HYDRODYNAMIC REGIMES AND STRUCTURES IN SLOPED WEIR BAFFLED CULVERTS AND THEIR INFLUENCE ON JUVENILE SALMON PASSAGE

by

David R. Thurman and Alex R. Horner-Devine
Department of Civil and Environmental Engineering, Bx 352700
University of Washington
Seattle, WA 98195

Washington State Transportation Center (TRAC)
University of Washington, Box 354802
1107 NE 45th Street, Suite 535
Seattle, Washington 98105

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16. ABSTRACT

The purpose of this study was to determine what hydraulic characteristics enhance or diminish upstream juvenile salmon passage within a sloped-weir baffled culvert. The culvert slope, baffle spacing, and baffle height were varied to observe flow regime trends that describe conditions suitable for fish passage. Biological testing was conducted in conjunction with the hydraulic micro-Acoustic Doppler Velocimeter (ADV) measurements. There was considerable spatial variability in the flow created by the sloped baffles within the culvert. The asymmetry of flow (A_s) decreased for increasing discharge, larger baffle spacing and smaller baffle heights. To describe the flow features essential to fish passage, the interrelation between flow asymmetry, depth, and velocity were presented in comparison with biological testing. For the range of parameters tested, flows were described by a series of three jet regimes which were a function of water depth over baffles. Comparing these regimes to the biological study revealed peak juvenile salmon passage was associated with a critical transition between jet regimes. Generalizing this transition for the entire data set using dimensionless scales provides professionals with guidance for retrofitting culverts.

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EXECUTIVE SUMMARY

This study addresses the hydraulics around sloped-weir baffles in relation to upstream juvenile salmon passage, which is one part of an ongoing project funded by the Washington State Department of Transportation (WSDOT). Concern for endangered salmon and their recovery has lead WSDOT to remediate culvert passage barriers with Washington Department of Fish and Wildlife (WDFW) recommended sloped-weir baffles. Recognizing the need for all salmon life stages to reach upstream habitat WSDOT has sought to determine if juvenile salmon passage is limited by culvert retrofits.

The purpose of this study was to determine what hydraulic characteristics enhance or diminish upstream juvenile salmon passage within sloped-weir baffled culverts. Hydraulics were examined in a culvert test bed (CTB) facility and characterized by an Acoustic Doppler Velocimeter (ADV) which measured all three components of velocity. Culvert slope, baffle spacing, and baffle height were varied to observe the evolution of flow structures and flow regimes trends that could describe conditions suitable for fish passage. Additionally, to determine juvenile salmon passage rates in weir baffled culverts and evaluate what hydraulic conditions may improve juvenile salmon passage a separate concurrent biological study was performed by Battelle Memorial Institute. The culvert test bed being located at the Skookumchuck fish hatchery, near Tenino, Washington provided access to hatchery juvenile coho salmon for the separate fish passage study. Comparisons between the hydraulic and biological studies indicated several important observations and hypotheses.

The biological study conducted by Battelle (Pearson et al. 2006) had several main conclusions that were used in comparison to our hydraulic study. They found that there was no statistical difference in fish passage rates between the unbaffled and baffled culvert configurations. Study results suggest that larger juvenile coho salmon may require an upstream passage cue associated with discharges larger than 42 l/s (1.5 cfs). Findings suggested juvenile coho may be achieving the same level of passage success for less effort in the baffle culvert compared with the unbaffled culvert. Overall, they observe that juvenile salmon are highly adaptive and use low velocity pathways to achieve passage.

Hydraulic results revealed a three-dimensional flow diversity established by the slope of the weir-baffles and the spiral culvert corrugations. Flow diversity in culverts is essential for fish passage creating regions of adequate velocity and flow depth. At all flow rates weir baffles form a jet on the low side of the baffle establishing flow asymmetry. As discharge increases flows became more symmetric as a second jet formed and grew on the high side of the baffle. The formation of jets and the lateral asymmetry were characterized into a series of jet regimes (J1, J2, J3) and compared with juvenile coho passage rates.

The transition between a J1 and J2 jet regime was observed to be associated with increased juvenile coho passage. Upon this observation it was recognized that baffle submergence may be a fundamental element in passage success. From real-time biological observations made with low-light high-resolution cameras, locations where juvenile coho crossed over baffles were documented as well. Based on the critical flow regime transition and locations were fish crossed baffles a critical minimum depth (H_c) for fish passage of 0.6 m was documented. The study indicating a critical minimum depth emphasizes the necessity of the baffle’s slope, which provides an adequate over baffle flow depth for a range of lower discharges. To generalize the critical jet regime transition and critical flow depth for the entire data set dimensionless scales were used and provided in this report for guidance and reference in retrofitting culverts.

INTRODUCTION

BACKGROUND/LITERATURE REVIEW

Culverts are a common means of conveying streams underneath roadways and have the potential to reduce or impede salmonid fish passage. Typical conditions limiting culvert passage include: high velocities, culvert length, inadequate water depths, lack of culvert roughness, and increased turbulence (Pearson et al. 2006). In Washington state alone, nearly 6,000 highway crossings have been inventoried by Washington State Department of Transportation (WSDOT), of which over 1,500 are classified as fish passage barriers (Wilder et al. 2006). An additional 1,600 plus culverts have been identified on Washington State Bureau of Reclamation and Forest Service lands as fish barriers (Thompson 2002). Stream connectivity is essential for the migration of anadromous adult salmon, but also the often overlooked juvenile life stage. Juvenile salmon travel upstream in search of lower flows, preferred water temperatures, reduced turbidity, food, predator refuge, and available habitat (Kahler and Quinn 1998; Kane et al. 2000). Allowing greater access to the entire drainage will lead to stronger and healthier juvenile salmon before their migration to the ocean. The genetic diversity and ultimate survival of salmonids may also depend on improving upstream passage (Gregory et al. 2004).

Possibly the greatest factors limiting upstream movement of salmon through culverts are increased velocities in combination with culvert length. Fish swimming abilities have been classified into prolonged, sustained, and burst speeds. Culvert velocities are larger and more uniform that those of natural channels. These velocities are often well beyond the prolonged swimming abilities of fish and culvert length prohibits fish passage using sustained and burst speeds (Katapodis 1992). Juvenile coho salmon with an average fork length of 40-70 mm have burst speeds averaging about 0.7 m/s with a maximum burst speed of 1.0 m/s (Powers 1997). In most cases, replacing a culvert with a bridge or bottomless (natural streambed) culvert is the optimum solution to fish passage barriers, but this is often cost prohibitive. Retrofitting culverts with baffles, however, provides an economical means of breaking up flow patterns, thereby increasing flow depths and reducing the average velocities. A series of studies completed by Ead et al. (2002) at the University of Alberta show the relationship between the dimensionless depth and relative baffle height along the centerplane for several baffle configurations. They also describe a general discharge scale for the baffle systems and dimensionless velocity profiles to aid in the hydraulic design. However, they acknowledge the need to study velocity fields away from the culvert centerline, observing weir baffles to generate regions of recirculation that might create areas for ascending fish to rest.

Pool and weir fishway recirculating vertical eddies were first discussed by Clay (1961) who described the flow regimes in terms of plunging and streaming flow. These flow regimes were further analyzed in rectangular laboratory flumes by Rajaratnam et al. (1988) and Ead et al. (2004) for a wider range of parameters. Plunging flow consists of two counter-rotating vertical eddies separated by the plunging jet (**Fig. 1a**). The surface vertical eddy extends from the impinging plunge to the downstream baffle and the lower eddy is contained between the plunge and baffle. Ead et al. (2004) then described a series of transitional regimes between plunging and streaming flow. Streaming flow consists of a single recirculating eddy occupying the entire baffle cell (**Fig. 1b**). The main flow travels well above the baffles and interaction with the lower vertical eddy is minimal. They also describe an additional supercritical jet regime where larger baffle spacing and discharges cause plunging flow to form a jet along the culvert bottom and a hydraulic jump downstream (**Fig. 1c**). Rajaratnam et al. (1988) developed dimensionless discharges for both plunging and streaming flow using momentum balances. To describe the transition between these flow states Rajaratnam et al. (1988) similarly found a dimensionless discharge defined as

$$Q_{t*} = \frac{Q}{\sqrt{g}b_o S_o L^{3/2}} \qquad \textbf{Eq. 1}$$

where Q is the discharge, g is the gravity, b_o is the baffle width, S_o is the culvert slope, and L is the baffle spacing. Transition between flow regimes, such as from a plunging to a streaming flow, was observed to be primarily a function of the dimensionless discharge originally derived from the hydraulic head over the weirs. However, observations indicated that baffle spacing (L) had greater influence on determining the transition between flow regimes and therefore replaced the hydraulic head in **Eq. 1**.

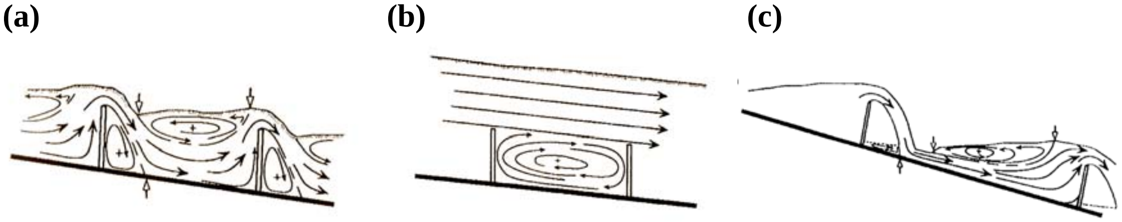


Figure 1: a) Schematics of plunging, **b)** streaming and **c)** supercritical jet flow regimes courtesy of Ead et al. (2004)

Our study differs from that of the pool and weir fishways and weir baffles studied by Ead et al. (2004) in that the weir baffles of this study were sloped laterally across the culvert based on Washington Department of Wildlife (WDFW) guidance (WDFW 2003). Sloped weir baffles and the spirally corrugated culvert introduced cross-stream variability through structures such as eddies, pools, plunges, and jets. These flow structures naturally form in rivers around boulders, alluvium deposits and large woody debris (LWD) and are often referred to by scientists and engineers as flow diversity. The diversity creates regions of lower velocity in which fish can rest and then use their burst speed to ascend the culvert (Katapodis 1992; Gregory et al. 2004; Bates et al. 2003). Fish take advantage of eddies, as well, by reducing the amount of energy they expend (Liao 2003).

Biological studies of fish crossing over baffles reveal turbulence, flow depths, velocity and flow patterns dictate fish passage. Salmonids leap and adaptively overcome obstacles (Stuart 1962; Pearson et al. 2005b). However, they avoid leaping in regions with aerated white water from plunging flows (Stuart 1962). Juvenile salmon have been observed to preferentially swim over or around baffles instead of leaping or jumping over the weirs (Kane et al. 2000; Pearson et al. 2006). This fish behavior would suggest that an adequate depth over weir-baffles is necessary for passage. Additionally, the over-weir velocities must be below the burst swimming abilities of the fish. The vertical recirculating eddy directly below the baffle was also observed to potentially disorient and overwhelm fish that approached too close (Pearson et al. 2006).

Correlated with culvert velocities and flow depths, culvert boundary roughness enhances fish passage, especially for juvenile and smaller resident fish. A non-spirally corrugated culvert examined by Ead et al. (2000) found reduced velocities in the boundary layer and near the surface. The culvert test bed facility used in our study has previously examined hydraulics without baffles as well (Guensch 2004; Pearson et al. 2005a; Richmond 2007). These studies found the spiral corrugations, sloped to the left side of the culvert (downstream perspective) created a reduced velocity zone (RVZ) on the left side of the culvert; concurrent biological testing yielded culvert ascending fish took advantage of this region (Pearson et al, 2005a; Richmond 2007). Other biologically studies have similarly found fish using lower velocity zones such as culvert roughness to minimize energy expenditure (Kane et al. 2000; Gregory et al. 2004).

The effect of turbulence on fish has been studied in detail with many suggested and observed effects. Turbulence associated with larger flows can act as a cue for migration (Stuart 1962). A cue for fish is defined as a stimulus or sensory signal causing a certain action or response. Smith et al. (2005) observed juvenile salmonids to avoided areas of low velocity with high turbulence, favoring locations with lower average velocities and low turbulence. In a sloped-weir baffled culvert test bed nearly identical to our study, Morrison et al. (2006) studied turbulence. They found that the turbulent kinetic energy (TKE) was greatest closest to the baffle and diminished downstream. A lateral variation in TKE was also observed at a cross-section 0.31 m below the baffle for flowrates below 198 l/s. A jet on the low side of the baffle produced slightly higher turbulence than the high side of the baffle. The cross-stream variation in turbulence is explained by the jet’s interaction with the lower velocities from the high side of the baffle creating a larger shear stress (Morrison et al. 2006).

CONCURRENT BIOLOGICAL STUDY

Fish passage using weirs and baffles in culverts has been studied by both biologists and engineers; however, they are rarely examined together. Our hydraulic study was conducted in conjunction with fish testing by Battelle Memorial Institute, Pacific Northwest Division at the WSDOT/WDFW culvert test bed (CTB) facility. Pearson et al. (2006) describe biological testing conducted within the same CTB. We describe these experiments here in order to draw comparisons to our hydraulic study. The 1.83 m diameter culvert was set at a 1.14% slope, normal height baffles (0.19 m) spaced 4.57 m apart. Discharges tested ranged from 42 l/s to 340 l/s. Biological testing was performed at night for a three hour periods with 100 test fish. Juvenile coho salmon (Oncorhynchus kisutch) with average length around 100 mm were used from the onsite WDFW Skookumchuck Fish Hatchery near Tenino, Washington. These fish were placed within the culvert tailwater tank and allowed to travel up the culvert for a three hour period, upon which the fish were isolated into either the headwater tank, culvert barrel or tailwater tank. Passage success was then defined by the percentage of fish entering and/or passing through the culvert into the headwater tank. Real-time observation of fish passage and traveling were made using low-light high-resolution cameras submerged at the culvert inlet and outlet and additional overhead cameras placed above and between baffles.

Results of passage success, shown in **Fig. 2**, indicate that passage was approximately 34% for 42 l/s and increased to 64% for 85 l/s. Passage success gradually declined for higher discharge rates, down to 7% for 340 l/s.

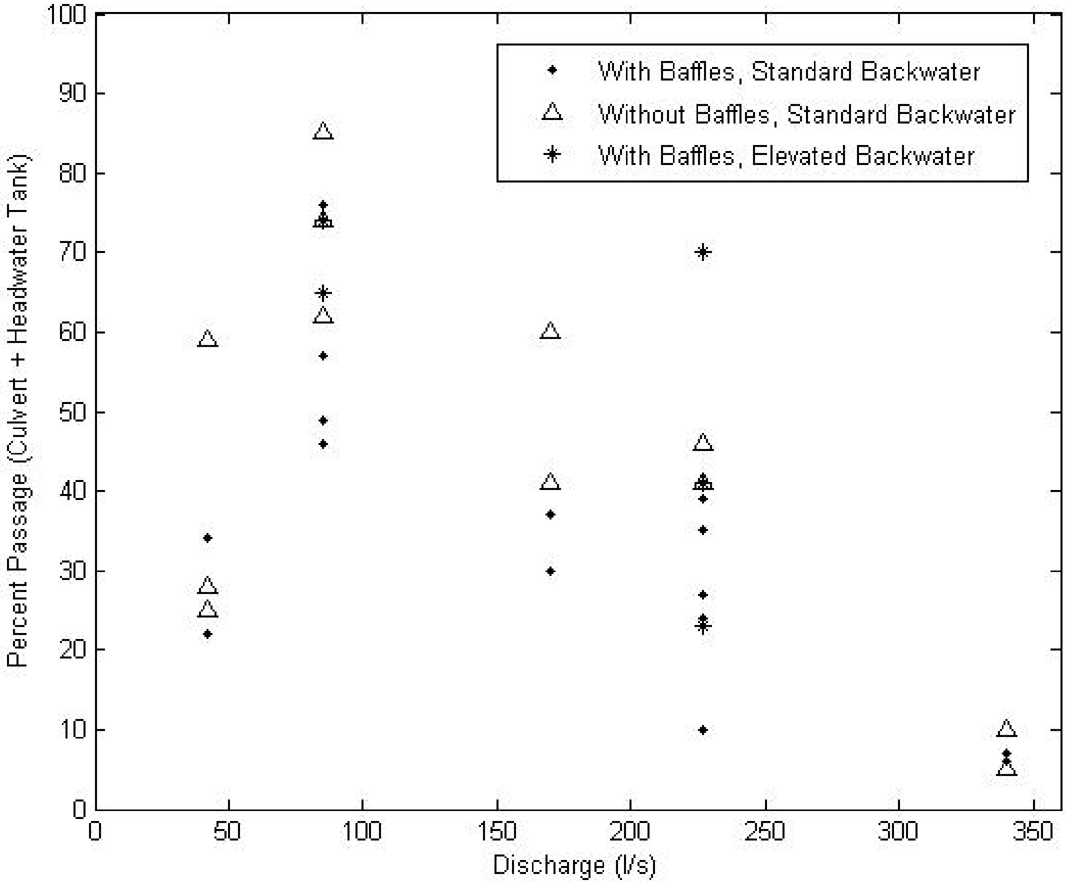


Figure 2: Percentage of fish passage versus discharge; Pearson et al. (2006)

Cameras positioned within the culvert revealed fish crossing over the weir baffles near the center using their bust speed for 42 l/s. As discharge increased to 85 l/s fish crossed over the entire baffle width with a more equal distribution. For flow rates greater that 85 l/s fish were now primarily found using the outer culvert walls to travel upstream and cross baffles. Juvenile coho accomplished upstream movement at higher discharges by maintaining resting positions within culvert corrugations.

Pearson et al. (2006) drew three main conclusions from their study. First, there was no significant difference for fish passage success between the baffled and the unbaffled culvert. However, when the water level on the downstream baffle was held at a fixed level (elevated condition) fish passage was higher than compared to the standard configuration. Second, the cumulative number of fish entries into the culvert was noticeably higher for the baffled configuration as compared with the unbaffled configuration, suggesting that same level of passage success may be obtained for less effort. The third finding indicates that passage success with relatively larger juvenile salmon (100 mm) may require a passage cue. This cue was present in their study for flows greater than 42 l/s, although this discharge rate should not be treated as an absolute threshold since it may be specific to the experimental setup. Overall, they reemphasize that fish are highly adaptive and are able to use low velocity pathways to achieve passage.

With the biological study's findings as the foundation, the objective of our study was to determine what hydraulic characteristics enhance or diminish juvenile salmonid passage.

We describe general hydraulic characteristics for an expanded range of parameters by focusing on mean velocities and flow depths. These flow characteristics are then used to describe flow regimes that appear to maximize juvenile fish passage. A direct comparison was made between fish passage and hydraulic flow for the 1.14% culvert slope, 4.57 m baffle spacing, 0.19 m baffles. The results from this comparison were then generalized to the other experimental configurations to provide guidance for professionals.

PROCEDURES

CULVERT TEST BED

To best simulate natural hydraulic conditions and accommodate the study of fish behavior and passage success, a full-scale culvert facility was constructed at the Skookumchuck Fish Hatchery. The culvert test bed consists of concrete foundations supporting steel construction of a headwater and tailwater tank. The culvert barrel connects these structures and its slope was adjusted via pulleys (Fig. 3). The spirally corrugated culvert was 12.19 m (40 ft) in length and has an internal diameter of 1.83 m (6 ft). Corrugations were 2.54 cm (1 in) deep by 7.62 cm (3 in) wide angled clockwise downstream at 5 degrees. Sloped-weir baffles made of galvanized steel were installed within corrugation troughs along the length of the culvert, placing strips of rubber underneath the baffles to simulate the seal that might be expected from alluvial deposits. The baffles were spaced at a WDFW and other agency recommended 0.06 m drop per baffle. Three different height baffles were used, each being sloped to the left (downstream perspective) at a 7.5 percent slope (Fig. 4). Water supplied from the upstream Skookumchuck Reservoir was regulated via valves, and discharges were measured using both magnetic and propeller flowmeters. Experimental discharges ranged from 42 to 227 l/s.

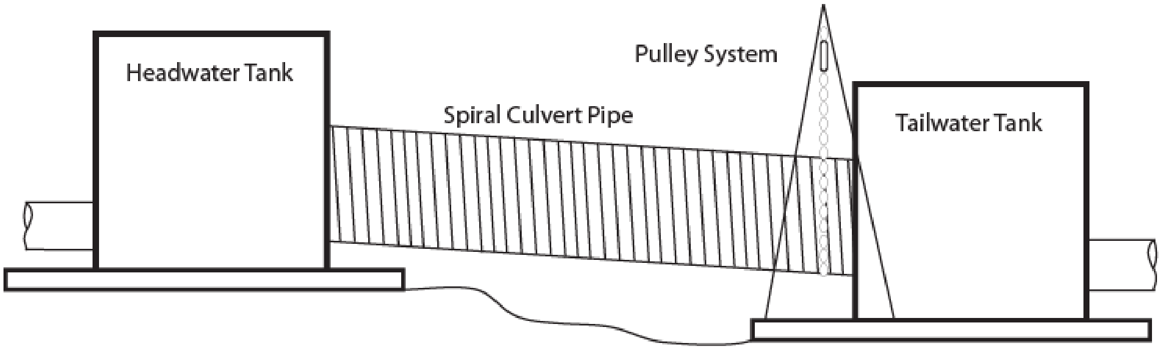


Figure 3: Schematic of 1.83 m diameter culvert test bed.

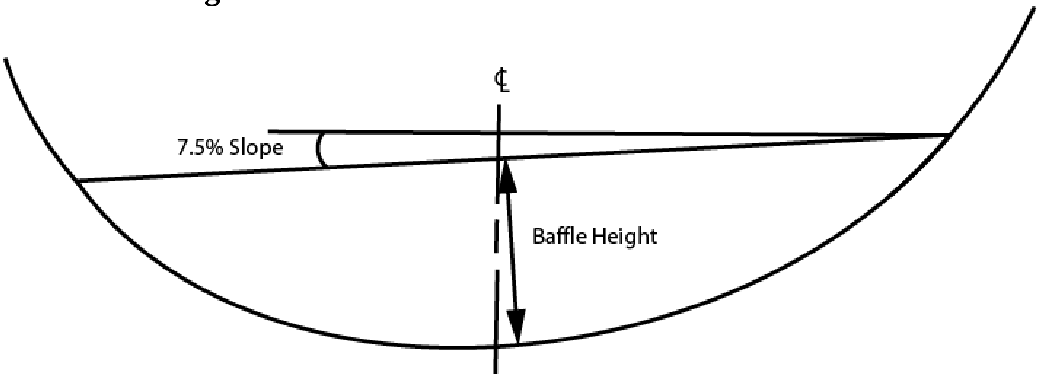


Figure 4: Weir baffles sloped to the left at 7.5%

DATA COLLECTION

A Sontek MicroADV (Acoustic Doppler Velocimeter) was used to infer the three dimensions of velocity at designated cross-sections. Measurements were taken at a sampling rate of 50 Hz for 120 seconds in a typical grid pattern of 23 points (Fig. 5). The ADV was mounted and repositioned within the culvert using worm gears attached to a gantry above the culvert. Water depths above and in between baffles were read off a measuring tape glued to a metal rod that was held in the water column. Experiments were performed for three slopes of 1.14, 4.3, and 10.96% and a variation of parameters summarized in Table 1. Culvert flow patterns were also made for all experiments using digital images and video.

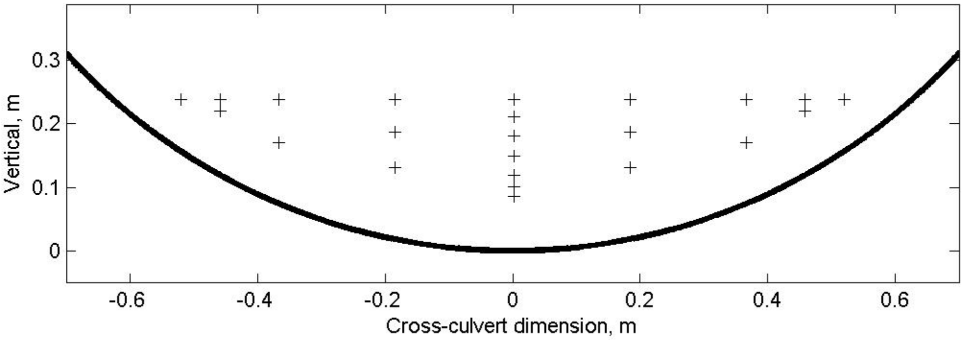


Figure 5: Acoustic Doppler Velocimeter measurement grid, locations indicated by (+) signs.

Table 1: List of experiments and parameters tested

S_o (%)	Q (l/s)	Baffle Spacing (m)	Baffle Height (m)
1.14	42, 57, 85, 113, 227	4.57	0.19
	42, 85	4.57	0.27, 0.34
	42, 85	2.29	0.19
4.3	42, 85, 113, 170, 227	2.29	0.19, 0.27, 0.34
	42, 85, 113, 170, 227	1.37	0.19
	42, 85	1.37	0.34
10.96	227	1.37	0.19
	42, 85, 113, 170, 227	0.54	0.19, 0.27, 0.34

DATA PROCESSING

The velocity data were processed using Matlab scripts to filter out data with signal-to-noise ratio (SNR) less than 10 and signal correlation less than 40%. Erroneous data were identified and removed using a despiking algorithm by Mori (2007). Data spiked when acoustic signal return was outside the normal detectable range as resulting from the culvert boundary, flow aeration or other interfering processes. Mori’s code incorporated the phase-space thresholding method of Goring and Nikora (2002) and replaces erroneous spikes with cubic polynomial interpolated values.

FINDINGS/DISCUSSION

RESULTS

Hydraulic Analysis

Sloped-weir baffle culverts have flow structures and regimes first described by Clay (1961), further examined by Rajaratnam et al. (1988) and analyzed in a rectangular flume weir by Ead et al. (2004). Our culvert test bed study differed from previous work in that a full-sized culvert with circular geometry was tested as well as larger baffle spacing. Our study differs most significantly due to the three-dimensionality of all flows, effectively created by the sloped baffles and helical corrugations of the culvert. To summarize culvert flow, dimensionless variables were described in Katopodis (1992) to establish dimensionless discharge and velocity curves. The dimensionless discharge was expressed as

$$Q_* = \frac{Q}{\sqrt{gS_o D^5}} \qquad \textbf{Eq. 2}$$

where, Q is the discharge, g is the gravity, S_o is the culvert slope, and D is the culvert diameter. Similarly they define a dimensionless velocity

$$U_+ = \frac{U}{\sqrt{gS_o D}} \qquad \textbf{Eq. 3}$$

Note that Katopodis (1992) calls this variable U_*. We plotted these dimensionless variables against a ratio of mean water depth over the baffle (Y_b) versus the culvert diameter (D). The dimensionless scaling yielded a collapse for the three-dimensional flow experiments which had a range of baffle spacing, baffle height and culvert slope

(**Fig. 6 and 7**). Therefore, the stage discharge curves allow for an approximation of Y_b given a set of hydraulic parameters.

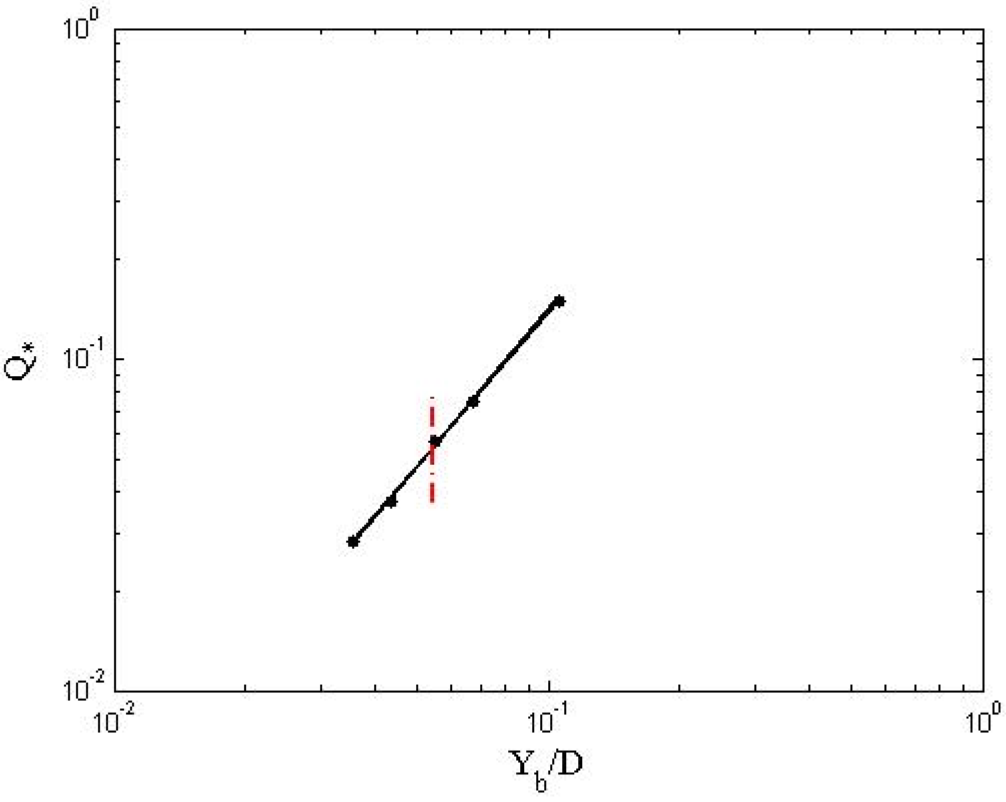


Figure 6: Dimensionless stage discharge curve for culvert parameters set at a 1.14% culvert slope, 4.57 m baffle spacing, and 0.19 m baffles. The solid line is a linear fit of the curve $Q_* = 0.647(Y_b / D) - 1.023$. The dashed line represents flow depth corresponding to greatest observed juvenile salmon passage.

Dimensionless average and maximum velocities (U_+) scaled by Y_b/D did not result in a clear reduction of the data. However, dimensionless velocity scales incorporating baffle spacing and baffle height Y_bL/DP collapsed data by integrating the effects of baffle roughness. The ratio of L/P accounts for the number of baffles along the culvert length. The average velocity used in the scaling was an average of data in the cross-section just upstream of the baffle. This cross-section was chosen because it was furthest away from the influence of near baffle flow structures, such as plunging flow, which creates a high variability with data hindering comparison between experiments.

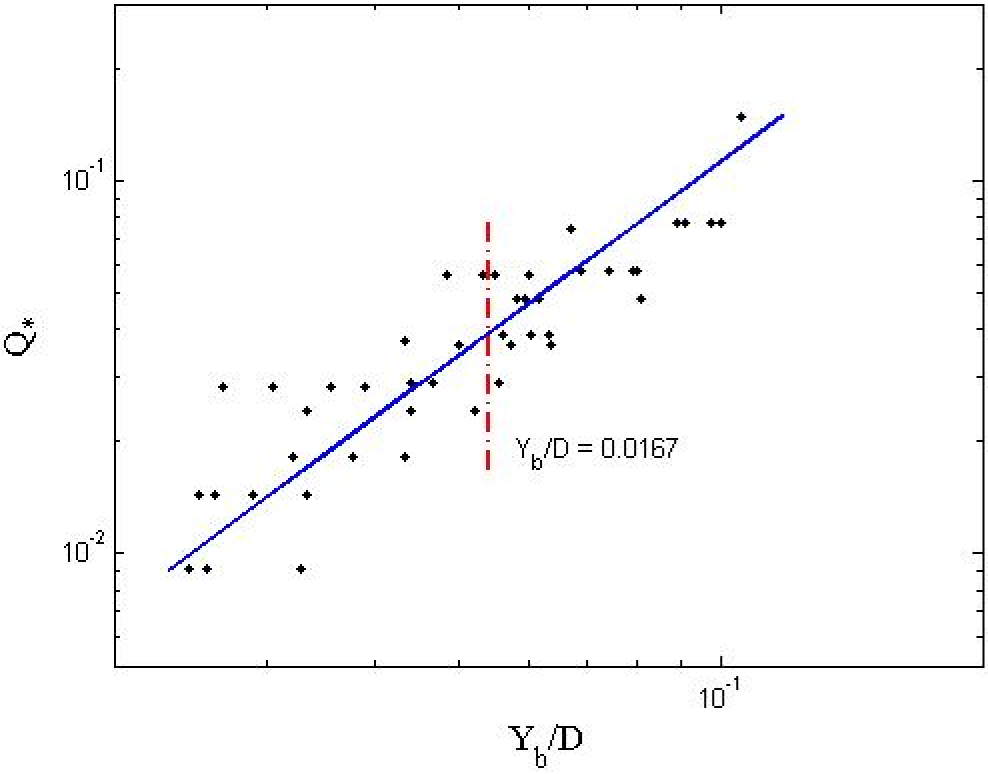


Figure 7: Dimensionless stage discharge curve for all experiments. The dashed line represents flow depth corresponding to increased juvenile salmon passage generalized to all experiments. The solid line is a linear fit, $Q_* = 0.58(Y_b / D) - 1.03$ for data.

Maximum velocities used were the highest averaged data point from any cross-section within the entire culvert cell as bounded by the baffles. These maximum velocities are found in either the left or right jets observed just below the baffle. They are not necessarily the true maximums since the downward looking ADV could not gather the velocity very close to the surface. The maximum velocities were generally not located at the surface because plunging flow forced maximums toward the culvert bed.

Additionally, the near culvert boundary velocities were difficult to collect because of the poor acoustic signal return very near the corrugated boundary.

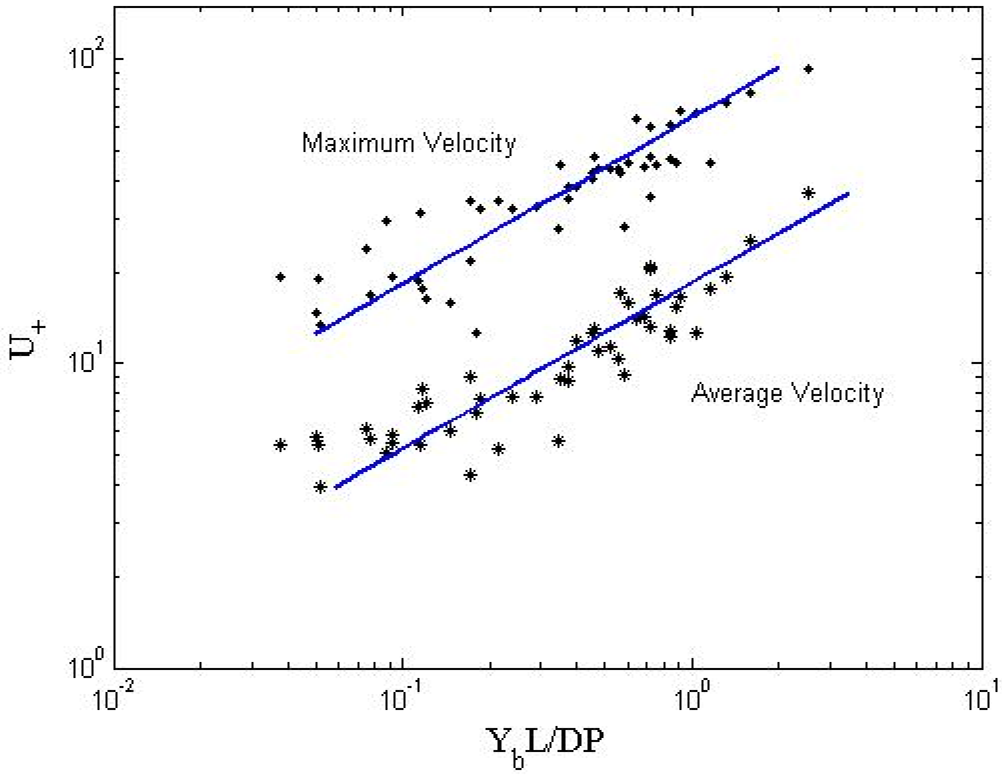


Figure 8: Maximum and average dimensionless velocity scales. Maximum velocity line $U_+ = 1.38(Y_b L / DP) - 7.61$ and average velocity line $U_+ = 1.83(Y_b L / DP) - 5.34$ are linear fits.

Although the scaling used in the plots shown in Figures 6, 7 and 8 are common (e.g. Katapodis (1992) and Ead et al. (2002)), caution must be used in their interpretation since the culvert diameter occurs in both the independent and dependent variables and may lead to spurious correlation. Spurious correlation arises when two variables that do not have correlation on there own are correlated by a third variable, particularly if the variable is in the denominator (Pearson 1897; Benson 1965). The dimensionless scaling in **Figures 6, 7 and 8** does incorporate this common third variable culvert diameter (D) in the denominator, but since the variable was constant it does not lead to spurious correlation. This implies that the regression line for stage discharge cannot necessarily be applied to culverts of other diameters.

Qualitative Flow Description

To describe changing regimes and flow structures of culvert flow an initial case was examined that had a discharge of 42 l/s, a 1.14 percent slope, and normal height baffles spaced 4.57 m apart. The flow structures of the initial setup consisted of five distinct elements (**Fig. 9**). The most prominent feature was a jet on the left side of the culvert that propagated downstream to the next baffle (**9a**). Across the remainder of the baffle, water plunged towards the culvert bed and formed a line visible on the surface exemplified by a surface roller (**9b**). This process created a vertical eddy directly downstream of the baffle (**Fig. 9c**). The baffles acting as weirs caused the water to contract and focus the direction of the jet (**9d**). The jet contraction or redirection was also derived from the water plunging over the baffle into the corrugations and consequently becoming channelized. The final structure was a lateral recirculation of water traveling in a clockwise direction, mainly driven by the motion of the jet (**9e**). All of these structures were seen to change with variation of parameters.

The most obvious change occurred for increasing discharge and was described best by surface averaged velocity fields (**Fig. 10**). Two flow structures previously described in **Figure 9** are again apparent; the jet over the low left side and upstream flow on the high right side (**Fig. 10a**). The vertical recirculating eddy below the baffle is not resolved because the velocity field is averaged across the culvert from the upper two water-surface data points.

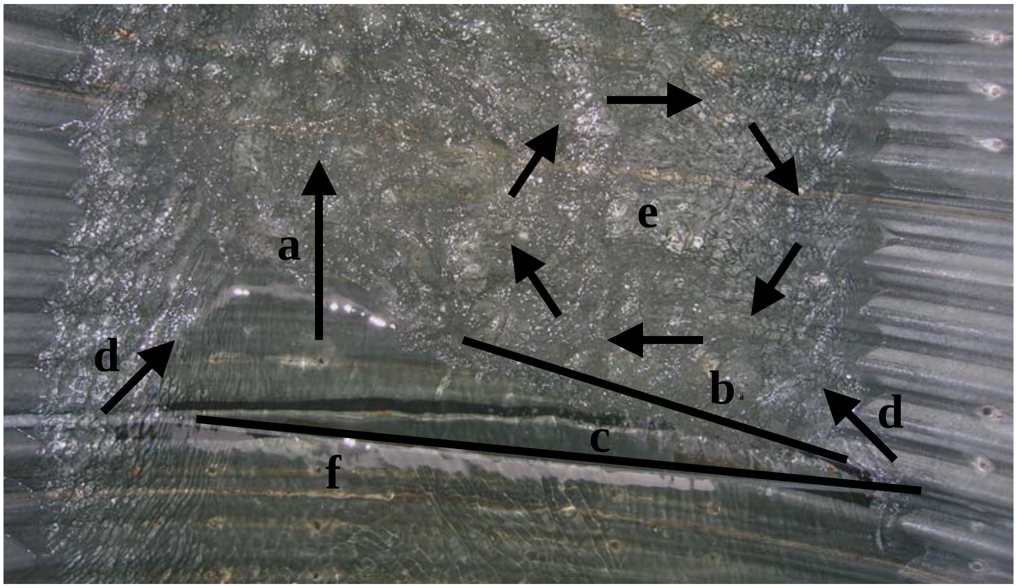
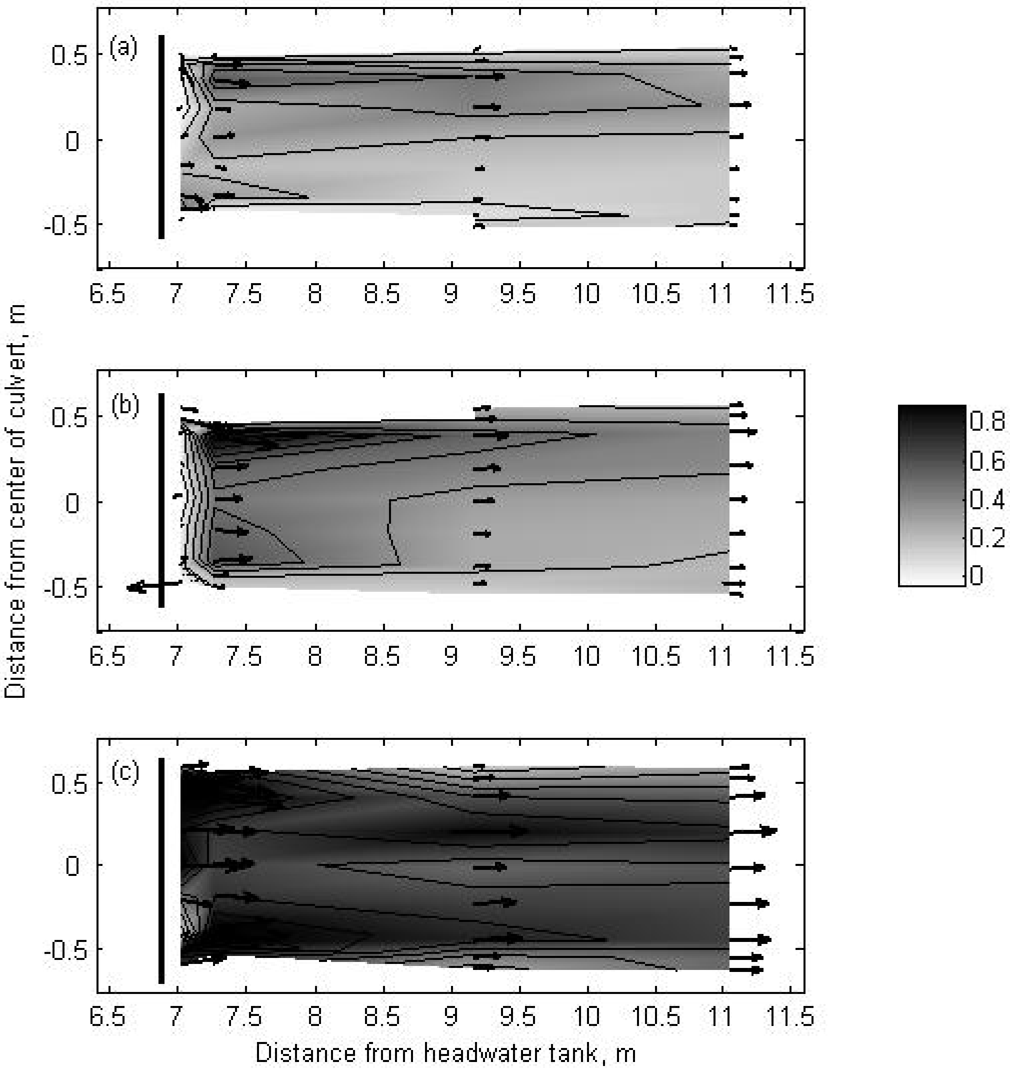


Fig. 9: Baseline flow at 42 l/s, 1.14% culvert slope, 4.57 m baffle spacing, 0.19 m baffles Downstream looking perspective with baffle sloping from low to high side (left to right) (a) Dominant Jet (b) Plunge line (c) Vertical Recirculation (d) Contraction (e) Lateral Recirculation (f) Baffle Crest

As the discharge was increased to 85 l/s the baffles became submerged and had less of an effect on the flow structures (**Fig. 10b**). The dominant jet on the low side of the baffle grew in magnitude and an additional jet on the right side of the baffle replaced the lateral recirculation. The jets for this discharge were both accentuated by the contraction that occurred over the outer edges of the baffle. The magnitude of the new jet was smaller than the original jet and did not persist to the downstream baffle. The effect of the baffle slope on the flow further diminished as the discharge was increased to 227 l/s and the jets approached similar magnitudes (**Fig. 10c**). This jet formation trend for increasing discharge was observed when parameters of baffle spacing, baffle height, and culvert slope were modified. It was additionally observed that the sloped baffles allow multiple regimes, such as those described in **Figure 1**, to exist simultaneously.



Figures 10: Plan view of surface averaged velocity field describing jet formation for increasing discharge. **(a)** 42 l/s **(b)** 85 l/s, and **(c)** 227 l/s Parameters set at a 1.14% culvert slope, 4.57 m baffle spacing, 0.19 m baffles, with discharge

Flow Regimes

The level of weir submergence defines the transition between different regimes which was a function of bed slope, baffle spacing and baffle height (Ead et. al 2004). The baffle's slope caused a multi-level submergence across its baffle width and thereby generated a combination of flow structures/regimes for any set of parameters. We observed six of the regimes described in Ead et al. (2004) and three new regimes. As determined by observations and reviewing of photographs and videos, multiple regimes were documented for a given set of parameters due to lateral variability associated with baffle slope. **Figure 11** labels, above the representative baffles, the different regimes observed for the coded experimental conditions. Experiments are coded as follows. The first number represents the bed slopes 1.14, 4.3, and 10.96% respectively as 1-3. The second letter (A-D), respectively, represents the baffle spacing (4.57, 2.29, 1.37, 0.54 m), and discharge is listed last in l/s.

Flow regimes observed included plunging (P) and streaming (S) as previously described in (**Fig. 1**), plunging transitional (PT), transitional baffle (TB), baffle (B), transitional streaming (TS). New flow regimes included a clockwise lateral recirculation (as seen in the initial case), a partially plunging flow, and jet flow. Partially plunging flow (PP) is similar to the plunging flow regime (P), however, the baffle is not submerged and the plunge occurs below the baffle elevation. Partially plunging flow has a plunge line accented by a nominal surface roller (**Fig. 12**). This differs from plunging flow which has a surface eddy extending the entire length of the baffled cell (**Fig. 1**). Plunging flow existed when baffle spacing was small enough to allow for the entire surface rotating eddy to form. The jet flow regime (J), distinguished by a jet on the low side of the baffle as described in the initial case, was present for any set of parameters because the water's direction at the end of the baffle was not impeded. Visually identifying these regimes was made difficult by the across-culvert lateral flow and across-culvert variation of water depth. Additionally, the number of regimes concurrently present and merging across the culvert width did not allow for an individual regime classification. For example in **Figure 11a** regimes transition from a jet on the low side of the baffle, to plunging transitional flow, and then a partially plunging flow as baffle submergence decreases.

To classify all flow patterns a series of new regimes was established based on jet formation as seen in **Figure 10**. The dominant jet and formation of the second jet on the right side of the culvert form regimes J1, J2 and J3 for increasing discharge (**Fig. 11**). **Figure 11** also shows the jet regime trend persisting for increasing slope.

For the lowest discharges and tallest baffles, water traveling over the right side of the baffle falls within the corrugations and is directed toward the culvert center (J1). With increased discharge and baffle submergence, a second jet forms on the right side similar to that of the left (J2). The right jet continues to grow in magnitude until it becomes comparable to the left jet (J3). Plotting the number of runs for which each jet regime was observed versus its discharge illustrates the association of J1 regimes with low discharges and J3 regimes with high discharges (**Fig. 13**). This trend again indicates the formation of the second jet and a more uniform flow occurring only for higher discharges. However (not shown here), increasing baffle height reduces the transition rate between a J1 and J3 regime. Thus higher baffles help to sustain flow diversity. Additionally, the contraction of the jets diminishes and they become increasingly parallel to the culvert for both increasing discharge and culvert slope.

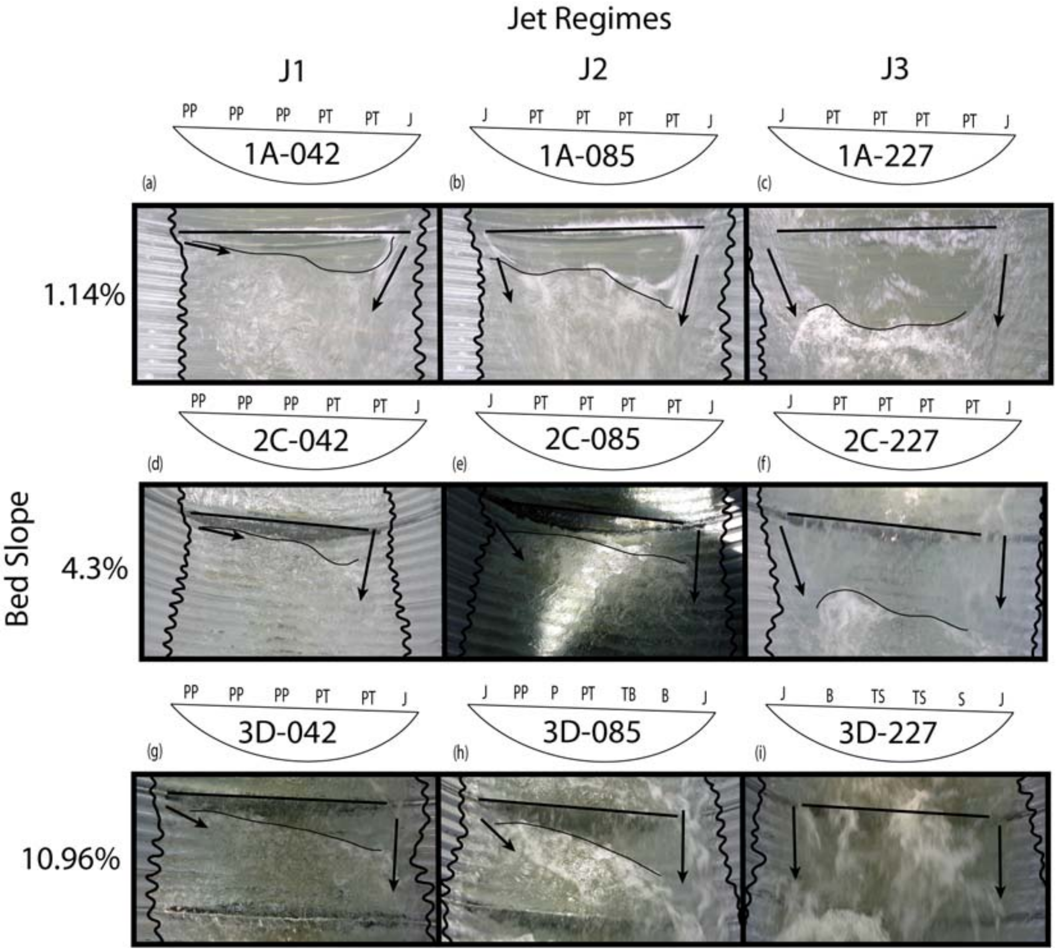


Fig. 11: Sloped weir-baffles flow regime sketches for increasing discharge (a,b,c) and bed slope (a,d,g). Experimental parameters are coded and described in text. Flow regimes vary across baffle width and are classified over a representative baffle. Camera orientation was switched and figure is in an upstream looking orientation.

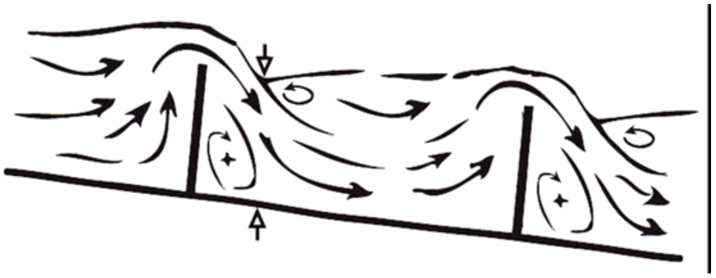


Fig. 12: Partially Plunging Flow Regime

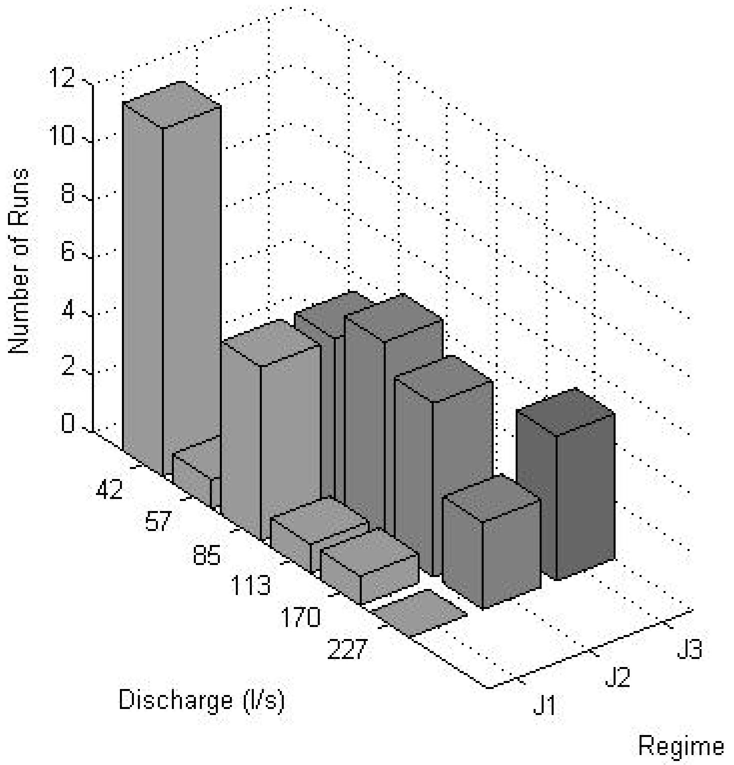


Fig. 13: Quantity and type of jet regime observed versus discharge.

Quantitative Flow Description

A representative average velocity for flow rates within the culvert was determined by dividing the discharge by the cross-sectional area over and just upstream of the baffle. The cross-sectional area was based on water depth measurements. One-dimensional average velocities directly over and upstream of the baffle ranged from 0.6- 1.5 m/s and 0.15- 0.9 m/s respectively (**Fig. 14**). Increased bed slopes resulted in higher velocities over the baffles and the magnitude of average velocities above the baffle were also a function of baffle height.

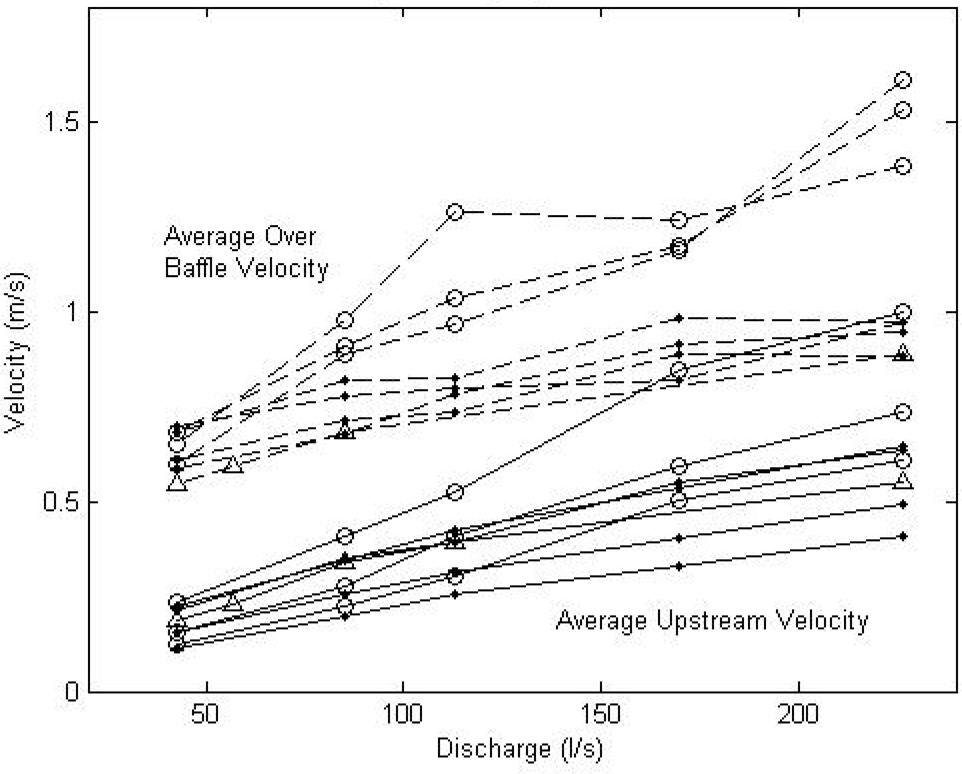


Fig. 14: Average velocity over (dashed line) and upstream (solid line) of the baffle. Lines connect experiments with the same parameters (except for discharge). Various slopes, 1.14, 4.3, 10.96% correspond to dots, triangles, and circles respectively.

Over the range of discharges tested, one distinctive trend was seen above the rest, a lateral shearing across the culvert created by the dominant jet. For higher discharges, the flow depth increased relative to the baffle height and the effect of the cross-culvert slope diminished. This was exemplified by the diagonal plunge line (as seen in the base case) becoming parallel to the baffle. The decreasing influence of the baffles with increasing discharge is observed by plotting the ratio of the average velocity for the baffled culvert just upstream of the baffle over the average velocity found in the same unbaffled culvert as studied by Guensch et al. (2004) (**Fig. 15**). The baffles begin to function as elements of roughness with increasing discharge, shown by the ratio of average velocity rising toward one and then plateauing near 0.5. The Manning's roughness coefficient is given by

$$n = \frac{1}{V} R_H{}^{2/3} S_o{}^{1/2}, \quad where \qquad R_H = \frac{A}{P_W} \qquad \textbf{Eq. 4}$$

where V is the average culvert velocity, R_H is the hydraulic radius, A is flow area, P_W is the wetted perimeter, and S_o is the culvert slope. The Manning's equation is an empirical formula for average velocity in fully developed uniform open channel flow. Though complete uniform flow in the culvert with baffles is unlikely, an approximation for the Manning's coefficient was made using an average velocity and hydraulic radius calculated geometrically using a culvert centerline flow depth measurement. Comparison of Manning's n between the baffled and non-baffled culvert shows values approaching each other for increasing discharge. Again, this describes baffles acting more as elements of roughness for high flow rates. As the flow begins to separate and travel above the baffles the large energy dissipation associated with the plunging flow disappears. The decrease in *n* with increasing discharge is also observed in river flow (Chow 1959). The declining effect of sloped baffles is best described through the development flow structures, however.

At lower discharges the asymmetrical flow included a clockwise eddy. As discharge and water depth over the baffle increased the lateral recirculation is replaced by a second jet over the right side of the baffle. The second jet increased in magnitude to the point of becoming equal if not greater at 227 l/s and 0.19 m baffles as previously described by the jet regimes. The development of the second jet and the reduction in lateral shear/asymmetry is shown by plotting the surface averaged velocity (top three data points) at a cross-section 0.4 m below the baffle, where the development of the jets is not influenced as much by the turbulent plunging (**Fig. 16**). For the same cross-section, the plunge direction and vertical recirculation are observed to transform (**Fig. 17**). In this plot y is the velocity measurement depth and h is the total water depth. The centerline profiles show a plunging jet for 42 and 57 l/s, which changed into a vertical recirculation zone for the higher flows. The magnitude of this recirculation also grows with increasing flow rates, in the same manner as the overall downstream velocity.

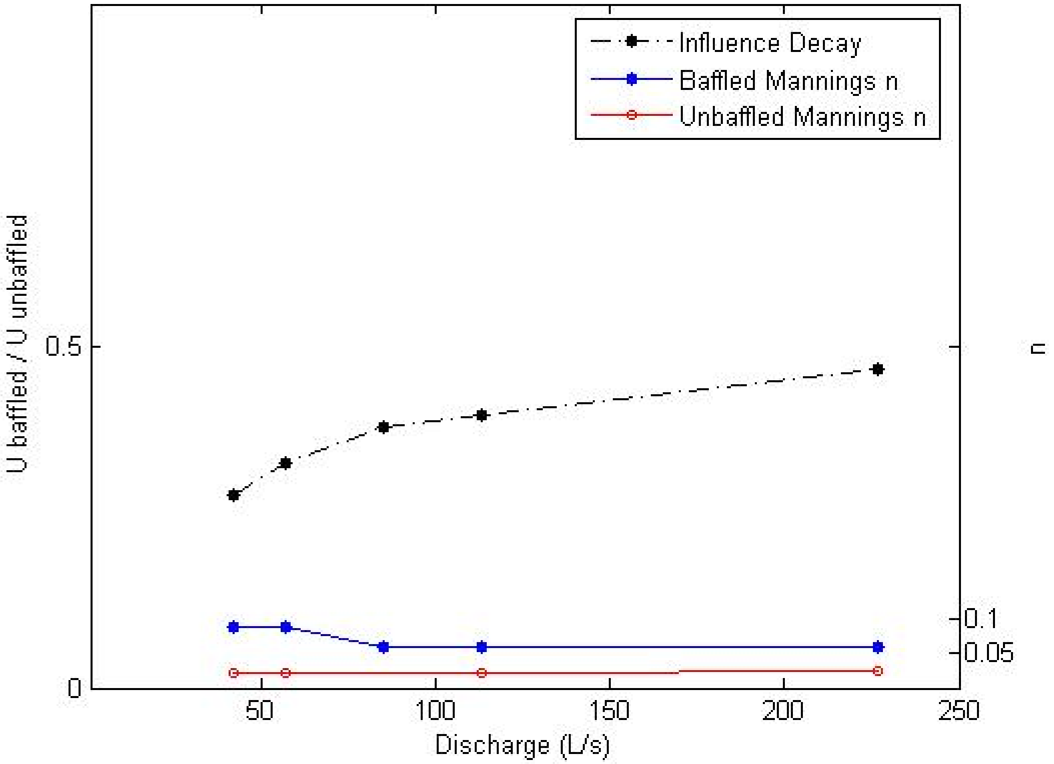


Fig. 15: Reduction in the effect of baffles compared with an unbaffled culvert for increasing discharge. Comparisons used a ratio of stream-wise velocities and Manning's coefficient for culvert parameters set at a 1.14% culvert slope, 4.57 m baffle spacing, and 0.19 m baffles.

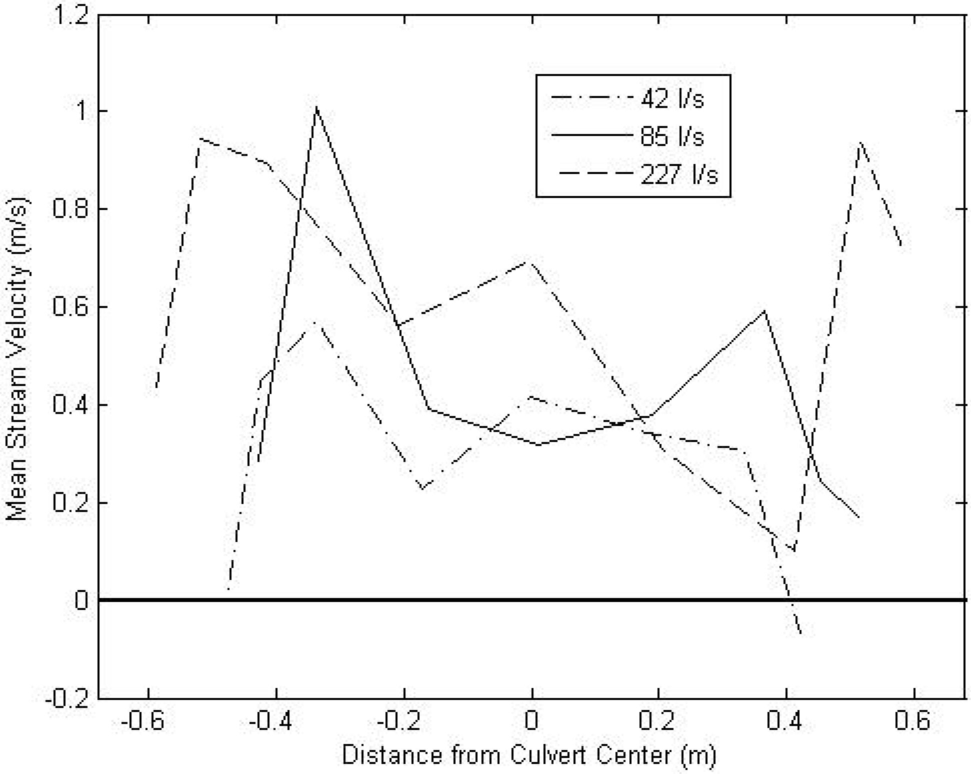


Fig. 16: Surface averaged stream velocity for range of discharges with culvert parameters set at a 1.14% culvert slope, 4.57 m baffle spacing, and 0.19 m baffles.

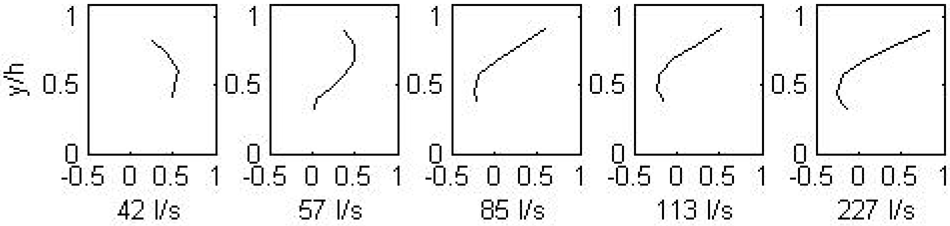


Fig. 17: Centerline stream-wise velocity profile (m/s) evolution for increasing discharge. Velocity profiles are normalized by measure velocity depth (y) per total water depth (h) with culvert parameters set at a 1.14% culvert slope, 4.57 m baffle spacing, 0.19 m baffles.

Increasing baffle heights had a compounding effect for the asymmetry or lateral shear by reducing the velocity on the right side of the culvert and focusing the dominant jet along the outer left culvert wall (**Fig. 18**). For higher baffles it was also observed that asymmetry decreases as discharges grows.

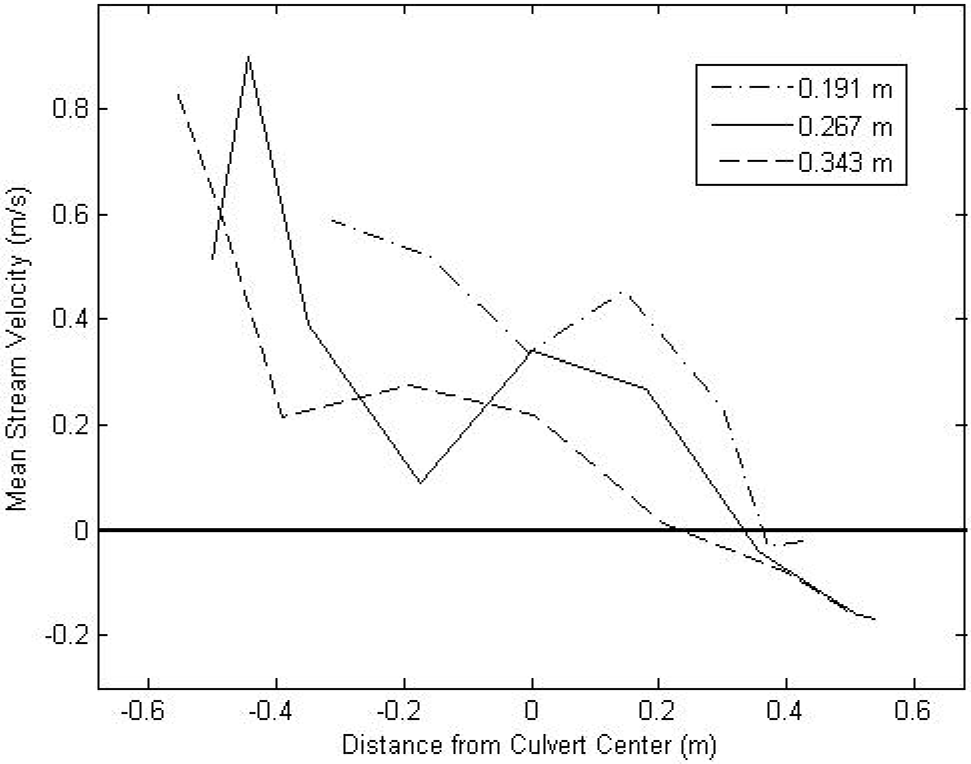


Fig. 18: Surface averaged stream velocity 0.4 m below baffle with varied baffle heights. Culvert parameters were set at a 42 l/s discharge, 4.3% culvert slope, and 2.29 m baffle spacing.

Asymmetry

To better describe and compare the lateral shear for all experiments, an index termed asymmetry (A_s) and its magnitude was defined as

$$A_s = 1 - \frac{1}{V_L / V_R} \qquad \textbf{Eq. 5}$$

where V_L is the averaged velocity for data to the left of the centerline and V_R is correspondingly for the right. Asymmetry values >1 are associated with flows forming a clockwise eddy where V_R is negative. Flow values approaching 1 are considered highly asymmetric, values approaching 0 are symmetric, and negative numbers occur when the magnitude of the right jet surpasses that of the left jet. Evaluating asymmetry (A_s) at the same cross-section 0.4 m below the baffle confirmed the trend, seen in **Figs. 16** and **18**, as a function of discharge (**Fig. 19**). Most configurations began with a value between 0.5 and 1 for the lowest discharge and approached 0 or below for the highest discharge. Thus the flow asymmetry decreases with increase flow rate for all configurations.

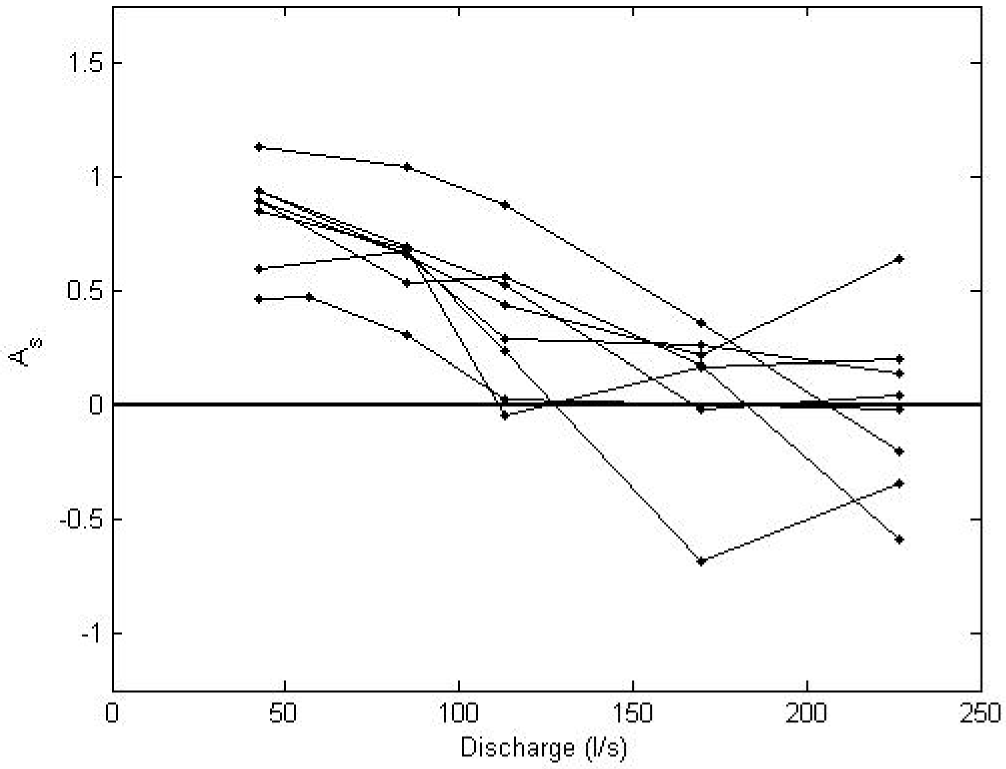


Fig. 19: Asymmetry (A_s) for varied discharge. Lines connect experiments with the same parameters.

DISCUSSION

Previous studies on fish passage have commonly focused on water depth and velocity as the critical parameters for successful passage (Gregory 2004). However, flow diversity is consistently emphasized as essential in the migration, spawning, life history of fish and the simulation of natural stream conditions. Regions of lower velocity and adequate flow depths are both key features of flow diversity for sloped-weir baffles. To describe the flow features essential to fish passage, the interrelation between flow asymmetry, depth, and velocity is presented in comparison with biological testing.

Our results described an across-channel variation as explained by the jet regimes and flow asymmetry. The asymmetry was seen to vary primarily with discharge, but was also observed to be affected by slope, baffle spacing, and height. To synthesize these results the value for asymmetry (**Eq. 5**) was plotted using the non-dimensional discharge Q_{t*} (**Eq.1**) and a ratio of baffle spacing (L) to baffle height (p) (**Fig. 20**). Greater flow regime symmetry is represented by darker data points.

The non-dimensional scaling using Q_{t*} presented in Ead et al. (2004) to describe the transition lines between different flow regimes are shown in **Figure 20**. Ead et al. transitional lines do not correspond to flow patterns because the three dimensional flows establish multiple regimes (**Fig. 11**). Additionally, our experiments cover a large range of baffle spacing to baffle height (L/P). Therefore, flow development was presented with the asymmetry index.

Figure 20 shows asymmetry decreasing for increased discharge, larger baffle spacing and smaller baffle heights. The scaling of the regimes gives a good general description of the flow diversity trends; however, the slope incorporated within the dimensionless discharge does not ideally reflect the jet regimes as baffle spacing is increased. Experiments at the same slope with larger baffle spacing than a 0.06 m drop per baffle generally have a lower asymmetry from increased contraction of water over the baffle and smaller baffle spacing has increased asymmetry. However, decreasing the baffle spacing enough reduces the lateral shearing driven asymmetry by approaching a streaming regime.

As indicated previously, possibly the largest factor contributing to asymmetry via jet formation is the contraction of water over the baffle. Contraction was observed to be stronger for larger baffle spacing because the greater drop of water over the baffles was magnified and subsequently channelized toward the center of the culvert by water falling within the pipe’s corrugations. The redirection of water was particularly obvious on the right side of the baffle where less flow was more easily influenced by the corrugation. Corrugations focusing water toward the culvert center also contributed to the accentuation and development of the plunge-line and the lateral recirculating eddy for low discharges. Similarly, asymmetry increases for higher baffles as a result of reduced flow contraction. Higher baffles have less contraction because culvert corrugations are more perpendicular to the water surface and do not redirect water toward the culvert center as much as baffles of lesser height. Geometrically more water is directed over the low side of the baffle as well.

Biological testing indicated that a specific minimum flow rate may stimulate a response in upstream passage of fish for discharges greater than 42 l/s (Pearson et al. 2006). However, for baffled culverts this cue is believed to be a function of velocity, flow depth and other characteristics in addition to discharge. The finding that fish cross over the baffles from center to center-left at 42 l/s and over the entire length of the baffle for 85 l/s indicates the importance of head over the baffles. This transition for greater baffle submergence between 42 and 85 l/s correlates to the establishment of the second jet regime. The visual representation of J2, defined as the formation of the second jet on the high side of the baffle, was also observed to completely submerge the baffle. The submergence or increased depth over the baffles results in a larger region in which fish may cross over the baffle. This suggests that fish passage may increase at or after the transition from the J1 to and J2 regime. Approximating this transition as a line onto **Figure 20** provides a prediction for increased or maximum fish passage. This transitional line, based on the qualitative description of jet flow regimes, was determined by plotting jet regime classification with the same variables Q_{t_*} and L/P used in scaling asymmetry.

Full baffle submergence at the transition between the J1 and J2 regimes occurs when plunging flow on the right side of the culvert is replaced with a plunging transitional flow. The plunging flow over the baffle causes increased aeration and turbulence which fish may avoid, requiring fish to leap over the baffle at this location as well. Therefore, the increased baffle submergence allows for fish to travel over the baffle without leaping. To approximate a critical depth (H_c) for fish passage a comparison of biological testing and flow depth was made. At 42 l/s fish were observed to prefer crossing over baffles at the center to center-left which corresponds to a 0.06 m water depth. As discharge increased to 85 l/s, and fish were observed to cross over the entire baffle width, the critical minimum flow depth (H_c) on the high right side of the baffle was again measured to be 0.06 m.

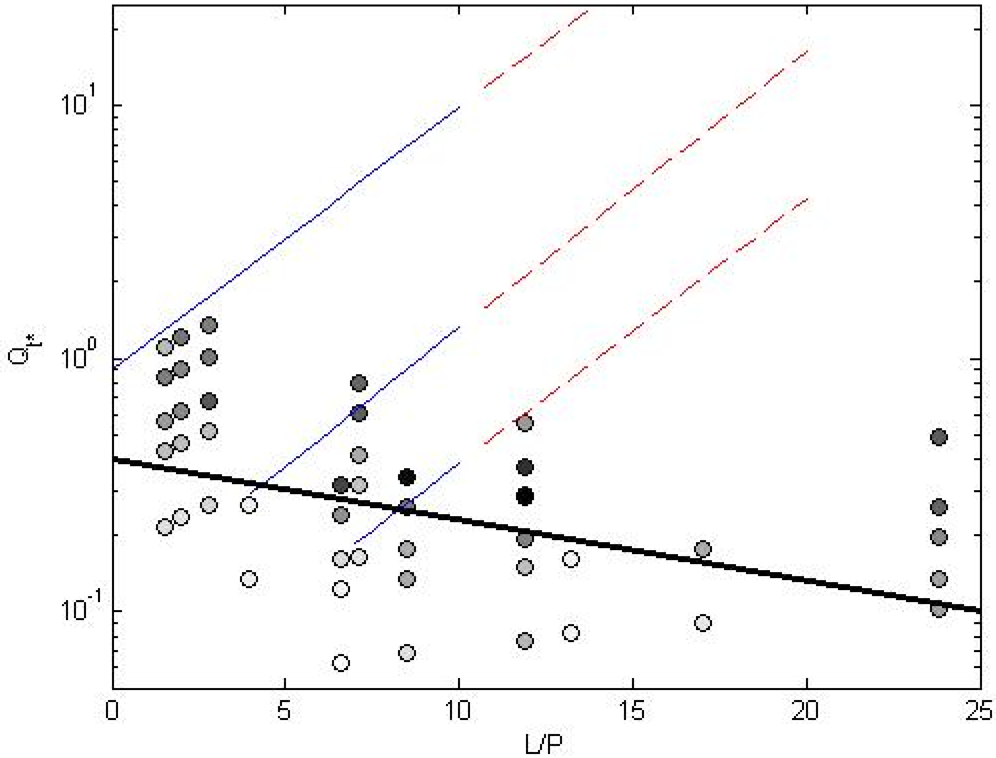


Figure 20: Asymmetry scaling using dimensionless discharge (Q_{t*}) versus ratio of baffle length (L) and baffle height (p). This scaling was incorporated from Ead et al. (2004). Asymmetry (A_s) decreases from lighter to darker points. The light lines represent regime scaling lines from Ead et al. (2004) Dark line represents observed transition between Jet Regime 1 and Jet Regime 2.

To show when H_c was achieved across the entire baffle width, a line corresponding to increased juvenile coho salmon passage was plotted with the stage discharge curve (**Fig. 6**). As a prediction of increased fish passage for all hydraulic configurations, a critical mean depth was generalized on the stage discharge scale in

Figure 7. The critical mean depth, approximately 0.1 m, is the average water depth over the baffle corresponding to when H_c was achieved across the baffle. This critical mean depth is represented on **Figure 7** by a Y_b/D value of 0.0167. Determining a peak or ideal passage conditions is important, but these settings can not be fixed when instream discharge naturally varies. The sloped nature of the weir baffles, however, may provide an adequate head over the baffles even in low discharge conditions.

Though the critical depth may be met across part or the entire baffle, the velocity may still be a barrier. Culvert velocities act as passage barriers when they exceed fish swimming abilities. Increased velocities may explain why even with sufficient baffle submergence fish passage decreases as discharge increases. A separate study of juvenile coho salmon burst swimming abilities by Powers (1997) found smaller coho (55 mm in avg. length) to have an average burst speed of 0.7 m/s. In the present study however, fish (100 mm in avg. length) passed upstream even when the average of over baffle velocities ranged from 0.6- 1.5 m/s. The near wall boundary layer, baffles, and culvert corrugations create regions of lower velocity for fish to rest, yielding increased and more energy efficient passage.

In summary, **Figure 21** shows the general trends of asymmetry (A_s) and average over-baffle water depths (m) and velocities (m/s) compared with juvenile salmon passage (%/100). Asymmetry (A_s) a quantitative description of flow diversity reveals asymmetric flows for low discharges becoming more symmetric for increasing discharge. As expected, both flow depths and average velocities are observed to grow with discharge. The peak passage at 85 l/s indicates a relationship to a critical combination of these parameters. Presented previously, it is believed that a critical over-baffle flow depth (H_c) and the absence of a fish passage cue for discharge may explain lower fish passage at 42 l/s. Since H_c is not suspected of being the limiting condition for passage at high discharges, increased velocities or reduction in A_s may contribute to lower fish passage.

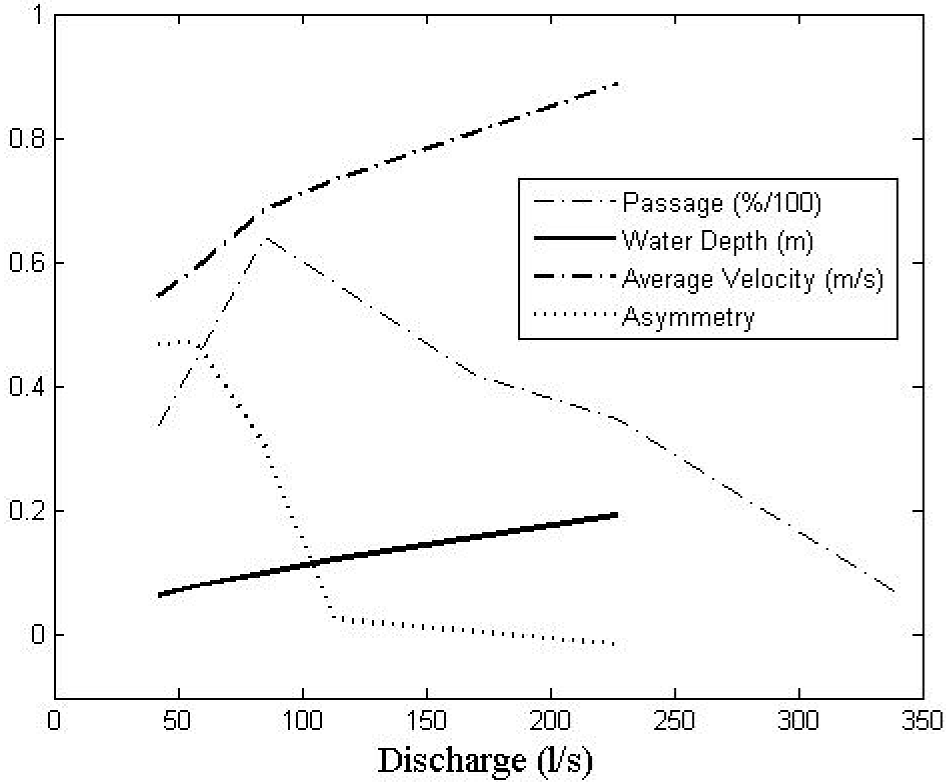


Figure 21: General trends for fish passage, over baffle water depth (Y_b), average over baffle velocity, asymmetry (A_s) versus discharge. Culvert parameters at a 1.14% culvert slope, 4.57 m baffle spacing, 0.19 m baffles.

PRACTICAL APPLICATION

The present experiments focused on the evolution of flow regimes and structures within a single culvert test bed facility. In the field, culvert diameter and length vary significantly to provide adequate conveyance. Many barrier culverts are located higher in watersheds where stream gradients are larger and discharges smaller. Smaller diameter culverts are often used in the upper watersheds and affect culvert hydraulics with smaller sized culvert corrugations, flow width and baffle spacing. Juvenile salmon observed to rest within corrugations and use the near wall lower velocities of larger diameter culverts may not have that advantage with smaller culvert corrugations. The lateral variability that we observed to increase with baffle width and increased asymmetry may be limited with the smaller culvert geometry as well. Increasing culvert slope requires closer baffle spacing and therefore a greater likelihood of streaming flow. Additionally, culvert length strains the ability for successful fish passage by requiring longer sustained and burst swimming by fish.

Furthermore, the experimentally controlled discharge does not take into account natural flow duration in streams and other conditions. Juvenile salmon and other resident and anadromous fish migrate at different times, experiencing a range of conditions. Understanding what instream discharges and flow duration curves are associated with the seasonal timing of fish passage is important. This information could be used with our plots predicting juvenile coho fish passage to determine what and how it might be best to place baffles within a culvert. Culvert retrofitting may be the most economical mediation, yet increased sedimentation and debris blockages can require additional maintenance for many culverts. Alluvium deposition in culverts will also alter hydraulics and flow patterns.

CONCLUSIONS

Hydraulic analysis of sloped-weir baffles in a culvert test bed for a range of parameters was related to a concurrent biological study of juvenile coho salmon passage. This comparison of hydraulic and biological results revealed several applicable conclusions. Visually, the most apparent observation was an asymmetry to the flow resulting in flow diversity. This diversity was classified into three jet regimes from observation of jet formation and further quantified as a variable termed Asymmetry. Asymmetry or lateral shear decreased for increased discharge, higher baffle spacing, and smaller baffle heights. Scaling the asymmetry and comparing the jet flow regimes with peak passage and biological observations yielded a predictive approximation for ideal parameters for culvert retrofitting.

Greater upstream movement of juvenile coho salmon was suggested to require a cue associated with discharges greater than 42 l/s by Pearson et al. (2006). They also speculate that this could actually be related to higher velocities, greater water depths, and distinct lower velocity pathways. In this report we describe that there is a critical combination of velocity, depth and asymmetry for sloped-weir baffled culverts that are observed in the jet regime (J2). The J2 regime was defined by the full submergence of the baffle and the formation of a second jet on the right high side of the baffle. Fish passage observations noted juvenile coho salmon’s reluctance to leap over a plunging flow and preferred baffle crossing locations. These locations corresponded with a critical minimum flow depth over the baffles of 0.06m. The critical depth (H_c) emphasizes the necessity of the baffles slope, which provides an adequate over baffle flow depth for a range of lower discharges. A critical mean depth, associated with (H_c) and peak passage, was plotted on dimensionless stage discharge curves to provide another prediction for greatest fish passage. Dimensionless average and maximum velocity scales, a function of water depth, were developed and also found to be related to a ratio of baffle spacing to baffle height. Velocities were observed to be a barrier to fish passage, but were largely avoided by fish using the lower velocities in the near wall corrugated culvert boundary layer.

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REFERENCES

Bates, K., Barnard R., Heiner B., Klavas P., and Powers P. (2003). Design of Road Culverts for Fish Passage. Washington Department of Fish and Wildlife, Habitat and Lands Program, Environmental Engineering Division. Olympia, Washington.

Bensen, M. A. (1965). “Spurious correlations in hydraulics and hydrology” *Journal of the Hydraulics Division*, July 1965: 91: 35-42.

Chow, V. T. (1959). *Open channel hydraulics*, McGraw Hill, New York.

Clay, C.H. (1961). *Design of fishways and other fish facilities*, The Department of Fisheries of Canada, Ottawa.

Ead, S.A., Rajaratnam, N., and Katopodis, C. (2000). “Turbulent Open-Channel Flow in Circular Corrugated Culverts” *Journal of Hydraulic Engineering*, Oct. 2000: 750-757.

Ead, S.A., Rajaratnam, N., and Katopodis, C. (2002). “Generalized Study of Hydraulics of Culvert Fishways” *Journal of Hydraulic Engineering*, Nov. 2002: 1018-1022.

Ead, S.A., Rajaratnam, N., and Katopodis, C. (2004). “Flow regimes and structure in pool weir fishways” *Journal of Environmental Engineering and Science*, Sep. 2004: 379-390.

Goring, Derek A., and Nikora, Vladimir I. (2002). “Despiking Acoustic Doppler Velocimeter Data” *Journal of Hydraulic Engineering*, Jan. 2002: 117-126.

Gregory, S., Klingeman P., McEnroe J., and Wyrick J. (2004). “Final Report: Fish Passage Through Retrofitted Culverts.” Oregon Department of Transportation, Portland, Oregon.

Guensch, G.R., Richmond, M.C., Tritico, H. and Pearson, W.H. (2004). “Characterization of Turbulent Open Channel Flow in a Full-Scale Spiral Corrugated Culvert” *World Water and Environmental Resources Congress* June 2004.

Kahler, T.H., and Quinn T.P. (1998). Juvenile and Resident Salmonid Movement and Passage through Culverts. Final Research Report for Project T9903, Task 96. Performed for Washington State Transportation Commission by the University of Washington. (http://www.wsdot.wa.gov/Research/Reports/)

Kane, D.L., Belke C.E., Gieck R.E., and McLean R.F. (2000). “Juvenile Fish Passage Through Culverts in Alaska.” INE/WERC 00.05. Water and Environmental Research Center, University of Alaska-Fairbanks. Fairbanks, Alaska.

Katopodis, C. (1992). “Introduction to Fishway Design.” Freshwater Institute, Central and Arctic Region, Dept. of Fisheries and Oceans; R3T 2N6. Winnipeg, Manitoba, Canada.

Liao, J.C., Beal, D.N., Lauder, G.V., and Triantafyllou. (2003). “Fish Exploiting Vorticies Decrease Muscle Activity” Science 302, Nov 2003: 1566–1569.

Mori, N., Suzuki, T., Kakuno, S., (2007). ”Noise of Acoustic Doppler Velocimeter Data in Bubbly Flows” Journal of Engineering Mechanics, Jan. 2007: 122-125.

Morrison, R., Thurman, D., Compton, A., Hotchkiss, R., Horner-Devine, A., (2006). **“**Turbulence Characteristics of Flow in a Culvert with Sloped-weir Baffles” *World Water and Environmental Resources Congress* May 2006.

Pearson, K. (1897). “Mathematical Contributions to the Theory of Evolution-On a Form of Spurious Correlation which may arise when Indices are used to Measurement of Organs. *Proceedings of the Royal Society of London,* 60: 489-498

Pearson, W., Richmond, M., Johnson, G., Sargeant, S., Mueller, R., Cullinan, V., Deng, Z., Dibrani, B., Guensch, G., May, C., O’Rourke, L. Sobocinski, K., and Tritico, H. (2005a). “Protocals for Evaluation of Upstream Passage of Juvenile Salmonids in an Experimental Culvert Test Bed” Final Report, May 2005.

Pearson, W., Richmond, M., Johnson, G., Sargeant, S., Mueller, R., Cullinan, V., Deng, Z., Dibrani, B., Guensch, G., May, C., O’Rourke, L. Sobocinski, K., and Tritico, H. (2005b). “Evaluation of Juvenile Salmon Leaping Ability and Behavior at an Experimental Culvert Test Bed, June 2005.

Pearson, W.H., Southard S.L., May C.W., Skalski J.R., Townsend R.L., Horner-Devine A.R., Thurman D.R., Hotchkiss R.H., Morrison R.R., Richmond M.C., Deng D. (2006). “Research on the Upstream Passage of Juvenile Salmon through Culverts: Retrofit Baffles” Final Report, April 2006.

Powers, P. D. (1997). “Culvert Hydraulics Related to Upstream Juvenile Salmon Passage” Washington Department of Fish and Wildlife, Land and Restoration Services Program.

Rajaratnam, N., Katopodis, C. and Mainali, A. (1988). Plunging flows in pool and weir fishways. ASCE Journal of Hydraulic Engineering 114: 939-944.

Richmond, M.C., Deng, Z., Guensch, G.R., Tritico, H., Pearson, W.H. (2007). Mean Flow and turbulence characteristics of a full-scale spiral corrugated culvert with implications for fish passage. Ecological Engineering 30(4): 333-340.

Smith, D., Brannon, E., and Odeh, M. (2005). "Response of Juvenile Rainbow trout to Turbulence Produced by Prismatoidal Shapes." Trans. Amer. Fish. Soc., 134, 741-753.

Stuart, T.A. (1962). The Leaping Behavior of Salmon and Trout at Falls and Obstructions. *Freshwater and Salmon Research* 28:1-46.

Thompson, T. Testimony, United States House of Representatives: Concerning Fish Passage Barriers and Pacific Salmon. Washington DC, 10 April 2002. http://www.fs.fed.us/congress/2002_testimony/04102002-3.shtml.

WDFW (Washington Department of Fish and Wildlife). (2003). *Design of Road Culverts for Fish Passage* Washington Department of Fish and Wildlife, Habitat and Lands Program, Environmental engineering Division, Olympia, Washington.

Wilder, E., Johnson, G., Barber M. (2006). WSDOT Fish Passage Inventory: Progress Performance Report. Washington State Department of Fish and Wildlife, Habitat and Lands and Technical Applications Division, Olympia Washington.