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CULVERT TESTING PROGRAM FOR JUVENILE SALMONID PASSAGE

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Abstract: The Washington State Department of Transportation (WSDOT) has identified the need to evaluate all aspects of Department programs that may affect Pacific salmon and their habitats under the Endangered Species Act, and to correct situations where adverse effects exist. The great deal of research and engineering conducted to date has resulted in enhanced passage of returning adult salmon. However, the movement of juvenile salmonid both up and downstream throughout the year is now recognized as substantial, and the need for them to pass this life stage has made the problem even larger in scope. Tens of thousands of culverts exist in the state of Washington alone, and many are judged as blocking juvenile salmonids from thousands of miles of habitat. Determining appropriate hydraulic and fish passage designs for new and retrofitted culverts before installation has both substantial cost and environmental implications. The optimal conditions for culvert passage by juvenile salmonids are not well understood, and thus are a key area upon which WSDOT has decided to focus its research efforts.

In partnership with WSDOT, the Pacific Northwest National Laboratory has undertaken a phased program to address the hydraulic and behavioral issues associated with juvenile salmonid fish passage through culvert systems. This program addresses the testing and assessment of culvert designs, along with associated measurements of hydraulic conditions and fish behavior occurring in full-scale physical models of culvert systems deployed in an experimental test bed. Experiments in the testing apparatus will measure the hydraulic conditions (velocity, turbulence, and water depth) associated with various culvert designs under various slopes and flow regimes and then relate these measures to repeatable, quantitative measures of fish passage success. The long-term intent is to develop the test bed into a regional and national-level capability that can be used by other agencies that need to develop appropriate culvert designs to enhance the passage juvenile fish.

Introduction

The Washington State Department of Transportation (WSDOT) has identified the need to evaluate all aspects of Department programs that may affect Pacific salmon and their habitats under the Endangered Species Act (ESA) and to correct situations where adverse effects exist. The great deal of research and engineering conducted to date has resulted in enhanced passage of returning adult salmon (Copstead et al. 1998; WDFW 1998). However, juvenile salmonid movement both up and downstream throughout the year is now recognized as substantial (Kahler and Quinn 1998), and the need for them to pass this life stage has made the problem even larger in scope. Barriers to movement across city, county, and state roads in the state of Washington block an estimated 3,000 miles of habitat; the U.S. Forest Service (USFS) in Washington and Oregon estimate there are between 6,000 and 9,000 culverts on their lands and 80% of those act as barriers to movement. WSDOT alone has over 500 barriers out of 1,585 culverts that should pass fish. Tens of thousands of culverts exist in the State of Washington, and many will be found to be barriers to habitat. Moreover, with the recent Endangered Species Act listing of Atlantic salmon, the issues associated with culvert passage could become more widespread.

Determining appropriate hydraulic and fish passage designs for new and retrofitted culverts before installation now has both substantial cost and environmental implications at state, regional, and national levels. The optimal conditions for culvert passage by juvenile salmonids are not well understood and thus are a key area upon which WSDOT has decided to focus its research efforts. In partnership with WSDOT, the Pacific Northwest National Laboratory (PNNL) has undertaken a phased program to address the hydraulic and behavioral issues associated with juvenile salmonid fish passage through culvert systems. After providing a preliminary conceptual model of juvenile fish passage, this paper outlines the approach taken in the program and briefly describes the status and future directions of the program.

Conceptual Model of Juvenile Fish Passage

An initial step in the design of the program was the development of a conceptual model for the passage of juvenile salmonids through culverts. This preliminary conceptual model of fish passage emerged primarily from analysis of Powers et al. (1997), Kahler and Quinn (1998), WDFW (1998), Reeve (1999) and Kane et al. (2000). Also, the conceptual model benefited from work by Byrant (1981), Taylor and McPhail (1985), and Kane et al. (1989) on juvenile salmonid swimming abilities. Most recently, Powers et al. (1997) in a temporary test culvert and Kane et al. (2000) in the field found that juvenile fish use the low-velocity boundary layer to pass upstream in culverts. Powers et al. (1997) found that juvenile salmon switched to a boundary layer near the water surface and next to the culvert wall when water velocity increased above 0.4 feet per second (fps). The maximum velocity in the boundary layer that permitted successful juvenile fish passage was at or below 2 fps. Increased turbulence lowered the maximum velocity at which juvenile fish can pass the culvert. Also, fish size influenced behavioral response to turbulence and to culvert structures. Powers et al. (1997) urged more research on turbulence and other culvert characteristics that determine successful fish passage.

It is clear that fish pass culverts at higher mean velocities than their swimming performance indicates because they utilize low-velocity pathways and adaptive behaviors to accomplish the passage. Two major factors determine the occurrence of upstream passage:

- Motivation. Environmental factors and cues provide the ultimate and proximate determinants of upstream movement.
- Capability and Behavior. Once motivated to move upstream, the capabilities and adaptive behaviors of the fish interact with the culvert physical structure and hydraulic conditions to determine the success of passage.

A variety of environmental factors have been hypothesized for motivating and influencing upstream movement, and there are several possible cues providing triggers and orientation in upstream movement (Table 1).

Table 1

Possible Environmental Factors and Cues Motivating and Influencing Upstream Movement of Juvenile Salmonids

Possible behaviors influenced by environmental factors:

- Avoiding extreme water temperatures
- Avoiding poor substrate
- Moving to low velocity habitats after hatching in the spring
- Moving from degrading habitat in the summer (e.g., low dissolved oxygen, high temperature)
- Moving to over-wintering habitat in the fall
- Avoiding high turbidity
- Avoiding predation
- Moving from high-density areas (from competition or occupied territories)
- Moving to feeding areas

Possible cues providing triggers and orientation:

- Abrupt changes in flow characteristics
 - Changes in water temperature
 - Changes in turbidity
 - Chemosensory cues for prey (food sources), conspecifics, or "habitat"
 - Light and dark patterns
-

The model suggests that once juvenile fish are motivated to move upstream, successful passage of the culvert is determined by interactions between the swimming abilities, adaptive behaviors, and stamina (i.e., endurance, time to fatigue) of the fish and the nature of the low-velocity and low-turbulence pathway(s) within the culvert system. The physical structure and the patterns of velocities, turbulence, and resting areas within

the culvert system determine the nature of the passage corridor. Adaptive behaviors in culvert passage include the following:

- Using burst speed (darting speed) to enter the downstream end of the culvert (outlet)
- Using low-velocity/low-turbulence pathways (e.g., boundary layer) to move up the barrel of the culvert
- Using prolonged swimming ability (cruising speed) to move up the culvert
- Using holding or resting areas (e.g., corrugations or other low-velocity areas)
- Using prolonged or burst speed to move through high-velocity areas from resting area to resting area
- Using burst speed (darting speed) to exit the upstream end of the culvert (inlet)
- Jumping.

Thus, passage of the culvert is determined by interactions between the swimming abilities and energy reserves of the fish and the pattern of velocities and resting areas in the culvert system.

Although the conceptual model provides insight into the mechanism of upstream passage, it is not complete enough to fully assess all the behavioral, environmental, and hydraulic issues influencing fish-passage success. Important factors such as fatigue and the ability to feed or avoid predators once through the culverts need to be included in a more detailed and realistic approach to understanding the influence of culverts on juvenile fish passage. Switches among behavioral strategies related to fish size that allow for successful passage through these culverts also need to be understood. The triggering factors and their quantitative thresholds need to be determined.

The conceptual model is at a basic stage. To guide culvert design, attempts have been made to develop mathematical models that incorporate fish swimming abilities and endurance plus hydraulic properties of culverts (Powers and Orsborn 1985, as cited in Reeve 1999; Behlke et al., 1991 and 1993, as cited in Moore et al. 1999; USFS 2000). Unfortunately, to convert the conceptual model to a mathematical model requires a better understanding of the relationships among the determinants plus empirical data to provide values for the model parameters. The experimental work necessary to obtain this understanding and data remains to be done for juvenile fish. Such research needs to be in a full-scale physical model in which both the fish behavior and the hydraulics can be well characterized in controlled experiments.

Approach: A Test Bed for Evaluation of Culvert Designs

To address the issues in culvert designs for juvenile fish passage, a multi-organizational partnership was developed to design and implement a passage research program. WSDOT lead the partnership that now includes Washington Department of Fish and Wildlife (WDFW), Alaska Department of Transportation, Alaska Department of Fish and Game, and the Pacific Northwest National Laboratory of the U.S. Department of Energy. The program will employ a specially fabricated test bed to identify the culvert designs and associated hydraulic conditions that allow successful upstream movement of juvenile salmonids at different life stages. The program addresses three main questions:

- What new culvert and retrofit designs pass juvenile salmonids?
- For such designs, how do hydraulic conditions and culvert characteristics influence the extent or degree of passage success?
- How does passage success vary with fish species and fish size?

The program addresses the testing and assessment of culvert designs, along with associated measurements of hydraulic conditions and fish behavior, occurring in full-scale physical models of culvert systems deployed in an experimental test bed. Experiments in the testing apparatus will measure the hydraulic conditions (velocity, turbulence, and water depth) associated with various culvert designs under various slopes and flow regimes and then will relate these measures to repeatable, quantitative measures of fish passage success.

Simulating actual full-scale culvert hydraulics is a complex undertaking. First, hydraulic effects cannot be scaled down and still generate natural responses from fish. The study by Powers et al. (1997) demonstrates why one must work at full scale to obtain appropriate results when behavior related to fish size interacts with the size patterns of culvert structures. Second, the quantity of water required to simulate the 2- to 3-fps velocities believed to be limiting to fish passage in culverts ranges up to 5 to 10 cubic feet per second (cfs) of

water flow with culverts ranging in diameter from 2 to 3 feet. This is a considerable volume of water flow to maintain for the 30 to 60 minutes that the fish require to move through culvert lengths of 30 to 40 feet (times estimated from Powers et al. 1997). The scale and water supply issues had to be addressed in the design of the testing program and test bed.

Similarly, the testing program needs to address how to conduct controlled experiments on upstream juvenile salmonid passage under a variety of different culvert system designs and under a range of flow conditions. The design features to be addressed included various types of baffling, bed configurations, and culvert types. The slopes to be tested were to be as high as 10% and the flows as high as 20 to 24cfs. As the combination of factors to be tested increases, the amount of testing to be done increases multiplicatively. Therefore, the program will need to assess the full range of factors and questions to be addressed and identify an appropriate order in which to address them.

Program Status

The program was structured to have the following phases:

- Develop a conceptual design of the testing program and test bed
- Develop draft protocols for behavioral testing and hydraulic measurements
- Select an appropriate site for the test bed
- Design, fabricate, and install the test bed and associated instrumentation
- Conduct behavioral and hydraulic testing using the test bed
- Prepare final program technical reports.

As of August 2001, the conceptual and detailed engineering designs of the test bed have been completed. An appropriate site has been selected and approved. The draft protocols have been prepared. A draft testing sequence has been submitted for discussion among the partners. Bids on fabrication and installation work have been received. Some preliminary preparations at the site have been accomplished.

The Test Bed Location

The test bed is to be installed at the WDFW's Skookumchuck Fish Hatchery near Tenino, Washington. The advantages of this location include the following:

- Availability (nearly year-round) of coho salmon
- Availability of different sizes of juvenile coho
- Capability of using trout as a test species
- Potential to use other species in testing reservoir, providing an abundant supply of high-quality water that supports the rearing of coho salmon

Test-Bed Design

The test bed (Figure 1) has been designed to test different culvert types and bed configurations. The test bed can accept culverts of about 40 feet in length. Insert supports have been designed for round culverts in widths of 2, 3, and 6 feet, as well as for 81-inch pipe arch and 60-inch box culverts, and can be designed for mounting other culverts. Once a given culvert is chosen for mounting in the test bed, then different configurations of baffles can be placed within the mounted culvert. Corrugations of different patterns and sizes can be tested as well as baffle systems of different sizes, shapes, and spacing. Gravel bed configurations up to 12 inches deep can be tested.

The test bed also allows testing at culvert slopes from level to 10% in increments of 0.66% slope. Valves and meters enable water flow to be measured and controlled from about 0.5cfs to 20cfs. Acoustic doppler velocimeters mounted in specially fabricated frameworks permit fine-scale, three-dimensional measurements of hydraulic conditions, including turbulence in the boundary layer and around corrugations and baffles. Overall, the test bed enables experimental trials to relate success of fish passage to hydraulic measurements for specific culvert and bed configurations.

Using the test bed offers several distinct benefits. Controlled trials can be conducted within an appropriate statistical design. Moreover, the program enables the trials to be conducted in a much shorter timeframe than is possible for field installations and evaluations. Coupling the behavioral and hydraulic data will enable the

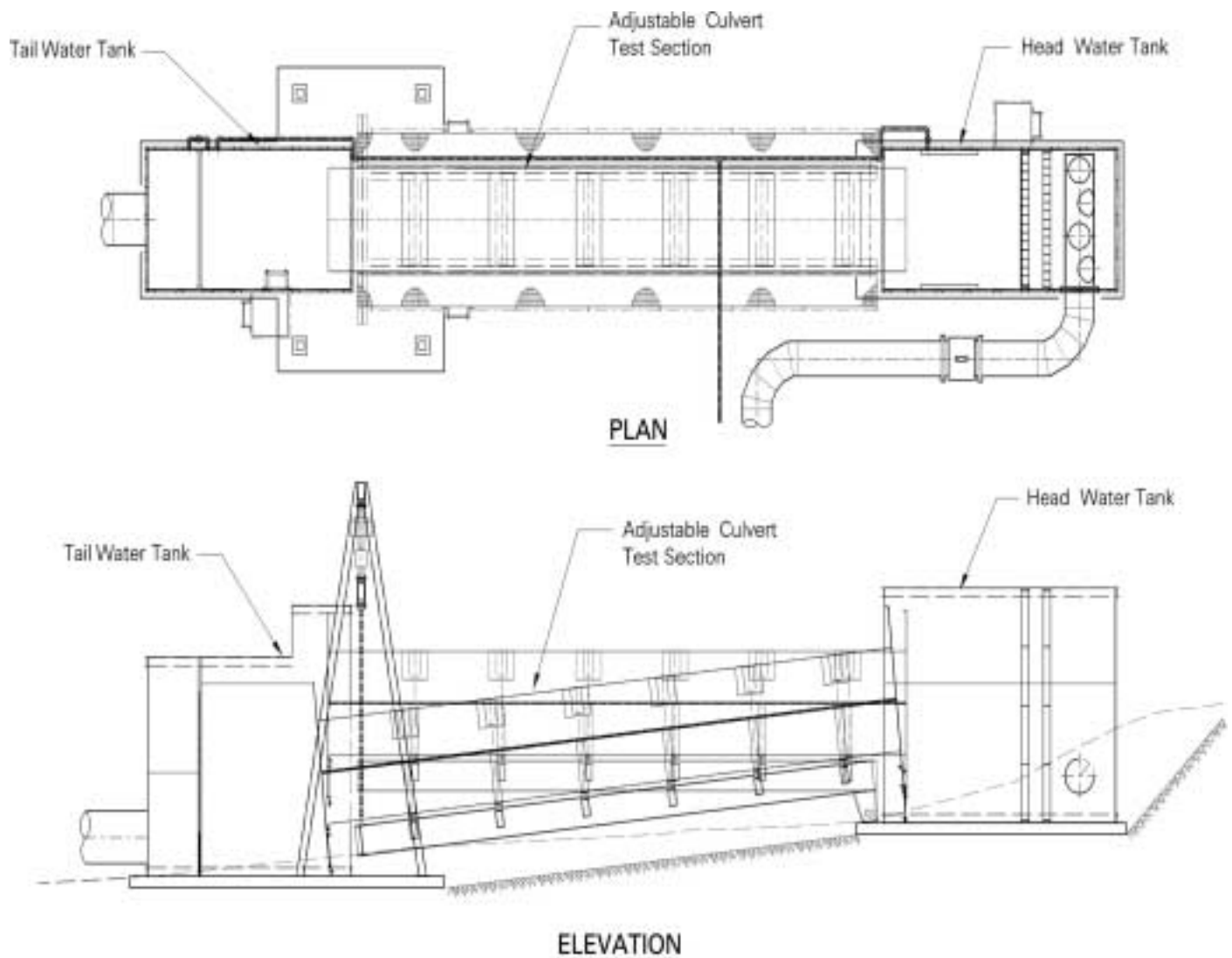


Fig. 1. Test Bed for Evaluation of Passage of Juvenile Salmon through Culverts designed by the Pacific Northwest National Laboratory and Montgomery Watson Harza for the Washington State Department of Transportation.

program to develop and test predictive numerical models for culvert hydraulics and fish passage. Analysis of the results for several designs and over a range of conditions will allow us to discern optimum engineering principles for future culvert and retrofit designs. Such information is extremely valuable to support engineering of cost-effective solutions to juvenile fish passage through culverts.

Future Directions

The next steps in the program are to fabricate and install the test bed and then begin hydraulic and behavioral evaluations of specific culvert designs and configurations. Our long-term goal is to develop the test bed into a regional- and national-level capability that can be used by other agencies that need to develop appropriate culvert designs to enhance the passage juvenile fish. In pursuit of that goal, the partnership is actively seeking to expand its membership to other interested parties.

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Biographical Sketch: Dr. Walter H. Pearson's primary area of expertise is the study of the effects of pollution and human activities on marine and estuarine environments, and especially on the fisheries they support. His recent experience has been in leading large multidisciplinary, multiorganizational studies to assess natural resource damages to fisheries and marine environments. Dr. Pearson returns to Battelle after 3 years in the United Arab Emirates, where he served as Head of the Marine Environmental Research Center and as Acting Head of the Terrestrial Environmental Research Center as part of the Environmental Research and Wildlife Development Agency. In this capacity, Dr. Pearson developed programs for sea turtles, dugong, fisheries, seagrasses, the inventory of biodiversity of protected areas, the rehabilitation of select species, water quality, oil spill contingency planning, and natural resource damage assessment in the Gulf region, among other issues.

Dr. Pearson is currently leading a phased program sponsored by the Washington State Department of Transportation to apply a specially fabricated test bed to identify culvert designs and hydraulic conditions that allow upstream passage of juvenile salmonids at different life stages. In other programs, he is presently reviewing background documents to address biological assessments of the Channel Improvement EIS in the Lower Columbia River and estuary. Drs. Ron Thom and Walt Pearson developed a conceptual model that provides a blueprint of physical and biological interactions, including structural and functional features relevant to the use and support of salmonids in the Lower Columbia River ecosystem.

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