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JUVENILE SALMON PASSAGE IN SLOPED-BAFFLED CULVERTS

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Abstract: The connectivity of river drainages has been decreased by the installation of roadway culverts, particularly for the salmonids of the Pacific Northwest. Thousands of culverts within the State of Washington have been designated by the state DOT as fish passage barriers. Though it is well known that the anadromous salmon travel upstream to spawn, recent evidence suggests that juvenile salmon also travel upstream to seek preferred habitats for feeding, which may ultimately improve their survival at sea. Retrofitting culverts is an economical solution that has been initially implemented to improve adult salmon passage. Baffles increase water depth for low flow conditions and reduce velocities for higher flowrates. To determine the effect of baffles on upstream passage of juveniles, sloped-baffles were studied at a culvert test bed near Tenino, Washington. Using an Acoustic Doppler Velocimeter (ADV), 3-D velocity fields were collected in a full-sized 12.2 m (40') long, 1.8 m (6') diameter corrugated culvert. The culvert slope, baffle spacing, and baffle height were varied to observe flow regime trends that describe conditions suitable for fish passage. This project is unique from other hydraulic studies in that biological testing was conducted in conjunction with the hydrodynamic measurements. Biologists randomly selected 100 juvenile Coho salmon from the on-site rearing facility and allowed the fish to ascend the culvert during a three hour period. The movement of the fish was recorded with video cameras and the passage rate was determined.

Results indicate that there is considerable spatial variability in the flow created by the baffles within the culvert. The flow is asymmetric, consisting of a jet traveling over the low side of the baffle and an area of re-circulating water on the high side of the baffle. The asymmetry decreases as the discharge increases and the mean water height surpasses the baffle height. The diversity of flow structures created by this asymmetry is important because it increases the number of reduced velocity paths that fish may travel. The fish passage success rates are also consistent with the trends of asymmetry: as the culvert discharge increases fish are limited to fewer possible paths, and passage rates decrease. The results suggest that both the structure of the flow and the average speed of the flow affect the passage rate. We present a scaling equation that relates the occurrence of flow structures to the independent study parameters in order to provide guidance in baffle implementation. Recommendations for future work include further biological interpretation and testing, so that the hydraulic and biological results may be more closely coupled.

Introduction

Within the Pacific Northwest, salmon and other anadromous species play an important historical, cultural, and environmental role. Many of these fish populations are suffering and are now listed under the Endangered Species Act. Stream connectivity is a crucial link in the survival and migration of salmonids. Unfortunately, man-made structures such as culverts may be making this more difficult.

Background

Since 1991, Washington State Department of Transportation (WSDOT) has spent nearly 40 million dollars inventorying stream crossings, conducting habitat studies, and correcting fish passage barriers. There are an estimated 5,853 WSDOT highway crossings. Of the crossings identified as fish bearing, approximately half of those (1,538) are considered fish passage barriers (Wilder *et al.*, 2006). An additional 1,620 culverts have been identified as fish barriers on Washington Bureau of Reclamation and Forest Service lands (Thompson 2002).

Though studies of salmon migration have historically focused on returning spawning adult passage, juvenile salmon are found to travel upstream in search of lower flows, reduced turbidity, preferred water temperature, predator refuge, food, and available habitat (Kahler and Quinn 1998; Kane *et al.*, 2000). The ability for juvenile salmon to access the entire drainage will lead to a stronger and healthier population with a reduced mortality rate. Thereby, juvenile salmon will be better prepared for migration and life in the ocean environment.

Biological Studies

Retrofitting of culverts is not the ideal solution for remedying fish passage barriers, yet is more economical and sometimes the only practical solution (Gregory *et al.* 2004; Clay 1961). Baffles improve the flow within culverts for fish by increasing water depths at low water conditions and reducing velocities at higher flowrates. A number of field studies have been completed throughout the Pacific Northwest. Kane *et al.*, (2000) studied four culverts across Alaska and determined that a food source was motivation enough for some drainages, and juvenile salmon sought out paths that minimized their energy expenditure. Gregory *et al.*, (2004) looked at seven different retrofitted culverts in Oregon and found that baffles allowed fish to maintain their positions within culverts allowing upstream passage. Several studies concluded that juvenile fish take advantage of culvert corrugation roughness and low velocity zones for passage (Kane et al., 2000; Gregory *et al.*, 2004; Pearson *et al.*, 2006). The majority of biological fish studies, however, have been completed in the absence of hydraulic testing and hence direct hydraulic comparison.

Hydraulic Studies

The hydraulics of ribbed roughness or corrugated culverts without baffles have been examined by a number of investigators. Ead *et al.*, (2000) examined the flow regimes in a culvert with corrugations perpendicular to the length of the culvert. They found reduced velocities in the boundary layer and near the surface. Hydraulic measurements have also been collected previously in the spirally corrugated culvert test bed facility used in the present experiments; however, these experiments were without baffles (Richmond 2007; Pearson *et al.*, 2005; Guensch 2004). The results indicated a reduced velocity zone (RVZ) on the right side of the culvert; where, the culverts corrugations slope downstream toward the right side. As we show in the present study, however, this structure does not appear to persist with the addition of baffles.

A series of studies at the University of Alberta in the 1980s and 1990s describe the hydraulics of culvert flow in the presence of different baffle systems. The conclusions from these separate studies are summarized in Ead *et al.*, (2002). They present a discharge scale general to all baffle systems, and show that the dimensionless depth is correlated with this scale for different values of the relative baffle height. Their study does not include sloped baffles such as those considered in the present study, however.

In a separate study, Ead *et al.*, (2004) examined flow regimes, first described by Clay (1961), in a rectangular laboratory flume with baffles and present an expanded description of the transition from plunging to streaming flow. In plunging flow, the cell between subsequent baffles consists of two counter-rotating vertical eddies that are divided by the plunging jet (fig. 1). The upper vertical eddy is a surface roller and the lower vertical eddy is immediately downstream of the baffle (fig. 1a). In streaming flow, on the other hand, a single vertical eddy forms downstream of the baffle that occupies the entire cell. In this case, the water surface is well above the top of the baffle and the flow passes completely above the cell (fig. 1b). There are a number of transitional regimes defined between pure plunging and pure streaming flow. Ead *et al.*, (2004) also describe a third regime, called supercritical jet flow (fig. 1c), in which the plunging flow over the baffle forms a jet along the culvert bottom and a hydraulic jump downstream. They present a regime diagram that describes the transition between these flow states for their rectangular channel.

The regime plot described by Ead *et al.*, (2004) uses a dimensionless discharge Q_{t*} and a ratio of baffle spacing to baffle height to describe the transitions they observed between the different regimes. They concluded that as discharge decreased and/or the ratio of baffle spacing to baffle height increased, regimes transitioned from a streaming flow to a transitional flow before becoming a plunging flow and finally a supercritical jet.

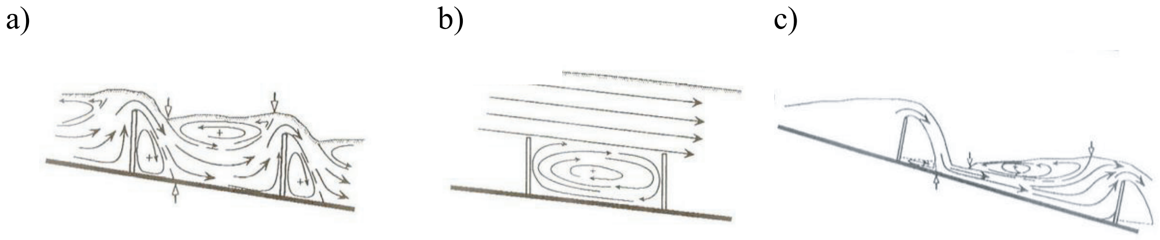


Figure 1. a) Schematics of plunging, b) streaming and c) supercritical jet flow regimes courtesy of Ead *et al.* (2004).

Fish passage in culverts using baffles or weirs has been studied by a number of different groups. However, most of these groups have considered the hydraulics of culvert flow in exclusion of biological testing, or visa-versa. Our study differs from most studies in that biological fish testing was completed in conjunction with the hydraulic testing. The sloped-weir baffles used for our study were found to introduce cross-stream variability and additional flow structures. This observed laterally variability was also created by the spiral culvert corrugations. Scientists and engineers studying fish passage often describe the amount of spatial variability in a flow as the diversity of the stream. The diversity of the flow increases habitat for migration, resting and feeding for fish and other aquatic species (Bates *et el.*, 2003). Baffles increase the flow diversity in culverts by introducing additional flow structures such as eddies, jets, and pools. These structures are important features that break up the symmetry of the flow. By mimicking a river's complex rock and log structures, baffles provide regions for fish to rest and travel. Studies have revealed that fish take advantage of eddies and are able to reduce the amount of energy they expend (Liao 2003).

In the present study we consider the flow in a sloped-baffled culvert to evaluate the structures generated by baffles. The report will also describe flow regimes associated with the variation of hydraulic parameters and their relationship with the biological fish testing results.

Methods

Experimental Setup

Hydraulic testing was performed at the Culvert Test Bed (CTB) at the Washington State Department of Wildlife Skookumchuck Fish Rearing Facility near Tenino, Washington. The CTB consists of a 12.2 m (40') long, 1.8 m (6') in diameter metal spirally corrugated culvert connecting a headwater (HW) and tailwater (TW) tanks. The culvert slope was varied with a pulley system on the tailwater side (fig. 2). Hydraulic parameters varied included three culvert slopes, three baffle heights and range of discharges. Discharge was set using magnetic and propeller flowmeters. Baffles were primarily spaced using a multi-agency recommended spacing of 0.06 m (0.2') drop per baffle as to allow for juvenile salmon passage. Baffles were sloped to the right side of the culvert looking upstream (fish perspective) at a 7.5% slope. A list of experiments and experimental parameters is provided in table 1.

Data Collection/Processing

Experimental data were collected using methodology similar to that used in previous hydraulic testing at the CTB (Pearson *et al.*, 2005). Three-dimensional velocity measurements were acquired using a Sontek micro–acoustic doppler velocimeter (ADV) at a sampling rate of 50 Hz for 120 seconds (6000 data points). The ADV was attached to a gantry system that allowed the device to be lowered and then precisely moved throughout the sampling region via worm gears. Measurements were taken in coarse and fine grid patterns of either 23 or 39 points for 3 to 4 cross-sections spaced between baffles (fig. 3) Velocity data was processed using Matlab coding to filter out data with signal-to-noise ratio (SNR) less than 10 and correlation less than 40%. Further removal of erroneous data was done using a despiking algorithm created by Nobuhito Mori from Osaka City University, Japan (Mori 2007). Spikes occur when acoustic signal return is outside the normal detectable range as resulting from flow aeration, the culvert boundary or other interfering processes. The program incorporates the phase-space thresholding method of Goring and Nikora (2002) and replaces the removed erroneous spikes.

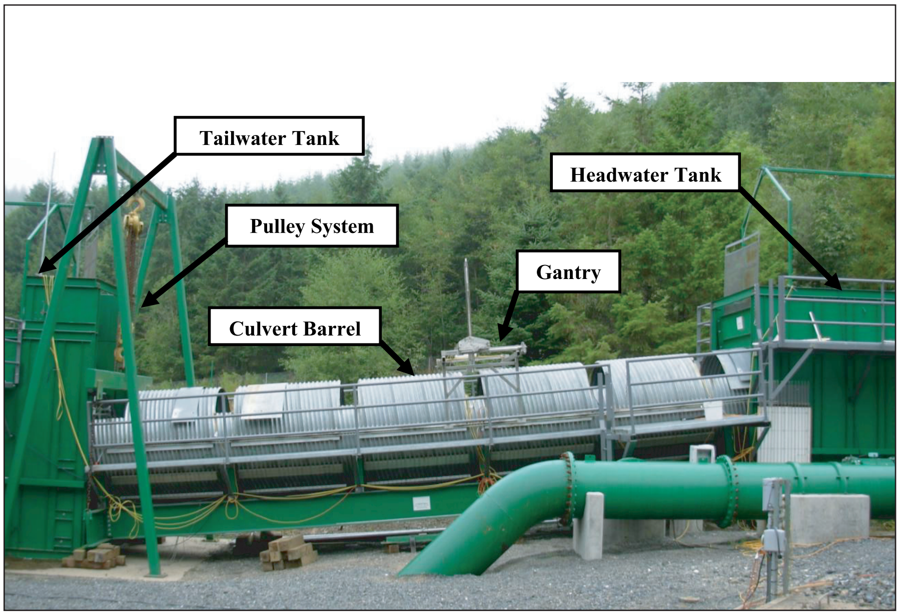


Figure 2. Culvert test bed at skookumchuck fish rearing facility near Tenino, WA.

Table 1: List of Experiments and Parameters Tested

Slope (%)	Discharge ($l/s-ft^3/s$)	Baffle Spacing (m-ft)	Baffle Height (cm-in)
1.14	42, 57, 85, 113, 227 - 1.5, 2.0, 3.0, 4.0, 8.0	4.57 - 15	19 - 7.5
	42, 85 – 1.5, 3.0	4.57 - 15	27, 34 - 10.5, 13.5
	42, 85 – 1.5, 3.0	2.28 - 7.5	19 - 7.5
4.3	42, 85, 113, 170, 227 - 1.5, 3.0, 6.0, 8.0	2.28 - 7.5	19, 27, 34 - 7.5, 10.5, 13.5
	42, 85, 113, 170, 227 - 1.5, 3.0, 6.0, 8.0	1.37 - 4.5	19 - 7.5
	42, 85 – 1.5, 3.0	1.37 - 4.5	34 - 13.5
10.96	227 – 8.0	1.37 - 4.5	19 - 7.5
	42, 85, 113, 170, 227 - 1.5, 3.0, 6.0, 8.0	0.54 - 1.8	19, 27, 34 - 7.5, 10.5, 13.5

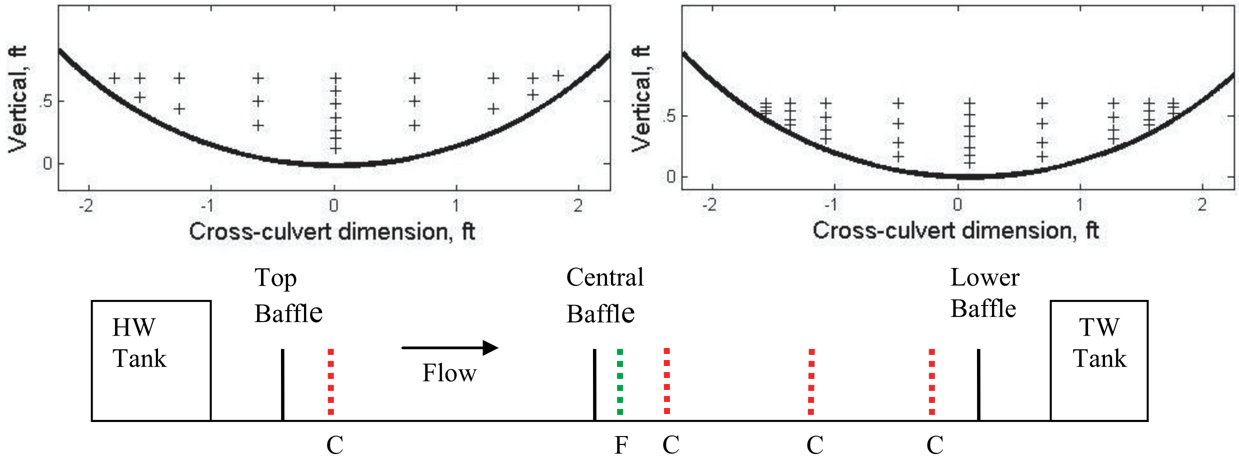


Figure 3. Measurement Grids Coarse (left) Fine (right) locations indicated by (+) signs
Example Measurement Cross-Sections for 4.57 m (15') (bottom).

Results

Sloped-weir baffles principal effect on flow was an observed cross-stream variability, which introduced flow structures that establish a flow asymmetry. Flow structure formation and asymmetry were determined to be a function of head over the baffle. The influence of the baffle's slope was reduced for higher discharges as the level of baffle submergence became a greater fraction of the laterally varying baffle height.

Base Flow

A base case was defined for comparison having a 1.14% culvert slope with baffles spaced 4.57 m (15') apart at 42 l/s (1.5 cfs). Under this combination of parameters five separate structures were identified (fig. 4). A jet over the low side of the baffle was observed to propagate down to the next baffle (fig. 4a). The high side of the baffle exhibited a lateral recirculation (fig. 4b) driven by the jet and contraction of water over the outer edges of the baffle (fig. 4c). The high side of the baffle acted as a weir, causing plunging flow to create a plunge line (fig. 4d) that was accentuated by the contraction. Finally, underneath the plunge and below the baffle a vertical recirculating eddy was formed visible through the aeration of the water (fig. 4e). These visual observations were observed by plotting the average velocity fields.

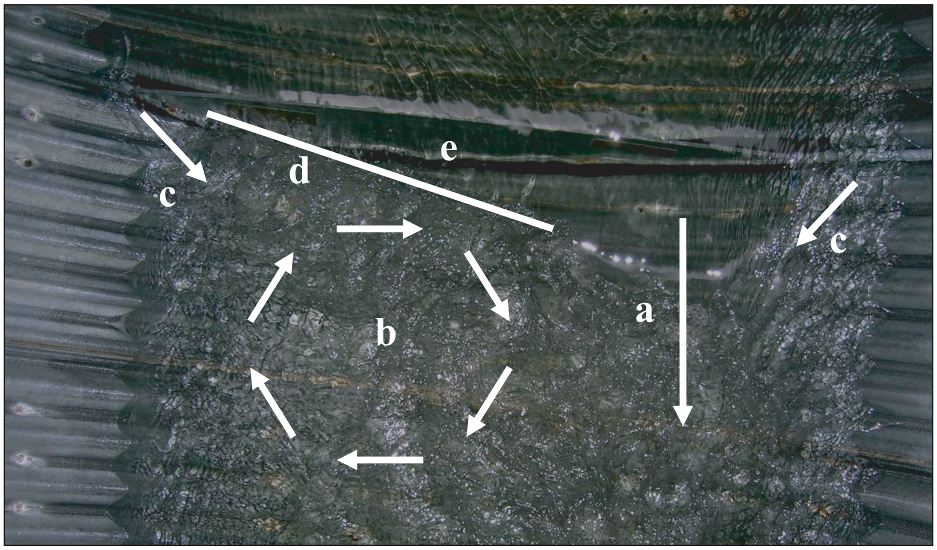
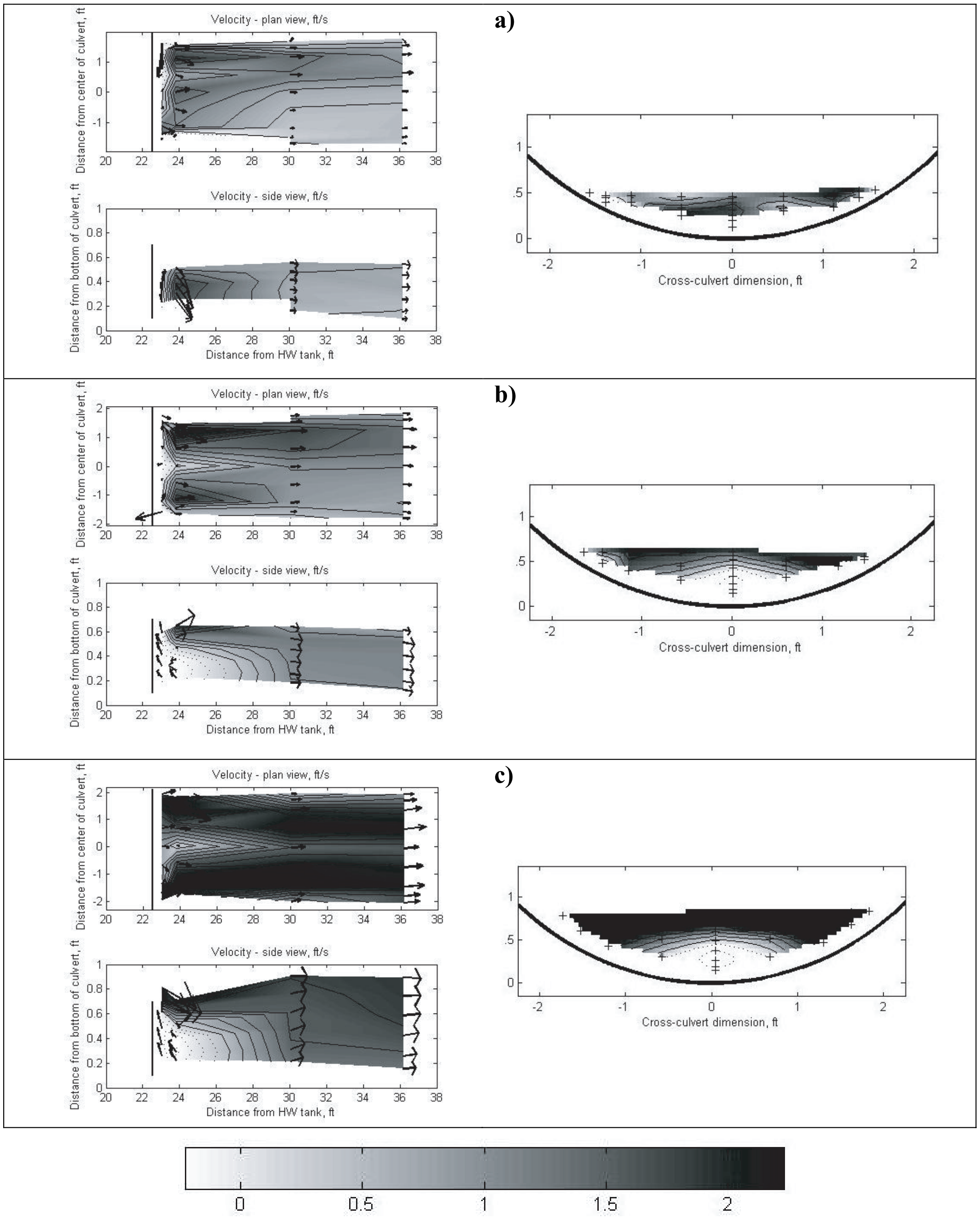


Figure 4. Baseline flow at 42 l/s (1.5 cfs), 1.14% culvert slope, 4.57 m (15') baffle spacing
(a) Dominant Jet (b) Lateral Recirculation (c) Contraction
(d) Plunge line (e) Lateral Recirculation.

Depth Averaged Velocity

The depth averaged velocity is plotted in fig. 5a for the base case experiments. The flow structures described above are apparent in the velocity fields, including the jet over the low side of the baffle, an upstream return flow on the high side of the baffle indicating the across channel lateral recirculation and a strong across channel flow from the right side.

As the discharge was increased to 85 l/s (3.0 cfs) for the same parameters the head over the baffles grew and the baffles had less of an effect on the flow structures (fig. 5b). The dominant jet on the low side of the baffle grew in magnitude, but the lateral recirculation on the high side of the baffle was replaced by an additional jet. These jets were both accentuated by the contraction that occurred over the outer edges of the baffle. The second jet was significantly smaller in magnitude than the dominant jet and was therefore not able to persist to the downstream baffle. The vertical recirculation between the plunging flow and the baffle intensified and extended further down the culvert with the plunge. The effect of the baffle slope on the flow continued to diminish as the discharge was increased to 8.0 cfs (fig. 5c). At this discharge the jets approached similar magnitudes and the flow became more uniform. The formation of a second jet and the jet increasing in magnitude for increased discharge is similarly described by cross-sections of along-culvert velocity (fig 5). The modification of the jet structure and the elongation of the vertical recirculation region occurred consistently with increasing discharge for all parameters considered in the study.



Figures 5. Velocity fields (ft/s) a) 42 l/s (1.5 cfs) b) 85 l/s (3.0 cfs), and c) 227 l/s (8.0 cfs)
Left: (Top panel) Plan view of depth averaged velocity field
(Bottom panel) Side view of the vertical section of centerline along-culvert velocity
Right: Cross-sections along-culvert velocity contour plots.

Jet Regimes

To classify the evolution of jets, flow conditions were characterized into three regimes (fig. 6). In regime J1, a dominate jet forms on the right and water begins to travel over the high side of the baffle into the corrugations and is directed toward the culvert center. The second jet regime J2 formed when the water over the left side of the culvert began to form a jet directed down the culvert. Finally, J3 is observed when the jets on either side of the culvert approach similar magnitudes.

In addition to changing with discharge, cross-stream asymmetry was also influenced by baffle height. Higher baffles have greater lengths in order to span the larger culvert width. Since all baffles were installed with the same slope, larger baffle lengths imply larger height differential from the low-side to the high-side of the baffle; hence, higher baffles require larger discharges to obtain the same level of submergence than smaller baffles. Therefore, asymmetry or lateral shear increases for higher baffles. Higher baffles also produce jets with a greater focus directed along the outer culvert wall. Both the increased asymmetry and jet focus were seen by plotting the depth averaged along culvert velocity for all three baffle sizes (fig. 7).

Average Velocity

Fish passage success is largely dependent on swimming abilities classified into sustained, prolonged or burst speeds. Utilizing these abilities, juvenile salmon must overcome the culvert flows, of which one measure is average culvert velocities. Average velocities were approximated by dividing the discharge by the cross-sectional area of flow. Flow area was geometrically determined using depth of water measurements. Average velocities ranged from about 0.6-1.5 m/s (2-4 ft/s) over the baffle and 0.15- 0.9 m/s (0.5-3 ft/s) just upstream of the baffle. It was observed that baffles acted as elements of roughness reducing velocities for higher baffles. As expected, steeper culvert slopes increase average velocities because velocity is proportional to stream gradient. Though average velocities are an important feature in juvenile salmon's perspective, flow diversity such as lateral shear creates variability that may play an essential role to passage success.

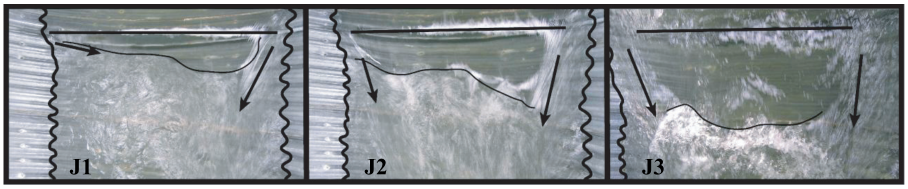


Figure 6. Jet Regimes J1-J3 (left to right), 1.14% culvert slope, 4.57 m (15') baffle spacing
J1 42 l/s (1.5 cfs), **J2** 85 l/s (3.0 cfs), **J3** 227 l/s (8.0 cfs).

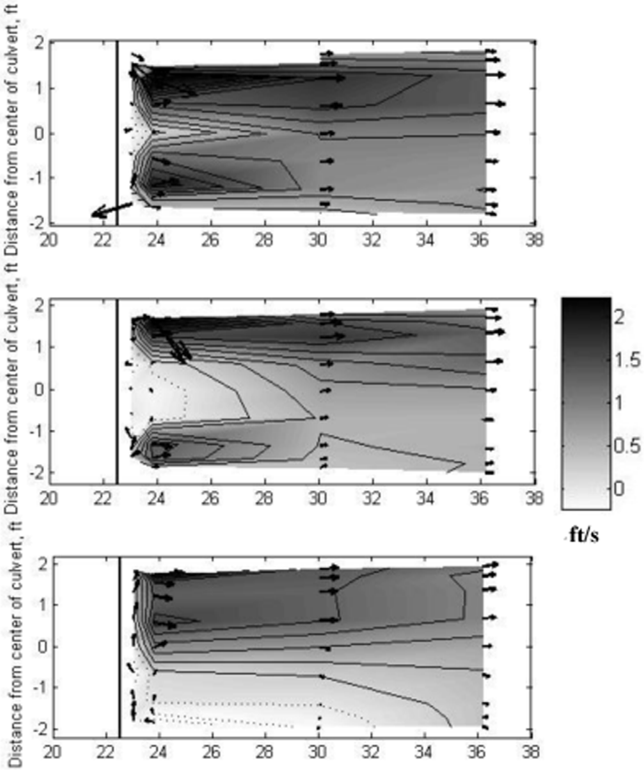


Figure 7. Velocity fields (ft/s) for normal to tallest baffles (top to bottom) at
85 l/s (3.0 cfs), 1.14% culvert slope, 4.57 m (15') baffle spacing.

Lateral Shear

Lateral shear, previously described as observed jet regimes, is a function of baffle submergence that persists downstream. To create an improved comparison of the asymmetry for all flows a standard measure was defined as:

$$LS = 1 - \frac{1}{R_{avg}/L_{avg}} \qquad \text{(Eq. 1)}$$

where R_{avg} is the averaged velocity for flows on the right (fish perspective) side of the culvert and L_{avg} is correspondingly for the left. Lateral Shear (*LS*) was evaluated at the cross-section 0.4 m (2 ft) below the baffle at a location far enough beyond the turbulent plunging and vertical recirculation but close enough to capture jet formation. Shear values greater than 1 correspond with flows forming a clockwise eddy, flow values near 1 are considered highly asymmetric, values nearer 0 are symmetric, and negative values occur when the magnitude of the right jet surpasses that of the left jet. Plotting LS values as a function of discharge confirmed the observed symmetric flows for higher discharges (fig. 8).

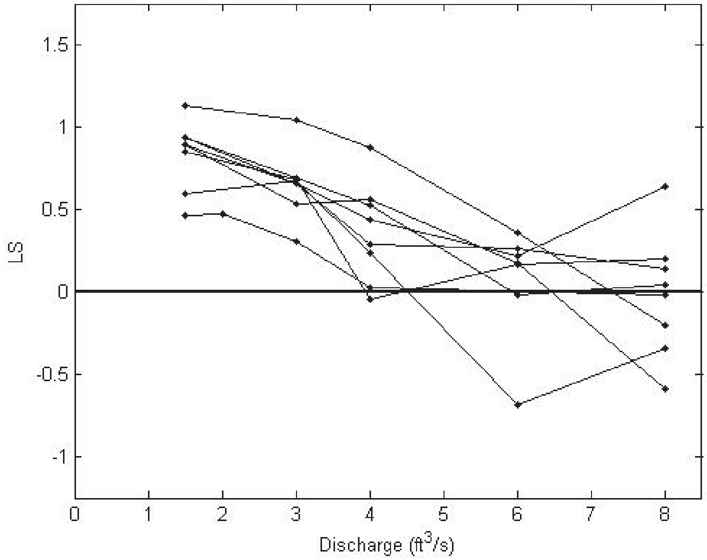


Figure 8. Lateral shear for all experiments.

Flow Scaling

Regimes, as described in the Ead *et al.*, (2004) and fig 1., are qualitatively observed to vary across the width of the baffle. Each regime is primarily a function of head over the baffle as dictated by discharge. Sloped-weir baffles have different levels of submergence and thus multiple regimes. To describe the relationship between the changing flow regimes and the study parameters Ead *et al.*, (2004) derived a regime diagram using a non-dimensional discharge defined as

$$Q_{t*} = \frac{Q}{\sqrt{g b_o S_o L^{1.5}}} \qquad \text{(Eq. 2)}$$

where Q is the discharge, g is gravity, b_o is the baffle width, S_o is the culvert slope, and L is the baffle spacing. They found the regimes to vary with the ratio of baffle spacing (L) to baffle height (P). Plotting our data using this scaling did not result in similar flow regimes because of the occurrence of multiple regimes. When our data are plotted using the Ead *et al.* (2004) scaling, however, we resolve variation in the lateral shear. In fig. 9 all of the experiments are plotted as separate points with darker points representing symmetric flows (*LS* values approaching zero or negative) and lighter points representing asymmetric flows (fig. 9). The scaled plot showed reduced lateral shear for greater discharge and larger lateral shear for higher baffles and smaller baffle spacing.

Separately, definitions of the three jet regimes were used to classify all experiments from photographs and videos. Most regimes were defined as either J1 or J2 regime with very few experiments reaching the J3 regime. From these classifications a unique plot using the same scaling as for the previously described Ead et al., (2004) was made of the three jet regimes. This plot yielded a transitional line between the first J1 regime and the second J2 regime, which is plotted on fig. 9. The transitional line, independently generated, is complimentary to the plot for Lateral Shear Scaling. Thereby, Lateral Shear is strongly associated with these flow structures.

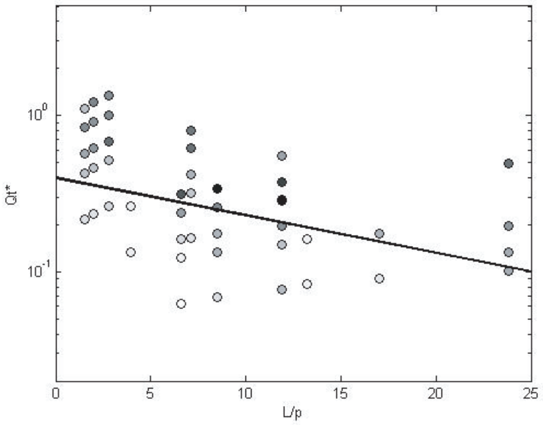


Figure 9. Lateral Shear Scaling, scaling from Ead et al., (2004)
Lateral Shear (LS) Decreases from Lighter to Darker Points
Line Represents Observed Transition between Jet Regime 1 and Jet Regime 2.

Biological Study

Fish testing was completed by Battelle Memorial Institute, Pacific Northwest Division in which their findings were prepared for WSDOT in the April 2006 Final Report. The following methodology and results are described in detail in Pearson *et al.*, (2006) and summarized here for comparison with the hydraulic measurements.

Biological Methods

Biological testing was conducted within the same culvert test bed facility at the 1.14% culvert slope, normal baffles spaced 4.57 m (15') for flows 42 l/s (1.5 cfs) to 340 l/s (12 cfs), identical to those described in the initial case and Fig. 5. Tests were conducted by Pearson *et al.*, (2006) at night for a three hour period with 100 test fish. Juvenile coho salmon (Oncorhynchus kisutch) were used from the WDFW Skookumchuck Rearing Facility and placed within a net pen in the tailwater tank initializing the test. At the conclusion of testing, screens were lowered over the culvert ends to capture and count fish within either the headwater tank, culvert barrel or tailwater tank. A successful passage was defined by a fish entering and/or passing through the culvert in to the headwater tank. Real time observations of fish were captured with low-light high resolution cameras positioned above baffles and submerged at the culvert's entrance and exit.

Biological Results

Fish passage tests were held under three configurations: a standard backwatered condition with and without baffles, or an elevated backwatered condition with baffles. The standard condition had a set backwater elevation as regulated by dam boards in the rear of the tailwater tank. The elevated backwater condition involves setting the level of water on the most downstream baffle to establish an average 0.05 m (0.16') drop over the baffle. Overall, fish passage success resulted in lower fish passage on average 28% passing at 42 l/s (1.5 cfs) that increased significantly at 85 l/s (3.0 cfs) to 53% passing. Passage success declined for increasing discharge with a minimal 6% passage at 340 l/s (12 cfs)(fig. 10). The results of the biological tests also suggest that the same level of passage success may be obtained for less effort with the baffled configuration as compared with the unbaffled configuration. Peak passing at 85 l/s (3.0 cfs) is thought to be explained for larger juvenile salmon by a cue for flows greater than 42 l/s (1.5 cfs) (Pearson *et al.*, 2006).

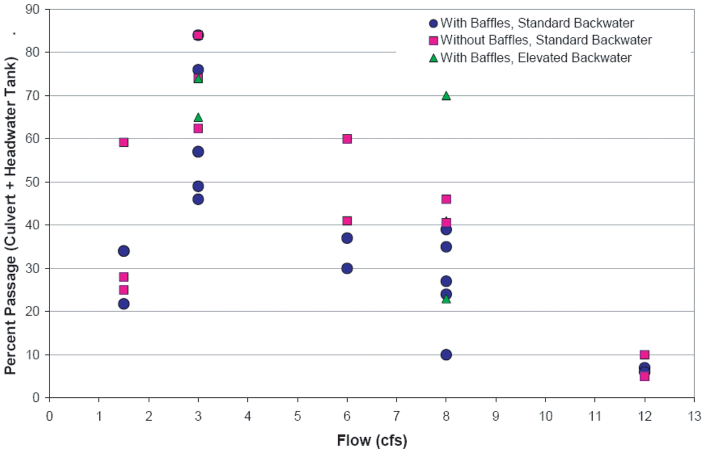


Figure 10. Percentage of fish passage versus discharge courtesy of Pearson et al. (2006).

Observations of fish traveling over baffles were made to determine if baffles hindered fish passage. At 42 l/s (1.5 cfs) fish crossed the baffle near the center using their burst speed, however at 85 l/s (3.0 cfs) fish traveled over the entire baffle width with a generally equal distribution. For discharges greater than 85 l/s (3.0 cfs) the passage success was reduced; fish that typically used the entire culvert barrel to travel up the culvert were driven primarily toward the outer culvert walls. Fish used the corrugated culvert wall (far right or left) for maintaining resting positions, traveling and crossing over the baffles.

Conclusions

Comparing the results from both the hydraulic and biological studies indicate that passage was greatest when flows were between an asymmetric and symmetric condition. At a 1.14% culvert slope, normal height baffles spaced 4.57 m (15'), and a discharge of 85 l/s (3.0 cfs), fish ascended the culvert with greatest success. These parameters corresponds to the formation of the second jet regime (J2); where, the entire baffle becomes submerged and the plunging flow over the high left side of the baffle is replaced by a jet. Thus, the plunging weir flow and vertical recirculation, which potentially combine to hinder fish from approaching or crossing over the baffle, is eliminated under these conditions. Observation of fish crossing over baffles also reveals that submergence under these conditions does not limit where fish pass over the baffle. Maximization of the paths by which fish may cross over the baffle is critical; since, it has been observed that juvenile salmon are reluctant to leap or jump over weirs, but instead swim over or around them (Kane *et al.*, 2000; Pearson *et al.*, 2006). To establish an initial prediction for the ideal passage condition for any set of parameters, the transition into J2 regime was plotted with non-dimensional parameters (Fig. 9). However, the fish passage cue and its association with the second jet regime J2 should be verified with additional biological and hydraulic testing. Lastly, the baffle's slope guarantees that plunging flow will not cover the entire culvert width, thus, potentially limiting passage for lower discharges. Instead the baffle slope is fundamental in creating an adequate flow depth and velocity for fish to cross over the baffle.

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