Three-dimensional behavioral results from acoustically tagged salmon smolts approaching hydroelectric dams

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Abstract

Acoustic tags were used to monitor the swimming patterns of downstream migrating salmon smolts approaching dams in the USA. Downstream migrating salmonids, yearling chinook (*Oncorhynchus tshawytscha*), steelhead (*Oncorhynchus mykiss*), sockeye (*Oncorhynchus nerka*), and sub-yearling chinook smolts were surgically implanted with acoustic tags. Juvenile salmonids were tracked in three-dimensions as they approached and passed into the turbine intakes, spillways, and surface bypass channel entrances at multiple dams on the Columbia River during the 2004-2008 spring and summer outmigration (Washington, USA). Significant advances in acoustic tag analysis techniques and software have been made over the past few years, the development of various fish density algorithms, stream trace modeling analysis, and advances of three-dimensional animation programs. Three-dimensional tracks of fish approaching turbine intakes, spillways, and surface bypass channel entrances will be presented. Concentrations of fish passage will be presented as three-dimensional fish densities superimposed over dam structures. Streamtrace modeling to predict fish passage routes will be shown.

Keywords: acoustic tags, fish behavior, fish movement, salmon smolt survival.

Introduction

Acoustic Tag Development

Acoustic tags have been used to monitor the swimming patterns of downstream migrating salmon smolts approaching dams in the USA. Traditionally, acoustic tags have been utilized for detecting only tagged fish presence or absence within a given study area. This information has been invaluable for estimation of project wide fish survival and to evaluate the success of measures taken to increase salmon smolt survival (Skalski et al. 2002, Townsend et al. 2006). However, acoustic tags have developed over the last 12 years from a tool to determine simple presence or absence to a highly sophisticated technique allowing researchers to observe underwater three-dimensional fish behavior (Ehrenberg and Steig 2003; Ransom et al., 2008; Steig 2000). The fine-scale behavioral information provided by acoustic tags has been used to determine the species-specific fish passage results required to assess fish bypass performance at hydroelectric dams (Skalski et al., 2009). Research has also been conducted to identify optimal acoustic tag operating and design parameters (Ehrenberg and Steig 2009). A method has also been developed for estimating acoustic tag position accuracy (Ehrenberg and Steig 2002).

Acoustic Tag Studies

Numerous acoustic tag studies evaluating the salmon smolt behavior have been conducted on the Columbia and Snake rivers over the last decade. Downstream migrating salmonids, specifically yearling chinook (*Oncorhynchus tshawytscha*), steelhead (*Oncorhynchus mykiss*), sockeye (*Oncorhynchus nerka*), and sub-yearling chinook smolts have been surgically implanted with acoustic tags. Results from these studies have included horizontal passage distributions, smolt travel times, and three-dimensional tracks of smolt movement approaching hydroelectric dams (Steig et al. 2009).

Over the last 25 years, survival studies of downstream migrating salmon smolts have primarily been conducted using passive integrated transponder tags (PIT). Fisheries agencies and project managers have widely accepted the results from PIT telemetry studies. A number of paired acoustic tag and PIT tag telemetry studies were conducted early in this decade and the results of both methods were determined to be positively correlated and statistically comparable by Steig et al. 2005. Advantages of the acoustic tag approach included the need to use far fewer tags for the equivalent precision and the availability of fish behavioral information.

Methods and Techniques

Acoustic Tags

For the study that will be discussed in this paper, HTI *Model 795m Acoustic Tags* were used for monitoring sockeye smolts. These tags were approximately 6.8 mm in diameter by 16.5 mm long and averaged 0.75 g in air. The average tag operating life was 17 days, based on acoustic tag life tests. Transmit power level for the tags were approximately 147 dB uPa @ 1 m. The tags were encapsulated with a non-reactive, inert, low toxicity resin compound. Ping rate, pulse width, and individual tag ID were programmed in the field. There were 2,589 individual tags that were uniquely coded for this study. The transmission rate (i.e., ping rate) for this study was set at 1 ping every 2.8-6.0 sec, with a broadcast pulse width of 1.0 msec.

Acoustic Tag System

An HTI *Model 290 Acoustic Tag Tracking System* was used for this study. Each Acoustic Tag Receiver (ATR) system can determine the presence or absence of tagged fish. In addition, the ATR can remotely track tagged fish in three dimensions with sub-meter resolution. The ATR operates at 307 kHz, selected as an optimum frequency with respect to detection ranges and resolution based on tests conducted at multiple hydropower dams (HTI 1997). The ATR system can simultaneously monitor up to 16 individual hydrophones. All hydrophones used in this study had an omni-directional detection beam. All systems were operated 24 h/d, 7 d/wk during the spring outmigration.

The ATR continuously receives and stores all tag transmit pulses for each hydrophone simultaneously. The calculation of the three-dimensional location of an acoustic tag requires that the transmitted signal be detected by four hydrophones whose positions are known and that are not located on the same plane. This requires approximately half of the hydrophones be mounted near the surface, while the other half are mounted near the bottom.

Calculation of Three Dimensional Positions

The method that is used by the acoustic tag system to determine fish position is the same principle used by Global Position Satellites (GPS). The acoustic tag transmits a signal which is received by at least four hydrophones. By knowing the positions of the four hydrophones and measuring the relative signal arrival times at each one, the locations of the tagged fish can be estimated.

For four hydrophones, there are three distinct signal arrival time difference equations. These nonlinear equations can be determined by solving the tagged fish coordinates, such that the mean squared difference between the measured and calculated time differences are minimized. The algorithms for accomplishing the minimization are described in Ehrenberg and Steig 2003.

Site Description and Hydrophone Placement

Rocky Reach Dam is located on the Columbia River, seven miles north of Wenatchee, Washington, USA at river mile 475. The dam's spillway is perpendicular and its powerhouse parallel to river flow. The powerhouse is 1,088 ft long and contains 11 vertical Kaplan turbines (Unit) numbered from south to north. Each Unit has three rectangular intakes, 20 ft wide by 50 ft high at the headgate slot. The spillway is over 750 ft long and has 12 automatic spill gates. Each gate is 50 ft wide and approximately 60 ft deep to the spill gate ogee.

Three ATR systems with 14-15 hydrophones each were used to monitor the Rocky Reach powerhouse forebay. Another two ATR systems with six hydrophones each were used in Rocky Reach gatewell slots 1 and 2. Lastly, another two ATR systems, with three hydrophones each, were used in the Rocky Reach spillway forebay. Figure 1 shows an underwater view of the hydrophone placement in the forebay of the Rocky Reach Dam powerhouse.

Analysis and Results

The results presented in this paper are from the 2008 sockeye smolt outmigration approaching and passing Rocky Reach Dam. A total of 1,524 sockeye were implanted with acoustic tags throughout the 2008 study period. A total of 400 acoustically tagged sockeye smolts were released upstream in the Wells tailrace and tracked through the Rocky Reach reservoir and dam. Once tagged, sockeye were held for 48 h prior to release to assess fish condition and to verify tag operation. A detailed description and analysis of this study can be found in Steig et al. 2009.

Upstream Horizontal Distribution

The region within 1000 ft upstream of the face of Rocky Reach Dam is restricted to boat traffic. Near the upper end of this boat restriction zone (BRZ), a hydrophone detection array was installed across the river. From this detection array, the horizontal distribution across the river of tagged sockeye smolts was determined. For each fish detection, the ultimate passage route through Rocky Reach Dam was summarized along with its horizontal distribution at the BRZ.

The overall horizontal distribution at the BRZ for sockeye smolts is presented in Figure 2. In general, the largest proportions of sockeye passing the BRZ were located in the center of the river. Overall, 98% of all sockeye approached the dam along the west and center portions of the river. The smallest proportions of detections at the BRZ were recorded along the east side of the river. In general, fish that passed the BRZ along the center and east side of the river were more likely to use Units 3-11 as a passage route as

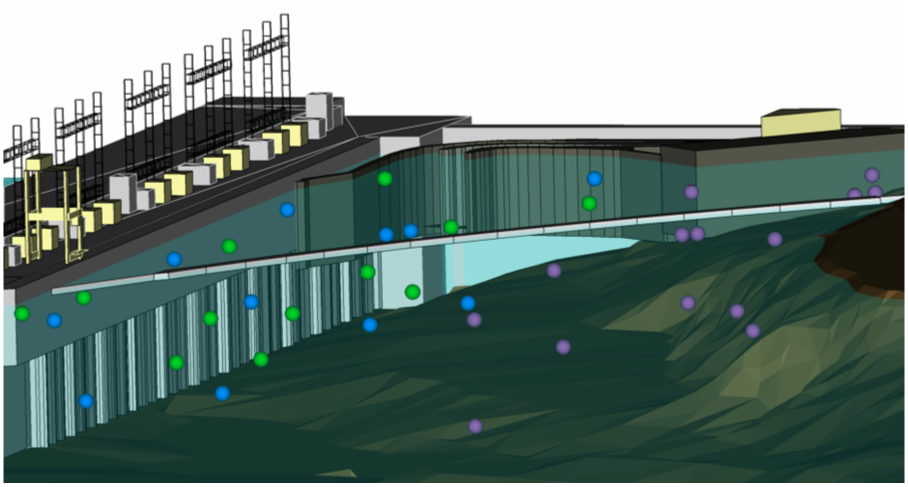

Figure 1. View of the Rocky Reach Dam powerhouse forebay showing the significant structures, hydrophone locations, and bathymetry. The different colored balls signify the hydrophone placements for the three separate ATR's.

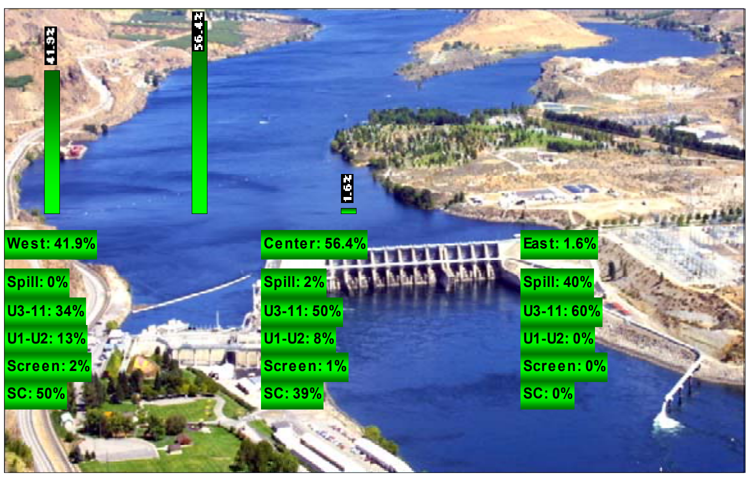

Figure 2. Proportion of sockeye across the river, directly upstream of Rocky Reach Dam at the Boat Restriction Zone, with the associated route specific passage at the dam in 2008. The proportions of detections have been grouped into three categories: west side, center or east side of the river.

compared to the fish that passed the west bank of the river. Conversely, fish that passed along the west side of the river were more likely to use the surface collector (SC) as a passage route as compared to the fish that passed the BRZ along the center and east side of the river.

Rocky Reach Dam Horizontal Distribution

Seasonal route specific passage (RSP) of sockeye smolts at Rocky Reach Dam was calculated for the SC, the bypass screens, Units 1-2, Units 3-11, and the spillway. Sockeye RSP is presented in Figure 3. Sockeye RSP distribution indicates that smolt passage was highest through Units 3-11 passing 43% of the tagged sockeye smolts, followed by the SC (41%), Units 1-2 (8.5%), the bypass screens (4.5%) and the spillway (2.5%).

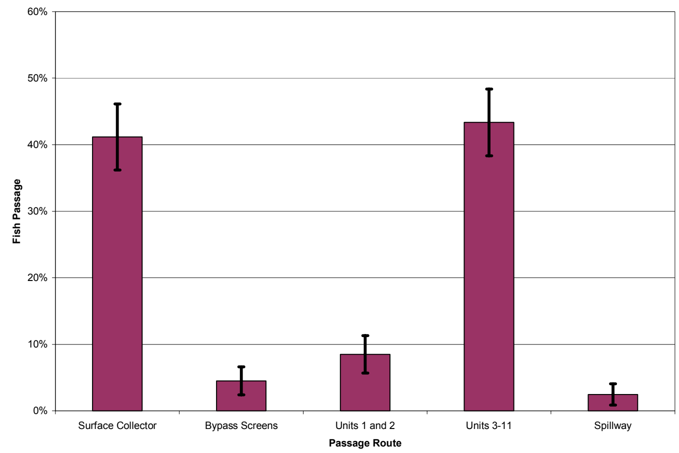

Figure 3. Seasonal percent route specific passage of sockeye (with 95% CI) at Rocky Reach Dam in 2008.

Rocky Reach Dam River Flow Distribution

Seasonal flows at Rocky Reach Dam were summarized for each available downstream passage route. The available routes were grouped as follows: Units 1-2, Units 3-11, and the spillway. Flow rates in thousand cubic feet per second (kcfs) for each of these passage routes are presented on a seasonal basis in Figure 4. The majority of mean project flow during the spring outmigration period passed through Units 3-11 (114.6 kcfs). Units 1 and 2 had a combined mean turbine flow of 26.0 kcfs, mean spillway flow was 13.2 kcfs and mean SC flow was 6 kcfs.

Three-Dimensional Sockeye Paths

Over 350 tagged sockeye smolts passing through the Rocky Reach Dam forebay in 2008 were processed to extract three-dimensional (3D) approach tracks. The 3D paths of the sockeye were calculated and displayed along with the plan view of Rocky Reach Dam. The three-dimensional paths of two sockeye passing into the SC are presented in Figure 5 as examples of the routes taken by the sockeye smolts. The path of Fish 4043.06 (Figure 5a) shows a relatively straight swimming path diagonally across the forebay, starting near the west shore of the river and concluding in the SC entrance. The path of Fish 4090.15 (Figure 5b) shows a route similar to the previous sockeye smolt. However, the path of Fish 4090.15 shows a meandering path, under the log boom, across the forebay to the powerhouse wall, and milling in the forebay prior to approaching the SC entrance. Both sockeye smolts were in the upper portion of the water column throughout most of their routes as shown by the color of the path (blue is the upper 20 ft of the water column).

Day/Night Sockeye Smolt Passage

Hourly project passage distributions were calculated based on the percentage of the sockeye smolts passing Rocky Reach Dam in any given hour over the study period. These data were used to evaluate diel patterns of sockeye smolt passage. Hourly mean project sockeye passage is summarized in Figure 6. In general, sockeye demonstrated a broad pattern of diel passage with peak passage extending from early morning to the mid-morning hours. Peak passage for sockeye occurred during 0400-0900 h. Lowest hourly passage occurred during the evening (2000 h) and late night (2300 h) hours.

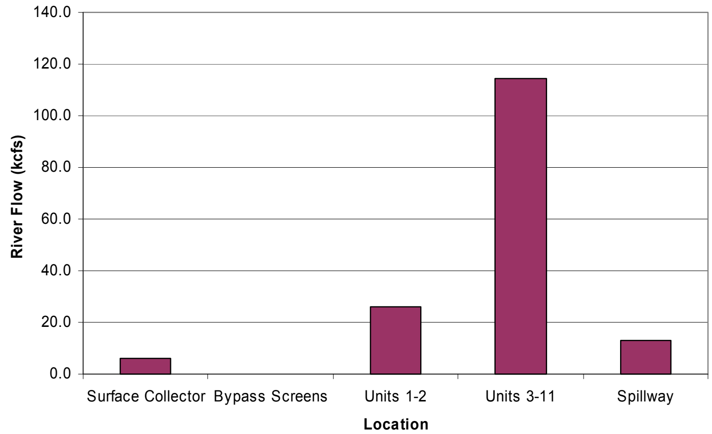

Figure 4. Mean flow rates (kcfs) by passage route at Rocky Reach Dam in 2008.

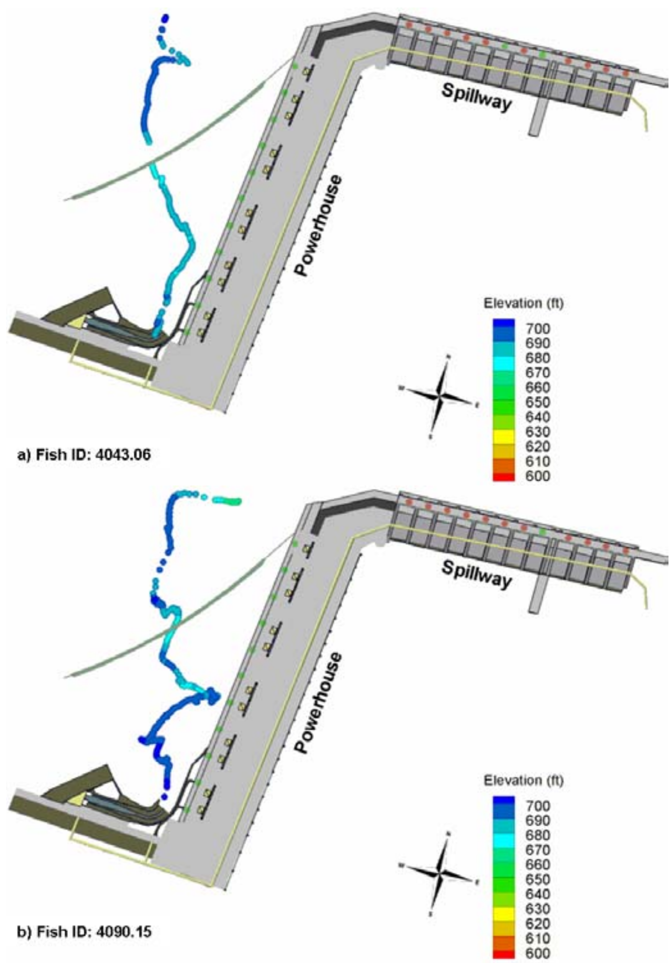

Figure 5. Sockeye swimming pathways at Rocky Reach Dam in spring 2008. Each fish passed downstream through the surface collector; a) Fish ID: 4043.06 and b) Fish ID: 4090.15. Color corresponds to elevation in feet.

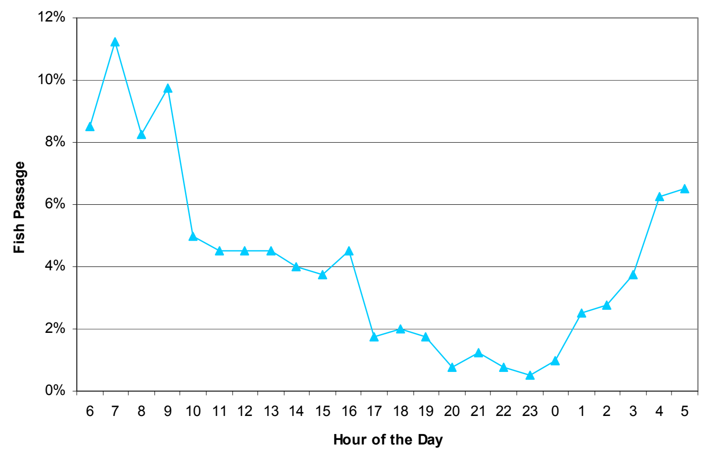

Figure 6. Project hourly sockeye passage at Rocky Reach Dam in 2008.

Combination of Results

The software program *Eonfusion*™ was used to display and combine multiple study results. *Eonfusion*™ is a data visualization, analysis and fusion program which was designed for time series data. Juvenile sockeye smolt passage results displayed in *Eonfusion*™ are presented in Figure 7.

The plan view of Rocky Reach Dam along with the upstream BRZ detection array is presented in Figure 7a. The east side of the river (and the detection array) is represented by the red dot in the figure. The center of the river is represented by the yellow dot and the west side of the river is represented by the green dot. Zooming in on the view of the dam (Figure 7b) shows the sockeye smolt paths for the entire 2008 study. The colored dots of the paths represent the location that the individual sockeye path crossed at the BRZ (red, yellow, or green). The color of each sockeye path corresponds to the passage depth with blue representing near surface and red representing near bottom of the reservoir. The turbine flow results are represented by the colored cones above each turbine unit with green corresponding to normal flow and red corresponding to the turbine not in operation. A time clock in the figure shows the time of day that each sockeye approached the dam including daylight and darkness periods. Finally, all of these results can be animated with a time slider at the bottom of the figure. The *Eonfusion*™ program provided a powerful tool to evaluate relationships between multiple variables over time.

Binary Density Results

To illustrate the distribution of sockeye smolts in the Rocky Reach Dam forebay, density plots of fish concentrations were produced using the *TECPLOT*™ software program. The monitored forebay area was subdivided into individual cells each measuring 50 ft x 50 ft x 10 ft. Each cell was assigned a value based on the total number of sockeye that entered each cell, regardless of how long each fish remained in a particular cell. Data were interpolated by kriging (Davis 1986) between cells. These binary density plots remove the masking effect of milling and provide a more representative indication of the overall spatial distribution of sockeye smolts in the forebay.

Binary density distributions of sockeye passage through the Rocky Reach Dam Surface Collector (SC), by elevation, are presented in Figure 8. Sockeye passage through the surface collector comprised 41% of total passage. In general, the majority of sockeye passing through the SC were distributed in the middle of the water column (i.e. elevation 660-680 ft), above the floor of the SC. The highest sockeye smolt densities occurred in the vicinity of the SC entrance and in front of Units 1-2. Sockeye entering the SC appeared to be distributed in the upper 40 ft of the water column and did not demonstrate large-scale vertical movement in the forebay.

a)

b)

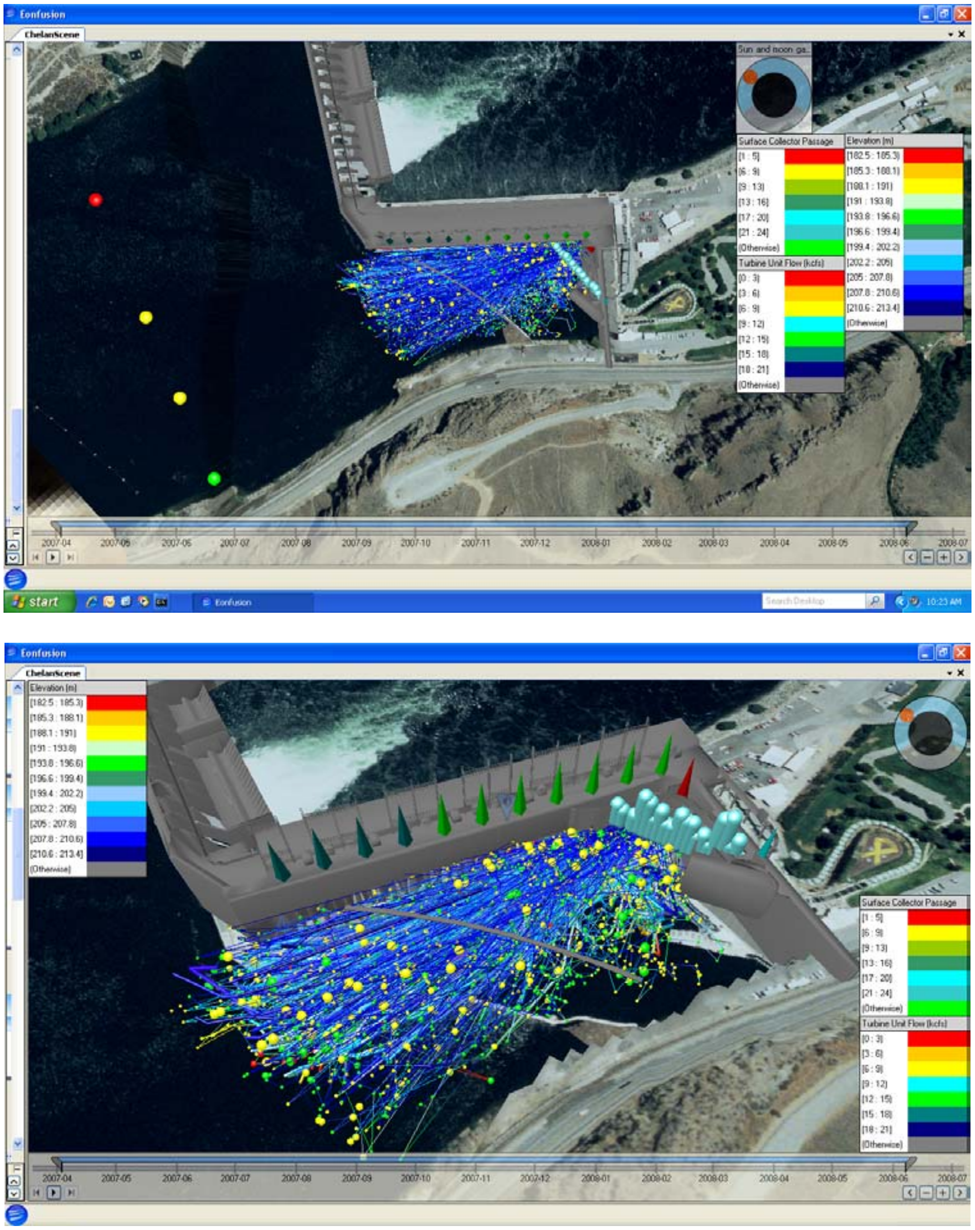

Figure 7. Examples of combined results using the display program Eonfusion for: a) Rocky Reach Dam to the upstream detection array; and b) Rocky Reach Dam showing the powerhouse forebay.

Streamtrace Modeling Results

The *TECPLOT*™ software program can also be used for conducting streamtrace analysis. Utilizing the summarized data in each of the 50 ft x 50 ft x 10 ft cells of the Rocky Reach Dam forebay, streamtrace analysis can be used as a predictive model. An example of streamtrace modeling is presented in Figure 9. The tracks in the figure are paths a fish would take from the point of release to their ultimate passage location based on the average trajectory of all sockeye that passed through each of the cells. The results predict that surface-oriented fish (blue and green) would primarily pass into the SC. Deeper traveling fish (yellow and red) would primarily pass into the Units. This analysis is useful for predicting the ultimate passage route for fish, based on their initial location in the forebay.

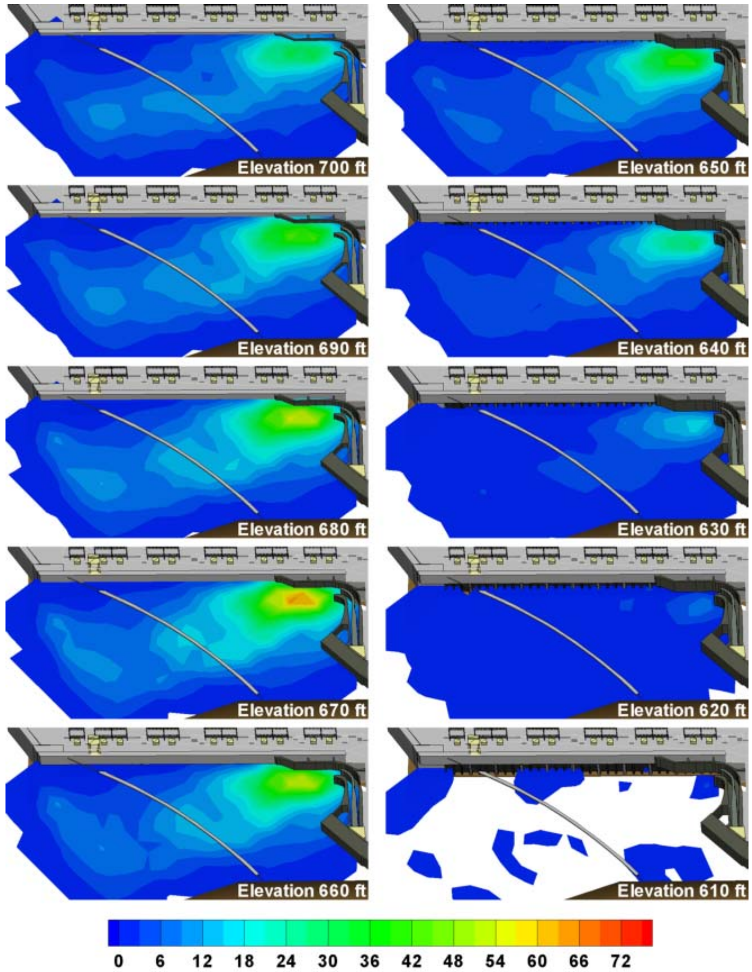

Figure 8. Binary densities of sockeye passage through the SC at Rocky Reach Dam during the spring of 2008. Density plan view figures are shown in 10 ft slices from elevation 700 ft (top left) to elevation 610 ft (bottom right).

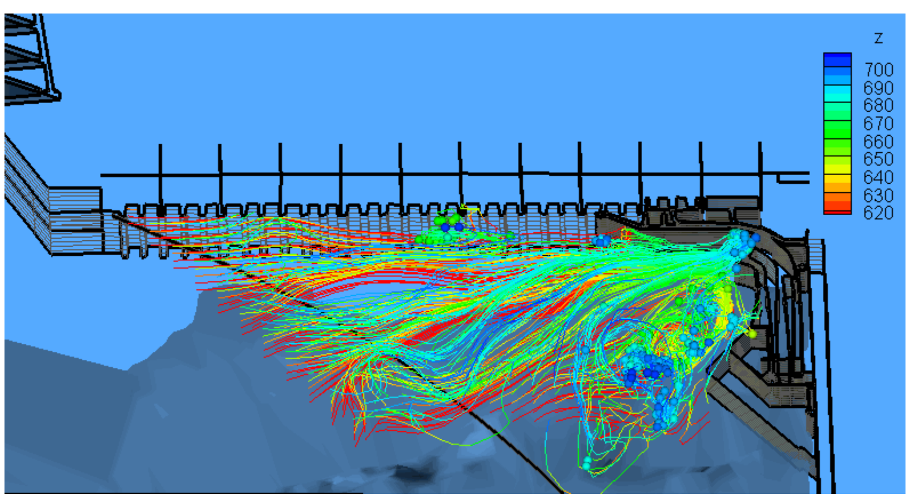

Figure 9. Streamtrace analysis modeling of Rocky Reach Dam sockeye smolt passage.

Conclusions

Acoustic tags have been routinely used over the last 10 years to monitor downstream migrating salmon smolt survival and distribution on the Columbia River. Advances in acoustic tag technology have enabled researchers to not only detect tagged juvenile salmonids, but also to track the fish in three-dimensions as they approached and passed into the turbine intakes, spillways, and surface bypass channel entrances. Results from the 2008 spring outmigration of sockeye salmon smolts approaching Rocky Reach Dam improved our understanding of the relationship between how smolts approach the dam and their ultimate passage routes.

A number of advances in the analysis techniques and software have been made over the past few years. Some of these improvements include the development of various fish density algorithms, streamtrace modeling analysis, and advances of three-dimensional animation and visualization programs. Acoustic tag studies have proven to be an effective method for monitoring and analyzing fish behavior and movement.

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