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Final Report

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April 2006

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Washington State Department of Transportation
WSDOT Agreement No. GCA2677

Battelle Memorial Institute
Pacific Northwest Division

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by

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16. ABSTRACT

This report provides data from biological tests conducted November 2005 through January 2006 by Battelle for the WSDOT at the Culvert Test Bed Facility located at the WDFW Skookumchuck Hatchery near Tenino, Washington. Fish tests evaluated passage success in a 40-ft corrugated culvert without baffles or with three weir baffles at one culvert slope (1.14%) and over five flows (1.5, 3, 6, 8, and 12 cfs). The 3- and 8-cfs flows were tested under an additional backwatering condition. The relationships between natural logarithm of passage success of juvenile coho salmon (94 mm to 104 mm) and culvert discharge were statistically significant and curvilinear for all three configurations. For the configuration without baffles, passage success was about 40% at 1.5 cfs, increased to about 70% at 3 cfs, and then decreased to less than 10% at 12 cfs. The curves for configurations without baffles and with baffles and elevated backwatering condition did not differ significantly. Both these curves were significantly greater than the curve for the configuration with baffles and standard backwatering condition. Backwatering influences passage success through baffled culverts and needs to be considered as an experimental variable in future studies. Behavioral observations indicate the fish used low-velocity pathways and that these pathways differed between the baffled and unbaffled conditions and perhaps differed with flow for the baffled condition.

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Abstract

Washington State Department of Transportation leads a cooperative program to study juvenile salmonid passage through culverts by systematically conducting statistically designed experiments in a full-scale culvert system at the Culvert Test Bed (CTB) at the Washington Department of Fish and Wildlife (WDFW) Skookumchuck Hatchery near Tenino, Washington. The main objective of this part of the program is to determine the upstream passage success of juvenile salmon swimming through a series of standard baffles.

In 2005 and 2006, testing was conducted using the culvert-baffle configuration recommended by WDFW to enhance upstream adult salmonid passage. The primary question to be addressed is what passage success is achieved for juvenile salmon with the WDFW standard baffle. The fish-passage tests evaluated passage success in a 40-ft corrugated culvert with three weir baffles at one culvert slope (1.14%) and over five flows conditions (1.5, 3, 6, 8, and 12 cfs). The 3- and 8-cfs flows were tested under two backwatering conditions; the remainder of the flows were tested under only one backwatering condition.

The relationships between natural logarithm of passage success of juvenile coho salmon (94 mm to 104 mm) and culvert discharge were statistically significant and curvilinear for all three configurations. For the configuration without baffles, passage success was about 40% at 1.5 cfs, increased to about 70% at 3 cfs, and then decreased to less than 10% at 12 cfs. The curves for configurations without baffles and with baffles and elevated backwatering condition did not differ significantly. Both these curves were significantly greater than the curve for the configuration with baffles and standard backwatering condition.

Backwatering influences passage success through baffled culverts and will need to be considered as an experimental variable in future tests. Differences between our results and other previous results indicate that fish size has substantial influence on passage success and that these tests will need to be repeated for smaller juveniles. The lower passage success at 1.5 cfs relative to the higher flows both with and without baffles indicates that the lower passage success at 1.5 cfs is not a function of baffling conditions, i.e., baffles or no baffles, but rather is due to some aspect of culvert discharge. More exploratory behavior was observed at 1.5 cfs than at higher flows. The observations also suggest that consistent upstream movement may require a cue that is associated with higher flows. The nature of the cue is not known but could be related to higher velocities, greater depth, or more distinct low-velocity pathways. Behaviors associated with successful upstream passage were more complex with baffles than without baffles. A significant quadratic relationship between the probability of passage success and the number of entries was found for all configurations at flows above 1.5 cfs. These relationships suggest that fish may be achieving the same level of passage success for less effort in the baffled configuration.

The behavioral observations indicate that the fish use low-velocity pathways to accomplish passage and that these pathways differ between the baffled and unbaffled conditions and perhaps differ with flow for the baffled condition. The fish appear to be able to find and use low-velocity pathways to accomplish the passage in several different settings.

Executive Summary

Road culverts located on federal, state, and private lands currently block upstream passage of juvenile salmon to thousands of miles of suitable juvenile rearing habitat. Washington State Department of Transportation (WSDOT), in cooperation with partner agencies, currently leads a cooperative program to study juvenile salmonid passage through culverts by systematically conducting experiments in a full-scale culvert system at the Culvert Test Bed (CTB) at the Washington Department of Fish and Wildlife (WDFW) Skookumchuck Hatchery near Tenino, Washington.

The overall goal of the CTB program is to identify culvert configurations and the associated hydraulic conditions that facilitate successful upstream passage of juvenile salmonids. Previous studies have used juvenile coho salmon to examine the factors influencing passage success and leaping ability. This study begins research focused on retrofitted culverts. A retrofitted culvert is one in which the bed characteristics of an existing culvert are modified or engineered to improve fish passage. The main objectives of this study are to determine the passage success of juvenile salmon swimming through a culvert configured with WDFW weir baffles and to relate fish passage success to culvert slope, water flow, water velocity, turbulence intensity, water depth, and other hydraulic parameters for the installed retrofit design.

In 2005 and 2006, the initial phase of culvert retrofit testing was conducted using the WDFW recommended culvert-baffle configuration designed to enhance upstream adult salmonid passage. This report summarizes the results of this initial round of retrofit testing with respect to fish behavior. The University of Washington (UW) has also completed a companion report on the hydraulics of the baffled culvert configuration (Thurman and Horner-Devine 2006). Additional culvert-retrofit hydraulic measurements concerning turbulence are underway at Washington State University (WSU).

The primary question in this initial culvert retrofit-testing phase of the CTB program is what passage success is achieved for juvenile salmon with the WDFW weir baffle over a set of slopes and flows. The fish passage tests described in this report evaluated fish passage success in a culvert with three weir baffles at one culvert slope (1.14%), over five flows (1.5, 3, 6, 8, and 12 cfs). The 3 and 8 cfs flows were tested under two backwatering conditions; the remainder of the flows were tested under only one backwatering condition.

The statistical study design of the retrofit evaluations entailed paired comparisons of two culvert bed configurations observed with replication over a series of flows, i.e., 1.5, 3, 6, 8, and 12 cfs. This design proved effective in determining that the relationships between natural logarithm of passage success of juvenile coho salmon (94 to104 mm) and culvert discharge were statistically significant and curvilinear for all three configurations examined. For the configuration without baffles, passage success was about 40% at 1.5 cfs, increased to about 70% at 3 cfs, and then decreased to less than 10% at 12 cfs. We have no observations beyond 12 cfs; however, the equation for configuration without baffles suggests that the passage success would be expected to fall below 1% at 14 cfs. There was no significant lack of fit of these statistical models, and the lack of interactions demonstrates that the curves for the three configurations are parallel. The curves for configurations without baffles and with baffles and elevated backwatering condition do not differ significantly. Both these curves are significantly greater than the curve for the configuration with baffles and standard backwatering condition. Because these findings indicate that degree of backwatering influences passage success through baffled culverts, we recommend that backwatering be considered as an experimental variable in future studies.

Comparison of these results with previous results for the unbaffled configuration (Pearson et al. 2005) indicates that fish size, or perhaps season, influences passage success. We recommend that the study

design used here be repeated with small juvenile coho in the spring to determine whether the patterns of success versus culvert discharge are similar for small coho salmon.

Behavioral patterns with and without baffles at 1.5 cfs differed from those at higher flows. The fish at 1.5 cfs exhibited more exploratory behavior. The observations suggest that consistent upstream movement by larger juvenile coho in this setting may require a cue that is associated with flows greater than 1.5 cfs. The nature of the cue is not known but could be related to higher velocities, greater depth, or more distinct low velocity pathways.

At flows above 1.5 cfs, statistical analysis found a significant quadratic relationship between the probability of passage success and the number of entries for all configurations. This relationship for the baffled configurations proved to be significantly different from that for the unbaffled, standard backwatering configuration. The findings suggest that fish may be achieving the same level of passage success for less effort in the baffled configuration than the unbaffled configuration. Also, these findings further support our recommendation for repeating the study design with smaller coho salmon, for which the baffled condition can be hypothesized to offer more benefit than the unbaffled condition.

The behavioral observations indicate that the fish used low velocity pathways to accomplish passage and that these pathways differed between the baffled and unbaffled condition and perhaps differed with flow for the baffled condition. Without baffles, fish moved, held position, and swam predominantly on the right side of the culvert looking upstream. Pearson et al. (2005) observed this same behavioral pattern in which smaller coho used the reduced velocity zone to move upstream and exit the culvert. With baffles, the behavior and hydraulics were more complex. As culvert discharge increased, the fish shifted the locations where they crossed baffles, held position, and swam to accomplish passage to the locations in the culvert with the lowest velocities. Further understanding of the relationship between hydraulics and behavior requires hydraulics measurements at all the discharges at which biological test are conducted. We recommend that additional hydraulics measurements be undertaken to provide data at all test discharges for which we do not have hydraulics measurements.

Overall, the results obtained thus far in the culvert test bed system demonstrate that the juvenile coho salmon have remarkable abilities to adapt their behavior to accomplish upstream passage in different system configurations and under different flows. The fish appear able to find and use low velocity pathways to accomplish upstream passage.

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Acronyms

ADV	Acoustic Doppler Velocimeter
ANODEV	analysis of deviance
ANOVA	analysis of variance
BKD	bacterial kidney disease
cfs	cubic feet per second
CTB	culvert test bed
EDF	energy dissipation factor
GLM	generalized linear models
h/D	height-to-culvert-diameter ratio
LOF	lack of fit
LWD	large woody debris
PNW	Pacific Northwest
TAG	Technical Advisory Group
UW	University of Washington
WDFW	Washington Department of Fish and Wildlife
WSDOT	Washington State Department of Transportation
WSU	Washington State University

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1.0 Introduction

Road culverts located on federal, state, and private lands currently block upstream passage of juvenile salmon to thousands of miles of suitable juvenile rearing habitat. Therefore, optimal upstream passage conditions in culverts for juvenile salmon must be determined. Washington State Department of Transportation (WSDOT), in cooperation with partner state and federal agencies, as well as private partners, is currently leading a cooperative program to study juvenile salmonid passage through road culverts and to evaluate innovative culvert designs to improve the success of upstream passage by juvenile salmonids. Much of this research is being carried out at the Culvert Test Bed (CTB) at the Washington Department of Fish and Wildlife (WDFW) Skookumchuck Hatchery near Tenino, Washington (Figure 1).

Between 2003 and 2004, testing conducted at the CTB focused on hydraulic measurements and behavioral observations of juvenile fish in a series of tests leading to standard CTB testing protocols for use in future CTB testing (Pearson et al. 2005a). In 2004 and 2005, studies on the leaping ability of juvenile salmon as a function of culvert perch height were conducted (Pearson et al. 2005b).

One key area of interest involves determining appropriate hydraulic and fish-passage designs for retrofitted culverts. A retrofitted culvert is one in which the bed characteristics of an existing culvert are modified or engineered to improve fish passage. Research on adult salmonid passage through retrofitted culverts has been conducted, but the optimal retrofit conditions for culvert passage by juvenile salmonids are not well understood.

To successfully negotiate a culvert, a fish must be able to enter the culvert, traverse the length of the barrel, exit the culvert, and proceed to an upstream resting area. Based on a review of current scientific literature, little is known about the capability of juvenile salmonids to access upstream habitat by overcoming barriers. The WDFW *Design of Road Culverts for Fish Passage* manual (WDFW 1999) currently has a recommended design for baffles developed to provide for improved adult salmon passage (Figure 2). Retrofitted culverts designed by this method provide passage for adult fish, but passage success for juvenile fish is largely unknown. It is thought, that at low flow when the baffles are operating as weirs, if the hydraulic drop (i.e., distance from water surface above the baffle to that below the baffle) is relatively small and the downstream baffle-pool volume is adequate, these retrofitted culverts are passable to juvenile fish. At higher flows, it is thought that there may be pathways created by baffle hydraulics that also support upstream juvenile-fish movement. These are the areas of uncertainty that the research described here is beginning to address.

The overall goal of the CTB program is to identify culvert configurations and the associated hydraulic conditions that facilitate successful upstream passage of juvenile salmonids. The objectives of the initial culvert retrofit-testing phase of the CTB program are as follows:

- Determine the passage success of juvenile salmon swimming through a series of configurations of WDFW standard baffles under different culvert slopes and water flow conditions.
- Relate fish-passage success to culvert slope, water flow, water velocity, turbulence intensity, water depth, and other hydraulic parameters for the installed retrofit design.
- Make recommendations for future culvert retrofit designs based on CTB test results.

Figure 1. Culvert Test Bed Facility

Figure 2. Washington Department of Fish and Wildlife Culvert-Retrofit Baffle Installation

In 2005 and 2006, the initial phase of culvert retrofit testing was conducted. This research used the WDFW-recommended culvert-baffle configuration designed to enhance upstream adult salmonid passage (WDFW 1999). This report summarizes the results of this initial round of retrofit testing with respect to fish behavior. The University of Washington (UW) has also completed a companion report on the hydraulics of the baffled culvert configuration (Thurman and Horner-Devine 2006). Additional culvert-retrofit hydraulic measurements are underway at Washington State University (WSU), focusing on turbulence.

The primary question addressed in this initial culvert retrofit-testing phase of the CTB program is what passage success is achieved for juvenile salmon with the WDFW standard baffle over a set of slopes and flows. Secondary questions are what changes in spacing, baffle height, or baffle angle enhance juvenile salmon-passage success. The fish-passage tests described in this report evaluated fish-passage success in a culvert with three weir baffles at one culvert slope (1.14%), over five flows (1.5, 3, 6, 8, and 12 cubic feet per second [cfs]). The 3- and 8-cfs flows were tested under two backwatering conditions; the remainder of the flows were tested under only one backwatering condition. Here we report that juvenile fish of 94 mm to 104 mm standard length showed a curvilinear responses to flow, starting with 1.5 cfs, peaking above 3 cfs, and then falling to minimal passage at 12 cfs. The same curvilinear pattern was observed both with and without baffles.

2.0 Background

2.1 Culvert Fish Passage

In fish-bearing watersheds, passage barriers can pose a significant obstacle to migration into preferred seasonal habitat areas. A barrier to fish passage is defined as any physical instream feature that causes excessive delay in migration or abnormal expenditure of energy during any life-stage movements (Evans and Johnston 1980). A culvert could be a *complete barrier* to all species of fish, adult and juvenile, under all flow conditions; a *partial barrier* to adult or juvenile fish; and/or a *temporal barrier* to adult or juvenile fish under specific flow conditions (WDFW 1999). The most common manmade fish-passage barriers found in the Pacific Northwest (PNW) are road culverts.

WDFW has estimated that over 2000 culverts in Washington State were significant barriers to salmonids and that over 3000 miles of habitat have been lost as a result of these problem culverts. During the ongoing WSDOT road-culvert inspection program, 4590 crossings have been inventoried, with 2533 evaluated as fish bearing. Approximately 44% of the surveyed WSDOT road crossings have been identified as fish-passage barriers (WDFW 2004). Restoring access to functioning habitat upstream of culverts is a high priority for WSDOT and WDFW.

Culverts are a rigid boundary set into a dynamic stream environment. Even under normal conditions, the presence of a culvert can create some inherent fish-passage problems. Culverts provide a conveyance pathway for water, bed-load sediment, and large woody debris (LWD) under a roadbed while providing for fish passage. If designed and installed properly, a culvert can perform both purposes concurrently under a range of flow conditions. However, culverts are usually uniform and efficient to optimize water passage; they often do not have the roughness and variability of stream channels and, therefore, do not dissipate energy as readily (WDFW 1999). Fish passage through culverts includes upstream migration of anadromous and resident adult fish during the spawning season, as well as upstream movement of juveniles or resident adults at various times of the year (Kahler and Quinn 1998).

The most common conditions that can create a migration barrier at a culvert include the following (Dane 1978, Normann et al. 1985, Bell 1986, Baker and Votapka 1990, Behlke et al. 1991, Powers 1996, Allen and Pyles 1999, WDFW 1999, Klingeman 2000):

- Excessive drop at culvert outlet (so-called “perched” culvert)
- High water velocity in the culvert (beyond the swimming capability of fish)
- Excessive culvert inlet or outlet flow velocity preventing fish from entering or exiting the culvert
- Culvert inlet channel constriction, resulting in a “hydraulic jump” at the upstream end of the culvert

- Turbulent flow conditions within the culvert
- Inadequate water depth within culvert barrel
- A lack of hydraulic roughness within the culvert
- Debris accumulation and blockage at the culvert inlet or within the culvert
- Misaligned culvert with respect to the natural stream channel
- Culvert that is too long (beyond the endurance of fish)
- A culvert installed at too steep a gradient (beyond the capability of fish).

Excessive water velocity is a common factor common to many of the culvert-passage barrier conditions listed above. In general, water velocity within a culvert is a function of the cross-sectional area, slope, and roughness of the culvert, as well as stream discharge. Culvert roughness is the most readily manipulated factor that influences velocity. Over the years, a variety of methods for increasing culvert roughness have been investigated, including baffles, corrugations, and the placement of bed-load material. Each of these methods has the common objective of producing a region (boundary layer) of lower flow velocity within the culvert that fish are able to use while the velocity in the remainder of the culvert exceeds their swimming ability (WDFW 1999).

2.2 Culvert Baffles

Total replacement of inadequate road crossings with a bridge or stream-simulated culvert is the most desirable solution but not always financially or logistically possible. There may be some circumstances in which baffles are the only practical and cost-effective option for mitigating fish-passage impacts (Watts 1974, Clay 1995). Retrofitting culverts with baffles and flow deflectors to make internal hydraulics more conducive to fish movement may be a less expensive and less labor-intensive alternative. Although these retrofits are not long-term solutions, they potentially allow fish passage until it is financially and logistically possible to replace the existing culvert. In addition, baffles may be suitable for remedying existing culvert barriers where replacement of the culvert is not feasible because of physical constraints, such as very long culverts with excessive road fill, or where fish usage does not justify the expense of a full culvert replacement (Gregory et al. 2004).

In general, baffles are hydraulic obstructions installed at regular intervals within a culvert to increase roughness, reduce velocity, and create hydraulic conditions suitable for fish passage over a range of flow conditions (Katopodis et al. 1981, Katopodis 1991, Clay 1995). As baffles act in concert to increase the hydraulic roughness of the culvert, they reduce the average cross-section velocity. Weirs, on the other hand, act as individual hydraulic control structures. The flow over a series of baffles at high flow is a streaming pattern; for weirs, it is a plunging pattern. To create streaming flow, the baffles have to be relatively close together and short compared with the flow depth. Typical baffles act as weirs at low flows and transition to roughness elements as the flow increases (WDFW 1999).

Based on current guidance (WDFW 1999), the installation of baffles within a culvert is not the preferred method to meet velocity criteria and is not appropriate for new culvert installations. There are several inherent problems with baffles. Sets of baffles create an artificial environment that requires fish to repeatedly use burst-speed swimming behavior to traverse the baffles. Baffles also tend to reduce the culvert conveyance capacity and can require frequent maintenance (Gregory et al. 2004). Many culverts currently being addressed for hindering fish passage were designed only for hydraulic capacity. Adding baffles reduces hydraulic capacity and often becomes a limit to flood capacity. The tendency of baffles to catch LWD and other debris exacerbates the culvert-capacity problem and creates an added possibility of a fish barrier, as well as culvert plugging and road fill failure. Because of the requirement for maintenance access, baffles should not be installed in culverts with less than 5 ft of headroom (WDFW 1999). Baffled culverts are generally limited to slopes less than or equal to 3.5% slope. This slope is based on direct observation of existing baffle systems; improved baffle systems may change this limit (WDFW 1999).

The need for frequent inspection and maintenance of baffled culverts is widely recognized, but few maintenance programs establish the protocol or budget for adequate maintenance. Passage for many salmonid species is most critical in freshets during the winter months, which also coincides with the time of greatest risk of flooding and presence of debris. Maintenance is usually impossible during high-flow fish-passage seasons, so passage is lost for at least part of a season when culverts fail or are obstructed. Since the baffles and the potential barriers are out of sight, they often go unaddressed. Finally, the added roughness raises the hydraulic profile through the culvert and is, therefore, more difficult to match to the profile of the downstream channel (WDFW 1999).

Various culvert shapes have been equipped with baffles, including box, circular, and elliptical culverts (Watts 1974). Baffles can be constructed of steel, concrete, or other rigid materials. The baffles shown in Figure 3 are typical of those currently in use. Boulders held in place by steel reinforcement bars can also be used as baffles. The slotted-weir baffle is sometimes used, because it provides larger and more consistent resting spots for fish and promotes the maintenance of a low-flow channel through the culvert (Williamson and Nilson 2001).

Numerous laboratory experiments have been conducted on culverts fitted with baffles (Rajaratnam et al. 1988, Rajaratnam et al. 1989, Rajaratnam et al. 1990, Rajaratnam and Katopodis 1990). Baffles change the velocity distribution across the culvert and along the culvert from one set of baffles to the next (Katopodis 1991). The maximum velocity occurs near the water surface, at the furthest point from the culvert lining, directly above each set of baffles. This point varies slightly depending on the shape of the baffles. Lower velocities occur between baffles, especially near the invert and along the culvert walls (Rajaratnam et al. 1991). Studies of various combinations of baffle geometries, heights, spacings, slopes, and flows in models of round culverts are reported in Rajaratnam and Katopodis (1990) and Rajaratnam et al. (1989). Hydraulic model studies for weir baffles in square box culverts were studied by Shoemaker (1956).

Powers (1996) observed in an experimental culvert that juvenile salmon used a low-velocity zone near the culvert wall to accomplish upstream passage and called for more studies of turbulence as a factor in passage success. Pearson et al. (2005a) found that hydraulic conditions near the boundary layer of corrugated culverts may be important, because turbulent velocity bursts could exceed the swimming ability of fish. Research has been conducted on turbulent open-channel flow through corrugated culverts (Ead et al. 2000), and rough-bottom open-channel flow using an Acoustic Doppler Velocimeter (ADV) or other measurement devices (Song and Chiew 2001, Balachandar and Patel 2005, Stone 2005, Tritico and Hotchkiss 2005), but little information exists in the literature regarding the measurement of turbulence parameters in a culvert fitted with baffles (Morrison 2005).

From a hydraulic perspective, the best performance from a baffle system appears to occur when the baffle height-to-culvert-diameter ratio (h/D) is between 0.1 and 0.15, and the spacing between the baffles is less than the culvert diameter (Ead et al. 2002). Because of their simplicity and effectiveness, the weir and slotted-weir baffle systems appear to be the best choices for producing flows through culverts that are most likely to pass fish (Ead et al. 2002). The offset baffle arrangement has also proven to be effective in improving adult fish passage in culverts (Clay 1995).

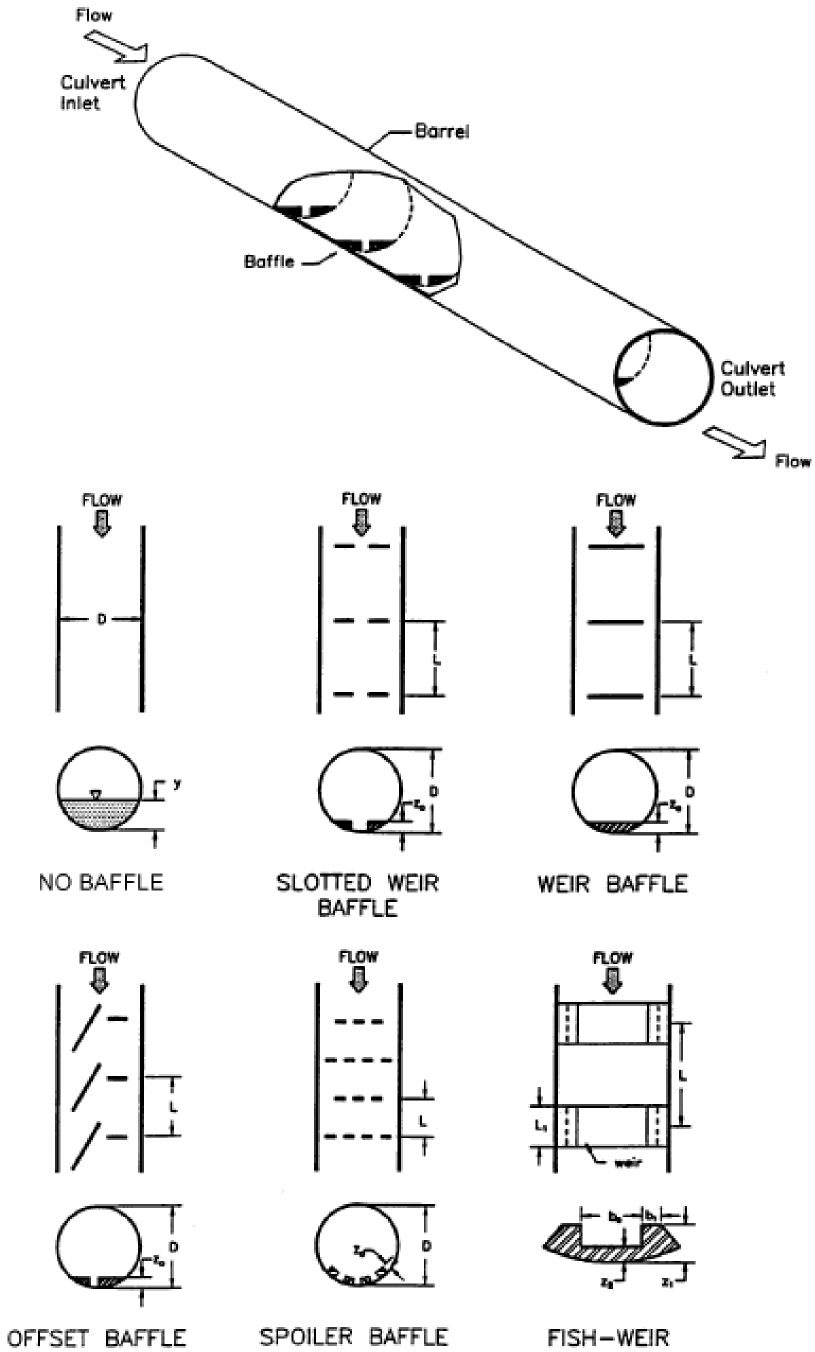

Figure 3. Culvert Baffle Configurations (Adapted from Rajaratnam and Katopodis 1990)

Hydraulic characteristics of baffled culverts have been related to laboratory determinations of swimming speeds and endurance capabilities of the fish species of concern for design purposes (McKinley and Webb 1956, Shoemaker 1956, Katopodis 1981, Rajaratnam and Katopodis 1990). However, there is little information on whether fish can move through these culverts outside of a laboratory and which baffle design is the most efficient at passing fish.

There have been few studies of juvenile fish passage through culverts outside of the laboratory setting. However, the effects of baffles on fish migration were observed in a field study in Alaska, where a baffled culvert placed at a 10% grade was used to examine the swimming ability of resident adult and juvenile coho salmon, Dolly Varden, and cutthroat trout (Bryant 1981). Offset baffles were used in a 36-in. diameter and 30-ft long culvert, and the flow ranged from 0.3 cfs to 0.68 cfs. The baffles were installed at 2-ft intervals throughout the length of the culvert. Below 0.2 cfs, the flow in the culvert was too low for fish passage, and at a discharge greater than 0.65 cfs, no fish moved up the culvert (Bryant 1981).

In a study by Kane et al. (2000), minnow traps were baited with salmon eggs to assess juvenile salmonid movement through four different culverts in Alaska. Only one culvert had baffles. Researchers found that all age classes of juvenile coho salmon successfully passed upstream through a 90-m (295-ft) culvert with 13 baffles and velocities of up to 1.52 m/s (5 ft/s). This study concluded that food (salmon eggs) was sufficient incentive for upstream juvenile movement in Alaskan streams (Kane et al. 2000). This study also tracked the path of juvenile movement through the baffled culvert with underwater video cameras. They concluded that juvenile fish did not leap over the baffles but swam through a slot between the culvert wall and the end of the baffle. They concluded that slots may be an acceptable technique for improving juvenile fish passage in culverts with baffles. In each case, this study (Kane et al.2000) concluded that juvenile fish look for the paths that minimize energy expenditure. This finding is consistent with another study in Washington, where it was observed that juvenile salmon swimming upstream in culverts use the low-velocity zones located close to the culvert wall (Barber and Downs 1996, Powers 1996). Apparently, roughness of the corrugated culvert wall provides a low-velocity boundary zone where passage for these small fish is possible (Pearson et al. 2005a, Morrison and Hotchkiss 2006).

Gregory et al. (2004) performed an in-depth study on the effects of baffles on fish passage through culverts. In the study, three baffle types were used: 90^0-baffle weirs, 30^0-angled baffles, and 45^0-angled baffles. Seven culvert sites were selected for the study. During the testing, fish were released at the outlet of a culvert for 3 h, after which drop screens were released to separate the culvert into sections. The fish were then collected and counted, and the locations of the fish within the culvert were noted. Results from this study showed that all designs resulted in a lower maximum, minimum, and average velocities compared with the culvert not fitted with baffles, and weir-type baffles exhibited the best fish-passage conditions (Gregory et al. 2004). These baffles created areas of low velocity behind the weirs that fell within the range of swimming capabilities of most salmonids, but much higher velocities existed across the top of the weirs. The velocities at the weir crests were comparable to the average velocities in the culvert without weirs, and were approximately twice as high as the velocities in the sections between weirs (Gregory et al. 2004).

2.3 Culvert-Baffle Hydraulics

Baffles are added to culverts as roughness elements to reduce the water velocity in a culvert to a level acceptable for fish passage. Baffles must satisfy two hydraulic criteria at all flows up to the fish-passage design flow. The velocity created by them must comply with WAC 220-110-070, and the turbulence must not be so much that it creates a barrier to passage (WDFW 1999). In general, the hydraulic characteristics of interest with respect to baffled culverts include velocity around the baffles, turbulence analyses for fish passage, and hydraulic capacity with baffles installed (WDFW 1999).

The velocity of flow associated with various combinations of baffle geometries, heights, spacing, slope, and flow in culvert baffle systems has generally been derived from hydraulic laboratory work with round culverts (Rajaratnam et al. 1989, Rajaratnam and Katopodis 1990, Ead et al. 2002). Hydraulic model studies for weir baffles in square box culverts were studied by Shoemaker (1956). These models can be used for both the fish-passage-velocity and culvert-capacity analyses. Flow equations were developed by Rajaratnam and Katopodis (1990) for all the styles tested.

To maintain a desired velocity within the baffled culvert, energy must be dissipated. Energy of falling water is dissipated by turbulence. Turbulence in the culvert is defined by the energy dissipation per unit volume of water and is referred to as the energy dissipation factor (EDF). Few research data are available to determine the appropriate maximum EDF for fish passage. However, based on field experience, it is recommended that the EDF be kept below a threshold of 3.0 foot-pounds per cubic foot per second (ft-lb/ft^3/sec) for passage of adult salmon and below 2.25 ft-lb/ft^3/sec for adult trout (WDFW 1999). The EDF is calculated using the following equation (WDFW 1999):

$$(EDF = wQS/A)$$

where

EDF = the energy dissipation factor in ft-lb/ft/sec

w = the unit weight of water (62.4 pounds per cubic foot)

Q = the flow in cubic feet per second

S = the dimensionless slope of the culvert (ft/ft), and

A = the cross sectional flow area at that flow between baffles in square feet.

3.0 Methods

3.1 Mobilization and Protocol Development

Preparation for testing of the CTB retrofit baffle configuration began in July 2005 with the acquisition of a set of baffles that would fit inside the 6-ft diameter culvert and additional video cameras and lighting equipment to support fish-behavior observations. The video and lighting systems were installed inside the culvert and connected to power sources and recording devices located inside a portable trailer. In addition, standard operating procedures were developed for installing, adjusting, and removing baffles. Following recent modifications of the hatchery water system that serves the CTB and hatchery fish rearing ponds, revised water-flow management procedures were also developed.

3.2 Baffle Installation

The WDFW provided the 2-piece retrofit baffles (Figure). Fish-passage tests were conducted only under a “standard baffle configuration,” with three sloped baffles spaced approximately 15 ft apart within the 40-ft-long culvert with 1.14% slope (Figure and Figure). Spacing was determined roughly using the recommendation of 0.2-ft drop/culvert slope, though the actual drop per baffle varied depending on the flow and backwatering condition. The spacing was slightly less than calculated to allow for placement of three baffles inside the culvert, rather than only two. The slope of the baffles was held constant at 7.5%, with the lower side on the right (facing upstream). Determination of final baffle spacing and position, as well as backwater conditions, were developed in consultation with the CTB Technical Advisory Group

(TAG), consisting of representatives from WDFW, WSDOT, UW, WSU, and Battelle Pacific Northwest Division.

Terminology used during fish-passage tests differs somewhat from that used in hydraulic testing (Figure 6). For fish testing, the culvert was described from the perspective of a fish moving upstream. For example, the culvert entrance is the downstream end at the junction between the tailwater tank and culvert, where fish first enter the culvert. The first baffle (B1) is the baffle furthest downstream, and is the baffle that fish encounter first when swimming up the culvert. B2 is the middle baffle, and B3 is the upstream baffle. The culvert exit is upstream, at the junction of the culvert and the headwater tank.

In addition to this standard baffle configuration, several additional configurations involving baffle spacing and baffle height were tested by the hydraulics measurement team, with members from the UW and WSU (Thurman and Horner-Devine 2006). To determine the effects of increased baffle spacing, a configuration of 5 baffles with a spacing of approximately 7.5 ft was tested. Finally, the baffle heights were increased twice by attaching two different extensions that bolted onto the original baffles. The extensions were kept at the same slope as the original baffles (7.5%) and increased the baffle heights by approximately 0.25 ft and 0.5 ft. Results of this hydraulic testing can be found in the UW report (Thurman and Horner-Devine 2006).

Figure 4. Two-Piece Baffles

Figure 5. Standard Baffle Configuration

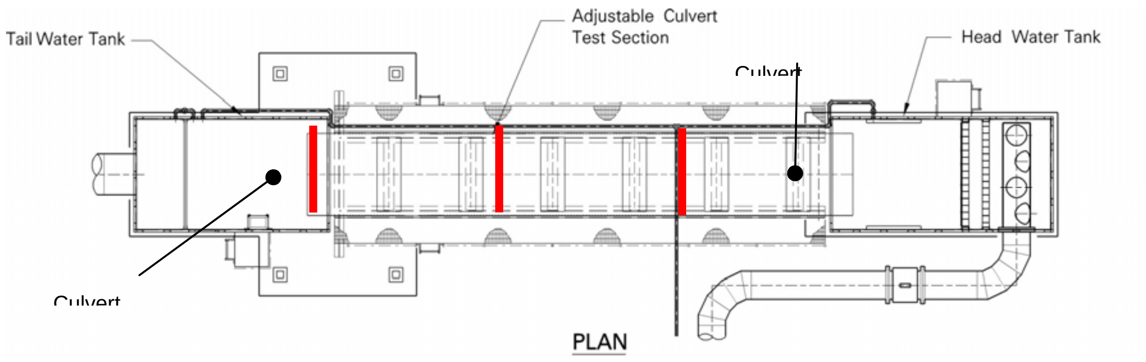

Figure 6. Schematic of the Culvert Test Bed, Indicating Placement of Baffles 1, 2, and 3

3.3 Hydraulic Tests

Hydraulic testing conducted during August and September 2005 is provided in the companion UW report (Thurman and Horner-Devine 2006). Excerpts and summaries from Thurman and Horner-Devine (2006) are included in this fish-passage report to provide context for the results and conclusions of fish-passage tests. Hydraulic data were collected using methods similar to those used in previous testing (Pearson et al. 2005a). Differences for this period of testing included the use of both a downward-looking and side-looking Sontek micro-ADV at a sampling rate of 50 Hz for 120 sec (6000 data points) at each location in the measurement grid (Figure and 8). Also, a Nortek Vectrino ADV was used for a short period to collect longer data sets and was mounted on a 4-by-4 piece of lumber with c-clamps. The Vectrino ADV collected data at a sampling rate of 200 Hz for 30-min periods (360,000 data points) per location to help resolve periodicity of vortices created within the flow field. The gantry extension arm was also used to gather data at locations between the access hatches that were not previously sampled.

Hydraulic testing was to be performed concurrently with fish-passage testing, but problems with fish availability precluded this approach. Hydraulic testing took place in advance of the fish-passage testing, and as such, it was not possible to match exactly the fish-passage test flows with the hydraulic test flows. No hydraulic testing was performed with an elevated backwater condition (see Section 3.4.2). Fish-passage tests with and without baffles were performed at 1.5, 3.0, 6.0, 8.0, and 12.0 cfs. Hydraulic testing with baffles (Thurman and Horner-Devine 2006) and without baffles (Pearson et al. 2005a) was matched to some of the fish-passage tests, including 1.5, 3.0, and 8.0 cfs. Hydraulic tests performed with and without baffles at 8.0 cfs provide insight for the fish-passage test conducted at 6.0 and 12.0 cfs. Hydraulic testing in 2003 without baffles was also performed at 16.0 cfs.

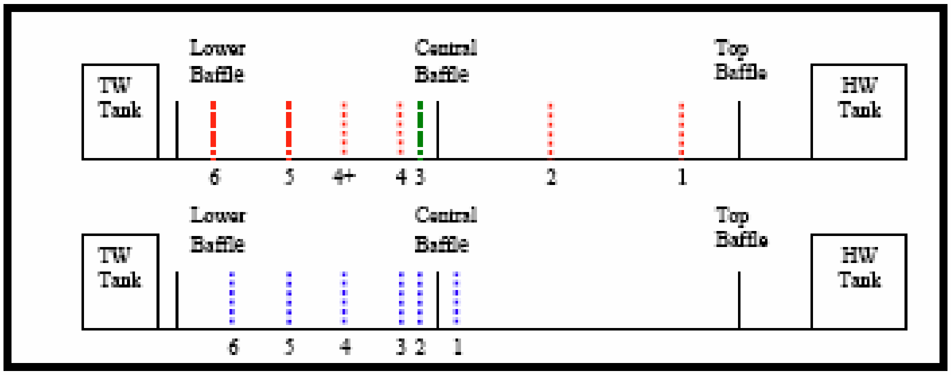

Figure 7. Hydraulic Measurement Locations. Water flows from right to left. Solid lines are baffles; dotted green line = fine grid; dotted red lines = coarse grid; dotted blue lines = super-fine grid.

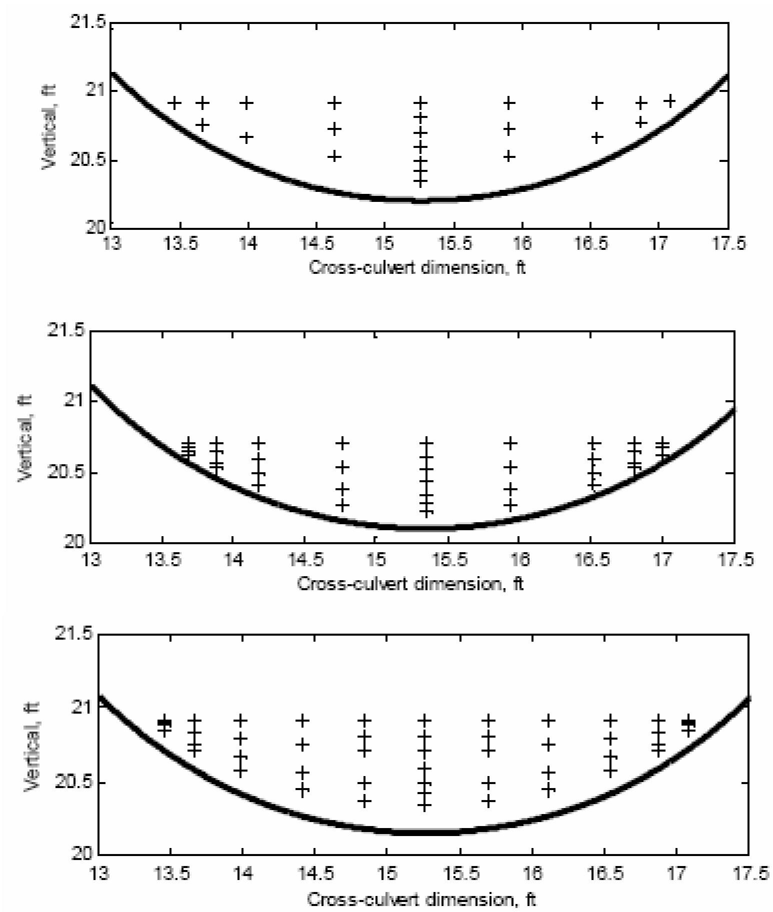

Figure 8. Hydraulic Measurement Grids (relative locations): Coarse (upper panel), Fine (middle panel), and Super Fine (lower panel)

3.4 Fish-Passage Tests

3.4.1 Fish Source

Juvenile coho salmon (*Oncorhynchus kisutch*) used for testing were obtained from the WDFW Skookumchuck Hatchery. The fish remained under the care of WDFW personnel at all times. These juvenile coho salmon were assumed to represent typical juvenile salmonid species swimming capabilities and behaviors.

In July 2005, the hatchery population experienced an outbreak of coldwater disease and underwent two weeks of treatment. During this period, approximately 250,000 fish were lost. Preliminary fish testing began August 9, 2005 to determine whether the test fish had recovered from the disease outbreak. A total of six tests were conducted. Based on comparison with previous testing of similar-size fish, the fish-passage results were below expectations. It was determined that a flare-up of bacterial kidney disease (BKD) was affecting activity levels and perhaps the physical ability to move upstream under test conditions. Tests were halted and not resumed until it was certain that the remaining hatchery population was in good health. To track changes in fish condition, the wet weights and fork lengths of 100 individual fish were measured five times between August 16, 2005 and January 7, 2006. A pathologist with WDFW declared the Skookumchuck hatchery fish in good health and BKD at a low prevalence on October 28, 2005. Fish-passage testing restarted on November 14, 2005.

3.4.2 Test Conditions

Test conditions for the fish-passage tests are summarized as follows:

<u>Culvert and Baffles</u>

Type:	Round, corrugated steel culvert (40-ft long, 6-ft diameter, with 3-in wide by 1-in deep spiral corrugations
Slope:	1.1% slope
Baffle Design:	WDFW-designed retrofit weir baffles
Baffle Height:	9-in height to 6-in height (7.5% slope, with lowest part on the right, facing upstream)
Baffle Spacing:	Located at 2.1 ft, 17.4 ft, and 32.3 ft from the culvert entrance (i.e., distances are downstream to upstream)
Water Flows:	1.5, 3.0, 6.0, 8.0, 12.0 cfs
Pool depth:	False floor adjusted in the tailwater tank to achieve the shallowest depth possible (approximately 15- to 23.5-in. water depth, measured from the water surface of the pool to the false floor, depending on the water flow and backwatering condition)
Backwatering:	Standard and elevated
	<u>Standard</u>: The standard condition used the same number of stop logs downstream of the tailwater pool regardless of water flow. Flows of 1.5, 3.0, 6.0, 8.0, and 12.0 cfs were tested with and without baffles under the standard backwater condition.

The stop-log height was set prior to testing such that the tailwater pool backed up to plunge over the most downstream baffle at 1.5 to 3.0 cfs. The objective was for the plunging conditions to be similar for all three baffles. All hydraulic tests were performed subsequently under the standard backwater condition. This condition was determined after consultation with the TAG.

Elevated: The elevated backwater condition involved increasing or decreasing the number of stop logs behind the tailwater pool for individual baffled-flow conditions, as if the backwater were designed and set for each flow. The guidance involved setting a standard center drop of approximately 2 in. from the upstream side of each baffle to the downstream side of each baffle, including the first baffle (B1) near the culvert entrance. Paired tests at the standard and elevated backwater conditions were conducted for flows of 3.0 and 8.0 cfs. Elevated backwater conditions were also based on TAG recommendations.

Tests

Time of Day: At night, after full dark

Test Duration: 3 hr

Number of Tests: Two paired tests per night (either with baffles and without baffles, or with baffles only, but with standard backwater and elevated backwater). Tests were repeated the following night, with order reversed, before moving to a new set of test conditions.

Test Fish: Juvenile coho salmon from the Skookumchuck Hatchery, Washington

Fish Size: Juveniles, with a mean size ranging from 94 mm to 104 mm over the test period (from weekly averages)

Fish Numbers: 100 fish per test (the range in density in the tailwater tank at the start of the test was 0.6 to 1.0 fish per cubic foot, depending on the water flow and backwater condition).

3.4.3 Fish Handling

For a given test, fish were handled in a sequence of events that started when the test fish were obtained from a rearing pond and ended after the test, when they were deposited in a holding raceway. Fish were not fed between the time of collection and testing. Immediately before testing, the test fish were counted by two people and carried from the holding tank to the tailwater tank. When the water was flowing at the prescribed flow and all other test conditions were properly set, the fish were released into the tailwater tank net pen, starting the 3-h test period.

At the conclusion of the 3-hr test period, the end screens at the headwater and tailwater tanks were lowered at the same time to isolate the fish in one of three areas: tailwater tank, culvert barrel, or headwater tank. Water flow was turned off, and fish were retrieved from each area and counted. Fish from each of the three sections were anesthetized, measured (fork length), and examined for general condition. When greater than 20 fish were recaptured from a single section, only 20 randomly chosen fish were measured. After all test fish were accounted for, they were returned to the holding raceway, isolated from the main hatchery population so they would not be tested again. The primary biological data were the counts of test fish in the three areas at the end of each test: the tailwater tank, the culvert, and the headwater tank.

3.4.4 Real-Time Observations

Portions of the culvert test system could be observed real-time during testing with the aid of high-resolution, low-light-capable video cameras and associated lighting and recording equipment. For these baffle retrofit tests, two underwater cameras were placed near the culvert entrance (in the tailwater tank) to view fish entering the culvert from both sides. One underwater camera was placed at the culvert exit (in the headwater tank) to view fish exiting the culvert. Four additional overhead cameras were positioned inside the culvert above the culvert entrance and first baffle (B1), above the second baffle (B2), between the second and third baffle (B/T), and above the third baffle (B3). All cameras were monochrome CCD type 1/2- and 1/3-in. images. Above-water and underwater infrared illuminators (880 nm) were used in conjunction with each camera. This wavelength is beyond the spectral visual range of juvenile salmonids (Bowmaker and Kunz 1987, Lythgoe 1988). The cameras were connected to two digital video recorders that displayed real-time images from all seven cameras on two monitors while storing the multiplexed images to their hard drives. The video-recording systems were housed in an onsite work trailer.

For the duration of each test, two researchers observed the video images in real time. The researchers recorded information on the number of fish observed entering the culvert from the tailwater tank in 10-min increments, and also recorded the time and location of interesting baffle passage or swimming behaviors that were observed. Although it was not physically possible for the observers to note all significant events in real time, these observations comprised a qualitative dataset that was applied in interpreting the quantitative passage-success data. Additional comments were added as specific behaviors or behavioral changes were observed. The observational records will facilitate future scrutiny of video recordings of events of interest.

3.4.5 Fish-Passage Success Metrics and Statistical Study Design

The 34 culvert passage trials conducted in 2005 to 2006 were analyzed using generalized linear models (GLM) based on a binomial error structure and log-link function (Aitkin et al. 1989). This link function describes the probability of culvert passage as follows:

$$p_i = e^{\underset{\sim}{\beta}'\underset{\sim}{x}}$$

where

p_i = probability of culvert passage for the *i*th trial

$\underset{\sim}{\beta}$ = vector of regression coefficient

$\underset{\sim}{x}$ = vector of covariates.

In this analysis, passage success was defined as

$$p_i = \frac{C_i + HW_i}{C_i + HW_i + TW_i}$$

where

C_i = number of fish present in the culvert at end of the ith trial

HW_i = number of fish in the headwater above the culvert at the end of the ith trial

TW_i = number of fish in the tailwater below the culvert at the end of the *i*th trial.

In other words, passage success was defined as the fraction of fish that enter and/or passed through the culvert into the headwater.

Three culvert configurations were evaluated: standard backwatering condition with and without baffles and elevated backwatering condition with baffles.

For each culvert configuration, between 2 and 5 flow velocities were examined (i.e., 1.5, 3, 6, 8, and 12 cfs). The GLM analysis was used to model the flow-passage relationship and to assess whether that relationship was dependent on culvert configuration.

The effects of culvert configuration and flow velocity were assessed using analysis of deviance (ANODEV) based on a binomial error structure and log-link. A degree-of-freedom table for the ANODEV is depicted in Table 1 below.

The ANODEV was used to test the significance of flow, squared flow, and configuration. Within-treatment replicates also allowed partitioning the error term into lack-of-fit (LOF) and pure error components to ensure model fit. Choice of error term in testing the significance of flow and configuration depended on whether LOF was significantly different from pure error. In this analysis, there was no difference, and the overall pooled error term with 29 degrees of freedom could be used.

Table 1. Degrees-of-Freedom for the ANODEV

Source	DF	DEV	MDEV	*F*
$\text{Total}_{\text{Cor}}$	33			
Flow	1	FDEV	MFDEV	$F_{1,29} = \frac{\text{MFDEV}}{\text{MEDEV}}$
Flow^2	1	FSQDEV	MFSQDEV	$F_{1,29} = \frac{\text{MFSQDEV}}{\text{MEDEV}}$
Configurations	2	CDEV	MCDEV	$F_{2,29} = \frac{\text{MCDEV}}{\text{MEDEV}}$
Error	29	ERDEV	MEDEV	
Lack-of-Fit	7	LOFDEV	MLOFDEV	$F_{7,22} = \frac{\text{MLOFDEV}}{\text{MPEDEV}}$
Pure Error	22	PEDEV	MPEDEV	

3.5 Culvert Slope Change

An increase in culvert slope was scheduled following the conclusion of the fish-passage testing. This task involved several steps, including

- loosening crossbolts on the headwater and tailwater tanks
- loosening stop-adjustment bolts on the tailwater tank
- removing bolts joining the tailwater plates
- removing cribbing supporting the culvert under the tailwater section
- replacing and tightening the stop-adjustment bolts and then crossbolts
- testing the system for leaks.

Changing the culvert slope was accomplished in February 2006.

4.0 Results

4.1 Hydraulic Tests[2]

4.1.1 Measurements at the Culvert Test Bed, 2005

The UW and WSU hydraulics team studied the hydraulic characteristics of the baffled test culvert. An asymmetry in the culvert flow is the most apparent effect of the sloped weir baffles. The effect of the asymmetry was reduced as flows increased. A jet on the low side of the baffle, a plunge line, and a recirculation area characterized flow over the baffles (Figure). The well-defined plunge line and recirculation disappeared as the flow rate increased. Recirculation between the baffle and the plunging flow was present for all flow rates.

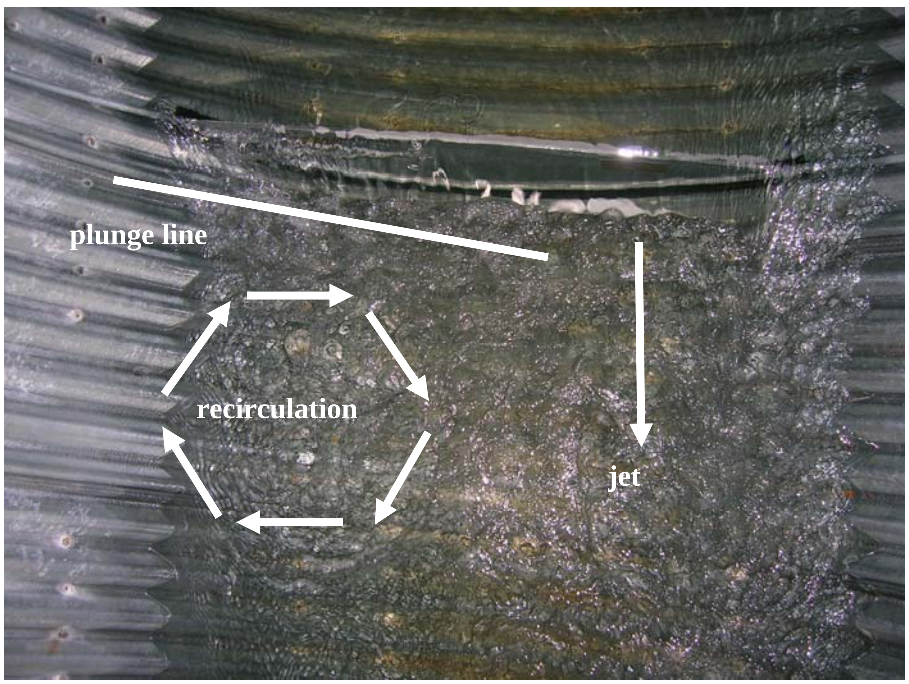

Figure 9. General Flow Pattern Formed at Each Baffle, Using a WDFW Weir Retrofit Baffle (Thurman and Horner-Devine 2006)

The flow structures through the main cell below B2 were mapped in detail by plotting the depth-averaged velocity along the culvert length, and the culvert centerline velocity for flow-rates 1.5, 3.0, and 8.0 cfs (Figure through 12). The plot for 1.5 cfs (Figure) showed a strong cross-channel flow close to the baffle from the right side of the culvert. Downstream, a jet with higher velocity traveled down the right side of the culvert (looking upstream). Upstream velocity on the left side of the culvert indicated a region of recirculation, which was consistent with the qualitative observations. Recirculation between the baffle and the plunging flow impinging on the bottom of the culvert was also visible.

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[2] These hydraulic results are summaries and excerpts from the companion report by Thurman and Horner-Devine (2006). Please see the full report for more detail.

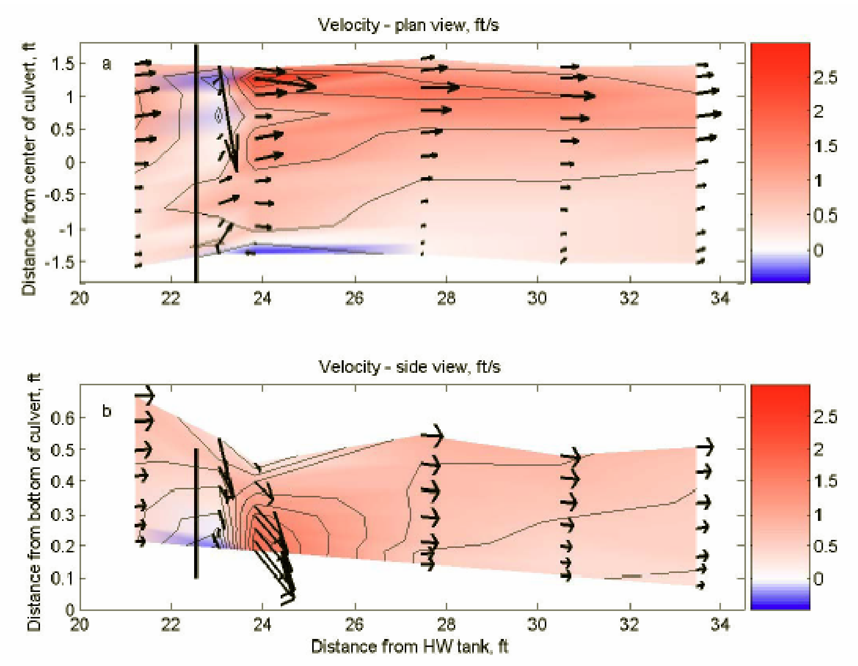


Figure 10. Velocity Fields for 1.5 cfs. Top panel: plan view of depth averaged velocity field; bottom panel: side view of the vertical section of along-culvert velocity on the centerline (Thurman and Horner-Devine 2006).

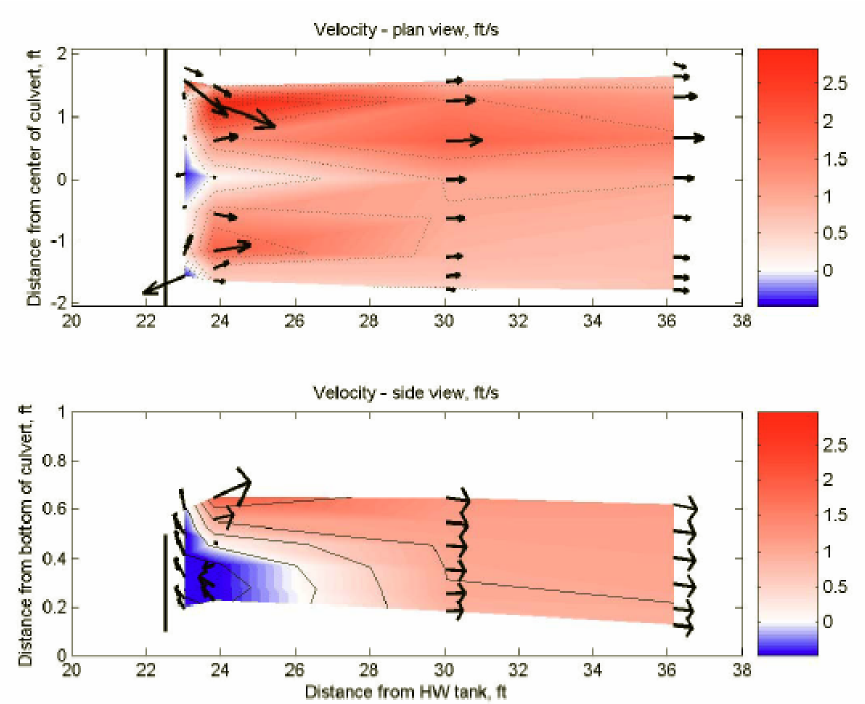


Figure 11. Velocity Field for 3.0 cfs. Top panel: plan view of depth averaged velocity field; bottom panel: side view of the vertical section of along-culvert velocity on the centerline (Thurman and Horner-Devine 2006).

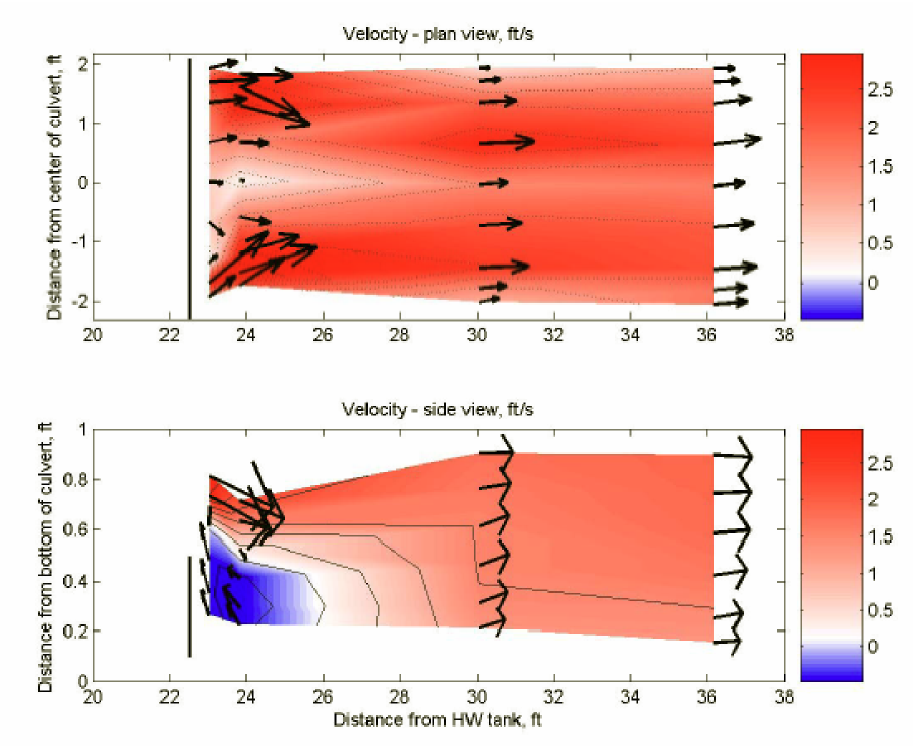


Figure 12. Velocity Field for 8.0 cfs. Top panel: plan view of depth averaged velocity field; bottom panel: side view of the vertical section of along-culvert velocity on the centerline (Thurman and Horner-Devine 2006).

The water elevation above the baffles increased when the discharge was increased from 1.5 cfs to 3.0 cfs, causing the cross-culvert slope to have less of an effect on the flow characteristics. A second jet formed on the left side of the culvert and was directed toward the center of the culvert and then consumed by the jet on the right side (Figure). The recirculation zone between the baffle and the plunging flow intensified and extended further down the culvert with increasing flow rate. Finally, at 8.0 cfs, the intensity of the left and right side jets was roughly equal, and the flow downstream was more uniform across the culvert (Figure).

Figure shows the cross sections for along-culvert velocity and centerline profiles recorded at Grid Location 4. The plots verify the formation of the two jets, and show the development of the vertical recirculation zone directly below the baffle.

4.2 Fish-passage tests

4.2.1 Fish Lengths

By the week of testing, the mean salmon fork length ranged from 93.8 mm in November 2005, to 104.3 mm in January 2006 (Figure). There was not a significant difference in fish length over the test period.

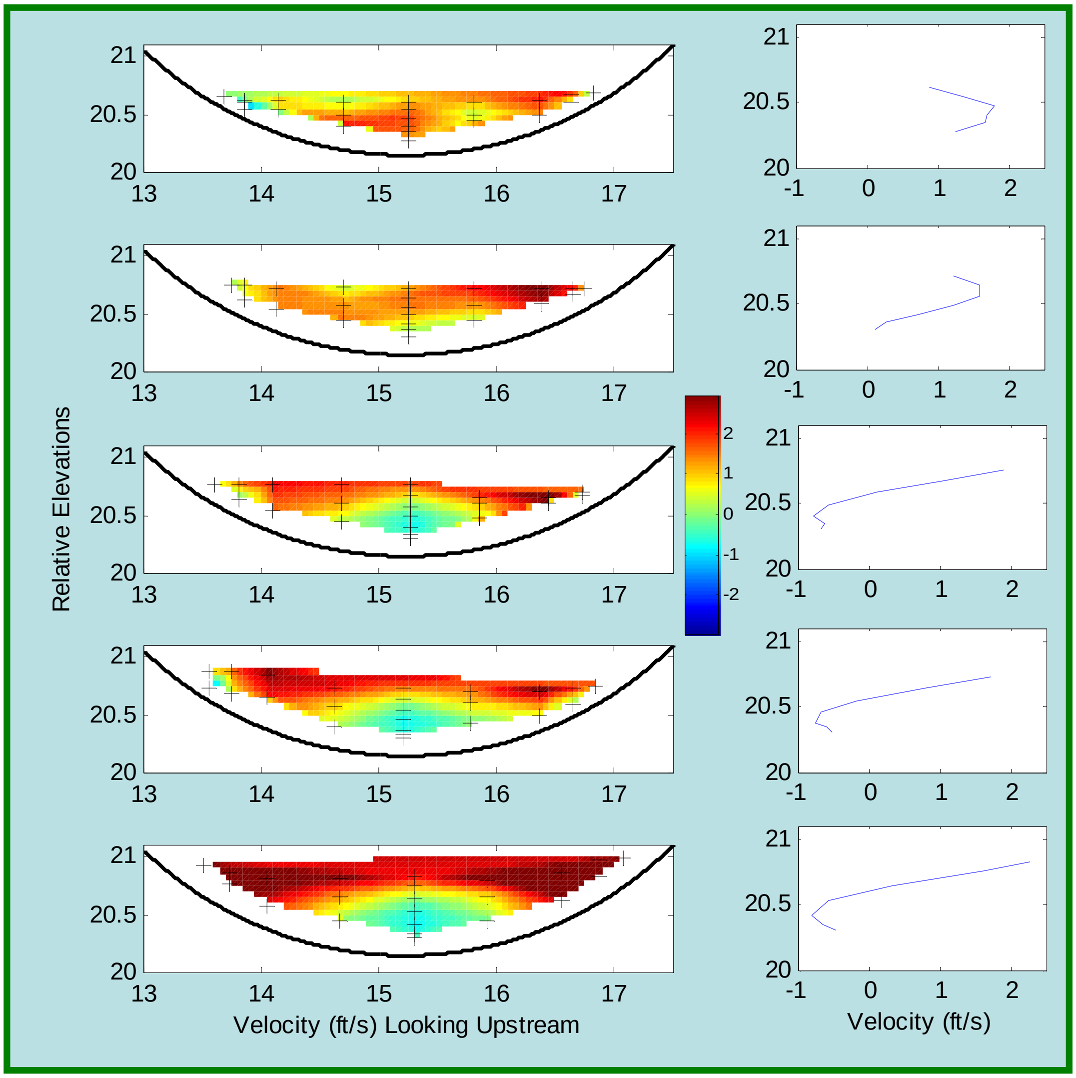


Figure 13. Cross Sections Along-Culvert Velocity Contour Plots (ft/s) (left), and Centerline Velocity Profiles (ft/s) at Location 4 for the Flow Rates of 1.5, 2.0, 3.0, 4.0, and 8.0 cfs (descending) (right) (Thurman and Horner-Devine 2006)

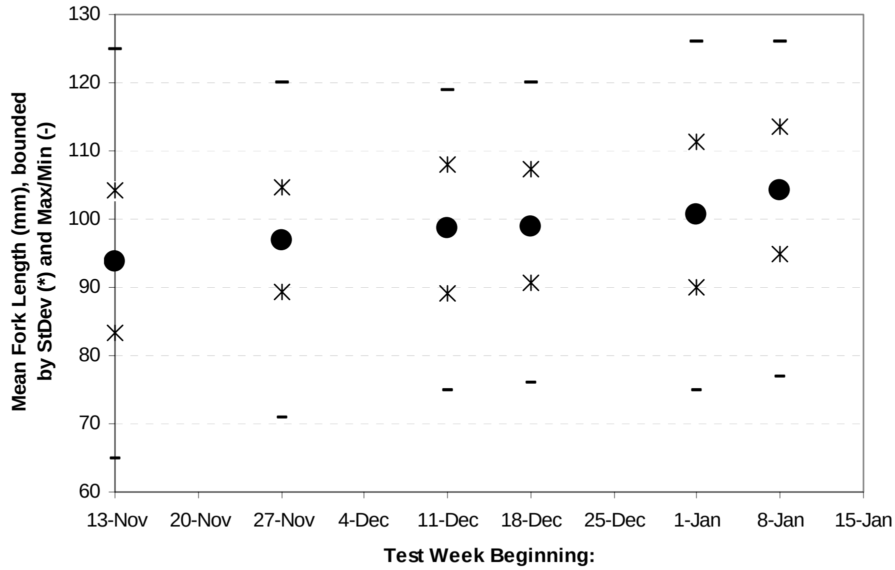


Figure 14. Mean (●), Standard Deviation (∗), and Maximum and Minimum Fork Lengths in Millimeters of Fish (–), by Week of Testing

4.2.2 Fish Passage

Thirty-four fish-passage tests were conducted between November 14, 2005, and January 12, 2006. The test conditions and number of fish in each of the three sections at the end of each test is provided in Table 2 along with the percentage of fish in the headwater tank, and in both the culvert and headwater tank. In general, fish passage was low at 1.5 cfs, but increased dramatically when flows were increased to 3 cfs (Figure). The percentage of successful passages then gradually declined through 6 and 8 cfs, with very few passages occurring at 12 cfs.

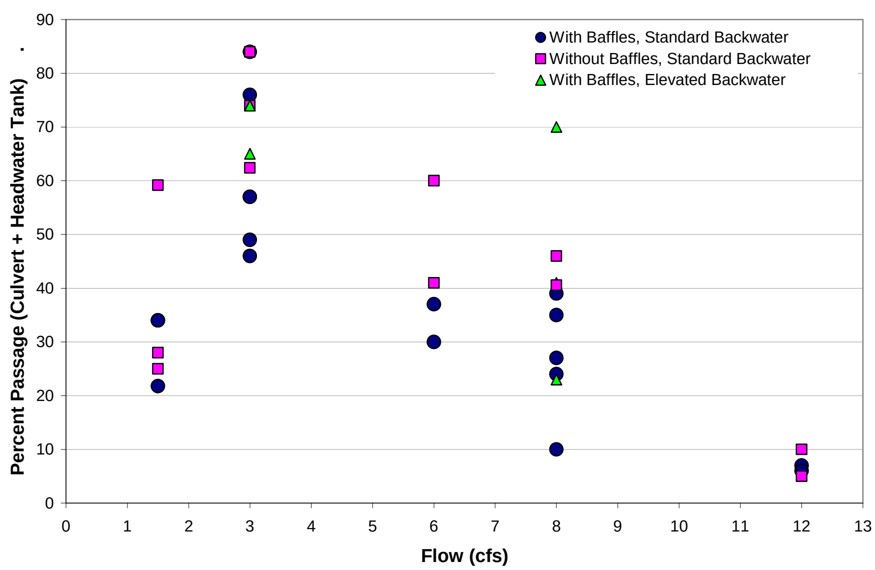


Figure 15. Percentage of Fish Passage Versus Flow

Table 2. Fish-Passage Test Results

Test No	Flow (cfs)	Baffle Configuration[‡]	Backwater Condition*	Tailwater Tank	in Culvert	Headwater Tank	% in Headwater Tank	% in Headwater Tank + Culvert
R007	1.5	with	standard	66	11	23	23	**34**
R010	1.5	with	standard	79	8	14	14	**22**
R011	1.5	with	standard	66	6	28	28	**34**
R008	1.5	***without***	standard	75	0	25	25	**25**
R009	1.5	***without***	standard	40	0	58	59	**59**
R012	1.5	***without***	standard	72	1	27	27	**28**
R014	3.0	with	standard	43	39	18	18	**57**
R015	3.0	with	standard	51	27	22	22	**49**
R013	3.0	***without***	standard	26	0	74	74	**74**
R016	3.0	***without***	standard	38	4	59	58	**62**
R017	6.0	with	standard	63	16	21	21	**37**
R020	6.0	with	standard	70	13	17	17	**30**
R018	6.0	***without***	standard	40	7	53	53	**60**
R019	6.0	***without***	standard	59	6	35	35	**41**
R021	8.0	with	standard	61	11	28	28	**39**
R024	8.0	with	standard	73	11	16	16	**27**
R022	8.0	***without***	standard	60	6	35	35	**41**
R023	8.0	***without***	standard	54	7	39	39	**46**
R025	12.0	with	standard	93	5	2	2	**7**
R028	12.0	with	standard	94	0	6	6	**6**
R026	12.0	***without***	standard	90	6	4	4	**10**
R027	12.0	***without***	standard	95	2	3	3	**5**
R029	3.0	with	***elevated***	26	32	42	42	**74**
R032	3.0	with	***elevated***	35	31	34	34	**65**
R030	3.0	with	standard	54	19	27	27	**46**
R031	3.0	with	standard	43	29	28	28	**57**
R033	3.0	with	standard	24	30	46	46	**76**
R034	3.0	***without***	standard	16	1	83	83	**84**
R035	8.0	with	***elevated***	59	21	20	20	**41**
R038	8.0	with	***elevated***	77	11	12	12	**23**
R039	8.0	with	***elevated***	30	24	46	46	**70**
R036	8.0	with	standard	90	2	8	8	**10**
R037	8.0	with	standard	76	11	13	13	**24**
R040	8.0	with	standard	65	15	20	20	**35**

‡ The "with baffle" configuration: 3 baffles inserted approximately 2.1 ft, 17.4 ft, and 32.3 ft above the tailwater-end of the culvert. Each baffle was 9 in. high on the left, slanting to 6 in. high on the right, (looking upstream).

* For the elevated backwater conditions, at 3 cfs one additional board was added; at 8 cfs two additional boards were added in addition to the standard number of boards.

The effects of culvert configuration and flow velocity were assessed as described in the methods section. Analysis of deviance indicated a significant quadratic relationship between culvert-passage success and flow (i.e., P = 0.00004 linear, P = 0.00002 quadratic) (Table 3). The fitted model for the standard configuration without baffles (Figure) was

$$\ln p_i = -1.20021 + 0.37324 \text{ flow } - 0.04303 \text{ flow}^2 .$$
$$(\text{SE } 0.24360)(\text{SE} = 0.10993)(\text{SE} = 0.01044)$$

The ANODEV indicated that the culvert trial data were 8.22 times more variable (i.e., MEDEV) than binomial data alone would predict.

The standard backwater configuration with baffles was estimated to pass 0.7648 times (SE = 0.0934) as many fish as the standard backwater configuration without baffles at all flows. This estimate indicates a statistically significant difference between these two configurations ($t_{29} = -2.1956$, P = 0.0363).

The elevated backwater configuration with baffles was estimated to pass 1.1306 times (SE = 0.1540) as many fish as the standard backwater configuration without baffles at all flows. This estimate indicates no significant difference in passage rates between the two configurations (t_{29} = 0.9011, P = 0.3750).

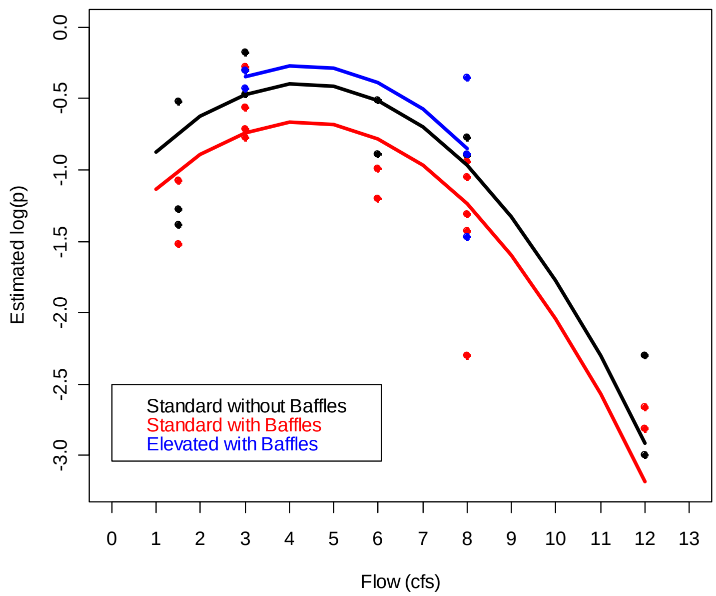
Finally, the elevated backwater configuration with baffles was estimated to pass 1.4783 times (SE = 0.0725) as many fish as the standard configuration with baffles at all flow levels. This estimate is significantly different from the value 1 (t_{29} = 2.7820, P = 0.0094); i.e., the elevated configuration passed significantly more fish than the standard backwater configuration with baffles.

The ANODEV indicates no significant lack-of-fit of the passage data to the quadratic model (P = 0.8086). Further testing indicated no significant treatment-by-flow (P = 0.6892) or treatment-by-flow-squared (P = 0.7395) interaction. This finding means the passage curves on the ln-scale are indeed parallel (Figure a), implying the estimated configuration effects apply across the range of flow conditions tested.

Table 3. Analysis of Deviance (ANODEV) Table for Proportion Successful Culvert Passage (i.e., Culvert and Headwater Count), Based on Binomial Error and Log-Link

Source	DF	Deviance	Mean Deviance	*F*	*P* value
$\text{Total}_{\text{Cor}}$	33	720.47			
Flow	1	193.15	193.15	23.50	0.00004
Flow^2	1	218.66	218.66	26.60	0.00002
Treatments	2	70.35	35.18	4.28	0.0235
Error	29	238.31	8.22		
Pure Error	22	158.32	7.20	0.63	0.8086
Lack of Fit	7	79.99	11.43		

(a)



(b)

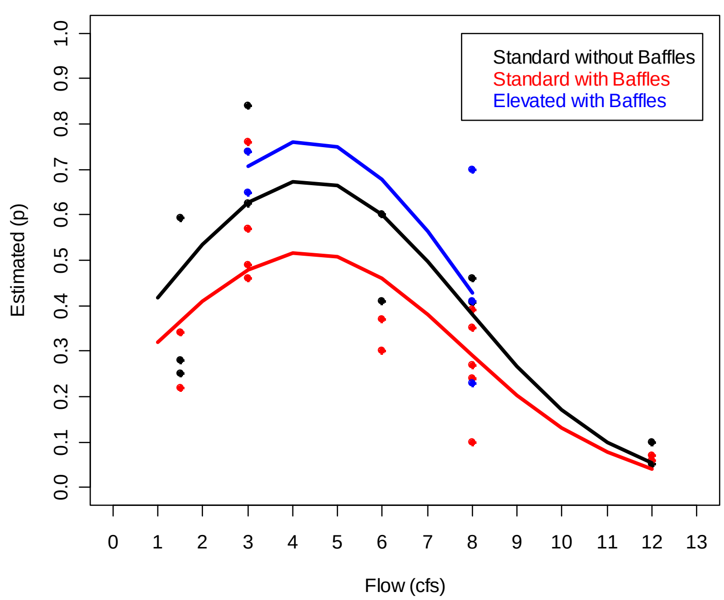


Figure 16. Fitted Quadratic Curves of Proportion Successful Culvert Passage (i.e., Culvert and Headwater Count) as a Function of Flow (cfs) for Three Different Culvert Configurations on (a) Ln-Scale, and (b) Arithmetic Scale

4.2.3 Fish Swimming Behavior

The following statements regarding fish swimming behavior under each flow condition are based on the documentation made during real-time test observations, along with a targeted review of the recorded video footage.

4.2.3.1 1.5 cfs

Without Baffles, Standard Backwater (1.5 cfs): Fish began to enter the culvert during the first 20 min of testing (Figures 17 and 18). The number of fish entering during each 10-min interval of the 3-h test gradually increased, and generally peaked somewhere between 60 min and 100 min after the test began. Entries into the culvert then declined steadily during the final hour of testing.

Fish attempted to enter the culvert from the left side, center, and right side, but successful entries occurred slightly more often on the right side or in the center than on the left side. Fish were usually observed holding for several seconds in the tailwater tank immediately outside the culvert entrance before suddenly increasing their swimming effort and crossing the threshold.

More fish were observed being swept downstream into the tailwater tank after successfully entering the culvert than were observed successfully swimming upstream past the point where the first baffle would be installed. It appeared that the majority of fish did not sustain their swimming effort and were swept backwards as they continued to swim against the current. A lesser number of fish turned around after entry and swam head-first back into the tailwater tank. Fish that could not hold position "fell back", while fish that turned around were considered to "swim out". Most fish fell back or swam out before reaching the point where the first baffle would be installed during the "with baffle" tests (i.e., fish fell back before swimming more than 2 ft upstream).

Figure 17. Real-Time Observations of Fish Entering the Culvert from the Tailwater Tank, Mean Entries per 10-min Period at 1.5 cfs

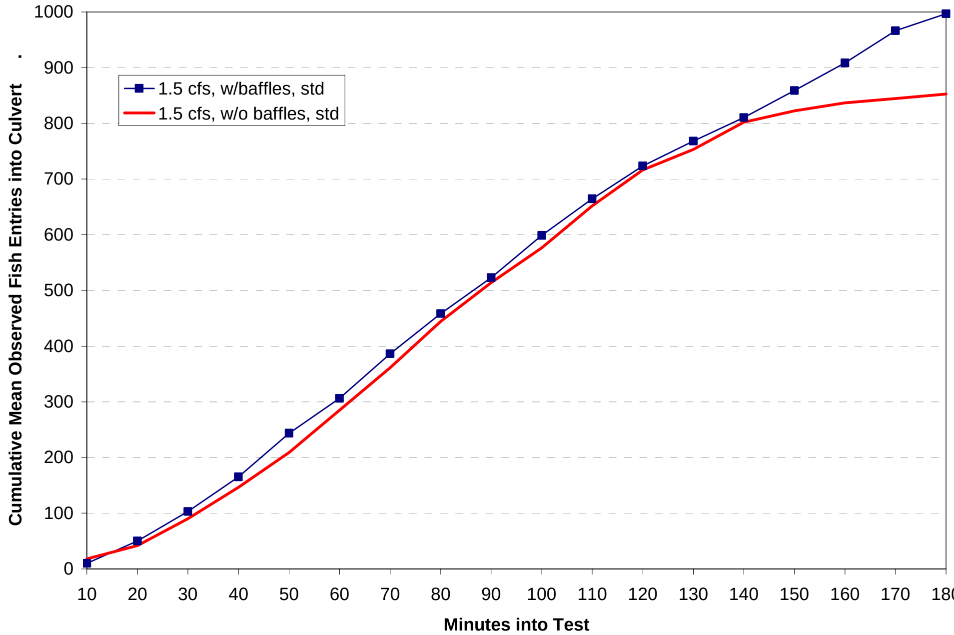


Figure 18. Real-Time Observations of Fish Entries into the Culvert from the Tailwater Tank, Cumulative Entries at 1.5 cfs

Fish were observed swimming through the field-of-view of the cameras positioned overhead at the B1, B2, and B3 regions (cameras were fixed, even though baffles were not installed). Fish appeared to pass through the B1 camera somewhat more frequently on the left side and at the center than on the right side. Fish passed through the B2 and B3 cameras almost equally in all three positions (left, right, and center). These fish most often used sustained swimming techniques to move upstream. Rapid upstream progress was made by most fish, some estimated to transit between camera B2 and camera B3 in 15 sec or less (approximately 1 ft/s). Other fish progressed at a slower pace. Some moved continuously upstream but in repetitive short bursts. Others rested in the current for several seconds to several minutes before continuing their progress steadily upstream. Those fish that moved forward slowly or were observed resting were more frequently on the right side or center side of the culvert. None appeared to have difficulty holding their position in the flow after they had moved beyond the culvert entrance. Fish generally moved individually (i.e., no schooling behavior was observed), and there did not seem to be any schooling while holding position.

With Baffles, Standard Backwater (1.5 cfs): Fish began to enter the culvert during the first 20 min of testing. The rate of entry gradually increased during the first hour of testing, and peaked between 50 min and 100 min. At the peak, greater than 100 entries into the culvert were recorded during some 10-min periods, but the average was 17.3 fish entries per 10-min period. The number of fish entries then declined during the last hour of testing.

Fish attempted to enter the culvert from the left side, center, and right side, but were most successful entering on the left side, where there appeared to be less current due to the baffle angle, sloped downward to the right. Fish were usually observed holding for several seconds in the tailwater tank immediately outside the culvert entrance before suddenly increasing their swimming effort and entering the culvert.

Approximately one third of the fish entering the culvert were observed being swept downstream into the tailwater tank after successfully entering the culvert. These fish crossed the threshold and immediately drifted backwards into the tailwater tank. Many fish entered on the left and swam to – or almost to – B1, then turned to their right and swam alongside the baffle on the downstream side, and then fell back at the center or on the right side. Some fish turned around after entry and swam head-first back to the tailwater tank. Some fish that paused next to the baffle obviously struggled to hold their position. They appeared to become pinned against the downstream side of the baffle in a reverse current, or hydraulic undertow, and then tumbled around before they fell back into the tailwater tank.

Fish most often crossed B1 at the center or right-center. However, a few fish were observed crossing B1 on the left, including the extreme left side, where they swam up to the water surface in the trough of the corrugation adjacent to the baffle, and then struggled and sometimes jumped to clear the baffle where it connected with the side of the culvert. Most fish continued swimming upstream out of the B1 camera view. A few were observed holding position just upstream of B1.

Fish traveled upstream above B1 on the left, right, and center, most often crossing B2 and B3 with some burst speed near the center. A smaller number of fish crossed B2 and B3 on the right and left sides. There were several recorded failed attempts at passing B2.

Between baffles, fish either used sustained swimming techniques or rested. Most fish continued swimming slowly, but steadily upstream of the baffle and out of camera view. However, a few were observed holding position for several minutes, three to eight corrugations upstream of the baffle, near the center or center-right. Few fish appeared to have difficulty holding position in the flow. There were several recorded failed attempts at passing B2, along with several observations of fish falling back downstream over a baffle, but these were infrequent.

In general, fish appeared to act as individuals, rather than as schools, though there were times when multiple fish entered the culvert simultaneously, and times when several fish (perhaps three at a time) were holding upstream of a baffle at the same time.

4.2.3.2 3.0 cfs

The timing of fish entries at 3.0 cfs are depicted in Figure and 20Figure .

Without Baffles, Standard Backwater (3 cfs): Fish began entering the culvert early in the test, with entrance activity peaking between 20 min and 90 min into the test. The rates of entering the culvert then gradually tapered off over the remainder of the test. On average, 14 fish entered the culvert every 10 min.

Most fish struggled to enter the culvert, but were able to enter from the left, center, and right. The salmon swam vigorously to cross the threshold. Once inside the culvert, most swam upstream past just two or three corrugations (6 in. to 9 in. inside the culvert) before falling back into the tailwater tank. The incidence of fallbacks appeared to decrease over time. A few fish were observed entering and then holding position on the right side near where B1 would have been located.

Fish crossing the B1 location generally entered the culvert and swam directly upstream in a straight line. In other words, if a fish entered the culvert on the left side, it usually crossed the B1 location on the left side. Fish entered the culvert successfully on both sides and at the center.

Above the B1 location, fish almost always used the far right side of the culvert to travel upstream (approximately 90% far right; 10% far left). Swimming was steadily forward, with several short pauses taken during transit before resuming swimming. Fewer fish were observed resting than swimming, but those that did rest were observed holding on the far right side for several minutes at a time. Several fish were also observed holding position above the B3 location on the far right side for at least 5 min before exiting the culvert into the headwater tank, but the majority of the fish swam continuously straight through to the culvert exit.

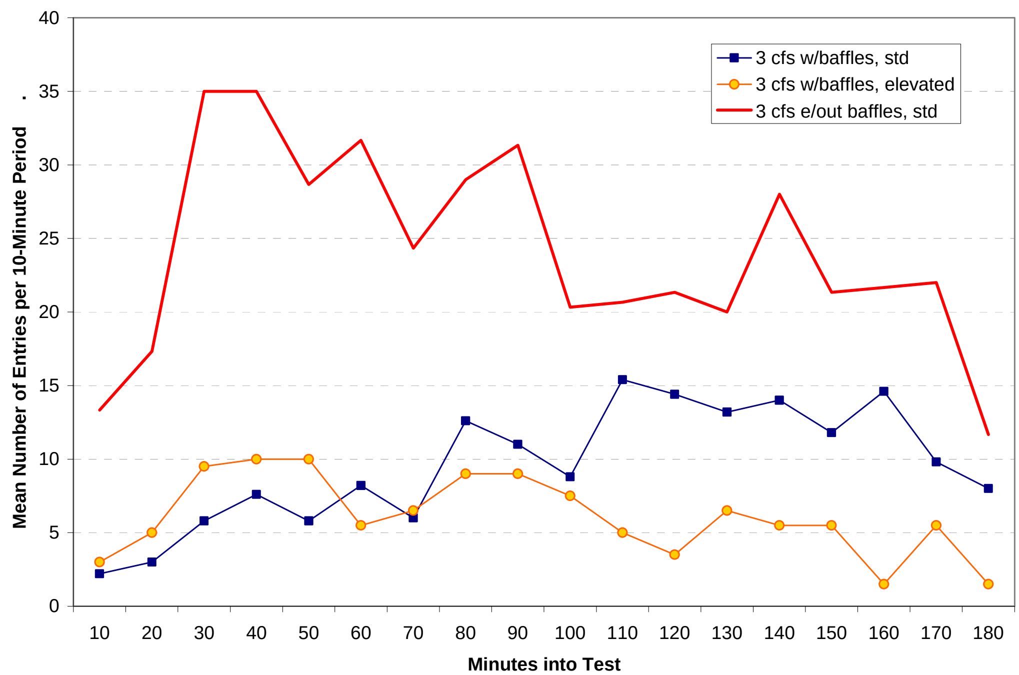


Figure 19. Real-Time Observations of Fish Entering the Culvert from the Tailwater Tank, Mean Entries per 10-min Period at 3 cfs

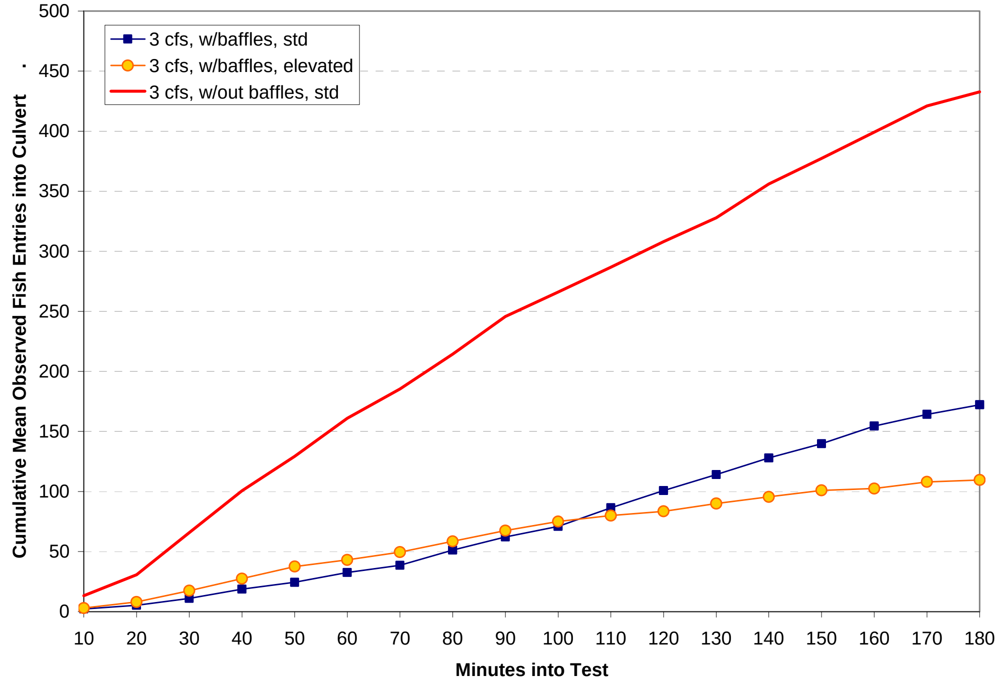


Figure 20. Real-Time Observations of Fish Entries into the Culvert from the Tailwater Tank, Cumulative Entries at 3 cfs

With Baffles, Standard Backwater (3 cfs): Fish began showing increased interest in entering the culvert approximately 30 min into the test period. Entries were steady, and even increased slightly during the second half of the test, but did not usually exceed 15 entries in a 10-min period. On average, 5.9 fish entered the culvert every 10 min. Fish swam vigorously to enter the culvert, with many just making it over the threshold before being swept back into the tailwater tank. They approached the entrance from the center and both sides, but appeared to prefer the center and left.

Fish crossed B1 at all locations, sometimes with a burst of speed and possibly a small leap. There were a number of failed attempts at crossing B1, and at least one instance of fallback over each of the three baffles. Fish usually crossed B2 near the center or on the right, but were observed crossing B3 on the right, left, and center.

Most fish were observed to hold on the upstream side of a baffle near the center, about two to eight corrugations upstream, for at least several minutes. As many as 7 fish were observed holding above B2 at one time. These fish were spread out horizontally and vertically in the water column, as some could be seen swimming over the top of others. Most were holding off-center, but usually not at the far-right or far-left sides of the culvert. More time was spent holding than swimming. Following a rest period, fish would move upstream very slowly and then stop to rest again. At least one fish was observed holding position above B2 for nearly 20 min. Very few fish exhibited sustained swimming behaviors above B1. Several fish were observed to fall back over B2 and B3 near the end of the test.

With Baffles, Elevated Backwater (3 cfs): Fish entries into the culvert peaked between 30 min and 50 min into the test at approximately 10 entries per 10-min period. Entries then slowly declined for the remainder of the test. The overall average was just 1 entry per 10-min period.

Fish entered the culvert from all positions. The combination of entry and passage over B1 happened very quickly. Fish crossed B1 in about the same place that they entered the culvert (right, left, or center). The number of fish that entered and swam past B1 outnumbered those that immediately fell back into the tailwater tank. Fish crossed B2 on the left, right, and center, but most often at the center or on the right side. Fish appeared to cross B3 fairly equally on the left, right, and center.

It was difficult to observe fish moving upstream, but they appeared to move upstream slowly. There were very few sustained swimmers. None of the fish used the far right or left edges to rest between baffles; all were closer to the center. At one time, nine fish were observed to be spread out and holding between B2 and B3 at the same time. Because some fish appeared to be much lighter than others (as viewed on a black-and-white monitor), it may be assumed that some swam closer to the water surface than others.

4.2.3.3 6.0 cfs

The timing of fish entries at 6.0 cfs are depicted in Figure and 22Figure .

Without Baffles, Standard Backwater (6 cfs): Fish began entering the culvert immediately after the test began. Entries peaked at 15 between 30 min and 40 min into the test, then declined slightly before leveling off. On average, there were 4.4 entries per 10-min period.

Fish entered the culvert from all positions but appeared to have the most success continuing upstream past the B1 location at the center and on the left side. The number of fish that entered and swam up past the B1 location was similar to the number of fish that entered and immediately fell back to the tailwater tank.

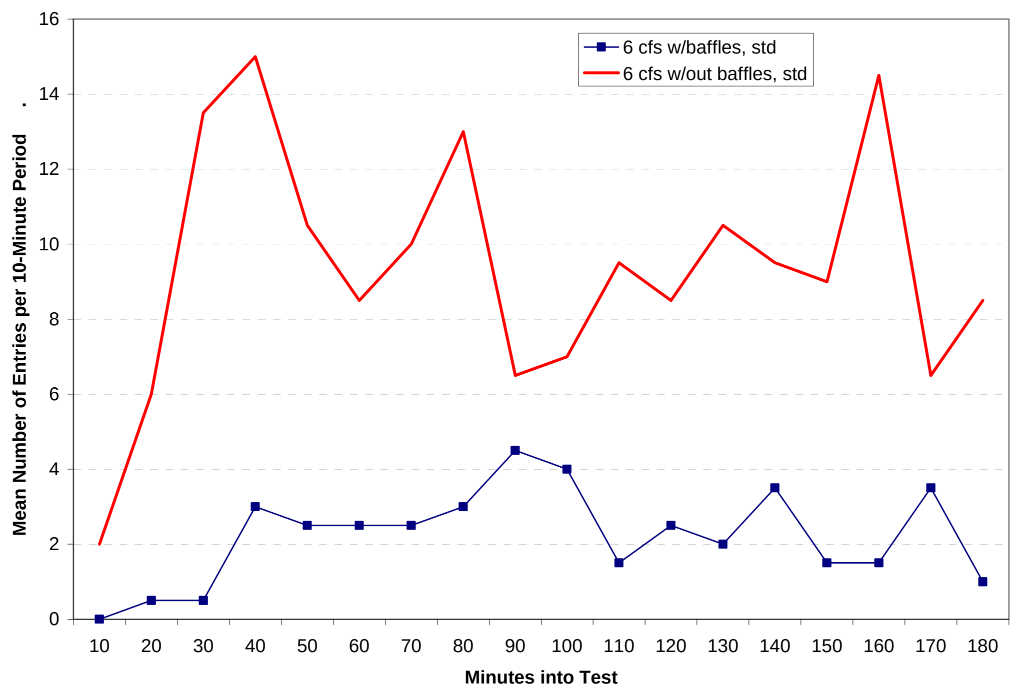


Figure 21. Real-Time Observations of Fish Entering the Culvert from the Tailwater Tank, Mean Entries per 10-min Period at 6 cfs

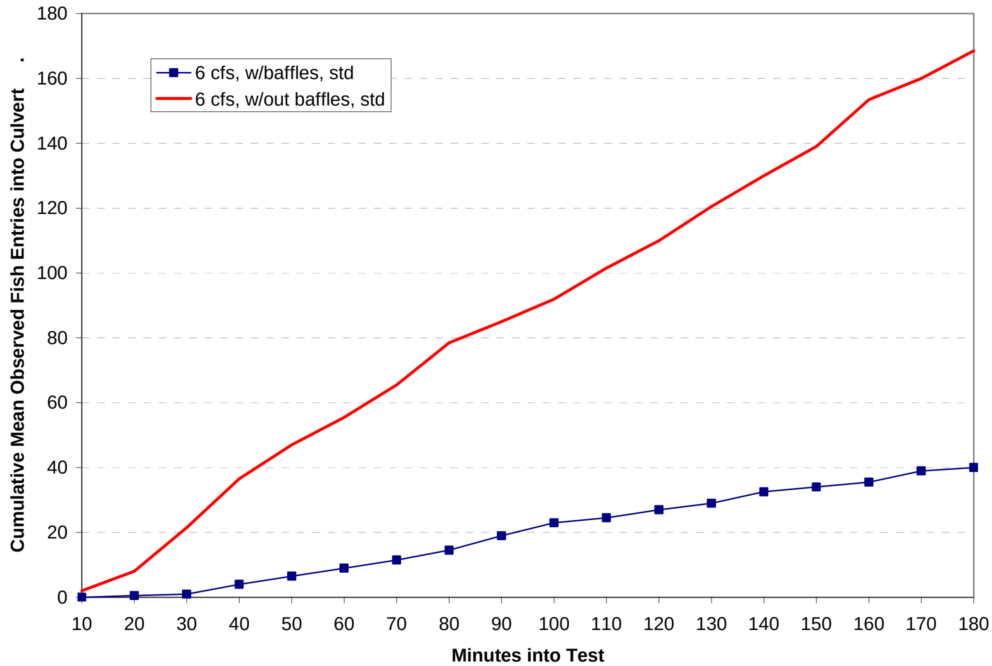


Figure 22. Real-Time Observations of Fish Entries into the Culvert from the Tailwater Tank, Cumulative Entries at 6 cfs

Fish crossed the B1 location and then angled over to the far right or to the far left side to continue swimming upstream. Most fish appeared to navigate up the far right side, including passage past the B2 and B3 locations. There were two distinct swimming techniques observed. One group of fish swam steadily up the culvert without appearing to stop and rest before exiting the culvert. We estimated that one fish traversed the 40-ft length of the culvert in just 35 sec. Other fish moved upstream slowly. Some swam slowly and steadily, but other fish rested for up to a half hour before continuing upstream. Some fish that were observed resting would end the rest period by darting forward and swimming quickly forward out of camera range. One fish that was resting just upstream of the B2 location exhibited an initial burst of speed followed by sustained swimming past the B3 location and passed two fish that were resting on the far right immediately above the B3 location, before stopping to rest. This fish remained above the B3 location for more than 5 min before exiting the culvert into the headwater tank.

With Baffles, Standard Backwater (6 cfs): Few fish entered the culvert during the first half hour of testing. Fish entries then increased, peaking between 80 min and 100 min into the test at just over 4 entries in 10 min. On average, there were 1.3 entries per 10-min period.

At 6 cfs, the hydraulic jump at B1 forced by the expansion of the culvert outlet was located at the culvert entrance. This apparently made it difficult for fish to enter the culvert. More fish were successful entering on the left side than on the right side. However, it seemed that more fish were attempting to enter the culvert on the right side than they did in the baffle tests conducted at lower flows.

Fish crossed B1 on the right, left, and center. Most fish crossed B2 and B3 on the far right or far left and then held position against the wall of the culvert. Several swam quickly past the baffles and out of view, but these were in the minority.

Fish rested between the baffles. Most held upstream of B2 and B3 for several minutes, but some held position for over an hour. Fish traveled between baffles using the far right and far left sides. Only one fish was observed holding in the center. However, at 6 cfs and above, it was very difficult to see fish swimming up the center of the culvert because of the increased water depth.

4.2.3.4 8.0 cfs

The timing of fish entries at 8.0 cfs are depicted in Figure and 24.

Without Baffles, Standard Backwater (8 cfs): Fish entry into the culvert was markedly slower than in tests at lower flows, but did occur within the first 20 min. Entries peaked near 15 entries in a 10-min period, 50 min into the test. Thereafter, entries were slow but steady until the test ended, averaging 4.3 entries per 10-min period.

Fish were observed entering from the right, left, and center, and moved up to the B1 location from the right, left and center positions. Fish did not appear to have any difficulty moving upstream. They passed the B1 location from all threel positions, but appeared to favor the right side. Passage past the B2 and B3 locations was predominately on the right side.

After passing the B1 location, most fish moved to the far right side to navigate upstream. A minority used the far left side or the right-center. While some fish swam quickly and steadily up the sides, others held position on the far sides or, in a few instances, were observed to drift slowly backward through the culvert. Swimming fish had no difficulty passing the fish that were holding their position. The fish holding their position moved very slowly, sometimes backward and then forward, making almost imperceptible progress upstream.

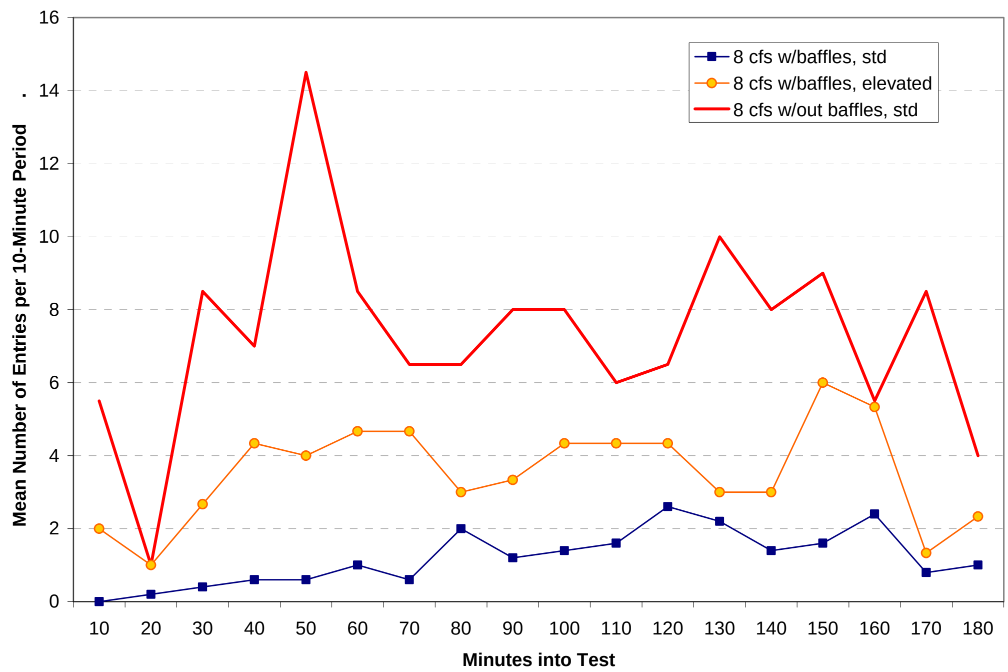


Figure 23. Real-Time Observations of Fish Entering the Culvert from the Tailwater Tank, Mean Entries per 10-min Period at 8 cfs

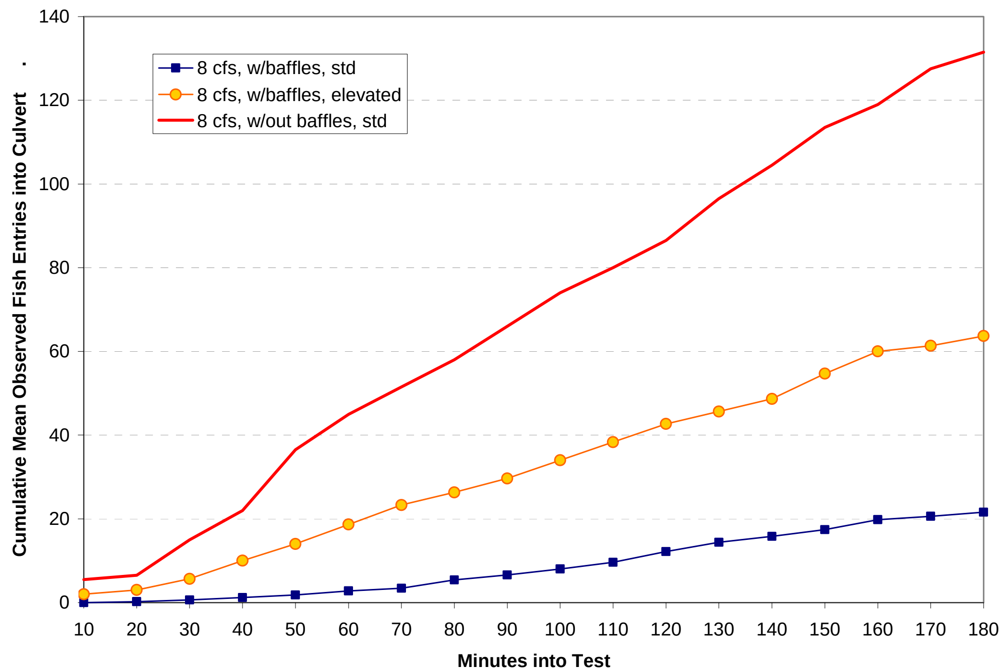


Figure 24. Real-Time Observations of Fish Entries into the Culvert from the Tailwater Tank, Cumulative Entries at 8 cfs

With Baffles Standard Backwater (8 cfs): Few entries were observed during the first half hour of testing. Entries gradually increased through the first 2 h of testing and then declined slightly. There were usually fewer than 5 observed entries in a 10-min period, and on average there were only 0.7 entries observed per 10-min period.

Fish entries were observed most often on the left side, followed by the center and then the right side. Most fish that moved into the culvert fell back out immediately afterwards.

Fish often made several attempts before successfully crossing B1. Fish would swim up close to the baffle and appear to swim more vigorously in several quickly repeated efforts to cross over B1. Fish generally crossed B2 and B3 on the far right or far left sides and did not appear to have any difficulty passing over these baffles.

After passing B1, fish almost always moved to the far right or far left, with the right side being dominant. Above B2 and B3, fish often rested, usually on the far left or far right. After remaining in place for a few minutes to more than 30 min, most moved slowly forward at a steady pace or in short, forward spurts. Fish sometimes inched forward, a few corrugations at a time, then drifted back a few corrugations, and then would move forward again. A few fish quickly passed through the culvert swimming at a fast and steady pace, but most fish rested somewhere in the system, and often for a long time.

With Baffles, Elevated Backwater (8 cfs): Few entries were observed during the first half hour of testing. Entries then peaked near 14 in a 10-min period at 50 min into the test and then leveled off. On average there were 2.3 entries observed per 10-min period.

Fish entered the culvert predominately at the center and on the left side. Few entered on the right side. Fish crossed B1 primarily at the center, but were also observed crossing at the far right and far left sides.

Most fish crossed B2 at the center, with fewer numbers crossing on the left and right sides. At B3, most fish crossed on the far right, with a minority crossing on the right and at the left.

Most movement between the baffles was very slow, with most fish holding position at some point. Few fish swam upstream without pausing; those that did usually swam up the far right side, easily passing any fish that were holding. Most fish paused above B3 before exiting.

4.2.3.5 12.0 cfs

The timing of fish entries at 12.0 cfs are depicted in Figure and 26Figure .

Without Baffles, Standard Backwater (12 cfs): At least one fish entered the culvert during the first 10 min of testing. Entry rates were very low, averaging only 0.1 observed entries in a 10-min period. Fish entered slightly more often at the center than on the left and right combined. Initial movement upstream was observed slightly more often at the center and on the right than on the left side. Above the B2 location, fish were observed predominately on the right side.

Although very few fish were observed in the culvert during the 12 cfs tests, they were fairly evenly divided between holding and swimming behaviors. Fish that held position were almost always on the right side. Fish that were actively swimming upstream were observed most often on the right side, but in one instance, were also observed at the far left and center.

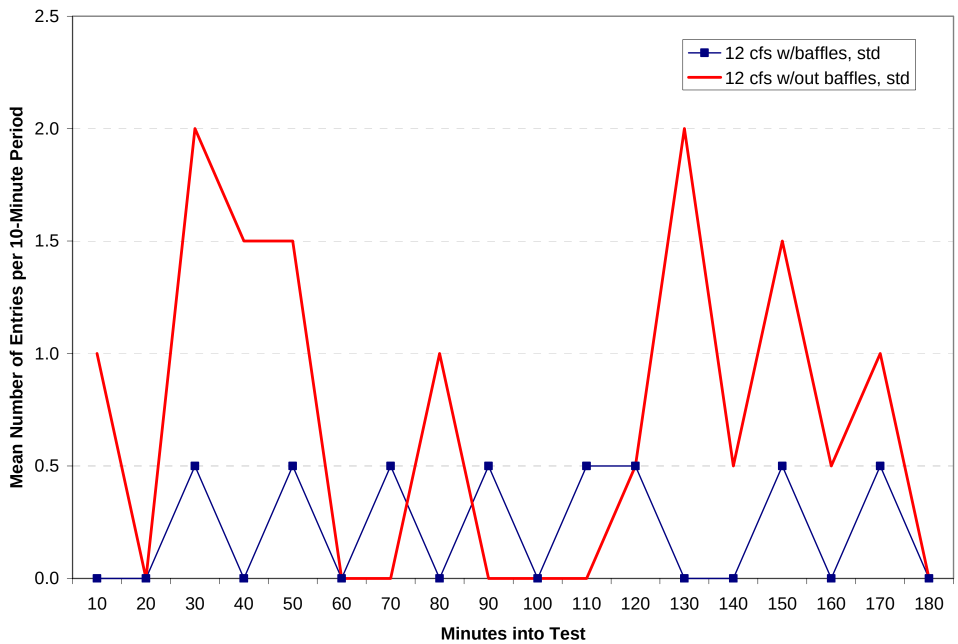


Figure 25. Real-Time Observations of Fish Entering the Culvert from the Tailwater Tank, Mean Entries per 10-min period at 12 cfs

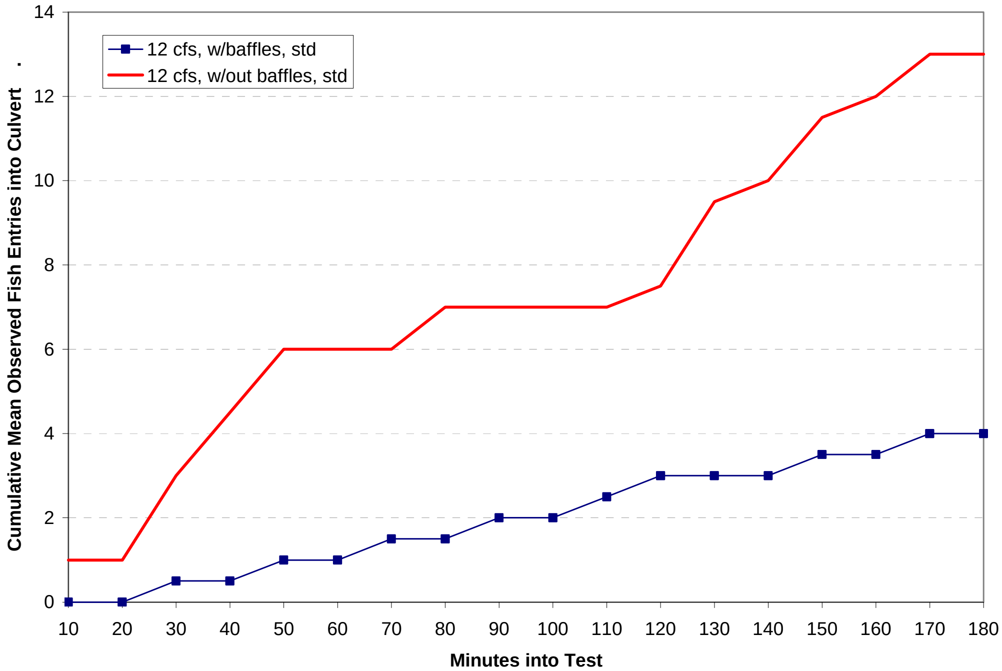


Figure 26. Real-Time Observations of Fish Entries into the Culvert from the Tailwater Tank, Cumulative Entries at 12 cfs

With Baffles, Standard Backwater (12 cfs): Initial fish entry into the culvert did not occur until 20 min to 40 min into testing. The entry rate remained low for the duration of the test and averaged just 0.1 entries per 10-min period. Fish entered more frequently on the right and left sides than in the center.

Fish crossed B1 at the center and on the right side. Fish crossed B2 most often on the right, followed by crossings on the far left and then at the center. No fish were observed crossing B3, but one fish was observed holding above B3 at the far right for at least 40 min.

4.2.4 Fish Behavior Summary

4.2.4.1 Entry into the Culvert

Based on observations made during real-time tests, the number of fish observed entering the culvert varied with flow (Figure). At 1.5 cfs, many fish were observed to enter the culvert and then immediately fall back out of the culvert without crossing any baffles or swimming very far upstream. At the peak of 1.5-cfs testing, over 80 fish entries were observed in a 10-min period, and over 900 entries were observed during a single 1.5-cfs test. As flows increased, the number of entries declined. At 12 cfs, one or no entries per 10-min period were typical.

Fish used different pathways to enter the culvert, based on baffle configuration, backwater condition, and flow (Figure). Between 1.5 cfs and 6.0 cfs with baffles and at the standard backwater condition, fish usually entered the culvert from the left side. At 8 cfs, the left side was still used most often, but the center and right sides were used as well. At 12 cfs, the right side began to dominate, with the left and center also being used as entry points. When baffles were used with elevated backwater condition, fish entry was most often at the center of the culvert, followed closely by entry on the left side. Fish entered on the right side as well, but at a much lower frequency. When baffles were not used in the culvert, no entry point dominated over any others.

A quadratic regression on the passage success versus the number of entries for each culvert configuration was performed for trials with flows greater than 1.5 cfs. The analysis of variance (ANOVA) indicates that the number of entries and the configuration, as well as their interaction, were very significant ($P < 0.05$)Table 4). A plot of the estimated passage success versus the number of attempts for each culvert configuration is provided (Figure).

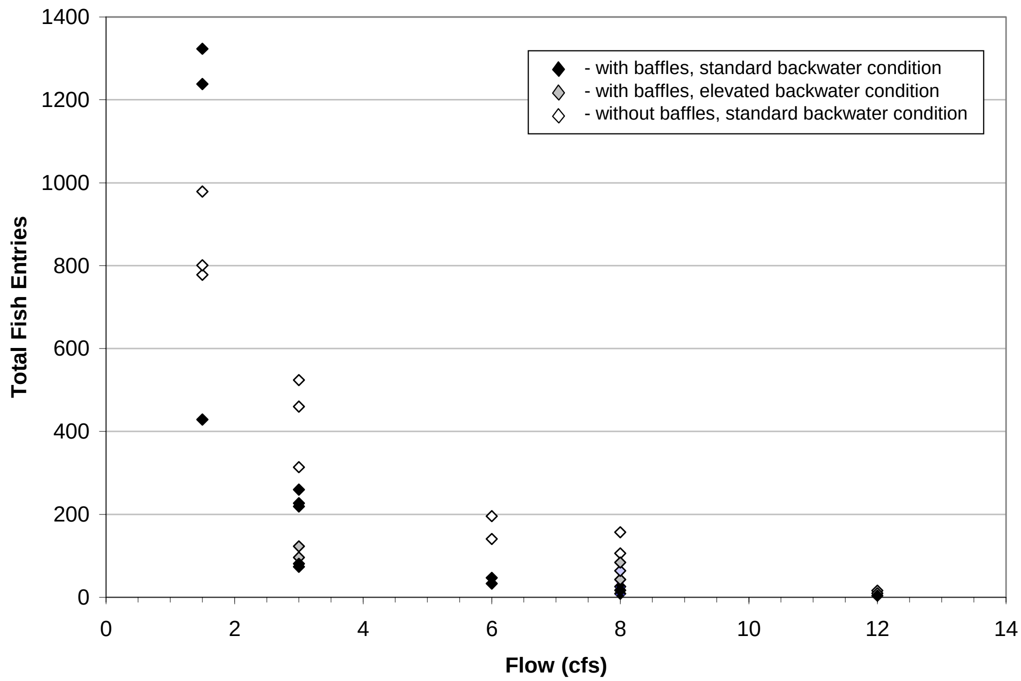


Figure 27. Total Fish Entries by Flow and Backwater Condition

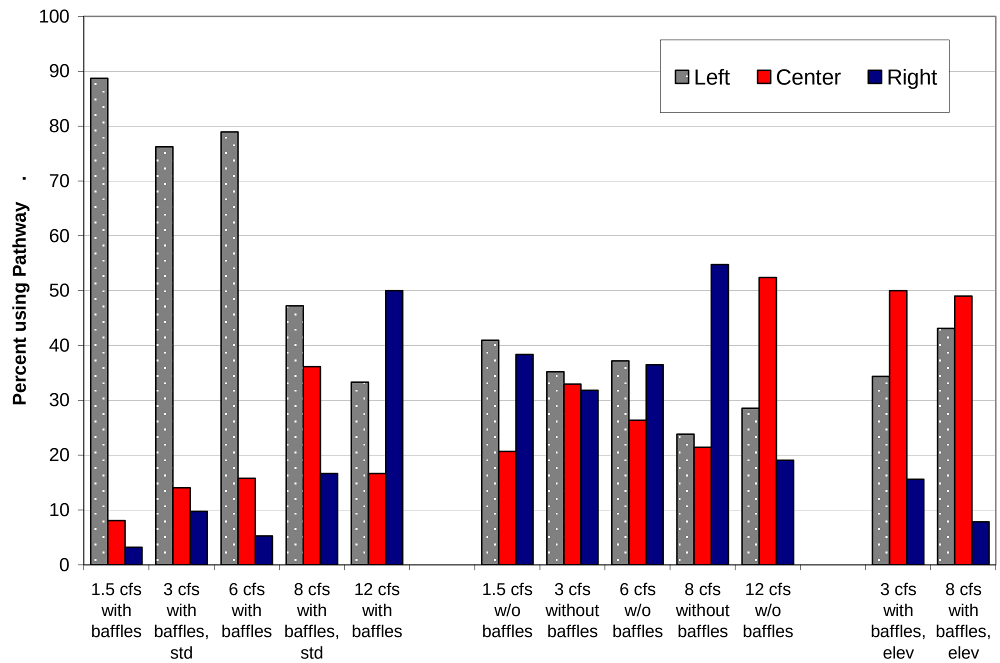


Figure 28. Percentage of Observed Fish Entering the Culvert at the Left, Center, and Right

Table 4. Analysis of Variance (ANOVA) Table for Proportion Successful Culvert Passage (i.e., Culvert and Headwater Count)

Source	DF	Deviance	Mean Deviance	*F*	*P* value
$Total_{Cor}$	27	1.4616			
Main Effects					
Num. Attempts	1	0.7588	0.7588	60.78	0.0000002
$(\text{Num. Attempts})^2$	1	0.1660	0.1660	13.30	0.0017
Configuration	2	0.1626	0.0813	6.51	0.0070
Interactions					
Config. x Num. Attempts	2	0.0384	0.0192	1.54	0.2406
Config. x $(\text{Num. Attempts})^2$	2	0.0986	0.0493	3.95	0.0368
Error	19	0.2372	0.0125		

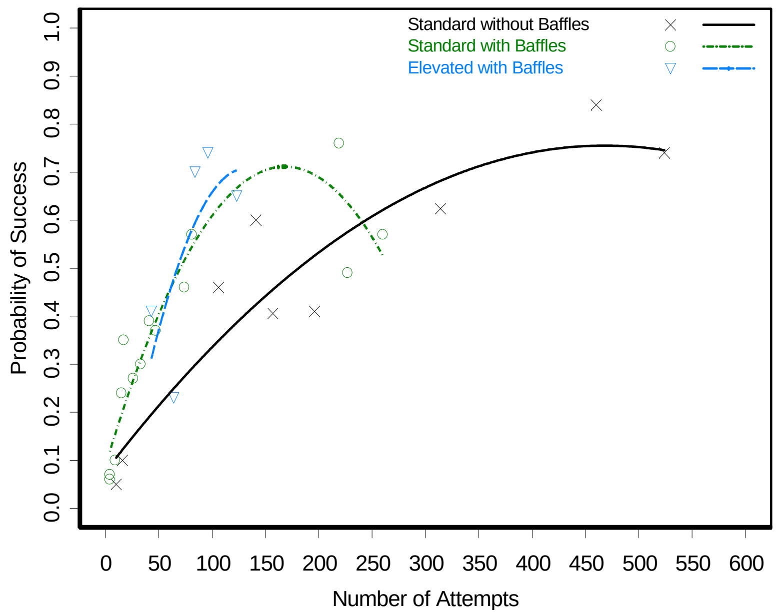


Figure 29. Proportion of Successful Culvert Passage (i.e., Culvert and Headwater Count) as a Function of the Total Number of Attempts for Three Different Culvert Configurations, for Flows Greater than 1.5 cfs. Symbols indicate configuration.

Table 5 displays the results for three pair-wise comparisons of the culvert configurations for the passage success as a function of entries. The standard configuration with baffles is significantly different from the standard configuration without baffles ($P = 0.0155$). The insignificant difference between the curves for elevated configuration and the standard without baffles configuration ($P = 0.6422$) is likely due to the limited data available for the elevated with-baffles configuration. The curves for the standard configuration with baffles and the elevated configuration are also not significantly different ($P = 0.8360$), and this comparison is on the full data set.

Table 5. Pair-Wise Comparisons of Culvert Configuration Passage Success Using Chi-Square Tests

Configuration Comparison	χ^2_{6df}	*P* value
Standard without baffles vs. standard with baffles	15.6945	0.0155
Standard without baffles vs. elevated with baffles	4.2552	0.6422
Standard with baffles vs. elevated with baffles	2.7792	0.8360

4.2.4.2 Passage over Baffles

Fish crossed the baffles at various positions, depending, in part, on flow (Figure through 32). A comparison of fish passage through those regions of the culvert for “without-baffle tests” is also presented for comparison.

For tests ***with baffles at the standard backwater condition,*** fish moved predominately over B1 at the center and right side. The utilization of the center became more pronounced as flows increased above 6 cfs. Fish moved over B2 most often near the center at low flows (1.5 cfs and 3 cfs). At higher flows, fish crossed B2 more frequently on the right and/or left sides than at the center. A similar pattern was observed at B3, with fish crossing in the center most often at low flows, and then crossing at the right or left side more frequently at flows of 6 cfs and above.

For tests ***with baffles at the elevated backwater condition***, fish crossed B1 most often at the center and left sides, though nearly 25% of the B1 crossings were observed on the right side. Observed passage over B2 occurred most frequently at the center of the baffle, with right and left crossings nearly even at approximately 20% each. At B3, passage was greatest at the center for 3 cfs tests, but greatest on the far right at 8 cfs.

For tests ***without baffles at the standard backwater condition,*** fish moved past B1 location at all three positions, without appearing to favor any pathway over another. However, there may be a slight shift from passing B1 line predominately on the left or center at low flows to passing on the right side or center at higher flows. At the B2 location, the center pathway dominated at 1.5 cfs, but then transitioned to the right side at 3 cfs. Fish crossed the B2 location predominately on the right side at 6 cfs and higher. A similar pattern was observed at the B3 location, with fish crossing at the center most often at 1.5 cfs, and then crossing predominately on the right side at 3 cfs and above.

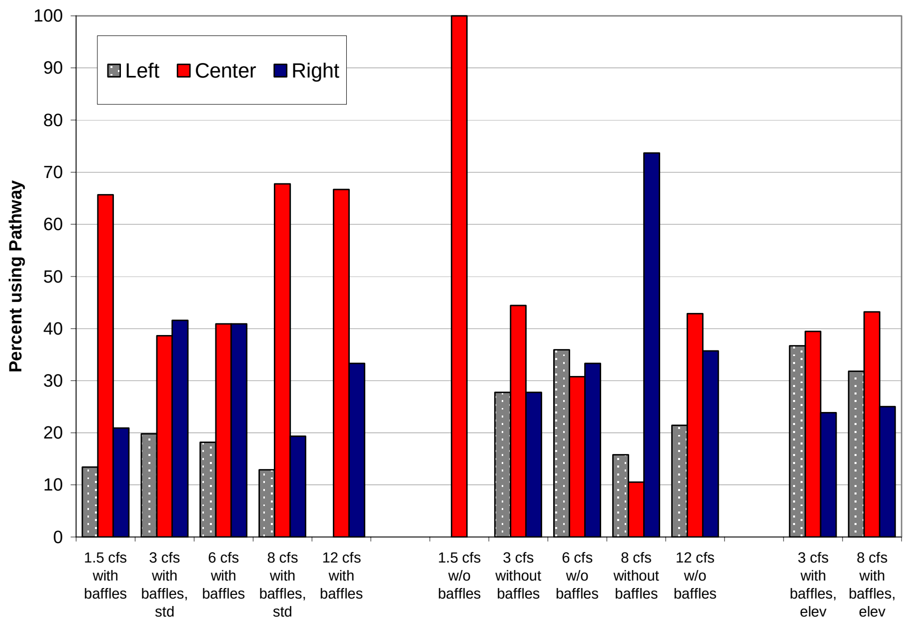


Figure 30. Percentage of Fish Observed Crossing Baffle 1 at the Left, Center, and Right

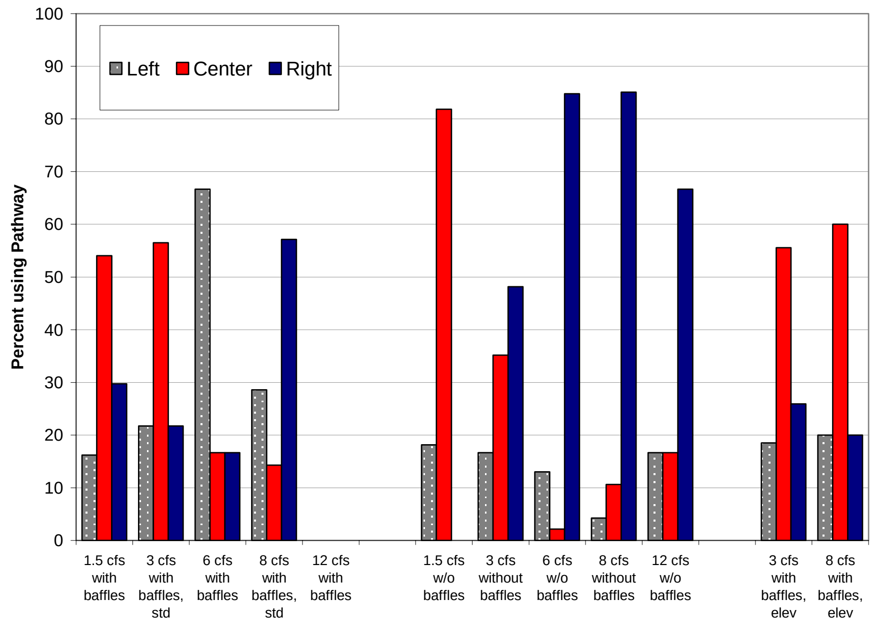


Figure 31. Percentage of Fish Observed Crossing Baffle 2 at the Left, Center, and Right

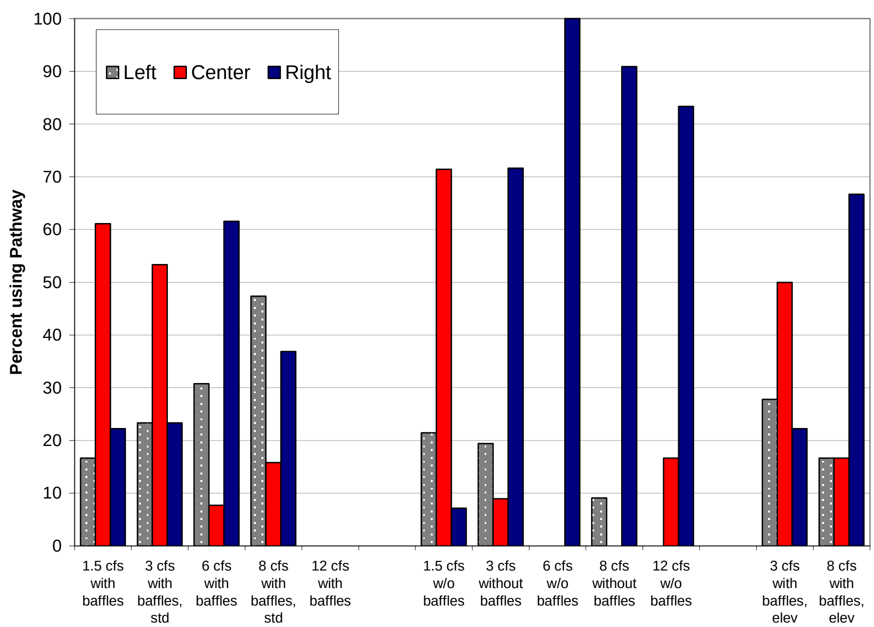


Figure 32. Percentage of Fish Observed Crossing Baffle 3 at the Left, Center, and Right

Swimming and Holding Between Baffles: Fish swam or held position between the baffles at various locations, depending, in part, on flow (Figure through 38). A comparison of fish swimming and holding behavior through these regions of the culvert for “without-baffle tests” is also presented for comparison.

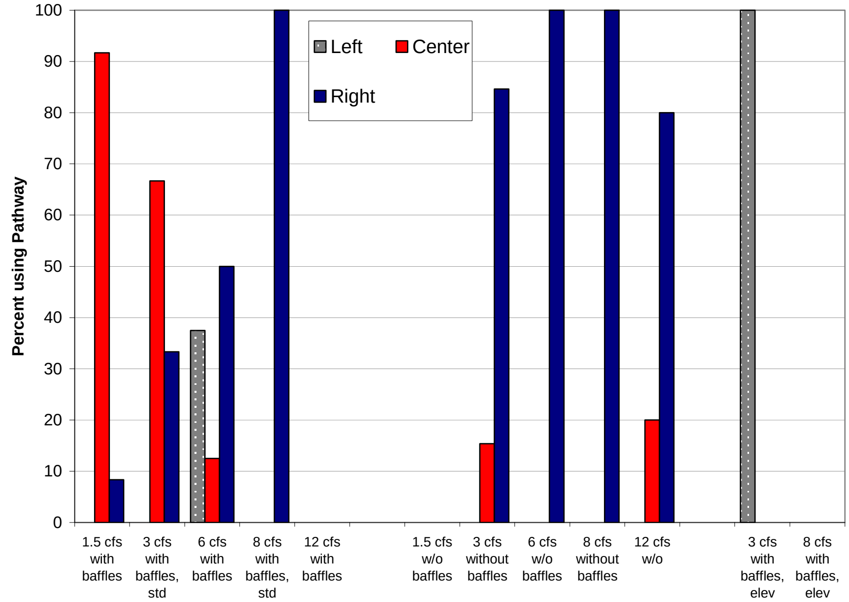


Figure 33. Percentage of Fish Observed Holding Between Baffle 1 and Baffle 2

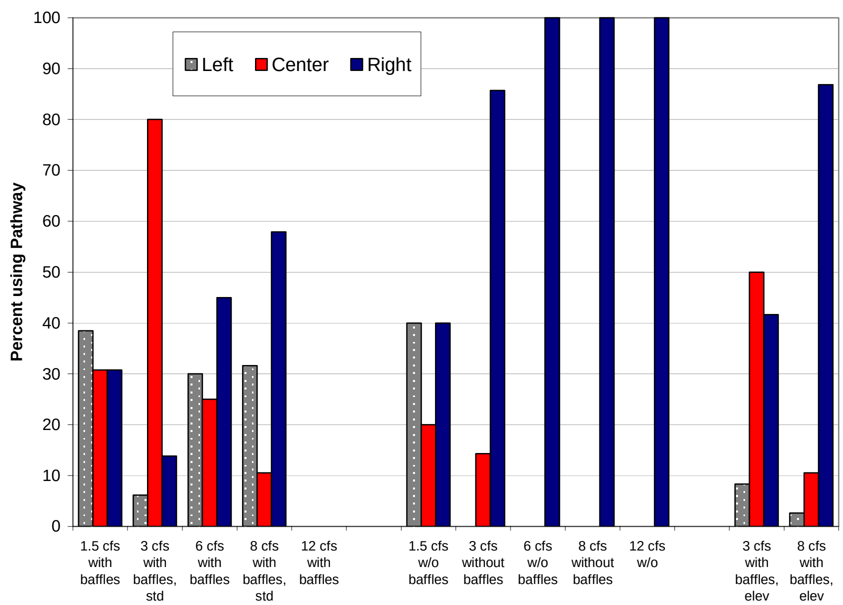


Figure 34. Percentage of Fish Observed Holding Between Baffle 2 and Baffle 3

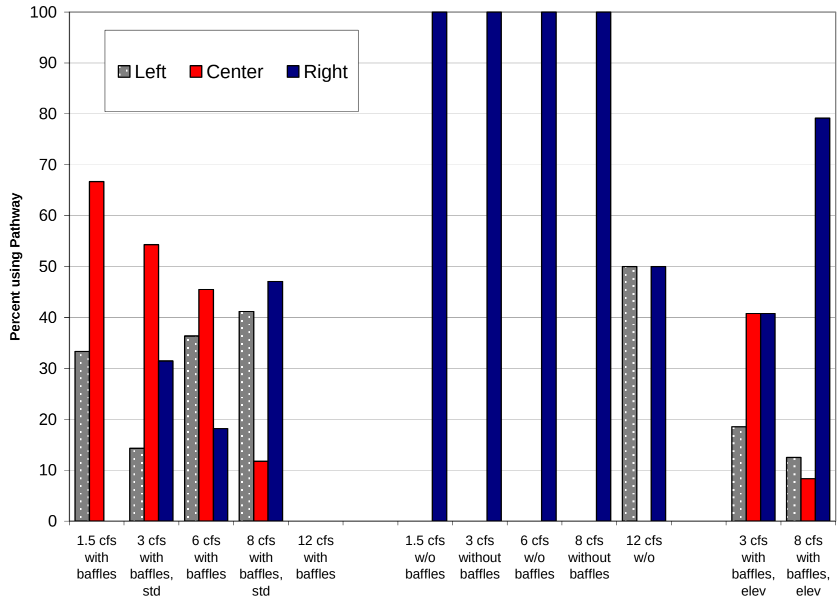


Figure 35. Percentage of Fish Observed Holding Between Baffle 3 and the Headwater Tank

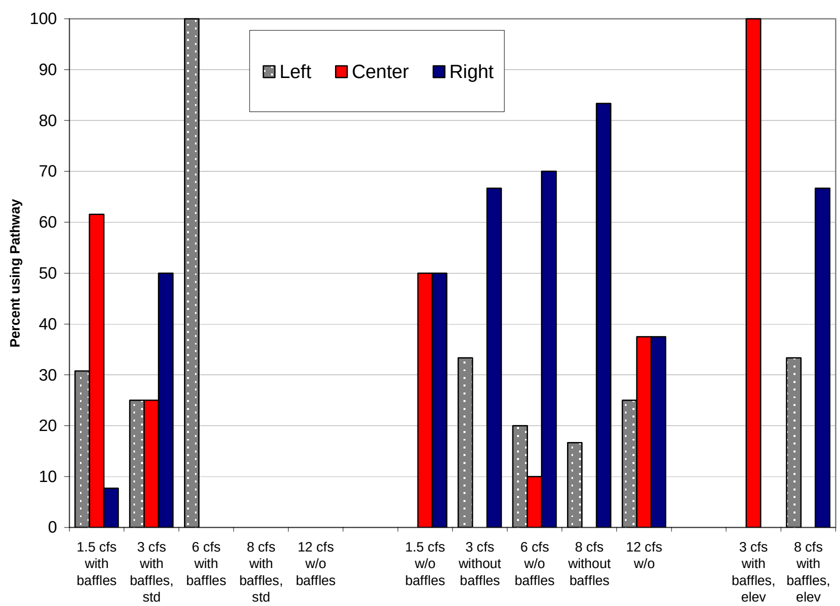


Figure 36. Percentage of Fish Observed Swimming Between Baffle 1 and Baffle 2

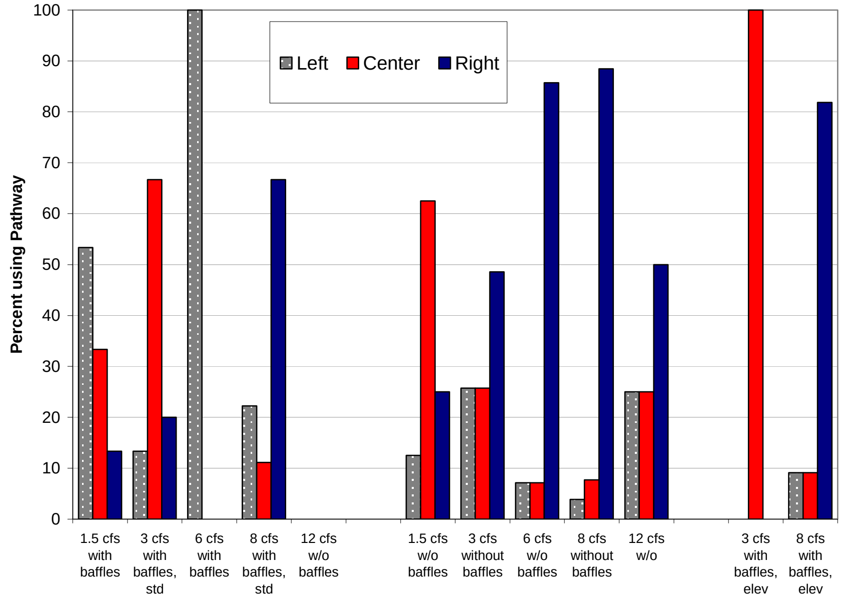


Figure 37. Percentage of Fish Observed Swimming Between Baffle 2 and Baffle 3

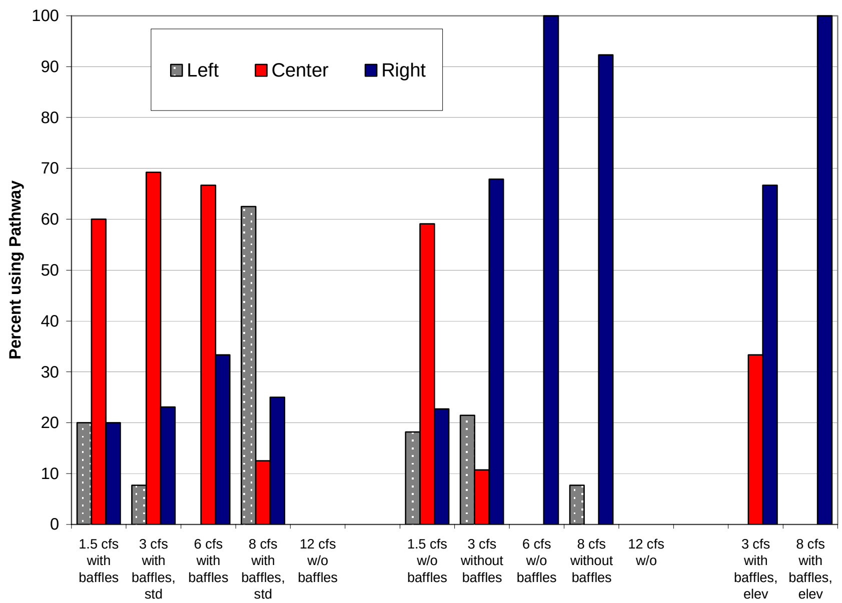


Figure 38. Percentage of Fish Observed Swimming Between Baffle 3 and the Headwater Tank

For tests ***with baffles at the standard backwater condition,*** fish were observed holding and swimming between B1 and B2 most often near the center at 1.5 cfs and 3 cfs, but shifted to the far right or far left at 6 cfs and above. Between B2 and B3, there was no preference for position at 1.5 cfs, near the center at 3 cfs, and then fish began using the right and left sides more frequently at 6 cfs and above. Fish swimming between B2 and B3 appeared to use the left side and center most often from 1.5 cfs to 6 cfs, and then began to use the right side most often at 8 cfs. Fish holding or swimming above B3 were most often observed in the center at flows between 1.5 cfs and 6 cfs, and then holding or swimming on the far right or far left sides at 8 cfs.

For tests ***with baffles at the elevated backwater condition***, fish were seldom observed holding or swimming between B1 and B2 because of poor lighting inside the culvert at that point. However, it appeared that fish used the center most frequently to swim upstream at 3 cfs, but moved to the far right and far left at 8 cfs. Between B2 and B3, fish held predominately at the center and right at 3 cfs, and almost all fish held on the right side at 8 cfs. Fish that were observed swimming between B2 and B3 moved up the center at 3 cfs, but moved up the right at 8 cfs. More fish were observed holding between B2 and B3 than actively swimming between the baffles. Above B3 at 3 cfs, fish held position at the center and right sides more often than on the left. When the flow increased to 8 cfs, most of the fish held on the far right. Fewer fish were observed actively swimming above B3, but they were observed moving up the center and right sides at 3 cfs and on the right side at 8 cfs.

For tests ***without baffles at the standard backwater condition,*** fish that were observed holding between the B1 and B2 locations were almost always observed on the right side. Fish swimming between the B1 and B2 locations also appeared to use the right side of the culvert most of the time, although fish were also observed using the left side and center to move upstream. Between the B2 and B3 locations, fish were observed holding in all locations at 1.5 cfs, but shifted to the far right side at 3 cfs and above. Fish were observed swimming between the B2 and B3 locations much more often than they were observed holding. Between the B2 and B3 locations, fish used the center and right sides most often to swim upstream at 1.5 cfs and 3 cfs, and then used the right side most often at 6 cfs and above. More fish were observed holding than swimming above the B3 location. These fish were most often observed at the far right or center at 3 cfs and at the far right at 8 cfs. Fish that did not pause after crossing the B3 location were observed at the right and center at 3 cfs and on the right at 8 cfs.

4.3 Culvert Slope Change

On February 8, 2006, the culvert slope was changed from 1.14% to 4.33% to determine how long the slope change would require and to develop a standard protocol for changing the slope (Figure and 40). The tailwater tank's culvert plate was lowered four bolt-holes to reach the new grade. The following day, water was supplied to the system and leaks were identified and then sealed. It was determined that two people can change the culvert slope in approximately one day. Additional time and materials will be required to increase the slope further, as the procedure will require the removal of a metal panel and replacement of gasket material.

Figure 39. Culvert at 1.1% Slope

Figure 40. Culvert at 4.3% Slope

5.0 Discussion and Conclusion

The statistical study design used paired comparisons of the passage success of juvenile coho salmon of two culvert bed configurations (baffled and unbaffled) observed with replication over a series of flows, i.e., 1.5, 3, 6, 8, and 12 cfs. The relationships between natural logarithm of passage success of juvenile salmon (94 to104 mm) and culvert discharge were statistically significant and curvilinear for all three configurations examined. For the configuration without baffles, passage success was about 40% at 1.5 cfs, increased to about 70% at 3 cfs, and then decreased to less than 10% at 12 cfs. The curves for configurations without baffles and with baffles and elevated backwatering condition do not differ significantly. Both these curves are significantly greater than the curve for the configuration with baffles and standard backwatering condition. Because these findings indicate that backwatering influences passage success through baffled culverts, we recommend that the degree of backwatering be considered as an experimental variable in future studies.

Comparison of these results with previous results for the unbaffled configuration (Pearson et al. 2005) indicates that fish size or perhaps season influences passage success. We recommend that the study design used here be repeated with small juvenile coho in the spring to determine whether the patterns of success versus culvert discharge are similar for small coho in the spring.

Different behaviors occurred with and without baffles at 1.5 cfs and not at higher flows. The fish at 1.5 cfs exhibited more exploratory behavior than those at higher flows. The observations suggest that consistent upstream movement in larger juvenile coho in this setting may require a cue that is associated with flows greater than 1.5 cfs. The nature of the cue is not known but could be related to higher velocities, greater depth, or more distinct low velocity pathways.

Fish behavior above 1.5 cfs appears to be distinctly different from that at 1.5 cfs. Statistical analysis found a significant quadratic relationship between the probability of passage success and the number of entries for all configurations at flows above 1.5 cfs. This relationship for the baffled configurations proved to be significantly different from that for the unbaffled, standard backwatering configuration. The findings suggest that fish may be achieving the same level of passage success for less effort in the baffled configuration than the unbaffled configuration. Also, these findings further support our recommendation for repeating the study design with smaller coho salmon.

The behavioral observations indicate that the fish used low velocity pathways to accomplish passage and that these pathways differed between the baffled and unbaffled condition and perhaps differed with flow for the baffled condition. Without baffles, fish moved, held position, and swam predominantly on the right side of the culvert looking upstream. Pearson et al. (2005) observed this same pattern in which smaller coho used the reduced velocity zone to move upstream and exit the culvert. With baffles, the behavior and hydraulics were more complex. As culvert discharge increased, the fish shifted their locations when they crossed baffles, held position, and had a tendancy to swim in the lowest velocity pathways when accomplishing passage. Further understanding of the relationship between hydraulics and behavior requires hydraulics measurements at all the discharges at which biological tests are conducted. We recommend that additional hydraulic measurements be conducted to provide data at all test discharges for which we do not have hydraulic measurements.

Overall, the results obtained thus far in the culvert test bed system demonstrate that the juvenile coho salmon have remarkable abilities to adapt their behavior to accomplish upstream passage in different system configurations and under different flows. The fish appear to be able to find and use low velocity pathways to accomplish the passage.

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