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Factors Affecting Route Selection and Survival of Steelhead Kelt at Snake River Dams in 2012 and 2013

December 2014

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U.S. DEPARTMENT OF ENERGY

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Abstract

In 2012 and 2013, Pacific Northwest National Laboratory conducted a study that summarized the passage proportions and route-specific survival rates of steelhead kelts that passed through Federal Columbia River Power System (FCRPS) dams. To accomplish this, a total of 811 steelhead kelts were tagged with Juvenile Salmon Acoustic Telemetry System (JSATS) transmitters. Acoustic receivers, both autonomous and cabled, were deployed throughout the FCRPS to monitor the downstream movements of tagged-kelts. Kelts were also tagged with Passive Integrated Transponder tags to monitor passage through juvenile bypass systems and detect returning fish. The current study evaluated data collected in 2012 and 2013 to identify individual, behavioral, environmental and dam operation variables that were related to passage and survival of steelhead kelts that passed through FCRPS dams. Bayesian model averaging of multivariable logistic regression models was used to identify the environmental, temporal, operational, individual, and behavioral variables that had the highest probability of influencing the route of passage and the route-specific survival probabilities for kelts that passed Lower Granite (LGR), Little Goose (LGS), and Lower Monumental (LMN) dams in 2012 and 2013. The posterior probabilities of the best models for predicting route of passage ranged from 0.106 for traditional spill at LMN to 0.720 for turbine passage at LGS. Generally, the behavior (depth and near-dam searching activity) of kelts in the forebay appeared to have the greatest influence on their route of passage. Shallower-migrating kelts had a higher probability of passing via the weir and deeper-migrating kelts had a higher probability of passing via the JBS and turbines than other routes. Kelts that displayed a higher level of near-dam searching activity had a higher probability of passing via the spillway weir and those that did less near-dam searching had a higher probability of passing via the JBS and turbines. The side of the river in which kelts approached the dam and dam operations also affected route of passage. Dam operations and the size and condition of kelts were found to have the greatest effect on route-specific survival probabilities for fish that passed via the spillway at LGS. That is, longer kelts and those in fair condition had a lower probability of survival for fish that passed via the spillway weir. The survival of spillway weir- and deep-spill passed kelts was positively correlated with the percent of the total discharge that passed through turbine unit 4. Too few kelts passed through the traditional spill, JBS, and turbine units to evaluate survival through these routes. The information gathered in this study describes Snake River steelhead kelt passage behavior, rates, and distributions through the FCRPS as well as provide information to biologists and engineers about the dam operations and abiotic conditions that are related to passage and survival of steelhead kelts.

Summary

Steelhead (*Oncorhynchus mykiss*) populations in the Columbia River basin have declined throughout the last century. Snake River steelhead are among the declining populations, and are currently listed as threatened under the *Endangered Species Act of 1973*. In response to these declines, the 2008 Biological Opinion calls for an increase in Snake River female steelhead abundance through an increase in iteroparity rates, with a focus on B-run fish. Increases in iteroparity rates may be realized through a combination of in-river survival and reconditioning. The goal of this study was to extract additional information from the acoustic telemetry data collected in 2012 and 2013 to improve the understanding of the factors (behavioral, individual, operational, and environmental) that influence route selection and survival of steelhead kelts. These data may be used to inform managers and dam operators of potential ways to increase the survival of kelts during their seaward migrations. These data may also be helpful in identifying ways to increase the number of kelts collected for the reconditioning program.

Objectives

In this report, we present the results of several data mining tasks that were designed to help provide a better understanding of the factors that influence the route selection and survival of steelhead kelts through Lower Granite (LGR), Little Goose (LGS), and Lower Monumental (LMN) dams. The objectives were as follows:

- Estimate dam passage and route-specific survival probabilities at LGR, LGS, and LMN (pooling data across years).
- Examine the relationship between route of passage and environmental, temporal, operational, individual, and behavioral covariates.
- Examine the relationships between steelhead kelt survival and environmental, temporal, operational, individual, and behavioral covariates.

Methods

Acoustic telemetry studies were conducted in the lower Snake and Columbia rivers in 2012 and 2013. A total of 811 steelhead kelts were tagged with Juvenile Salmon Acoustic Telemetry System (JSATS) transmitters and passive integrated transponder (PIT) tags to monitor their downstream migration and any upstream migration of returning fish. Fish were captured, tagged, and released in tributaries of the lower Snake River, upstream of LGR, and at the LGR juvenile fish facility. Cabled receiver arrays were deployed on the upstream dam face of LGR, LGS, and LMN to record the three-dimensional (3-D) behavior of the fish in the forebay of the dams and to identify the route of passage. Autonomous receiver arrays were deployed throughout the lower Snake and Columbia rivers and were used to estimate survival using the single-release mark-recapture model.

Likelihood ratio tests were conducted to determine whether or not overall and route-specific dam passage survival estimates differed significantly between years (2012 and 2013) at LGR, LGS, and LMN. If similar, survival data was pooled across years. This was done to increase the precision of the survival estimates and provide a better indication of survival over a range of environmental and operational conditions.

The effect of multiple environmental, operational, individual, and behavioral factors on passage route, overall survival, and route-specific survival was evaluated using logistic regression modeling. Environmental factors included forebay and tailrace water temperatures, total dissolved gas (TDG) %, and total discharge. Temporal variables included the ordinal day of dam passage, and the predominant diel period during forebay residence. Operational factors included such variables as the percent of discharge through each turbine unit and spill bay at the time of passage and the percent spill. Individual characteristics used in the models included fork length, condition (good or fair), and relative condition (weight to length relationship). Behavioral variables were primarily estimated from 3-D tracking of tagged kelts in the forebay of each dam (LGR, LGS, and LMN) that was equipped with cabled receiver arrays. Kelt behaviors included such variables as median depth in the forebay, cross-sectional approach location, near-dam searching activity, forebay residence time, and tailrace egress time. Bayesian model-averaging was used to identify the factors that best explained route of passage, overall survival, and route-specific survival of tagged kelts at LGR, LGS, and LMN in 2012 and 2013.

Results

The variability in overall dam passage survival estimates was substantial enough that the survival estimates could not be pooled across years at any of the three dams to increase precision. However, survival estimates for the turbine and traditional (deep) spill routes were similar enough to be pooled across 2012 and 2013 at LGR, LGS, and LMN. Additionally, survival estimates for the juvenile bypass system (JBS) were pooled for LGS and LMN, as well as the spillway weir survival estimates at LGS. Pooling estimates across years indicated JBS survival was 0.93 (Standard error = 0.04) at LGS and 0.97 (0.03) at LMN; turbine survival was 0.90 (0.09) at LGR, 0.82 (0.07) at LGS, and 0.74 (0.08) at LMN; spillway weir survival was 0.95 (0.01) at LGS; and traditional spill survival was 0.84 (0.05) at LGR and 0.88 (0.03) at both LGS and LMN.

Models constructed to explain the probability of passage through spillway weir, traditional spill, JBS, and turbine routes for tagged kelts shared many similarities among the dams. In general, it appeared as though the behavior of kelts in the forebay had the greatest influence on route of passage. Kelts that migrated shallower, those that approached the dam on the powerhouse side of the river, and those that did more near-dam searching were more likely to pass over the spillway weir. Kelts that approached the dam on the spillway side of the river, did less traveling back-and-forth across the forebay or dam face, and migrated at deeper depths had a higher probability of traditional spill passage. Finally, kelts that approached the dam on the powerhouse side of the river, at deeper depths, with little near-dam searching were more likely to pass via one of the two powerhouse routes (JBS or turbines). Some evidence exists from the models to suggest that operations may also affect route of passage. A higher percent of discharge from traditional spill bays tended to result in higher probabilities of passage through this route. Individual characteristics of kelts may also influence their passage route at LGR, where smaller kelts were more likely to pass via the JBS than larger kelts.

Individual characteristics of kelts appeared to have the greatest effect on survival. At LGR and LGS, fair condition kelts had a lower probability of survival than good condition kelts. The results suggested that fork length contributed to the probability of survival at LGS, where smaller kelts had a higher probability of surviving spillway weir passage and at LMN, where smaller kelts had a higher probability of survival in the model that combined all routes. Finally, the relative condition (weight to length relationship) of kelts also influenced survival (all routes) at LMN; kelts with a higher relative condition had a higher probability of survival. Operational variables were also identified by the models as contributing to survival of kelts. However, additional analyses are needed to understand the mechanism behind the observed relationships.

Conclusions

The results obtained from this study indicate the behavior of kelts in the forebay of LGR, LGS, and LMN may have the greatest influence on their ultimate route of passage. However, we observed a higher proportion of kelts passing via the spillway weir at all three dams in 2013, when the percent discharge passing over the weir was higher than in 2012. Therefore, it is possible that dam operations are affecting the behavior of kelts in the forebay. Additional analyses are required to identify potential relationships between operations and behaviors to better understand the true mechanisms driving route selection. We also found smaller kelts had a higher probability of JBS passage at LGR than larger kelts. It is likely that a combination of operations (which depend on environmental conditions), behavior, and individual characteristics of kelts (i.e., condition and fork length) all contribute to route selection.

Survival of kelts appeared to be most heavily influenced by their individual characteristics. Specifically, kelts determined to be in good condition at the time of tagging had a higher probability of survival than those in fair condition. Additionally, it appeared as though smaller kelts had a higher probability of dam passage survival than larger kelts.

The modeling results have implications for when and where kelts should be retained for reconditioning. The collection of kelts is currently restricted to the JBS at LGR. However, LGR had the lowest proportion of kelts pass the JBS of the three dams over the two years. Additionally, it appeared that smaller kelts were more likely to pass through the JBS at LGR than larger kelts. In order to improve iteroparity rates of the larger B-run kelts, it may therefore be necessary to expand collection to other dams or tributary weirs. For example, LGS had the highest proportion of kelts pass via the JBS, making it a logical choice as a kelt collection site. Our results also have implications for which kelts should be retained for reconditioning. Because fair condition and larger kelts had low probabilities of surviving dam passage, they may be good candidates for reconditioning.

Over the two years, the majority of kelts passed LGR, LGS, and LMN via the spillway weir; passage survival was generally higher for kelts that passed over the weir compared to all other routes. Because the modeling results indicated that the behavior of kelts in the forebay greatly affected route of passage, the best option for improving iteroparity rates may be to 1) mimic those operations used in 2012 and 2013 to influence the behavior of kelts to pass via the spillway weir, 2) retain all JBS-passed kelts for reconditioning, and 3) expand the collection of kelts for reconditioning to other dams (e.g., LGS) and/or tributary weirs. However, an evaluation of the success of the reconditioning program is needed to ensure reductions in fecundity and gamete viability are minimal, kelts return to the spawning grounds upon release, and spawn successfully upon returning to the spawning grounds.

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Acronyms and Abbreviations

3-D	Three-dimensional
AML	Approximate maximum likelihood
BIC	Bayesian Information Criterion
BMA	Bayesian model-averaging
FCRPS	Federal Columbia River Power System
FL	Fork Length
IHR	Ice Harbor Dam
JBS	Juvenile bypass system
JSATS	Juvenile Salmon Acoustic Telemetry System
LGR	Lower Granite Dam
LGS	Little Goose Dam
LMN	Lower Monumental Dam
PIT	Passive integrated transponder
PNNL	Pacific Northwest National Laboratory
PRI	Pulse repetition interval
SNR	Signal-to-noise ratios
TDG	Total dissolved gas
TMT	Technical Management Team

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Tables

1.0 Introduction

This report documents the results from the third year of a steelhead kelt migration and Federal Columbia River Power System (FCRPS) dam passage study conducted by Pacific Northwest National Laboratory (PNNL) for the U.S. Army Corps of Engineers (USACE), Walla Walla District. The goal of this study was to extract additional information from the acoustic telemetry data collected in 2012 and 2013 to improve the understanding of the factors (environmental, temporal, operational, behavioral, and individual) that influence route selection and survival of steelhead kelts. These data may be used to inform managers and dam operators of potential ways to increase the survival of kelts during their seaward migrations. These data may also be helpful in identifying ways to increase the number of kelts collected for the reconditioning program.

1.1 Background

Steelhead (*Oncorhynchus mykiss*) populations within the Pacific Northwest of the United States have declined over the past several decades. As a result, several stocks, including those from the Snake River basin, have been listed for protection under the *Endangered Species Act of 1973* (McClure et al. 2003; NMFS 2004). Reasons for the population declines are numerous and complex, including overharvest, habitat loss and degradation, failed hatchery supplementation practices, predation, and various effects of passage through hydroelectric facilities (Lichatowich 2001; Budy et al. 2002; McClure et al. 2003; Brannon et al. 2004). Reasonable and Prudent Alternative (RPA) 33 of the 2008 Biological Opinion (BiOp) calls for an increase in the abundance of female Snake River steelhead through an increase in iteroparity (repeat spawning) rates. The BiOp recognizes that increases in iteroparity rates can be realized through a combination of reconditioning and in-river survival of kelts (post-spawn steelhead). Understanding the variables important for improving iteroparity rates is critical for helping to manage the population and potentially contribute to population recovery.

Steelhead are unique to other Pacific salmon as they can exhibit an iteroparous life history strategy. Post-spawn steelhead can migrate downstream to the ocean where they can rebuild their energy stores in an attempt to return to freshwater in future months to spawn again (Busby et al. 1996). A recent study estimated that annual iteroparity rates for Snake River steelhead range from 0.5 to 1.2% (Keefer et al. 2008), which is lower than pre-dam estimates (2%; Long and Griffin 1937). Similarly, Colotelo et al. (2014) reported that 1.2% and 0.2% of the kelts that were tagged in 2012 and 2013, respectively, were detected at BON adult fish ladder during upstream migrations. Iteroparity is thought to be a crucial step in rebuilding steelhead populations as fish can have multiple spawning opportunities in their lifetime, which can result in increased lifetime fitness (Fleming and Reynolds 2004). The results of these studies suggest that there is a need to investigate the factors that affect survival and ultimately iteroparity rates of Snake River kelts that migrate downstream through the river.

In 2012 and 2013, acoustic telemetry studies were conducted in the lower Snake and Columbia rivers to measure the proportion of steelhead kelts that pass through the available routes at hydroelectric dams (e.g., spillway weir, traditional (deep) spill, juvenile bypass system [JBS], turbines, sluiceway) during their downstream migration through the FCRPS (Colotelo et al. 2013, 2014). These studies also estimated overall dam, route-specific, and reach survival throughout the FCRPS. The results of these studies showed that most kelts passed via the spillway weirs, if available, and survival was generally higher for these routes. Comparatively, few fish passed through the powerhouse routes (i.e., JBS, turbines), and survival tended to be lower for these fish. The results of these studies were important for understanding how steelhead kelts pass through hydroelectric dams; however, further analysis is needed to understand which variables (i.e., environmental, temporal, operational, behavioral, individual) influence route selection and survival of kelts in the FCRPS. This information could be used by dam operators and fisheries managers to adaptively manage the configuration and operation of FCRPS dams to maximize kelt survival, and potentially iteroparity rates.

1.2 Research Objectives

The overall goal of this study was to define the relationships between environmental, operational, individual, and behavioral variables and steelhead kelt route selection and survival through the FCRPS. The specific objectives were as follows:

- Estimate dam passage and route-specific survival probabilities at FCRPS dams (pooling data across years).
- Examine the relationship between route of passage and environmental, temporal, operational, individual, and behavioral covariates.
- Examine the relationships between kelt survival and environmental, temporal, operational, individual, and behavioral covariates.

1.3 Report Contents

The ensuing sections of this report present the methods (Section 2.0), results (Section 3.0), and discussion and conclusion (Section 4.0). Sources cited in the text may be found in Section 5.0. Appendix A contains the Bayesian model-averaging results.

2.0 Methods

The data sources for environmental, temporal, operational, behavioral, and individual fish conditions, as well as the statistical processes used in these analyses are described below.

2.1 Dam Passage and Route-Specific Survival Probabilities Pooled Across Years

Colotelo et al. (2013, 2014) used a virtual single-release study design to estimate dam passage survival, both overall and route-specific, from the dam faces of LGR, LGS, and LMN to an autonomous receiver array located 13 to 59 km downstream of the dam. Virtual release groups are groupings of fish based on detection at a similar location independent of when or where those fish were released and were formed at cabled array on each dam. For route-specific survival estimates, virtual release groups consisted of all fish that passed through the same route at a specific dam. Likelihood ratio tests were conducted to determine whether or not overall and route-specific dam passage survival estimates differed significantly between years (2012 and 2013) at LGR, LGS, and LMN. Estimates determined to be similar among years were pooled to provide a more precise estimate of survival.

2.2 Analysis of 3D Acoustic Telemetry Data

Detections on the cabled receiver arrays that were located on LGR, LGS, and LMN in 2012 and 2013 were processed according to the methods outlined in Colotelo et al. (2013, 2014). The output of this process was a data set of events that included accepted tag detections for all times and locations where receivers were operating. Each unique event record included a basic set of fields that indicated the unique identification number of the fish, the first and last detection time for the event, the location of detection, and the number of messages detected within the event.

2.2.1 Three-Dimensional Localization

An approximate maximum likelihood (AML) solver (Li et al. 2014) was used for 3-D tracking of tagged fish as they passed each cabled receiver array. It was expanded from the two-dimensional AML method developed by Chan et al. (2006). The AML solver is different from exact solvers (Spiesberger and Fristrup 1990; Wahlberg et al. 2001; Bucher and Misra 2002) in that it was developed based on the maximum-likelihood method and can solve nonlinear localization equations considering the influence from measurement noise. Because accuracy was our priority, maximum-likelihood methods were optimum in the sense that its estimation performance can asymptotically attain the highest accuracy, especially when there are more than four hydrophones detecting the same transmission. This robust 3-D AML solver can accurately and efficiently estimate the time sequence of locations of fish tagged with Juvenile Salmon Acoustic Telemetry System (JSATS) acoustic transmitters. It is generic in nature and not specific to any particular sound source or receiving hydrophone array geometry. All of the solver functions are independently compiled and connected by software interfaces that can be easily modified to meet the needs of other 3-D tracking projects.

2.2.2 Data Filtering and Interpolation

Because of the uncertainties associated with field environments, the AML tracking results could be affected by many factors including hydrophone locations, river temperature, temperature gradients, tag transmission signal-to-noise ratios (SNRs), and tag transmission multipath propagation. Occasionally, some tracked points could have large errors and some points could even be physically impossible. Additional quality-control steps were added to filter out potential tracking results with large errors in field applications.

Step 1: PRI Filter. Detection requires that at least six transmissions were received within an appropriate time interval, which was set to be a 12 pulse repetition interval (PRI) range between the leading edges of successive messages. The PRI of transmitters used in this study was 4.2 sec, and so at least six transmissions were required within a 50.4 sec interval (i.e., 4.2 sec PRI x 12 = 50.4 sec). The PRI filter removed sporadic tracked points based on the assumption that tracked points were valid only when they were continuous in terms of time. After applying the PRI filter, a fish track might be separated into one or more segments. Tracked points within each segment were continuous in terms of time, and every two consecutive segments were more than five times the nominal PRI apart. Since the PRI of transmitters using in this study was 4.2 sec, every two consecutive segments were more than 21 sec apart (i.e., 4.2 sec [PRI] x 5 = 21 sec).

Step 2: Swim-speed Filter. A swimming speed filter was applied to remove erroneous tracked points. The maximum swimming speed was assumed to be nine times the fork length (FL) per second and was specific to each fish (Puckett and Dill 1984). For each tracked point, the swimming speeds to that point from the fish's previous tracked point and to the fish's next tracked point were calculated. If both speeds were faster than the maximum fish speed (9 FL/s), the tracked point was removed.

Step 3: Interpolation. A linear interpolation method was applied to interpolate points between every two consecutive tracked points in each segment if there were missing transmissions. Interpolation was performed along the X, Y, and Z directions independently, where X represents the upstream distance of the tag from the dam, Y represents the cross-sectional location of the tag across the width of the river, and Z represents the depth of the tag. After the interpolation, each tracked point represented a time period of the nominal PRI (4.2 sec).

2.2.3 Selection Criteria for Median Depth Analysis in Forebay

Although there is a large amount of information on the vertical distributions of fish in lakes and in the marine environment (Mehner 2012), we have not found studies that examined vertical distributions of fish near hydroelectric dams or techniques for defining 3-D telemetry data in terms of the depth distribution of individual fish in the forebay of a dam. With reliable 3-D tracking results and the associated tracking accuracy, the depth where fish could be neutrally buoyant (i.e., acclimated) can be estimated. For this study, this was done after excluding the influence of the approach flow of the powerhouse and erroneous 3-D tracking points. Based on results from controlled field testing (Deng et al. 2011b) performed in 2012 and 2013, sub-meter tracking accuracy of individual fish locations could be achieved in the forebays of the dams when the horizontal distance to the dam face was within 75 m. Therefore, only 3-D tracking data within 75 m of the dam face in the forebay at the three Snake River dams (LGR, LGS, and LMN) were included in the acclimation depth and depth distribution analyses.

Identification of the depth of acclimation (or neutral buoyancy) prior to dam passage using average depth can be biased by including depth measurements when fish are influenced by the flow velocities near the dam face. The simplest way to exclude the period when fish were influenced by the flow velocities near the powerhouse is to set a horizontal distance limit. Tracked points that were within this distance limit to the dam face were excluded from the calculations of acclimation depth. To establish this horizontal distance, a sensitivity analysis was performed from 0 m to 60 m from the dam face. The results of this analysis demonstrated that a horizontal distance of 20 m was sufficient to eliminate bias in the estimation of the depth of neutral buoyancy.

For an individual tagged fish, a representative depth value was needed to describe the depth where fish could be neutrally buoyant (i.e., acclimated). Because of the lack of knowledge regarding acclimation depth distributions (i.e., normal distribution, tailed distribution, or combinations of distributions), the median depth was used in this study. The median depth was calculated for each fish based on all tracked points that were a horizontal straight-line distance of 20 to 75 m from the dam face.

2.3 Model Variables

2.3.1 Environmental Variables

Hourly environmental data of water temperatures in the tailrace and at three depths in the forebay (1.5 m, 15 m, and 30 m) as well as total dissolved gas percentages (TDG) in the forebay and tailraces of LGR, LGS, and LMN were downloaded from the USACE Technical Management Team (TMT) website (http://www.nwd.usace.army.mil/Missions/WaterManagement/ColumbiaRiverBasin/WaterQualityProgram.aspx). Dam passage times were rounded to the nearest hour for assignment of temperature and TDG values and to the nearest 5 minutes for assignment of total discharge values to best represent the conditions encountered by each kelt at their time of passage. The final list of environmental variables included in the logistic regression modeling included 1) forebay TDG, 2) forebay temperature at 1.5 m, 15 m, and 30 m depths, 3) the ratio of the temperature at 1.5 m depth to the temperature at 30 m depth, 4) tailrace TDG, 5) tailrace temperature, and 6) total discharge.

2.3.2 Temporal Variables

Temporal variables included in the models were day of passage and diel period during forebay residence. Day of passage is the ordinal day (365 day scale used for each year) when each kelt passed the dam. This was determined based on the last detection on the cabled array at each dam. Diel period is based on the period of time each fish spent in the forebay. For each fish, each tracked point was assigned to either day or night. Diel period was defined as day if the fish had more tracked points defined as day, or defined as night if the fish had more tracked points defined as night. Separation between day and night were done using civil twilight.

2.3.3 Dam Operation Variables

The percent of discharge passing through each “hole” in the dam (i.e., spill bay or turbine unit), recorded in 5-minute intervals, was calculated from USACE dam operations data for LGR, LGS, and LMN. Again, dam passage times were rounded to the nearest 5 minutes for assignment of the %

discharge through each hole (and total percent spill) at the time of passage for each kelt. The dates that the weir crest changed position at LGS were obtained from either Fish Passage Center reports or from USACE staff. Weir crest position was treated as a nominal variable; kelts that passed LGS when the crest was in the "low" position were assigned a "1" and those that passed when the crest was in the "high" position were assigned a "2".

2.3.4 Individual Fish Variables

Data on individual fish were collected at the time of tagging as outlined in Colotelo et al. (2013, 2014). Individual fish variables included in the logistic regression models were fork length (cm) and condition (good/fair). Relative condition factor (Le Cren 1951; Pope and Kruse 2007) was calculated for each kelt that had both a measured length and weight by comparing the actual weight of each fish to a standard predicted by the weight-length regression based on the entire population of tagged kelts. Relative condition was calculated as:

$$K_n = (W/W') \times 100$$

where W is individual fish weight and W' is the predicted length-specific weight based on $\log_{10}$ transformed data.

2.3.5 Fish Behavior Variables

Fish behavior variables included median depth, approach location, near-dam searching, total Y distance traveled, forebay residence time, and tailrace egress time. These variables are defined as follows:

- **Median depth (m)** is the median depth that each fish was detected at while in the truncated area of the forebay (20 to 75 m from the dam face). Depth was defined by assigning the water surface a value of zero. Therefore, the deeper a fish was, the more negative its median depth.

- **Approach location (m)** is the location on the y-axis (cross-sectional location across the channel width) where each fish was first detected by the cabled receiver array. Approach location was defined by assigning a value of zero to the pier nose located between turbine units 1 and 2 at each dam. Values increased from this pier in a northerly direction and decreased from this pier in a southerly direction. Therefore, the approach location for a kelt that was first detected along the north shoreline would be a positive value at LGR and LGS and a negative value at LMN.

- **Near-dam searching** is the difference of "hole" (i.e., spill bay or turbine unit) numbers between the "hole" a kelt approached once it was within 10 m of the dam face for the first time and the "hole" the kelt ultimately passed through. For example, if a kelt was first detected within 10 m of the dam in front of turbine unit 2 at LGR and passed through spill bay 5, the near-dam searching value would equal 9.

- **Total Y distance traveled (m)** is the sum of the Y distance (back-and-forth across the river channel) traveled by each kelt. The distance was calculated between each sequential tracked point, and these distances were summed for each fish.

- **Forebay residence time (hours)** is defined as the time required to travel from the upstream boundary of the forebay to dam passage. It was calculated as the difference in time between the last detection on the cabled receiver array and the last detection on the forebay autonomous receiver array located 1 to 2 km upstream of the dam.

- **Tailrace egress time (hours)** is defined as the time required to travel from the dam face to the downstream boundary of the tailrace. It is calculated as the difference in time between the last detection on the cabled receiver array and the first detection on the tailrace receiver array located 1 to 2 km downstream of the dam.

2.3.6 Model-building

Logistic regression was used to assess the factors that affected the route of passage and survival of steelhead kelts at LGR, LGS, and LMN in 2012 and 2013. Models were created for each route (spillway weir, traditional spill, JBS, turbines) at each dam to examine the relationship between environmental, temporal, operational, individual, and behavioral variables as well as the probability of passing a particular route. For survival, we were only able to evaluate the variables that affected overall passage survival (all routes combined) and spillway weir survival at each dam due to insufficient sample sizes of kelts that passed through traditional spill, JBS, and turbine routes. Survival was defined as the proportion of kelts known to have passed the dam that were detected on any downstream detection array. This approach was possible due to the high detection probabilities of the arrays, which all exceeded 0.95 in 2012 and 0.99 in 2013. The first downstream array was located 59 km downstream of LGR, 33 km downstream of LGS, and 27 km downstream of LMN. Therefore, an unknown level of mortality incurred between the tailrace of each dam and the first downstream detection array is included in the survival estimates.

The distribution of each predictor variable was assessed for normality prior to any modeling. Those variables that displayed a highly skewed distribution were log-transformed to achieve normality. Skewed variables were consistent among data sets used to construct each route/dam-specific model and included forebay residence time, tailrace egress time, and total Y distance traveled, which were all highly right-skewed.

The strength and direction of effect of each variable was first assessed by fitting the values of each variable against the probability of passage through a particular route (versus all other routes) or the probability of survival using bivariate logistic regression models. Variables that were correlated (α = 0.10) with the response variability (probability of passage or survival) were retained for inclusion in the multivariable logistic regression modeling procedure. We chose an α level of 0.10 to eliminate some variables from the rather long candidate list to reduce the chance of including spurious correlations in the final model and so that the final model was both parsimonious and interpretable. The α level of 0.10 was chosen instead of 0.05 in an attempt to reduce the chances of making a type II error.

Variables found to be significantly correlated with the response variable (probability of passage or survival) were included in the model-building process, which consisted of Bayesian model-averaging

(BMA) conducted using the BMA package in R (version 2.14.1; R Core Team 2011). We did not assume to know which variables affected route of passage or passage survival prior to the model-averaging procedure. Therefore, no prior probabilities were assigned to any of the variables.

Advantages of BMA over other multivariable model-building processes, such as step-wise procedures, include the assignment of a level of uncertainty, in the form of posterior probabilities, to each variable and model. Variables included in any of the top five models were assessed for multicollinearity using pairwise comparisons. "Sign-switching", whereby the direction of the relationship between a predictor and response variable changed from the bivariate to multivariable model, was also used as an indication of multicollinearity. Often, the BMA package recognized linear dependencies when a high degree of multicollinearity existed between predictor variables and prevented the model run. When a high level of multicollinearity was encountered, the predictor variable that provided a better fit to the response variable (as judged by P and $\chi 2$ values) in the bivariate models was retained for inclusion in the multivariable model-averaging, the other predictor variable was removed, and the model was re-run. The resultant models were compared using each model's posterior probability, which is the probability of the model being the correct model, given that one of the models considered is correct. The variables were evaluated using their posterior probability, which is the probability that each variable should be included in the model.

3.0 Results

3.1 Dam Passage and Route-Specific Survival Probabilities Pooled Across Years

Dam passage survival, as measured from the dam face to an autonomous receiver array located 27 to 59 km downstream, differed significantly between years for all Snake River dams (Table 3.1). That is, the variability in overall dam passage survival estimates is substantial enough that the data should not be pooled across years to increase precision of the estimate. However, several of the route-specific survival estimates were similar enough that the data could be pooled across years to improve the precision of those estimates (Table 3.1).

Survival of JBS-passed kelts could be pooled across years for both LGS (S = 0.93; SE = 0.04) and LMN (S = 0.97; SE = 0.03). Data for turbine-passed kelts could be pooled across years at all three Snake River dams with pooled survival estimates equaling S = 0.90 (SE = 0.09) at LGR, S = 0.82 (SE = 0.07) at LGS, and S = 0.74 (SE = 0.08) at LMN. Spillway weir survival was similar enough at LGS between years to allow for pooling. The pooled estimate equaled S = 0.95 (SE = 0.01). Finally, survival of kelts that passed via traditional spill routes was similar enough at all three dams to pool the two years. Pooled survival through traditional spill routes was S = 0.84 (SE = 0.05) at LGR and S = 0.88 (SE = 0.03) at LGS and LMN.

Table 3.1. Dam passage survival, as measured from the dam face[1] to an array of autonomous receivers located 27 to 59 km downstream, estimated for acoustic-tagged steelhead kelt at Snake River dams in 2012 and 2013. Results of likelihood ratio tests (χ^2 and p) conducted to determine whether overall and route-specific survival differed between years are also shown. Pooled survival estimates (2012 and 2013 combined) are displayed when a significant difference was not observed between years. Standard errors are shown in parentheses. IHR was not fitted with cabled JSATS systems in 2012 or 2013; therefore, route-specific survival estimates are not available. River kilometers are presented as measured from the mouth of the Snake River.

Dam	2012	2013	χ^2	*p*-value	Pooled
LGR (rkm 173) to rkm 114	0.89 (0.03)	0.66 (0.04)	20.07	<0.001*	NA
JBS	0.86 (0.13)	0.33 (0.19)	3.94	0.047*	NA
Turbine	0.88 (0.12)	1.00 (0.00)	0.47	0.492	0.90 (0.09)
Spillway weir	0.90 (0.04)	0.67 (0.05)	12.24	<0.001*	NA
Traditional spill	0.91 (0.05)	0.71 (0.11)	3.14	0.076	0.84 (0.05)
LGS (rkm 113) to rkm 81	0.94 (0.01)	0.89 (0.02)	5.76	0.016*	NA
JBS	0.97 (0.03)	0.88 (0.07)	1.47	0.225	0.93 (0.04)
Turbine	0.78 (0.12)	0.84 (0.08)	0.19	0.660	0.82 (0.07)
Spillway weir	0.97 (0.01)	0.94 (0.02)	1.96	0.162	0.95 (0.01)
Traditional spill	0.94 (0.03)	0.82 (0.05)	3.51	0.061	0.88 (0.03)
LMN (rkm 67) to rkm 40	0.94 (0.01)	0.89 (0.02)	4.30	0.038*	NA
JBS	1.00 (0.00)	0.94 (0.06)	1.54	0.214	0.97 (0.03)
Turbine	0.58 (0.14)	0.84 (0.08)	2.53	0.112	0.74 (0.08)
Spillway weir	0.98 (0.01)	0.93 (0.02)	7.37	0.007*	NA
Traditional spill	0.93 (0.04)	0.83 (0.06)	2.31	0.128	0.88 (0.03)
IHR FB (rkm 17) to rkm 3	0.98 (0.01)	0.94 (0.02)	4.78	0.029*	NA

[1] Dam passage survival, as measured for Ice Harbor Dam (IHR), was estimated from an array of autonomous receivers deployed in the forebay (FB) 1 km upstream from the dam to an array located 13 km downstream of IHR.

3.2 Factors Affecting Route of Passage

The “best” models for explaining the probability of kelt passage through available routes at LGR, LGS, and LMN are described below. This typically includes the top one or two models for each dam and passage route. Full details, including the posterior probabilities, the full list of predictor variables tested, and the cumulative posterior probability for each model are outlined in Appendix A.

3.2.1 Lower Granite Dam

3.2.1.1 Spillway Weir

The “best” model for explaining the probability of kelt passage through the spillway weir at LGR included median depth, approach location, and the percent discharge through turbine unit 1 (T1%Q). The median depth at which kelts traveled in the forebay had a 1.0 probability of inclusion in the model, and was positively correlated with the probability of spillway weir passage, which indicated that shallower-migrating kelts had a higher probability of passing via the weir. Approach location had a posterior probability of 0.73, and was negatively correlated with the probability of weir passage, which indicates kelts that approached LGR closer to the south shore were more likely to pass via the spillway weir. Finally, the probability of weir passage was negatively correlated with the percentage of total discharge passing through turbine unit 1 (T1%Q), which had a posterior probability of 0.46. This variable (T1%Q) was quite highly negatively correlated with the percent discharge over the spillway weir, with a correlation coefficient of -0.706, indicating some level of multicollinearity. The posterior probability of the model that included median depth, approach location, and T1%Q was 0.136, indicating a relatively high level of uncertainty associated with the model.

3.2.1.2 Traditional Spill

Two models constructed to describe the variable effects on the probability of traditional (deep) spill passage at LGR had similar posterior probabilities. The “best” model included approach location (posterior probability = 1.0) and the percent discharge through spill bay 7 (S7%Q; posterior probability = 0.50). Both variables were positively correlated with the probability of traditional spill passage, suggesting kelts that approached LGR closer to the north shore and those that passed at higher levels of S7%Q were more likely to pass via traditional spill routes. This model had a posterior probability of 0.241. The second “best” model had a posterior probability of 0.227 and also included approach location, which was positively correlated with traditional spill passage probability, in addition to the percent of discharge through spill bay 3 (S3%Q). Similar to S7%Q, S3%Q was positively correlated with traditional spill passage probability and had a posterior probability of 0.47. Again, the relatively low posterior probabilities of these models indicate a fair amount of uncertainty associated with the models.

3.2.1.3 Juvenile Bypass System

The model that included near-dam searching, approach location, and fork length had the highest probability (posterior probability = 0.40) of being the correct model for explaining the effects of the variables studied regarding the probability of JBS passage at LGR. The near-dam searching variable had a 1.0 probability of inclusion in the model and was negatively correlated with the probability of JBS passage, indicating kelts that did less near-dam searching (i.e., passed fewer bays within 10 m of the dam face) were more likely to pass via the JBS. Approach location had a posterior probability of 1.0, and was also negatively correlated with the probability of JBS passage, suggesting kelts that approached LGR closer to the south shore were more likely to pass through the JBS. Finally, fork length was negatively correlated with the probability of JBS passage and had a 0.86 probability of inclusion in the model.

3.2.1.4 Turbine

The “best” model for explaining the probability of turbine passage at LGR had a posterior probability of 0.117, indicating a high level of uncertainty, and included median depth and percent spill (SW%Q). Although the model had high uncertainty, the probability of the inclusion of median depth in the correct model was 1.0. The probability of turbine passage was negatively correlated with median depth, indicating deeper-migrating kelts were more likely to pass via the turbines at LGR than other routes. Turbine passage probability was negatively correlated with SW%Q, which had a posterior probability of 0.31.

3.2.2 Little Goose Dam

3.2.2.1 Spillway Weir

Two models had near equal posterior probabilities of being the correct model for explaining the probability of spillway weir passage at LGS. The first model included median depth, near-dam searching, and the percent discharge through spill bay 5 (S5%Q); the posterior probability was 0.164. The second model included median depth, near-dam searching, S5%Q, and condition (good/fair), and had a posterior probability of 0.161. Both median depth and near-dam searching had a posterior probability of 1.0, and both were positively correlated with spillway weir passage, indicating shallower-migrating kelts and those that did more near-dam searching had a higher probability of passing via the spillway weir. S5%Q was negatively correlated to the probability of spillway weir passage and had a posterior probability of 0.63. The inclusion of condition in the second "best" model had a posterior probability of 0.48 and indicated that good condition fish had a higher probability of passing the weir than kelts in fair condition.

3.2.2.2 Traditional Spill

Two models stood out as having the highest posterior probability for describing the probability of traditional (deep) spill route passage at LGS. Both models included approach location, which was positively correlated with the probability of traditional spill passage, and total Y distance traveled, which was negatively correlated with traditional spill passage. Both variables had a probability of inclusion in the model of 1.0. The "best" model (posterior probability = 0.213) also included the percent discharge through spill bay 2 (S2%Q), which was positively correlated with the probability of traditional spill passage and had a probability of model inclusion of 0.32. The other model, which had a posterior probability of 0.19, also included percent spill, which was positively correlated with traditional spill passage and had a probability of model inclusion of 0.27.

3.2.2.3 Juvenile Bypass System

The "best" model for explaining JBS passage at LGS had a posterior probability of being the correct model of 0.332 and included three variables, all of which had a posterior probability of 1.0. Approach location, near-dam searching, and median depth were all negatively correlated with the probability of JBS passage, indicating kelts that approached LGS closer to the south shore, those that did less near-dam searching, and those that migrated at deeper depths, had a higher probability of passing via the JBS.

3.2.2.4 Turbine

The model that included median depth, approach location, and near-dam searching had relatively low uncertainty associated with it (posterior probability = 0.727), and was therefore selected as the "best" model for explaining the probability of turbine passage at LGS. Median depth and approach location each had a probability of model inclusion of 1.0 and indicated deeper-migrating kelts, and those that approached closer to the south shore had a higher probability of JBS passage. Near-dam searching had a posterior probability of 0.89, and suggested kelts that did less near-dam searching were more likely to pass through turbines.

3.2.3 Lower Monumental Dam

3.2.3.1 Spillway Weir

Two models were identified as better than all other 18 models tested to evaluate the probability of spillway weir passage at LMN. The models had posterior probabilities of 0.224 and 0.203, and both included median depth and approach location. These two variables had a high probability of model inclusion (>0.98), and indicated kelts that migrated shallower and those that approached LMN closer to the north shore were more likely to pass via the spillway weir. The "best" model also included the near-dam searching variable, with a posterior probability of model inclusion of 0.51, and indicated kelts that did more near-dam searching had a higher probability of passing over the spillway weir than other routes. The second "best" model included a similar variable, total Y distance, which had a posterior probability of 0.41; this model also suggested kelts that did more traveling back-and-forth across the forebay had a higher probability of passing via the weir.

3.2.3.2 Traditional Spill

The top five models created to explain traditional spill passage at LMN all had similar (and low) posterior probabilities of being the correct model, ranging from 0.063 to 0.106. A total of five variables were included in various combinations in these five models, including approach location (posterior probability = 1.0), median depth (posterior probability = 0.67), the percent discharge through spill bay 5 (S5%Q; posterior probability = 0.57), total Y distance traveled (posterior probability = 0.45), and percent spill (SW%Q; posterior probability = 0.35). These models indicated kelts that approached the dam closer to the south shoreline, those that migrated at deeper depths, those that did less traveling back-and-forth across the forebay, and those that passed the dam when S5%Q and SW%Q were higher, had a higher probability of passing LMN through traditional spill routes compared to all other routes.

3.2.3.3 Juvenile Bypass System

The probability of kelts passing LMN through the JBS was negatively correlated with median depth and percent spill according to the "best" multivariable model, which had a posterior probability of 0.421. Both variables had a high posterior probability of model inclusion (>0.79), and indicated that both kelts that migrated deeper and those that passed LMN when percent spill was lower had a higher probability of passing via the JBS.

3.2.3.4 Turbine

The "best" model for explaining the probability of turbine passage at LMN had a posterior probability of being the correct model of 0.483 and included near-dam searching, approach location, and median depth. Both near-dam searching and approach location had posterior probabilities of 1.0, suggesting high certainty regarding their inclusion in the model; median depth had a posterior probability of 0.60. The model indicated kelts had a higher probability of passing through turbines if they did less near-dam searching, approached the dam closer to the north shore, and migrated at deeper depths.

3.3 Factors Affecting Survival

The “best” models for explaining the probability of survival through the spillway weir and all routes combined at LGR, LGS, and LMN are described below. This typically includes the top one or two models for each dam and passage route. Full details, including the posterior probabilities, the full list of predictor variables tested, and the cumulative posterior probability for each model are outlined in Appendix A.

3.3.1 Lower Granite Dam

3.3.1.1 All Routes

The model selected as the “best” model for explaining the survival of kelts from LGR dam passage to the array located 59 km downstream included both condition (good/fair) and the percent discharge through turbine unit 6 (T6%Q); the posterior probability of being the correct model was 0.304. There was relatively little uncertainty that either of these models should be included; condition had a posterior probability of 1.0 and T6%Q had a posterior probability of 0.88. The model indicated good condition kelts, and those that passed LGR when T6%Q was higher had a higher probability of survival.

3.3.1.2 Spillway Weir

The “best” model for explaining spillway weir survival of kelts at LGR included the same variables as the model constructed for all routes combined (condition and T6%Q). A likely explanation of this occurrence is that the majority of tagged kelts passed LGR via the spillway weir in 2012 and 2013. The model had a posterior probability of 0.565, and both variables had a 1.0 posterior probability of model inclusion. Again, the model indicated survival of kelts that passed via the spillway weir had a higher probability of survival if they were in good condition and if they passed when T6%Q was higher.

3.3.2 Little Goose Dam

3.3.2.1 All Routes

Condition had the highest posterior probability (1.0) of all variables considered for inclusion in the models constructed to describe the probability of kelts surviving from LGS to the array located 33 km downstream. Condition and the percent discharge through turbine unit 4 (T4%Q; posterior probability = 0.60) were included in the “best” model, which had a posterior probability of being the correct model of 0.372. The model indicated survival was higher for good condition kelts and for those that passed LGS when T4%Q was higher.

3.3.2.2 Spillway Weir

All the multivariable models created to explain the probability of spillway weir survival had a large amount of uncertainty associated with them. The top three models had posterior probabilities that ranged from 0.087 to 0.095. All three models shared a single variable, the percent discharge through turbine unit 2 (T2%Q), which had a posterior probability of 0.76 and was negatively correlated with spillway weir survival. Fork length, which was negatively correlated with spillway weir survival, was included in two of the three models and had a posterior probability of 0.46. Condition was included in the third “best” model, and indicated that good condition kelts had a higher probability of surviving spillway weir passage than fair condition kelts.

3.3.3 Lower Monumental Dam

3.3.3.1 All Routes

The model that had the highest posterior probability (0.178) of being the correct model for explaining survival of kelts from LMN passage to the detection array located 27 km downstream included fork length, relative condition, and diel passage period. Fork length and relative condition had high posterior probabilities of model inclusion (>0.80), and indicated kelts that were smaller and had higher relative condition values had a higher probability of survival. The inclusion of diel passage period, which had a posterior probability of inclusion of 0.59, indicated kelts that passed LMN during the day had a higher probability of survival than those that passed at night.

3.3.3.2 Spillway Weir

The “best” model for explaining spillway weir survival of kelts at LMN had a posterior probability of 0.232, and included just a single variable, the percent discharge through spill bay 6 (S6%Q). All of the variables included for consideration in the model-averaging had a high degree of uncertainty associated with their inclusion. S6%Q, which was negatively correlated with weir survival, had the highest posterior probability at 0.36.

4.0 Discussion

The results obtained from this study indicate the behavior of kelts in the forebay of LGR, LGS, and LMN may have the greatest influence on their ultimate route of passage. However, we observed a higher proportion of kelts passing via the spillway weir at all three dams in 2013 when the percent discharge passing over the weir was higher than in 2012. Therefore, it is possible that dam operations are affecting the behavior of kelts in the forebay. Additional analyses are required to identify potential relationships between operations and behaviors to better understand the true mechanisms driving route selection. We also found smaller kelts had a higher probability of JBS passage at LGR than larger kelts. It is likely that a combination of operations (which depend on environmental conditions), behavior, and individual characteristics of kelts (i.e., condition and fork length) all contribute to route selection.

Survival of kelts appeared to be most heavily influenced by individual characteristics of the kelts. Specifically, kelts determined to be in good condition at the time of tagging had a higher probability of survival than those in fair condition. Additionally, it appeared as though smaller kelts had a higher probability of dam passage survival than larger kelts.

The modeling results have implications for when and where kelts should be retained for reconditioning. The collection of kelts is currently restricted to the JBS at LGR. However, LGR had the lowest proportion of kelts pass the JBS of the three dams over the two years. Additionally, it appeared smaller kelts were more likely to pass through the JBS at LGR than larger kelts. In order to improve iteroparity rates of the larger B-run kelts, it may therefore be necessary to expand collection to other dams or tributary weirs. For example, LGS had the highest proportion of kelts pass via the JBS, making it a logical choice for a collection site for the kelt reconditioning program. Our results also have implications for which kelts should be retained for reconditioning. Because fair condition and larger kelts had low probabilities of surviving dam passage, they may be good candidates for reconditioning.

Over the two years, the majority of kelts passed LGR, LGS, and LMN via the spillway weir, and passage survival was generally higher for kelts that passed over the weir compared to all other routes. Because the modeling results indicated that the behavior of kelts in the forebay greatly affects route of passage, the best option for improving iteroparity rates may be to 1) mimic those operations used in 2012 and 2013 to influence the behavior of kelts to pass via the spillway weir, 2) retain all JBS-passed kelts for reconditioning, and 3) expand the collection of kelts for reconditioning to other dams (e.g., LGS) and/or tributary weirs. However, an evaluation of the success of the reconditioning program is needed to ensure 1) reductions in fecundity and gamete viability are minimal, 2) kelts return to the spawning grounds upon release with minimal straying, and 3) kelts spawn successfully upon returning to the spawning grounds.

5.0 References

Brannon EL, MS Powell, TP Quinn, and A Talbot. 2004. Population structure of Columbia River Basin Chinook salmon and steelhead trout. *Reviews in Fisheries Science* 12(2-3):99−232.

Bucher R and D Misra. 2002. A Synthesizable Low Power VHDL Model of the Exact Solution of a Three-Dimensional Hyperbolic Positioning System. *VLSI Des*. 15:507–510.

Budy PG, P Thiede, N Bouwes, CE Petrosky, and H Schaller. 2002. Evidence linking delayed mortality of Snake River salmon to their earlier hydrosystem experience. *North American Journal of Fisheries Management* 22:35–51.

Busby PJ, TC Wainwright, GJ Bryant, LJ Lierheimer, RS Waples, FW Waknitz, and IV Lagomarsino. 1996. *Status review of west coast steelhead from Washington, Idaho, Oregon, and California*. NOAA Technical Memorandum NMFS-NWFSC-27, National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, Washington, and National Marine Fisheries Service, Southwest Region, Long Beach, California. Available at http://www.nwfsc.noaa.gov/assets/25/4245_06172004_122523_steelhead.pdf (December 2012).

Chan YT, HYC Hang, PC Ching. 2006. Exact and Approximate Maximum Likelihood Localization Algorithms. *IEEE Trans. Vehic. Tech.* 55:10–16.

Colotelo AH, BW Jones, RA Harnish, GA McMichael, KD Ham, ZD Deng, GM Squeochs, RS Brown, MA Weiland, GR Ploskey, X Li, and T Fu. 2013. *Passage Distribution and Federal Columbia River Power System Survival for Steelhead Kelts Tagged Above and at Lower Granite Dam*. PNNL-22101, prepared for the U.S. Army Corps of Engineers, Walla Walla District, Contract Number W912EF-08-D-0004, by Pacific Northwest National Laboratory, Richland, Washington.

Colotelo AHA, RA Harnish, BW Jones, AC Hanson, DM Trott, MJ Greiner, GA McMichael, KD Ham, Z Deng, RS Brown, MA Weiland, X Li, and T Fu. 2014. Passage Distribution and Federal Columbia River Power System Survival for Steelhead Kelts Tagged Above and at Lower Granite Dam, Year 2 . PNNL-23051 FINAL, Pacific Northwest National Laboratory, Richland, WA.

Deng Z, MA Weiland, T Fu, TA Seim, BL Lamarche, EY Choi, TJ Carlson, and MB Eppard. 2011. A cabled acoustic telemetry system for detecting and tracking juvenile salmon: Part 2. Three-dimensional tracking and passage outcomes. *Sensors* 11(6):5661–5676.

Fleming IA and MR Reynolds. 2004. “Salmon breeding systems.” In *Evolution Illuminated: Salmon and Their Relatives,* AP Henry and SC Stearns (eds.), pp. 264–294. Oxford University Press, Oxford, United Kingdom.

Keefer ML, RH Wertheimer, AF Evans, CT Boggs, and CA Peery. 2008. Iteroparity in Columbia River summer-run steelhead (*Oncorhynchus mykiss*): implications for conservation. *Canadian Journal of Fisheries and Aquatic Sciences* 65(12):2592−2605.

Le Cren ED. 1951. The length-weight relationship and seasonal cycle in gonad weight and condition in the perch (*Perca fluviatilis*). *Journal of Animal Ecology* 20:201–219.

Li X, Z Deng, Y Sun, JJ Martinez, T Fu, GA McMichael, and TJ Carlson. 2014. A 3D approximate maximum likelihood solver for localization of fish implanted with acoustic transmitters. *Scientific Reports* 4:7215.

Lichatowich JA. 2001. *Salmon without Rivers: A History of the Pacific Salmon Crisis*. Island Press, Washington, D.C.

Long JB and LE Griffin. 1937. Spawning and migratory habits of Columbia River steelhead trout as determined by scale studies. *Copeia* 1937:62.

McClure MM, EE Holmes, BL Sanderson, and CE Jordan. 2003. A large-scale multispecies status assessment: Anadromous salmonids in the Columbia River basin. *Ecological Applications* 13(4):964–989.

Mehner T. 2012, Diel vertical migration of freshwater fishes – proximate triggers, ultimate causes and research perspectives. *Freshwater Biology* 57: 1342–1359.

NMFS (National Marine Fisheries Service). 2004. *Endangered Species Act status of West Coast salmonids, June 17, 2004*. National Marine Fisheries Service, Northwest Region, Portland, Oregon. Available at http://www.nwr.noaa.gov (December 2012).

Pope KL and CG Kruse. 2007. Condition. Pages 423 – 471 *in* C.S. Guy and M.L. Brown, editors. Analysis and interpretation of freshwater fisheries data. American Fisheries Society, Bethesda, Maryland.

Puckett KJ and LM Dill. 1984. Cost of sustained and burst swimming to juvenile coho salmon (*Oncorhynchus kisutch*). *Canadian Journal for Fisheries and Aquatic Sciences*. 41: 1546-1551.

R Core Team. 2011. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Spiesberger JL and KM Fristrup. 1990. Passive localization of calling animals and sensing of their acoustic environment using acoustic tomography. *American Naturalist* 135(1): 107-153.

Wahlberg M, B Møhl, PT Madsen. 2001. Estimating source position accuracy of a large-aperture hydrophone array for bioacoustics. *Journal of the Acoustical Society of America*. 109: 397-406.

Appendix A

Bayesian Model-Averaging Results

Appendix A

Bayesian Model-Averaging Results

Table A.1. Bayesian model-averaging results displaying the top five models for explaining the probability of spillway weir passage for tagged steelhead kelts at Lower Granite Dam in 2012 and 2013. Top models were selected and ranked by their Bayesian Information Criterion (BIC) and posterior probabilities. The posterior probability of each variable being included in the model is also shown, along with the mean parameter value and standard deviation, and the parameter value of each variable in the top five models. Also displayed are the number of kelts that were included in the model construction, the number of models created from which the top five were selected, the cumulative posterior probability of the top five models, and the number of variables included in each of the top five models.

n kelts =	240							
n models selected =	48							
Cum. post. prob. =	0.349							
Variable	Prob.	Mean	SD	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.000	2.322	1.382	2.792	3.386	3.134	2.761	2.187
Median Depth	1.000	0.141	0.028	0.142	0.144	0.137	0.141	0.143
First Y	0.730	-0.003	0.003	-0.005	-0.005	-0.004	.	.
T1 % Q	0.460	-0.022	0.027	-0.050	-0.046	.	.	-0.049
S7 % Q	0.334	-0.075	0.133	.	-0.185	.	.	.
Discharge	0.202	-0.002	0.005	.	.	-0.011	-0.012	.
S1 % Q	0.181	0.020	0.047	.	.	.	.	.
T2 % Q	0.074	0.003	0.014	.	.	.	.	.
S5 % Q	0.060	0.002	0.056	.	.	.	.	.
S3 % Q	0.058	-0.004	0.038	.	.	.	.	.
Temp Ratio	0.035	0.140	0.936	.	.	.	.	.
T5 % Q	0.033	0.000	0.007	.	.	.	.	.
Fork Length	0.028	0.001	0.005	.	.	.	.	.
Ln Y Dist	0.019	0.002	0.021	.	.	.	.	.
T6 % Q	0.017	0.000	0.005	.	.	.	.	.
n variables				3	4	3	2	2
BIC				-1056	-1054	-1054	-1054	-1054
Posterior prob.				**0.136**	**0.061**	**0.054**	**0.051**	**0.047**

Table A.2. Bayesian model-averaging results displaying the top five models for explaining the probability of traditional spill passage for tagged steelhead kelts at Lower Granite Dam in 2012 and 2013. Top models were selected and ranked by their Bayesian Information Criterion (BIC) and posterior probabilities. The posterior probability of each variable being included in the model is also shown, along with the mean parameter value and standard deviation, and the parameter value of each variable in the top five models. Also displayed are the number of kelts that were included in the model construction, the number of models created from which the top five were selected, the cumulative posterior probability of the top five models, and the number of variables included in each of the top five models.

n kelts =	241							
n models selected =	21							
Cum. Post. prob. =	0.719							
Variable	Prob.	Mean	SD	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.000	-4.936	0.745	-4.929	-4.872	-5.171	-5.218	-4.795
First Y	1.000	0.014	0.003	0.014	0.014	0.014	0.013	0.014
S7 % Q	0.499	0.178	0.200	0.362	.	.	0.377	.
S3 % Q	0.465	0.133	0.159	.	0.290	0.305	.	.
Median Depth	0.219	-0.011	0.025	.	.	-0.053	-0.051	.
S5 % Q	0.091	0.014	0.075	.	.	.	.	0.264
T1 % Q	0.042	0.001	0.006	.	.	.	.	.
S1 % Q	0.038	-0.001	0.012	.	.	.	.	.
Ln Y Dist	0.034	-0.002	0.026	.	.	.	.	.
T5 % Q	0.034	0.000	0.004	.	.	.	.	.
Discharge	0.033	0.000	0.001	.	.	.	.	.
T2 % Q	0.032	0.000	0.005	.	.	.	.	.
n variables				2	2	3	3	2
BIC				-1136	-1136	-1135	-1134	-1133
Posterior prob.				**0.241**	**0.227**	**0.107**	**0.098**	**0.046**

Table A.3. Bayesian model-averaging results displaying the top five models for explaining the probability of JBS passage for tagged steelhead kelts at Lower Granite Dam in 2012 and 2013. Top models were selected and ranked by their Bayesian Information Criterion (BIC) and posterior probabilities. The posterior probability of each variable being included in the model is also shown, along with the mean parameter value and standard deviation, and the parameter value of each variable in the top five models. Also displayed are the number of kelts that were included in the model construction, the number of models created from which the top five were selected, the cumulative posterior probability of the top five models, and the number of variables included in each of the top five models.

n kelts =	240							
n models selected =	11							
Cum. Post. prob. =	0.821							
Variable	Prob.	Mean	SD	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.000	11.206	9.148	7.779	22.780	6.759	23.020	0.091
Search	1.000	-0.562	0.174	-0.565	-0.570	-0.530	-0.527	-0.612
First Y	1.000	-0.019	0.005	-0.019	-0.021	-0.019	-0.021	-0.018
Fork Length	0.861	-0.104	0.059	-0.122	-0.127	-0.113	-0.118	.
Temp Ratio	0.306	-4.257	7.703	.	-13.670	.	-14.900	.
Median Depth	0.252	-0.017	0.034	.	.	-0.061	-0.070	.
Surface Temp	0.034	-0.005	0.046	.	.	.	.	.
Pass Day	0.028	0.000	0.004	.	.	.	.	.
Temp 15m	0.027	-0.002	0.034	.	.	.	.	.
n variables				3	4	4	5	2
BIC				-1220	-1218	-1217	-1216	-1215
Posterior prob.				**0.400**	**0.182**	**0.118**	**0.072**	**0.049**

Table A.4. Bayesian model-averaging results displaying the top five models for explaining the probability of turbine passage for tagged steelhead kelts at Lower Granite Dam in 2012 and 2013. Top models were selected and ranked by their Bayesian Information Criterion (BIC) and posterior probabilities. The posterior probability of each variable being included in the model is also shown, along with the mean parameter value and standard deviation, and the parameter value of each variable in the top five models. Also displayed are the number of kelts that were included in the model construction, the number of models created from which the top five were selected, the cumulative posterior probability of the top five models, and the number of variables included in each of the top five models.

n kelts =	241							
n models selected =	48							
Cum. Post. prob. =	0.363							
Variable	Prob.	Mean	SD	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.000	-2.210	2.718	-0.708	-6.067	0.216	-4.951	0.816
Median Depth	1.000	-0.159	0.040	-0.160	-0.154	-0.167	-0.160	-0.166
T1 % Q	0.327	0.035	0.059	.	0.115	.	0.127	.
SW % Q	0.305	-0.036	0.065	-0.125	.	.	.	-0.098
T2 % Q	0.305	-0.048	0.083	.	.	-0.178	.	-0.142
S3 % Q	0.207	-0.101	0.246	.	.	-0.588	-0.402	.
S6 % Q	0.122	-0.068	0.232	.	.	.	.	.
T6 % Q	0.094	0.010	0.036	.	.	.	.	.
S1 % Q	0.081	-0.022	0.085	.	.	.	.	.
S2 % Q	0.067	-0.022	0.163	.	.	.	.	.
S7 % Q	0.063	-0.009	0.169	.	.	.	.	.
S4 % Q	0.061	-0.023	0.114	.	.	.	.	.
S8 % Q	0.053	-0.021	0.191	.	.	.	.	.
n variables				2	2	3	3	3
BIC				-1247	-1246	-1246	-1246	-1246
Posterior prob.				**0.117**	**0.073**	**0.061**	**0.061**	**0.051**

Table A.5. Bayesian model-averaging results displaying the top five models for explaining the probability of spillway weir passage for tagged steelhead kelts at Little Goose Dam in 2012 and 2013. Top models were selected and ranked by their Bayesian Information Criterion (BIC) and posterior probabilities. The posterior probability of each variable being included in the model is also shown, along with the mean parameter value and standard deviation, and the parameter value of each variable in the top five models. Also displayed are the number of kelts that were included in the model construction, the number of models created from which the top five were selected, the cumulative posterior probability of the top five models, and the number of variables included in each of the top five models.

n kelts =	591							
n models selected =	39							
Cum. Post. prob. =	0.433							
Variable	Prob.	Mean	SD	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.000	1.344	0.853	1.269	1.385	0.537	0.712	2.113
Median Depth	1.000	0.092	0.016	0.094	0.093	0.092	0.091	0.090
Search	1.000	0.189	0.045	0.193	0.198	0.145	0.154	0.191
S5 % Q	0.632	-0.144	0.120	-0.233	-0.245	-0.228	-0.240	.
Condition	0.483							
	0.002	-0.320	0.378	.	-0.663	.	-0.627	-0.680
Discharge	0.231	-0.002	0.005	.	.	.	.	-0.013
S4 % Q	0.163	-0.041	0.104	.	.	.	.	.
Ln Y Dist	0.104	0.015	0.050	.	.	0.143	0.130	.
S1 % Q	0.101	0.010	0.033	.	.	.	.	.
SW % Q	0.063	-0.002	0.010	.	.	.	.	.
Pass Diel	0.055							
	0.001	0.020	0.096	.	.	.	.	.
Day	0.046	0.000	0.002	.	.	.	.	.
First Y	0.035	0.000	0.000	.	.	.	.	.
S7 % Q	0.033	-0.008	0.044	.	.	.	.	.
T1 % Q	0.030	0.001	0.005	.	.	.	.	.
S2 % Q	0.029	-0.006	0.037	.	.	.	.	.
S3 % Q	0.000	0.000	0.000	.	.	.	.	.
S6 % Q	0.000	0.000	0.000	.	.	.	.	.
n variables				3	4	4	5	4
BIC				-3090	-3090	-3088	-3087	-3087
Posterior prob.				**0.164**	**0.161**	**0.046**	**0.032**	**0.030**

Table A.6. Bayesian model-averaging results displaying the top five models for explaining the probability of traditional spill passage for tagged steelhead kelts at Little Goose Dam in 2012 and 2013. Top models were selected and ranked by their Bayesian Information Criterion (BIC) and posterior probabilities. The posterior probability of each variable being included in the model is also shown, along with the mean parameter value and standard deviation, and the parameter value of each variable in the top five models. Also displayed are the number of kelts that were included in the model construction, the number of models created from which the top five were selected, the cumulative posterior probability of the top five models, and the number of variables included in each of the top five models.

n kelts =	669							
n models selected =	24							
Cum. Post. prob. =	0.598							
Variable	Prob.	Mean	SD	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.000	-1.761	0.930	-1.814	-2.521	-1.238	-1.009	-1.581
First Y	1.000	0.009	0.001	0.009	0.009	0.009	0.009	0.009
Ln Y dist	1.000	-0.493	0.090	-0.497	-0.499	-0.487	-0.488	-0.505
S2 % Q	0.395	0.116	0.158	0.316	.	.	.	.
SW % Q	0.267	0.016	0.028	.	0.060	.	.	.
Condition	0.130							
	0.002	0.071	0.212	.	.	.	.	.
S3 % Q	0.105	0.021	0.068	.	.	0.222	.	.
S5 % Q	0.098	0.018	0.059	.	.	.	0.194	.
S7 % Q	0.089	0.018	0.063	.	.	.	.	.
S4 % Q	0.088	0.025	0.088	.	.	.	.	0.311
S6 % Q	0.050	0.010	0.049	.	.	.	.	.
Day	0.047	0.000	0.003	.	.	.	.	.
Discharge	0.027	0.000	0.001	.	.	.	.	.
Pass Diel	0.014							
	0.001	-0.003	0.040	.	.	.	.	.
n variables				3	3	3	3	3
BIC				-3824	-3823	-3822	-3821	-3821
Posterior prob.				**0.213**	**0.185**	**0.070**	**0.066**	**0.063**

Table A.7. Bayesian model-averaging results displaying the top five models for explaining the probability of JBS passage for tagged steelhead kelts at Little Goose Dam in 2012 and 2013. Top models were selected and ranked by their Bayesian Information Criterion (BIC) and posterior probabilities. The posterior probability of each variable being included in the model is also shown, along with the mean parameter value and standard deviation, and the parameter value of each variable in the top five models. Also displayed are the number of kelts that were included in the model construction, the number of models created from which the top five were selected, the cumulative posterior probability of the top five models, and the number of variables included in each of the top five models.

n kelts =	524							
n models selected =	13							
Cum. Post. prob. =	0.726							
Variable	Prob.	Mean	SD	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.000	0.555	2.182	-0.362	2.492	-1.500	0.257	2.347
First Y	1.000	-0.014	0.002	-0.014	-0.014	-0.015	-0.014	-0.014
Search	1.000	-0.485	0.107	-0.488	-0.487	-0.488	-0.483	-0.480
Median Depth	1.000	-0.082	0.021	-0.082	-0.083	-0.082	-0.081	-0.081
Temp 30m	0.235	-0.059	0.123	.	0.253	.	.	.
Discharge	0.160	0.002	0.005	.	.	0.012	.	.
T1 % Q	0.079	-0.003	0.012	.	.	.	-0.037	.
Fork Length	0.078	0.000	0.001	.	.	.	.	.
S8 % Q	0.078	-0.019	0.081	.	.	.	.	.
Day	0.058	-0.001	0.006	.	.	.	.	-0.020
Crest	0.054							
	0.002	-0.039	0.193	.	.	.	.	.
Forebay TDG%	0.018	0.001	0.008	.	.	.	.	.
n variables				3	4	4	4	4
BIC				-3019	-3017	-3017	-3015	-3015
Posterior prob.				**0.332**	**0.142**	**0.134**	**0.059**	**0.058**

Table A.8. Bayesian model-averaging results displaying the top five models for explaining the probability of turbine passage for tagged steelhead kelts at Little Goose Dam in 2012 and 2013. Top models were selected and ranked by their Bayesian Information Criterion (BIC) and posterior probabilities. The posterior probability of each variable being included in the model is also shown, along with the mean parameter value and standard deviation, and the parameter value of each variable in the top five models. Also displayed are the number of kelts that were included in the model construction, the number of models created from which the top five were selected, the cumulative posterior probability of the top five models, and the number of variables included in each of the top five models.

n kelts =	591					
n model selected =	3					
Cum. Post. prob. =	1					
Variable	Prob.	Mean	SD	Model 1	Model 2	Model 3
Intercept	1.000	-2.125	0.472	-2.000	-2.207	-2.830
Median Depth	1.000	-0.085	0.020	-0.084	-0.087	-0.091
First Y	1.000	-0.007	0.002	-0.007	-0.007	-0.006
Search	0.890	-2.262	0.137	-0.296	-0.292	.
T6 % Q	0.163	0.010	0.026	.	0.061	.
n variables				3	4	2
BIC				-3538	-3535	-3534
Posterior prob.				**0.727**	**0.163**	**0.110**

Table A.9. Bayesian model-averaging results displaying the top five models for explaining the probability of spillway weir passage for tagged steelhead kelts at Lower Monumental Dam in 2012 and 2013. Top models were selected and ranked by their Bayesian Information Criterion (BIC) and posterior probabilities. The posterior probability of each variable being included in the model is also shown, along with the mean parameter value and standard deviation, and the parameter value of each variable in the top five models. Also displayed are the number of kelts that were included in the model construction, the number of models created from which the top five were selected, the cumulative posterior probability of the top five models, and the number of variables included in each of the top five models.

n kelts =	488							
n models selected =	20							
Cum. post. prob. =	0.629							
Variable	Prob.	Mean	SD	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.000	1.187	0.686	1.475	0.556	1.733	1.915	0.204
Median Depth	1.000	0.109	0.020	0.106	0.110	0.105	0.116	0.110
First Y	0.986	0.004	0.001	0.004	0.004	0.004	0.005	0.004
Search	0.505	0.069	0.077	0.138	.	0.146	.	.
Ln Y Total	0.413	0.927	0.124	.	0.230	.	.	0.237
S5 % Q	0.144	-0.011	0.030	.	.	-0.081	.	.
Pass Diel	0.085							
	0.001	0.325	0.126	.	.	.	.	0.404
S7 % Q	0.073	-0.006	0.024	.	.	.	.	.
S4 % Q	0.058	-0.004	0.022	.	.	.	.	.
S3 % Q	0.054	-0.004	0.022	.	.	.	.	.
S1 % Q	0.036	-0.003	0.019	.	.	.	.	.
n variables				3	3	4	2	4
BIC				-2461	-2461	-2459	-2459	-2458
Posterior prob.				**0.224**	**0.203**	**0.088**	**0.074**	**0.040**

Table A.10. Bayesian model-averaging results displaying the top five models for explaining the probability of traditional spill passage for tagged steelhead kelts at Lower Monumental Dam in 2012 and 2013. Top models were selected and ranked by their Bayesian Information Criterion (BIC) and posterior probabilities. The posterior probability of each variable being included in the model is also shown, along with the mean parameter value and standard deviation, and the parameter value of each variable in the top five models. Also displayed are the number of kelts that were included in the model construction, the number of models created from which the top five were selected, the cumulative posterior probability of the top five models, and the number of variables included in each of the top five models.

n kelts =	538							
n models selected =	57							
Cum. post. prob. =	0.421							
Variable	Prob.	Mean	SD	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.000	-3.662	0.977	-4.074	-4.831	-2.795	-2.491	-3.556
First Y	1.000	-0.011	0.001	-0.011	-0.011	-0.010	-0.010	-0.010
Median Depth	0.665	-0.033	0.028	-0.050	-0.053	-0.047	.	-0.050
S5 % Q	0.573	0.106	0.100	0.196	.	0.195	0.199	.
Ln Y Total	0.450	-0.105	0.132	.	.	-0.228	-0.243	-0.222
SW % Q	0.352	0.015	0.022	.	0.045	.	.	0.044
Condition	0.110							
	0.002	0.072	0.238	.	.	.	.	.
S4 % Q	0.064	0.013	0.056	.	.	.	.	.
T6 % Q	0.056	-0.002	0.009	.	.	.	.	.
S7 % Q	0.051	0.008	0.041	.	.	.	.	.
S3 % Q	0.047	0.007	0.040	.	.	.	.	.
S6 % Q	0.042	0.004	0.020	.	.	.	.	.
S1 % Q	0.040	0.006	0.039	.	.	.	.	.
Pass Diel	0.035							
	0.001	-0.011	0.078	.	.	.	.	.
T4 % Q	0.013	0.000	0.003	.	.	.	.	.
T5 % Q	0.000	0.000	0.000	.	.	.	.	.
n variables				3	3	4	3	4
BIC				-2958	-2958	-2958	-2958	-2957
Posterior prob.				**0.106**	**0.089**	**0.084**	**0.078**	**0.063**

Table A.11. Bayesian model-averaging results displaying the top five models for explaining the probability of JBS passage for tagged steelhead kelts at Lower Monumental Dam in 2012 and 2013. Top models were selected and ranked by their Bayesian Information Criterion (BIC) and posterior probabilities. The posterior probability of each variable being included in the model is also shown, along with the mean parameter value and standard deviation, and the parameter value of each variable in the top five models. Also displayed are the number of kelts that were included in the model construction, the number of models created from which the top five were selected, the cumulative posterior probability of the top five models, and the number of variables included in each of the top five models.

n kelts =	539							
n models selected =	13							
Cum. post. prob. =	0.776							
Variable	Prob.	Mean	SD	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.000	-0.447	1.817	-1.115	2.287	-2.140	1.746	-0.695
Median Depth	0.917	-0.072	0.031	-0.078	-0.075	-0.082	-0.079	.
SW % Q	0.792	-0.054	0.034	-0.068	-0.065	.	.	-0.066
Fork Length	0.224	-0.001	0.003	.	-0.006	.	-0.006	.
S5 % Q	0.185	-0.059	0.134	.	.	-0.321	-0.321	.
S2 % Q	0.076	-0.013	0.057	.	.	.	.	.
Ln Y Total	0.027	-0.003	0.031	.	.	.	.	.
S4 % Q	0.025	0.003	0.035	.	.	.	.	.
T6 % Q	0.024	0.000	0.006	.	.	.	.	.
S3 % Q	0.024	0.003	0.030	.	.	.	.	.
S1 % Q	0.022	-0.008	0.056	.	.	.	.	.
S8 % Q	0.000	0.000	0.000	.	.	.	.	.
S6 % Q	0.000	0.000	0.000	.	.	.	.	.
T4 % Q	0.000	0.000	0.000	.	.	.	.	.
n variables				2	3	2	3	1
BIC				-2783	-2781	-2781	-2780	-2779
Posterior prob.				**0.421**	**0.140**	**0.100**	**0.059**	**0.058**

Table A.12. Bayesian model-averaging results displaying the top five models for explaining the probability of turbine passage for tagged steelhead kelts at Lower Monumental Dam in 2012 and 2013. Top models were selected and ranked by their Bayesian Information Criterion (BIC) and posterior probabilities. The posterior probability of each variable being included in the model is also shown, along with the mean parameter value and standard deviation, and the parameter value of each variable in the top five models. Also displayed are the number of kelts that were included in the model construction, the number of models created from which the top five were selected, the cumulative posterior probability of the top five models, and the number of variables included in each of the top five models.

n kelts =	488						
n models selected =	4						
Cum. Post. prob. =	1.000						
Variable	Prob.	Mean	SD	Model 1	Model 2	Model 3	Model 4
Intercept	1.000	-1.115	0.582	-1.210	-0.649	-1.962	-1.290
Search	1.000	-0.641	0.154	-0.609	-0.684	-0.619	-0.697
First Y	1.000	0.011	0.003	0.011	0.011	0.011	0.011
Median depth	0.601	-0.041	0.039	-0.068	.	-0.072	.
T4Tot	0.181	0.010	0.024	.	.	0.055	0.049
n variables				3	2	4	3
BIC				-2828	-2827	-2825	-2824
Posterior prob.				**0.483**	**0.336**	**0.118**	**0.063**

Table A.13. Bayesian model-averaging results displaying the top five models for explaining the probability of survival from dam passage (all routes combined) to the detection array located 59 km downstream for tagged steelhead kelts at Lower Granite Dam in 2012 and 2013. Top models were selected and ranked by their Bayesian Information Criterion (BIC) and posterior probabilities. The posterior probability of each variable being included in the model is also shown, along with the mean parameter value and standard deviation, and the parameter value of each variable in the top five models. Also displayed are the number of kelts that were included in the model construction, the number of models created from which the top five were selected, the cumulative posterior probability of the top five models, and the number of variables included in each of the top five models.

n kelts =	254							
n models selected =	18							
Cum. Post. prob. =	0.682							
Variable	Prob.	Mean	SD	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.000	1.019	0.859	1.293	0.202	1.984	0.137	1.117
Condition	1.000							
	0.002	-2.023	0.447	-2.096	-2.045	-1.971	-1.902	-1.951
T6 % Q	0.881	0.100	0.052	0.123	0.118	0.102	.	0.103
Ln tailrace egress	0.288	-0.093	0.168	.	-0.326	.	.	.
T5 % Q	0.184	-0.007	0.017	.	.	-0.032	.	.
Discharge	0.135	0.002	0.006	.	.	.	0.020	.
T1 % Q	0.082	0.002	0.010	.	.	.	.	0.031
S1 % Q	0.027	-0.001	0.012	.	.	.	.	.
T2 % Q	0.026	0.000	0.003	.	.	.	.	.
SW % Q	0.022	0.000	0.003	.	.	.	.	.
T3 % Q	0.020	0.000	0.003	.	.	.	.	.
S4 % Q	0.019	0.000	0.014	.	.	.	.	.
Tailrace temp	0.019	0.000	0.010	.	.	.	.	.
n variables				2	3	3	2	3
BIC				-1178	-1177	-1176	-1175	-1175
Posterior prob.				**0.304**	**0.163**	**0.099**	**0.059**	**0.057**

Table A.14. Bayesian model-averaging results displaying the top five models for explaining the probability of survival from dam passage to the detection array located 59 km downstream for tagged steelhead kelts that passed Lower Granite Dam via the spillway weir in 2012 and 2013. Top models were selected and ranked by their Bayesian Information Criterion (BIC) and posterior probabilities. The posterior probability of each variable being included in the model is also shown, along with the mean parameter value and standard deviation, and the parameter value of each variable in the top five models. Also displayed are the number of kelts that were included in the model construction, the number of models created from which the top five were selected, the cumulative posterior probability of the top five models, and the number of variables included in each of the top five models.

n kelts =	186							
n models selected =	9							
Cum. Post. prob. =	0.829							
Variable	Prob.	Mean	SD	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.000	1.049	0.530	1.070	1.638	0.508	0.421	0.994
Condition	1.00							
	0.002	-2.083	0.521	-2.087	-2.014	-2.115	-2.113	-2.027
T6 % Q	1.000	0.231	0.084	0.232	0.213	0.247	0.222	0.219
T5 % Q	0.100	-0.003	0.010	.	-0.026	.	.	.
Ln tailrace egress	0.056	-0.011	0.073	.	.	.	-0.189	.
S4 % Q	0.056	0.005	0.033	.	.	0.085	.	.
T1 % Q	0.052	0.001	0.007	.	.	.	.	0.016
Discharge	0.043	0.000	0.002	.	.	.	.	.
S1 % Q	0.043	0.001	0.015	.	.	.	.	.
T2 % Q	0.042	0.000	0.005	.	.	.	.	.
T3 % Q	0.042	0.000	0.004	.	.	.	.	.
n variables				2	3	3	3	3
BIC				-773.0	-769.6	-768.4	-768.4	-768.2
Posterior prob.				**0.565**	**0.100**	**0.056**	**0.056**	**0.052**

Table A.15. Bayesian model-averaging results displaying the top five models for explaining the probability of survival from dam passage (all routes combined) to the detection array located 33 km downstream for tagged steelhead kelts at Little Goose Dam in 2012 and 2013. Top models were selected and ranked by their Bayesian Information Criterion (BIC) and posterior probabilities. The posterior probability of each variable being included in the model is also shown, along with the mean parameter value and standard deviation, and the parameter value of each variable in the top five models. Also displayed are the number of kelts that were included in the model construction, the number of models created from which the top five were selected, the cumulative posterior probability of the top five models, and the number of variables included in each of the top five models.

n kelts =	676							
n models selected =	13							
Cum. Post. prob. =	0.815							
Variable	Prob.	Mean	SD	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.000	1.086	1.271	1.952	0.471	1.038	0.140	1.687
Condition	1.000							
	0.002	-1.228	0.303	-1.287	-1.165	-1.199	-1.199	-1.238
T4 % Q	0.597	0.046	0.042	0.086	.	0.052	.	0.080
Discharge	0.503	0.012	0.014	.	0.025	0.014	0.033	.
S7 % Q	0.063	-0.013	0.054	.	.	.	-0.200	.
Tailrace temp	0.030	0.008	0.058	.	.	.	.	.
S6 % Q	0.030	0.003	0.025	.	.	.	.	0.112
T1 % Q	0.024	-0.001	0.005	.	.	.	.	.
S5 % Q	0.024	-0.003	0.024	.	.	.	.	.
S3 % Q	0.024	-0.003	0.024	.	.	.	.	.
T2 % Q	0.022	0.000	0.005	.	.	.	.	.
S1 % Q	0.021	-0.001	0.009	.	.	.	.	.
T6 % Q	0.021	-0.001	0.009	.	.	.	.	.
T5 % Q	0.019	0.000	0.005	.	.	.	.	.
S8 % Q	0.000	0.000	0.000	.	.	.	.	.
n variables				2	2	3	3	3
BIC				-4010	-4009	-4007	-4006	-4005
Posterior prob.				0.372	0.250	0.099	0.063	0.030

Table A.16. Bayesian model-averaging results displaying the top five models for explaining the probability of survival from dam passage to the detection array located 33 km downstream for tagged steelhead kelts that passed Little Goose Dam via the spillway weir in 2012 and 2013. Top models were selected and ranked by their Bayesian Information Criterion (BIC) and posterior probabilities. The posterior probability of each variable being included in the model is also shown, along with the mean parameter value and standard deviation, and the parameter value of each variable in the top five models. Also displayed are the number of kelts that were included in the model construction, the number of models created from which the top five were selected, the cumulative posterior probability of the top five models, and the number of variables included in each of the top five models.

n kelts =	443							
n models selected =	59							
Cum. Post. prob. =	0.374							
Variable	Prob.	Mean	SD	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.000	6.713	3.226	9.512	5.281	10.010	5.364	5.090
T2 % Q	0.764	-0.100	0.079	-0.116	-0.121	-0.108	-0.114	-0.079
Fork Length	0.458	-0.003	0.004	-0.007	.	0.007	.	.
Condition	0.437							
	0.002	-0.547	0.702	.	.	-1.266	-1.142	.
Crest	0.353							
	0.002	-0.504	0.770	.	.	.	.	-1.172
S8 % Q	0.132	0.090	0.272	.	.	.	.	.
Pass Day	0.088	-0.097	0.388	.	.	.	.	.
Discharge	0.084	0.002	0.009	.	.	.	.	.
S6 % Q	0.038	-0.008	0.067	.	.	.	.	.
S3 % Q	0.033	-0.007	0.050	.	.	.	.	.
T4 % Q	0.028	0.001	0.010	.	.	.	.	.
T1 % Q	0.018	0.000	0.005	.	.	.	.	.
T5 % Q	0.017	0.001	0.010	.	.	.	.	.
S5 % Q	0.015	-0.001	0.024	.	.	.	.	.
Tailrace temp	0.005	0.001	0.039	.	.	.	.	.
n variables				2	1	3	2	2
BIC				-2518	-2518	-2518	-2517	-2517
Posterior prob.				**0.095**	**0.094**	**0.087**	**0.055**	**0.043**

Table A.17. Bayesian model-averaging results displaying the top five models for explaining the probability of survival from dam passage (all routes combined) to the detection array located 27 km downstream for tagged steelhead kelts at Lower Monumental Dam in 2012 and 2013. Top models were selected and ranked by their Bayesian Information Criterion (BIC) and posterior probabilities. The posterior probability of each variable being included in the model is also shown, along with the mean parameter value and standard deviation, and the parameter value of each variable in the top five models. Also displayed are the number of kelts that were included in the model construction, the number of models created from which the top five were selected, the cumulative posterior probability of the top five models, and the number of variables included in each of the top five models.

n kelts =	501							
n models selected =	31							
Cum. Post. prob. =	0.457							
Variable	Prob.	Mean	SD	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.000	1.245	3.687	0.488	1.074	-1.055	1.593	0.979
Fork Length	0.901	-0.006	0.003	-0.007	-0.007	-0.006	-0.007	-0.007
Relative Condition	0.805	0.049	0.031	0.062	0.062	0.060	0.062	0.062
Pass Diel	0.588							
	0.001	0.560	0.543	0.959	.	0.974	.	0.913
Discharge	0.193	0.002	0.006	.	.	0.012	.	.
S8 % Q	0.147	-0.016	0.044	.	.	.	-0.112	-0.100
T2 % Q	0.083	-0.003	0.013	.	.	.	.	.
S6 % Q	0.064	-0.004	0.019	.	.	.	.	.
T4 % Q	0.060	0.002	0.010	.	.	.	.	.
S7 % Q	0.057	0.010	0.052	.	.	.	.	.
n variables				3	2	4	3	4
BIC				-2847	-2847	-2845	-2845	-2845
Posterior prob.				**0.178**	**0.120**	**0.065**	**0.047**	**0.047**

Table A.18. Bayesian model-averaging results displaying the top five models for explaining the probability of survival from dam passage to the detection array located 27 km downstream for tagged steelhead kelts that passed Lower Monumental Dam via the spillway weir in 2012 and 2013. Top models were selected and ranked by their Bayesian Information Criterion (BIC) and posterior probabilities. The posterior probability of each variable being included in the model is also shown, along with the mean parameter value and standard deviation, and the parameter value of each variable in the top five models. Also displayed are the number of kelts that were included in the model construction, the number of models created from which the top five were selected, the cumulative posterior probability of the top five models, and the number of variables included in each of the top five models.

n kelts =	384							
n models selected =	23							
Cum. Post. prob. =	0.596							
Variable	Prob.	Mean	SD	Model 1	Model 2	Model 3	Model 4	Model 5
Intercept	1.000	3.714	1.245	4.621	2.718	4.750	3.012	2.521
S6 % Q	0.355	-0.054	0.083	-0.155	.	.	.	.
S7 % Q	0.321	0.248	0.465	.	0.864	.	.	.
S8 % Q	0.168	-0.028	0.073	.	.	-0.192	.	.
T1 % Q	0.139	0.009	0.026	.	.	.	.	0.076
SW % Q	0.089	-0.003	0.013	.	.	.	.	.
T4 % Q	0.068	0.003	0.013	.	.	.	.	.
Discharge	0.055	0.001	0.005	.	.	.	.	.
T2 % Q	0.048	-0.002	0.012	.	.	.	.	.
n variables				1	1	1	0	1
BIC				-2136	-2135	-2135	-2134	-2134
Posterior prob.				**0.232**	**0.133**	**0.113**	**0.060**	**0.058**

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