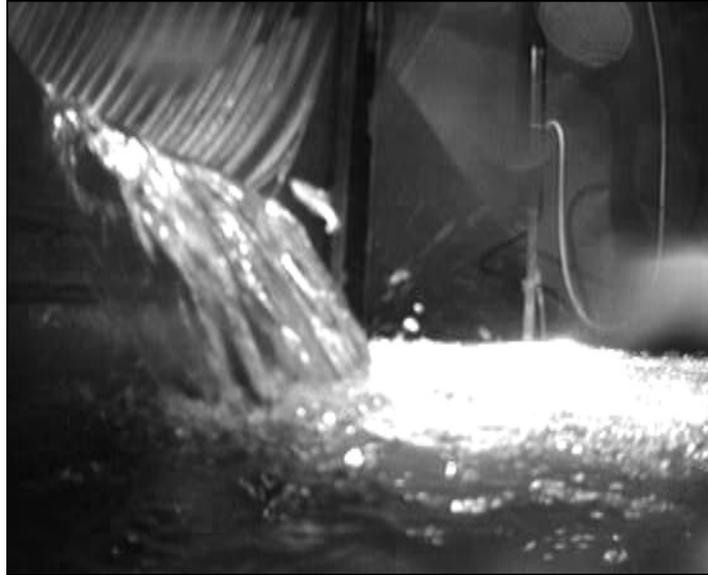


## **Evaluation of Juvenile Salmon Leaping Ability and Behavior at an Experimental Culvert Test Bed**



W. H. Pearson  
R. P. Mueller  
S. L. Sargeant  
C. W. May

FINAL REPORT  
June 2005

Prepared for:  
Washington State Department of Transportation  
WSDOT Agreement No. GCA2677

**Battelle Pacific Northwest Division**

Richland, WA 99352

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## Executive Summary

Determining conditions in culvert systems that enhance upstream passage of juvenile salmon has become increasingly important for two reasons. First, recent research has shown that upstream movement of juvenile salmon is more common than previously supposed. Second, large numbers of culverts are blocking thousands of miles of stream habitat throughout the Pacific Northwest. The Battelle Pacific Northwest Division (PNWD) conducts the Culvert Test Bed (CTB) program for the Washington Department of Transportation (WSDOT) to provide systematic, controlled assessments of culvert designs, along with associated measurements of hydraulic conditions and fish behavior, occurring in full-scale physical models of culvert systems. The experimental test bed is located at the Washington Department of Fish and Wildlife (WDFW) Skookumchuck Hatchery near Tenino, Washington.

Little is known about the capability of juvenile salmonids to access upstream habitat by overcoming barriers. Juvenile fish accomplish passage into and through culverts by using their swimming capabilities and adaptive behaviors. One example of these capabilities and behaviors is the leaping ability of juvenile salmon, which the juvenile fish may use to enter perched culverts. Many culverts can become barriers to juvenile passage when they are *perched*. A perched culvert is one where the culvert invert at the downstream end is above the water surface of the downstream pool, thereby creating a waterfall. This report provides data from the initial research that Battelle conducted in December 2004 and January 2005. The work reported here aimed to evaluate the ability of juvenile coho salmon to leap or swim into a perched culvert.

The basic approach was to present juvenile salmon with one of five different outfall drops and then measure the success with which the juvenile fish swam or leaped into the culvert. The outfall drop is the vertical distance between the water surface in the culvert at its entrance and the water surface in the tailwater tank downstream. All trials were performed with naïve juvenile coho salmon (~103 mm, hatchery stock). Also, all trials were of 3-h duration, completely at night, and with 100 fish per trial. In the main experiment, all trials had a flow rate of 1 cfs and tailwater pool depth of 30 cm. The culvert tailwater tank and culvert entrance (used here to refer to the downstream end of the culvert) were configured to examine for the ability of juvenile salmon to enter the culvert at 5 different outfall drops. These outfall drops were 0 cm, 12-cm, 20 cm, 26 cm, and 32 cm. The 0-cm outfall drop had streaming flow; the other outfall drops of 12 cm and greater had plunging flow. Several video cameras recorded fish behavior in the tailwater pool and the leaps of fish from the pool into the culvert. A successful entry

event was taken as occurring when a fish was observed to leap or swim into the culvert and to remain in the culvert for 3 sec or more. In addition to data on entry rates, data on leaping attempts, both successful and unsuccessful, and on culvert passage success were collected and analyzed. Passage success was measured as the proportion of the total number of fish released into the tailwater tank that were found in the headwater tank at the end of the trial. Because there is currently no way to track individual fish, data on leaping attempts per fish were not collected.

Results of the trials showed that culvert entry rate and passage success decreased as outfall drop increased. The highest entry rate was 71% success at the 0-cm outfall drop (streaming flow), followed by 30% at the 12-cm drop, 18% at the 20-cm drop, 3% at the 26-cm drop, and 0% at the 32-cm drop. The dominant behavior used to accomplish entry varied with outfall drop. When overcoming the 0-cm and 12-cm outfall drops, juvenile coho salmon predominantly used swim-in behavior. For the greater outfall drops of 20 and 26 cm, leaping was the dominant behavior. Leaping events were typically characterized by initiating the leap near the floor of the tailwater tank and using burst swimming to propel their bodies from near the standing wave (produced by the fall of the water exiting the culvert) into the culvert entrance. Both high and low trajectory leaps were observed, with some fish attaining a height up to 5.2 times their body length. However, no fish were able to successfully overcome the 32-cm outfall drop, which was equivalent to approximately 3 body lengths for the 100-mm coho salmon used in this study.

Failed entry attempts were also documented and occurred mostly at outfall drops greater than 12 cm. The rate of successful entry events increased with time as each 3-h test period progressed. Cold weather in January lowered water temperatures and a lower entry success was measured during two trials during cold weather. The potential effect of the cold temperatures may have led to underestimating entrance success at the two lowest outfall drops. The zone of turbulence (entrained air) in the tailwater pool produced from the plunging flow of water from the perched culvert ranged from 1.05 to 1.55 m<sup>2</sup>. The majority of successful leaps were initiated along the edges of this turbulent zone, apparently utilizing the upwelling areas associated with the plunge plume.

In our study, leaping success was greater for those fish observed to use the standing wave at the edge of the plunge plume. Leaping success is probably not only a function of the outfall drop and swimming performance but also a function of the hydraulic conditions in the downstream pool depth and the characteristics of the plunge plume. We suggest that additional research be conducted to determine how fish interact with the plunge plume and exploit its characteristics to support leaping behavior and culvert entry.

## **Acknowledgments**

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## 1.0 Introduction

Determining conditions in culvert systems that enhance upstream passage of juvenile salmon has become increasingly important for two reasons. First, recent research has shown that upstream movement of juvenile salmon is more common than previously supposed (Kahler and Quinn 1998, Kahler et al. 2001). Second, large numbers of culverts are blocking thousands of miles of stream habitat throughout the Pacific Northwest.

The Washington State Department of Transportation (WSDOT), in cooperation with partner state and federal agencies, as well as private partners, is currently leading a pooled-funds program to study juvenile salmonid passage through road culverts and to evaluate designs of retrofitted culverts to improve the success of upstream passage by juvenile salmonids. A large part of this research is being carried out at the Culvert Test Bed (CTB) at the Washington State Department of Fish and Wildlife (WDFW) Skookumchuck Rearing Facility near Tenino, Washington. The Pacific Northwest Division (PNWD) of Battelle conducted hydraulic and biological research on evaluation protocols at the CTB during 2003 and 2004 (Pearson et al. 2005).

Based on a review of the available scientific literature (Kahler and Quinn 1998), little is known about the capability of juvenile salmonids to access upstream habitat by overcoming barriers. 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. Excessive flow velocity, inadequate water depth within the culvert, an obstruction at the culvert outlet, or a perched condition at the culvert entrance (used in this report to refer to the downstream end of the culvert where fish enter) can restrict fish entry into a culvert (Figure 1). Juvenile fish accomplish passage into and through culverts by using their capabilities and adaptive behaviors. The success of passage depends upon the interaction of fish capabilities and behaviors with the culvert's physical structure and hydraulic conditions.

An example of these capabilities and behaviors is the leaping or jumping ability of juvenile salmon. Lauritzen et al. (2000 and 2001) has ascribed the inadequate designs of fish passage structures to lack of attention to the leaping abilities and other adaptive behaviors of fish during the design processes for fish passage structures. Collectively, *leaping* behavior can occur in at least three contexts in relation to culvert passage:

- 1) Entering a culvert
- 2) Passing over weirs or baffles inside a culvert

### 3) Moving up a fish ladder or similar passage structure associated with a culvert

This report presents the results of initial research for WSDOT by PNWD at the CTB in December 2004 and January 2005 to assess the leaping ability of juvenile coho salmon (*Oncorhynchus kisutch*). Although research components of the overall CTB program will attempt to address leaping ability in all three contexts, the initial work described here focuses only on how leaping ability is used to enter culverts (especially perched culverts). In addition, attention was given to observing the general abilities and adaptive behaviors of the juvenile fish that could support behavioral responses in all three contexts.

## 1.1 Background

Many culverts can be barriers to juvenile passage because they are *perched*. A perched culvert is one where the culvert invert at the downstream end is above the water surface of the downstream pool, thereby creating a waterfall. Perched culverts are relatively common in streams where flow conditions have changed due to changes in land cover or land use in the upstream contributing watershed, which cause channel-changing flows, as well as scour, incision, and head-cutting of the streambed. Perching can also occur through natural degradation of the streambed.

The term "perch height" has been used in various ways for various purposes. For example, culvert perch height is one of several parameters in the "FishXing" program of the U.S. Forest Service (USFS 1999), software intended to assist the assessment of culverts for fish passage. Here we offer the nomenclature to be used in this report, as follows:

***Perch Height:*** The vertical distance between the water surface in the tailwater tank and the culvert invert at the culvert outlet (Figure 2). This distance remains the same regardless of flow in the culvert. This definition is consistent with that used in the FishXing 3.0 Beta Version (K. Bates, Personal Communication).

***Outfall drop:*** The vertical distance between the water surface in the tailwater tank and the water surface in the culvert at the entrance (Figure 2). This distance does vary with flow. This definition is consistent with that for the term "vertical leap height" used in FishXing 2.2 (USFS 1999).

Under perched conditions, juvenile leaping height is typically measured by the outfall drop overcome in the leap or distance between the surface of the tailwater pool and the

surface of the water at the entrance to the culvert (Figure 2). Leaping success depends on a combination of fish characteristics and hydraulic conditions in the tailwater pool and in

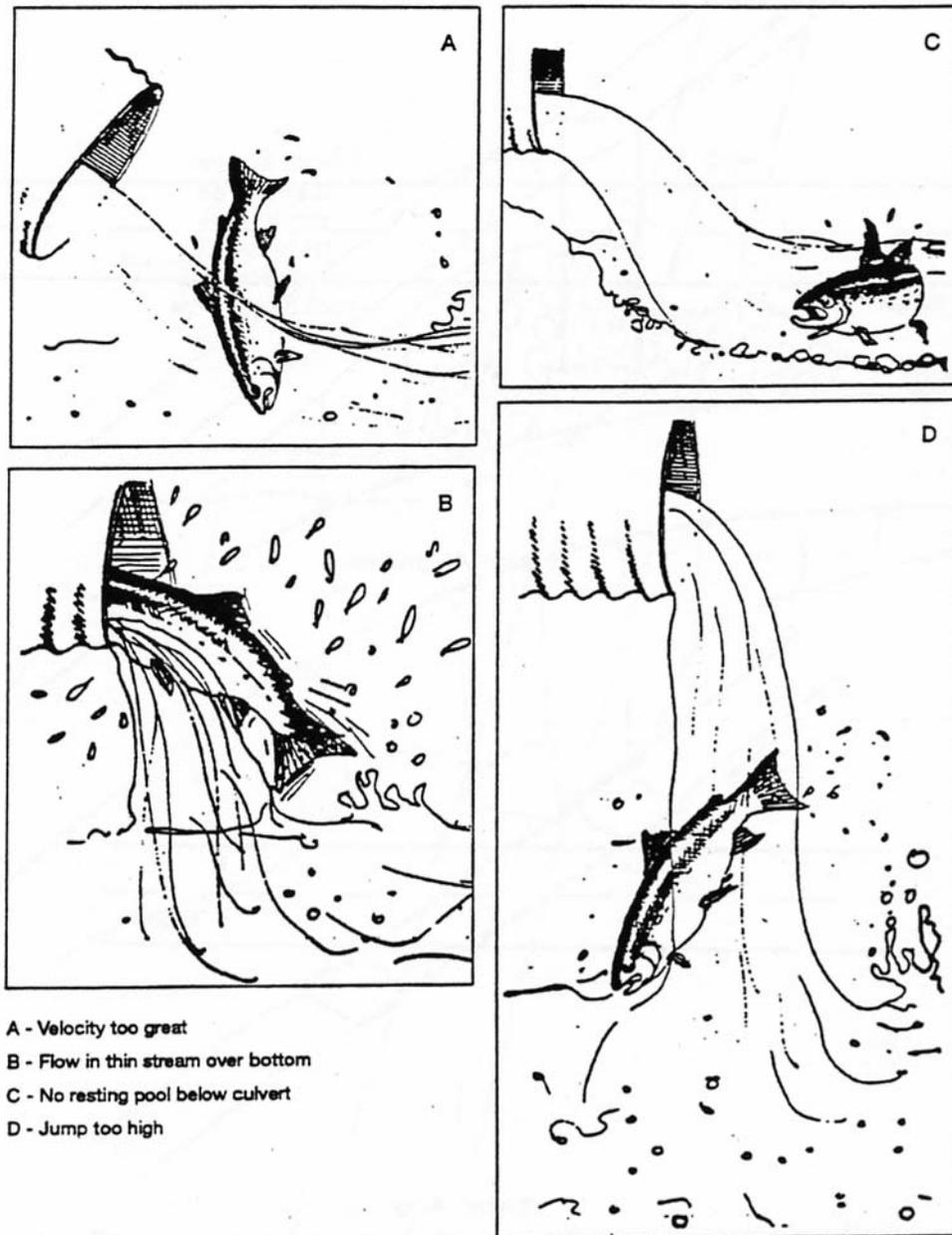


Figure 1. Examples of culvert fish-passage barrier conditions (Powers and Orsborn 1985).

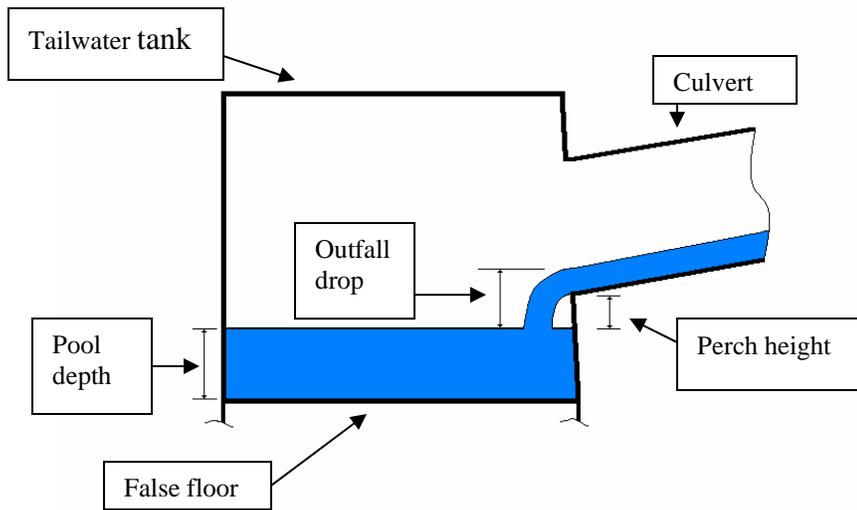


Figure 2. Diagram of culvert entrance showing outfall drop, perch height, and tailwater pool depth (net pen excluded from drawing for clarity).

the culvert. Leaping ability has a significant bearing on the ability of fish to pass over baffles or weirs within culverts and through fish ladders and similar passage structures.

Juvenile fish passage research to date has focused on characterizing the hydraulic conditions and culvert under which juvenile fish successfully swim through a culvert (Powers et al. 1997, Kane et al. 2000). Few studies have been conducted on the ability of juvenile salmon to leap in order to overcome obstacles or falls, both natural and manmade, and enter a perched culvert.

A study of salmon and trout leaping behavior at waterfalls and other obstructions was one of the first research efforts conducted in this focus area (Stuart 1962). Stuart conducted a series of laboratory flume tests and field observations to investigate the leaping behavior of juvenile salmon and trout and mature minnows faced with obstructions and falls. In the laboratory experiment, about 150 salmon parr and trout (1+ and 2+ years, ranging from 60 cm to 150 cm) were introduced in groups of 20 to a flume outfitted with a series of pools and varying weir configurations (broad spillway, rectangular notch, triangular notch, and trapezoidal notch). The height of the falls between pools could be changed by adjusting dam heights. Pool depth was adjustable by changing the gradient of the flume. The overall dimensions of the flume were 15.25 m x 0.38 m x 0.46 m (50 ft x 1.25 ft x 1.5 ft). The flume consisted of two sections, of which the upper section was 44.8 cm (20

in) above the lower section. Water temperatures were not regulated and ranged between 10°C and 12°C. A skylight illuminated the channel.

Stuart (1962) varied the flow from 0.009 cubic feet per second (cfs) or 4 gallons/minute (gpm) to 0.067 cfs (30 gpm). He also varied the pool depth. He found that when a standing wave formed (where the scouring and depositional processes were in equilibrium), the salmon were stimulated to leap. If the pool depth was sufficient to submerge the wave at the toe of the falls, the salmon were able to orient their leap. If the standing wave formed too distant (downstream) from the obstacle – which occurred if the pool was too shallow and the weir was sloped - the fish were unable to successfully leap the crest of the falls, and their leaps were not orientated in any consistent manner. The leap was initiated near the surface at the point where the standing wave was neutral. Stuart (1962) suggests that the visual stimulus, as it relates to the height of the obstacle and the ability to orient the leap, is important. The evidence for this was the cessation of leaping under low light conditions. Stuart (1962) also found that most fish were observed leaping from the surface. Stuart (1962) indicated that the plunge pool depth should be 25% greater than the outfall drop in order to establish the hydraulic conditions for leaping.

Lauritzen (2002) studied the behavior of adult sockeye salmon at waterfalls and fish ladders and in a laboratory waterfall, and his findings support some but not all of the conclusions of the earlier research by Stuart (1962). Both Lauritzen (2002) and Stuart observed that some water flow was necessary to induce upstream movement and leaping. Both observed that salmon use the standing wave to facilitate their leaps. In the Lauritzen (2002) study, most adult salmon initiated their leap from depth, bursting to the surface at high speed. In contrast, Stuart (1962) observed leaping initiated from the surface with a C-Start response. Mayama (1987) has also postulated that swim-up ascents might be more successful for juvenile salmonids. Whereas Stuart (1962) indicates that an outfall-drop:pool-depth ratio of 1:1.25 is conducive to leaping, Lauritzen (2002) found that ratios around 1:1 were conducive of leaping. Lauritzen (2002) also found that very deep plunge pool depths could actually inhibit leaping due to the loss of upward turbulence that aided the fish in initiating leaping. Lauritzen (2002) concluded that adult salmon have very specific hydrodynamic preferences for initiating leaping behavior. Factors such as water flow rate, plunge pool depth, outfall drop, and the falls gradient all proved influential (Lauritzen 2002). The research of Lauritzen (2002) also lead to a theoretical model describing the relationship between the barrier height and two leap-related parameters: distance between takeoff and successful landing and takeoff velocity.

Concerning pool depth, Powers and Orsborn (1985), citing the findings of Aaserude (1984), offered two recommendations concerning the preferred depth of the plunge pool below the culvert outlet. First, the depth of the plunge pool should be greater than the length of the fish. Second, the depth of penetration of the falling water should be less than the depth of the plunge pool.

Symons (1978) found that juvenile coho salmon proved to be capable of leaping as high as five body lengths in height in a laboratory waterfall. The experimental setup included a laboratory flume with a headwater pool where the falls initiated, and a plunge pool at the base of the falls. The headwater pool was at least 10 cm deep and incorporated a net system to prevent fish that successfully made the leap from being washed back over the falls. The plunge pool was greater than 100 cm in depth and the falls height could be varied between 0 cm and 57 cm (Symons 1978). The coho salmon used in these experiments were between 7 cm and 11.5 cm in length. Three falls heights were tested; 12 cm, 27 cm, and 57 cm. For the 12-cm falls, 8 of 25 (32%) fish made the leap. For the 27-cm falls, 5 of 30 (17%) fish were successful in leaping the falls. Only 2 of 30 (7%) fish tested were able to leap the 57-cm falls (Symons 1978). The Symons (1978) study concluded that falls of these heights do not present an absolute barrier to upstream movement of juvenile coho salmon if the optimum hydrodynamic conditions exist (e.g. adequate plunge pool depth, reasonable water velocity, and the availability of a low-velocity headwater pool at the top of the leap). With regard to perched culverts, Symons (1978) concluded that the limiting feature for successful leaping was more likely to be the lack of a headwater pool with low velocity and little turbulence. In most cases, there is an adequate plunge pool scoured out at the outlet of a perched culvert to support leap initiation.

A study of brook trout tested 0-age brook trout (76 mm total length) in laboratory experiments to test the leaping ability and effects of light intensity for fish introduced to waterfalls 2 cm to 24 cm in height and plunge pools 8 cm to 18 cm in depth (Brandt et al. 2005). They found that brook trout were most likely to leap at waterfalls <10 cm and pool depths >10 cm or more. Tests conducted indicated that different light intensities did not have a significant impact on the leaping success (Brandt et al. 2005).

Besides light, water temperature may be a factor in leaping. Symons (1978) found that proportionately more fish leapt at higher water temperatures (between 14°C and 17°C) than at lower temperatures. Also, swimming performance, including sustained and burst speed, decreases as temperature decreases below the optimal metabolic temperature (Glova and McInerney 1977).

## 1.2 Objectives of This Study

The review of Kahler and Quinn (1998) indicates a lack of research on the capability of juvenile salmonids to access upstream habitat by overcoming barriers and on the behavior of juveniles during passage of barriers. This gap in our knowledge includes poor understanding of the leaping ability of juvenile salmonids and other fish. More effective designs of fish-passage systems require attention to leaping and other behaviors (Lauritzen et al 2000, 2001).

Several research questions related to “leaping ability” need to be answered and include:

- Is there a threshold of outfall drop that juvenile fish cannot overcome?
- At what outfall drop do juvenile fish shift from a “swim-in” to a “leaping” behavior (current understanding is that this is in the range of one “fish-length” of outfall drop)?
- Is there a minimum required pool depth for successful leaping or is there a specific range in the relationship between pool depth and outfall drop (e.g. pool depth > 1.25 outfall drop) that facilitates leaping success?
- How do juvenile fish approach a barrier that requires leaping ability to overcome?
- Do juvenile fish leap from the surface of the pool or do they swim at burst speed from a depth in the pool?
- Does the location of leap initiation affect leaping and passage success?
- Do juvenile fish leap more successfully from the upwelling zone just downstream of the plunging water or from some other position?
- What are the hydraulic characteristics of the tailwater pool that cue fish orientation and enhance leaping success?
- What are the hydraulic characteristics of the culvert outlet that enhance leaping success?

The above list of questions is not an exhaustive one but does offer pertinent starting points to the study of leaping ability. Many of the research questions are behavioral in nature. One area of interest is to define the conditions under which juveniles may switch from one adaptive behavior to another, e.g., at what outfall drop do juvenile fish shift from a “swim-in” behavior to a “leaping” behavior in accessing a perched culvert. This switch, if it can be detected, likely depends on fish capabilities as well as culvert-flow or plunge-pool conditions. It is also unclear exactly how juvenile fish swim or leap over barriers.

The overall goal of the work reported here was to provide more information on the quantitative relationships between leaping success of juvenile coho salmon and culvert characteristics. The specific objectives of the observations reported here were the following:

- Determine the relationship between leaping success and outfall drop.
- Determine the outfall drop at which juvenile coho salmon switch from "swim-in" behavior to "leaping".
- Make a preliminary exploration of the relationship between leaping success and pool depth.
- Describe the general behaviors involved in leaping.

To address these questions, a series of trials were conducted to measure the leaping success of juvenile hatchery coho salmon under a variety of conditions, e.g., culvert outfall drops, water flows, and tailwater pool depths.

## **2.0 Methods**

A total of 18 tests were conducted during the study period, which ran from mid-December 2004 to mid-January 2005. Our initial leaping-ability testing focused on quantifying the success of juvenile fish in entering a perched culvert and on qualitative behavioral observations of juvenile fish leaping. Test trials were conducted at the CTB facility to measure the leaping success of juvenile hatchery coho salmon over a range of outfall drops. Analysis of behavioral observations and video records provided information on the behaviors used to accomplish entry into perched culverts.

### **2.1 Test Fish**

Experimental trials used 1,800 juvenile coho salmon from the WDFW Skookumchuck Rearing Facility. The hatchery fish available at the time of the trials ranged from 60 to 138 mm and averaged 103 mm. The fish remained under the care of WDFW personnel until used in the culvert test bed experiments. Fish to be tested were taken from Rearing Pond 1, and then returned to Rearing Pond 2 at the conclusion of each trial, ensuring each fish was tested only once.

### **2.2 Test Conditions**

Leaping ability trials were conducted at the Culvert Test Bed (CTB). The CTB is described in detail in the appendices of Pearson et al. (2005). The culvert installed in the CTB for the tests here was a 1.8-m (6-ft) round corrugated steel culvert, set at 1.1% slope. The culvert was bare, without bed material or baffles. To vary outfall drop (at a fixed culvert slope and flow), the stop-logs in the downstream weir were adjusted to raise or lower the water depth in the tailwater tank. A net pen constructed from 3/16 in nylon mesh netting with 2.54 cm (1-in) diameter PVC frame was placed in the tailwater tank to facilitate removal of fish at the conclusion of each trial. The pen is 2 m wide x 2.2 m long. Just below the pen was a false floor constructed of perforated steel and adjusted by winch and cable systems. The perforations were 1/8 in by 1 in and provided a 44% open area.

The findings of recently completed pool-size and fish-density testing were used to set conditions that were conducive to fish movement upstream through the culvert. Because shallow pool depth may inhibit jumping and thereby negatively influence leaping ability measurements, the tests reported here incorporated a slightly deeper pool depth than was found to elicit the greatest percent passage during previous tests (i.e., 30 cm as opposed to 23 cm) (Pearson et al. 2005). To maintain a constant pool depth for all outfall drops,

the false floor and the net pen in the tailwater tank were raised or lowered using hand-operated winches. The water depth in the culvert at the downstream end was similar for all tests (~7 cm).

Leaping ability testing was conducted using 100 juvenile coho salmon per trial. Previous testing at the CTB with juvenile coho salmon showed that fish were most likely to move upstream during the night (Pearson et al. 2005). Therefore, all tests were conducted after dark and were of 3-h duration. The first trial of the night was initiated at full dark (after 1800h) and the second was initiated as soon as practicable, following completion of the first trial. The second trial was always terminated well before daybreak (usually by ~ 3 am). When possible, a paired series of trials were performed over one night (Table 1). There were two sets of trials. The first set was to determine the threshold outfall drop at which juvenile fish failed to enter the culvert system. For the first set, three replicate trials were performed for each outfall drop. All trials in the first set were done under a flow of 1 cfs. The second set of trials were initial trials to examine the influence of pool depth and flow on leaping ability and were conducted at 1.5 and 2.0 cfs and/or at a 42-cm or 30-cm pool depth (Table 1).

Table 1. Leaping ability tests conducted in December 2004 and January 2005. (Fish length [FL] is equivalent to approximately 100 mm for the fish used in this phase of the test program).

Outfall drop (Approximate Fish Lengths)	Replicates	Flow (cfs)	Tailwater Pool Depth (cm)
<u>First Series</u>			
0 cm (streaming)	3	1	30
12 cm (1 FL)	3	1	30
19-20 cm (2 FL)	3	1	30
26 cm (2.5 FL)	3	1	30
32 cm (3 FL)	3	1	30
<u>Second Series</u>			
0 cm (streaming)	1	2	42
12 cm (1 FL)	1	1	42
12 cm (1 FL)	1	1.5	30

The first set of trials were conducted with the culvert initially set to a condition where the water was “streaming” out of the culvert into the tailwater pool with no vertical plunge and no backwater effects. In contrast, "plunging flow" has a visible drop and the water

falls or "plunges" into the downstream segment. Following the trials at streaming flow, the outfall drop was increased sequentially in increments (12, 20, 26, and 32 cm) until a outfall-drop threshold was established where fish did not successfully leap into the culvert. Outfall drop was measured as the distance between the water surface in the tailwater tank and the surface of the water at the outlet of the culvert (Figure 2). Three replicate trials were done at each outfall drop, including the steaming flow. The photographs in Figures 3 and 4 illustrate the conditions for each outfall drop condition tested.

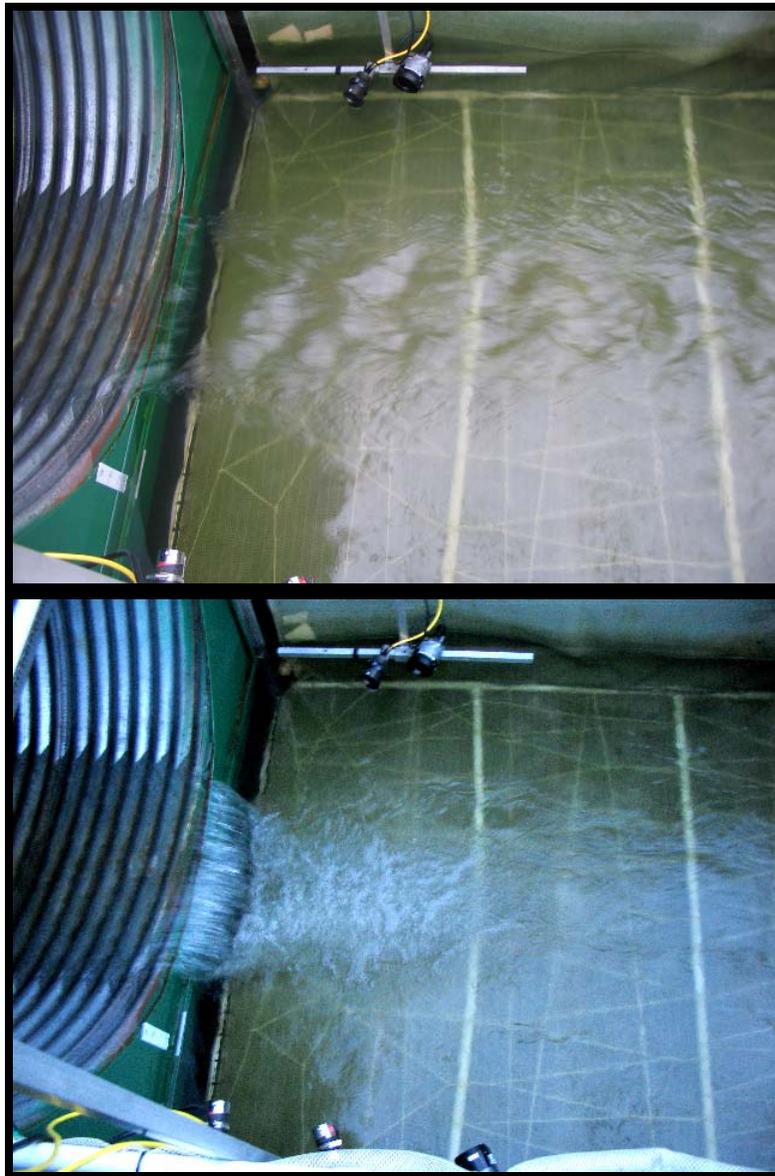


Figure 3. Culvert entrance with 0-cm outfall drop (streaming flow, top) and 12-cm outfall drop (bottom)



Figure 4. Culvert entrance with a 26-cm outfall drop (plunging flow, top) and 32-cm outfall drop (plunging flow, bottom)

### 2.3 Monitoring System

A combination of two underwater cameras and two above-water cameras with associated lighting equipment were placed at the culvert entrance to monitor and record fish movement and behavior throughout the testing period (Figure 5). Underwater cameras were situated at either side of the culvert entrance. One above-water camera was positioned above the culvert entrance and a second above-water camera was positioned perpendicular to the culvert entrance to record fish leaping behavior. To enable viewing at night, above-water and underwater infrared illuminators operating at 880 nm were used in conjunction with each camera. The cameras were connected to a digital multiplexer and video recording system housed in a nearby work trailer.

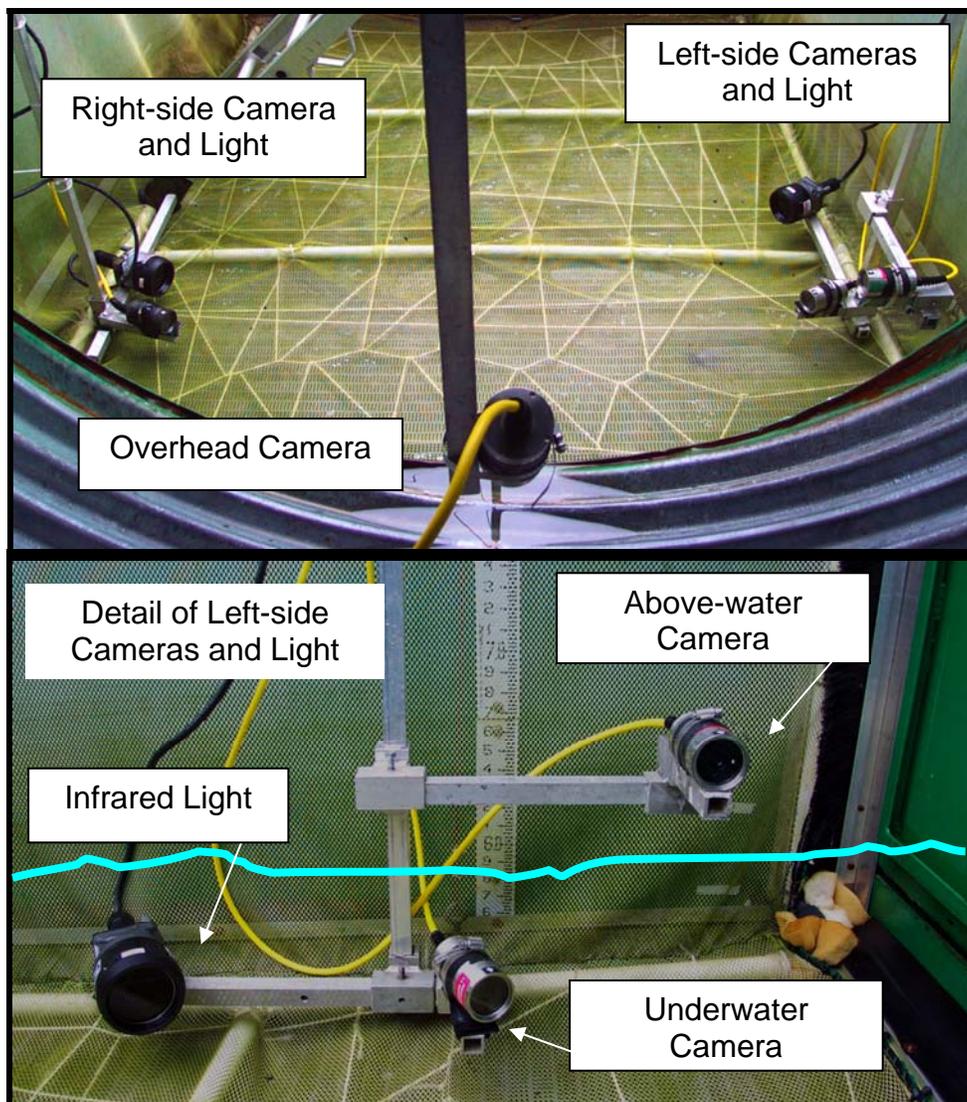


Figure 5. Cameras and infrared lighting used to observe fish behavior (blue line indicates waterline).

## **2.4 Test Protocol**

On the day of testing, fish were captured from a rearing pond with dip-nets and transported in 5-gallon buckets to a recirculating holding tank supplied with hatchery pond water originating from the Skookumchuck Reservoir. Fish were not fed between the time of collection and testing. Immediately before testing, the test fish were counted and carried from the holding tank to the CTB tailwater tank. With the CTB in operation at the prescribed flow and test conditions, the fish were released into the tailwater tank net pen to start the test.

During each 3-h test, two observers stationed in a trailer located near the CTB watched the video monitor and each recorded fish behavior and culvert entry events in real-time. An entry event occurred when a fish was observed to leap or swim into the culvert and to remain in the culvert for 3 sec or more. Attempts and failures were also noted but these events were often difficult to observe in real time. Review of all of the video records was not undertaken. At test completion, the end screens at the culvert entrance and culvert exit were lowered simultaneously to isolate the fish in one of three areas: tailwater tank, culvert barrel, or headwater tank. Water flow was lowered to retrieve fish in the tailwater pool, then turned off completely prior to retrieving fish in the headwater and culvert sections. Fish were retrieved from each area separately and counted. A subset of fish (up to 20 fish per section) were anesthetized and measured (fork length) prior to returning all tested fish to a second rearing pond.

## **2.5 Data Analysis**

Fish behavior and culvert entries and attempts were observed in real-time and recorded on data sheets by two observers. Data recorded included the test number and test conditions, number of fish tested and number of fish recovered at the end of testing. All fish were counted and a subset of fish from each of the three sections was measured to provide a comparison of fish size between those that entered the culvert and those that remained in the tailwater tank. Other information recorded in real-time included the time of each entry or attempt at entry that was observed, and typical behaviors observed in the fish during every 10-minute increment for the duration of the test (e.g., milling, holding). In addition, video from each camera was stored in the CTB digital video recording system to preserve the possibility for detailed analysis after the testing was completed. Statistical analyses, including regression analyses and a nonparametric (Kruskal-Wallis) test, were performed on the data to determine if there were significant differences between fish entry into the culvert at each outfall drop.

## 3.0 Results

### 3.1 Culvert Entry Rates

Table 2 summarizes the test conditions and percent entry into the culvert during this leaping ability testing. An outfall drop of 0 cm represented streaming flow, 12 cm = approximately 1 fish length, 20 cm = approximately 2 fish lengths, 26 cm = approximately 2.5 fish lengths, and 32 cm = approximately 3 fish lengths. Flow was held constant at 1 cfs for all but two tests. The number of fish tested (100) was the same for all trials. Pool depth was set at 30 cm with the exception of two tests conducted with a 42 cm pool depth. The water depth was measured at the culvert entrance in the center of the culvert.

Table 2. Results of fish testing during December 2004 and January 2005 (Outfall drop of 0 cm = streaming flow); n=100 for all tests. ND = no data. The thermometer was broken on night of Trial 36.

Test	Outfall drop (cm)	Pool Depth (cm)	Flow (cfs)	Water Depth in Culvert (cm)	Percent Entered Culvert	Water Temperature (°C)
25	0	30	1	5.5	85	4
26	0	30	1	8	88	4
35	0	30	1	9	39	2
27	12	30	1	7	34	4
28	12	30	1	7	40	4
36	12	30	1	7	16	2
32	20	30	1	7	20	4
31	20	30	1	7	29	4
38	20	30	1	7	4	ND
29	26	30	1	7	2	4
30	26	30	1	7	6	3
39	26	30	1	7	0	ND
33	32	30	1	7	0	1.5
34	32	30	1	7	0	1.5
37	32	30	1	7	0	ND
41	13	42	1.5	8	23	6
40	12	42	1	7	23	ND
42	0	30	2	10	40	6

Successful entry into the culvert barrel decreased with increasing outfall drop (see Figures 6, 7, and 8). A nonparametric (Kruskal-Wallis) test indicates there was no significant difference between the proportions of fish entering the culvert at adjacent outfall drops tested (e.g., between 0-cm and 12-cm outfall drops ( $p = 0.127$ )). However, based on a linear regression analysis, the proportion of fish entering the culvert at a outfall drop of 12 cm was significantly different from those entering at a outfall drop of 32 cm ( $p = 0.03$ ). There was a significant linear regression ( $p < 0.001$ ) of the percent of fish entering the culvert outlet as a function of outfall drop. Two trials (35 [0-cm outfall drop] and 36 [12-cm outfall drop]) were conducted during a period of unusually cold air temperatures (approximately  $-4^{\circ}\text{C}$  [ $25^{\circ}\text{F}$ ]) and had considerably lower passage rates than tests conducted during periods with warmer air temperatures (39% entry at 0-cm outfall drop [cold] compared to an average of 86% entry at 0-cm outfall drop [warm]) and (16% entry at 12-cm outfall drop [cold] compared to an average of 37% entry at 12-cm outfall drop [warm]). For tests conducted with a 30-cm pool depth and 1 cfs flow and including the two cold temperature trials (No. 35 and 36), the streaming flow trials (0-cm outfall drop) had the highest mean percent entry into the culvert (71%). The 12-cm outfall drop produced the next highest mean percent entry at 30%, followed by means of 18% for the 20-cm outfall drop, 3% for the 26-cm outfall drop, and 0% for the 32-cm outfall drop.

To determine if the plunge-pool depth had any impact on passage rates, two tests were conducted at a pool depth of 42 cm with a 12-13 cm outfall drop and flows of 1 cfs and 1.5 cfs. The mean passage rate for both tests was 23% while the mean passage rate for the 30-cm pool depth tests was 34% at 1 cfs. Figure 6 shows the results of both the first and second series of trials, including those at the deeper pool depth and cold temperature dates. Figure 7 shows the regression analysis results for the first series of trials on leaping success and outfall drop. The regression included all the data (both trials 35 and 36). The dependent variable used in regression was the arc-sine-root-square transformation of the proportion of fish successfully entering the culvert. The arc-sine-root-square transformation is routinely used with data expressed as proportion to satisfy the assumption of normal distribution in the application of regression analysis.

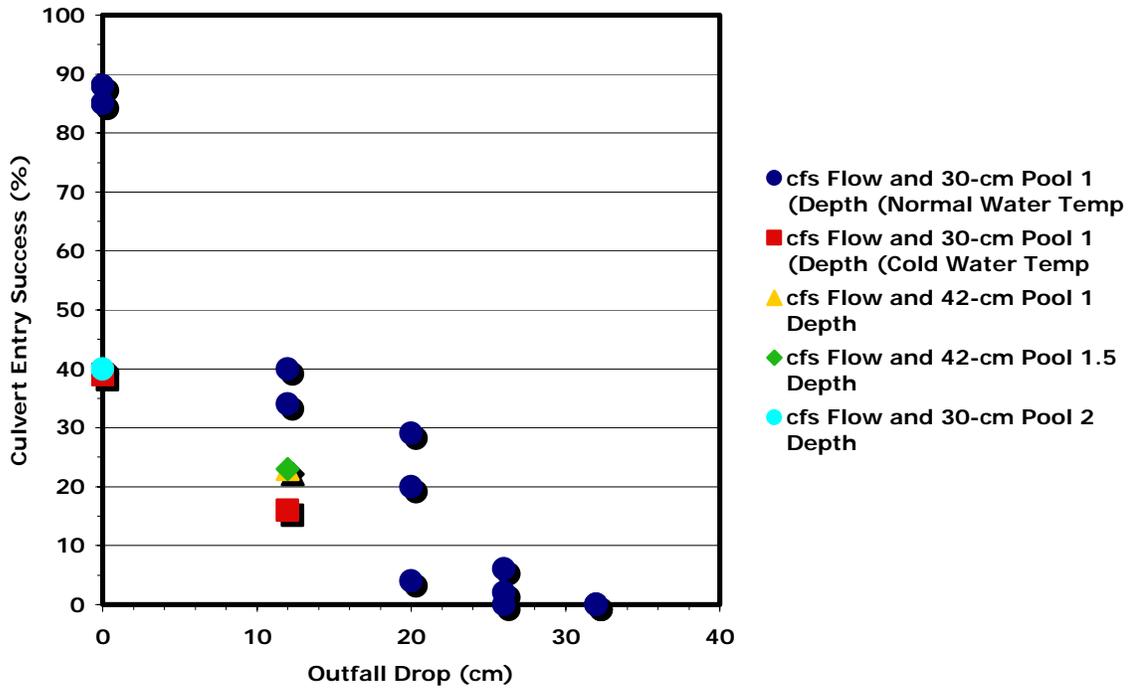


Figure 6. Culvert entry success for all tests including 42-cm pool depth, cold temperature, and higher flow tests.

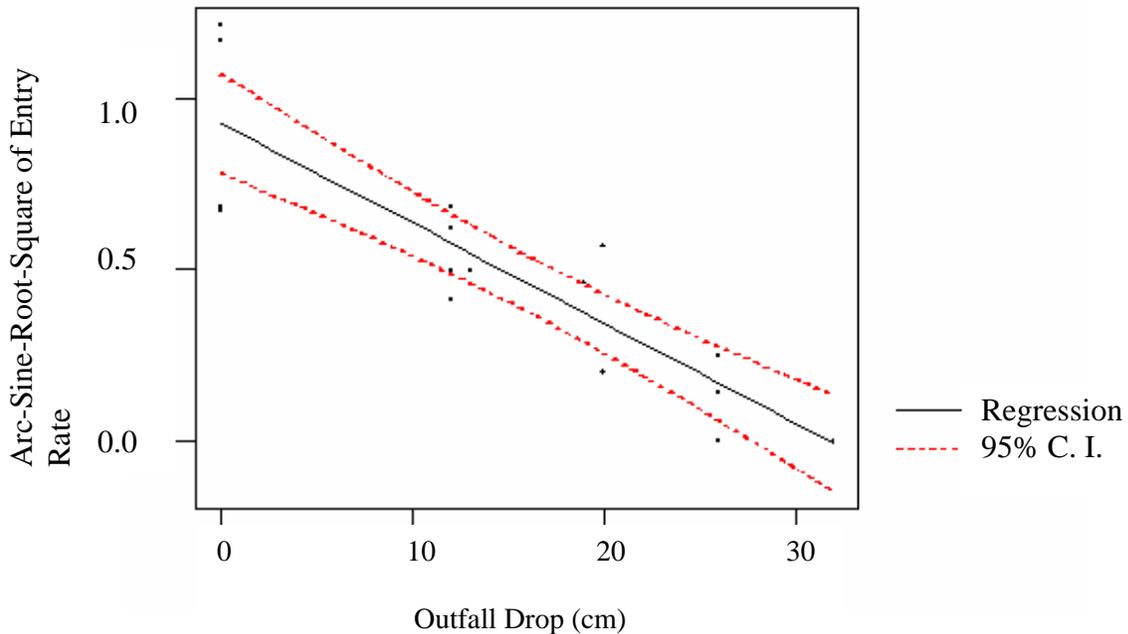


Figure 7. Regression of arc-sine-square-root transformation of the proportion of fish entering the culvert in relation to outfall drop. Dashed lines represent the 95% confidence interval for the fitted line.

### 3.2 Fish Behavior at the Culvert Entrance

During our trials, juvenile coho salmon were observed both swimming and leaping into the culvert. Due to camera placement in the tailwater pool, only fish near the culvert entrance were observed. Swim-in events were defined as fish entering the culvert outlet with at least a portion of their body in contact with the water surface. Fish leaping was defined as those events in which the fish's entire body was out of the water during the passage event. When fish were not actively trying to swim up or leap into the culvert, the most common type of fish behavior was a combination of milling and holding.

Territorial and/or aggressive type behavior was also observed rarely and typically near the beginning of the trials, usually during the first hour, while fish were presumably still acclimating to the CTB.

Observations of fish tested under streaming flow conditions (0-cm outfall drop) indicate that most of the fish approached and entered from the middle portion of the culvert. Other entry pathways observed included approaching and entering from the sides of the plunge plume and then swimming up the middle of the culvert. The plunge plume is the area of turbulence created by water plunging into the downstream pool when the culvert is perched. All fish used a swim-in mode of entry to the culvert under streaming-flow conditions. Fish usually were observed near the surface when swimming into the culvert. Fallback events from the culvert to the tailwater tank were also observed under streaming flow conditions at both 1 cfs and 2 cfs.

Fish behavior observed near the culvert entrance during the 12-cm and 20-cm outfall drop tests included holding and milling with erratic movements in and out of the plunge plume periphery. Other common fish behaviors included darting toward the water surface and passing back and forth under the culvert lip within the non-turbulent zone. The level of fish activity generally increased as each trial period progressed.

Fish behavior observed during the 26-cm and 32-cm outfall-drop tests included swimming in and out of the plunge plume near the surface and at the base. The fish appeared to be attracted to the turbulent flow. Only a few examples of failed leaping attempts were observed under the highest outfall drop condition (32 cm), although many fish were seen burst swimming upward into the plunge plume.

A detailed review of video footage from a subset of tests revealed that the fish utilized two culvert entry methods and that these were related to outfall drop. Fish used a combination of swimming and leaping to enter the culvert at the 12-cm outfall drop, but used only leaping to enter the culvert at the 20-cm and 26-cm outfall drops. At the 12-cm

outfall drop, the swim-in entry to leap-in entry ratio was approximately 2:1 for the tests conducted with a 30-cm pool depth and 1 cfs flow. For tests conducted with a 42-cm pool depth and 1-cfs or 1.5-cfs flow, the swim-in entry to leap-in entry ratio was reversed, at 2:3. It may be that the deeper pool depth better facilitated leaping, but the difference between swim-in to leap-in ratios at the two pool depths was not statistically different. No fish successfully swam or leapt into the culvert at the 32-cm outfall drop. The swim-in and leaping events were verified by reviewing the video records, which corresponded to the entry events recorded by researchers real-time during video observations. A few entry events were not observed (unobserved entry in Table 3) due to the very short time interval (1-2 sec) for an individual swim-in or leaping event, which make them very difficult to detect during real-time observations and during video playback analysis. It is likely that unobserved fish entries were of the swim-in variety, because entering below the water surface made fish more difficult to observe.

A review of notes recorded by researchers during the tests indicates the greatest number of observed failed attempts occurred at the 20-cm and 26-cm outfall drops (Table 3). Due to the inherent difficulty in observing juvenile fish behavior in real-time, this should be considered a qualitative comparison. Most unsuccessful events were categorized by fish burst-swimming toward the pool surface from near the bottom of the net pen and leaping toward the culvert entrance but landing below the crest.

Table 3. A qualitative comparison of numbers of fish observed swimming and leaping into the culvert entrance, number of observed failed attempts, and test conditions.

Outfall drop (cm)	Swim-in Entry	Leaping Entry	Unobserved Entry	Observed Failed Attempts	Pool Depth (cm)	Flow (cfs)	Total Number of Fish Tested
0	173	0	0	0	30	1	300
12	41	25	24	7	30	1	300
19-20	0	37	16	18	30	1	300
26	0	8	0	21	30	1	300
32	0	0	0	9	30	1	300
0	40	0	0	0	30	2	100
12	8	17	3	3	42	1	100
13	8	11	4	5	42	1.5	100

To determine behavior prior to and during successful leaps, we reviewed the video records of successful leaping events from two tests (No. 27 and No. 28) at the 12-cm outfall drop and tallied individual fish in categories of location during the leaping events

(Figure 8). An individual fish can be in more than one category (e.g., "from depth" and from "middle"). Most fish started a successful leap from near the floor of the net pen, near the right or left side of the plunge plume, and at or just downstream from the standing wave.

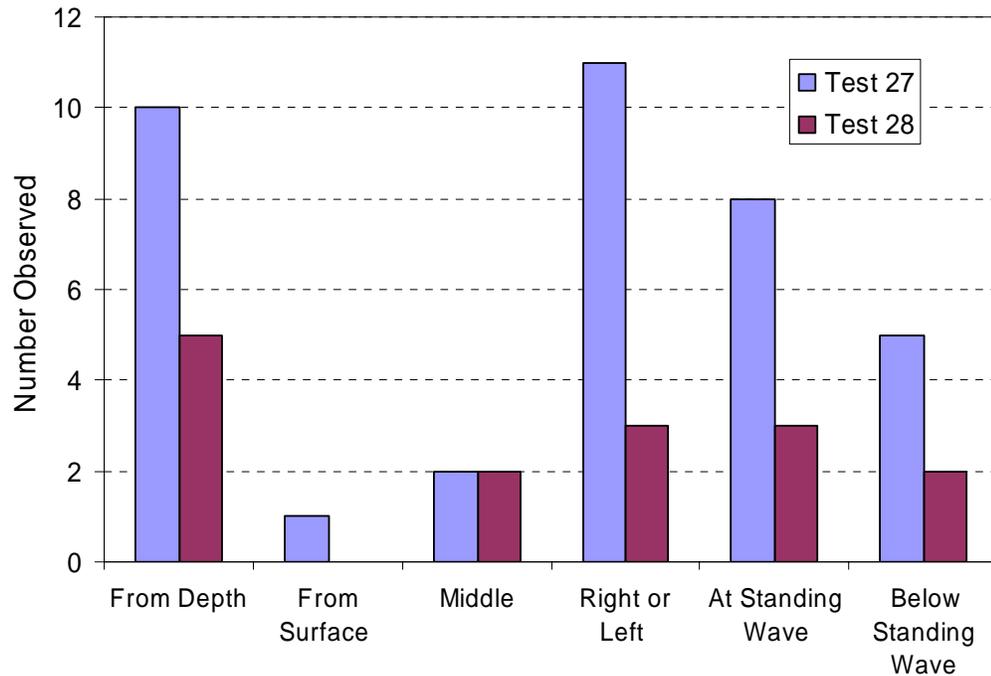


Figure 8. Summary of leaping fish for tests 27 and 28 (12 cm outfall drop) with depth of fish just prior to successful leap, and their position relative to the culvert entrance when leaping from the tailwater pool.

A vertical body orientation was often observed when fish were attempting to leap toward the culvert. Most of the fish that were successful at navigating the 20-cm outfall drop appeared to initiate the leap, almost from a "standing" start, by approaching the edge of the plunge plume and hovering just above the floor. The fish would casually swim into the upwelling plume and, with a few strong tail flexions, aim straight upwards and then accelerate upwards at a steep angle ( $\sim 20^\circ$  pitch) just prior to reaching the pool surface (Figures 9 and 10). It should be noted that some fish began their trajectory from mid-depth, but none were observed leaping directly from the surface. It appears as though fish were more likely to be successful at the 20- and 26-cm outfall drops when they originated the leap from just beyond the standing wave at an angle of near  $20^\circ$  toward the culvert entrance.

Once cleared of the pool surface they were oriented at a 15° to 30° angle from vertical and most gained a height of about 25 cm (about 2-3 fish lengths) before landing inside the culvert (Figure 11). Upon becoming airborne, fish that were classified as high leapers (those taking a relatively steep angle of ascent) reached a maximum height about 20 cm beyond the culvert lip and then descended to land just inside the culvert outlet. These fish leapt up to 5.2 times their body length (maximum 60-cm leap) (Figure 12). During the leap the fish would continue to beat their caudal fin until landing and then quickly swam upstream beyond the camera's view. For fish classified as low leapers, their trajectory carried them at a relatively shallow angle from vertical landing just beyond or at the lip of the culvert. This was especially evident at the 12-cm outfall drop. Fish landed inside the culvert across the entire wetted portion, generally about 7 to 8 cm inside the lip (Figure 13). Once inside the culvert, very few fish fell back into the tailwater pool.

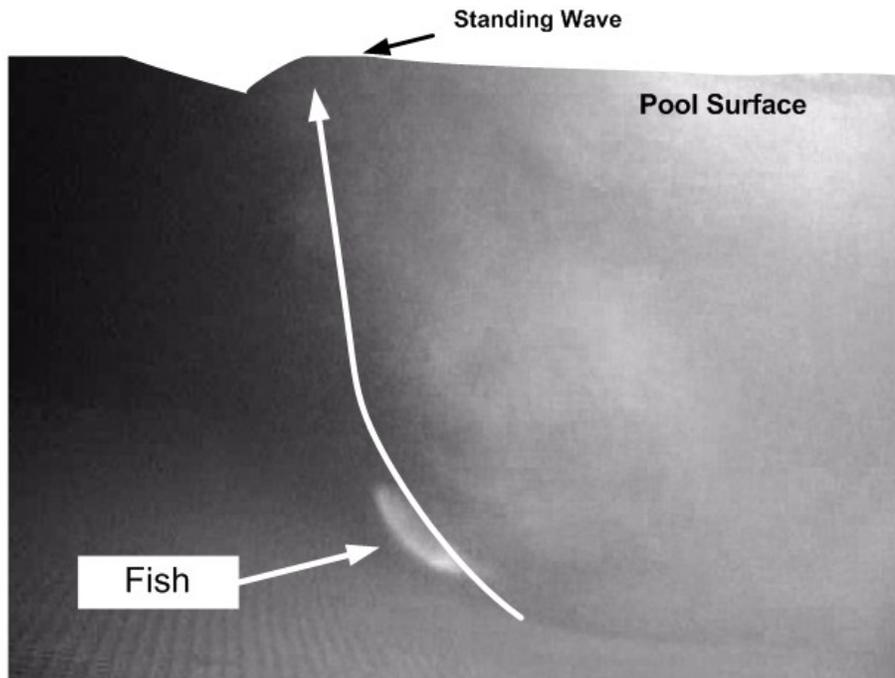


Figure 9. Fish location near the floor of net pen near the edge of the plunge plume and its eventual trajectory line to the water surface at a 20-cm outfall drop (~15° angle to the water surface).



Figure 10. Trajectory of juvenile coho salmon just prior to exiting the pool from the edge of the plunge plume turbulence at a 20-cm outfall drop (~30° angle to the water surface).



Figure 11. Example of a typical low-leap trajectory for a juvenile coho salmon leaping into the culvert set at a 20-cm outfall drop.

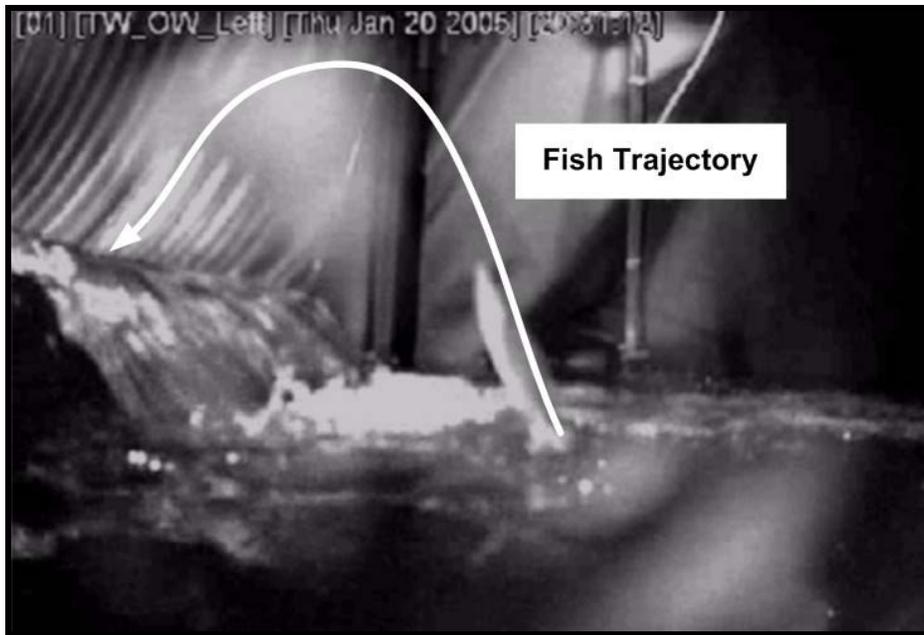


Figure 12. Example of a high-leap trajectory for a juvenile coho salmon leaping into the culvert set at a 12-cm outfall drop.



Figure 13. Overhead view of culvert entrance indicating where a sub-sample of fish landed inside the culvert after successful leaps (examples are from 12-cm and 20-cm outfall drop tests). The wetted width of the culvert as shown is 76 cm.

### 3.3 Preliminary Estimate of Fish Velocity during Leaping

Analysis of two video records of successful leaps provided preliminary estimates of the fish velocity during leaps at 12 and 20 cm outfall drops. For both cases, the maximum estimated fish velocity was approximately 1.5 m/s. The durations of leaping were less than approximately one-half second.

### 3.4 Timing of Passage

The number of culvert entry events increased over time during individual trials with one exception at the 26-cm outfall drop (Figure 14). Fish were observed to engage in exploratory behavior before attempting to enter the culvert. Often during the first 10-20 minutes of a test, few fish were observed near the culvert entrance. Fish appeared to become increasingly active in the vicinity of the plunge plume as each test progressed. Although we could not determine if individual fish were making several entry attempts before finally entering the culvert, it was apparent through our observations that fish became more successful at culvert entry as each test period progressed.

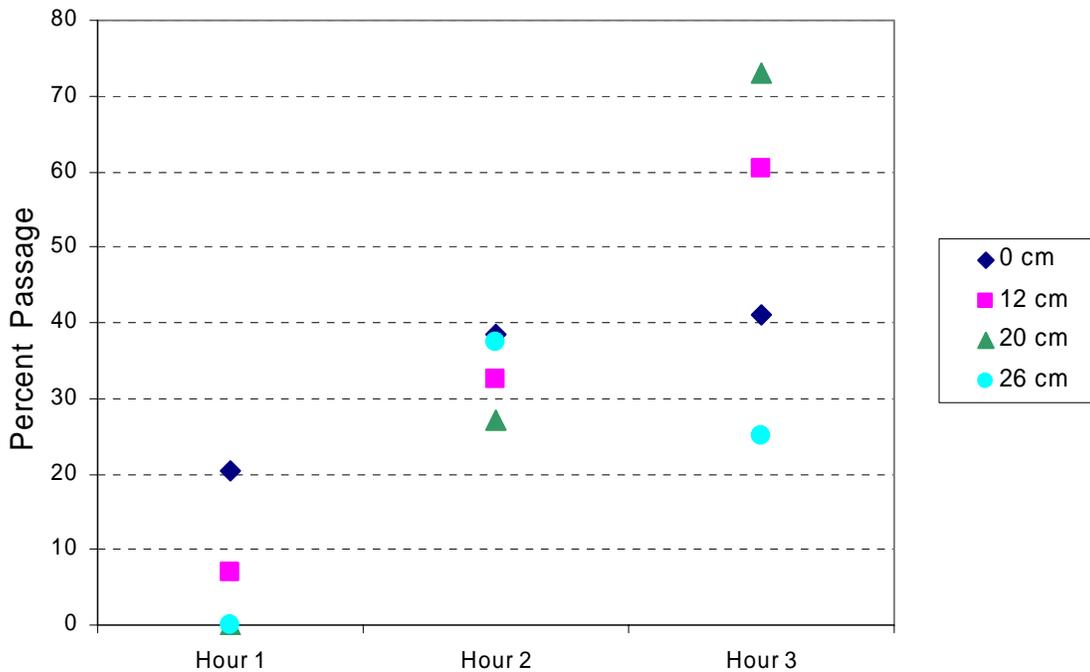


Figure 14. A qualitative estimate of hourly culvert entry rates for fish successfully entering perched culvert (n=3 for all outfall-drop conditions). Data are based on real-time observations recorded during each test.

### 3.5 Fish Size

Fish recaptured in the culvert and headwater tank did not differ greatly in size from those that were recaptured in the tailwater tank (Table 4). Thus, with the range of sizes within the test population, fish size did not affect its ability to enter the culvert under the test conditions.

Table 4. Fork Length (FL) of subsets of juvenile coho used in leaping ability tests in December 2004 and January 2005.

0-cm Outfall drop (Streaming Flow)	Mean FL (mm)	Minimum FL (mm)	Maximum FL (mm)
Fish in Culvert and Headwater Tank (n=82)	102	84	124
Fish in the Tailwater Tank (n=70)	104	80	125
<b>12-cm Outfall Drop</b>			
Fish in Culvert and Headwater Tank (n=120)	107	80	138
Fish in the Tailwater Tank (n=111)	103	79	130
<b>20-cm Outfall Drop</b>			
Fish in Culvert and Headwater Tank (n=60)	100	83	122
Fish in the Tailwater Tank (n=48)	100	74	135
<b>26-cm Outfall Drop</b>			
Fish in Culvert and Headwater Tank (n=60)	104	93	121
Fish in the Tailwater Tank (n=8)	98	60	120
<b>32-cm Outfall Drop</b>			
Fish in Tailwater Tank (n=60)	100	78	126

### 3.6 Zone of Turbulence

After the water exits the perched culvert, the exiting water falls, plunging into the water in the tailwater tank and forming a plunge plume (Figure 15). Because of the amount of entrained air within the plunge plume zone, we were unable to measure the extent and magnitude of turbulence using an Acoustic-Doppler Velocimeter (ADV). Instead, we measured the area of the turbulence zone using photographs taken above-water. Imaging software drew an outline around the perimeter of the zone and utilized known measurements of objects in the photographs to calculate the areal extent. These turbulence zone areas ranged from 1.05 m<sup>2</sup> at the 12-cm outfall drop to 1.55 m<sup>2</sup> at the 20-cm outfall drop (Table 5). Figure 15 provides an example of a turbulence zone area.

Table 5. Approximate surface area of turbulent flow of the plunge plume at tested outfall drops.

Outfall drop (cm)	Turbulent Zone (m <sup>2</sup> )
12	1.05
20	1.55
26	1.27
32	1.23



Figure 15. Photo showing extent of the turbulence zone at the 32-cm outfall drop.

### 3.7 Pool Depth

Previous studies by Stuart (1962) suggested that the ratio of the height of the falls to pool depth should be 1:1.25 for optimal leaping conditions while studies by Lauritzen (2002) suggested that a outfall drop to pool depth ratio of 1:1 was conducive to leaping. Powers and Orsborn 1985 citing studies by Aaserude 1984 found that two conditions conducive to leaping: 1) depth of penetration of the plunge plume should be less than the pool depth and 2) the depth of the plunge pool must be equal to or greater than, the length of the fish for a successful leap. To maintain consistent conditions for all outfall drops, we maintained a pool depth of 30 cm for all but two tests. Thus, we were able to meet or exceed Stuart's ratio for all but the 32 cm outfall drop, which was just under 1:1 (Table 6).

Table 6. Outfall drop to pool depth ratios in fish leaping ability tests conducted in December 2004 and January 2005 at the Culvert Test Bed Facility.

Outfall drop (cm)	Outfall drop to Pool Depth Ratio
12	1: 2.5
20	1: 1.4
26	1: 1.2
32	1: 0.95

## 4.0 Discussion

The results of these initial tests of the ability of fish to leap into perched culverts show that hatchery juvenile coho salmon are able to access perched culverts and are more successful entering at lower outfall drops. Successful culvert entry declined steadily from the 0-cm outfall drop to the 26-cm outfall drop, and ceased at the 32-cm outfall drop although several failed leaping attempts were observed at the 32 outfall drop. Based on our observations and for the specific test conditions, the threshold for leaping success appears to correspond to occur between 2.5 and 3 times the body length of the juvenile coho salmon tested. These experimental observations confirm previous anecdotal observations made by field biologists. Except for the 0-cm and 12-cm outfall drops conditions, all fish leapt into the culvert as opposed to swimming in. The ratio of swimming to leaping entries was 1:0 at the 0-cm outfall drop and nearly 2:1 at the 12-cm outfall drop. At and above the 20-cm outfall drop, swim-in behavior was not observed.

Our observations of fish leaping behavior were similar in some respects to Stuart (1962) and Lauritzen (2002) who described successful fish leaping as originating near the standing wave. However, Stuart (1962) observed most fish initiating their leaps from near the water surface, rather than from depth as was observed in our study and in Lauritzen (2002). Both Stuart (1962) and Lauritzen (2002) recognize that the hydraulic structure of the falls and plunge plume provide the fish with three things: 1) cues that orient the the fish's movements, 2) pathways that are obstacles to movement, and 3) pathways that do not inhibit and may facilitate movement. It is important to understand that loss or reduction in strength of a relevant cue can inhibit a behavioral response in a way that can not be distinguished from a change in motivation.

Our observations of exploratory behavior suggest that the fish do search for orientation cues. Our finding that exploratory behavior and leaping occurs at night is contrary to the interpretation of Stuart (1962) that fish need a visual target for leaping and suggests that the fish can find the relevant cues at night. Our observation that leaping entry success rate increases with time for outfall drops of 0-cm, 12-cm, and 20-cm, but not for the 26-cm outfall drop leads to a hypothesis that some learning is occurring.

Patterns in ratios of failed attempts to success entries (Table 3) suggest that learning, fatigue, or loss of cues may have occurred. The ratio of failed attempts to successful entries was 0.5:1 (18 failed attempts vs. 37 entries) at the 20-cm outfall drop and increased to 2.6:1 (21 failed attempts vs. 8 entries) at the 26-cm outfall drop. At the 30-cm outfall drop there were no successful entries and there only 9 failed attempts. Entry

rate was still increasing in the third hour of the trials for outfall drops of 0 cm, 12 cm, and 20 cm but fell in the third hour for the trails at the 26-cm outfall drop. At the 26-cm outfall drop, the increase in failed attempts for the whole trial and the drop in entry in the third hour suggest that the fish either learned not to leap or became fatigued. At the 30-cm outfall drop, the lack of entries and the low rate of failed attempts suggest that either the fish learned rapidly not to leap or had lost the cues orienting the leap. The observation at the 30-cm outfall drop that many fish began burst swimming from depth without a leap suggests that orienting cues might have been lost as the fish approach the leaping point. In future studies, more attention should be given to discerning patterns in the failed attempts.

Previous studies by Stuart (1962) have shown that the ratio of the height of the falls to pool depth should be 1:1.25 for optimal passage conditions (Stuart 1962), while studies by Lauritzen suggest an average ratio of 1:1 is conducive to leaping. To maintain consistent conditions for all outfall drops, we maintained a pool depth of 30 cm for all but two tests. Thus, we were able to meet or exceed Lauritzen's ratio in all tests and Stuart's ratio for all but the 32-cm outfall drop, for which the ratio was just under 1:1.0. The recommendations of Powers and Osborn (1985) based on the findings of Aaserude (1984) indicate the mechanism behind enhanced leaping success may not be the pool depth by itself, but rather the depth of the plunge plume in relationship to the depth of the downstream pool.

Our observations are too preliminary to suggest a preferred or optimal pool depth. Due to limited resources we were only able to conduct two tests using a pool depth of 42 cm. The results of the 42-cm pool depth tests conducted at 1 cfs and 1.5 cfs showed a slightly lower successful entry rate (23% for each test) compared to a mean of 34% for tests conducted with a 30-cm pool depth. Lower fish density, increased water depth, and colder water temperatures are variables that may have resulted in the lower entry rate. Another contributing factor may be the extent of the plunge plume. At the 42-cm pool depth, the extent of the turbulent flow appeared to be mostly dissipated before reaching the false floor. Research conducted by Aaserude (1984) found that the depth of penetration of the falling water should be less than the depth of the plunge pool for a successful leap. However, Lauritzen (2002) found that very deep plunge pool depths could actually inhibit adult salmon leaping due to the loss of upward turbulence that aided fish in initiating leaping. Additional testing of outfall-drop and pool-depth combinations with attention to the whole of the hydraulic structure in the downstream pool would be needed to provide perspective on the influence of pool depth on leaping success.

Some of the results of our study here have implications for the test conditions of future evaluations at the CTB. The streaming flow tests had the highest culvert entry rates (86%) for tests conducted at 1 cfs, with no backwatering of the culvert. Similar tests conducted in November of 2004 at the CTB were conducted at 1.5 cfs with the lower portion of the CTB in a backwater condition (same fish stocks with 92.5 mm average fork length) and pool depth of 23 cm elicited a mean entry rate into the culvert of approximately 40% (Pearson et al. 2005). These findings support the concept of a “hydraulic stimulus for movement” earlier postulated by Stuart (1962) and re-affirmed by Lauritzen (2002). However, we found that increasing the flow above 1.5 cfs in the fish leaping ability tests did not produce higher entry rates, although other factors (e.g., colder water temperature or more turbulence) may have had an impact on fish behavior. There was also a much higher fallback rate during a single streaming flow test at the higher, 1.5 cfs flow, perhaps suggesting that swimming speed was the limiting factor.

Water temperature may have had some impact on activity levels of the test fish during tests conducted during a period of cold weather. Fewer culvert entry attempts were observed and entry success was substantially less for those days when the temperature was lowest (Figure 14, Table 2). Symons’ 1978 study also found that proportionally more juvenile coho salmon leapt at higher temperatures (between 14°C and 17°C) than at lower temperatures. He also found that warmer water temperature (>14°C) was more conducive to successful leaping than colder water (< 9°C). Griffiths and Alderdice (1972) concluded from their investigation of the influence of temperature on critical swimming speed that the juvenile coho salmon were well adapted to maintain a high level of swimming performance over a broad range of temperatures. Swimming speed at 2°C was only half that at 20°C (Griffiths and Alderdice 1972). Our results here suggest that trials should be suspended when the water temperature falls below 4°C.

Here we have defined entry as occurring when a fish was observed to leap or swim into the culvert and to remain there for 3 sec or more. As did Pearson et al. (2005), we also measured passage success as the proportion of fish released in the tailwater tank that were present in the headwater tank at the end of the trials. Passage success was often greater than the sum of the swim-in and leaping entries, suggesting two items to note. First, the observed entry rates are minimum ones. Second, the processes of entry and passage were not so fatiguing as to cause large numbers of fish to fall back. In future tests with more difficult conditions for passage, the relationship between entry rates and passage success rates could differ more substantially than what was observed here.

Conducting the tests during the night did not prohibit leaping ability, culvert entry, or upstream passage through the culvert. All of the tests in this study were conducted after

dusk and before dawn. Stuart (1962) found that juvenile salmonids only jumped during periods of daylight and all leaping activity ceased at low light intensities. This is contrary the findings of this study and to those of Brandt et al. (2005) who found no significant differences between successful passage of simulated waterfalls and light intensities corresponding to dawn/dusk, noon and night-time.

The actual leaping height achieved by the test fish was variable but some achieved a leap height of 5.2 times their body length. The highest leapers initiated their leap from maximum water depth and exited the water at a steep angle at the base of the plunge pool near the standing wave. Fish that originated their leap from beyond the standing wave were, for the most part, low leapers and attained a maximum height of 2-3 body lengths. Symons (1978) and Stuart (1962) also described juvenile salmon successfully leaping barriers and making leaps of 3 and 5 times their body length. As in our study, Symons (1978) found that successful juvenile coho salmon passage of waterfalls decreased with increasing fall drops.

In general, there is a complexity of factors that influence juvenile fish leaping success. These factors include the species of fish, the stock of fish, fish size and maturity, water temperature, flow conditions, outfall drop, culvert type, barrier hydraulic characteristics, and others. An experimental approach using the CTB proved able to provide a successful first step in research on leaping ability and understanding the behavior and capabilities of juvenile salmonids with regard to upstream migration at perched culverts.

The results of this study clearly show that passage success is strongly negatively correlated with outfall drop and that the number of failed attempts increases proportionally as the outfall drop increases. No data on the number of multiple attempts by individual fish were available for these tests, so no conclusions can be drawn as to the potential decrease in success as the number of attempts increases. This problem could be remedied if some method of “tagging” or marking (e.g., dye or branding) each fish could be used to track individual fish behaviors.

Although Stuart (1962) showed that the bio-energetic costs of leaping were less than such costs for swim-in behavior, our study did not directly address the bio-energetics of upstream movement or whether leaping is less costly. Recent studies by Liao et al. (2003a, b) found that trout actively interacted with the turbulence field and exploited vortices in a way that decreased the cost of locomotion. In our study, leaping success was greater for those fish observed to use the standing wave at the edge of the plunge plume. Leaping success is probably not only a function of the outfall drop and swimming performance but also a function of the hydraulic conditions in the downstream pool and

the plunge plume. Lauritzen et al. (2000, 2001) called for the design process for fish passage structures to be grounded in a more thorough understanding of the adaptive behaviors and capabilities of the fish. We suggest that more research is needed on how fish interact with the plunge pool and exploit its characteristics to support leaping. Specific attention to how the fish approach the culvert outlet and how the fish seek orientation cues would be of benefit.

## 5.0 Conclusions

The research conducted at the CTB showed that, under the test conditions, juvenile coho salmon are able to overcome a perched-culvert and move upstream. As with previous research, the results of this study indicate that flow and outfall drop appear to be the major constraints on leaping success. Generally, the lower the outfall drop (perch) the more successful fish entry becomes. In addition, a certain set of conditions in the downstream pool, including pool depth and plunge pool characteristics, appear to influence success of leaping. In general, the complexity of factors that influence juvenile fish leaping ability made this type of research very difficult. In spite of these confounding factors, this research should be considered a successful first step.

The observations and results of this study support the findings of earlier research that juvenile salmon are capable of overcoming barriers to upstream movement. Previous studies have focused on natural barriers (e.g., waterfalls) and artificial fishways. This research is one of the only studies to look at the problem of perched culverts and juvenile salmon.

Concerning the questions with which the study began (see Introduction), this initial research indicates the following:

- *Is there a threshold of outfall drop that juvenile fish cannot overcome?*

Juvenile coho salmon (~100 mm hatchery fish) were capable, although at a very low percentage (3%), of overcoming a culvert-outlet outfall drop equivalent to approximately 2.5 body lengths. For the test conditions, the threshold for leaping success occurred at outfall drops between 2.5 and 3 body lengths. The majority of fish gaining entry into the culvert were able to traverse the full length (40 ft) of the culvert to gain access to the upstream headwater holding pool.

- *At what outfall drop do juvenile fish shift from a “swim-in” to a “leaping” behavior (current understanding is that this is in the range of one “fish-length” of outfall drop)?*

Both swim-in and leaping behavior were observed in this study. Swim-in behavior dominated for the 0-cm outfall drop (streaming-flow) condition and for outfall drops of approximately one fish-length. For outfall drops greater than one fish-length, leaping behavior was the dominant behavior for entry.

- *Is there a minimum required pool depth for successful leaping or is there a specific range in the relationship between pool depth and outfall drop (e.g. pool depth > 1.25 outfall drop) that facilitates leaping success?*

The trials with deeper pool depth were too limited to offer conclusions. More research on the influence of pool depth on leaping success is needed.

- *How do juvenile fish approach a barrier that requires leaping ability to overcome?*

Most of the fish that were successful at entering the culvert by leaping appeared to initiate the leap, almost from a "standing" start, by approaching the edge of the plunge plume and hovering just above the floor. The fish would casually swim into the upwelling plume and, with a few strong tail flexions, aim straight upwards and then accelerate upwards at a steep angle (~20° pitch) just prior to reaching the pool surface.

- *Do juvenile fish leap from the surface of the pool or do they swim at burst speed from a depth in the pool?*

While some fish began their trajectory from mid-depth, none were observed leaping directly from the surface. Most fish started a successful leap from near the floor of the net pen, near the right or left side of the plunge plume, and at or just downstream from the standing wave.

- *Does the location of leap initiation affect leaping and passage success?*

Yes, fish appear to be using the standing wave and edges of the plunge plume in leaping.

- *Do juvenile fish leap more successfully from the upwelling zone just downstream of the plunging water or from some other position?*

Fish were more likely to be successful at the 20- and 26-cm outfall drops when they originated the leap from just beyond the standing wave at an angle of near 20° toward the culvert entrance.

- *What are the hydraulic characteristics of the tailwater pool that cue fish orientation and enhance leaping success?*

The fishes clearly used the standing wave formed in the tailwater tank to facilitate their leaps. The plunge plume and standing wave probably provided orientation cues. The standing wave may have provided a pathway that probably did not inhibit and may have facilitated the burst swimming preceding the leap. More than pool depth alone is probably involved in providing both the orientation cues and a facilitating pathway. The plunge plume depth, pool depth, pool bottom

type, and other hydraulic factors probably all interact to influence the occurrence and success of leaping.

- *What are the hydraulic characteristics of the culvert outlet that enhance leaping success?*

The hydraulic characteristics of the culvert outlet that enhance leaping success are less obvious from these tests than those of the tailwater pool. The experiments in this study were designed to address outfall drop so that the influence of water depth and nappe at the culvert outlet need to be examined as specific experimental variables in future studies.

Care must be taken in extrapolating the results of this testing to other species of fish or fish of a different size-class or stock origin (i.e., hatchery vs. wild). Further testing of Skookumchuck hatchery juvenile coho salmon at a smaller size class (50-60 mm) is recommended to fully characterize the leaping ability of these fish. Testing of wild coho should also be considered to establish any differences between wild and hatchery fish. The leaping ability of other species could also be investigated at the CTB.

In our study, leaping success was greater for those fish observed to use the standing wave at the edge of the plunge plume. Leaping success is probably not only a function of the outfall drop and swimming performance but also a function of the hydraulic conditions in the downstream pool, pool depth, and the characteristics of the plunge plume. It should be noted that the false floor in tailwater tank at the CTB is constructed of perforated steel plate and does not fully simulate the hydraulics of an actual culvert plunge pool where the bottom is continuously impenetrable, hard substrate. Lauritzen et al. (2000, 2001) called for the design process for fish passage structures to be grounded in a more thorough understanding of the adaptive behaviors and capabilities of the fish. We suggest that more research is needed on how fish interact with the plunge pool and exploit its characteristics to support leaping. Specific attention to how the fish approach the culvert outlet and how the fish seek orientation cues would be of benefit.

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