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The Role of Physical and Numerical Modeling in Design Development of the Priest Rapids Fish Bypass

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ABSTRACT

This paper describes a number of years of physical and numerical modelling that were instrumental in the development of the final fish bypass design at Priest Rapids Dam. Three physical models and multiple numerical models were used to guide the design of the fish bypass including its location on the dam, impact on forebay and tailrace flow patterns, intake configuration, design flow rates, flow control scheme, tailrace egress, potential for scour near the dam, potential impacts on total dissolved gas (TDG), impacts on spillway and powerhouse operation, and overall fish friendliness of the bypass.

Throughout those years of design work, results from actively tagged salmonid smolt studies were used to guide and validate each step of the design process. In 2011, a construction contract was awarded, and the Priest Rapids Fish Bypass facility was completed in the early spring of 2014. Final validation of this newly constructed facility came in the spring of 2014 with a survival and behavior study conducted using acoustic tagged yearling Chinook and juvenile steelhead smolts to evaluate the salmonid smolt survival rate through the bypass along with the fish passage efficiency (FPE) of the bypass facility.

This paper discusses the physical models plus CFD models used to support the design development of a non-turbine fish bypass and presents the results of the survival and behaviour studies conducted after the fish bypass was installed at Priest Rapids Dam.

Keywords: *Fish passage, modeling, dams, fish bypass, salmonids, spillway*.

1. INTRODUCTION

Priest Rapids Dam is a large hydroelectric dam on the Columbia River in central Washington, USA, owned and operated by Public Utility District No. 2 of Grant County, Washington (The District). Construction of the dam was completed in 1959. It creates a reservoir that extends 29 km (18 miles) upstream to the spillway of Wanapum Dam. Figure 1 shows the project site and an aerial view of the dam. The dam consists of a ten-unit powerhouse and a twenty-two bay spillway. The total powerhouse capacity is 955.6 MW.

Two fish ladders incorporated into the design of Priest Rapids Dam have been successful in passing adult salmonids upstream past the dam, but concerns related to the survival of juvenile salmonids passing the dam on their downstream migration led to a number of studies and field tests in the 1980s to assess various means of collecting juvenile salmonids in the forebay and transporting them downstream. Concerns regarding the use of screens to collect the juvenile fish led to examining whether an efficient passage route could be designed that allowed juvenile fish to bypass the turbines and pass the dam directly into the tailrace without resorting to large flow releases through the spillway.

As part of regulatory requirements associated with its FERC (Federal Energy Regulatory Commission) license and other agreements, the District was required to design and install a non-turbine fish passage for downstream migrating juvenile salmonids at the dam in order to help meet its pre-established survival standards for salmonid smolts passing through the Priest Rapids Hydroelectric Project during their downstream migration. The standards include a 93% juvenile dam and reservoir survival.

In 2002, a study was undertaken to identify a number of fish passage alternatives for Priest Rapids Dam including screening systems, use of the spillways, and collecting and bypassing fish through surface-oriented openings and/or through modified turbine passages (Voskuilen et al. 2003). This fish passage alternatives study (FPAS) suggested several options that had the potential to provide high fish passage efficiency and survival in a manner different and more efficient than high-volume tainter-gate spill programs. Options that made use of existing spillbays and released flow from the surface rather than from the underside of the radial gates were selected for field-testing as prototypes. This decision was based upon observations of fish passage from other projects where flow released from the surface appeared to be associated with a greater efficiency of smolt passage than flow released from depth.

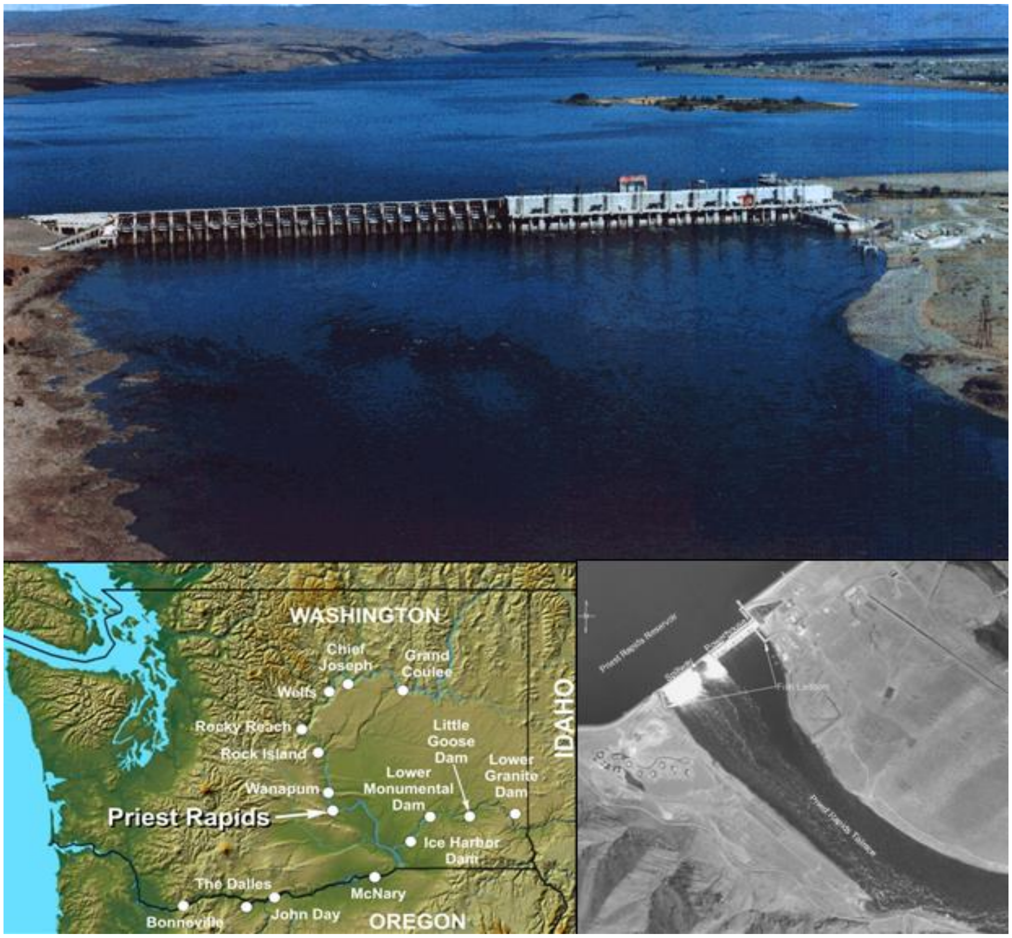

Figure 1. Priest Rapids Dam perspective photo, map, and satellite view.

2. APPROACH

To facilitate the study and design development of a fish bypass, IIHR-Hydroscience & Engineering (IIHR) developed comprehensive three-dimensional physical models of the forebay and tailrace of Priest Rapids Dam and a model of spillbays 19-22 and powerhouse unit 1. The three physical models were used in conjunction with computational fluid dynamics (CFD) models and a numerical fish surrogate (NFS) model to develop and test various aspects of the fish bypass design. The NFS model was developed by the Engineering Research and Development Center (ERDC) of the US Army Corps of Engineers (USACE).

The physical and CFD models were used in conjunction with prototype tests to advance the design of a non-turbine passage route. Field data on the percent passage and the percent survival through the turbine and non-turbine route was obtained through prototype tests conducted at the dam over a period of several years. The field data and CFD and laboratory models were used to design prototype tests and, ultimately, the final bypass design.

The laboratory and numerical models helped define the following hydraulic characteristics that were incorporated in evaluation of various bypass options, along with other parameters:

- Proximity of the non-turbine passage opening to where the highest density of salmonids was expected to be;
- The degree to which there was competition between flow through the powerhouse and flow through the non-turbine passage route;
- The stability of the flow and acceleration field upstream of the non-turbine passage route;
- The source of bypass water and zone of influence of the bypass;
- The egress of the bypass water in the tailrace with respect to proximity to areas of potential high predation; and,
- The egress of the bypass water with respect to minimizing the uptake of gas in the tailrace.

3. PHYSICAL MODEL DESCRIPTIONS

The three physical models used for the design development and final design of the fish bypass included a forebay model, a tailrace model, and a spillway sectional model. The scale models were built at the University of Iowa over a period of several years. A general description of each model is provided below:

- The 1:64 scale forebay model replicated a portion of the Priest Rapids forebay over an area 1,768 meters (5,800 feet) wide by 1,745 meters (5,725 feet) long upstream of the dam to Goose Island. The model included a fully operational spillway, powerhouse, and left and right bank fish facilities that could be set to match prototype operating conditions. Structural details included spillway piers, ogee profiles, radial tainter gates, and powerhouse intakes. The model replicated prototype river flows up to 11,327 cms (400,000 cfs).
- The 1:64 scale tailrace model replicated a portion of the Priest Rapids tailrace over an area approximately 853 meters (2,800 feet) wide by 2,316 meters (7,600 feet) long downstream of the dam as shown in Figure 2. The model included a fully operational spillway, powerhouse, and left and right bank fish facilities which could be set to match prototype operating conditions. Structural details included spillway piers, ogee profiles, radial tainter gates, and powerhouse draft tubes. The model replicated prototype river flows up to the probable maximum flood (PMF) flow rate of approximately 39,644 cms (1.4 million cfs).
- The 1:20 scale sectional model replicated a portion of the Priest Rapids tailrace over an area approximately 91 meters (300 feet) wide by 244 meters (800 feet) long downstream of the dam. The model included fully operational spillbays 19-22 and powerhouse unit 1 exterior features. The model replicated prototype flows up to the PMF flow through a full-open single spillbay.

Figure 2. Hydraulic model of the Priest Rapids Dam and tailrace.

4. CFD MODEL DESCRIPTIONS

The four numerical models used for the design development of the fish bypass at Priest Rapids Dam include a forebay model, a top spill model, an ogee shaped bypass model, and a numerical fish surrogate (NFS) model. The first three models were implemented in the CFD solver ANSYS FLUENT. The NFS model utilized the results of the forebay model to predict the behavior of outmigrating salmonid smolts in the forebay of Priest Rapids Dam. Each model is described briefly below:

- The forebay model comprised approximately 5,182 meters (17,000 feet) of the forebay of Priest Rapids Dam and used a flat rigid-lid approach. The forebay model included the river bathymetry, 10 powerhouse units with 3 intakes per unit, 22 spillway bays, and an ice-trash sluiceway located in the tainter gate of spillbay 22. Spillbays 19 and 20 were initially modeled as top spill, the other spillbays as bottom spill. The model also included Goose Island. The forebay model grid contained roughly 2 million grid points.
- The top spill model predicted the flow conditions downstream of spillways 19 to 22. This model used a VOF (Volume of Fluid) method to predict the free surface and calculate pressures and accelerations associated with flows through the fish bypass prototypes in spillbays 19 and 20. The model of the prototype top spill bays was developed to assess the hydraulics in the tailrace immediately downstream of the top spills. Figure 3 provides an illustration of this model. This model simulated flow through bays 19 and 20 and was used to determine the pressure loads on particles (fish) traveling through the bays. The VOF method allowed the water surface profile in the forebay, tailrace, and nappe to be obtained by the simulation for an incoming flow rate.
- The ogee shaped bypass model also used the VOF method, and it was developed to compute cavitation indices and total hydraulic loads on the fish bypass surfaces of the final design. The VOF method was used to simulate the flow field over the spillbays for the final design. To reduce computing time and grid size, instead of simulating the entire geometry, simplified geometries were used. Simulations with spillbays 21 and 22 required the modeling of one full bay and a half bay resulting in a grid with about 3.1×10^6 cells. A small region of the tailrace was incorporated into the model to account for the effect of the bypass submergence condition.
- The NFS model, which is based on a particle tracking algorithm, was used to predict the distribution of smolts passing the dam for given flow releases. This model used the hydrodynamic data results obtained with the forebay model as inputs. IIHR worked with the USACE for many years to develop a method for predicting the movement and behavior of migratory salmon by providing the hydrodynamic data obtained by computational fluid dynamics (CFD) simulations of a given waterway. This collaborative effort led to the development an Eulerian-Lagrangian-Agent Method (ELAM) that tracks fish as particles in the waterway and moves the fish according to certain "behavior rules." The behavior rules are a function of fluid properties such as acceleration, strain, velocity, and velocity gradients. This particular ELAM is known as the NFS model. The USACE took the lead in the development of the biological responses of the salmonids that ultimately comprised the NFS model (Nestler et al. 2001, Goodwin et al. 2004).

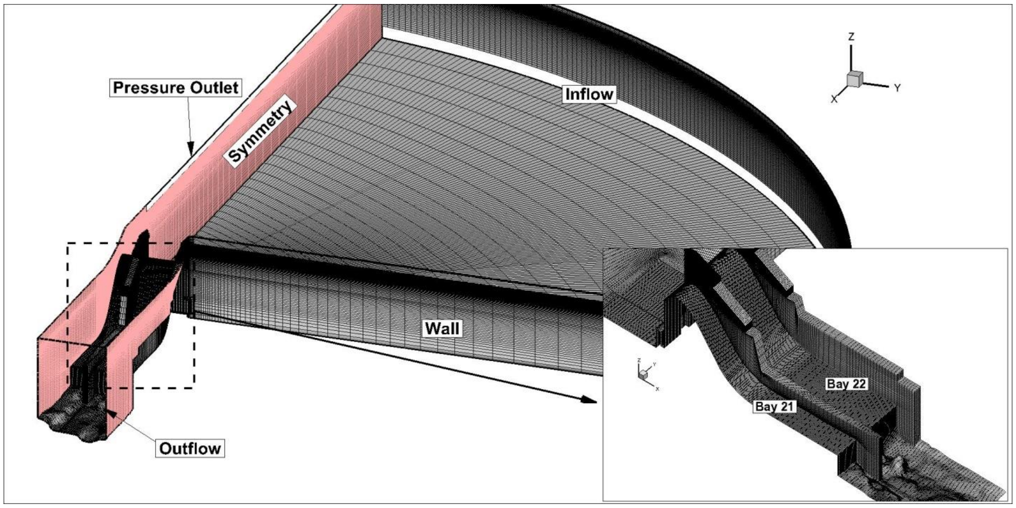

Figure 3. Ogee shaped model.

5. FISH BYPASS DESIGN DEVELOPMENT

The District began work at Priest Rapids Dam in 2002 by commencing the FPAS and also prototype testing of spillway gate 17 fully open. The hydraulic model test program at IIHR began in earnest in 2002 with the construction of the 1:64 scale forebay model followed by construction of the tailrace model and development of the forebay CFD model. The CFD and laboratory models supported investigations and decisions related to field-testing of prototypes. Over the next eight years, the District used a variety of tools in the design and evaluation process of the fish bypass, including the following:

- Acoustic tagged fish;
- CFD models of forebay and tailrace;
- Physical models of forebay, tailrace, and bypass;
- The numerical fish surrogate model.

Observations from the fully opened spillbay tests in 2002 together with the CFD and hydraulic modeling of top spills led to the decision to prototype test top spills in spillbays 19 and 20 starting in 2006. As a result, extensive work was undertaken in 2004-2005 to develop a top spill fish bypass concept, which was field-tested in 2006 and 2007 (Fig. 4).

To develop the top spill concept, the forebay and tailrace hydraulic models were used to evaluate bulkheads that released flow from the surface of the forebay. The forebay model was primarily used to examine approach-flow conditions, entrance characteristics such as shockwaves and flow separations, and measure tainter gate clearance. The tailrace model was used to examine nappe characteristics such as trajectory and impact location, test various bulkhead sill shapes, examine stilling basin hydraulics, develop a bypass flow rating, and document egress flow patterns. Approach flow to the topspill bypass was also studied using the forebay CFD model to observe the zone in the forebay that was influenced by the flow withdrawal for various conditions. The CFD model was also used to define flow patterns, examine where the water passing the fish bypass originated in the forebay, and examine the velocities and accelerations of flow approaching the bypass. The CFD top spill model was also used to calculate sectional nappe profiles along the spillbay centerline to determine the nappe clearance beneath the tainter gate and to determine the jet impact location.

Figure 4. Topspill bulkheads tests at Priest Rapids in 2006 and 2007.

The prototype testing in 2006 and 2007 was undertaken in conjunction with studies of acoustically tagged fish to determine the effectiveness of the top spills. While prototyping proved successful in assessing the effectiveness of attracting and passing juvenile salmonids through top spills, it raised the concern that pressures and accelerations experienced by fish might result in injury or mortality that would render free-fall top spills unsuitable for a permanent fish bypass design. Two initiatives were undertaken to assess these concerns; a field study by Battelle (Duncan 2009) using sensor fish and the development of the ogee shaped bypass CFD model, from which accelerations and pressures along streamlines could be extracted.

Ultimately, the percent of fish using the top spills in 2006 and 2007 to bypass the powerhouse did not appear to be adequate to achieve the survival goal for the project. This led to two study initiatives which started in 2007; one initiative was to study and assess the benefits of increasing the rate of bypass flow and/or changing the bypass location; the second initiative was to study and assess whether more fish could be guided to bypass the powerhouse through the use of training walls or training velocities.

The concept of using training walls to guide outmigrating fish had been prototyped by the US Army Corps of Engineers (USACE) at the Lower Granite Lock and Dam on the Snake River, and it was being prototyped at the second powerhouse at Bonneville Dam when consideration was being given to prototype tests at Priest Rapids Dam in 2008 and 2009.

The concept of guiding fish through the use of submerged water jets was advanced by Mr. Gordon C. Burns and patented in May 2004 as a Flow Velocity Enhancement System. The system envisaged the placement of nozzles in low velocity areas within a river, lake, or reservoir “as a method to create water flow velocities that fish are reluctant to pass through for a barrier or curtain to further guide the fish” (Burns 2004).

The hydraulic modeling of the training walls and jets was undertaken in concert with CFD/NFS modeling, with the physical modeling used to gain some qualitative visual insights and the numerical modeling used to define velocities, accelerations, and the source of bypassed water. The CFD forebay model was used to estimate the hydrodynamic loads on training walls that might be used to enhance the number of fish using the bypass. It was also used to examine the effectiveness of using jets of pumped water to guide fish to a bypass. Insights from the tests and numerical modeling, along with an assessment of the costs and effectiveness of these measures elsewhere, were used to decide whether training walls or jets would be prototyped.

The modeling led to the decision in 2008 to increase the amount of bypass flow by leaving the topspill bulkheads in spillbays 19 and 20 but adding a bottom release in spillbay 21 and a release from the sluiceway in spillbay 22. It was observed in the models that the increase in total bypass flow created a stronger draw from the forebay to the bypass routes, and releasing flow through spillbays 21 and 22 enhanced flow conditions in the tailrace for egress of the smolts.

Also based on the model tests, inadvertent spill was released through the higher numbered spillbays in 2008. The 2008 prototype testing condition is shown in Figure 5.

Figure 5. Topspill in bays 19, 20, and 22 and bottom spill in bay 21 as tested in 2008.

As was the case for the 2006 and 2007 prototype tests, it was decided to leave the 2008 bypass configuration in place for the 2009 season in order to obtain an additional year of fish passage data without making any changes to the prototype. There was no prototyping of training walls or velocity enhancement jets undertaken; instead, these techniques were left as potential additional measures that might be considered for implementation should the survival goal not be achieved following construction and commissioning of the final bypass design.

Throughout the design process, the NFS model was useful in comparing the percent of fish using a non-turbine passage for various bypass configurations, bypass enhancements, and plant loadings on a relative basis to give indications as to which configurations were most likely to produce the best bypass efficiencies. Results indicated that bypass efficiency would be greater with the bypass located close to the powerhouse rather than at a more central position on the spillway. They also supported the observation from the field that the bypass efficiency could be higher with bypass flows drawn from the surface. All the modeled configurations indicated that location of the bypass and withdrawals from the surface were more important parameters than the total bypass flow alone.

Prototype testing guided by laboratory and CFD modeling proved successful, with an increase in percent fish passage over a period of five years. The percent fish passage by year of prototype testing is summarized in Table 1.

Table 1. Topspill bulkhead percent fish passage

Year	Chinook	Steelhead	Sockeye
2006	12%	15%	20%
2007	13%	19%	12%
2008	23%	33%	22%
2009	n/a	50%	39%
2010	n/a	64%	52%

6. THE FINAL FISH BYPASS DESIGN

In 2010, the final design of a production bypass was initiated. The primary factors that determined the design characteristics were as follows:

- The bypass entrance should be located near a high concentration of fish approaching the project;
- The bypass exit should be near additional flows and away from areas of high concentrations of predators;
- No deceleration or upwelling should be present at the entrance;
- Bypass flow should be selected to achieve the required survival goal through top spill or combination of top and bottom spill;

- Bypass flow of a single bay should be limited to 283 cms (10 Kcfs) to minimize total dissolved gas and maximize tailrace survival;
- To minimize mortality, impacts and shear should be minimized at the exit;
- To minimize uptake of dissolved gas, plunging flow should be avoided at the exit;
- The dam must be able to pass probable maximum flood after the bypass is installed; and
- Installation of the bypass must not result in a reduction of dam stability.

These factors resulted in the following decisions:

- The bypass will be located adjacent to the powerhouse;
- The bypass will be installed in spillbays 20, 21, and 22;
- There is no need for special control of accelerations at the entrance; and
- The target flowrate is 255 cms (9 Kcfs) per bay.

Based on an analysis of the four years (2006 – 2009) of fish passage data, it was estimated that a total bypass top spill flow of 765 cms (27 kcfs) would be required from spillbays close to the powerhouse in order to meet the target of at least 95% survival of smolts passing the dam with the assumption of 99% survival through the top spill.

A review of the probable maximum flood (PMF) that would be required to pass Priest Rapids Dam, together with a review of the hydraulic capacity of the spillway (Larry Weber, personal communication, 2010), indicated that three spillbays, each with a design bypass flow of 255 cms (9 kcfs), could be dedicated to fish passage while still maintaining sufficient hydraulic capacity in the spillway to pass the PMF.

For the final design, the NFS model was used to give an estimate of the three-spillbay bypass route efficiencies, and CFD work was undertaken using the ogee shaped model to compute pressures and cavitation indices. The hydraulic loads and center of pressure on the spillway face for the various simulations were provided for use in structural engineering and stability analysis of the fish bypass.

The physical models were used extensively to test the final design. For example, the models were used to analyze approach conditions in the forebay for various river flows and powerhouse loadings, perform a flow rating, determine water surface profiles through the bypass, measure pressures on the ogee surface, determine maximum velocity on the apron, determine the optimum apron elevation and length, assess pier extension heights and lengths, characterize jet performance over a range of tailwater elevations, examine egress flow patterns, and assess downstream scour potential. In addition, the tailrace model was used to assess wave and velocity characteristics in the fish bypass construction zone that were likely to be encountered by crews and equipment during construction. A number of tests were also conducted on the 1:64 scale tailrace model to help determine the appropriate apron elevation when releasing bypass flows. It became apparent that it would be necessary to raise the invert elevation of the stilling basin and extend the spillway pier tails downstream over the apron in order to preclude the bypass flow from plunging to depth in the tailrace. Subsequent tests indicated it was necessary to extend the pier tails beyond the end of the spillway apron to curtail return flow from the tailrace moving upstream on the apron along the walls of the pier, creating a condition of turbulence and shear that was potentially adverse for fish. Testing of the final apron design is shown in Figure 6. Figure 7 shows a photograph of the final design being tested in the tailrace model. Figure 8 is a photograph of the final bypass in operation on the dam.

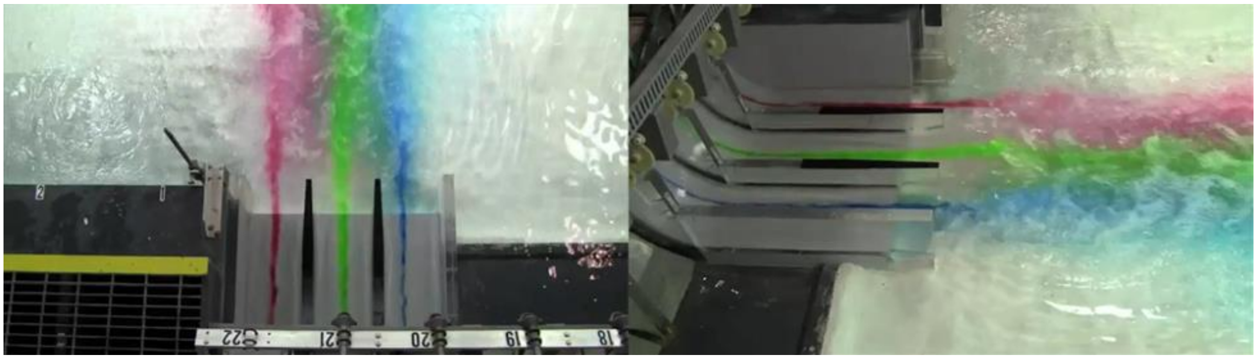

Figure 6. Fish bypass apron design being tested on the tailrace model.

Figure 7. The final fish bypass design in the tailrace model.

Figure 8. Photograph of the final fish bypass in operation.

7. SURVIVAL AND BEHAVIOUR STUDY RESULTS

Final validation of the newly constructed facility came in the spring of 2014 with a survival and behavior study conducted using acoustic tagged yearling Chinook and juvenile steelhead smolts to evaluate both the salmonid smolt survival rate through the bypass and the fish passage efficiency (FPE) of the bypass facility. Results showed that 47.2% of steelhead and 38.1% of yearling Chinook used the fish bypass (Hatch et al. 2015). The selection of passage routes for both species is shown in Figure 9. Steelhead had slightly higher passage rates through the bypass compared to yearling Chinook, with similar passage rates through the spillway and powerhouse. Survival rates through the bypass for steelhead and yearling Chinook were 99.6 and 99.8%, respectively.

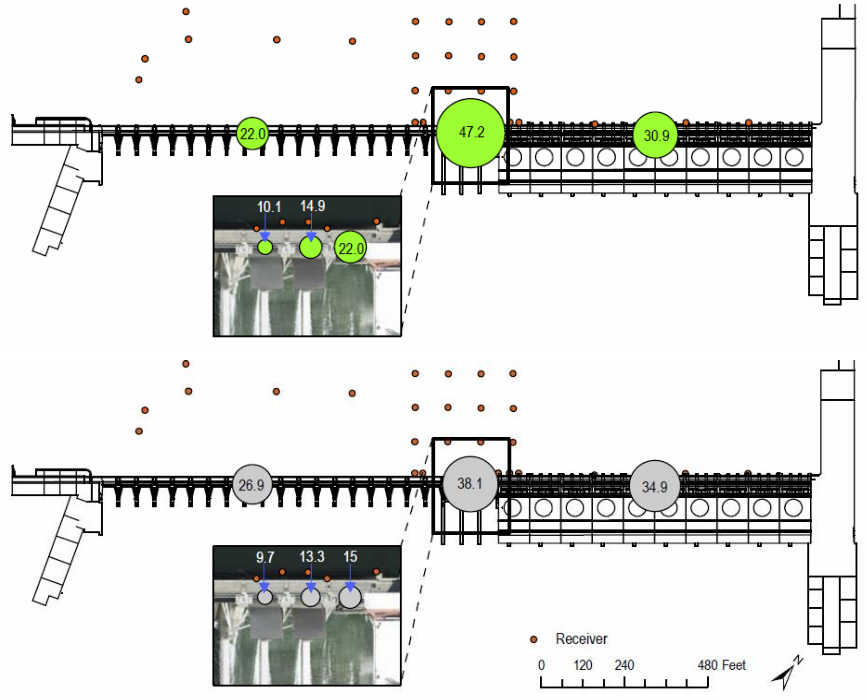

Figure 9. Passage rates for Chinook (top panel) and steelhead (bottom panel) for 2014.

8. ACKNOWLEDGMENTS

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