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Passage Route Survival and Behavior of Juvenile Salmon at Priest Rapids Dam, Columbia River, WA

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PASSAGE ROUTE SURVIVAL AND BEHAVIOR OF JUVENILE

SALMON AT PRIEST RAPIDS DAM, COLUMBIA RIVER, WA

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by

Kyle Barrett Hatch

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Graduate Studies

We hereby approve the thesis of

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ABSTRACT

PASSAGE ROUTE SURVIVAL AND BEHAVIOR OF JUVENILE

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Columbia River hydropower is an economic mainstay of the Pacific Northwest. However, it is well known that the construction of hydropower dams has added anthropogenic pressure to Columbia River salmon populations. Juvenile salmon that pass through powerhouse turbines at large hydropower dams display higher mortality rates than salmon passing through alternative routes; thus at Priest Rapids Dam, a top-spill fish bypass was constructed as a safer alternate downstream passage. To investigate the efficacy of this new passage structure, an acoustic telemetry study was conducted in the spring of 2014 to determine the ability of the bypass to collect and safely pass juvenile steelhead and Chinook salmon. The bypass collected 47% of the monitored steelhead and 38% of the monitored yearling Chinook salmon. Analysis of route choice identified forebay temperature, powerhouse discharge, spillway discharge and forebay approach patterns as significant drivers of passage selection. Immediately following dam passage, steelhead and Chinook salmon that used the bypass had higher survival and migrated faster compared to powerhouse route fish. The Priest Rapids Fish Bypass served its intended purpose by reducing the anthropogenic footprint of this hydroelectric facility on migrating juvenile salmon, which will aid the potential recovery of Columbia River salmon.

ACKNOWLEDGMENTS

I would like to thank Grant County PUD and the Priest Rapids Coordinating Committee for funding this study and their staff who were vital to its success, notably: Robert Weedmark, Ed Perez, and Ty Ehrman, along with dozens of Grant County PUD and Blue Leaf fisheries staff. Additionally, I would like to thank my graduate advisor Dr. Clay Arango for his support and guidance, as well as the rest of my committee, which includes Dr. Paul James and Dr. Alison Scoville. Further acknowledgements go to the LGL crew, led by Megan Mathews, who performed all fish handling and acoustic tagging during the study duration. Special thanks to the database crew at Blue Leaf Environmental for their hand in the data organization and processing.

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CHAPTER I

INTRODUCTION

Anadromous salmon are pivotal to the ecology and function of the Columbia River watershed and are considered a foundation species. Columbia River salmon play an irreplaceable role in the biogeochemical transfer of marine-derived nutrients to inland aquatic and terrestrial ecosystems, thereby creating a unique cross-boundary ecological subsidy where riparian productivity is affected (Cederholm 1999). In Washington State, at least 137 different aquatic and terrestrial species depend on salmon to some degree (Cedarholm et al. 2000, Helfield and Naiman 2002, Scholz and McLellan 2010, Quinn et al. 2009). However, historic and modern declines in anadromous salmonids have led to a diminished population estimated at 13% of pre-development size (Chapman 1986). Population declines have led to the listing of many Columbia River salmon species as threatened or endangered under the Endangered Species Act (ESA).

Beyond being ecologically important, Columbia River salmon are also economically important. In 2005, the Columbia River salmon industry generated an estimated $109 million of local income annually, and a 1996 report on the economics of Columbia River salmon estimated that up to $13 billion in revenue has been lost due to the reduction of salmon populations from pre-development sizes (IFR 1996, IEAB 2005). Additionally, Columbia River salmon hold an immeasurable recreational value to the many people who love to fish for them within the Columbia River watershed. Finally, salmon have been referred to as the lifeblood of original Columbia Basin cultures, and still hold their place as a priceless symbol of cultural and spiritual identity (CRITFC 2014). The decline of Columbia River salmon largely began around the mid-1800s due to the advent of commercial canning (Scholz and McLellan 2010). In the years that followed, salmon were aggressively harvested leading to a dramatic reduction in returning adults (Bottom et al. 2005). By the early 1900s anthropogenic pressure on the Columbia River watershed increased due to timber overharvest, land development, mining activities, widespread irrigated agriculture with unscreened diversions, and dam construction (Raymond 1979). Among these factors, existing hydropower facilities continue to complicate salmon restoration efforts today. Large hydropower facilities can affect the river ecosystem by changing historic flow patterns, raising water temperatures, and inundating spawning areas (Raymond 1979, Scholz and McLellan 2010). On top of this, they act as an impediment that requires passage for adult salmon traveling upstream to spawning areas and juvenile salmon migrating downstream to ocean feeding grounds (Raymond 1979, McClure et al. 2003).

Previous research focused on mortality of out-migrating juvenile salmon, or smolts, has shown that passage through turbines at hydroelectric dams increases the likelihood of downstream mortality compared to smolts that use alternate passage routes such as a juvenile fish bypass or spillway (Muir et al. 2001, Mighetto and Ebel 1994, Raymond 1979). Passage through turbines can cause direct mortality by turbine blades or delayed indirect mortality caused by sub-lethal damage incurred during turbine passage, such as physical abrasion, shearing, descaling, or sensory damage from high water pressure (Ferguson et al. 2006, Abernathy et al. 2001, Coutant and Whitney 2000). To put this into perspective, a comprehensive survival analysis through the Snake and Columbia Rivers found that a one standard deviation change in the occurrence of powerhouse passage, through all downstream dams, was predicted to decrease salmonid freshwater survival by 43% (CSSOC 2015). Therefore, to mitigate the negative effects of dam passage on out-migrating juvenile salmon, hydroelectric organizations have actively worked to improve downstream passage (Ransom et al. 2008), particularly since the early 1980s when Columbia River salmon restoration efforts increased due to realization of the benefits of a healthy salmon population (Mighetto and Ebel 1994, Ransom et al. 2008).

One such hydroelectric organization operating in the mid-Columbia River is Grant County Public Utility District #2 (GCPUD). GCPUD own and operate Priest Rapids Dam, a hydroelectric facility located at River Mile, RM 397. Since construction in 1963, GCPUD has contributed to Columbia River salmon restoration by means of avian predator dissuasion, the northern pikeminnow (*Ptychocheilus oregonensis*) removal program, seasonal flow augmentation, and by funding habitat restoration projects (GCPUD 2015). Additionally, altering powerhouse operations during the spring and summer juvenile out-migrations has improved downstream smolt passage and survival (Timko et al. 2011). In 2008, GCPUD constructed a unique surface-spill fish bypass on Wanapum Dam (WADM, RM 416) to provide safe and effective alternative downstream passage for juvenile migrants. The subsequent evaluation of the Wanapum Fish Bypass (WFB) conducted in 2008-2010 found this enhancement a success due in part to higher fish collection efficiency and a 5.6% average increase in smolt survival through the bypass relative to passage through the turbines (Sullivan et al. 2009, Timko et al. 2010, Timko et al. 2011). At Priest Rapids Dam, a similar surface bypass structure with parallel project objectives was completed in early 2014 and is referred to as the Priest Rapids Fish Bypass (PRFB). The PRFB is a surface-flow, top-spill bypass comprised of three 12-m wide chutes, each designed to pass 9,000 cubic feet per second (cfs) of water while gradually decelerating passing smolts without shear or abrasion (Figure 1). The spring 2014 juvenile salmon out-migration was the first juvenile run to use the operating PRFB, thus prompting an evaluation of its efficacy.

The principal goal of this research was to analyze the survival and passage trends of smolts that chose alternate routes through Priest Rapids Dam. Downstream survival associated with the three passage routes (i.e., spillway, turbine, fish bypass) were modeled to allow for comparison. I included passage data from Wanapum Dam, which is upstream of Priest Rapids, to determine if this preceding passage event affected Priest Rapids Dam passage survival. Secondarily, smolt migration rate, the time it takes a smolt to travel between two points of interest, was modeled as a function of Priest Rapids Dam passage route to detect how behavioral changes from passage route selection altered out-migration. Finally, environmental and operational factors were modeled to analyze how they influenced route selection.

Figure 1: The Priest Rapids Fish Bypass (PRFB). Showing the three surface-spill bays next to the powerhouse.

The results of this study further knowledge regarding methods for improving survival of out-migrating juvenile salmon in impeded waterways, advance understanding regarding the impact of hydroelectric passage route choice on juvenile salmon survival, and explore the factors that influence passage route decision. These results will help guide future hydroelectric enhancements and allow for a more effective restoration of salmonid populations.

CHAPTER II

METHODS

Study Site and Project

Priest Rapids Dam (RM 397) is located on the mid-Columbia River between Wanapum Dam (RM 416) and McNary Dam (RM 292). The study site stretches from the forebay of Priest Rapids Dam through Hanford Reach, and it ends just above the Yakima River confluence (Figure 2). The powerhouse, with 10 turbine units, is located on the northeast half of the dam and the spillway is on southwest half, with the PRFB in the center of the dam.

Design

Upper Columbia River stocks of spring Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*O. mykiss*), both of which ESA-listed (FWS 2003), were selected for use in this passage analysis. A total of 1,170 steelhead and 1,169 spring Chinook salmon, both hatchery and wild stocks, were collected and implanted with an acoustic tag. These totals were divided between 400 steelhead and 399 spring Chinook salmon that were released below Rock Island Dam and 770 steelhead and 770 spring Chinook that were released below Wanapum Dam (Figure 2). Upon encountering Priest Rapids Dam, all released fish self-segregated into one of three passage route groups based on volitional smolt passage (fish bypass, spillway or the powerhouse).

The Juvenile Salmon Acoustic Telemetry System (JSATS) was used to track study fish as they migrated downstream. First, a study fish is tagged with a *L-AMT-1.421* JSATS acoustic tag that emits a unique acoustic signal every three seconds. Once that tagged study fish is within range (100-300m) of a Teknologic JSATS Autonomous Receiver (Model #11003), a detection record is logged for that event.

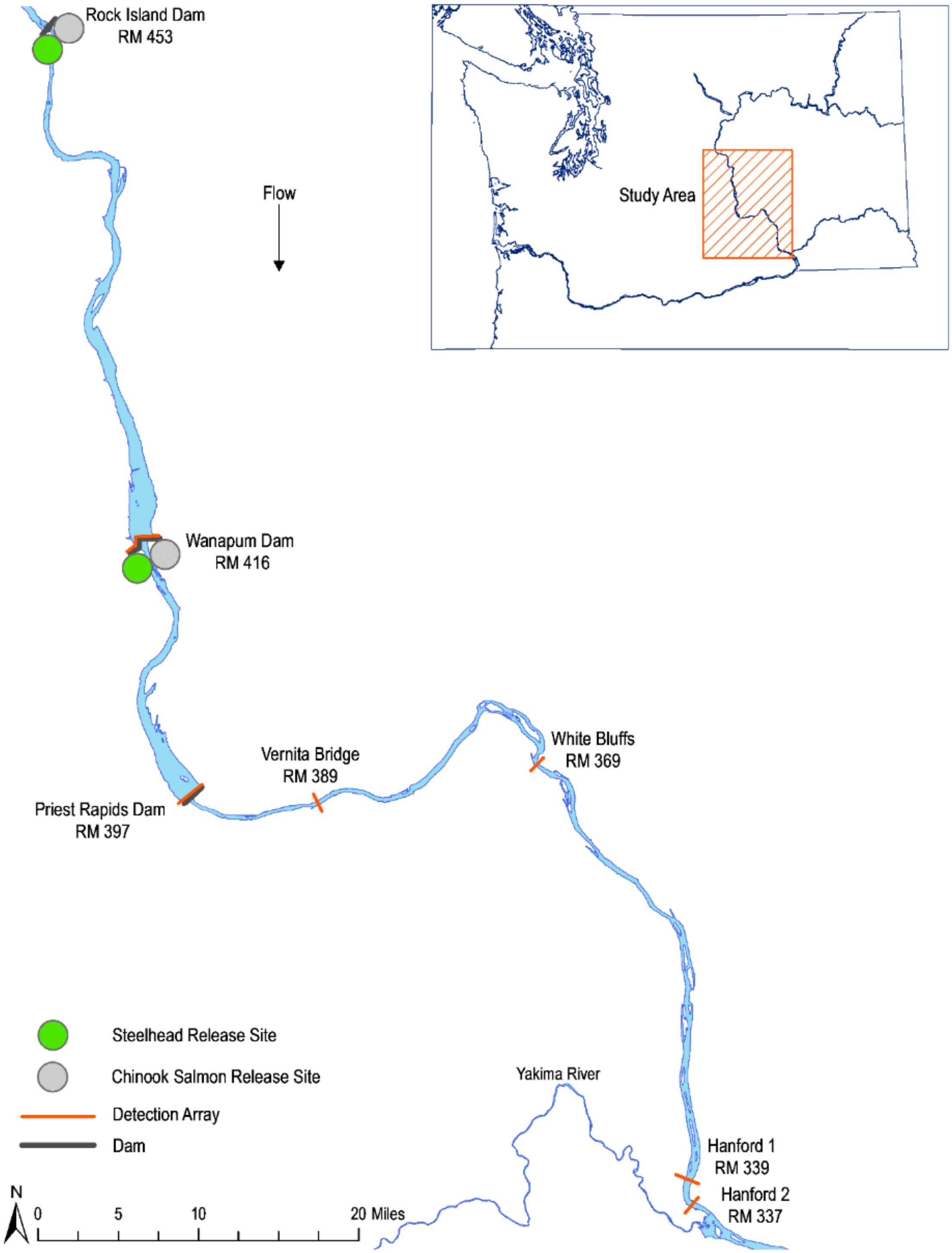

Figure 2 : Map depicting the two release sites. Shown in green and grey circles, one below Rock Island Dam and the other below Wanapum Dam, as well as the location of each downstream acoustic detection array (orange bars).

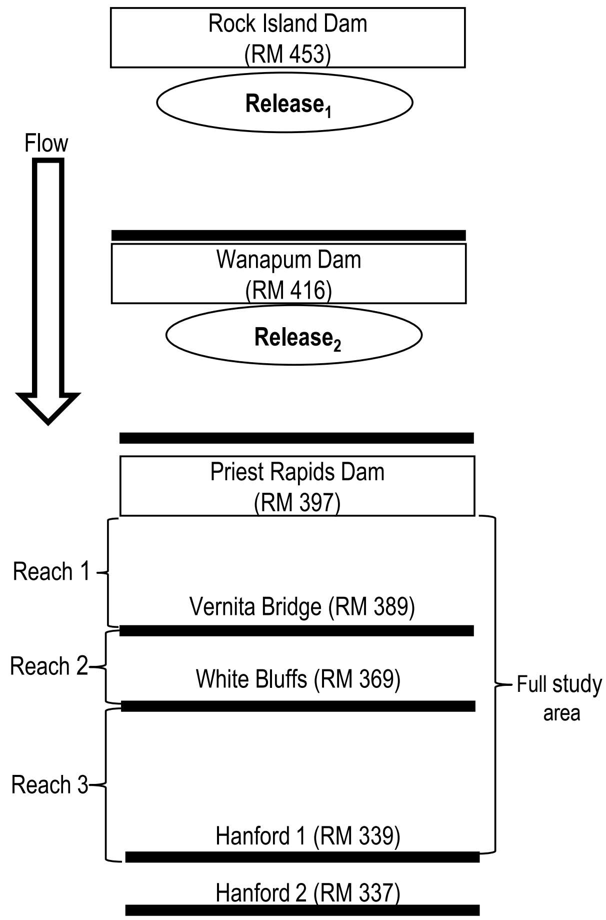

Figure 3 : Study area release sites, array configurations, and reach distinctions. Note that the furthest downstream array at RM 337 is not used to distinguish reaches but was used for calculations of detection efficiencies.

Acoustic receivers were aligned in a series of downstream detection arrays that divide the study area into three distinct reaches (Figure 3). Each array was designed to detect tagged study fish as they migrated downstream, allowing downstream detection rates to be quantified and compared between release sites and among passage routes. From upstream to downstream, reach 1 stretches from Priest Rapids Dam to the first array at RM 389 (8 RM in length), reach 2 lies between the first and second array (20 RM in length), and reach 3 ends at RM 339 and totals 30 RM in length (Figure 3). Reach-specific survival was determined by detection history. A fish detected at an array is interpreted as having survived the upstream reach, but an undetected fish at an array is interpreted as mortality after the prior upstream detection.

Collection and Surgery

Out-migrating steelhead and yearling Chinook salmon were collected by gatewell dip netting at Wanapum and Priest Rapids dams. The gatewells are narrow columns that exist between the turbines and the deck of the dam. Juvenile salmon can become volitionally entrained in these gatewells, therefore allowing an established source of study fish (Park and Farr 1972, Timko et al. 2011).

Collected fish were trucked to the west bank of Wanapum Dam to commence sorting and the surgical implantation of acoustic transmitters. Captured smolts were placed into a light sedation bath (MS-222 at 15 mg/L), sorted by species, size, and physical condition, and then held in fresh river water for 24 h prior to surgery. Following the 24-h holding period, all study fish were anesthetized in MS-222 at 60-80 mg/L and then moved to the surgical station. MS-222 administration continued directly into the gills, while JSATS tags were implanted via a surgical incision made off the mid-ventral line. Stitching was completed with two Vicyl coated sutures, and study fish were given an additional 24 h to recover before release. Tagging and handling mortalities during the 24 h holding period were less than 1% of all fish tagged during the 2014 study. Fish that failed to achieve the standard tag weight to body weight ratio (3%) were removed and left untagged to reduce the possibility of tag-related bias (Timko et al. 2011, Peven et al. 2005). All fish handling and acoustic tagging was solely completed by LGL Limited (Ontario, Canada) due to their extensive experience in salmonid surgery; explicit culling criteria are described in Timko et al. (2010).

Acoustic Tags

The collected steelhead and yearling Chinook salmon were implanted with a *L-AMT-1.421* JSATS acoustic tag (10.5 x 5.2 x 3.0 mm – 0.32 g dry weight), manufactured by Lotek, Ontario (Canada), and a HPT8 Biomark PIT tag (8.4mm, 134.2 kHz), manufactured by Biomark, Boise, Idaho. To avoid the potential effects of tag failure and a subsequent mis-identification of mortality, tag-life test tags were randomly tested from available acoustic tags to quantify tag-life curves and the probability of tag failure. In 2014, the probability of tag failure for all release groups remained below 1% over the out-migration period.

Releases

Acoustically tagged out-migrating steelhead and spring Chinook salmon were released by helicopter into the tailraces of Rock Island Dam and Wanapum Dam (Figure 2, Figure 3). In preparation for release, study fish were transferred into watered filled “fly-tanks”. The water supply was shut off and pre-attached oxygen tanks were engaged immediately before lift off. Study fish were released no higher than 3 m from the river surface, prompted by specialized controls within the pilot’s cockpit. An onshore spotter assisted the pilot and confirmed that all releases stayed within the 3 m protocol. Study fish were released in multiple groups over a four week period with varied quantities to match the natural curve of the out-migration; during the beginning and end of the migration period fewer fish were released, while during the peak of the migration, more fish were released. Additionally, during previous acoustic tag studies within the same study area in 2006-2010, acoustically tagged dead (purposely euthanized) smolts were released below both dams to quantify the probability of misidentifying a passage related mortality event. Results showed that no dead smolts were detected downstream at the detection arrays (Timko et al. 2011).

Therefore the first array below Priest Rapids Dam (Vernita Bridge, Figure 2) was far enough downstream to preclude an additional analysis of misidentifying smolt mortality in the current study.

Passage Route Analysis

Multinomial logistic regression was used to identify key factors that influenced route selection by smolts. Passage route (powerhouse, fish bypass, or spillway) was modeled as a function of several operational and environmental factors that were measured and recorded at the moment of passage. First, I included forebay temperature (°C) as a predictor variable because juvenile salmon are known to change behavior when experiencing different temperature regimes (Sauter et al. 2001). Second, I included powerhouse discharge (kcfs), spillway discharge (kcfs), and fish bypass discharge (kcfs) because these factors affect the flow dynamic within the forebay. I also included discharge through the spillway and powerhouse structures closest to the bypass (powerhouse turbines 1 and 2, and spillway gates 18 and 19) due to their close proximity to the bypass.

Data receivers hung from the boat restricted zone (BRZ) barrier, a buoy line that restricts boat access from the immediate forebay of a hydropower dam, were queried by last detection records to investigate the influence of forebay approach patterns (Figure 4). The BRZ data receivers were numbered 1-8 (from west to east) and the receiver number in which a smolt was last detected represented that individual’s numeric approach variable. The approach pattern was included as a predictor variable to better understand how spatial trends affect passage route choice. No interaction terms between the aforementioned predictor variables were included in the analysis.

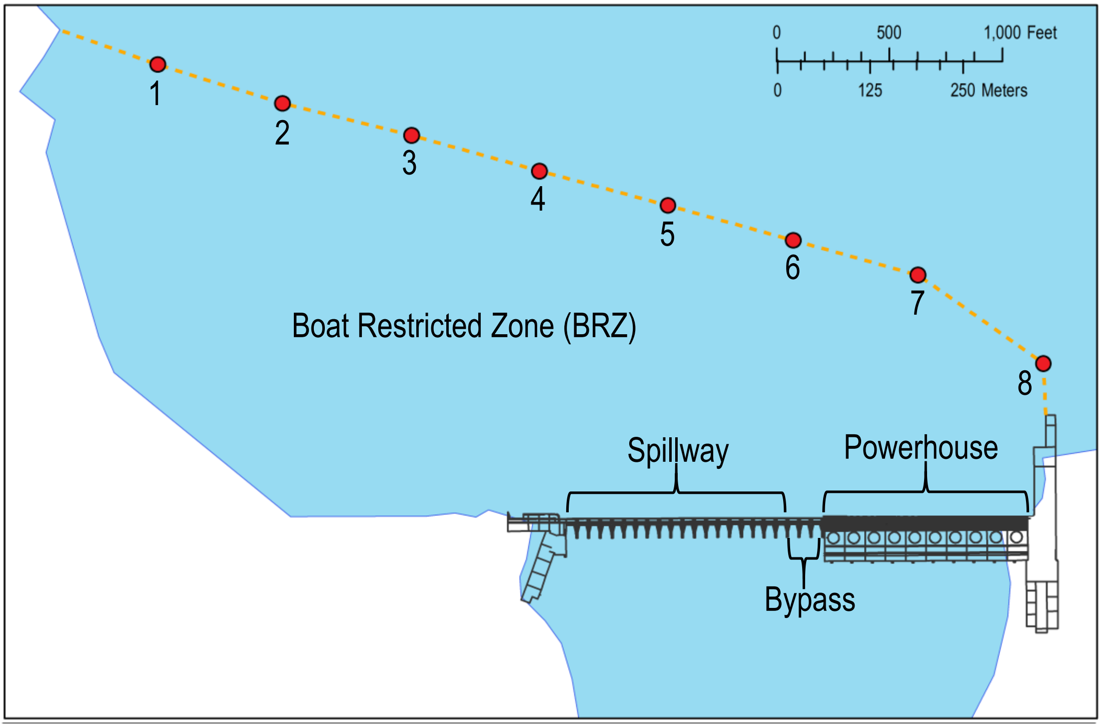

Figure 4. Numeric arrangement of data receivers hung from the boat restriction zone (BRZ) buoy line. Study fish were assigned an approach number (1-8) based on the location of the fish's last detection, enabling analysis of how a fish approached the dam.

Model selection was performed through a combination of forward and backward stepwise regression using AIC values to guide the retention of influential predictor variables. Overall performance of the final model vs. a null model was evaluated using a likelihood ratio test. Likelihood ratio tests were also used to assess the significance of each predictor variable retained in the final model. Finally, I report a McFadden Pseudo R^2 value as a measure of the ability of the final model to explain route passage trends. Model results were visualized by graphing the probability of passage through each route (e.g. bypass) relative to the alternative routes (e.g. powerhouse or spillway) as a function of each predictor variable.

Survival Analysis

A generalized linear model with a binomial distribution of error terms (i.e., a logistic regression) was used to predict downstream detection as a function of the following predictor variables: Wanapum Dam route (3 levels), Priest Rapids Dam route (3 levels), and release site (2 levels). Wanapum Dam route was analyzed using only fish released from the furthest upstream release site (release site 1, Figure 3); therefore, this variable was modeled separately using this subset of data. A cloglog link function was used to accommodate a disproportionate number of ones relative to zeros (Zuur et al. 2009).

Downstream detection probability, the response variable, was defined as what proportion of study fish were detected through each study reach. For example, detection probabilities through reach 1 were the proportion of study fish that successfully passed Priest Rapids Dam and were subsequently detected at the next downstream array. Each downstream reach was analyzed separately and non-cumulatively. Detection through reach 2 was defined as the quantity that successfully migrated through reach 1 divided by those that were detected at the end of reach 2. This non-cumulative method allows for analysis on a reach-by-reach basis, where mortality cataloged in reach 2 did not affect survival within reach 3.

Additionally, mortality rates per river mile were calculated from the mortality per reach (1-detection probability) divided by the length of the reach. This allowed for a visualization of survival among reaches with varying lengths that complement the aforementioned detection analysis. The mortality rates and detection probabilities presented were used to represent downstream survival but do not include corrections for missed detection, tag failure and/or handling effects. Therefore, these calculations were analyzed and interpreted relative to different passage routes or reaches rather than as an absolute measure of downstream survival or mortality.

Similar to the route analysis described above, model selection was performed using a combination of forward and backward stepwise regression based on AIC values. Overall performance of the final model vs. a null model was evaluated using a likelihood ratio test. Likelihood ratio tests were also used to assess the significance of each predictor variable retained in the final model. Finally, I report a McFadden Pseudo R^2 value that measures the ability of my final model to explain survival through each downstream reach.

Migration Rate Analysis

A generalized linear model was used to predict migration rate as a function of the same three predictor variables as the survival analysis: Wanapum Dam route (3 levels), Priest Rapids Dam route (3 levels) and release site (2 levels). Migration rates through each reach were analyzed on a reach-by-reach basis, as well as cumulatively through the entire study area. Similar to the survival analysis, Wanapum Dam route was analyzed using a subset of the data that included only upstream released fish.

Juvenile salmonid migration rate was highly non-normal. The majority of individuals migrated downstream quickly while some individuals delayed. Therefore, the migration rate data contained large outliers that were nonetheless important for interpretation. To account for this non-normality, an inverse Gaussian error distribution was used to model this response. The inverse Gaussian error distribution mimics the distribution of salmonid migration (Figure 5) and has been used for similar modeling exercises (Zabel et al. 1998). I performed model selection through a combination of forward and backward stepwise regression using AIC values to guide variable retention. Performance of the final model vs. the null model was assessed through a likelihood ratio. Individual predictor variables were also assessed for significance by using likelihood ratio tests. Finally, I report an explained deviance (D-squared) value to describe the relative ability of my final model to predict migration rates (Guisan and Zimmerman 2000).

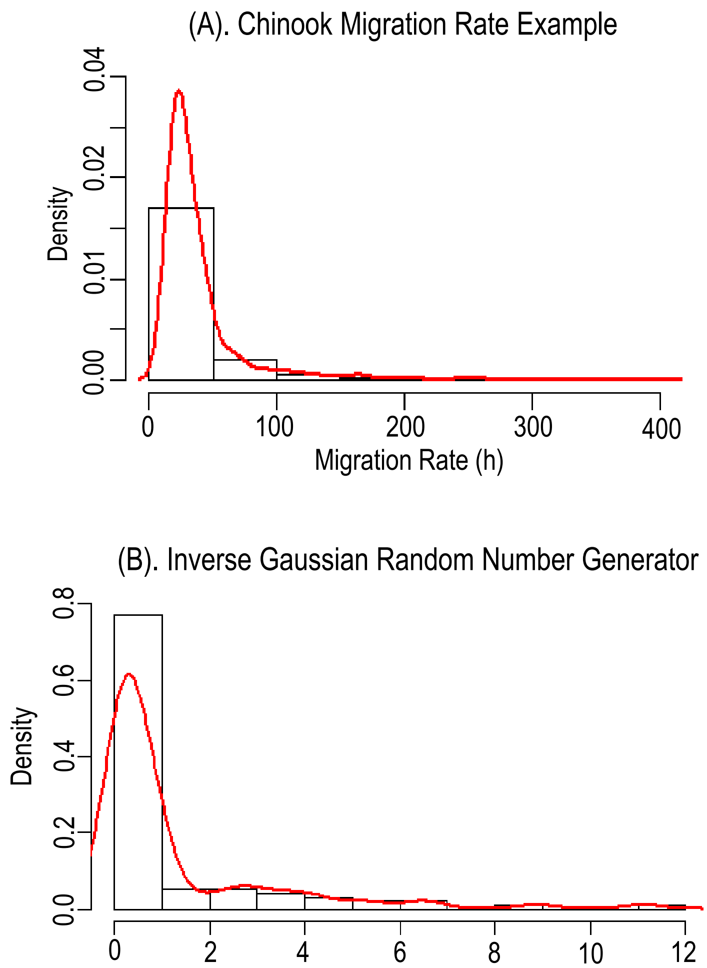

Figure 5: An example of an Inverse Gaussian error distribution. (A) Chinook salmon migration rate data through study reach 1 as density over time (h). (B) An Inverse Gaussian distribution made by a random number generator. Scales are different as these are different data sets with different parameters.

CHAPTER III

RESULTS

Passage Route Proportions

During the 2014 spring out-migration, the PRFB collected 47.2% of study steelhead and 38.1% of study Chinook salmon (Figure 6). The powerhouse, on the other hand, collected 30.9% of study steelhead and 34.9% of study Chinook salmon. The remaining steelhead (22.0%) and Chinook salmon (26.9%) passed through the spillway. In 2014, the observed passage proportions for steelhead ($\chi^2 = 123.69$, DF= 2, p-value= <0.0001) and Chinook salmon ($\chi^2 = 19.633$, DF= 2, p-value= <0.0001) were statistically different than the null expectation in which each Priest Dam route has an equal passage probability.

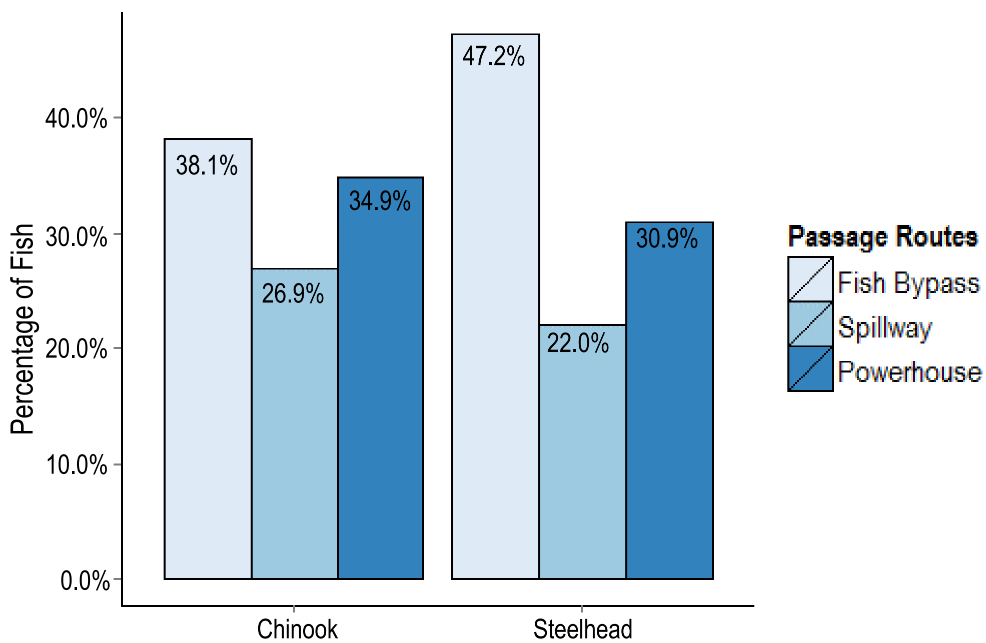

Figure 6. Passage percentages at Priest Rapids Dam in 2014. Displayed by species, steelhead and Chinook salmon, per route.

Passage Route Analysis

The steelhead and Chinook salmon passage route analysis indicated that forebay temperature, powerhouse discharge, spillway discharge, and forebay approach pattern significantly affected eventual route choice (Table 1). The final model, including all four retained variables, yielded a McFadden Psuedo R^2 value of 20.5% for steelhead and 31.6% for Chinook salmon.

Table 1: Steelhead and Chinook salmon results from likelihood ratio tests of nested models. Displayed below is the test statistic (*D*), the degrees of freedom (DF) and the associated p-value for each modeled variable.

	Steelhead			**Chinook Salmon**		
Variable	*D-statistic*	*DF*	*p-value*	*D-statistic*	*DF*	*p-value*
Forebay Temperature	11.02	2	0.0040**	8.04	2	0.01794*
Powerhouse Discharge	16.81	2	0.000223***	39.06	2	3.29e-09***
Spillway Discharge	10.96	2	0.004177**	59.7	2	1.09e-13***
Forebay Approach	379.55	2	< 2.2e-16***	568.66	2	< 2.2e-16***

An increase in forebay temperatures resulted in a higher probability of spillway passage for both study species (Figure 7). For Chinook salmon, bypass passage probability generally decreased in response to warmer forebay temperatures. Steelhead trends were mixed, and warmer forebay temperatures increased the probability of bypass passage in relation to the powerhouse.

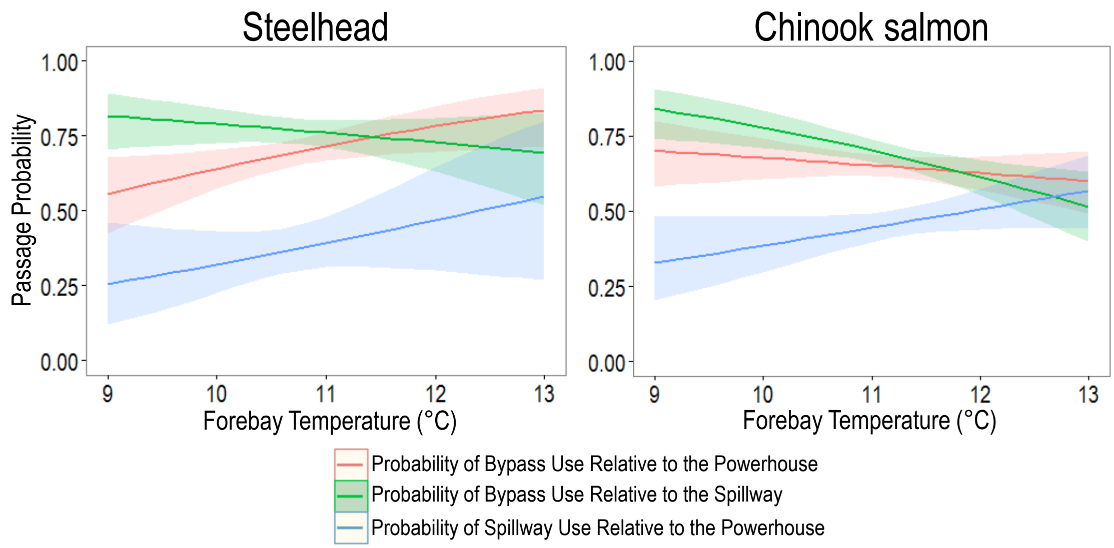

Figure 7: Passage probabilities in response to changes in forebay temperature (°C). Probability of steelhead (left) and Chinook salmon (right) bypass and spillway use in response to forebay temperature (°C), displayed as a comparison between two routes. Each passage relationship is plotted within 95% confidence intervals.

In general, as powerhouse discharge increased, the probability of powerhouse passage improved for both study species (Figure 8). Whereas increasing spillway discharge improved the probability of spillway passage for both study species (Figure 9). For steelhead specifically, the probability of bypass passage increased relative to the spillway in response to more powerhouse discharge. Additionally, increasing spillway discharge improved the probability of bypass passage relative to the powerhouse. Chinook salmon exhibited the opposite trend, where more spillway discharge decreased bypass passage relative to the powerhouse.

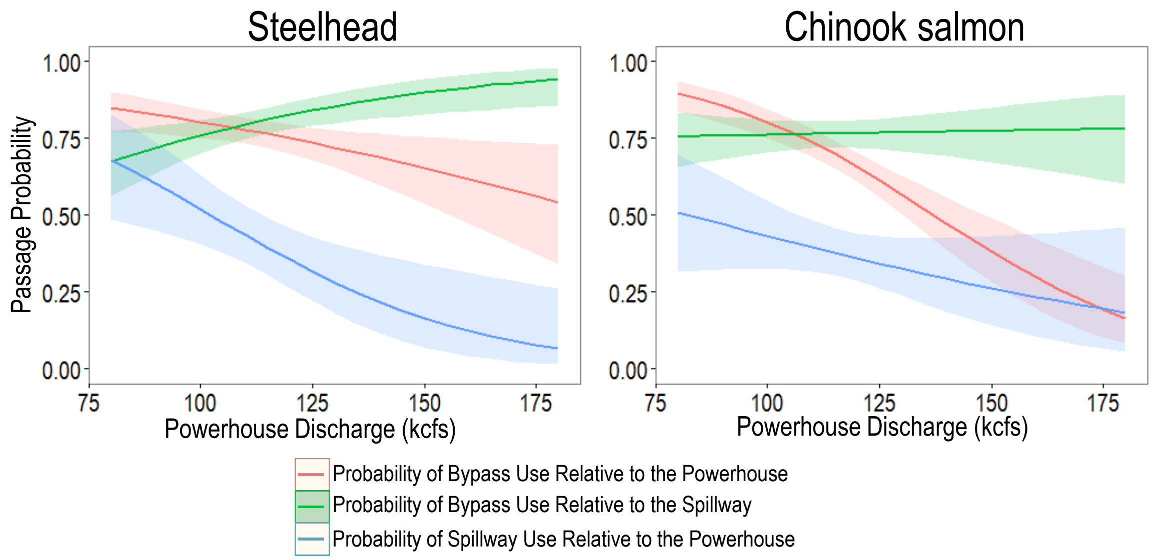

Figure 8: Passage probabilities in response to changes in powerhouse discharge (kcfs). Probability of steelhead (left) and Chinook salmon (right) bypass, powerhouse and spillway use in response to powerhouse discharge (kcfs) , displayed as a comparison between two routes. Each passage relationship is plotted within 95% confidence intervals.

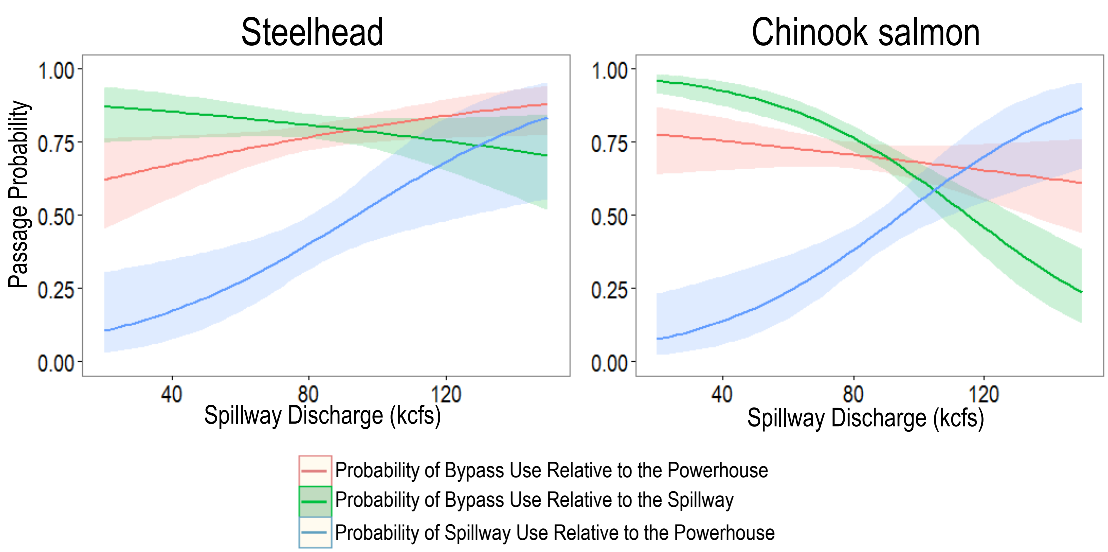

Figure 9: Passage probabilities in response to changes in spillway discharge (kcfs). Probability of steelhead (left) and Chinook salmon (right) bypass, powerhouse and spillway use in response to spillway discharge (kcfs), displayed as a comparison between two routes. Each passage relationship is plotted within 95% confidence intervals.

The most dramatic factor affecting both steelhead and Chinook salmon route choice was the forebay approach pattern (Figure 10). A low forebay approach number (an individual that entered the forebay from the west/spillway end) resulted in more bypass and more spillway passage relative to the powerhouse while a high forebay approach number (an individual that entered the forebay from the east/powerhouse end) resulted in more bypass and powerhouse passage relative to the spillway.

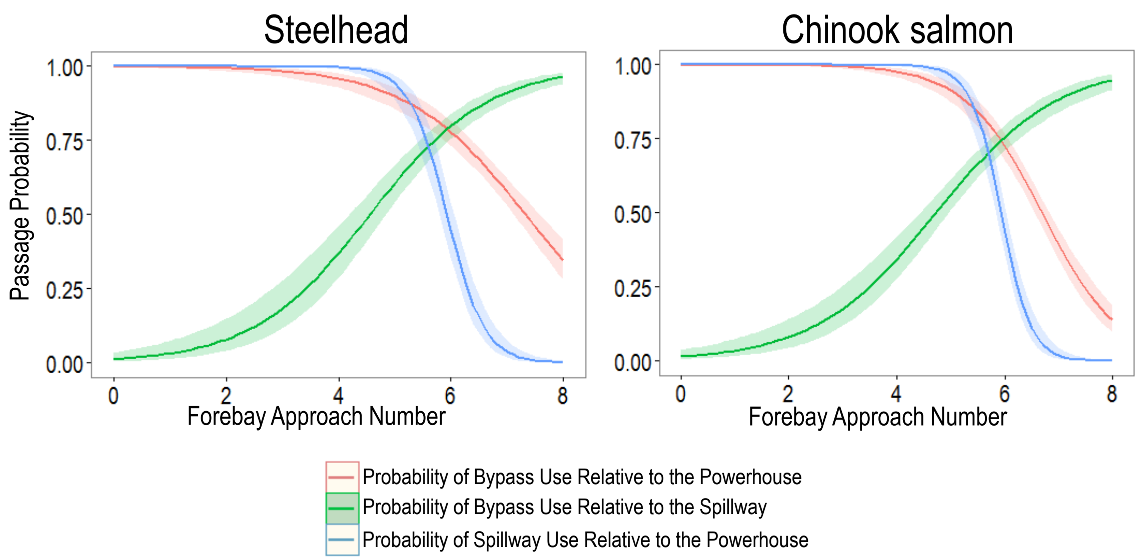

Figure 10: Passage probabilities in response to changes in forebay approach number. Probability of steelhead (left) and Chinook salmon (right) bypass, powerhouse and spillway use in response to forebay approach number, displayed as a comparison between two routes. Each passage relationship is plotted within 95% confidence intervals.

Downstream Survival

Priest Rapids Dam passage route was a notable variable affecting steelhead and Chinook salmon survival through reach 1 (Figure 11). Bypass mortality rates through reach 1 were lower than the alternative routes while the highest mortality was experienced by powerhouse route steelhead and Chinook salmon. Priest Rapids Dam route was a statistically significant predictor of survival through reach 1 for both steelhead (D = 25.28, DF= 2, p-value = 3.23e-06) and Chinook salmon (*D* = 30.62, DF= 2, p-value = 2.25e-07). The McFadden R^2 value through reach 1 was 10.5% for steelhead and 11.3% for Chinook salmon.

Steelhead and Chinook salmon mortality rates through reach 2 displayed minimal variability among the different Priest Rapids Dam passage routes (Figure 11). Priest Rapids Dam route was not a statistically significant predictor of survival through reach 2 for either species. Further downstream, Priest Rapids Dam route did not affect steelhead survival through reach 3. Chinook salmon survival through reach 3, however, was affected by Priest Rapids Dam route and this relationship was statistically significant (*D* = 18.37, DF= 2, p-value = 0.0001), with a McFadden R^2 of 10.2%.

Cumulative mortality through all downstream reaches was lowest for bypass route steelhead and Chinook salmon and highest for powerhouse route fish. This relationship was also statistically significant for both steelhead (*D* = 17.36, DF= 2, p-value = 0.0002) and Chinook salmon (*D* = 39.49, DF= 2, p-value = 2.67e-09). The McFadden R^2 value through all downstream reaches was 3.1% for steelhead and 8.7% for Chinook salmon.

Neither Wanapum Dam passage route nor release location were statistically significantly predictors of steelhead or Chinook salmon survival through any of the analyzed reaches below Priest Rapids Dam.

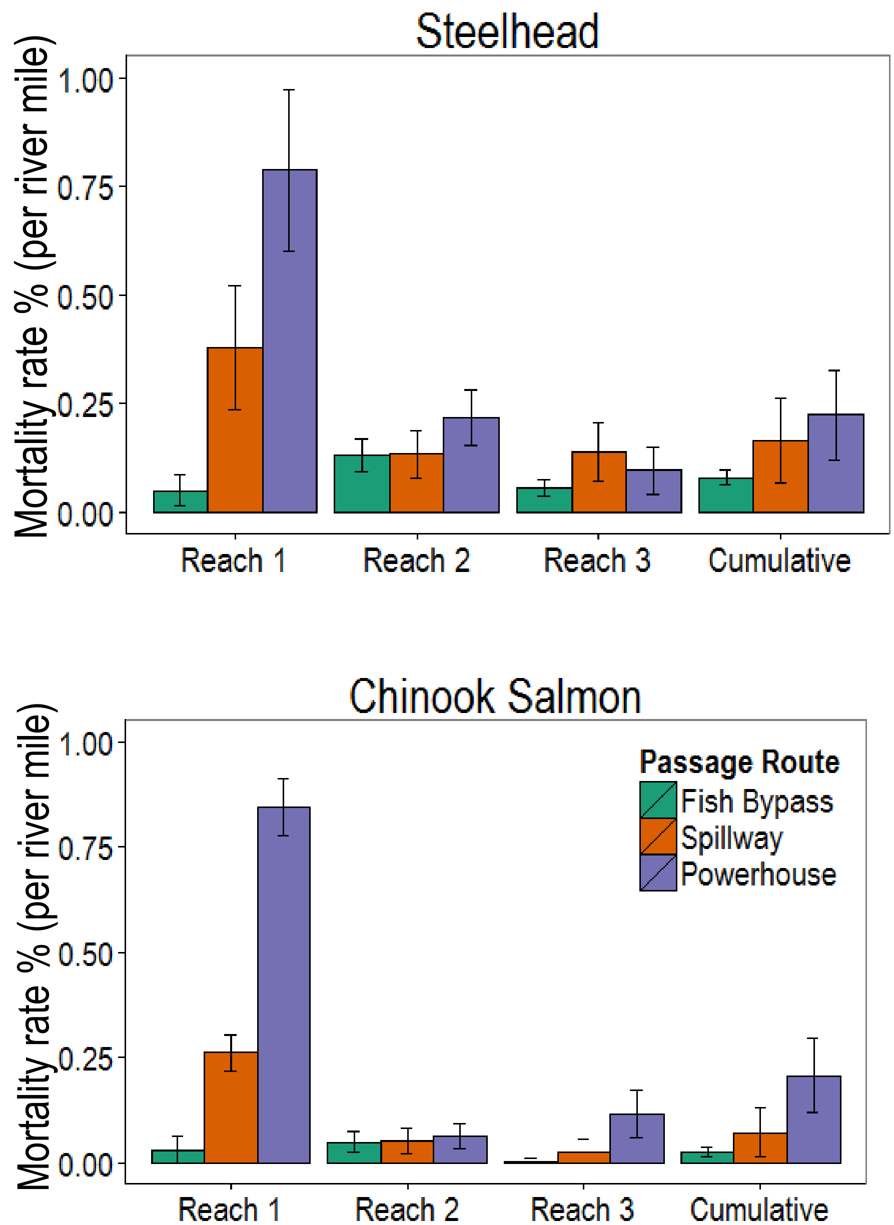

Figure 11: Steelhead (top) and Chinook salmon (bottom) mortality rates per river mile. Displayed with ±1 standard error and separated by reach and passage route. Reaches 1-3 were analyzed separately and non-cumulatively; while the reach labeled cumulative refers to all downstream reaches.

Downstream Migration Rate

Analysis of downstream migration rate revealed a pattern congruent with the survival results. Steelhead and Chinook salmon migration rates through reach 1 were fastest for bypass route fish and slowest for powerhouse route fish (Figure 12). Model selection identified Priest Rapids Dam route as a statistically significant predictor of migration rates through reach 1 for both steelhead (*D* = 593.4, DF= 2, p-value = <2.2e-16) and Chinook salmon (*D* = 446.92, DF= 2, p-value = <2.2e-16). The explained deviance (D^2) was 45.8% for steelhead and 36.3% for Chinook salmon.

Priest Rapids Dam route did not affect steelhead or Chinook salmon migration rates through reaches 2 or 3 (Figure 12). However, the cumulative analysis of all downstream reaches revealed Priest Rapids Dam route as a statistically significant predictor of migration rates for steelhead (*D* = 26.63, DF= 2, p-value = 1.63e-06) and Chinook salmon (*D* = 22.71, DF= 2, p-value = 1.17e-05). Bypass route steelhead and spillway route Chinook salmon migrated the fastest through the cumulative reaches (Figure 12). The McFadden R^2 for the cumulative analysis was only 2.9% for steelhead and 2.3% for Chinook salmon.

Similar to the survival analysis, Wanapum Dam passage route and release site were not statistically significant predictors of migration rate through any downstream reach.

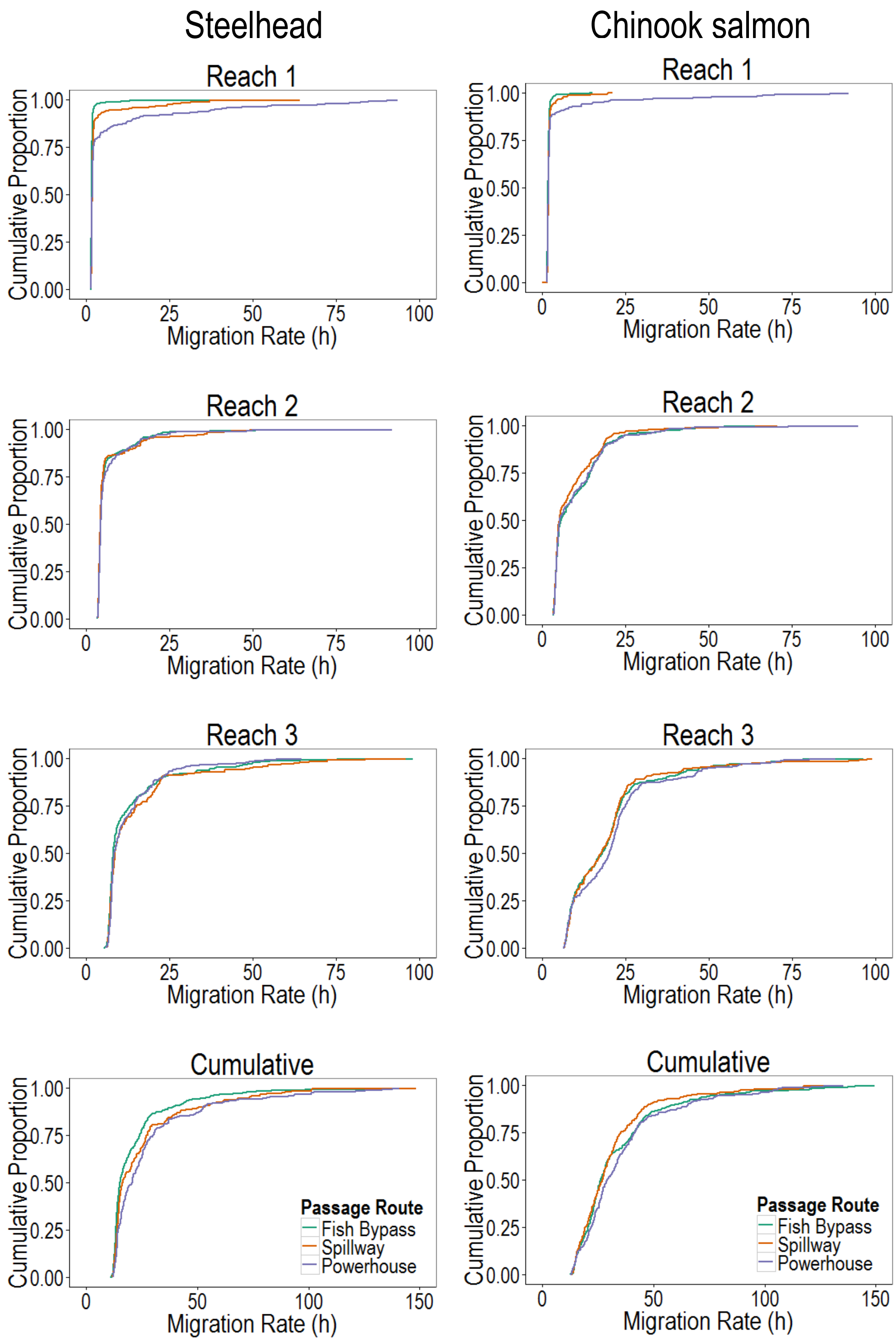

Figure 12: Steelhead (left) and Chinook salmon (right) migration rates. Displayed as the proportion of study fish that successfully migrating through each reach versus time. Notice that in these figures, the lines deviate primarily through reach 1; this signifies a notable difference in study fish migrations.

CHAPTER IV

DISCUSSION

Previous Columbia River research has consistently found that hydroelectric passage is an important factor when considering migratory juvenile salmonid survival. Specifically, passage through powerhouse structures increases salmonid mortality, so hydroelectric entities (including GCPUD) have spent millions of dollars to provide alternative passage routes that encourage fish to pass at non-turbine routes. In the mid-Columbia River, the PRFB was operated during its inaugural season in 2014 with these same objectives. Acoustic tag results from this study show reductions in downstream mortality, faster migration rates, and moderate fish collection efficiency associated with the bypass route; thus identifying the PRFB as an effective passage structure.

The PRFB collected a notable quantity of juvenile migrants (47.2% steelhead, 38.1% Chinook salmon) and the passage route analysis showed that forebay temperature, powerhouse discharge, spillway discharge and forebay approach patterns are significant drivers of passage route choice. Both multinomial models yielded relatively high McFadden R^2 values, with steelhead at 20.5% and Chinook salmon at 31.6%, which means the modeled variables account for a noteworthy portion of the observed variability in Priest Rapids Dam route choice.

For both species, the most notable predictor variable was forebay approach pattern, which heavily influenced passage choice. A model including forebay approach pattern as its only predictor variable had a 17.3% McFadden R^2 for steelhead and a 24.0% McFadden R^2 for Chinook salmon. The results from the approach pattern analysis show that fish entering from the low numbered data receivers (1-4 on the west end of the forebay) have a higher probability of using the bypass or the spillway, while fish that enter from the high numbered data receivers (6-8 on the east end of the forebay) have a higher probability of passing through the powerhouse. Migrating juvenile salmon frequently follow the dominant flow dynamic and are attracted by that downstream directionality (Haro et al. 1998; Kemp et al. 2012); therefore this correlation is likely the result of that well documented behavior.

Higher forebay temperatures contributed to more spillway use for both species. As forebay temperatures rise, migrating salmon might begin to behaviorally thermoregulate and seek refuge in cooler, deeper water (Sauter 2001; Brewitt and Danner 2014). Additionally, the spillway entrance is at the bottom of the forebay water column, possibly making this route more attractive to migrants under warm water conditions.

Changes in powerhouse and spillway discharge also affected passage trends. An increase in powerhouse discharge encouraged more powerhouse passage, while an increase in spillway discharge encouraged more spillway passage. However, a more nuanced effect in steelhead passage was also seen in response to fluctuating powerhouse and spillway discharges. An increase in powerhouse discharge encouraged bypass use relative to the spillway and more spillway discharge encouraged more bypass use relative to the powerhouse. It is possible that the powerful flow output of either the spillway or powerhouse attracts steelhead in that general direction, but while traveling towards these respective routes they enter the attractive top-spill influence of the fish bypass and pass through that route instead. Discharge through the fish bypass, interestingly, did not significantly contribute to passage trends for either species. Flows through the bypass remained relatively constant at 26.8 ± 2.6 kcfs for the duration of the season while the powerhouse and spillway operations fluctuated more noticeably, at 112.8 ± 16.5 kcfs and 86.9 ± 22.3 kcfs.

Upper Columbia River stocks of juvenile steelhead and Chinook salmon experience an arduous migration to their ocean feeding grounds that includes the need to safely pass at least seven major hydroelectric impediments. Each dam passage can cause direct mortality, but indirect mortality may also occur (Mighetto and Ebel 1994, Muir et al. 2001). For example, if smolts become disoriented by dam passage, they may become more vulnerable to predation which would lead to mortality after successful dam passage (Mighetto and Ebel 1994, Muir et al. 2001). This study was unable to differentiate between direct and indirect mortality through reach 1 immediately below the dam. However, statistical differences in passage route survival through reaches 2 and 3 would indicate an indirect mortality event and the possibility of lingering passage effects. Steelhead survival through reaches 2 and 3 was not affected by Priest Rapids Dam route. Chinook salmon survival through reach 2 was also not affected by Priest Rapids Dam route but survival through reach 3 was, implying the existence of lingering passage effects. These effects, however, are minor in relation to the pronounced mortality rates that occur immediately following passage, i.e. through reach 1. The Wanapum Dam passage event also displayed no correlation with survival rates below Priest Rapids Dam. Therefore, these findings collectively suggest that each dam represents a largely independent and unique passage challenge for out-migrating fish.

More specific to individual routes, downstream survival and mortality rates (per river mile) revealed that the Priest Rapids Fish Bypass was the ideal passage route in 2014. Bypass mortality rates through reach 1 remained <0.06% for both species while spillway mortality was estimated at 0.38% and 0.26% for steelhead and Chinook salmon, respectively. Furthermore, powerhouse passage had the highest mortality rate through reach 1 with a steelhead estimate of 0.79% and a Chinook salmon estimate of 0.84%.

Survival modeling results described Priest Rapids Dam route as a significant variable for both species but yielded low McFadden R^2 values (steelhead = 3.1%-10.5%, Chinook salmon = 8.7%-11.3%). The relatively low R^2 values imply that the model does not account for other significant predictor variables that could comprehensively describe variation in downstream survival. Some of the missing variables may be those related to juvenile salmon predation. Evans et al. (2012) found that avian predators, more specifically Caspian Terns *(Hydroprogne caspia*), are a significant factor in the Columbia River, and they prey on between 2.5%-16% of migrating juvenile steelhead and Chinook salmon. Additionally, aquatic predators such as northern pikeminnow, smallmouth bass (*Micropterus dolomieu*) and walleye (*Sander vitreus*) have been known to contribute heavily to juvenile salmon mortality in impeded waterways, with recorded predation rates of 7-11% in the John Day Reservoir (Rieman et al. 1991, Ward et al. 1995, Vigg et al. 1991).

Faster juvenile salmon migration rates correlate with increased survival (Faulkner et al. 2007, Muir et al. 2001, Thompson et al. 2012), and I observed that fish using the bypass in 2014 experienced faster migration and increased survival through reach 1. Ninety-seven percent of the steelhead and Chinook salmon that used the bypass migrated through reach 1 in under 3 hours. This result is in contrast to powerhouse route fish where only 77% of steelhead and 88% of Chinook salmon migrated through reach 1 in under 3 hours. The explained deviances (Psuedo R^2) of steelhead and Chinook salmon migration rates through reach 1 were 45.8% and 36.2%, respectively. Therefore, passage route choice affected steelhead migration rates more strongly than Chinook salmon migration rates. Additionally, Priest Rapids Dam route passage was not related to migration rates through reaches 2 and 3, which further indicates that the immediate effects of dam passage are most important in the first nine miles directly following the passage event.

Hydroelectric impediments are a reality of the modern Columbia River ecosystem, and the associated anthropogenic effects on salmon survival are a concern for commercial, sport, and subsistence fisheries as well as for cultural persistence for mid-Columbia indigenous people. Modeling results herein concur with previous research and show that juvenile salmon passage route through hydroelectric impediments is a significant factor affecting downstream survival and migration rates. This analysis shows that the effect of Priest Rapids Dam route passage is most significant in the initial reach following dam passage and that lingering effects of passage events appear minimal. The design and construction of the Priest Rapids Fish Bypass improved smolt survival and downstream migration rate, reducing the anthropogenic footprint of this hydroelectric impediment on migrating juvenile salmon for future downstream migrations of juvenile salmonids. Increasing the number of similarly designed bypass structures throughout the Columbia River Basin and increasing the collection efficiency of those already constructed would likely positively impact successful passage rates and contribute to higher cumulative survival rates of out-migrating juvenile salmon.

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