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# Survival of Wild Hanford Reach and Priest Rapids Hatchery Fall Chinook Salmon Juveniles in the Columbia River: Predation Implications

**October 2014**

RA Harnish  
ED Green  
KA Deters  
KD Ham  
Z Deng

H Li  
B Rayamajhi  
KW Jung  
GA McMichael

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Pacific Northwest National Laboratory  
Richland, Washington 99352

<sup>1</sup>Mainstem Fish Research, 65 Park St., Richland WA 99354



## Abstract

The population of fall Chinook salmon that inhabits the Hanford Reach comprises the majority of the Columbia Upriver Bright (URB) stock and is one of the most productive Chinook salmon stocks in the Pacific Northwest. Recent studies indicated that much of the high productivity of the population may be attributed to very high survival during early freshwater life stages within the Hanford Reach. However, some evidence suggests significant mortality of smolts occurs over a short period of time and distance as they migrate from the Hanford Reach to McNary Dam. Large populations of piscivorous fishes and birds inhabit the Columbia River and may be responsible for this mortality. We implanted 200 wild Hanford Reach and 200 Priest Rapids Hatchery (PRH) URB fall Chinook salmon with acoustic transmitters and estimated their survival through multiple reaches of the Columbia River to identify mortality “hot spots” and to help classify the putative source(s) of mortality.

Acoustic-tagged wild Hanford Reach fall Chinook salmon had an estimated survival probability of 0.50 from release to McNary Dam. This estimate is considerably higher than was observed in 2014 for the group of wild Hanford Reach fall Chinook salmon juveniles implanted with passive integrated transponders (PIT-only;  $S = 0.34$ ). The large discrepancy between survival estimates derived from acoustic-tagged versus PIT-only groups is likely a result of the difference in fish size between groups. We attempted to minimize the effect of the transmitter on the performance of implanted fish by only tagging fish that measured  $\geq 80$  mm FL; whereas, fish as small as 60 mm FL were implanted with PIT tags. As we demonstrated, survival of these fish is strongly, positively correlated with fish length. Therefore, we expect that the survival of the overall population of juvenile wild Hanford Reach fall Chinook salmon through the study area was substantially lower than it was for acoustic-tagged fish. However, we believe that the relative losses of tagged fish by reach were representative of the overall population.

Acoustic-tagged PRH smolts also had an estimated survival probability of 0.50 from release to McNary Dam; albeit over a longer reach than was traversed by the wild group. This estimate is substantially lower than what was observed for PIT-only PRH smolts in 2014 ( $S = 0.66$ ). The difference in survival between groups of acoustic-tagged and PIT-only PRH fall Chinook salmon juveniles may have been the result of a reduction in performance of acoustic-tagged fish caused by the tagging procedure or presence of the tag, and/or a result of acoustic transmitter loss (i.e., tag shedding). Although results from a 60-day laboratory study conducted at PNNL found a very high rate of fish survival (99.2%) and tag retention (100%) of 126 fish implanted with the same transmitter and surgical technique, we observed relatively high post-tagging, pre-release mortality for the group of PRH fall Chinook salmon we implanted with acoustic transmitters for the in-river survival evaluation described in this report.

Because reaches differed in length, survival is better compared among reaches on a per-kilometer basis to identify potential mortality “hot spots”. Survival-per-kilometer ( $S_{km}$ ) was generally lower in the transition area between the Hanford Reach and McNary Reservoir, within McNary Reservoir, and in the upper half of John Day Reservoir (down to Crow Butte) than in reaches located downstream of Crow Butte. The lowest  $S_{km}$  was observed in the immediate forebay of McNary Dam for both wild and hatchery fish. As expected, travel rates were fastest in flowing reaches (i.e., Hanford Reach and dam tailraces) and slowest through reservoirs. We observed a significant, positive relationship between the probability of survival to McNary Dam and fish length.

Data from this study and others indicate much of the mortality incurred by URB fall Chinook salmon juveniles between Priest Rapids and Bonneville dams can likely be attributed to predation from resident piscivorous fish. Analyzing 8 years of data, we observed no significant relationship between the survival of PIT-only wild Hanford Reach fall Chinook salmon to McNary Dam and the size of the primary avian predator nesting colonies located in McNary Reservoir. We also did not observe mortality “hot spots” in the reaches of the Columbia River that contain the largest colonies of predaceous waterbirds. Instead, we observed relatively consistent mortality rates between release and Crow Butte, which is more indicative of predation from piscivorous fish, which are more widely distributed than avian predators. In addition, results of studies conducted to assess avian predation rates have consistently estimated very low predation rates (<2%) on subyearling fall Chinook salmon upstream of Bonneville Dam. Alternatively, predation rates estimated for piscivorous fish suggest they may be consuming 17% of the juvenile salmon that enter John Day Reservoir during June, July, and August, when most salmon smolts entering the reservoir are subyearling fall Chinook salmon.

Our study confirmed that the loss rates of juvenile URB fall Chinook salmon from the Hanford Reach were high in areas where habitat has been influenced by hydropower development and native and non-native predatory fish species. Whereas our study had some limitations due to 1) the size of fish we were able to tag, 2) the potential for a tag or tagging effect on fish performance, and 3) possible tag loss, we believe that the relative loss rates are representative for the wild Hanford Reach and Priest Rapids Hatchery portions of the URB stock. Much of the mortality appears to be concentrated in the river/reservoir transition area where large predator-rich tributaries enter as well as in the immediate dam forebays where travel rates of outmigrating smolts are slowed. Additional work to document how the predation rates we observed in the larger size classes of juvenile URB fall Chinook salmon relate to the overall population, as well as efforts to determine the potential effectiveness of management actions intended to reduce the populations and/or productivity of piscivorous fish species will provide the information necessary to enable managers to design and implement strategies to improve the freshwater survival of this important stock.

## Acknowledgments

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## Acronyms and Abbreviations

AABM	Aggregate Abundance Based Management
ATLAS	Acoustic Tag Life Adjusted Survival
CJS	Cormack-Jolly-Seber
CR	Columbia River
CRITFC	Columbia River Inter-Tribal Fish Commission
DOE	Department of Energy
FCRPS	Federal Columbia River Power System
FL	fork length
HR	Hanford Reach
HRFCPPA	Hanford Reach Fall Chinook Protection Program Agreement
JBS	juvenile bypass systems
JDA	John Day
JSATS	Juvenile Salmon Acoustic Telemetry System
MCN	McNary
NPM	northern pikeminnow
ODFW	Oregon Department of Fish and Wildlife
PIT	passive integrated transponder
PNNL	Pacific Northwest National Laboratory
PRD	Priest Rapids Dam
PRH	Priest Rapids Hatchery
PRI	pulse rate interval
SMB	smallmouth bass
TDA	The Dalles
URB	Upriver Bright
VBASA	Vernita Bar Settlement Agreement
WAL	walleye
WDFW	Washington State Department of Fish and Wildlife

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# 1.0 Introduction

The population of fall Chinook salmon *Oncorhynchus tshawytscha* that inhabits the Hanford Reach comprises the majority of the Columbia River Upriver Bright (URB) stock and is one of the most productive Chinook salmon stocks in the Pacific Northwest (Peters et al. 1999; Langness and Reidinger 2003; Harnish et al. 2012, 2013). As such, it is able to sustain high rates of harvest and therefore has great economic and cultural importance to native peoples and commercial and recreational fishers. The URB stock is a far north-migrating stock and is an important contributor to all three Aggregate Abundance Based Management (AABM) fisheries and a primary contributor to Columbia River fisheries.

Recent studies have indicated that much of the high productivity of the population may be attributed to very high survival during early freshwater life stages. In fact, results from a cohort reconstruction indicated that nearly two-thirds (65%) of the broods from 1975 through 2004 that displayed above-average egg-to-presmolt survival also had above-average adult/spawner production. Thus, Hanford Reach fall Chinook salmon brood year strength appears to be largely determined by interannual variation in freshwater survival, indicating the importance of the freshwater life phase to the overall productivity of the population. Enactment of operational constraints to limit discharge fluctuations downstream of Priest Rapids Dam have resulted in increased productivity and egg-to-pre-smolt survival rates. Harnish et al. (2014) observed a 217% increase in egg-to-pre-smolt productivity (Ricker  $\alpha$ ) that corresponded with constraints enacted by the Vernita Bar Settlement Agreement (VBSA), which limited redd dewatering, and an additional 130% increase that coincided with enactment of the interim Hanford Reach Fall Chinook Protection Program Agreement (HRFCPPA) in 1999, which limited stranding and entrapment of juveniles. Additionally, the average egg-to-pre-smolt survival probability estimate increased from 0.30 during the pre-VBSA period (brood years [BY] 1975–1983) to 0.36 during the period of the VBSA (BY 1984–1998) to 0.42 during the HRFCPPA period (BY 1999–2004<sup>1</sup>). In addition, a study conducted in 2012 estimated the egg-to-fry survival of fall Chinook salmon to be 71% in the Hanford Reach (Oldenburg et al. 2012). The survival rates discovered during these studies for the Hanford Reach population are much higher than those reported for other populations of Chinook salmon. From 215 published and unpublished estimates for wild or naturally rearing populations of Chinook salmon, Quinn (2005) calculated a mean egg-to-fry survival of 38% and a mean egg-to-smolt survival of 10%.

Although egg-to-pre-smolt survival has been found to be very high for the Hanford Reach fall Chinook salmon population, survival from pre-smolt to age-3 adult equivalent averaged just 0.29% for BY 1986–2004. Some evidence suggests significant mortality of smolts occurs over a short period of time and distance as they emigrate from the Hanford Reach to McNary Dam. Survival from release in the Hanford Reach to McNary Dam has averaged just 37% since 1995 for PIT-tagged wild fall Chinook salmon juveniles (Fish Passage Center 2013). Annual losses of this magnitude represent an obvious bottleneck to production.

Large populations of piscivorous fishes, such as smallmouth bass *Micropterus dolomieu*, northern pikeminnow *Ptychocheilus oregonensis*, walleye *Sander vitreus*, and channel catfish *Ictalurus punctatus* inhabit the Columbia River along with nesting colonies of avian predators, such as terns, cormorants,

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<sup>1</sup> The Priest Rapids Project is currently operated under the HRFCPPA. The productivity analysis conducted by Harnish et al. (2012, 2013) included BY 1975–2004.

gulls, and pelicans. The objective of this study was to estimate survival of acoustic-tagged Hanford Reach fall Chinook salmon juveniles through multiple reaches of the Columbia River to identify mortality “hot spots” and help to classify the putative source(s) of mortality (i.e., fish or birds).

## 2.0 Materials and Methods

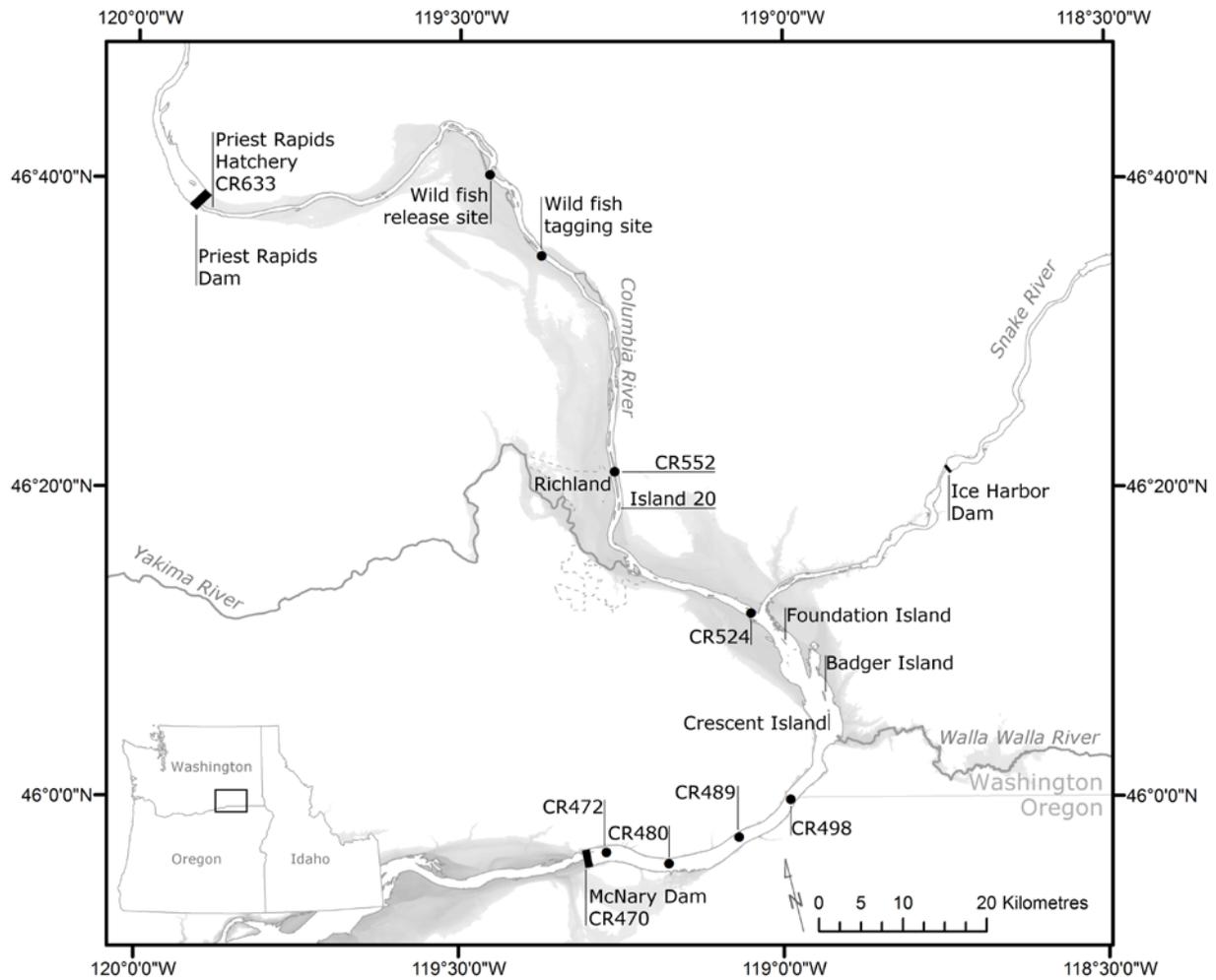
### 2.1 Fish Collection, Tagging, and Release

#### 2.1.1 Fish Collection and Holding

##### *Wild Hanford Reach fall Chinook salmon*

Wild fall Chinook salmon juveniles were collected from multiple locations in the Hanford Reach during the first week of June 2014 by Columbia River Inter-Tribal Fish Commission (CRITFC) personnel using stick and beach seines (4.8 mm mesh size). Seining was conducted in sections of the river with moderate velocity and 0.3 m to 1.4 m depth that were primarily located upstream of the tagging site at the Hanford town site boat ramp (river kilometer [rkm] 582; as measured from the mouth of the Columbia River) to reduce the likelihood of re-capturing previously tagged fish (Figure 2.1).

Captured wild fall Chinook salmon juveniles were temporarily placed into 19-L plastic buckets before being transferred to the oxygen-aerated holding tank of the boat. Once a full load of approximately 10,000 fish had been captured, or, more commonly, until about three hours had passed, the fish were transported to the tagging site located at the Hanford town site boat ramp. Fish were then transported from the boat in the 19-L plastic buckets to a 0.9 m × 0.9 m × 4.9 m fiberglass tank equipped with a pump to provide a continuous flow of river water. Fish that measured  $\geq 80$  mm fork length (FL) were held separately from smaller fish in four partially-perforated 76-L buckets within the fiberglass tanks. Captive fish were not directly fed; however, they did have access to organisms present in the river water. On June 5, 2014, surgical candidates were netted from the perforated holding buckets in batches of 20 to 50 and transferred in a 38-L bucket to the mobile tagging trailer.



**Figure 2.1.** Map of the Columbia River from Priest Rapids Dam to McNary Dam. Locations of cabled and autonomous acoustic telemetry receiver arrays deployed in 2014 are shown as a concatenation of “CR” and the river kilometer (as measured from the mouth of the Columbia River) at which they were deployed. Other locations of interest are also shown: these include the tagging and release location for acoustic-tagged wild Hanford Reach fall Chinook salmon juveniles; and the islands that host avian predator nesting colonies.

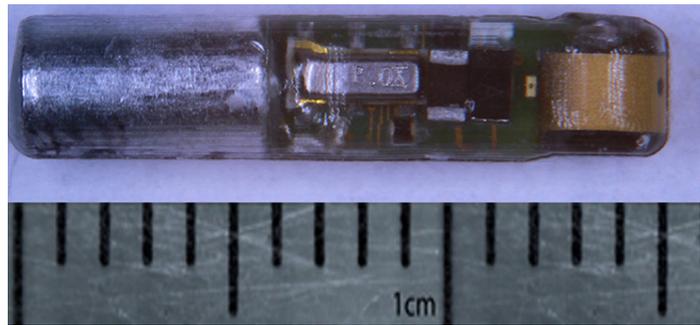
*Priest Rapids Hatchery fall Chinook salmon*

Hatchery URB fall Chinook salmon juveniles were reared at the Priest Rapids Hatchery (PRH) from the time of spawning until release to the river in June 2014. The hatchery is located along the bank of the Columbia River immediately downstream of Priest Rapids Dam and is operated by Washington State Department of Fish and Wildlife (WDFW) and owned by the Public Utility District No. 2 of Grant County, Washington. Prior to tagging, juvenile hatchery fall Chinook salmon were held at PRH in a concrete raceway supplied with a continuous flow of river water. Food was withheld for 24 h prior to tagging. On May 28, 2014, surgical candidates were netted from the raceway and transferred to the mobile tagging trailer in a 38-L plastic bucket in batches of 20 to 50 fish.

### 2.1.2 Transmitter Specifications

All Chinook salmon were implanted with an acoustic transmitter and a passive integrated transponder (PIT). The mean dimensions of the downsized Juvenile Salmon Acoustic Telemetry System (JSATS) acoustic transmitter (developed by the U.S. Army Corps of Engineers and Pacific Northwest National Laboratory [PNNL]; Chen et al. 2014) were 15.0 mm long by 3.3 mm in diameter (Figure 2.2).

Transmitters had a mean weight in air of 0.22 g, a mean weight in water of 0.11 g, and a mean volume of 0.11 mL. The transmitters had a nominal pulse rate interval (PRI) of one complete transmission every 3 seconds with a source level of 155–156 dB. The nominal transmitter life was expected to be about 60 days. The PIT tag (Model HPT12, Biomark, Inc., Boise, Idaho) was 12.5 mm long, 2 mm wide, and weighed 0.10 g in air (0.06 g in water; 0.04 mL volume; 134.2 kHz). The combined weight of the tags gave each implanted fish an added burden of 0.32 g in air.



**Figure 2.2.** Photo of the Juvenile Salmon Acoustic Telemetry System (JSATS) acoustic transmitter implanted in juvenile fall Chinook salmon in the Hanford Reach and at Priest Rapids Hatchery in 2014. The transmitter is shown next to a metric ruler to display the size of the transmitter.

### 2.1.3 Tagging Procedure

After surgical candidates were delivered to the mobile tagging trailer, they were anesthetized in batches of 2-3 fish. A dose of 80 mg/L of tricaine methanesulfonate (MS-222; buffered with 80 mg/L of sodium bicarbonate) was used to sedate juvenile Chinook salmon to stage 4 anesthesia (as described by Summerfelt and Smith 1990). The FL and weight of sedated fish were obtained as the acoustic transmitter and PIT tag codes were assigned. Only fish that measured  $\geq 80$  mm FL were selected for this study based on results from a 60-day laboratory study conducted at PNNL that found a very high rate of fish survival (99.2%) and tag retention (100%) of fish implanted with both a PIT tag and downsized JSATS transmitter ( $n = 126$  fish) using the same surgical technique described below.

An anesthetized fish and tags were delivered to one of two surgeons. The fish was placed on its left side in a small pool of water on a foam pad lubricated with PolyAqua, a water conditioner. The surgeon then made a shallow incision 3 mm in length with a sterile #11 surgical blade approximately 3-5 mm away from the linea alba and beneath the distal end of the pectoral fin. The PIT tag was then inserted through the incision into the peritoneal cavity. With the subsequent insertion of the acoustic transmitter, there was an attempt by the surgeon to get the two tags side-by-side (not end-to-end), by slightly changing the angle of insertion, with the intent to reduce the likelihood of tag expulsion through the open wound. In addition, the wound was gently massaged posteriorly, to ensure the tags were completely inside the peritoneal cavity and to move them away from the incision opening. Immediately, the tagged fish was

placed in a recovery bucket filled with aerated river water. The entire surgical process took approximately 20 to 30 s per fish. The same two surgeons tagged all fish in the wild Hanford Reach and Priest Rapids Hatchery groups; each surgeon tagged half of each group.

#### **2.1.4 Recovery, Holding, and Release**

##### *Wild Hanford Reach fall Chinook salmon*

Following implantation, the 200 acoustic-tagged wild Hanford Reach fall Chinook salmon juveniles were held at densities of less than 5 g/L in four partially-perforated 76-L buckets that were placed into a 0.9 m × 0.9 m × 4.9 m fiberglass holding tank equipped with a pump to provide a continuous flow of river water. The buckets remained in the holding tank for about 24 hours until the day of release (June 6) when they were loaded into a trailered boat and transported with continuous aeration to the White Bluffs boat launch (rkm 595; Figure 2.1). The dissolved oxygen and water temperature in the buckets were measured with an YSI meter before and during transport to ensure these metrics stayed within acceptable limits. Once at the ramp, the boat was launched and maneuvered downstream 0.5 km to the release location. Equal numbers of fish were released at four locations along a line transect across the river. Before release, buckets were checked for dead fish and dropped tags then each bucket was submerged in the water so that fish could swim out on their own volition.

##### *Priest Rapids Hatchery fall Chinook salmon*

After each group of PRH fall Chinook salmon juveniles were implanted with transmitters and had recovered from surgery, they were placed in one of four partially-perforated 76-L buckets that were suspended in the concrete raceway. The 200 tagged fish recovered at densities less than 5 g/L for approximately 24 hours, at which time holding buckets were removed from the raceway and inspected for dead fish and dropped tags. The buckets were taken to the adjacent channel pond and submerged in the water so that fish could swim out on their own volition. Tagged hatchery Chinook salmon resided in the channel pond for a full two weeks before releases of all fish in the channel ponds began with the removal of the pond gates on June 12, 2014. However, acoustic-tagged juveniles were detected on PIT and acoustic receiver arrays migrating from the outflow channel between June 12 and 21, 2014.

## **2.2 Site Description and Array Locations**

The area of the Columbia River between Priest Rapids and McNary dams defines the primary study area. However, data collected opportunistically from reaches of the Columbia River located between McNary and The Dalles dams are also presented. The array locations used in this study were chosen to differentiate survival among important reaches of the river and were selected because the associated river characteristics allow for good detection of acoustic tags. This section provides details about where detection arrays were deployed.

### **2.2.1 Site Description**

The Hanford Reach, an 80-km stretch of river located between Priest Rapids Dam (river kilometer [rkm] 639) and the head of McNary Reservoir (rkm 557) near the town of Richland, Washington, is the last segment of the Columbia River that has not been inundated, dredged, or channelized (Whidden 1996)

and is available to anadromous salmonids (Figure 2.1). As such, the Hanford Reach contains the only remaining substantial mainstem spawning area for fall Chinook salmon in the Columbia River (Bauersfeld 1978; Chapman et al. 1986; Dauble and Watson 1997).

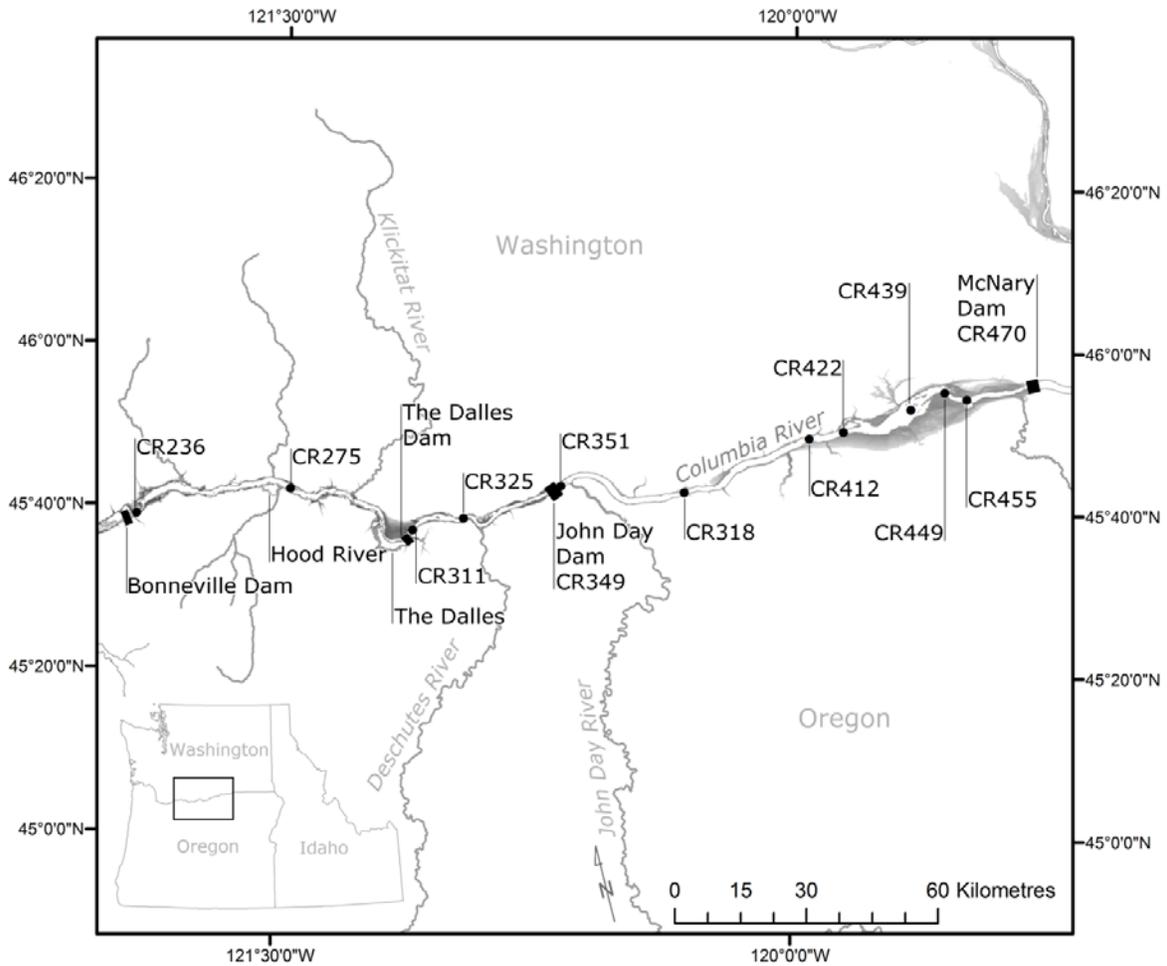
Three major tributaries, the Yakima, Snake, and Walla Walla rivers flow into the Columbia River in McNary Reservoir. The Yakima River flows into McNary Reservoir at rkm 538, near the town of Richland, Washington. The Yakima River has been identified as a major spawning area for smallmouth bass of the Columbia River (Fritts and Pearsons 2004). The Snake River flows into McNary Reservoir at rkm 522 and the Walla Walla River enters McNary Reservoir at rkm 505. Between the mouths of these two rivers are three islands used as nesting and roosting sites by multiple piscivorous water bird species. These include a nesting colony of cormorants on Foundation Island at rkm 518, a nesting colony of pelicans on Badger Island at rkm 510, and nesting colonies of terns, gulls, and herons on Crescent Island, a manmade island constructed of dredge spoils, at rkm 508 (Antolos et al. 2004, 2005; Evans et al. 2012).

## **2.2.2 Acoustic Receiver Locations**

Acoustic transmissions from tagged fish were decoded by stationary JSATS autonomous receivers (Model N201, Sonic Concepts, Inc., Bothell, Washington; and SR5000 Trident, Advanced Telemetry Systems, Inc., Isanti, Minnesota), which were deployed via the methods described by Titzler et al. (2010). In total, autonomous acoustic telemetry receivers were deployed at 48 locations between the head of McNary Reservoir (near the town of Richland, Washington) and McNary Dam and at 94 locations between McNary and Bonneville dams during the outmigration of fall Chinook salmon juveniles (June 6 to August 1). The majority of these receivers ( $n=133$ ) were deployed for studies funded by the U.S. Army Corps of Engineers, but data were made available for analyses for this predation loss assessment. Receivers were deployed in lines, referred to as arrays, which ran approximately perpendicular to the shore. Based on their effective detection range, receivers were spaced about 100 to 200 m apart.

A total of six autonomous receiver arrays were deployed upstream of McNary Dam and an additional 12 arrays were deployed downstream of McNary Dam (Figures 2.1 and 2.3; Table 2.1). JSATS acoustic transmissions were detected and decoded by these receiver arrays and used to estimate survival and travel times of acoustic-tagged natural-origin Hanford Reach and PRH fall Chinook salmon juveniles in the reaches located between the arrays.

In addition to the autonomous receivers deployed to detect acoustic-tagged fish in the Columbia River, cabled JSATS receiver systems (Weiland et al. 2011) were deployed in the PRH outflow channel and on the face of McNary and John Day dams for dam passage survival studies conducted by PNNL for the U.S. Army Corps of Engineers. The deployment of hydrophones along the dam faces generally followed the design and methodology described by Deng et al. (2011). Prior to field deployment, all autonomous and cabled receivers were calibrated in an acoustic tank located at the PNNL Bio-Acoustics and Flow Laboratory, which is accredited by the American Association for Laboratory Accreditation (Deng et al. 2010). Detections of acoustic-tagged fall Chinook salmon juveniles on autonomous and dam face systems were used for estimation of reach survival and travel times.



**Figure 2.3.** Map of the Columbia River from McNary Dam to Bonneville Dam. Locations of cabled and autonomous acoustic telemetry receiver arrays deployed in 2014 are shown as a concatenation of “CR” and the river kilometer (as measured from the mouth of the Columbia River) at which they were deployed.

**Table 2.1.** Locations of cabled and autonomous acoustic telemetry receiver arrays deployed in the Columbia River to detect JSATS acoustic transmitters during the spring and summer of 2014.

Array	Location	Latitude	Longitude	Autonomous or Cabled	# of Hydrophones
CR633	Priest Rapids Hatchery	46.637033	-119.878798	Cabled	4
CR552	Richland, WA	46.352325	-119.2610833	Autonomous	6
CR524	Snake River	46.19887143	-119.051	Autonomous	7
CR498	Port Kelly, WA	45.99767042	-118.9906672	Autonomous	8
CR489	Van Skinner Island	45.95559753	-119.0678685	Autonomous	9
CR480	Hat Rock	45.92761134	-119.1772737	Autonomous	10
CR472	McNary Dam forebay	45.9393581	-119.2732181	Autonomous	8
CR470	McNary Dam	45.93569206	-119.2974027	Cabled	89
CR455	Irrigon, OR	45.90591741	-119.4938649	Autonomous	6
CR449	Paterson, WA	45.92042962	-119.5584028	Autonomous	6
CR439	Boardman, OR	45.88502679	-119.6585717	Autonomous	10
CR422	Crow Butte	45.83856001	-119.8555434	Autonomous	7
CR412	Willow Lake	45.82475567	-119.9559078	Autonomous	8
CR381	Sundale, WA	45.71256584	-120.3204116	Autonomous	6
CR351	John Day Dam forebay	45.72255187	-120.6810192	Autonomous	8
CR349	John Day Dam	45.71583597	-120.6929465	Cabled	85
CR325	Wishram, WA	45.65323093	-120.9653195	Autonomous	18
CR311	The Dalles Dam forebay	45.62699729	-121.1126313	Autonomous	15
CR275	Bingen, WA	45.70758426	-121.472588	Autonomous	6
CR236	Bonneville forebay	45.64968612	-121.9202764	Autonomous	4

The cabled system deployed in the PRH outflow channel consisted of four hydrophones located in the deepest pool of the channel, which was located about 1.5 km downstream from the holding ponds and 1.1 km upstream from the mouth of the channel (Figure 2.4). A PIT array consisting of multiple antennas was also present in the outflow channel about 200 m upstream from the mouth of the channel. Detections of the double-tagged (acoustic + PIT) fall Chinook salmon juveniles on the cabled JSATS and PIT arrays were used to evaluate post-tagging/pre-release mortality and tag loss/failure and to estimate the number of tagged fish that actually left the hatchery with an active acoustic transmitter. Detections of double-tagged fall Chinook salmon in the juvenile bypass systems (JBS) of McNary and John Day dams were also used to evaluate acoustic tag loss/failure.



**Figure 2.4.** Google Earth image of Priest Rapids Dam that displays the channel pond in which acoustic-tagged fish were held following surgery and the cabled JSATS array (CR633) and PIT array that were located in the outflow channel to detect acoustic- and PIT-tagged fish as they migrated from the channel pond to the Columbia River.

## 2.3 Autonomous Receiver Data Processing and Validation

Signals received by JSATS receivers were processed and filtered to validate the presence of a tagged fish within the vicinity of a receiver at a specific time. Receivers recorded receptions of possible tag signals along with a timestamp for each reception. Raw files from autonomous receivers were time-corrected and files from both autonomous and cabled receivers were filtered to remove spurious receptions. The time series of validated locations for individual fish were then used to estimate survival rates and travel times. A laboratory study of tag-life was conducted to allow estimates to be corrected for early tag failures if necessary.

### 2.3.1 Time Correction

Some of the autonomous receivers used in this study were subject to clock errors that resulted in timestamps being incorrect at unpredictable times throughout the file. Raw files were processed through a time correction application to repair incorrect timestamps based upon correct timestamps that preceded it. In many cases, the algorithm precisely identified a correction that was accurate to the second, whereas in others, the correction resulted in a difference of a few seconds for the block of data being corrected. After time correction, the files are referred to as time-corrected files, whether or not a correction was needed and applied.

### 2.3.2 Filtering

Because JSATS autonomous receivers are configured to detect tag signals just above the acoustic noise floor, raw files often include spurious receptions that arise from noise in addition to valid tag signals (Ingraham et al. 2014). To filter out detections that did not meet criteria (false detections), a post-processing program was used (McMichael et al. 2010). This program comprised a sequence of steps that included comparing each detection to a list of tags that were released (only detections of tags that were released were kept), then comparing the detection date to the release data (only tags detected after they were released were kept). Then, a minimum of four detections in 60 seconds was required, and the time spacing between these detections had to match the PRI of the tag or be a multiple of the PRI for the detections to be kept in the valid detection file. This final filter takes advantage of the fact that spurious receptions do not exhibit the temporal consistency among pulses that is characteristic of an actively transmitting JSATS tag.

## 2.4 Tag-Life

For the tag-life study, 32 tags (3-s PRI) were randomly chosen over time from the manufacturing line of tags used in this study. All tag-life tags were enclosed in water-filled plastic bags and suspended from a rotating foam ring within a 2-m (diameter) fiberglass tank. Two  $90^\circ \times 180^\circ$  hydrophones were positioned  $90^\circ$  apart in the bottom of the tank and angled upward at approximately  $60^\circ$  to maximize coverage for detecting acoustic signals. Hydrophones were cabled to a quad-channel receiver that amplified all acoustic signals, which were then saved, decoded, and post-processed. Post-processing software calculated the number of hourly decodes for each acoustic tag, allowing tag failure times to be determined within  $\pm 1$  hour.

## 2.5 Survival Estimation

Survival estimates were derived from conventional statistical models for mark-recapture data (Cormack 1964; Jolly 1964; Seber 1965; Skalski et al. 1998). This model is known by various names, including Cormack-Jolly-Seber (CJS), Single-Release, or Single-Release-Recapture Model. For survival ( $S_i$ ) and detection ( $p_i$ ) probability estimation of mark-recapture data, detection data are summarized as the “detection history” for each marked fish. With only two opportunities for detection, the possible detection histories for tagged fish are:

00 = never detected;

10 = detected by the upstream (primary) array but not the downstream (secondary) array(s);

- 01 = detected by the downstream (secondary) array(s) but not by the upstream (primary) array;  
and
- 11 = detected by the upstream (primary) array and the downstream (secondary) array(s).

To estimate survival to the primary array for a release group of tagged fish, the number of fish in the group with each detection history is determined, denoted  $n_{00}$ ,  $n_{10}$ ,  $n_{01}$ , and  $n_{11}$ , along with the total number of fish released ( $R$ ). The proportion of fish detected on the primary array  $[(n_{10} + n_{11})/R]$  is an estimate of the joint probability that a fish survived from release to the primary array and that the fish was detected given that it survived. The joint probability of both events occurring is the simple product of the two probabilities.

To separate the two probabilities in the product requires a method to estimate either of the probabilities individually. The remaining probability can then be estimated by dividing the joint estimate by the estimate of the first. Detection probability of the primary array can be estimated independently by assuming that fish that survived to the secondary array and were detected there ( $n_{11} + n_{01}$ ) represent a random sample of all fish from the group that were alive as they passed the primary array. Detection probability of the primary array is then estimated as the proportion of the sample detected by the primary array (i.e.,  $n_{11}/[n_{11} + n_{01}]$ ).

The program ATLAS (Acoustic Tag Life Adjusted Survival; version 1.5.3; <http://www.cbr.washington.edu/analysis/apps/atlas>) and the methods described by Townsend et al. (2006) were used to adjust CJS survival estimates for the probability of premature tag failure. Preliminary tag-life data were fit with the two- and three-parameter Weibull models and the vitality model of Li and Anderson (2009). The model that provided the best fit to the tag-life data was used to adjust survival estimates by the conditional probability of a tag being active at each detection array.

Cumulative survival of acoustic-tagged PRH and wild Hanford Reach fall Chinook salmon was estimated from release to the each downstream detection array. For PRH fish, only those fish that were detected by the cabled JSATS receiver array located in the outflow channel were included in the estimate<sup>1</sup>. Survival was also estimated for each river reach located between receiver arrays by forming a “virtual release” of fish detected by the upstream (primary) array.

Because the distance between receiver arrays was not equal, it was desirable to have a measure of reach survival that was independent of the distance over which it was estimated. Therefore, survival per river kilometer was estimated from each reach survival estimate by:

$$S_{km} = S_{reach}^{1/L}$$

where

$S_{km}$  is the estimate of survival per river kilometer,

$S_{reach}$  is the reach survival estimate, and

$L$  is the reach length in river kilometers.

We assessed the effect of fish length on the probability of survival to McNary Dam for acoustic-tagged fall Chinook salmon in 2014 using program SURPH (SURvival under Proportional Hazards; version 3.5.2), whereby survival probabilities were modeled as a function of FL as an individual-based covariate using the hazard link (Skalski et al. 1993; Smith et al. 1994). A nonparametric survival curve

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<sup>1</sup> Survival from tagging to acoustic tag detection in the outflow channel was estimated separately.

that did not depend on the parameters of any particular model was also plotted. The nonparametric curve can be thought of as a “moving average” survival as the selected individual covariate (i.e., fish length) increases across the range of observed values. The size of the “window” for which the moving average survival probability was calculated ranged from a minimum of eight individuals up to 20% of the entire number at risk in the selected interval (Smith et al. 1994). The effect of fish length on survival probability was evaluated using the likelihood ratio test to compare the fish length covariate model to a model of no covariate effect.

## **2.6 Travel Time and Travel Rate**

Travel time was calculated for acoustic-tagged wild Hanford Reach and PRH fall Chinook salmon in each river reach studied in 2014. Travel time was calculated for each fish detected at both the upstream and downstream arrays by subtracting the date and time of first detection (or release) at the upstream array from the date and time of the first detection at the downstream array. Travel rate was calculated from each travel time by dividing the travel time by the distance between arrays. Because calculation of travel time requires detection at both the upstream and downstream arrays, estimates of travel time and travel rate within each reach only consider fish that successfully migrated through the entire reach and were detected at both arrays.

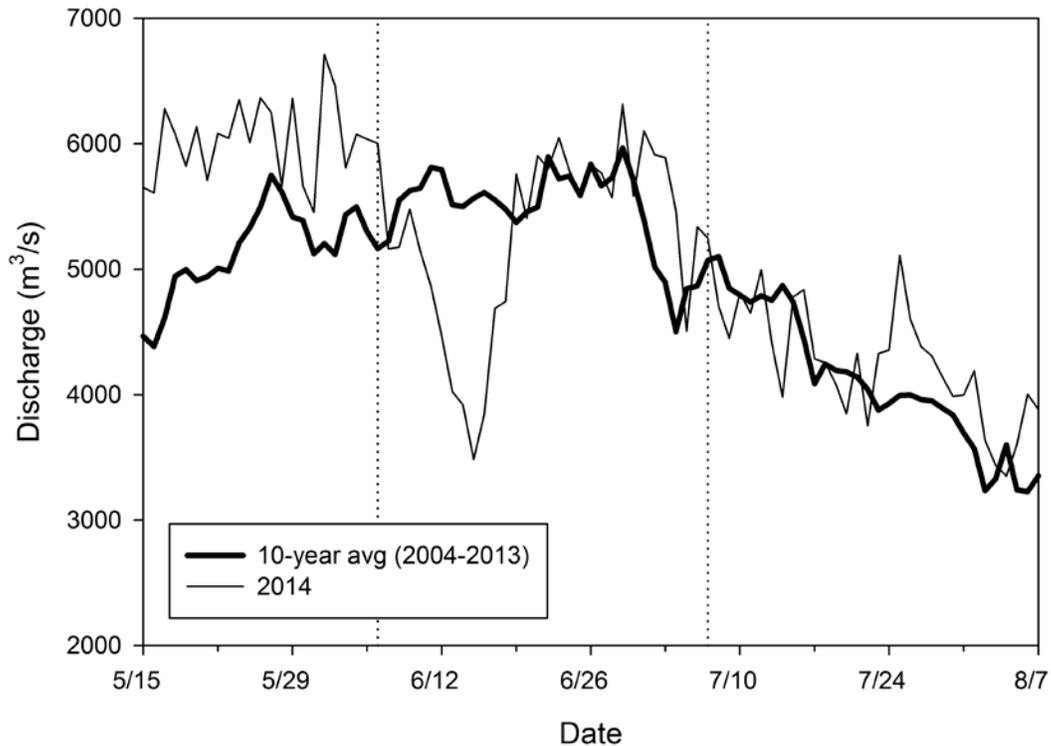


### 3.0 Results

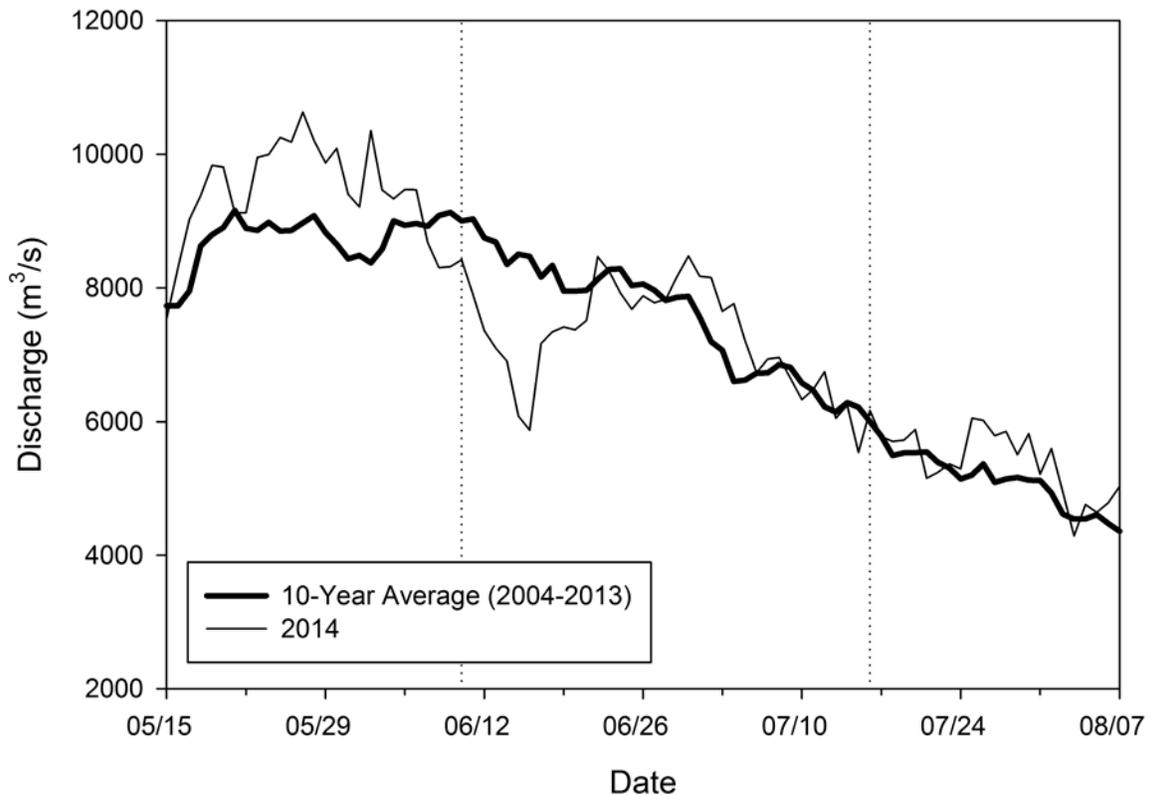
The results section includes a brief summary of the environmental conditions in the mid-Columbia River during the study period to provide context for the detailed results of the estimated survival and travel time of acoustic-tagged fish in this study. The tag-life and detection probability information for the JSATS used in this study are presented to provide the necessary background information on system performance.

#### 3.1 Environmental Conditions

A sharp decline in total daily discharge, as measured at Priest Rapids (Figure 3.1) and McNary (Figure 3.2) dams, coincided with the release and early migration period of acoustic-tagged wild Hanford Reach fall Chinook salmon, which were released on June 6. Discharge from Priest Rapids Dam declined from about 6,000 m<sup>3</sup>/s on June 6 to about 3,500 m<sup>3</sup>/s on June 15. This reduction in discharge was part of normal spring river management to allow for the refilling of reservoirs by June 30. The volitional release of acoustic-tagged fall Chinook salmon from PRH began on June 12; thus, discharge was increasing throughout much of their early migration period before stabilizing around the 10-year average.

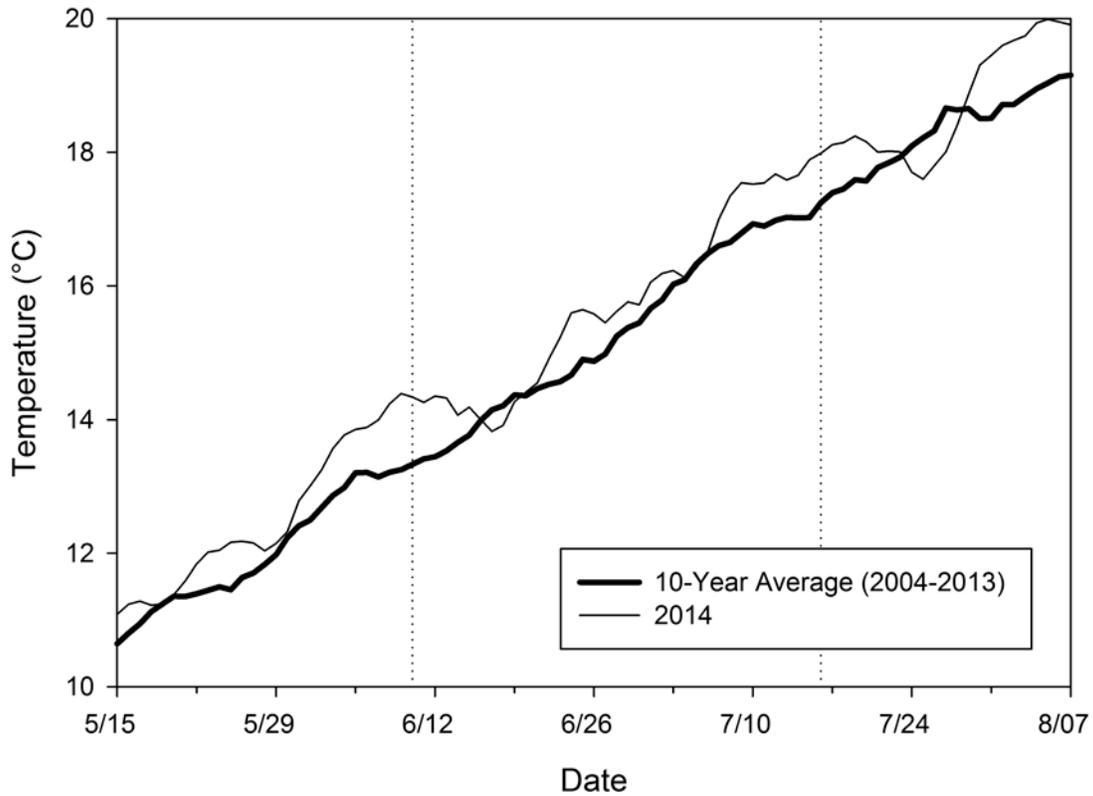


**Figure 3.1.** Priest Rapids Dam (PRD) discharge from May 15 through August 7, 2014 versus the 10-year (2004–2013) average. Dotted lines indicate the approximate time period in which acoustic-tagged fish were affected by PRD discharge. This period included the time between the release of wild Hanford Reach fall Chinook salmon (June 6) and the last detection at McNary Dam (CR470; July 7).

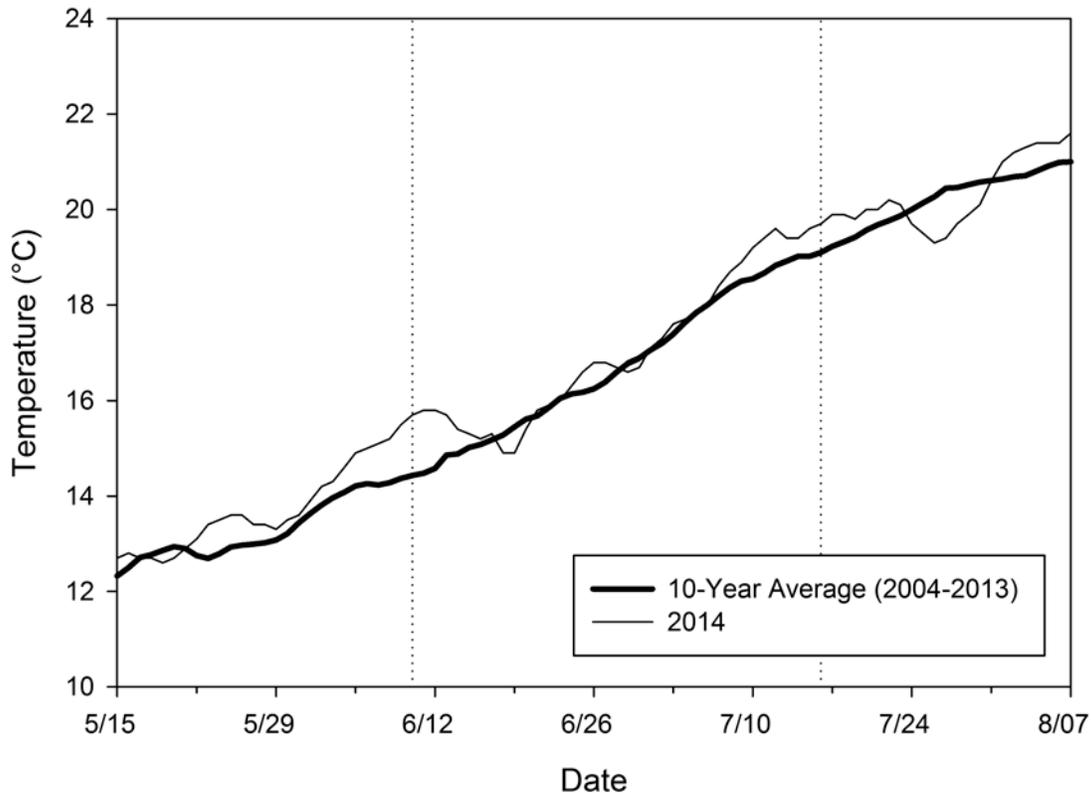


**Figure 3.2.** McNary Dam (MCN) discharge from May 15 through August 7, 2014 versus the 10-year (2004–2013) average. Dotted lines indicate the approximate time period in which acoustic-tagged fish were affected by MCN discharge. This period included the time between the first detection of acoustic-tagged fish at MCN (CR470; June 10) and the last detection at CR275 (July 15).

The temperature of the mid-Columbia River, as measured at Priest Rapids Dam, was slightly above-average during most of the study period (Figure 3.3). Colder than average water temperatures in the Snake River resulted in near-average temperatures at McNary Dam during the period of interest (Figure 3.4).



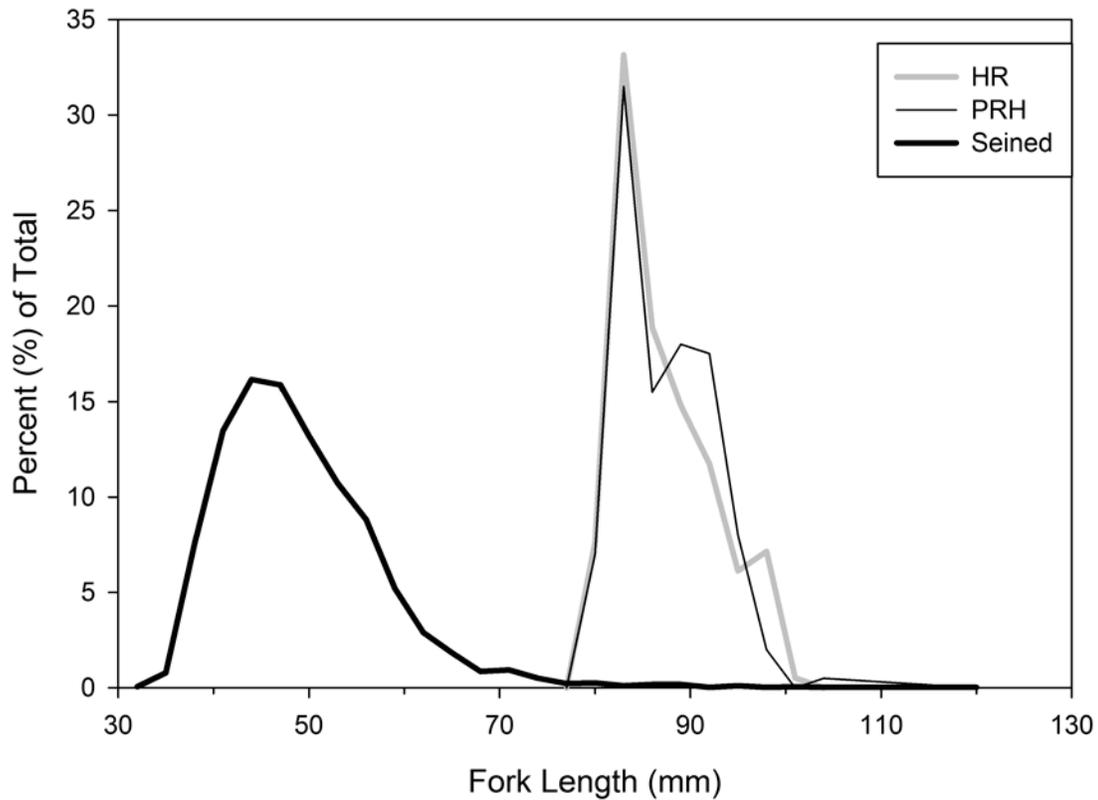
**Figure 3.3.** Water temperature, as measured at Priest Rapids Dam, from May 15 through August 7, 2014 versus the 10-year (2004–2013) average. Dotted lines indicate the approximate time period in which acoustic-tagged fish were affected by the temperature in this area of the Columbia River. This period included the time between the release of wild Hanford Reach fall Chinook salmon (June 6) and the last detection at McNary Dam (CR470; July 7).



**Figure 3.4.** Water temperature, as measured at McNary Dam (MCN), from May 15 through August 7, 2014 versus the 10-year (2004–2013) average. Dotted lines indicate the approximate time period in which acoustic-tagged fish were affected by water temperatures near MCN. This period included the time between the first detection of acoustic-tagged fish at MCN (CR470; June 10) and the last detection at CR275 (July 15).

### 3.2 Size of Tagged Fish

The length distributions of acoustic-tagged PRH and wild Hanford Reach fall Chinook salmon were similar at the time of tagging (Figure 3.5; Table 3.1). However, fish tagged at PRH were held in the channel ponds and fed for an additional two weeks after tagging, whereas wild Hanford Reach fall Chinook were released the day after tagging. Based on the water temperature of the Columbia River during this time (~12 °C) and the temperature-growth relationship of PRH fall Chinook salmon from a laboratory study, we would expect these fish to grow an additional 9 mm between tagging and release. Thus, we suspect the acoustic-tagged PRH fish were significantly larger, on average, than the acoustic-tagged wild Hanford Reach fish at the time they entered the river in the Hanford Reach. Both tagged groups were substantially larger than the random subsample of wild Hanford Reach fall Chinook salmon that were captured in seines and measured for length by the CRITFC (Figure 3.5). We attempted to minimize tag burden (tag weight expressed as a percentage of fish weight) and any potential tag or tagging effects by only implanting tags into fish that measured 80 mm FL or greater. Therefore, the size distribution of wild Hanford Reach fall Chinook salmon implanted with transmitters differed significantly from the size distribution of the general population.



**Figure 3.5.** Length frequency distributions for acoustic-tagged Priest Rapids Hatchery fall Chinook salmon smolts (PRH), wild Hanford Reach fall Chinook salmon juveniles captured via seining that were implanted with acoustic transmitters (HR), and wild Hanford Reach fall Chinook salmon juveniles captured via seining that were randomly selected for length measurement in 2014 (Seined).

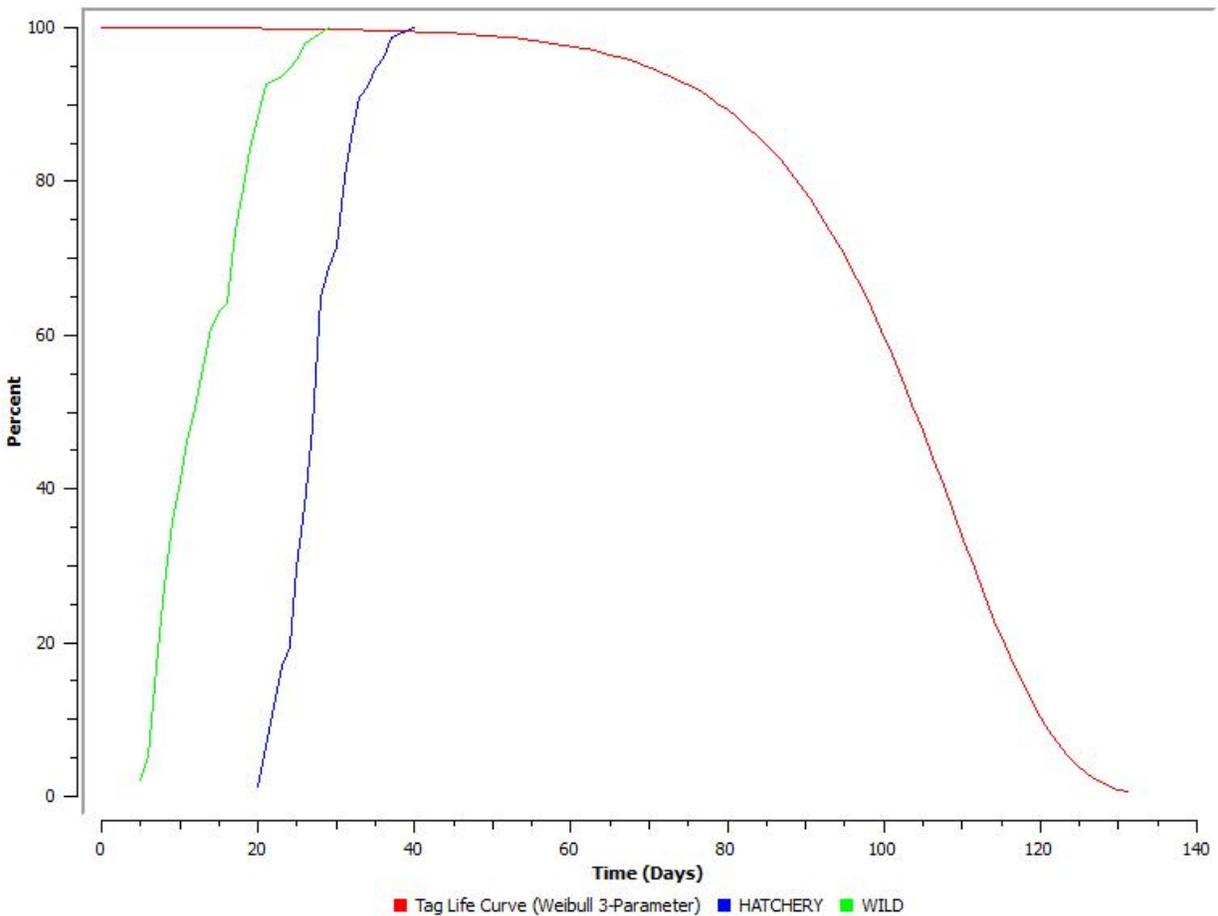
**Table 3.1.** Number, fork length, tag burden, (acoustic + PIT tag weight expressed as a percentage of fish body weight), and release dates for acoustic-tagged Priest Rapids Hatchery upriver bright fall Chinook salmon juveniles (H-URB) and wild Hanford Reach upriver bright fall Chinook salmon juveniles (W-URB) released into the Columbia River at Priest Rapids Hatchery or in the Hanford Reach in 2014 (rkm = river kilometer; min = minimum; max = maximum)

Release location	Release rkm	Rearing type	Release date	n	Fork length (mm)			Tag burden (%)		
					Min	Max	Mean	Min	Max	Mean
Priest Rapids Hatchery	633	H-URB	June 12	200	80	103	87	2.6	6.8	4.6
Hanford Reach	595	W-URB	June 6	198	80	100	87	3.1	6.8	4.9

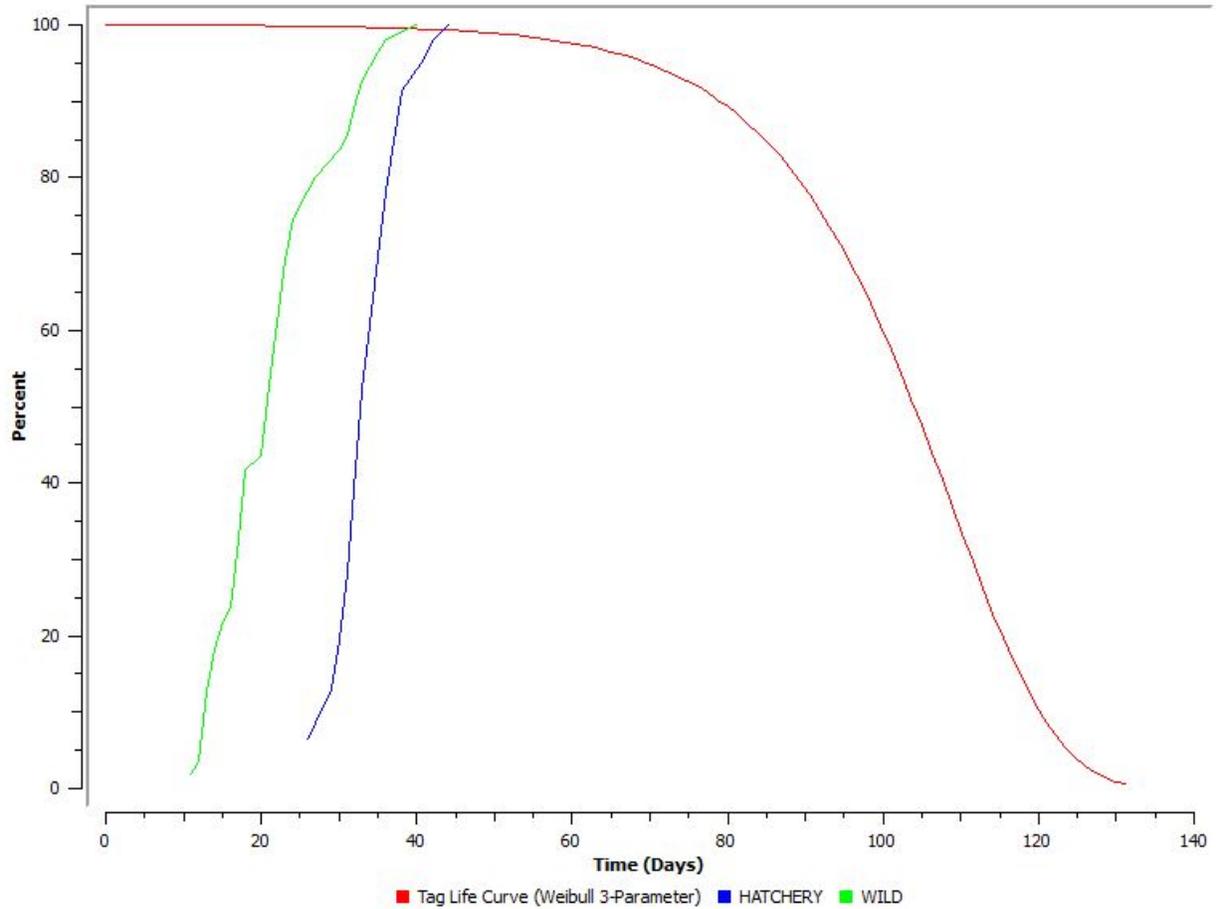
### 3.3 JSATS Performance

#### 3.3.1 Tag-Life

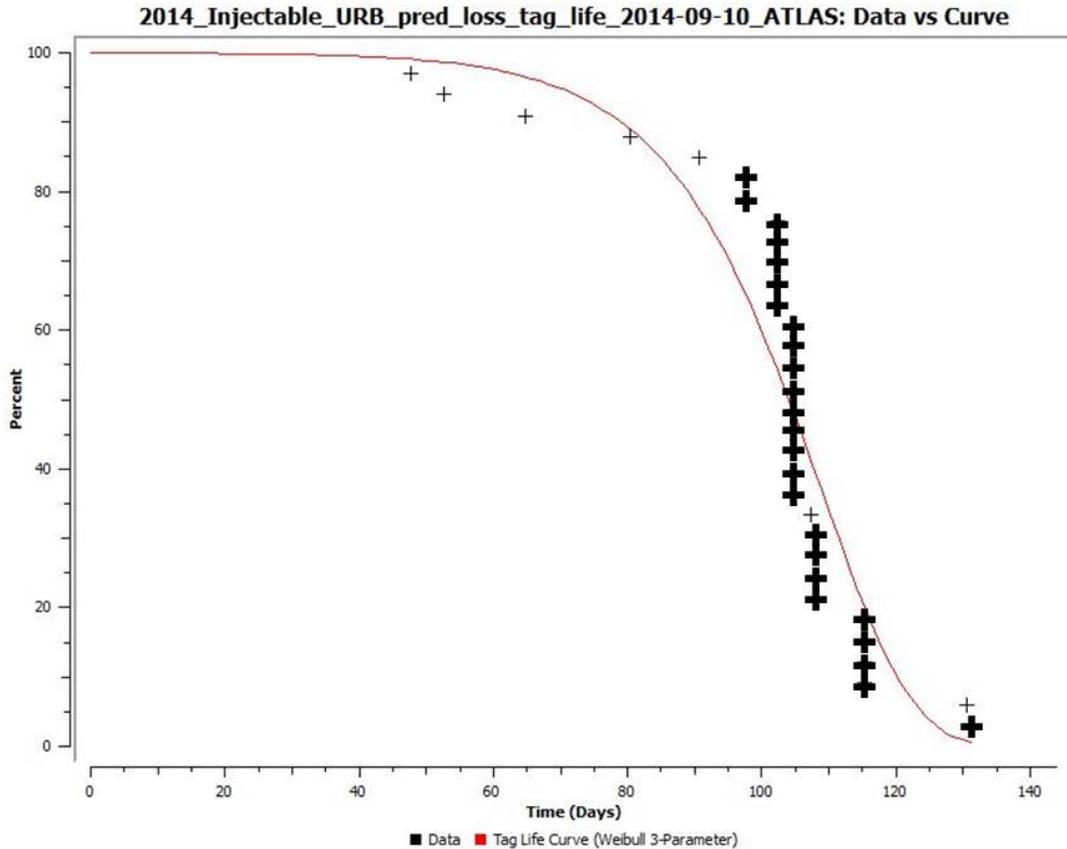
Although tag-life expectancy was 60 days for acoustic tags in this study, 30 of the 32 (93.8%) tag-life transmitters lasted longer than 60 days. In fact, the average transmitter life was 101.5 days at the time of this report (September 10, 2014). However, 25 of the tags were still transmitting at the time of this report, having been activated 97 to 131 days ago. Therefore, the actual average life of tag-life transmitters is greater than 101.5 days. The first tag-life transmitter expired after 47.6 days. Because greater than 99% of the fish we tagged migrated through the study area before the time at which any tag failure was observed during the tag-life study (Figures 3.6 and 3.7), only a relatively small adjustment for tag failure was required. The three-parameter Weibull model (Figure 3.8) fit the preliminary tag-life data better than either the two-parameter Weibull model or the four-parameter vitality model of Li and Anderson (2009). Therefore, this tag-life survivorship model was subsequently used to estimate the probabilities of tag failure and provide tag-life adjusted estimates of juvenile fall Chinook salmon survival.



**Figure 3.6.** Fitted three-parameter Weibull model tag-life survivorship curve (red line) and the arrival-time distributions of acoustic-tagged wild Hanford Reach (green line) and Priest Rapids Hatchery (blue line) fall Chinook salmon juveniles at the McNary Dam cabled array (CR470).



**Figure 3.7.** Fitted three-parameter Weibull model tag-life survivorship curve (red line) and the arrival-time distributions of acoustic-tagged wild Hanford Reach (green line) and Priest Rapids Hatchery (blue line) fall Chinook salmon juveniles at the autonomous array located near Bingen, Washington (CR275).



**Figure 3.8.** Observed failure times of tag-life acoustic transmitters (+) and the fitted three-parameter Weibull model survivorship curve used to adjust survival estimates for tag-life. The average tag-life at the time of this report was 101.5 days. Bold crosses (+) indicate transmitters that were still transmitting at the time of this report (September 10, 2014); thus, the model does not fit the data particularly well and tag-life is likely underestimated.

### 3.3.2 Array Detection Probability

Detection probability was quite high at all arrays for both PRH and wild Hanford Reach fall Chinook salmon (Table 3.2). The probability of detecting acoustic-tagged fish was  $\geq 0.945$  for PRH fish and  $\geq 0.959$  for wild fish at all arrays and equaled 1.000 at most arrays.

**Table 3.2.** Probability of detecting acoustic-tagged Priest Rapids Hatchery and wild Hanford Reach fall Chinook salmon at autonomous and cabled JSATS acoustic telemetry receiver arrays deployed in the mid and lower Columbia River in 2014.

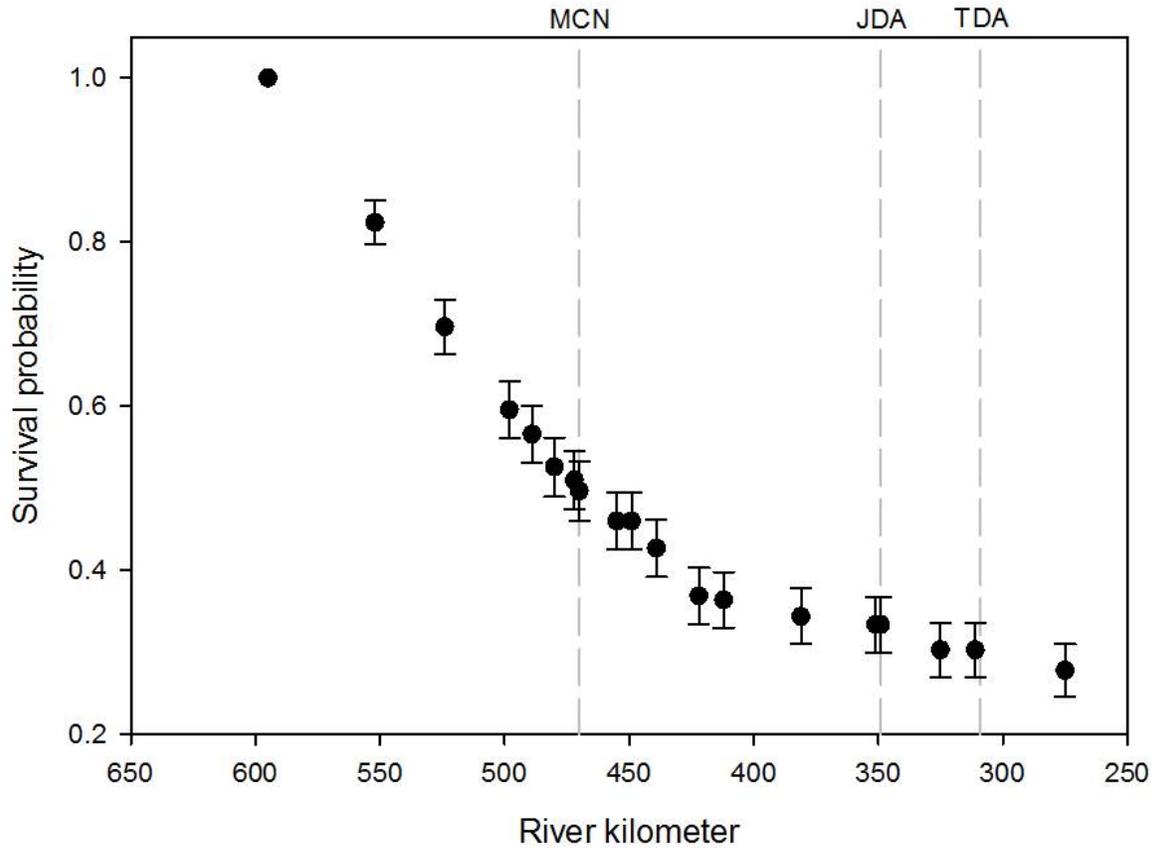
Array	Wild Hanford Reach	Priest Rapids Hatchery
CR633	N/A	1.000 (0.000)
CR552	1.000 (0.000)	1.000 (0.000)
CR524	1.000 (0.000)	1.000 (0.000)
CR498	1.000 (0.000)	1.000 (0.000)
CR489	0.990 (0.010)	1.000 (0.000)
CR480	1.000 (0.000)	1.000 (0.000)
CR472	1.000 (0.000)	1.000 (0.000)
CR470	0.967 (0.019)	0.945 (0.027)
CR455	1.000 (0.000)	1.000 (0.000)
CR449	1.000 (0.000)	1.000 (0.000)
CR439	0.959 (0.023)	0.984 (0.016)
CR422	1.000 (0.000)	1.000 (0.000)
CR412	1.000 (0.000)	0.983 (0.017)
CR381	1.000 (0.000)	1.000 (0.000)
CR351	1.000 (0.000)	1.000 (0.000)
CR349	1.000 (0.000)	1.000 (0.000)
CR325	1.000 (0.000)	1.000 (0.000)
CR311	1.000 (0.000)	1.000 (0.000)
CR275	1.000 (0.000)	1.000 (0.000)

### 3.4 Survival Probability

Survival is an important metric for identifying when or where unfavorable conditions may exist for juvenile fall Chinook salmon. Evaluating survival on a per-kilometer basis can put the reach survival estimates into a relative context for comparisons between reaches. This section provides reach survival probabilities and  $S_{km}$  estimates for each river reach examined in this study. Cumulative survival probabilities, as estimated from release to each downstream detection array, are also presented.

#### 3.4.1 Wild Hanford Reach Fall Chinook Salmon

The probability of acoustic-tagged wild fall Chinook salmon surviving migration through the lower half of the Hanford Reach (from release at rkm 595 to CR552) was estimated to be 0.824 (SE = 0.027) and the probability of surviving from release to McNary Dam was 0.497 (0.036) in 2014 (Figure 3.9). Survival probability from release to the most downstream array, located in the reservoir of Bonneville Dam at rkm 275 (CR275), was 0.278 (0.032).



**Figure 3.9.** Overall cumulative survival probability estimates for acoustic-tagged wild Hanford Reach fall Chinook salmon from release in the Hanford Reach (rkm 595) to downstream acoustic telemetry receiver arrays. Error bars denote standard errors.

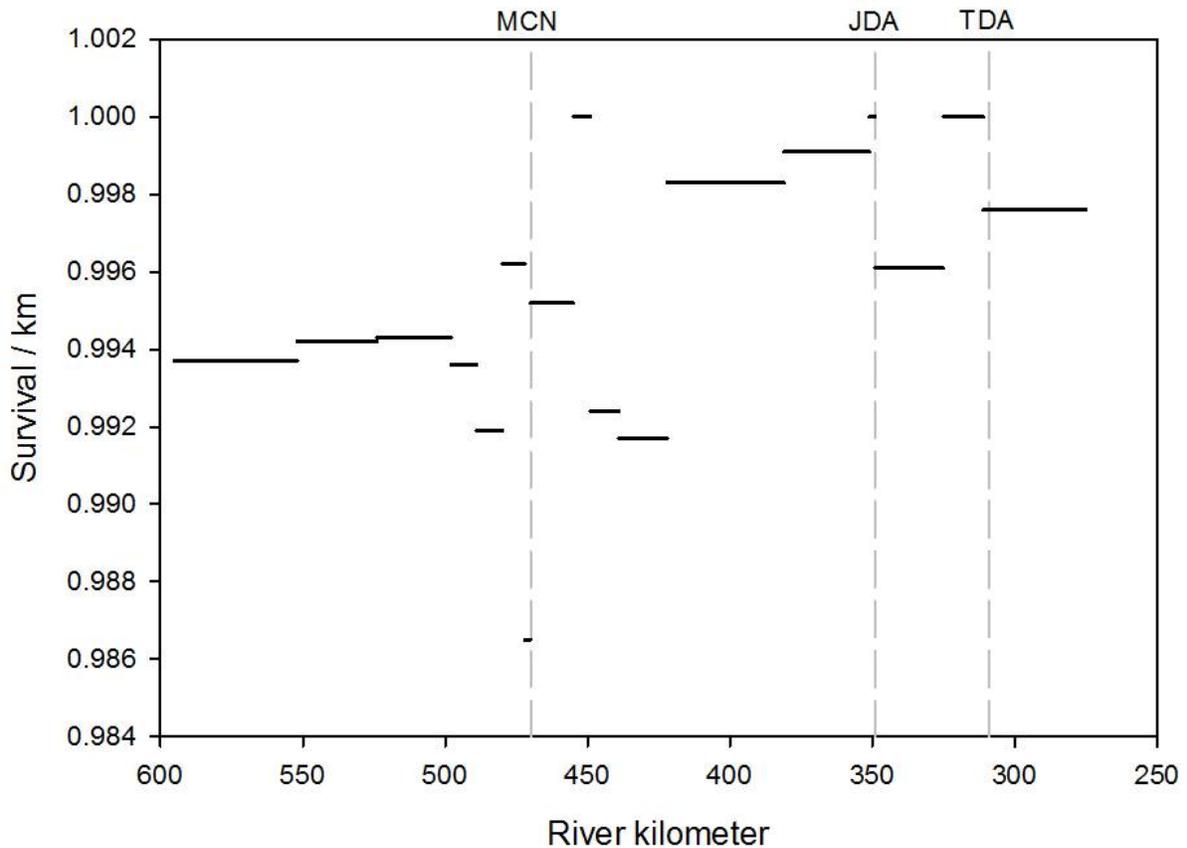
Survival of acoustic-tagged wild Hanford Reach fall Chinook salmon varied among reaches, from 0.824 (SE=0.027) between release and CR552 to 1.00 (multiple reaches; Table 3.3). Because reaches differed in length, survival is better compared among reaches using  $S_{km}$  estimates.

**Table 3.3.** Reach-specific survival probability estimates ( $S$ , and associated SE) for acoustic-tagged wild Hanford Reach fall Chinook salmon juveniles through each river reach studied in 2014 from release at rkm 595 to CR275. Survival-per-kilometer ( $S_{km}$ ) estimates are also shown.

Reach	$S$ (SE)	$S_{km}$
Release to CR552	0.824 (0.027)	0.9937
CR552 to CR524	0.847 (0.028)	0.9942
CR524 to CR498	0.855 (0.030)	0.9943
CR498 to CR489	0.950 (0.020)	0.9936
CR489 to CR480	0.928 (0.025)	0.9919
CR480 to CR472	0.971 (0.017)	0.9962
CR472 to CR470	0.973 (0.017)	0.9865
CR470 to CR455	0.926 (0.027)	0.9952
CR455 to CR449	1.000 (0.003)	1.0000
CR449 to CR439	0.928 (0.028)	0.9924
CR439 to CR422	0.864 (0.038)	0.9917
CR422 to CR412	0.986 (0.014)	0.9983
CR412 to CR381	0.945 (0.027)	0.9983
CR381 to CR351	0.971 (0.021)	0.9991
CR351 to CR349	1.000 (0.004)	1.0000
CR349 to CR325	0.909 (0.036)	0.9961
CR325 to CR311	1.000 (0.004)	1.0000
CR311 to CR275	0.917 (0.036)	0.9976

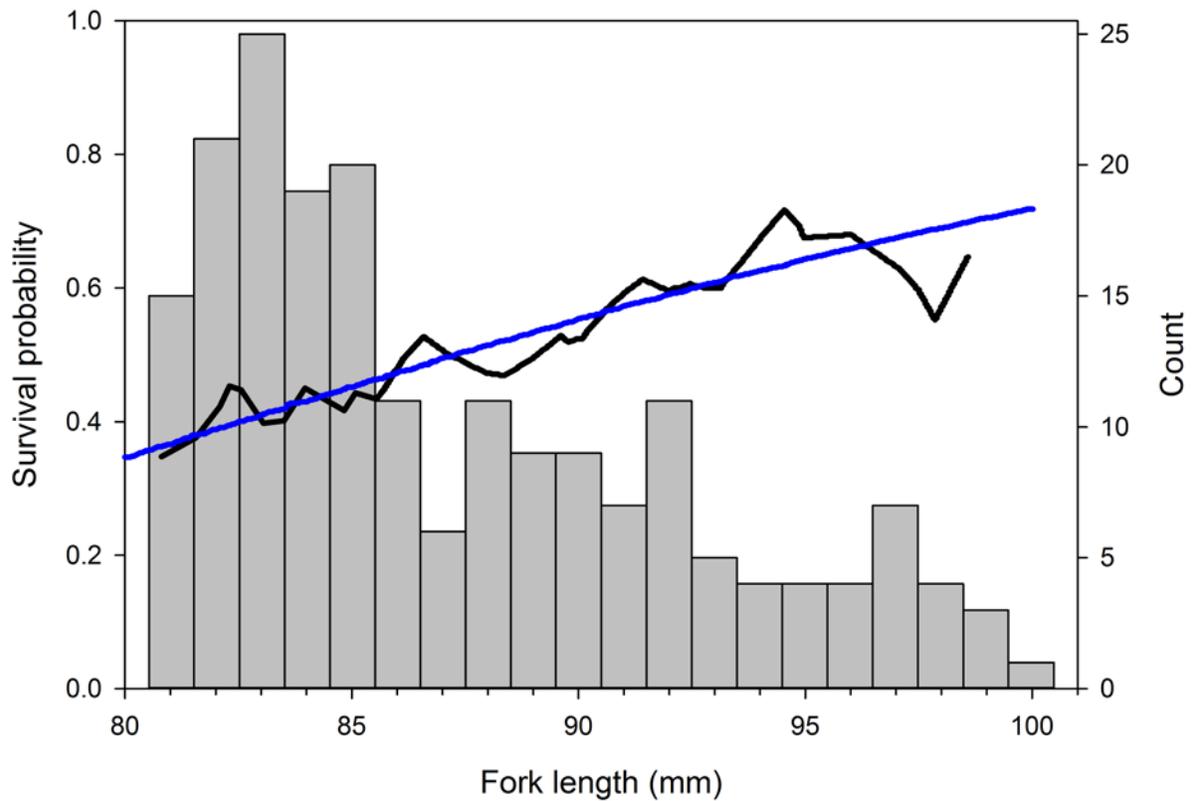
Upstream of McNary Dam,  $S_{km}$  was considerably lower in the immediate forebay of McNary Dam ( $S_{km} = 0.9865$ ; CR472 to CR470) compared to all other reaches (Figure 3.10). The other reach upstream of McNary with a  $S_{km}$  estimate that was notably low was also near McNary Dam between CR489 and CR480 ( $S_{km} = 0.9919$ ). Anomalously, the reach located between these two reaches (CR480 to CR472) had the highest  $S_{km}$  of all reaches upstream of McNary Dam for acoustic-tagged wild Hanford Reach fall Chinook salmon. Survival-per-kilometer estimates were generally similar among all reaches located between release and CR489, ranging from 0.9936 to 0.9943.

Downstream of McNary Reservoir, two reaches had  $S_{km}$  estimates that were considerably lower than all others for acoustic-tagged wild Hanford Reach fall Chinook salmon. These included the reach located between Boardman, OR (CR439) and Crow Butte (CR422;  $S_{km} = 0.9917$ ) and the next upstream reach, located between Paterson, WA (CR449) and Boardman, OR (CR439;  $S_{km} = 0.9924$ ).



**Figure 3.10.** Survival probability-per-kilometer estimates for acoustic-tagged wild Hanford Reach fall Chinook salmon through reaches of the Columbia River, 2014. Dashed vertical lines indicate the locations of McNary (MCN), John Day (JDA), and The Dalles (TDA) dams.

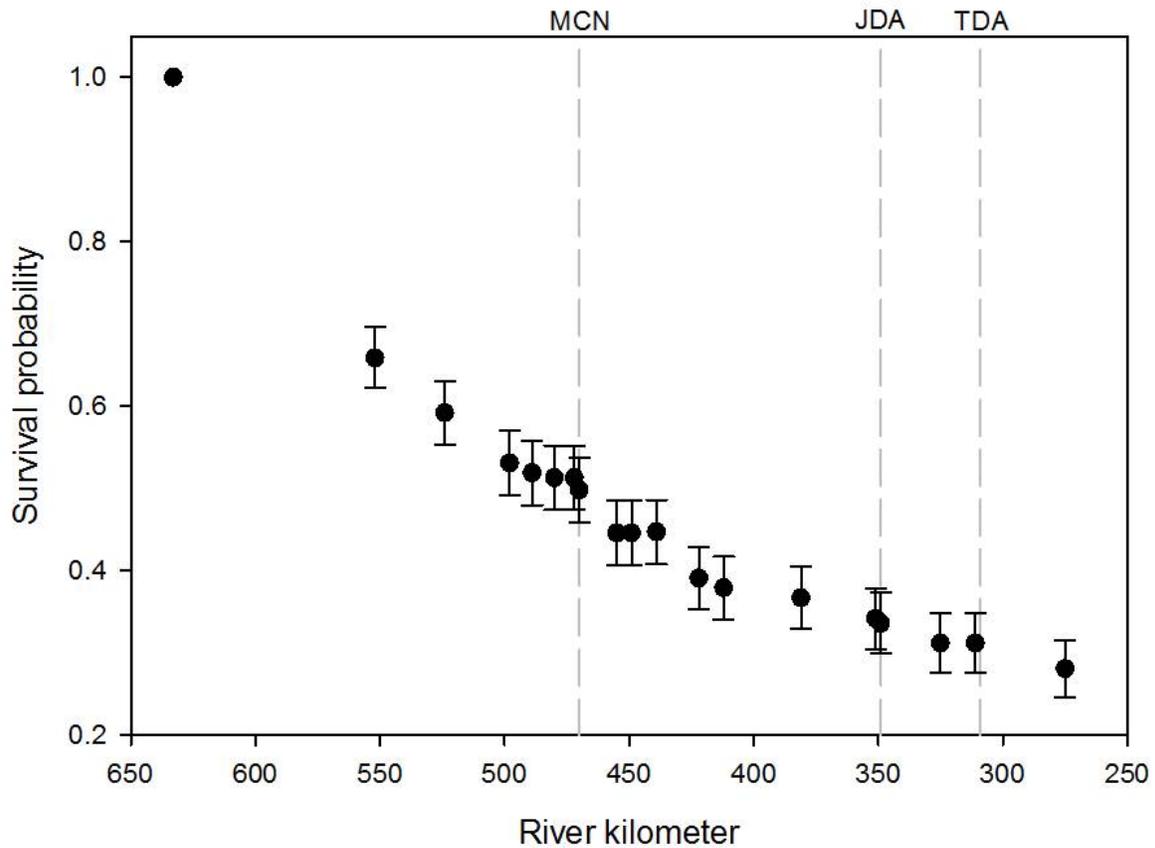
We observed a significant, positive relationship between the probability of survival to McNary Dam and fish length for wild Hanford Reach fall Chinook salmon ( $\chi = 7.486$ ;  $p = 0.006$ ; Figure 3.11). The difference in survival was rather large across the length range of tagged fish. Those at the upper end of the length distribution (100 mm FL) were about twice as likely to survive to McNary Dam as fish at the lower end of the distribution (80 mm FL).



**Figure 3.11.** Covariate analysis results displaying nonparametric (black line) and modeled (blue line) survival probabilities of acoustic-tagged wild Hanford Reach fall Chinook salmon from release in the Hanford Reach (rkm 595) to McNary Dam (rkm 470) in relation to fork length. The frequency histogram displays the number of tagged fish in each 1-mm fork length bin.

### 3.4.2 Priest Rapids Hatchery Fall Chinook Salmon

The probability of acoustic-tagged PRH fall Chinook salmon surviving migration through the Hanford Reach (from CR633 to CR552) was estimated to be 0.659 (SE = 0.037) and the probability of surviving to McNary Dam was 0.498 (0.039) in 2014 (Figure 3.12). Survival probability from CR633 to the most downstream array, located in the reservoir of Bonneville Dam at rkm 275 (CR275), was 0.281 (0.035).



**Figure 3.12.** Overall cumulative survival probability estimates for acoustic-tagged Priest Rapids Hatchery fall Chinook salmon from acoustic detection in the PRH outflow channel (CR633) to downstream acoustic telemetry receiver arrays. Error bars denote standard errors.

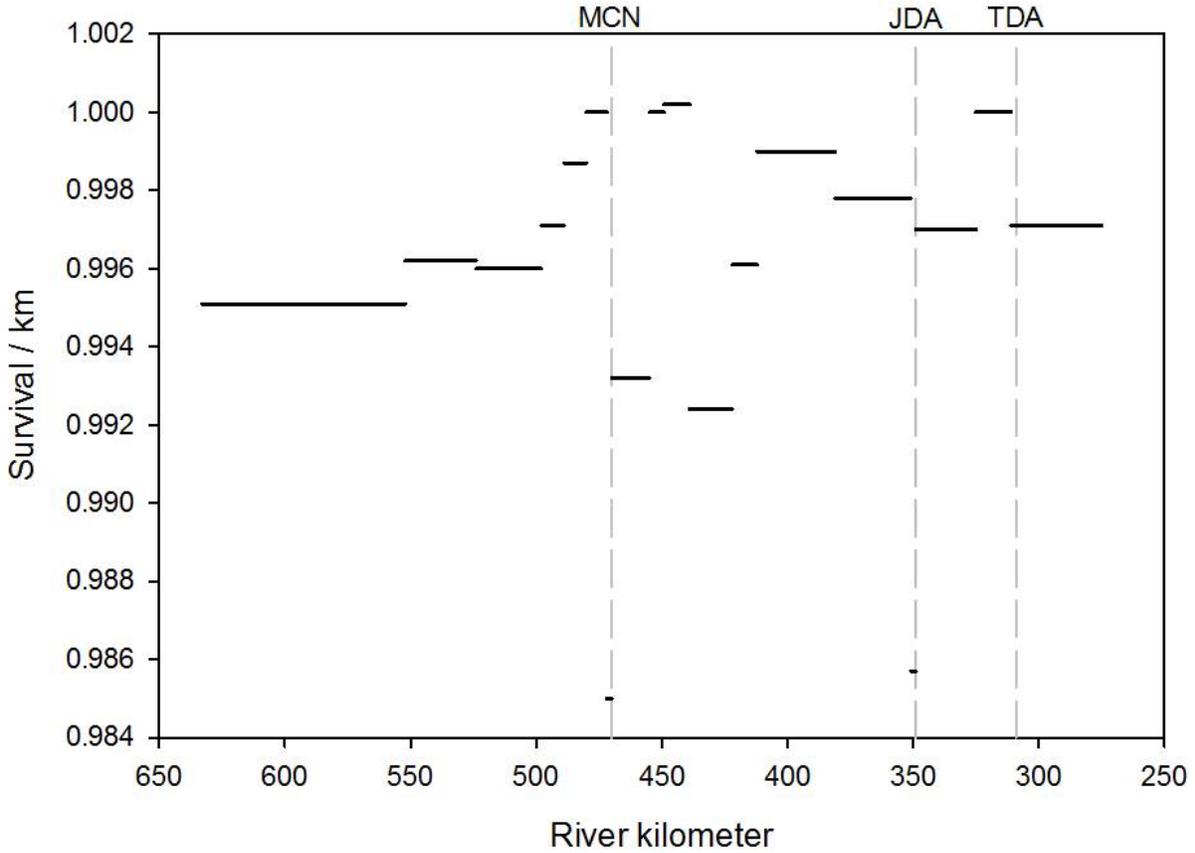
Survival of acoustic-tagged PRH fall Chinook salmon varied widely among reaches, from 0.659 (SE=0.037) between CR633 and CR552 to 1.00 (multiple reaches; Table 3.4). Because reaches differed in length, survival is better compared among reaches using  $S_{km}$  estimates.

**Table 3.4.** Reach-specific survival probability estimates ( $S$ , and associated SE) for acoustic-tagged Priest Rapids Hatchery fall Chinook salmon juveniles through each river reach studied in 2014 from virtual release (detection in the hatchery outflow channel) at rkm 633 to CR275. Survival from tagging to virtual release (Release to CR633) and survival-per-kilometer ( $S_{km}$ ) estimates are also shown.

Reach	$S$ (SE)	$S_{km}$
Release to CR633	0.821 (0.027)	N/A
CR633 to CR552	0.659 (0.037)	0.9951
CR552 to CR524	0.898 (0.029)	0.9962
CR524 to CR498	0.897 (0.031)	0.9960
CR498 to CR489	0.977 (0.016)	0.9971
CR489 to CR480	0.988 (0.012)	0.9987
CR480 to CR472	1.000 (0.003)	1.0000
CR472 to CR470	0.970 (0.021)	0.9850
CR470 to CR455	0.896 (0.035)	0.9932
CR455 to CR449	1.000 (0.003)	1.0000
CR449 to CR439	1.002 (0.004)	1.0002
CR439 to CR422	0.875 (0.039)	0.9924
CR422 to CR412	0.969 (0.022)	0.9961
CR412 to CR381	0.967 (0.023)	0.9990
CR381 to CR351	0.934 (0.032)	0.9978
CR351 to CR349	0.982 (0.018)	0.9857
CR349 to CR325	0.928 (0.035)	0.9970
CR325 to CR311	1.000 (0.005)	1.0000
CR311 to CR275	0.902 (0.042)	0.9971

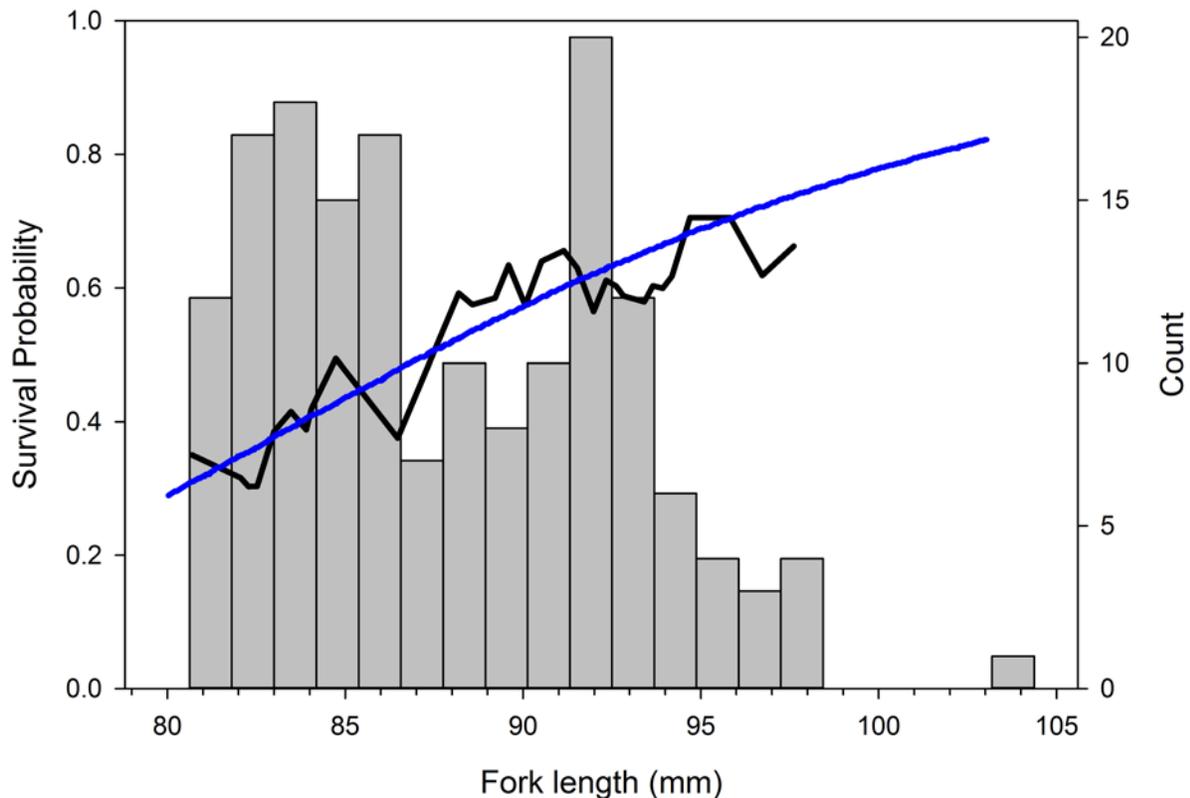
Similar to the results observed for wild tagged fish,  $S_{km}$  of PRH fall Chinook salmon was considerably lower in the immediate forebay of McNary Dam ( $S_{km} = 0.9850$ ; CR472 to CR470) compared to all other reaches upstream of McNary Dam (Figure 3.13). With the exception of this reach,  $S_{km}$  generally increased from upstream to downstream between CR633 and CR472 for acoustic-tagged PRH fall Chinook salmon.

Downstream of McNary Reservoir, the  $S_{km}$  of PRH fall Chinook salmon was considerably lower in the immediate forebay of John Day Dam ( $S_{km} = 0.9857$ ; CR351 to CR349) than all other reaches. The reach that included McNary Dam (CR470 to CR455) and the reach located between Boardman, OR and Crow Butte (CR439 to CR422) also had relatively low  $S_{km}$  estimates for PRH fall Chinook salmon (0.9932 and 0.9924, respectively).



**Figure 3.13.** Survival probability-per-kilometer estimates for acoustic-tagged Priest Rapids Hatchery fall Chinook salmon through reaches of the Columbia River, 2014. Dashed vertical lines indicate the locations of McNary (MCN), John Day (JDA), and The Dalles (TDA) dams.

Similar to the relationship found for wild Hanford Reach fall Chinook salmon, we observed an even stronger, positive relationship between survival probability to McNary Dam and fish length for PRH fall Chinook salmon ( $\chi = 14.164$ ;  $p < 0.001$ ; Figure 3.14). Again, there was a large difference in survival across the length range of tagged fish. Those at the upper end of the length distribution (~100 mm FL) were more than twice as likely to survive to McNary Dam as fish at the lower end of the distribution (80 mm FL).



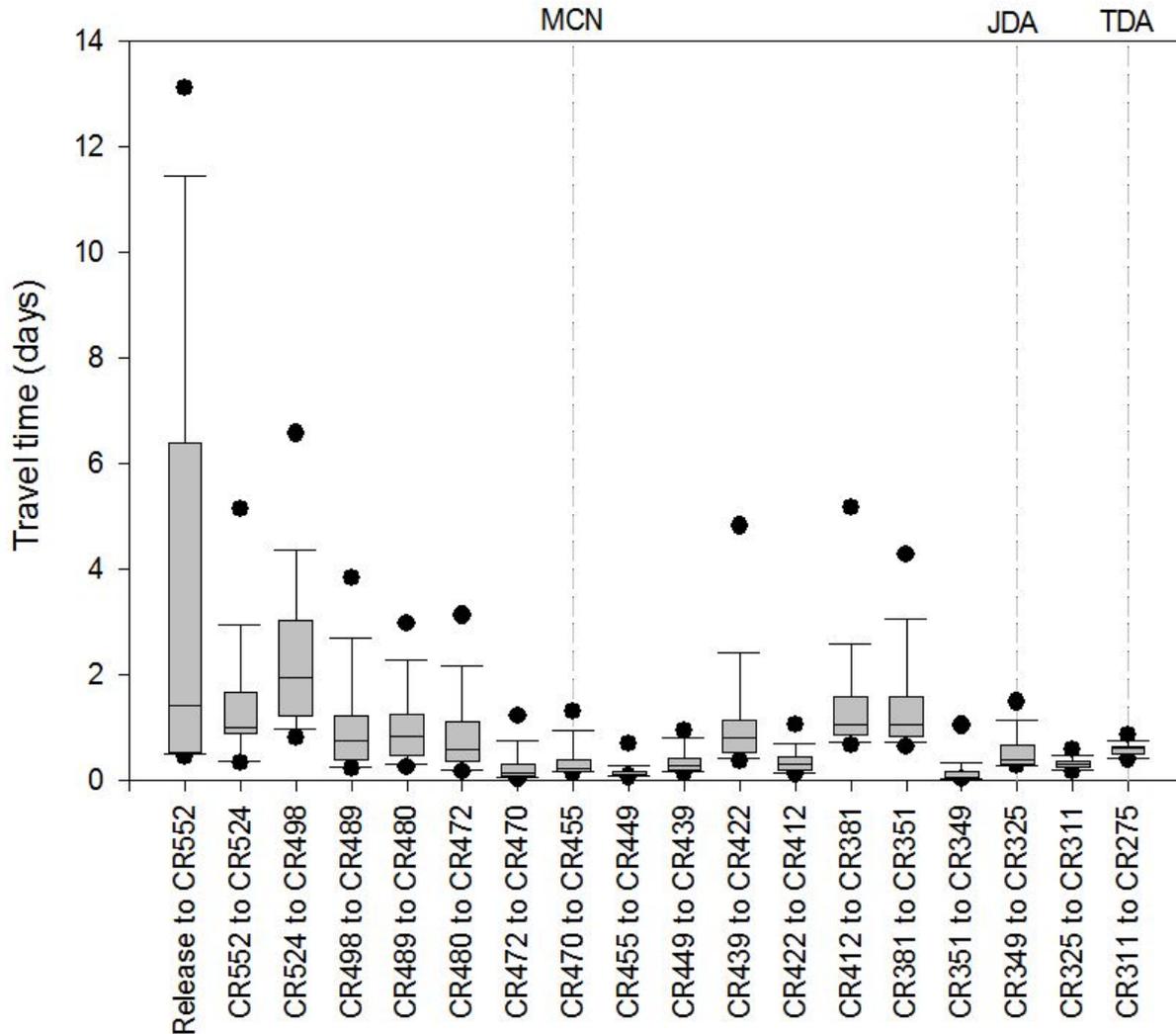
**Figure 3.14.** Covariate analysis results displaying nonparametric (black line) and modeled (blue line) survival probabilities of acoustic-tagged Priest Rapids Hatchery fall Chinook salmon from Priest Rapids Hatchery (CR633) to McNary Dam (CR470) in relation to fork length. The frequency histogram displays the number of tagged fish in each 1-mm fork length bin.

### 3.5 Travel Time and Travel Rate

The amount of time fish spend in a particular river reach and the speed at which they travel is often linked to survival probability. This section describes the travel times and rates of acoustic-tagged wild Hanford Reach and PRH fall Chinook salmon through reaches of the mid and lower Columbia River in 2014.

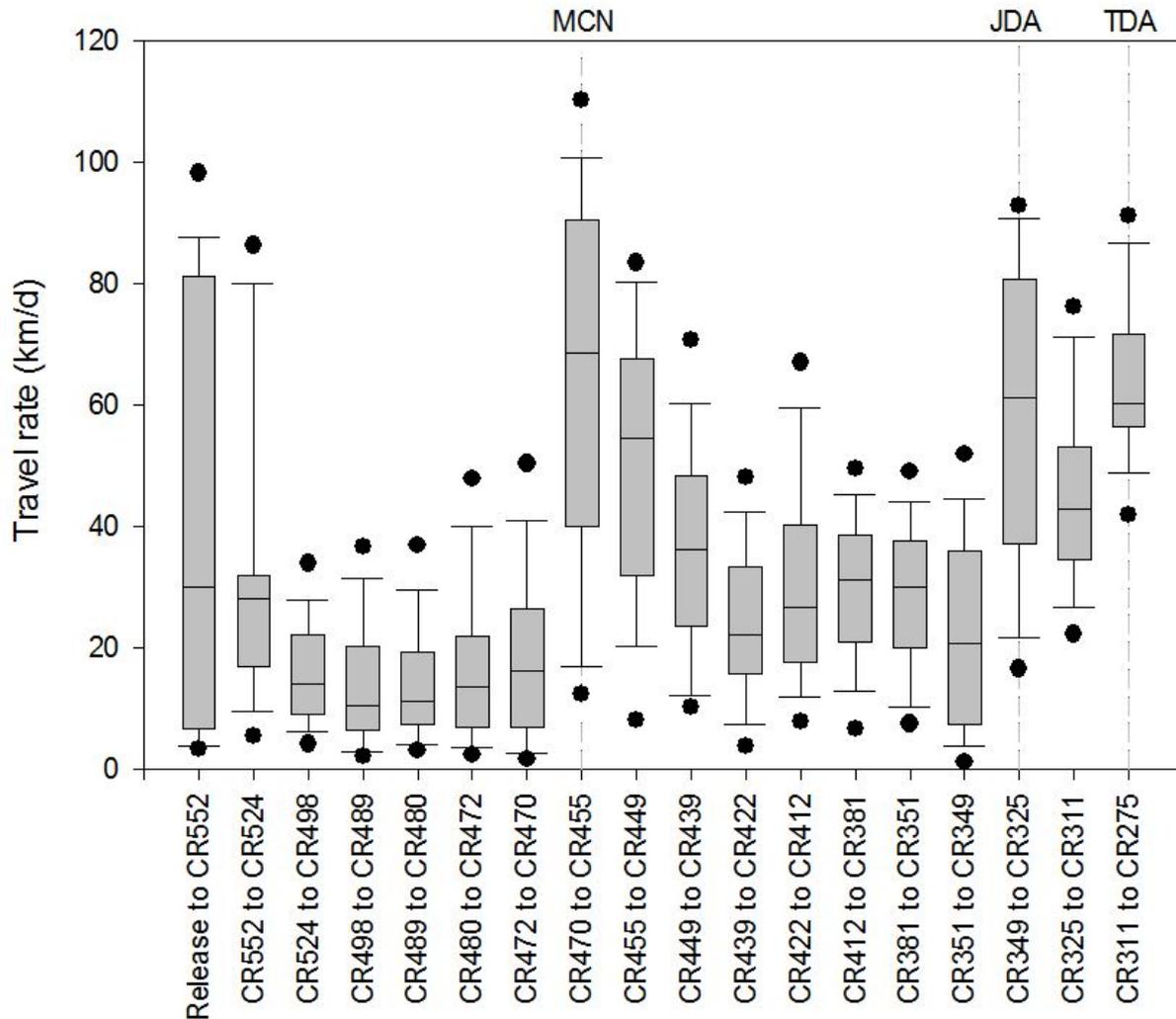
#### 3.5.1 Wild Hanford Reach Fall Chinook Salmon

The median travel time was less than 2 days for acoustic-tagged wild Hanford Reach fall Chinook salmon in each river reach examined in 2014 (Figure 3.15). We observed relatively little variability in travel times within each reach except in the first reach (release to CR552) where the median travel time was 1.4 days but over 25% of the fish took >6 d and 25% took <13 h to traverse the reach. The median travel time of wild Hanford Reach fall Chinook salmon detected at McNary Dam was 10.7 d (25<sup>th</sup> percentile = 6.7 d; 75<sup>th</sup> percentile = 16.2 d).



**Figure 3.15.** Travel time (days) of acoustic-tagged wild Hanford Reach fall Chinook salmon juveniles in each reach of the Columbia River studied in 2014. Solid lines within the boxes are median, the box boundary represents the 25<sup>th</sup> and 75<sup>th</sup> percentiles, whiskers indicate the 10<sup>th</sup> and 90<sup>th</sup> percentiles, and dots indicate the 5<sup>th</sup> and 95<sup>th</sup> percentiles. Dashed vertical lines indicate the locations of McNary (MCN), John Day (JDA), and The Dalles (TDA) dams.

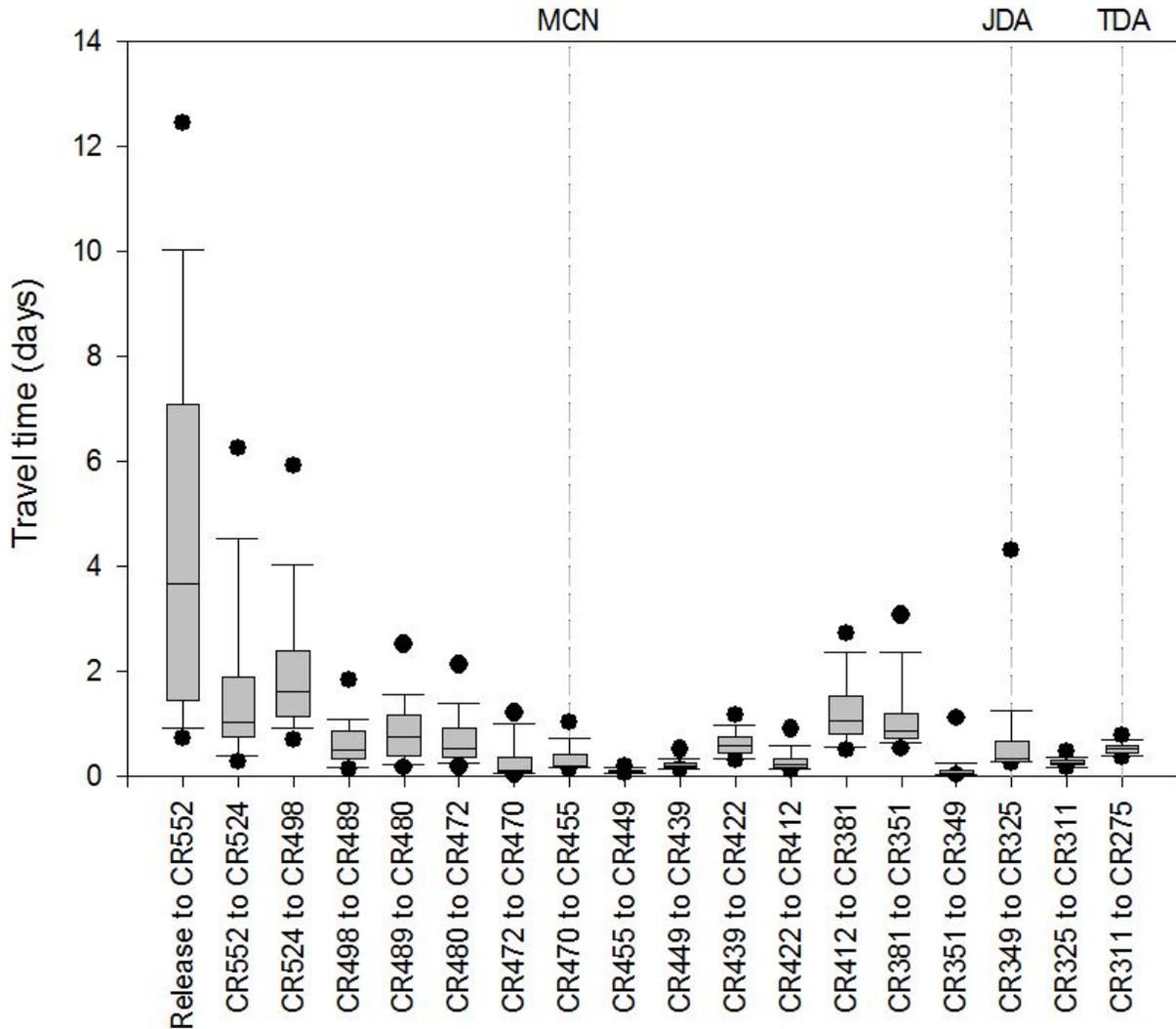
Acoustic-tagged wild Hanford Reach fall Chinook salmon generally migrated most quickly through the free-flowing Hanford Reach (release to CR552), and through the tailraces of Federal Columbia River Power System (FCRPS) dams (CR470 to CR455; CR349 to CR325; CR311 to CR275; Figure 3.16). We also observed the greatest variability in travel rate within these reaches. For example, wild Hanford Reach fall Chinook salmon had a median travel rate of 30 km/d from release to CR552; however, 25% of the fish had travel rates <10 km/d and 25% had rates >80 km/d. Conversely, travel rates were slowest, with the least amount of variability in reservoir reaches (all reaches between CR552 and CR470, between CR449 and CR349, and from CR325 to CR311). For example, median travel rates were generally around 10 km/d for acoustic-tagged wild Hanford Reach fall Chinook salmon in reaches of McNary Reservoir (part of CR552 to CR524, and all reaches between CR524 and CR470).



**Figure 3.16.** Travel rate (km/d) of acoustic-tagged wild Hanford Reach fall Chinook salmon juveniles in each reach of the Columbia River studied in 2014. Solid lines within the boxes are median, the box boundary represents the 25<sup>th</sup> and 75<sup>th</sup> percentiles, whiskers indicate the 10<sup>th</sup> and 90<sup>th</sup> percentiles, and dots indicate the 5<sup>th</sup> and 95<sup>th</sup> percentiles. Dashed vertical lines indicate the locations of McNary (MCN), John Day (JDA), and The Dalles (TDA) dams.

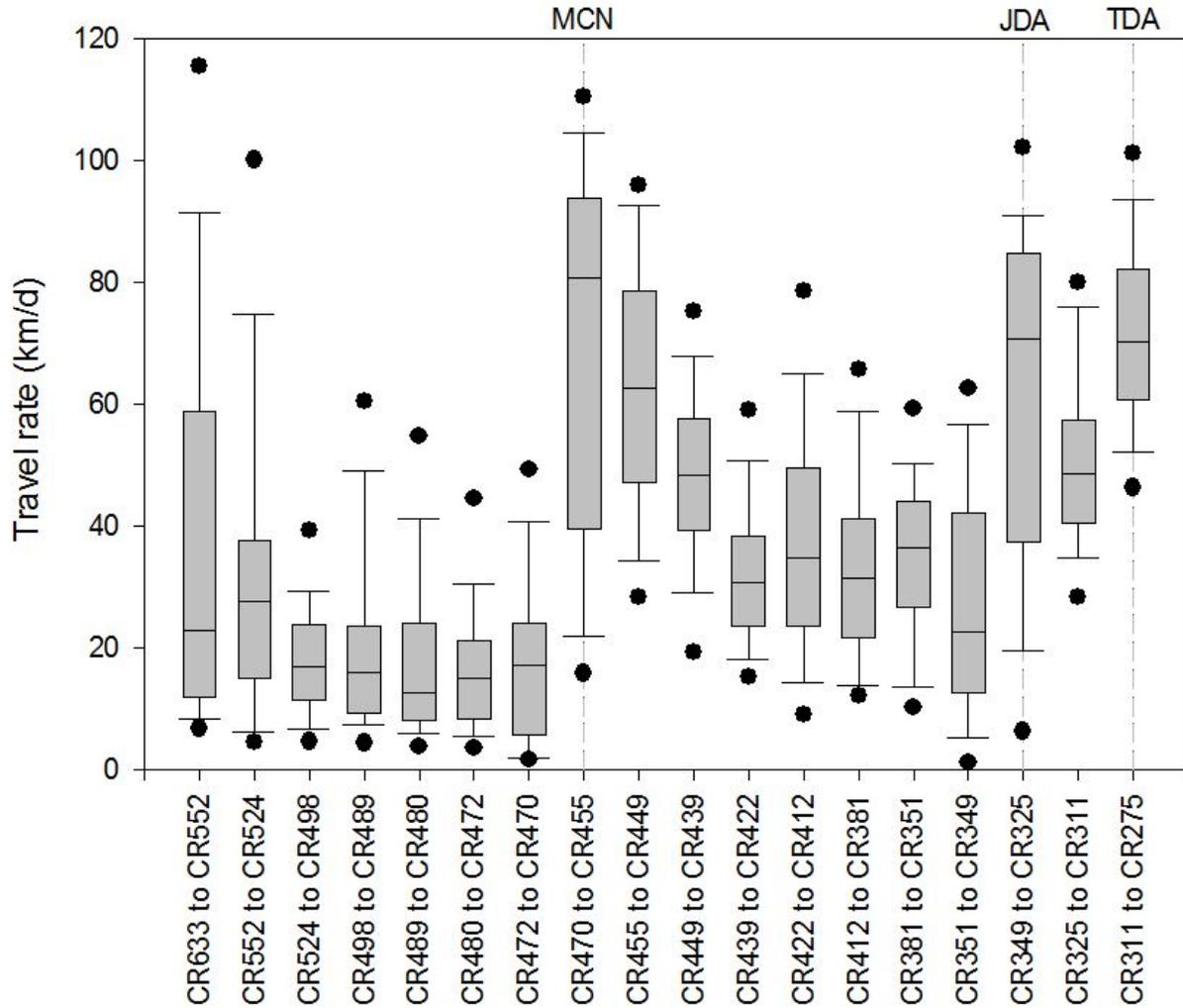
### 3.5.2 Priest Rapids Hatchery Fall Chinook Salmon

Similar to the trends observed for wild Hanford Reach fall Chinook salmon, acoustic-tagged fall Chinook salmon from PRH migrated through most river reaches in less than 2 d (Figure 3.17). The one exception was the Hanford Reach (release at PRH to CR552) where the median travel time was 3.7 d. PRH fall Chinook salmon had a longer travel time through the Hanford Reach than wild fish because they had a longer distance to travel to CR552 (81 km versus 43 km). Also similar to the trend observed for wild fish, we found the variability in travel times was greatest for acoustic-tagged PRH fall Chinook salmon in the Hanford Reach where 25% of the fish had travel times <1.5 d and 25% of the fish took >7.0 d to migrate through the reach. The median travel time of PRH fall Chinook salmon detected at McNary Dam was 11.6 d (25<sup>th</sup> percentile = 9.1 d; 75<sup>th</sup> percentile = 14.1 d).



**Figure 3.17.** Travel time (days) of acoustic-tagged Priest Rapids Hatchery fall Chinook salmon juveniles in each reach of the Columbia River studied in 2014. Solid lines within the boxes are median, the box boundary represents the 25<sup>th</sup> and 75<sup>th</sup> percentiles, whiskers indicate the 10<sup>th</sup> and 90<sup>th</sup> percentiles, and dots indicate the 5<sup>th</sup> and 95<sup>th</sup> percentiles. Dashed vertical lines indicate the locations of McNary (MCN), John Day (JDA), and The Dalles (TDA) dams.

Similar to the trends observed for wild Hanford Reach fall Chinook salmon, acoustic-tagged PRH fall Chinook salmon migrated most quickly, with the greatest variability, through flowing reaches, particularly those downstream from FCRPS dams (Figure 3.18). Again, the slowest travel rates were observed in McNary Reservoir where median travel rates were around 15 km/d. PRH fall Chinook salmon had higher median travel rates than wild fall Chinook salmon through all reaches examined in 2014, except in the two most upstream reaches (release to CR552 and CR552 to CR524).



**Figure 3.18.** Travel rate (km/d) of acoustic-tagged Priest Rapids Hatchery fall Chinook salmon juveniles in each reach of the Columbia River studied in 2014. Solid lines within the boxes are median, the box boundary represents the 25<sup>th</sup> and 75<sup>th</sup> percentiles, whiskers indicate the 10<sup>th</sup> and 90<sup>th</sup> percentiles, and dots indicate the 5<sup>th</sup> and 95<sup>th</sup> percentiles. Dashed vertical lines indicate the locations of McNary (MCN), John Day (JDA), and The Dalles (TDA) dams.



## 4.0 Discussion

This study was the first to attempt to partition mortality of wild Hanford Reach and PRH fall Chinook salmon into specific river reaches to identify potential sources of mortality. We identified river reaches in which survival was low, relative to the length of the reach. These data, combined with existing knowledge from previous studies, provided us with the information necessary to make inferences about the causes of the observed mortality.

We found groups of acoustic-tagged wild Hanford Reach and PRH fall Chinook salmon had a 0.50 probability of surviving to McNary Dam. Whereas this estimate is considerably higher than has been previously found for wild Hanford Reach fall Chinook salmon juveniles, it is substantially lower than what is typical for PRH smolts.

Survival of wild Hanford Reach fall Chinook salmon juveniles to McNary Dam has been estimated since 1995 from annual releases of ~3,000 to ~23,000 PIT-tagged fish (Fish Passage Center 2013). Survival of these groups to McNary Dam has ranged from 0.27 to 0.62 with an average survival probability of 0.37 (SE = 0.02). Similarly, the 9,940 wild Hanford Reach fall Chinook salmon juveniles that were implanted with PIT tags (PIT only) and released in 2014 had a survival probability of 0.34 (SE = 0.02) to McNary Dam. The large discrepancy between survival estimates derived from acoustic-tagged versus PIT-only groups is likely a result of the difference in fish size between groups. For comparison, PIT-only fish that measured <80 mm FL had a 0.31 (SE = 0.02) survival probability from release to McNary Dam in 2014 compared to 0.72 (SE = 0.12) for PIT-only fish that measured  $\geq 80$  mm FL. As previously mentioned, we attempted to minimize the effect of the transmitter on the performance of implanted fish by only tagging fish that measured  $\geq 80$  mm FL; whereas, fish as small as 60 mm FL were implanted with PIT tags. As we demonstrated, survival of these fish is strongly, positively correlated with fish length. Therefore, we expect that the survival of the overall population of juvenile wild Hanford Reach fall Chinook salmon through the study area was substantially lower than it was for the fish we tagged. However, we believe that the relative losses of tagged fish by reach were representative of the overall population.

Survival of PRH fall Chinook salmon juveniles to McNary Dam has been estimated since 1997 from annual releases of PIT-tagged fish (Richards et al. 2013). Survival of these groups to McNary Dam has ranged from 0.50 to 0.84 with an average of 0.68 (SE = 0.02). In 2014, the 31,980 PRH fall Chinook salmon juveniles that were implanted with PIT tags (PIT-only) had a 0.66 (SE = 0.02) probability of surviving to McNary Dam. The difference in survival between groups of acoustic-tagged and PIT-only PRH fall Chinook salmon juveniles observed in 2014 may have been the result of a reduction in performance of acoustic-tagged fish caused by the tagging procedure or presence of the tag, and/or a result of acoustic transmitter failure or loss.

A laboratory study was conducted at PNNL in 2013 to determine the minimum size fish that could be implanted with the downsized acoustic transmitter without affecting fish performance or survival. Results from this study found only 1 of 126 (0.8%) fall Chinook salmon (80–104 mm FL) surgically implanted (no suture; same method as used in this study) with a PIT tag and downsized acoustic transmitter died over a 60-day examination period and no fish dropped either tag during the study. Based on the results of

this study, we felt confident in using this method during a field trial. However, we observed relatively high post-tagging, pre-release mortality for the group of PRH fall Chinook salmon we implanted with acoustic transmitters for the in-river survival evaluation described in this report.

Acoustic-tagged PRH fall Chinook salmon juveniles had an estimated probability of surviving from tagging to acoustic detection in the outfall channel of 0.82 (SE = 0.03). Although several great blue herons *Ardea herodias* were frequently observed foraging in the outfall channel, it is unlikely heron predation accounted for all the mortality we observed in the channel pond and outflow channel since we did not observe the same level of mortality for the PIT-only group. The group of 31,980 PIT-only PRH fall Chinook salmon, which were implanted on May 29 (the day after acoustic tagging), had an estimated survival probability of 0.97 (SE < 0.01) from tagging to PIT detection in the outfall channel. Thus, it appears the acoustic-tagged group may have suffered some tag- or tagging-related mortality.

It is also apparent that some level of acoustic tag loss or failure occurred between tagging and volitional release to the river for the PRH group. Of the 167 PRH juveniles implanted with acoustic transmitters and PIT tags that were detected by the PIT array in the outflow channel, only 159 (95.2%) were also detected by the cabled acoustic array located in the outflow channel. Because the acoustic array in the outflow channel had a detection probability of 1.0, these results suggest an acoustic tag loss or failure rate of 4.8% occurred between tagging and detection in the outflow channel. The first tag in the tag-life study that died did so after 47.6 days, with over 75% of the tags lasting >100 days. Therefore, it is likely tag loss and not tag failure accounted for the 5% non-detection rate observed during the first couple of weeks between tagging and detection in the outflow channel.

Because we estimated survival of acoustic-tagged PRH juveniles by forming a virtual release of only those fish detected by the cabled acoustic array located in the outflow channel (CR633), fish that died or dropped their tag prior to volitional release into the river were not included in the estimate. However, it is possible that some tag- or tagging-related mortality continued to occur once fish left the PRH outflow channel and entered the Columbia River. We also have evidence that tag loss continued after fish entered the river. Twenty-one acoustic-tagged hatchery fall Chinook salmon that had an active transmitter when they left PRH (i.e., they were detected at CR633) were detected by the PIT array in the JBS of McNary Dam. Of those, two (9.5%) were not detected by any adjacent acoustic receiver arrays, suggesting the fish were still alive but no longer had acoustic transmitters. Two of 27 (7.4%) acoustic-tagged wild Hanford Reach fall Chinook salmon that were detected by the McNary Dam JBS PIT array appeared to have dropped their acoustic tags (i.e., they were not detected by adjacent acoustic arrays). Three of 23 (13.0%) acoustic-tagged fish detected by the PIT array in the JBS of John Day Dam were not detected by adjacent acoustic receiver arrays.

Existing evidence suggests that fish routed through the JBS at hydroelectric dams of the FCRPS may be smaller or weaker, on average, than fish that pass the dams using other routes (Zabel et al. 2005). Fish that expelled their transmitter may be expected to have complications that could potentially inhibit their performance, making them more likely to pass through the JBS at FCRPS dams. Thus, the tag loss percentages presented above may be biased high and represent an absolute worst-case scenario. However, even at these rates, the effect of tag loss on survival estimation is relatively small. For example, 101 of the 198 (51.0%) acoustic-tagged wild Hanford Reach fall Chinook salmon were detected at CR472. Because this array had a detection probability of 1.0, the probability of survival from release

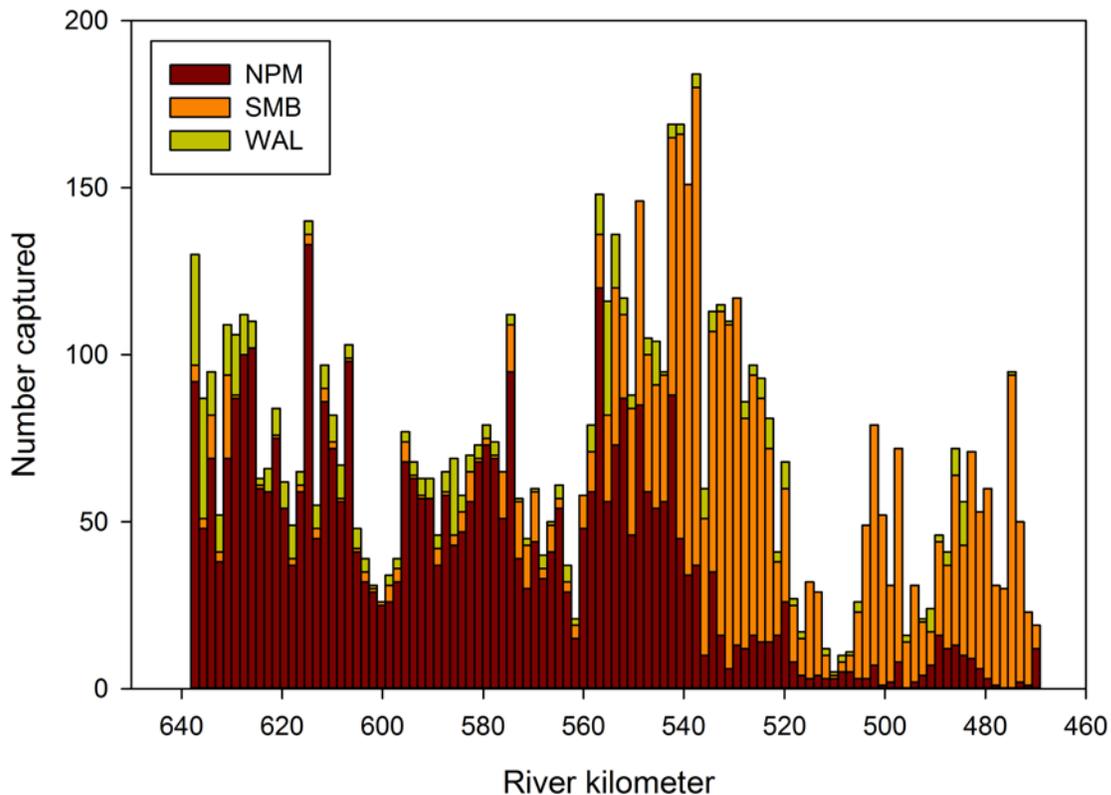
to CR472 is 0.51 (SE = 0.04). If we assume 7.4% of the fish that were not detected at CR472 were living fish that had expelled their transmitter, the survival estimate becomes 0.55, which is within the 95% confidence interval of the original estimate.

The greatest bias associated with the survival estimates for the group of wild Hanford Reach fall Chinook salmon may be the presence of a tag or tagging effect, which we would expect to manifest itself soon after implantation, as we observed for the PRH fish. Because wild Hanford Reach fall Chinook salmon were released just 24-h after tagging, they were not afforded the time to exhibit the tag or tagging effect prior to release. Thus, survival of the wild Hanford Reach group was likely underestimated in reaches located near the release site if they exhibited a tag or tagging effect similar to that experienced by the PRH group.

Reach survival of wild Hanford Reach fall Chinook salmon, estimated on a per-kilometer basis, was lower in all reaches located between release (rkm 595) and CR422 compared to those located downstream of CR422. We observed relatively low and similar estimates of  $S_{km}$  among the three most upstream reaches we studied. As mentioned previously, the presence of a tag or tagging effect may have contributed to relatively low survival of acoustic-tagged wild fall Chinook salmon in the Hanford Reach between release and CR552. However, the potential for predation from piscivorous birds and fishes exists within the Hanford Reach.

Each spring (May and June), the Oregon Department of Fish and Wildlife (ODFW) conducts electrofishing surveys for predators in the Columbia River. The focus of the electrofishing effort is to capture and tag as many pikeminnow as possible for estimation of sport-reward fishery exploitation rates. Therefore, capture priorities have focused on northern pikeminnow with other predators (particularly smallmouth bass, walleye, and channel catfish) sampled less consistently. However, these data provide empirical information of the distribution of piscivorous fish predators in the Columbia River. Electrofishing catches indicate northern pikeminnow and walleye are more abundant in the Hanford Reach than in McNary Reservoir (Peter McHugh, [ODFW], unpublished data; Figure 4.1). Using recoveries of marked fish at the sport reward stations and the Cormack-Jolly-Seber model for open populations (Seber 1982; Hayes et al. 2007), we estimated the annual (2001–2009) population abundance for northern pikeminnow  $\geq 228$  mm FL that inhabit the Columbia River between the mouth of the Yakima River and Priest Rapids Dam. Excluding two years that were obvious outliers due to low numbers of recaptures, population abundance averaged 37,392 (SE = 6,843) northern pikeminnow.

Northern pikeminnow have been identified as a major predator of juvenile salmonids in the Columbia River (Poe et al. 1991; Rieman et al. 1991; Vigg et al. 1991; Zimmerman 1999). Poe et al. (1991) and Zimmerman (1999) estimated juvenile salmonids accounted for 67% and >84%, respectively, of northern pikeminnow diets in reservoirs of the Columbia River. Although to a lesser extent, these same studies also identified walleye as a predator of juvenile salmonids. For example, Poe et al. (1991) found juvenile salmonids made up 14% of the diet of walleye. The presence of these predators has the potential to reduce survival of upriver bright fall Chinook salmon juveniles migrating through the lower Hanford Reach.



**Figure 4.1.** Total numbers of northern pikeminnow (NPM), smallmouth bass (SMB), and walleye (WAL) captured during Oregon Department of Fish and Wildlife electrofishing surveys conducted annually from 1993–2010 between McNary and Priest Rapids dams.

Upriver bright fall Chinook salmon are also susceptible to predation from Caspian terns *Hydroprogne caspia* that nest on Goose Island on Potholes Reservoir, which is located about 33 km north-northeast of the Hanford Reach. GPS-tagged terns from this colony have been recorded making foraging trips to the Hanford Reach. Avian predation rates, estimated as the proportion of PIT tags recovered (i.e., detected by mobile PIT antennas) on Goose Island that were previously detected by the PIT array at Rock Island Dam, averaged 0.2% for this colony on upper Columbia River summer/fall Chinook salmon between 2009–2012 (Roby et al. 2013). In 2014, the nesting colony consisted of 340 breeding pairs (Bird Research Northwest 2014).

Acoustic-tagged wild Hanford Reach fall Chinook salmon also experienced relatively low survival in the reach located between CR552 and CR524. Results from ODFW electrofishing surveys reveal an abundance of both northern pikeminnow and smallmouth bass within this reach (Figure 4.1). This reach contains the mouth of the Yakima River, which has been identified as a major spawning tributary for Columbia River smallmouth bass. From 1998 to 2001, Fritts and Pearsons (2004) observed an increase in the abundance of smallmouth bass >150 mm in the Yakima River from an annual average of about 3,000 bass in mid-March to almost 20,000 bass in mid-June. The authors attributed the increase primarily to immigration of fish from the Columbia River and estimated that an average of just over 200,000

salmonids, most of which were fall Chinook salmon, were consumed annually by smallmouth bass in the Yakima River during the spring. It is likely that high rates of smallmouth bass predation on fall Chinook salmon occur in the Columbia River during this time as well. A study conducted by Tabor et al. (1993) in a 6-km stretch of the Columbia River near Richland, WA found juvenile salmonids, primarily subyearling fall Chinook salmon, made up 59% of smallmouth bass diet by weight. The authors attributed the high predation rates to the abundance of subyearling fall Chinook salmon juveniles of suitable forage size emigrating from the Hanford Reach and the overlap of habitats of the two species. Others have identified the vulnerability of wild subyearling fall Chinook salmon juveniles to predation by smallmouth bass due to habitat overlap in low velocity nearshore areas (Curet 1993) and the small size of wild fall Chinook salmon juveniles at the time of emigration (Zimmerman 1999).

Although difficult to quantify, the Yakima River also seems to contain a rather sizeable population of channel catfish, which appear capable of consuming large numbers of juvenile salmonids (Pearsons et al. 2001). A naturally reproducing population of channel catfish also inhabits the Columbia River where they have been found to consume large numbers of juvenile salmonids (Poe et al. 1991). The presence of large populations of predatory fish, combined with the reduction in water particle travel rate as the river transitions from free-flowing to reservoir-influenced, makes juvenile fall Chinook salmon vulnerable to predation within this reach (CR552 to CR524).

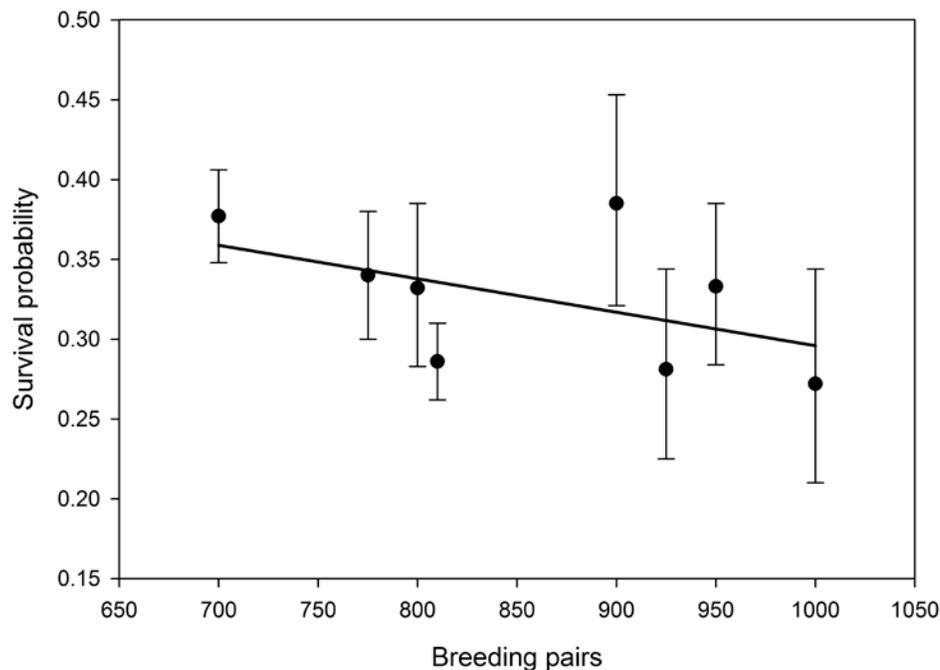
The risk of avian predation in this reach (CR552 to CR524) remains relatively unknown. Large nesting colonies of California gulls *Larus californicus* and ring-billed gulls *Larus delawarensis* inhabit Island 20 near the town of Richland, Washington at rkm 545 (Figure 2.1). In 2014, 12,500 nesting gulls were observed on the island (Bird Research Northwest 2014), which has only ever been partially scanned for PIT tags (Roby et al. 2013). Thus, reliable predation rate estimates do not exist for these colonies. However, diet analyses of gulls from colonies located upstream of McNary Dam indicated these birds consume very small amounts of salmonids (Roby et al. 2013).

The next downstream reach, CR524 to CR498, contains the mouth of the Snake River, a large backwater slough, several islands that host colonies of piscivorous birds, and the mouth of the Walla Walla River. The ODFW electrofishing survey data indicate the abundance of northern pikeminnow and walleye are relatively low in this reach. However, walleye are frequently the target of recreational fishers in this section of the Columbia River, suggesting they are present. Electrofishing catches indicate a rather sizeable smallmouth bass population is present in this reach as well (Figure 3.18). In addition, the Snake and Walla Walla rivers are two of the few rivers in Washington that contain naturally reproducing populations of channel catfish (Lower Columbia Fish Recovery Board 2004). Thus, there is no shortage of piscivorous fishes in this reach of the Columbia River that may contribute to the below-average survival estimate we observed for acoustic-tagged wild Hanford Reach fall Chinook salmon.

As mentioned, the reach located between CR524 and CR498 is also home to several nesting colonies of piscivorous waterbirds. These include populations of double-crested cormorants *Phalacrocorax auritus* on Foundation Island, American white pelicans *Pelecanus erythrorhynchos* on Badger Island, and California gulls, ring-billed gulls, and Caspian terns on Crescent Island (Evans et al. 2012). Bird Research Northwest conducted waterbird surveys of the islands during the spring and summer of 2014 and counted 390 nesting pairs of double-crested cormorants on Foundation Island, 273 American white pelicans on Badger Island, and 395 nesting pairs of Caspian terns and 6,200 California gulls on Crescent

Island (Bird Research Northwest 2013). Several other bird species, including great blue herons, great egrets *Ardea alba*, black-crowned night-herons *Nycticorax nycticorax*, and ring-billed gulls, were frequently observed on the islands in relatively small numbers.

The outmigration timing of upriver bright fall Chinook salmon coincides with the chick rearing period (May and June) for the majority of birds on these colonies. Thus, juvenile fall Chinook salmon from the Hanford Reach are migrating through this reach during the period of highest energy demand for these predatory birds. Roby et al. (2012) found salmonids accounted for almost 70% of tern prey items at the Crescent Island colony over a 12-year period between 2000 and 2011, representing an average of about 500,000 salmonids consumed annually. However, this estimate includes steelhead, coho, sockeye, spring Chinook, and Snake River fall Chinook in addition to URB fall Chinook salmon. During the period of URB fall Chinook salmon outmigration, salmonids, which would be primarily fall Chinook salmon at this time, still make up about 60–70% of the Crescent Island tern diet (Roby et al. 2013). We observed a negative relationship between survival to McNary Dam as estimated for PIT-tagged wild Hanford Reach fall Chinook salmon and the number of Caspian tern breeding pairs counted on colonies of the Columbia Plateau (primarily Crescent and Goose islands; Figure 4.2). However, the relationship was not significant ( $p = 0.210$ ;  $R^2 = 0.248$ ) but should continue to be evaluated into the future to determine whether a significant trend develops. It is unlikely cormorants of the Foundation Island colony substantially affect survival rates of URB fall Chinook salmon in McNary Reservoir. Roby et al. (2013) found salmonids accounted for only 10% of the prey biomass in the diet of Foundation Island cormorants during the outmigration period of URB fall Chinook salmon juveniles.



**Figure 4.2.** Relationship between annual survival probability of PIT-tagged wild Hanford Reach fall Chinook salmon and the number of Caspian tern breeding pairs counted on colonies of the Columbia Plateau (2005, 2007–2013). Error bars denote standard errors.

Although the estimated number of smolts consumed by the Crescent Island tern colony is relatively large, it may not represent a significant percentage of the population of salmonid smolts that migrate past the island. Avian predation rates, estimated as the proportion of tags recovered (i.e., detected by mobile PIT antennas) on the islands that were previously detected by PIT arrays at upstream dams, have been consistently low for subyearling fall Chinook salmon juveniles at these colonies. In a study to estimate avian predation rates on Endangered Species Act-listed salmonid evolutionary significant units of the Columbia River basin between 2007 and 2010, Evans et al. (2012) found that all colonies in this reach combined to consume an annual average of 1.6% of the Snake River fall Chinook salmon that were last detected at Lower Monumental Dam. Although this should be viewed as a minimum estimate due to the large distance between the colonies and Lower Monumental Dam (76 km) and uncertainty regarding the off-colony deposition of tags (Roby et al. 2013), it indicates the actual predation rate on juvenile Snake River fall Chinook salmon may be quite low. We would expect the predation rate of URB fall Chinook salmon to be similarly low.

The reaches with the lowest  $S_{km}$  estimates were those located near McNary Dam, with the lowest being observed in the immediate forebay. An evaluation of predation by resident piscivorous fish on juvenile salmonids between McNary and John Day dams revealed predation was most intense in areas near the dams (Poe et al. 1988). The authors attributed this finding to the delay and disorientation of salmonids associated with dam passage and the increased densities of piscivorous fish species in slack water areas near dams. Indeed, we observed the slowest travel rates of acoustic-tagged fish in reaches of McNary Reservoir, indicating their migration was slowed by presence of the dam, thereby subjecting them to predation for a longer period of time. Electrofishing catches indicate the forebay of McNary Dam may contain a rather sizeable smallmouth bass population (Figure 4.1).

In addition to attracting predaceous fishes, feeding aggregations of piscivorous waterbirds are also frequently observed near dams of the Columbia River. In addition to terns and cormorants, even gulls find success preying on salmonid smolts near dams of the Snake and Columbia rivers. Low survival of acoustic-tagged juvenile salmonids in the tailrace of McNary Dam in 2012 was attributed to high rates of avian predation by ring-billed gulls (Hughes et al. 2013). Juvenile salmonids, disoriented after dam passage, are particularly susceptible to avian predation in the immediate tailrace of FCRPS dams (Williams 2006). For example, gull predation rates of 6% and 11% were observed in the tailrace of The Dalles Dam for radio-tagged subyearling and yearling Chinook salmon, respectively (Collis et al. 2002). High rates of avian predation at FCRPS dams has led to bird hazing and installation of wires stretched across the river to discourage birds from entering the tailrace.

The tailrace of McNary Dam has also been identified as an area of high salmonid predation by piscivorous fish. Poe et al. (1991) found that about 80% of northern pikeminnow and 60% of channel catfish diets (by weight) were composed of juvenile salmonids in the immediate tailrace of McNary Dam. Salmonids made up a smaller percentage of the diets of walleye (~15%) and smallmouth bass (<5%) in McNary tailrace. Rieman et al. (1991) estimated an average of 2.7 million juvenile salmonids were lost annually (for the period 1983–1986) to predation by piscivorous fish (northern pikeminnow, walleye, smallmouth bass) between McNary and John Day dams, which represented about 9% to 19% of all salmonids that entered the reach. Much of the loss (21%) was estimated to have occurred in the immediate tailrace of McNary Dam where northern pikeminnow and channel catfish were abundant (Poe et al. 1991; Rieman et al. 1991). Thus, the reported estimates would likely have been higher had

predation by channel catfish been included. Of the species that were included, northern pikeminnow accounted for 78% of the total salmonid loss, walleyes accounted for 13%, and smallmouth bass for 9%. However, the contribution of walleyes and smallmouth bass to the total mortality increased in July and August when mortality rates were highest and the majority of salmonids consumed were subyearling fall Chinook salmon.

Although Rieman et al. (1991) observed very high predation rates in the immediate tailrace of McNary Dam, predation in the main body of John Day Reservoir represented the majority (79%) of the total salmonid loss to piscivorous fish. The authors observed relatively low consumption rates by northern pikeminnow in the main body of the reservoir but emphasized the effect a low consumption rate can have when the abundance of predators is high, as appears to be the case in John Day Reservoir. Rieman et al. (1991) estimated there to be 85,000 northern pikeminnow and 10,000 walleyes >250 mm and 35,000 smallmouth bass >200 mm in the reservoir.

We observed low survival of acoustic-tagged wild Hanford Reach fall Chinook salmon between CR449 and CR422. This reach contains Paterson Slough on the Washington shore, McCormack Slough on the Oregon shore, a backwater area near Crow Butte, and many miles of heavily rip-rapped shorelines. The three embayments (Paterson, McCormack, and Crow Butte), which cover about 1,700 acres (U.S. Army Corps of Engineers 1995), have been identified as flow refugia and potential spawning areas for nonnative piscivorous fish species (Nigro et al. 1985). Smallmouth bass and walleye are frequently targeted by anglers in the area around Paterson Slough, McCormack Slough, and the Blalock Islands, suggesting increased densities of these predators in those areas.

In addition to providing habitat to nonnative predaceous fishes, several islands in this reach, including the Blalock Islands, are home to nesting colonies of multiple avian predators, including California and ring-billed gulls and Caspian and Forster's terns. Surveys conducted by Bird Research Northwest during the spring and summer of 2014, revealed colonies of 199 terns (both Caspian and Forster's terns) and 4,630 gulls (both California and ring-billed) on the island complex (Bird Research Northwest 2014). Other birds, such as great egrets, black-crowned night-herons, great blue herons, and American white pelicans were also observed on the island in smaller numbers. Minimum predation rates of Blalock Island-nesting terns on Snake River fall Chinook salmon have been historically quite low, averaging <0.1% from 2007–2010 (Evans et al. 2012). Again, we would expect the predation rate on URB fall Chinook salmon to be similarly low. Predation rates from the Blalock Island complex gull colonies have not been estimated to our knowledge.

Relative survival ( $S_{km}$ ) was high for acoustic-tagged wild Hanford Reach fall Chinook salmon from CR422 down to John Day Dam (CR349) before dipping slightly in the reaches that included passage through John Day and The Dalles dams and their tailraces (CR349 to CR325 and CR311 to CR275). The reach between CR349 and CR325 is home to a nesting colony of California gulls on Miller Rocks Island that numbered 3,100 individuals in 2014 (Bird Research Northwest 2014). Evans et al. (2012) estimated the average annual minimum predation rate of the Miller Rocks Island gulls to be 0.4% of the Snake River fall Chinook salmon that passed McNary Dam. The rate is likely similarly low for URB fall Chinook salmon juveniles.

Much of the mortality in the tailraces may be attributed to predation by resident fish, which is known to be a substantial source of mortality in dam tailraces and outfall locations (Lower Columbia River Fish Recovery Board 2004). The tailrace of John Day Dam has been identified as an area with relatively high densities of walleye (Porter 2009). The Dalles Dam tailrace has a complex basin with a series of downriver islands where predators reside, is relatively shallow with armored bedrock substrate, has an adjacent slough-like habitat on the south side of the river, and riprap-lined banks. Petersen et al. (2001) found relatively high numbers of smallmouth bass compared to northern pikeminnow in The Dalles Dam tailrace. The authors estimated 1,000 to 2,000 smallmouth bass were present in the immediate tailrace of The Dalles Dam, although this estimate was based on relatively few marked and recaptured fish.

Acoustic-tagged fall Chinook salmon from PRH survived at a higher rate than the wild group in most reaches, particularly those located upstream of McNary Dam. The lower survival of wild Hanford Reach fall Chinook salmon upstream of McNary Dam may have been a result of a tagging effect. As mentioned previously, the group of acoustic-tagged PRH fish suffered high mortality, likely as a result of a tagging effect during the two-week period between tagging and release. The wild group was released 24 hours after tagging and therefore suffered any potential tagging effect in-river. Trends in  $S_{km}$  were generally similar between groups of acoustic-tagged wild Hanford Reach and PRH fall Chinook salmon. The primary differences included higher  $S_{km}$  rates for PRH fish in the forebay of McNary Dam between CR498 and CR472 and lower  $S_{km}$  for PRH fish in the immediate forebay of John Day Dam.

Data from this study and others indicate much of the mortality incurred by URB fall Chinook salmon juveniles between Priest Rapids and Bonneville dams can likely be attributed to predation from resident piscivorous fish. We observed no significant relationship between the survival of PIT-tagged wild Hanford Reach fall Chinook salmon to McNary Dam and the size of the primary avian predator nesting colonies located in McNary Reservoir. We also did not observe mortality “hot spots” in the reaches of the Columbia River that contain the largest colonies of predaceous waterbirds. Instead, we observed relatively consistent mortality rates between release and CR422, which is more indicative of predation from piscivorous fish, which are more widely distributed than avian predators. Additionally, it is likely we “missed” much of the predation by piscivorous fish (thereby overestimating reach survivals) due to the relatively large size of fish we were able to implant with acoustic transmitters. Avian predators, on the other hand, appear to target larger individuals, as evidenced by their high predation rates on steelhead smolts (Collis et al. 2001; Antolos et al. 2005); thus, it is unlikely we would have “missed” any mortality “hot spots” due to avian predation. In addition, results of studies conducted to assess avian predation rates have consistently estimated very low predation rates on subyearling fall Chinook salmon upstream of Bonneville Dam (<2%; Evans et al. 2012; Roby et al. 2013). Alternatively, predation rates estimated for piscivorous fish suggest they may be consuming 17% of the juvenile salmon that enter John Day Reservoir during June, July, and August, when most salmon smolts entering the reservoir are subyearling fall Chinook salmon (Rieman et al. 1991). Harnish et al. (2013) estimated about 43 million URB fall Chinook salmon presmolts were produced annually in the Hanford Reach between BY 1984–2004. Assuming a survival probability of 0.37 to McNary Dam (as estimated from annual releases of PIT-only wild URB fall Chinook salmon in the Hanford Reach), about 16 million Hanford Reach URB juveniles enter John Day Reservoir annually. Thus, if piscivorous fish consume 17% of the population, an estimated 2.7 million URB fall Chinook salmon juveniles would be consumed annually in John Day

Reservoir. If predation rates are of similar magnitude in other reservoirs, predation by resident piscivorous fish is clearly an important source of mortality.

The high rate of salmonid smolt predation observed by Rieman et al. (1991) for resident piscivorous fish in John Day Reservoir led to development of the Northern Pikeminnow Management Program (NPMP) in 1990–1991. The NPMP consists of a “sport-reward” fishery, which offers public anglers a monetary incentive to catch northern pikeminnow, and “dam-angling”, whereby agency personnel are hired to angle for northern pikeminnow at FCRPS dams. The program was founded on modeling simulations that indicated a 10–20% exploitation rate on predator-sized northern pikeminnow would reduce predation on juvenile salmonids by 50% (Rieman and Beamesderfer 1990). The program has appeared effective at reducing the abundance of northern pikeminnow. The catch-per-unit-effort and abundance index data have shown a continued and persistent decrease in the number of northern pikeminnow  $\geq 250$  mm in the Snake and Columbia rivers since the NPMP was implemented (Gardner et al. 2013; Barr et al. 2014).

Removal of northern pikeminnow will only improve survival of migrating juvenile salmonids if a compensatory response by other predatory fishes does not offset the net benefit of removal. Although an increase in the proportion of smallmouth bass diets containing juvenile salmonids has not been observed from smallmouth bass captured annually during electrofishing and dam-angling efforts of the NPMP, smallmouth bass abundance and predation index values have increased in recent years in some areas of Snake and Columbia river reservoirs (Gardner et al. 2013; Barr et al. 2014). As noted by Carey et al. (2011), smallmouth bass have become a large component of the fish community of the Snake and Columbia rivers, largely due to the habitat created by human modifications (e.g., dams) of the landscape. Juvenile salmonids continue to be a common item in the diets of Columbia River walleyes, which have also shown an increase in abundance index in areas of John Day and The Dalles reservoirs (Gardner et al. 2013). Increases in the abundance index of these predators may be an early indication of a compensatory response to the removal of northern pikeminnow from the system (Gardner et al. 2013; Barr et al. 2014).

If indeed a compensatory response develops, the NPMP may need to be expanded to include other predatory species, such as smallmouth bass and walleye to achieve the same benefit to salmonid survival. Whereas smallmouth bass and walleye represent a potential significant threat to the survival of salmonid smolts in the Snake and Columbia rivers, options to manage these species are complicated because fisheries agencies are simultaneously charged with enhancing fishing opportunities and controlling predators of threatened and endangered salmon (Carey et al. 2011). However, if salmon survival and conservation is to be prioritized, there is a clear need to identify and test potential management options aimed at reducing predation from resident piscivorous fishes.

Altering dam operations is another potential management option that has been used successfully in the past to improve survival of smolts through the FCRPS. For example, increases in the amount and percentage of water that is routed through the spillways at dams has been attributed to increased survival of salmonid smolts in the Snake and Columbia rivers (e.g., Adams et al. 2012). It may be possible to manage reservoir levels in such a way as to disrupt the spawning activities or recruitment success of predaceous fish species. Several studies have demonstrated that fluctuations in discharge can negatively affect the reproductive success of smallmouth bass by flooding nests with cooler water, depositing silt,

driving away adult bass guarding nests, exposing eggs to desiccation, or stranding emerged fry (Henderson and Foster 1957; Becker et al. 1981; Lukas and Orth 1995). A study of factors that influence smallmouth bass production in the Hanford Reach indicated fluctuations in discharge from Priest Rapids Dam reduced productivity (Montgomery et al. 1980). In order to be successful, disruptions to spawning activities would need to occur throughout the major spawning areas for sufficient duration over multiple years to cause year-class failures. Major spawning areas would need to be identified and a feasibility study would be required to assess whether the operational flexibility exists at dams of the Columbia River to implement the operations necessary to create the desired disruptions.

Our study confirmed that the loss rates of juvenile URB fall Chinook salmon from the Hanford Reach were high in areas where habitat has been influenced by hydropower development and native and non-native predatory fish species. Whereas our study had some limitations due to 1) the size of fish we were able to tag, 2) the potential for a tag or tagging effect on fish performance, and 3) possible tag loss, we believe that the relative loss rates are representative for the wild Hanford Reach and Priest Rapids Hatchery portions of the URB stock. Most of the loss appears to be concentrated in the river/reservoir transition area where large predator-rich tributaries enter as well as in the immediate dam forebays where travel rates of outmigrating smolts are slowed. Additional work to document how the predation rates we observed in the larger size classes of juvenile URB fall Chinook salmon relate to the overall population, as well as efforts to determine the potential effectiveness of management actions intended to reduce the populations and/or productivity of piscivorous fish species will provide the information necessary to enable managers to design and implement strategies to improve the freshwater survival of this important stock.



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