions (no hydraulic jump) occurred at a gate opening of 45 percent. This gate opening was used to compare the air demand between free flowing conditions and the condition where a hydraulic jump occurs. Due to the difficulty in creating a stable hydraulic jump in the short conduit, only two heads were tested with a hydraulic jump. Figure 31 shows a great reduction in air demand as a hydraulic jump forms in the conduit. Comparing the velocity of the airflow in the vent pipe at heads of 6 and 18 inches, the free-flow air demand is significantly higher than the hydraulic jump air demand.

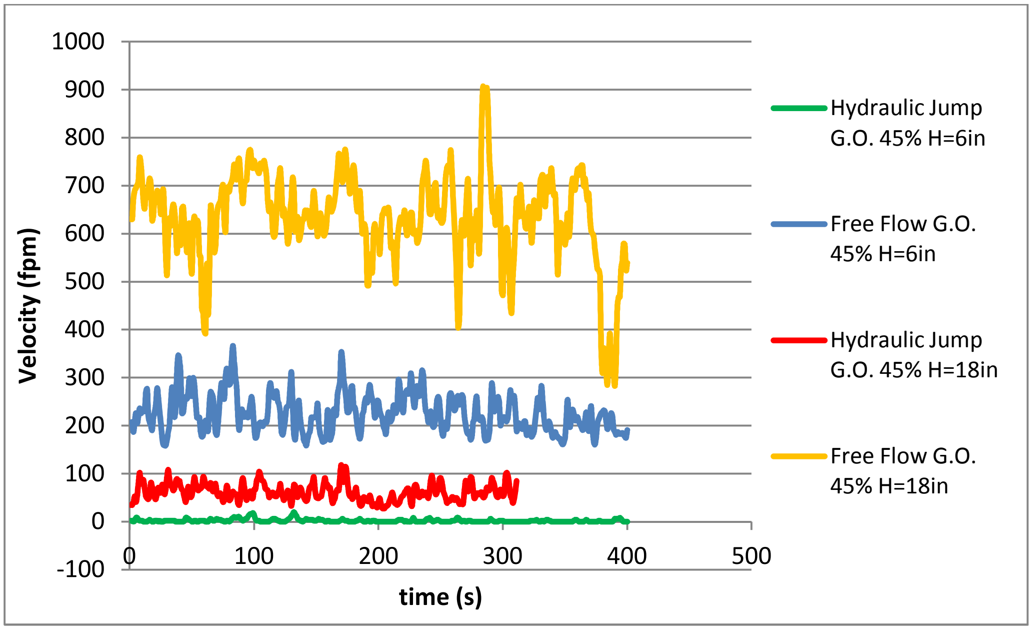

Figure 31: Effect of hydraulic jumps on air velocity

Different Air Supply Methods

There are multiple ways to supply air to low-level outlet works. Through this study we encountered five different methods to supply air to the system. Figure 32 shows each of the different methods. Although a thorough investigation of each of these methods was not carried out, it is anticipated that the method of supplying air to the conduit may impact the efficiency of the air vent system. The air supply lines began filling with water at different gate openings depending on their location. It was found that ports located in areas of minimal flow separation (located on outside of elbow) tended to fill with water at lower heads and smaller gate openings than air ports located where flow separation was apparent (located on inside of elbow). As the head increased the air supply lines would continue to fill with water until no air was supplied to the conduit.

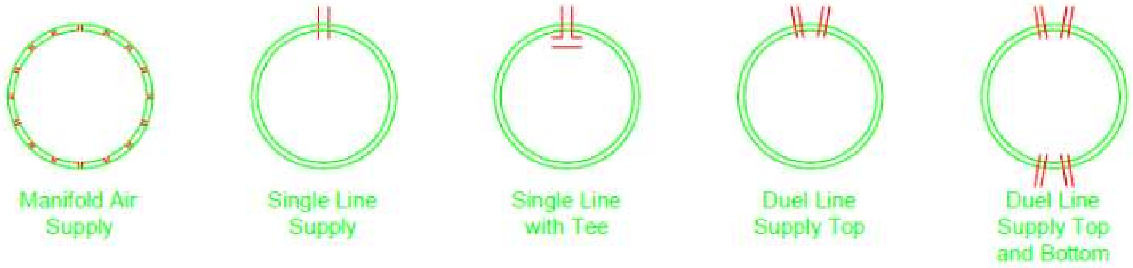

Figure 32: Various air supply methods

Trial Lake was originally designed to have an air supply similar to the Single Line Supply. They found that at higher heads they were experiencing loud noises similar to a gun shot, as previously mentioned. To prevent these loud noises a tee was put on the end of the line. This fixed the noise problem, but it still has not been investigated if this would affect the amount of air that could be supplied to the system.

In the lab, a similar thing happened to that of Trial Lake. For a gate opening of 70% and a $\Delta H/D=10$, water filled one of the two vents while the other vent acted as a drain for the other. As the pressures behind the gate continued to change both vents were filled with water and minimal air was being supplied to the system. Suddenly the water in both vents was sucked out of the vents and a large increase in air demand occurred. Figure 33 shows this instantaneous increase in air demand as both vents supplied air to the system.

To further investigate the effect of the location of the vents along the circumference of the outlet works the last two drawings in Figure 32 were tested at the same gate openings and heads. For each gate opening and head, the test was run twice to verify repeatability. The total air demand was calculated for both situations and the results can be seen in Table 2.

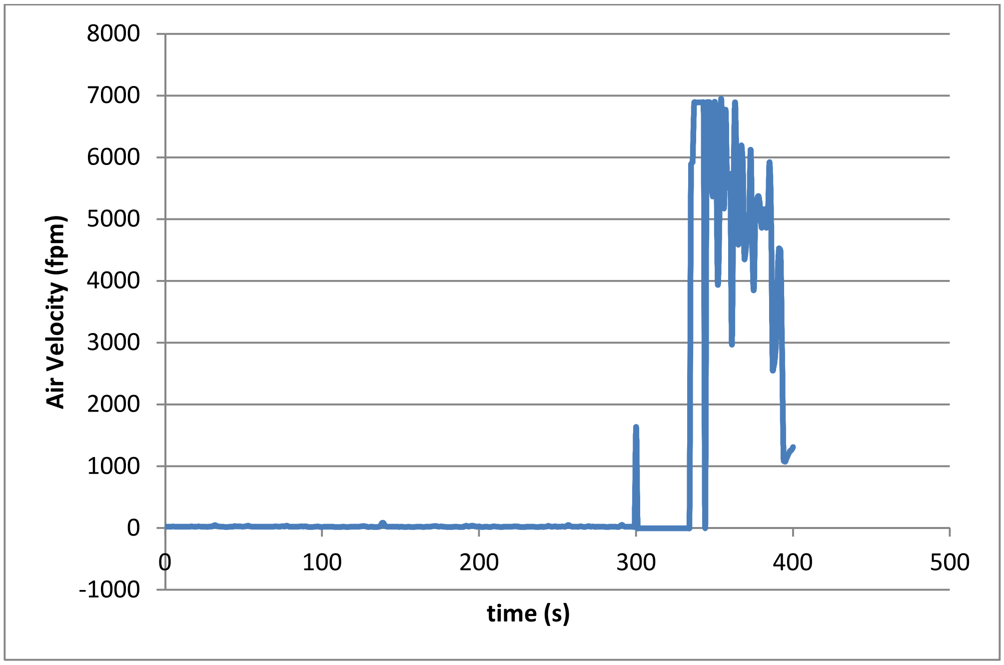

Figure 33: Air demand peak for partially submerged versus free flowing

For the tests ran with all four vents open it was found that some level of submergence occurred in the lower two vents. As only the total air demand was calculated, it is uncertain to the amount of air, if any, that entered the lower two vents. From the data in Table 2 it does however appear that there is minimal difference between the total air demands, especially at larger gate openings. It was also noted that at larger gate openings all four of the vents recorded some level of submergence.

Table 2: Air demand comparison for 2 vs. 4 open valves

	10% ave.	2 valves	4 valves	**30% ave.**	2 valves	4 valves	**50% ave.**	2 valves	4 valves
Test 1	H=18 in.	130.06 fpm	140.05 fpm	H=6 in.	150.12 fpm	140.11 fpm	H=30 in.	1218 fpm	1218.29 fpm
Test 2	H=18 in.	124.64 fpm	140.24 fpm	H=6 in.	133.49 fpm	129.30 fpm	H=30 in.	1231.61 fpm	1234.95 fpm
Test 1	H=54 in.	258.2 fpm	351.05 fpm	H=42 in.	910.58 fpm	958.87 fpm	H=54 in.	1471.20 fpm	1536.47 fpm
Test 2	H=54 in.	250.86 fpm	320.72 fpm	H=42 in.	887.16 fpm	925.48 fpm	H=54 in.	1519.86 fpm	1440.13 fpm
	10% max	2 valves	4 valves	**30% max**	2 valves	4 valves	**50% max**	2 valves	4 valves
Test 1	H=18 in.	148 fpm	163 fpm	H=6 in.	213 fpm	201 fpm	H=30 in.	1319 fpm	1341 fpm
Test 2	H=18 in.	140 fpm	157 fpm	H=6 in.	189 fpm	173 fpm	H=30 in.	1362 fpm	1354 fpm
Test 1	H=54 in.	301 fpm	415 fpm	H=42 in.	1061 fpm	1220 fpm	H=54 in.	1746 fpm	1870 fpm
Test 2	H=54 in.	291 fpm	382 fpm	H=42 in.	1067 fpm	1091 fpm	H=54 in.	1931 fpm	1795 fpm

CHAPTER IV

APPLICATION OF RESULTS

The purpose of this research was to help in the design of air vents. The design method presented represents the research done and should yield conservative results as can be seen from the data presented herein. This method uses the β max value instead of β average at the gate opening which yields the greatest air demand. For design purposes the parameters needed are the reservoir head (ΔH) and the diameter (D) of the low-level outlet works. $\Delta H/D$ is an independent variable for air vent design. The exact effect of slope, size scale effects, and the air supply methods are still unknown and therefore a factor of safety has been included in the method to assure the max air demand is met.

A few limitations are also apparent in the design method. First, no losses in the air vent pipe have been accounted for in this method. This will become more evident as the length of the air vent increases. The direct impact of slope is unknown as only two slopes have accurately been tested. It is expected that larger slopes will require a larger air demand. It has also been found that the method used to supply air to the system (e.g. tees, manifolds, single line, etc.) may reduce the amount of air the vent pipe can supply to the system. If manifold systems are used, the total area of all of the holes in the manifold should not be less than the area of the air vent.

A flow chart has been developed to show how this method may be applied in the field. An example is also presented using the data for Washington Lake. Both flow charts can be seen in Figure 34.

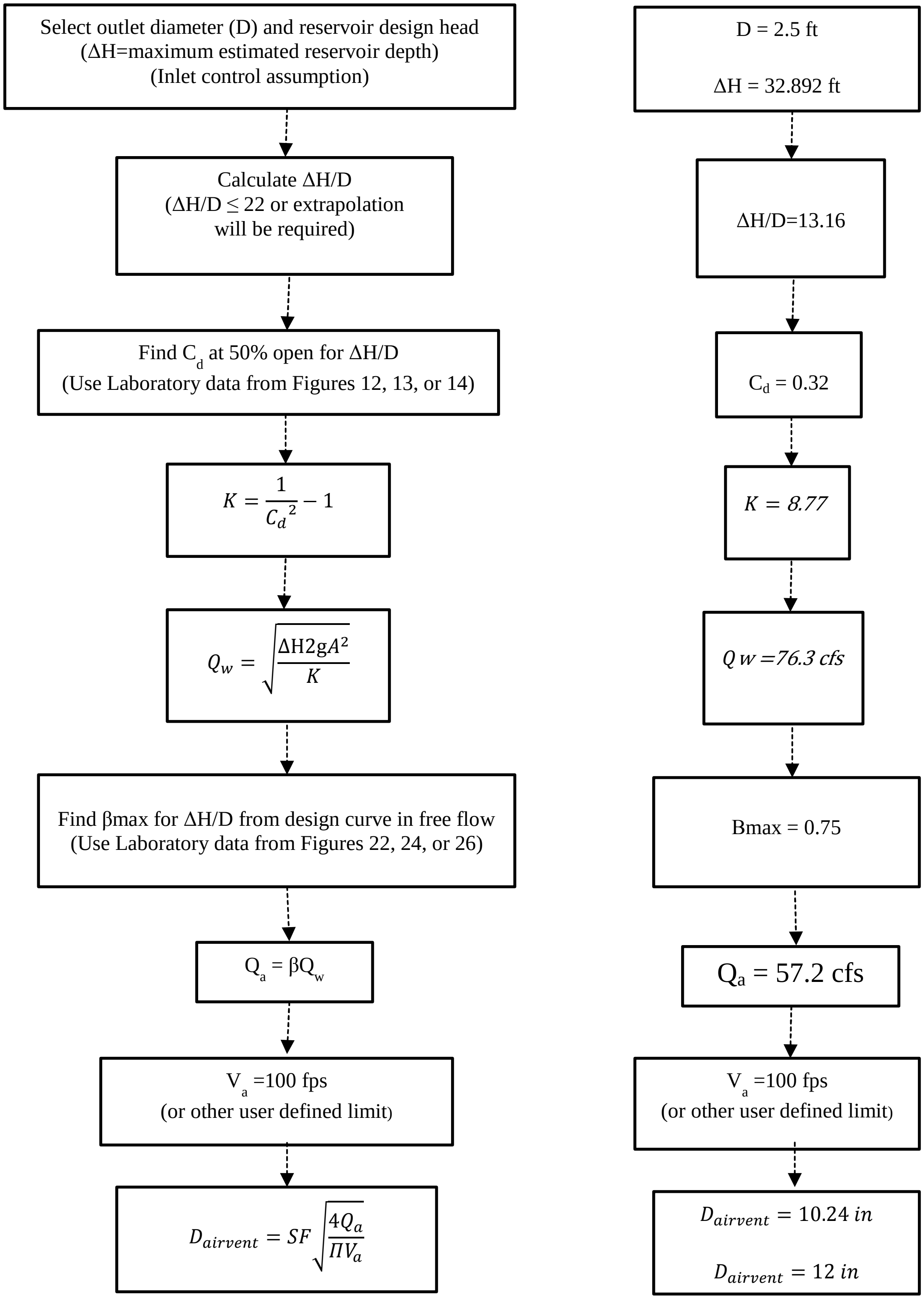

Figure 34: General flow chart and Washington Lake design example

All three of the dams tested in this study were found to require similar sized air vents. The actual diameter of the air vents of the dams tested were as follows; Lost – 6 inches, Trial – 4 inches, and Washington – 6 inches. Using this method found that the air vents should all have a diameter around 10 inches shows that all three of the dams may be considered to be undersized. This may be a reason why the air demand data for the prototype tended to be less than the laboratory data.

CHAPTER V

CONCLUSIONS

The research presents further insight into estimating the air demand for low-level outlet works. The traditional methods for estimating air demand using large-dam design methods do not apply to small-to-medium size embankment dam geometries. The following conclusions have been made based on the results of a comparison of the laboratory and prototype study for small-to-medium sized dams.

1. A good correlation was found between the laboratory and prototype C_d data as a function of gate opening and upstream head ($\Delta H/D$). This is significant in estimating the water flow rates which in turn are of great importance in calculating the airflow rate.
2. The maximum system air demand occurs at a gate opening of approximately 50 percent at the laboratory and prototype scales.
3. Vortices were found to form at $\Delta H/D \leq 10$ and gate openings$\geq$30 percent. They were found to affect flow aeration process. The air supplied by the air vent reduced slightly because of the supplemental air provided by the vortex. Vortices in the field were found to occur within the same head and gate-opening ranges found in the laboratory.
4. The submerged β versus $\Delta H/D$ data corresponded modestly for the field data and the results reported by Tullis and Larchar (2011).
5. The free-flow β versus $\Delta H/D$ data did not correlate well for the field and laboratory data collected in this study. The prototype β values were much

less than the lab values, suggesting that size scale effects are present in the air demand of the system for free flowing conditions. Free flowing β conditions were recommended for air vent design by Tullis and Larchar (2011) as they produce more conservative results. The results of this study confirm that finding.

6. The slope of the outlet works influences the air demand of the system, relative to the conduit slopes tested (0 and 4.5 degrees). The air demand decreased with decreasing conduit slope.
7. The presence of a hydraulic jump in the low-level outlet works conduit was found to decrease air demand relative to the free-flow, no hydraulic jump case.
8. Air vent location has been found to be significant in the amount of air that is supplied to the system. At gate opening above 50 percent some level of submergence occurred in all four vents in the laboratory. It was also found that complete submergence occurred in the field around 60 percent gate opening. Submergence reduces the air demand, but if air forces its way back into the system it may lead to large pulses of air demand. These pulses may lead to loud noises in the field.

Ideas for future research that will be beneficial to this topic include the following:

1. As slope was found to affect the air demand it would be beneficial to get a more complete range of slopes and how air demand changes with slope.

2. Evaluate the effects of air port configurations (e.g, manifolds, tees, single port, etc.) on air vent operation.
3. Gate design may also impact the air demand. Only a single square gate was tested. How do different dimensions like thickness impact the air demand?
4. A more complete set of prototype data may help with understanding size scale effects and how to better deal with this phenomena.
5. Investigate further ΔH/D values and the impact that will play on submergence of the air vent.

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