PNNL-28579

Passage and Survival of Yearling and Subyearling Chinook Salmon and Steelhead Smolts at Lower Granite Dam, 2018

Final Report

March 2019

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Prepared for the U.S. Army Corps of Engineers, Walla Walla District, Under an Interagency Agreement with the U.S. Department of Energy

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Pacific Northwest National Laboratory
Richland, Washington 99352

Preface

This study was conducted by the Pacific Northwest National Laboratory (PNNL) and the University of Washington (UW) for the U.S. Army Corps of Engineers, Walla Walla District (USACE). The PNNL and UW project managers were Kenneth D. Ham and John R. Skalski, respectively. The USACE technical lead was Derek Fryer. The study was designed to estimate dam passage survival at Lower Granite Dam as stipulated by the 2008 Federal Columbia River Power System Biological Opinion and provide additional performance measures at that site as stipulated in the Columbia Basin Fish Accords.

This report summarizes the performance and survival studies performed at Lower Granite Dam during spring and summer 2018.

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Executive Summary

The purpose of this passage and survival study was to estimate fish performance metrics associated with passage through Lower Granite Dam (LGR) for emigrating yearling and subyearling Chinook salmon and steelhead smolts in 2018. The performance metrics estimated during this study included dam passage survival, forebay-to-tailrace survival, forebay residence time, tailrace egress time, and spill passage efficiency (SPE). Under the 2008 Federal Columbia River Power System (FCRPS) Biological Opinion (BiOp), dam passage survival probability is required to be greater than or equal to 0.96 for spring migrants, greater than or equal to 0.93 for summer migrants, and estimated with a standard error (SE) less than or equal to 0.015. This 2018 study was designed to achieve a standard error of 0.025 to reduce the number of tagged fish required during testing. The study also estimated smolt passage survival from the forebay (1 km upstream of the dam) to the tailrace (2 km below the dam). These areas coincide with the boundaries of the Boat Restricted Zone (BRZ) upstream or downstream of the dam, so this metric is also known as "BRZ-to-BRZ survival." Forebay residence time, tailrace egress time, and SPE were also estimated, as required in the Columbia Basin Fish Accords (Fish Accords).

Two study designs were used to estimate dam passage survival at LGR: The virtual/paired-release model (VIPRE) and the virtual release/dead fish correction (ViRDCt) model. Both models relied on releases of acoustic-tagged smolts above LGR that contributed to the formation of a virtual release at the face of LGR. The VIPRE model used two additional downstream releases of live-tagged fish to adjust for mortality of the virtual release group that occurs between the immediate tailrace and the primary survival array, which was located 33 to 40 km downstream. The ViRDCt model used releases of dead tagged fish at the dam to correct the estimate for fish that died during passage but were detected on the array deployed in the immediate tailrace. A total of 455 yearling Chinook salmon, 675 steelhead, and 881 subyearling Chinook salmon were used in the virtual releases. Sample sizes for the below-dam paired releases were 299 and 298 yearling Chinook salmon, 500 and 501 steelhead, and 690 subyearling Chinook salmon. The Juvenile Salmon Acoustic Telemetry System (JSATS) injectable tag model number SS400, BR306 Battery, weighing 0.221 g in air, was used in this investigation.

All LGR passage and survival metrics measured in 2018 for yearling and subyearling Chinook salmon and juvenile steelhead are presented in Table ES.1.

Table ES.1 Lower Granite Dam 2018 Survival Study Summary

Year: 2018

Study Site(s): Lower Granite Dam

Objective(s) of study: Estimate dam passage survival and other performance measures for yearling Chinook salmon, steelhead, and subyearling Chinook salmon.

Hypothesis (if applicable): Not applicable; this is a compliance study.

Fish:
- Species-race: yearling Chinook salmon (CH1), steelhead (STH), subyearling Chinook salmon (CH0)
- Source: LGR Smolt Monitoring Facility

Implant Procedure:
- Surgical: Yes
- Injected: No

Size (median):	CH1	STH	CH0
Weight (g):	23.3	89.2	13.6
Length (mm):	138	222	110

Sample Size:	CH1	STH	CH0
# Release Sites:	3	3	3
Total # Released:	1063	1681	2773

Tag Type: Advanced Telemetry Systems (ATS)-156dB

Model	Weight (air)
SS400	0.221 g

Analytical Model: Virtual/paired-release model and virtual release/dead fish correction model

Characteristics of Estimate:
Effects Reflected (direct, total, etc.): Direct
Absolute or Relative: Absolute

Environmental/Operating Conditions (daily from 17 April 2018 through 26 May 2018):

Statistic	Mean	Min	Max
River Discharge (kcfs):	123.2	88.1	174.9
Spill Discharge (kcfs):	40.6	31.1	73.4
Percent Spill (24 h/d):	33.9	23.2	50.1
Temperature (°C):	10.9	8.9	12.8
Total Dissolved Gas % (tailrace):	117.1	114.1	127.9

Treatment(s): None
Unique Study Characteristics: Court-ordered spill to the gas cap

Environmental/Operating Conditions (daily from 31 May 2018 through 9 July 2018):

Statistic	Mean	Min	Max
River Discharge (kcfs):	71.1	30.4	153.6
Spill Discharge (kcfs):	27.7	17.4	45.4
Percent Spill (24 h/d):	42.5	24.2	75.5
Temperature (°C):	16.3	13.2	18.5
Total Dissolved Gas % (tailrace):	115.4	111.6	119.2

Treatment(s): None
Unique Study Characteristics: Court-ordered spill to the gas cap through 20 June

Survival and Passage Estimates (value & SE):	CH1	STH	CH0
Dam survival			
• VIPRE	0.9726 (0.0159)	0.9959 (0.0099)	0.9422 (0.0217)
• ViRDCt	0.9877 (0.0062)	0.9936 (0.0037)	0.9242 (0.0098)
Forebay-to-tailrace survival (season-wide)			
• VIPRE	0.9728 (0.0159)	0.9961 (0.0099)	0.8837 (0.0211)
• ViRDCt	0.9877 (0.0062)	0.9936 (0.0037)	0.9097 (0.0106)
Forebay residence time (hours; median; mean, [SE])	4.92; 10.13 [0.62]	4.07; 13.42 [1.34]	8.96; 62.10 [4.03]
Tailrace egress rate (hours; median; mean, [SE])	0.27; 2.00 [0.86]	0.27; 2.93 [2.27]	0.62; 2.15 [0.29]
Spill passage efficiency	0.6212 (0.0226)	0.5735 (0.0190)	0.7969 (0.0135)
Fish passage efficiency	0.9286 (0.0120)	0.9662 (0.0069)	0.9125 (0.0095)

Compliance Results: CH1 and STH $S \geq 0.96$; CHO $S \geq 0.93$

Acknowledgments

This study was the result of hard work by dedicated scientists and engineers from the Pacific Northwest National Laboratory (PNNL), Mainstem Fish Research (MFR), the U.S. Army Corps of Engineers, Walla Walla District (USACE), and the University of Washington (UW). Their teamwork and attention to detail, schedule, and budget were essential for the study to succeed in providing high-quality, timely results to decision-makers.

- MFR: Geoff McMichael, Ryan Flaherty.
- PNNL: Brian Bellgraph, Jarod Cable, Dustin Clelland, Daniel Deng, Bernardo Do Vale Beirao, Corey Duberstein, Joanne Duncan, Kristin Engbrecht, Nikki Fuller, Lysel Garavelli, Christopher Grant, Kris Hand, Josh Hubbard, Jill Janak, Kyle Larson, Huidong Li, Xinming Lin, Tim Linley, Jun Lu, Jayson Martinez, Erin McCann, Bob Mueller, Megan Nims, Brett Pflugrath, Briana Rhode, Aljon Salalila, John Stephenson, Scott Titzler, Yong Yuan, Shon Zimmerman.
- USACE: Brad Eppard, Derek Fryer, Stephen Hampton, Elizabeth Holdren, Chris Pinney, Tim Wik.

Acronyms and Abbreviations

ATS	Advanced Telemetry Systems
BiOp	biological opinion
BRZ	boat-restricted zone
C	degree(s) Celsius
CH0	subyearling Chinook salmon
CH1	yearling Chinook salmon
FCRPS	Federal Columbia River Power System
FPE	fish passage efficiency
g	gram(s)
h	hours(s)
JBS	juvenile bypass system
JSATS	Juvenile Salmon Acoustic Telemetry System
kcfs	thousand cubic feet per second
km	kilometer(s)
L	liter(s)
LGR	Lower Granite Dam
m	meter(s)
mg	milligram(s)
MLE	maximum likelihood estimation
mm	millimeter(s)
NA	not applicable
NOAA	National Oceanic and Atmospheric Administration
PIT	passive integrated transponder
PNNL	Pacific Northwest National Laboratory
PRI	pulse repetition interval
rkm	river kilometer(s)
ROR	run-of-river
SE	standard error
SMP	Smolt Monitoring Program
SPE	spill passage efficiency
STH	steelhead
TUR	turbines
USACE	U.S. Army Corps of Engineers
UW	University of Washington
VIPRE	virtual/paired-release
ViRDCt	virtual release/dead fish correction

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1.0 Introduction

The 2018 acoustic-tag study at Lower Granite Dam (LGR) was the first study to estimate dam passage survival at that project. Previous studies conducted by NOAA have estimated project passage survival using paired PIT-tag releases or single release-recapture designs. This study estimated dam passage survival for yearling and subyearling Chinook salmon and juvenile steelhead. For each fish stock, the following evaluations were performed:

1. Estimation of dam passage survival probability (with standard error ≤ 0.025):
    a. Validation of survival results through testing of survival model assumptions
2. Estimation of survival for the following zones of inference:
    a. Project passage survival (upstream hydraulic influence to downstream hydraulic influence)
    b. Passage route survival (all available routes)
    c. Forebay survival (upstream hydraulic influence to dam passage)
3. Estimation of passage distribution and standard passage efficiency metrics:
    a. Spill passage efficiency (SPE, spill passage/total passage)
    b. Fish guidance efficiency (FGE, proportion of powerhouse passage guided into JBS)
    c. Fish passage efficiency (FPE, proportion of fish passing non-turbine routes)
4. Estimation of passage timing:
    a. Forebay residence (upstream hydraulic influence of the dam to time of dam passage)
    b. Tailrace egress (dam passage to downstream hydraulic influence in the tailrace)
    c. Project passage (upstream hydraulic influence to downstream hydraulic influence)

These evaluations were performed using dual acoustic/PIT-tagged juvenile salmonids.

2.0 Release-Recapture Design

As part of the 2018 study to estimate smolt passage survival through LGR, two alternative release–recapture designs were employed and compared. One approach was the virtual/paired-release model (i.e., VIPRE) of Skalski et al. (2010). This model requires a release of fish above the dam and two releases of fish below the dam. The second approach was the virtual release/dead fish correction model (i.e., ViRDCt), which uses a single release of live-tagged fish above the dam and a second release of dead tagged fish at the dam (Harnish et al. 2017).

2.1 VIPRE Model

The first approach to estimate dam passage survival was based on the virtual/paired-release model (Skalski et al. 2010) consisting of a virtual release (V_1) of fish at the face of the dam and a paired release below the dam (Figure 2.1). The virtual release was formed from fish that arrived successfully at the face of the dam and were detected at a dam-face hydrophone array from an upstream release (R_1). By releasing fish far enough upstream, the fish should have arrived at the dam in a spatial pattern typical of run-of-river (ROR) fish. This virtual release group (V_1) was used to estimate survival through the dam and part of the way through the next reservoir (Figure 2.1). To account and adjust for this extra reach mortality, a paired release below LGR [i.e., R_2 and R_3 (Figure 2.1)] was used to estimate survival in that segment of the reservoir below the dam. Dam passage survival was then estimated as the quotient of the survival estimates from the virtual release to those of the paired release.

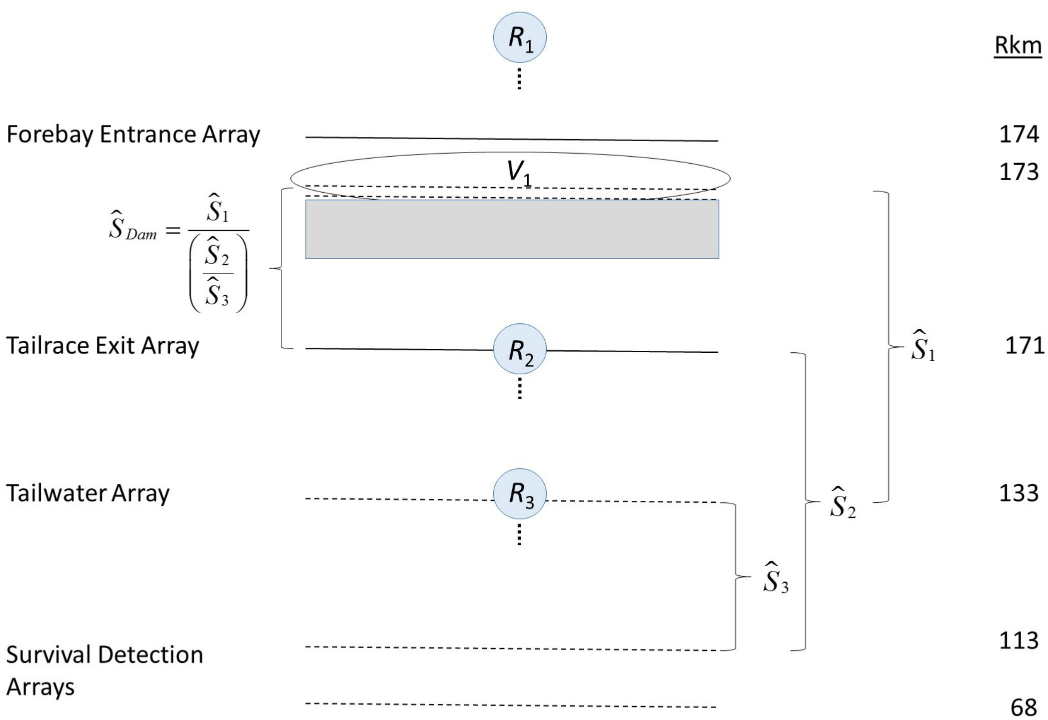


Figure 2.1. Virtual/Paired-Release-Recapture Design to Estimate Dam Passage Survival at LGR in 2018. Release groups R_1, R_2, and R_3 are denoted, along with the virtual release V_1 created at the face of the dam and associated hydrophone detection arrays and survival parameters.

The same release-recapture design was used to estimate forebay-to-tailrace survival, except that the virtual release group was constructed of fish known to have arrived at the forebay array. The same below-dam paired release used to adjust for the extra mortality below the dam was used to estimate dam passage survival. The double-detection arrays at the face of the dam (Figure 2.2) were analyzed as two independent arrays to allow estimation of detection probabilities by route of passage and assign the location of the last detection (i.e., the passage route) of each fish. These passage-route data were used to calculate SPE and FPE at LGR. The fish used in the virtual release were also used to estimate tailrace egress time.

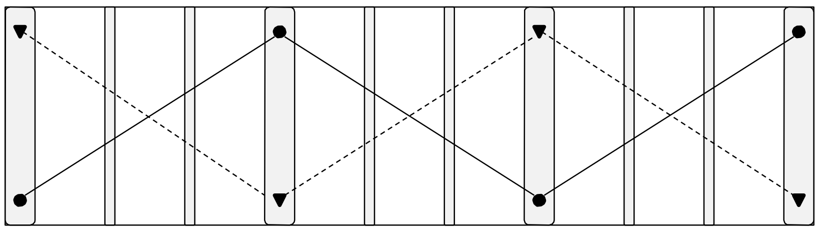


Figure 2.2. Front View Schematic of Hydrophone Deployments at Three Turbines Showing the Double-Detection Arrays. The circles denote the hydrophones of Array 1 and the triangles denote the hydrophones of Array 2.

2.2 ViRDCt Model

The second approach to estimating dam passage survival at LGR was based on the virtual release/dead fish correction model (ViRDCt) (Harnish et al. 2017). The approach used the same R_1 release to form a virtual release at the dam face as the VIPRE model. However, in this approach, the V_1 release was used to estimate the joint probability of fish alive or dead being detected at a tailrace array (Figure 2.3). This detection rate was then adjusted by the probability of a dead fish being carried downriver to the tailrace array and being detected there. Dead fish releases (D_1) were used to estimate the probability of fish that die during dam passage drifting downriver and being detected at the tailrace array.

Inferences to LGR dam passage survival in 2018 were based on the VIPRE results. Comparable results from the two different release-recapture models may permit the more cost-effective ViRDCt model to be used as the primary estimation technique for dam passage survival in future years.

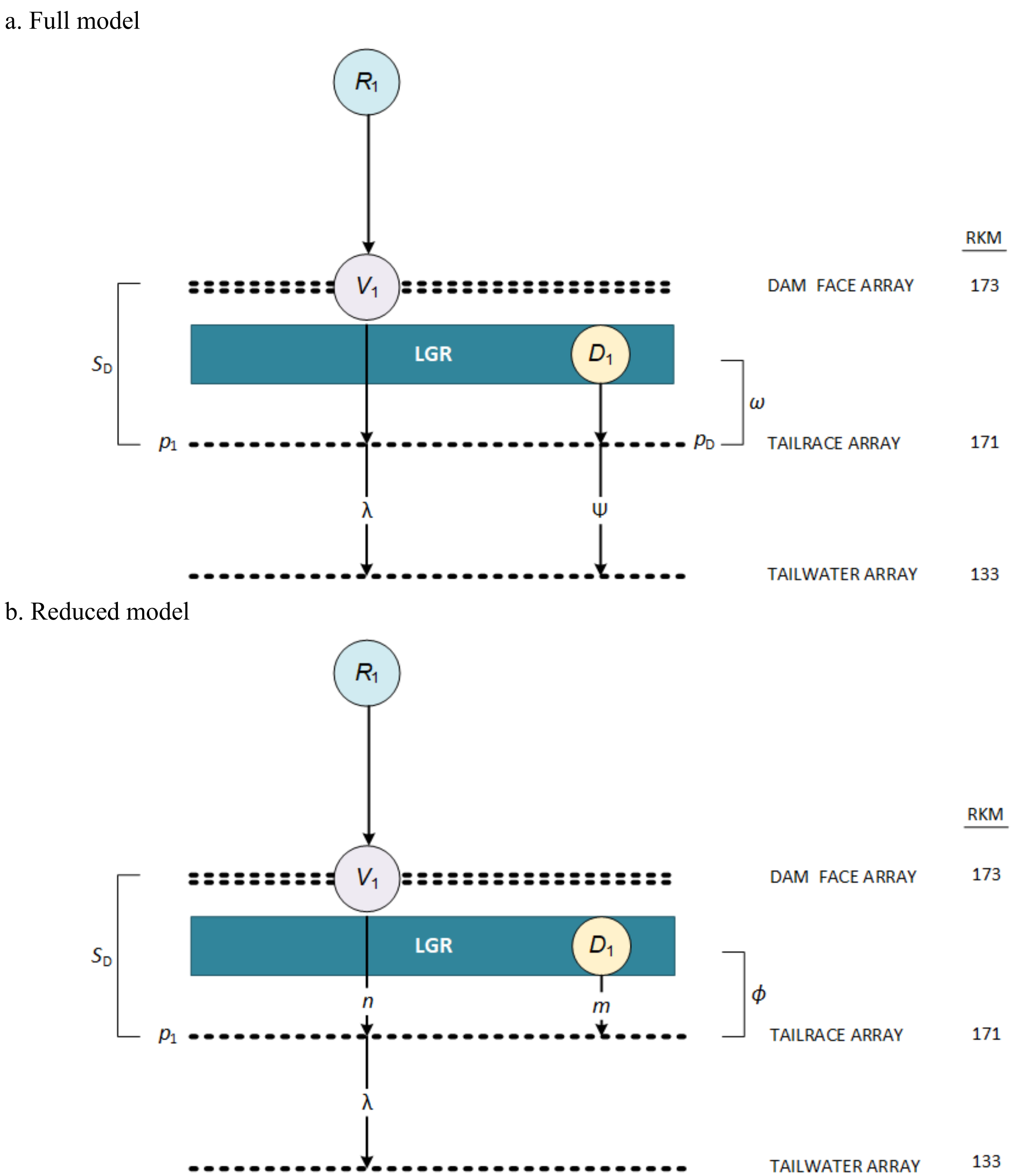


Figure 2.3. Schematic of the ViRDCt Release-Recapture Model to Estimate Dam Passage Survival at LGR in 2018. Alive (R_1), virtual (V_1), and dead fish (D_1) releases are denoted, along with hydrophone detection arrays. Schematic a) allows dead fish detection at both the tailrace and tailwater arrays, and b) permits dead fish detection at the tailrace only.

3.0 Statistical Methods

Statistical methods were used to test assumptions and estimate passage survival, tag life, forebay-to-tailrace survival, travel time, SPE and FPE, as described below.

3.1 Estimation of Dam Passage Survival

3.1.1 VIPRE Model

Maximum likelihood estimation was used to estimate dam passage survival at LGR based on the virtual/paired-release design. The capture histories from all the replicate releases, both daytime and nighttime, were pooled to produce the estimate of dam passage survival. A joint likelihood model was constructed as a product of multinomial distributions with separate distributions describing the capture histories of the separate release groups (i.e., V_1, R_2, and R_3).

The joint likelihood used to model the three release groups was fully parameterized. Each of the three releases was allowed to have unique survival and detection parameters. If precision was adequate with the fully parameterized model (i.e., Standard Error [SE] ≤ 0.025), no further modeling was performed. If initial precision was inadequate, then likelihood ratio tests were used to assess the homogeneity of parameters across release groups to identify the best parsimonious model to describe the capture history data. This approach was used to help preserve the precision and robustness of the survival results (Skalski et al. 2013). All calculations were performed using Program ATLAS (http://www.cbr.washington.edu/analysis/apps/atlas).
Dam passage survival was estimated by the function

$$\hat{S}_{\text{Dam}} = \frac{\hat{S}_1}{\left(\frac{\hat{S}_2}{\hat{S}_3}\right)} = \frac{\hat{S}_1 \cdot \hat{S}_3}{\hat{S}_2} \tag{3.1}$$

where $\hat{S}_i$ was the tag-life-corrected survival estimate for the i^{th} release group $(i = 1, \cdots, 3)$ (Figure 2.1). The variance of $\hat{S}_{\text{Dam}}$ was estimated in a two-step process that incorporated both the uncertainty in the tag-life corrections and the release-recapture process.

3.1.2 ViRDCt Model

Maximum likelihood estimation (MLE) was used to estimate dam passage survival using the ViRDCt model (Harnish et al 2017). Ideally, the tailwater array would be located sufficiently downstream such that none of the dead fish release (D_1) were detected by that array. An alternative model allowing detection of dead tagged fish at both the tailrace and tailwater arrays was also formulated. However, precision would be greater under the simplified model if valid.

For the full model with possible dead fish detections at both downriver arrays (Figure 2.3a), the likelihood can be written as follows:

$$
\begin{aligned}
L = &\binom{V_1}{\vec{n}}(S_D p_1 \lambda + (1-S_D)\omega p_D \Psi)^{n_{11}} \\
&\cdot (S_D(1-p_1)\lambda + (1-S_D)\omega(1-p_D)\Psi)^{n_{01}} \\
&\cdot \big(S_D p_1(1-\lambda) + (1-S_D)\omega p_D(1-\Psi)\big)^{n_{10}} \\
&\cdot \big[S_D(1-p_1)(1-\lambda) + (1-S_D)\big((1-\omega) + \omega(1-p_D)(1-\Psi)\big)\big]^{V_1-n.} \\
&\cdot \binom{D}{\vec{d}}(\omega p_D \Psi)^{d_{11}}(\omega(1-p_D)\Psi)^{d_{01}} \\
&\cdot \big(\omega p_D(1-\Psi)\big)^{d_{10}}\big((1-\omega) + \omega(1-p_D)(1-\Psi)\big)^{D-d.}
\end{aligned}
\tag{3.2}
$$

where

n_{ij} = number of V_1 release fish with capture history ij (i = 0 or 1 for detection at tailrace, j = 0 or 1 for detection at tailwater array);
S_D = dam passage survival;
p_1 = probability of an alive V_1 fish being detected at the tailrace array;
λ = joint probability of survival between tailrace and tailwater arrays, and being detected at the tailwater array;
ω = joint probability of a dead fish from D_1 arriving at the tailrace array;
p_D = probability of detecting a dead fish at the tailrace array;
Ψ = joint probability that a dead fish is washed down to the tailwater array from the tailrace array and is detected at the tailwater array.

Iterative procedures from Program USER (http://www.cbr.washington.edu/analysis/apps/user) were used to estimate the model parameters and associated variances. No attempt was made to adjust for tag life because travel times to the downstream array were well within minimum tag life.

For the reduced model with dead fish from D_1 only detected at the tailrace array, the joint likelihood model can be written as follows:

$$
\begin{aligned}
L = &\binom{V_1}{n}(S_D p_1 + (1-S_D)\phi)^n \big(S_D(1-p_1) + (1-S_D)(1-\phi)\big)^{V_1-n} \\
&\cdot \binom{D_1}{m}\phi^m(1-\phi)^{D_1-m} \cdot \binom{n_{11}+n_{01}}{n_{11}} p_1^{n_{11}}(1-p_1)^{n_{01}}
\end{aligned}
\tag{3.3}
$$

where

ϕ = joint probability of a dead released fish (D_1) arriving at the tailrace array and being detected at that array;
n = number of V_1 fish detected at the tailrace array;
m = number of D_1 fish detected at the tailrace array.

Parameter estimates and associated standard errors were calculated based on Program USER. The MLE for the estimate of dam passage survival was of closed form for this model where

$$\hat{S}_D = \frac{\left(\frac{n}{V_1} - \frac{m}{D_1}\right)}{\left(\hat{p}_1 - \frac{m}{D_1}\right)} \quad (3.4)$$

3.1.3 Sample Size Estimation

Sample sizes of R_1, R_2, and R_3 release groups were determined by using survival and detection probability data from past acoustic telemetry studies as inputs to program SampleSize (http://www.cbr.washington.edu/analysis/apps/samplesize). Sample sizes were adjusted until LGR VIPRE dam passage survival probability could be estimated with precision of SE $\leq$ 0.025. Dead tagged fish release sample sizes were selected to obtain a season- and dam-wide (i.e., all routes combined) dead tagged fish detection rate estimate with precision of SE < 0.030.

Table 3.1. Numbers of Fish Per Stock for Release Groups R_1, R_2, and R_3 and D_1, Along with Tag-Life Study Tags. Tags for R_1 not detected at the dam face were excluded from the virtual release V_1.

	Release size				
Fish stock	$\boldsymbol{R_1}$	$\boldsymbol{R_2}$	$\boldsymbol{R_3}$	$\boldsymbol{D_1}$	**Tag life**
Yearling Chinook salmon	466	299	298	212	97
Steelhead	680	501	500	183	97
Subyearling Chinook salmon	1393	690	690	289	125

3.2 Tag-Life Analysis

For the spring and summer releases, 97 and 125 acoustic tags, respectively, were monitored for tag life. Tags were monitored from activation to tag failure in continuous time with tags soaked in ambient river water. Failure times were fit to a four-parameter vitality model of Li and Anderson (2009). The vitality model tends to fit acoustic-tag failure times well because it allows for both early onset of random failure due to manufacturing as well as systematic battery failure later.

The survivorship function for the vitality model can be rewritten as

$$S(t) = 1 - \left(\Phi\left(\frac{1-rt}{\sqrt{u^2+s^2t}}\right)\right) - e^{\left(\frac{2u^2r^2}{s^4}+\frac{2r}{s^2}\right)}\Phi\left(\frac{2u^2r+rt+1}{\sqrt{u^2+s^2t}}\right)^{e^{-kt}} \quad (3.4)$$

where

Φ = cumulative normal distribution,

r = average wear rate of components,

s = standard deviation in wear rate,

k = rate of accidental failure,

u = standard deviation in quality of original components.

The random failure component, in addition to battery discharge, gives the vitality model additional latitude to fit tag-life data not found in other failure-time distributions, such as the Weibull or Gompertz. Parameter estimation was based on MLE.

For the virtual release group (V_1) based on fish known to have arrived at the dam face, the conditional probability of transmitter activation, given the transmitter was active at the dam-face detection array, was used in the tag-life adjustment for that release group. The conditional probability of transmitter activation at time t_1, given it was active at time t_0, was computed by the quotient

$$P(t_1|t_0) = \frac{S(t_1)}{S(t_0)} \tag{3.5}$$

where $S(t_0)$ was the average unconditional probability that the transmitter was active when detected at the dam-face detection array, and $S(t_1)$ was the average unconditional probability that the transmitter was active when detected at the first tailwater detection array.

3.3 Tests of Assumptions

Several tests of assumptions were performed and are described in the following sections.

3.3.1 Burnham et al. (1987) Tests

Tests 2 and 3 of Burnham et al. (1987) could be used to assess whether upstream detection history influences downstream survival. Such tests are most appropriate when fish are physically recaptured or segregated during capture, as in the case with PIT-tagged fish going through the juvenile bypass system (JBS). However, acoustic-tag studies do not use physical recaptures to detect fish. Consequently, these tests have little relevance in acoustic-telemetry studies. Furthermore, the very high detection probabilities present in acoustic-telemetry studies frequently preclude calculation of these tests. For these reasons, these tests were not performed.

3.3.2 Tests of Mixing

Evaluation of the homogeneous arrival of release groups at downriver detection sites was based on graphs of arrival distributions. The graphs were used to identify any systematic and meaningful departures from mixing. Ideally, the arrival distributions should overlap one another with similarly timed modes.

3.3.3 Tagger Effects

Subtle differences in handling and tagging techniques could affect the survival of juvenile salmonids used in the estimation of dam passage survival. For this reason, tagger effects were evaluated. The single release–recapture model was used to estimate reach survivals for fish tagged by different individuals. The analysis evaluated whether any consistent pattern of reduced reach survivals exists for fish tagged by any of the tagging staff.

For k independent reach survival estimates, a test of equal survival was performed using the F-test

$$F_{k-1,\infty} = \frac{s_{\hat{S}}^2}{\left(\frac{\sum_{i=1}^{k} \widehat{\text{Var}}\left(\hat{S}_i \middle| S_i\right)}{k}\right)} \tag{3.6}$$

where

$$s_{\hat{S}}^2 = \frac{\sum_{i=1}^{k} \left(\hat{S}_1 - \hat{\bar{S}}\right)^2}{k-1} \tag{3.7}$$

and

$$\hat{\bar{S}} = \frac{\sum_{i=1}^{k} \hat{S}_i}{k}. \tag{3.8}$$

The *F*-test was used in evaluating tagger effects as well as delayed tag effects.

3.3.4 Tag Life and Tag-Lot Effects

Tag life was monitored separately for spring and summer releases. Tag-life data were fit to the vitality model of Li and Anderson (2009). Tag-lot effects were evaluated with likelihood ratio tests by comparing the tag-life distributions of the tags used in the spring- and summer-run studies. Adequacy of tag life will be judged relative to the time required for fish released to make their way downstream beyond the downstream detection array at RKM 68.

3.3.5 Dead Tagged Fish Releases

For the VIPRE model, it was necessary to assure the detection array at the R_3 release was sufficiently far downstream to avoid detections of fish that died during dam passage with still-active tags. The dead tagged fish releases performed at LGR were used to test this assumption during each survival study. A total of 212 yearling Chinook, 183 steelhead, and 289 subyearling Chinook salmon were released at LGR over the course of the studies. Dead fish were released 3 to 4 times per week throughout the study to cover the range of flows during the season. To limit the impact on the populations of run-of-river fish, hatchery yearling Chinook salmon raised at the Pacific Northwest National Laboratory's Aquatic Research Laboratory (ARL) in Richland, Washington were used for dead fish releases. The sizes and release locations of hatchery yearling Chinook used as dead tagged fish releases were selected to mimic the expected size range and passage distribution of the associated species-run live-tagged release group.

3.3.6 Representativeness of Dead Tagged Fish Releases

An additional assumption required of the ViRDCt model is that dead tagged fish are representative of fish from the V_1 group that die during dam passage. For this reason, dead tagged fish were released into each passage route (i.e., turbine, spillway weir, deep spill bays, JBS) in proportion to the expected distribution of fish from the V_1 group that die during dam passage, estimated using data from past survival studies conducted at Snake River dams. Dead tagged fish releases occurred 3 to 4 times per week during both day and night throughout the period of acoustic-tagged fish LGR passage to accurately capture the variability in the dead tagged fish detection rate associated with dam operations and environmental conditions. The representativeness of the dead tagged fish releases was tested by comparing the spatial and temporal distribution of dead tagged fish releases to the spatial (i.e., route) and temporal distribution of fish from the V_1 group that were not detected downstream of the tailrace array (SR172).

The fish used in the dead tagged fish releases were obtained from the ARL and were euthanized by a standard protocol involving exposure to a solution of 250 mg/L tricaine methanesulfonate (MS-222) for at least 10 minutes after opercular movement has ceased. The standard protocol was designed to be consistent with American Veterinary Medical Association guidelines for euthanizing finfish (Leary 2013), which recommend immersion in a concentration of 250 to 500 mg/L, or 5 to 10 times the anesthetic dosage for 10 minutes following the loss of rhythmic opercular movement as sufficient for Euthanasia (Leary 2013). Unfortunately, this approach proved inadequate, and some fish that were thought to have been euthanized recovered after release to migrate down river. These revived fish were identified by their rapid exit from the tailrace and, in many cases, detection at Little Goose Dam and below. These revived fish were removed from the dataset of dead tagged fish and subsequent analyses. It is difficult to ensure all revived fish have been identified and removed, but results should be conservative because failure to remove all false-positive dead tagged fish detections would negatively bias the ViRDCt estimates of LGR passage survival.

3.3.7 Representative Fish Size

The VIPRE model assumes the release groups R_1, R_2, and R_3 come from the same fish source and share common baseline survival processes. We tested these assumptions by comparing the length distribution of the fish across release groups.

Another model assumption is that fish used in the survival study are representative of ROR fish passing LGR. To this end we compared the length distributions of the release groups R_1, R_2 and, R_3 to the fish sampled at LGR by the Smolt Monitoring Program during the respective study periods.

3.3.8 Passage Timing

In order for the estimates of dam passage survival to be representative of the ROR fish, the tagging studies needed to occur over the majority of the respective fish runs. Timing of the tag releases was compared to the passage timing of the respective fish runs as quantified by the Smolt Monitoring Program's run time monitoring at LGR.

3.4 Forebay-to-Tailrace Survival

The same virtual/paired-release (VIPRE) and virtual release/dead fish correction (ViRDCt) models used to estimate dam passage were used to estimate forebay-to-tailrace survival. The only distinction is the virtual release group (V_1) was composed of fish known to have arrived alive at the forebay array of LGR, rather than at the dam face (Figure 2.1).

3.5 Estimation of Travel Times

Travel times associated with forebay residence time and tailrace egress were estimated using arithmetic averages as specified in the Fish Accords, i.e.,

$$\bar{t} = \frac{\sum_{i=1}^{n} t_i}{n}, \tag{3.9}$$

with the variance of $\bar{t}$ estimated by

$$\widehat{\mathrm{Var}}(\bar{t}) = \frac{\sum_{i=1}^{n}(t_i - \bar{t})^2}{n(n-1)}, \tag{3.10}$$

and where t_i was the travel time of the i^{th} fish ($i = 1, \cdots, n$). Median and range in travel times were also computed and reported.

Tailrace egress time for fish arriving at LGR was calculated differently for bypassed and non-bypassed fish before their data were pooled. For bypassed fish, tailrace egress time was measured from the last detection in the fish bypass to the last detection at the tailrace array below the dam. For all other fish, tailrace egress time was measured from the last detection at the dam-face array to the last detection at the tailrace array below the dam. Both the arithmetic average and the median were calculated. Only fish known to have passed the dam alive were used in the calculations, based on fish observed to be alive downstream.

The estimated forebay residence times were based on the time from the first detection at the forebay BRZ array 1 km above the dam to the last detection at the double array on the upstream face of LGR.

3.6 Estimation of Spill Passage Efficiency

SPE was estimated by the fraction

$$\widehat{\mathrm{SPE}} = \frac{\hat{N}_{\mathrm{SPL}} + \hat{N}_{\mathrm{RSW}}}{\hat{N}_{\mathrm{SPL}} + \hat{N}_{\mathrm{RSW}} + \hat{N}_{\mathrm{JBS}} + \hat{N}_{\mathrm{TUR}}} \tag{3.11}$$

where $\hat{N}_i$ was the estimated abundance of tagged fish through the i^{th} route (i = spill bays [SPL], removable spillway weir [RSW], juvenile bypass system [JBS], and turbines [TUR]). The double-detection array at the dam face was used to estimate absolute abundance (*N*) through a route using the single mark–recapture model (Seber 1982:60) independently at each route. The variance of $\widehat{\mathrm{SPE}}$ was estimated as follows:

$$\widehat{\mathrm{Var}}\left(\widehat{\mathrm{SPE}}\right) = \frac{\widehat{\mathrm{SPE}}\left(1-\widehat{\mathrm{SPE}}\right)}{\sum_{i=1}^{4}\hat{N}_i} + \widehat{\mathrm{SPE}}^2\left(1-\widehat{\mathrm{SPE}}\right)^2 \cdot \left[\frac{\widehat{\mathrm{Var}}\left(\hat{N}_{\mathrm{SPL}}\right) + \widehat{\mathrm{Var}}\left(\hat{N}_{\mathrm{RSW}}\right)}{\left(\hat{N}_{\mathrm{SPL}} + \hat{N}_{\mathrm{RSW}}\right)^2} + \frac{\widehat{\mathrm{Var}}\left(\hat{N}_{\mathrm{TUR}}\right) + \widehat{\mathrm{Var}}\left(\hat{N}_{\mathrm{JBS}}\right)}{\left(\hat{N}_{\mathrm{TUR}} + \hat{N}_{\mathrm{JBS}}\right)^2}\right]. \tag{3.12}$$

3.7 Estimation of Fish Passage Efficiency

FPE was estimated as the fraction of fish through non-turbine routes, where

$$\widehat{\mathrm{FPE}} = \frac{\hat{N}_{\mathrm{SPL}} + \hat{N}_{\mathrm{RSW}} + \hat{N}_{\mathrm{JBS}}}{\hat{N}_{\mathrm{SPL}} + \hat{N}_{\mathrm{RSW}} + \hat{N}_{\mathrm{JBS}} + \hat{N}_{\mathrm{TUR}}}. \tag{3.13}$$

The variance of $\widehat{\mathrm{FPE}}$ was estimated as

$$\widehat{\mathrm{Var}}\left(\widehat{\mathrm{FPE}}\right) = \frac{\widehat{\mathrm{FPE}}\left(1-\widehat{\mathrm{FPE}}\right)}{\sum_{i=1}^{4}\hat{N}_i} + \widehat{\mathrm{FPE}}^2\left(1-\widehat{\mathrm{FPE}}\right)^2 \cdot \left[\frac{\widehat{\mathrm{Var}}\left(\hat{N}_{\mathrm{SPL}}\right)+\widehat{\mathrm{Var}}\left(\hat{N}_{\mathrm{RSW}}\right)+\widehat{\mathrm{Var}}\left(\hat{N}_{\mathrm{JBS}}\right)}{\left(\hat{N}_{\mathrm{SPL}}+\hat{N}_{\mathrm{RSW}}+\left(\hat{N}_{\mathrm{JBS}}\right)\right)^2} + \frac{\widehat{\mathrm{Var}}\left(\hat{N}_{\mathrm{TUR}}\right)}{\hat{N}_{\mathrm{TUR}}^2}\right]. \tag{3.14}$$

Because the detection probability of acoustic-tagged fish at the face of the LGR was virtually 1.0, passage calculations were reduced to binomial or multinomial proportions.

4.0 Results

4.1 Tests of Hypotheses

4.1.1 Downstream Mixing

Downstream mixing of arrival release groups V_1, R_2, and R_3 to the hydrophone array at rkm 113 show very good timing of the V_1, R_2, and R_3 releases as expected (Figure 4.1). The arrival modes are nearly identical with the V_1 fish having a slightly more spread-out distribution.

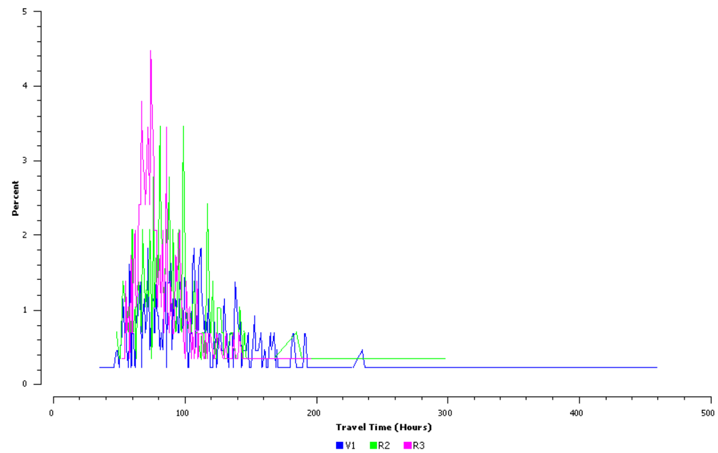
4.1.2 Tagger Effects

Any tagger effects can be minimized if the distribution of tagging effort is homogeneous among release groups. Homogeneous mixing is not necessary but can be beneficial if slight differences in survival of fish tagged by different staff occur and go undetected. Chi-square tests of homogeneity found tagger effect to be homogeneous ($P > 0.05$) within the R_1 and R_2 releases but not the R_3 release (Table 4.1). Reach survival of R_1 fish to rkm 133 (or rkm 140 in the case of the subyearling Chinook salmon) tagged by the different taggers were found to be homogeneous ($P > 0.05$) for all three fish stocks, allowing pooling of detection data across taggers (Table 4.2).

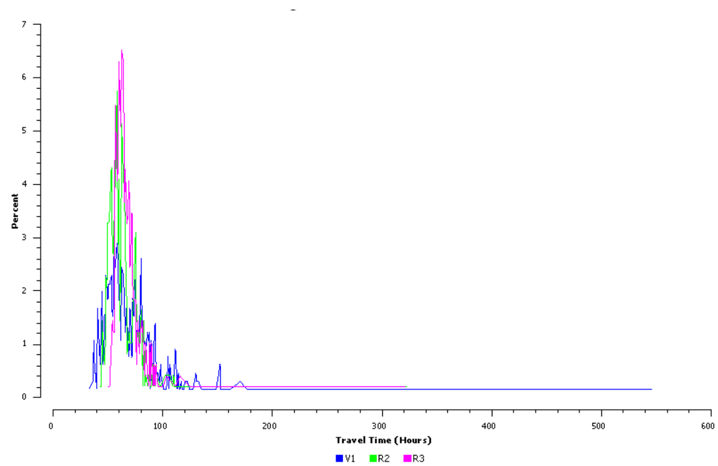
Table 4.1. Numbers of Yearling Chinook Salmon, Steelhead, and Subyearling Chinook Salmon Tagged by Individual Staff for Release Groups R_1, R_2, and R_3 During the Dam Passage Survival Study at Lower Granite Dam, 2018

Yearling Chinook salmon				
Tagger ID		**Numbers tagged**		
	R_1	R_2	R_3	
A	117	73	75	
B	113	62	68	
C	130	87	81	
D	106	77	74	$P(\chi^2 \geq 1.983) = .921$
Steelhead				
Tagger ID		**Numbers tagged**		
	R_1	R_2	R_3	
A	170	127	133	
B	167	98	112	
C	189	152	138	
D	154	124	127	$P(\chi^2 \geq 5.160) = .524$
Subyearling Chinook salmon				
Tagger ID		**Numbers tagged**		
	R_1	R_2	R_3	
A	356	176	193	
B	357	178	152	
C	373	156	157	
D	307	180	188	$P(\chi^2 \geq 14.97) = 0.021$

a. Yearling Chinook salmon



b. Steelhead



c. Subyearling Chinook salmon

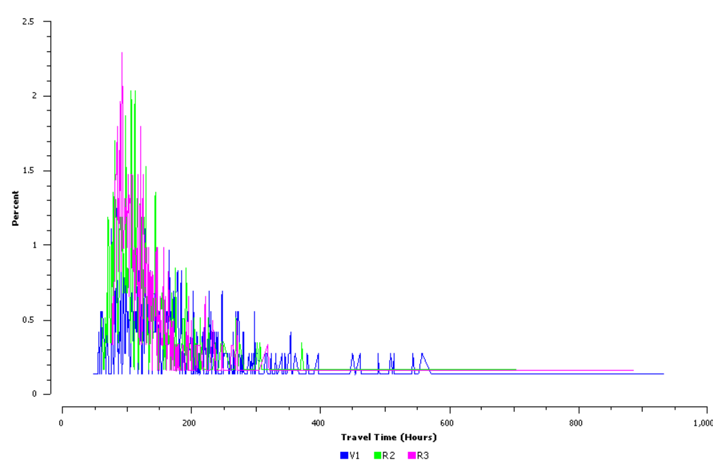


Figure 4.1. Frequency Distribution Arrival Plots to Detection Array at rkm 113 for Releases V_1, R_2, and R_3 Used in the Virtual/Paired-Release Model Analysis of Dam Passage Survival

Table 4.2. Reach Survival Estimates of R_1 Releases to rkm 133 (Yearling Chinook and Steelhead), or to rkm 140 (Subyearling Chinook) by Tagger Staff. Standard errors in parentheses. P-values associated with F-tests of homogeneous survival.

Tagger ID	Yearling Chinook salmon	Steelhead	Subyearling Chinook salmon
A	0.9569 (0.0189)	0.9821 (0.0102)	0.6905 (0.0247)
B	0.9732 (0.0153)	0.9880 (0.0084)	0.7192 (0.0241)
C	0.9536 (0.0185)	0.9947 (0.0053)	0.7772 (0.0217)
D	0.9609 (0.0192)	0.9673 (0.0144)	0.7608 (0.0246)
F-test	0.1693	0.9973	2.0570
P-value	0.9172	0.3929	0.1036

4.1.3 Tag Life

The spring- and summer-run tags had significantly different survivorship curves ($P = 0.001$), so were not pooled. For the spring releases, average tag life was estimated to be $\bar{t} = 61.11$ days ($\widehat{\mathrm{SE}}(\bar{t}) = 1.22$). For the summer releases, average tag life was estimated to be $\bar{t} = 56.94$ days ($\widehat{\mathrm{SE}}(\bar{t}) = 0.91$). Comparison of the cumulative arrival distributions of spring and summer stocks to the downstream detection array at rkm 68 to the tag-life curves indicate the tag life was adequate for all fish to pass through the study area before tag failure became an issue (Figure 4.2).

4.1.4 Representativeness of Dead Tagged Fish Releases

The proportion of dead tagged fish released into each route was similar to the route proportions of V_1 fish that were not detected downstream of the tailrace array for yearling Chinook salmon (Fisher's exact test $P > 0.314$) and steelhead (Fisher's exact test $P > 0.069$) (Table 4.3). The proportions of dead tagged subyearling Chinook salmon released into each route differed from the route proportions of V_1 subyearling Chinook salmon that were not detected downstream of the tailrace array for each route (Fisher's exact test $P < 0.001$) (Table 4.3). Too many dead tagged subyearling Chinook salmon were released into the JBS and turbines and too few were released into deep spill bays and the RSW. However, the dead tagged fish detection rate (d/D) did not differ significantly among routes for subyearling Chinook salmon (Fisher's exact test $P = 0.296$), thus ameliorating the effect of dead fish route distributions on the ViRDCt survival estimate.

No differences were observed in the temporal distributions of dead tagged fish releases and V_1 group mortality for yearling Chinook salmon (Wilcoxon $\chi^2 = 0.007$; $P = 0.934$), juvenile steelhead (Wilcoxon $\chi^2 = 0.747$; $P = 0.387$), or subyearling Chinook salmon (Wilcoxon $\chi^2 = 2.042$; $P = 0.153$), indicating the timing of dead fish releases was representative of the timing of V_1 mortality.

Table 4.3. Dead Tagged Fish Detection Rates, Proportions of Total Dead Tagged Fish Releases by Route, and Route Proportions of V_1 Fish Not Detected Downstream of the Tailrace Array for Acoustic-Tagged Yearling Chinook Salmon, Juvenile Steelhead, and Subyearling Chinook Salmon at LGR in 2018

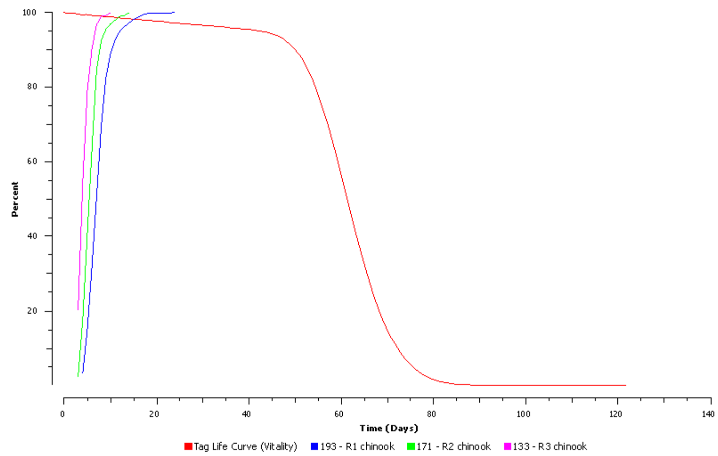
Route	d/D	Route proportion of D	Route proportion V_1 not detected
		Yearling Chinook salmon	
JBS	26/43 = 0.605	43/212 = 0.203	1/14 = 0.071
Deep spill	14/86 = 0.163	86/212 = 0.406	6/14 = 0.429
RSW	7/34 = 0.206	34/212 = 0.160	3/14 = 0.214
Turbines	14/49 = 0.286	49/212 = 0.231	4/14 = 0.286
		Juvenile steelhead	
JBS	28/50 = 0.560	50/183 = 0.273	0/11 = 0.000
Deep spill	9/39 = 0.231	39/183 = 0.213	2/11 = 0.182
RSW	16/60 = 0.267	60/183 = 0.328	6/11 = 0.546
Turbines	2/34 = 0.059	34/183 = 0.186	3/11 = 0.273
		Subyearling Chinook salmon	
JBS	15/84 = 0.179	84/289 = 0.291	3/79 = 0.038
Deep spill	4/42 = 0.095	42/289 = 0.145	33/79 = 0.418
RSW	7/82 = 0.085	82/289 = 0.284	40/79 = 0.506
Turbines	12/81 = 0.148	81/289 = 0.280	3/79 = 0.038

4.1.5 Representative Fish Size

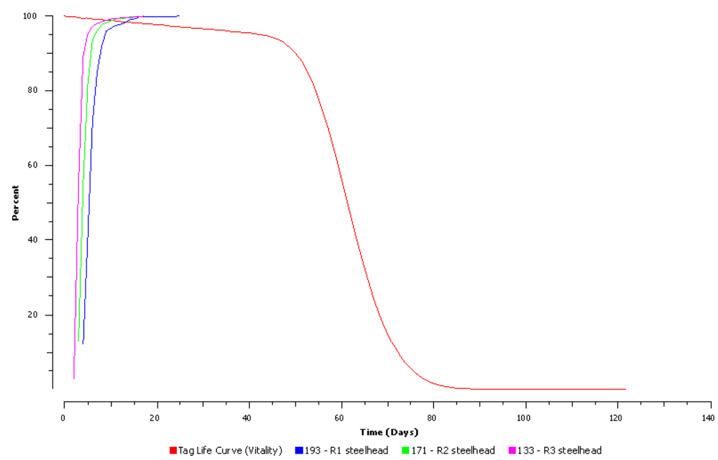
The assumption that release groups R_1, R_2, and R_3 come from the same fish source and share common baseline survival processes was tested by comparing the length distribution of the fish across release groups (Figures 4.3–4.5). In the case of all these fish stocks, the release groups were comparable in size.

The assumption that fish used in the survival study are representative of ROR fish passing LGR was tested by comparing the length distribution of the release groups R_1, R_2 and, R_3 to the fish sampled at LGR by the Smolt Monitoring Program during the respective study periods. For yearling Chinook salmon and steelhead, the size distributions of tagged and ROR fish were comparable (Figures 4.3–4.4). For subyearling Chinook salmon, the size distribution of the tagged fish was slightly truncated at the lower end because ROR fish in the 60 mm–95 mm range were not tagged (Figure 4.5).

a. Yearling Chinook salmon



b. Steelhead



c. Subyearling Chinook salmon

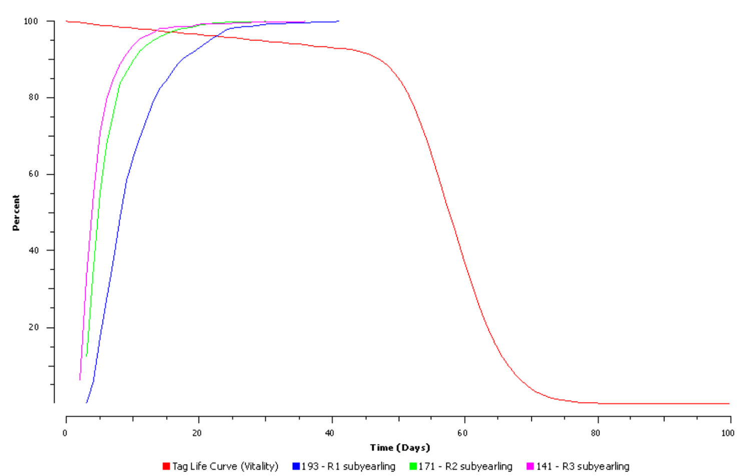
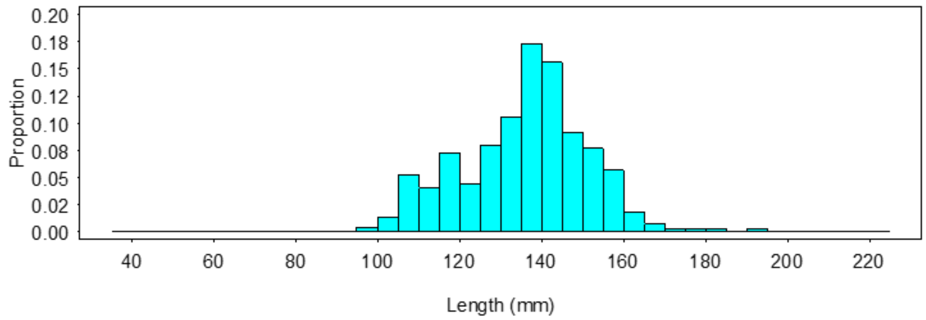
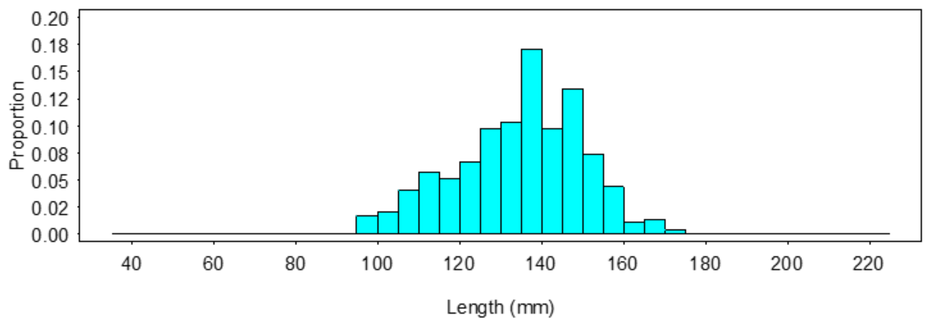


Figure 4.2. Comparison of Cumulative Distributions for Tag Life and Travel Times of All Released Fish to the Downstream Detection Array at rkm 68

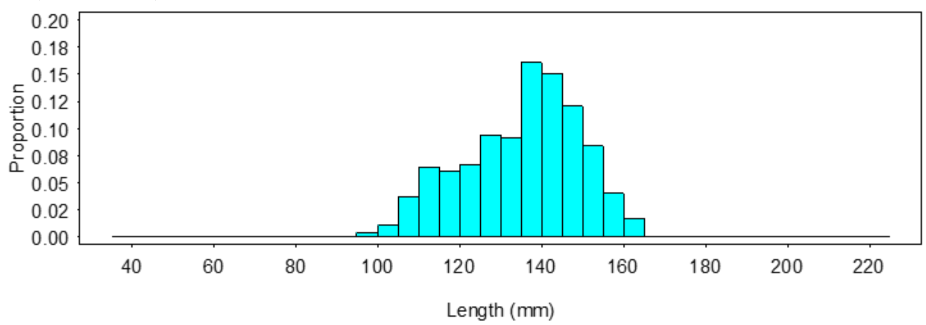
a. LGR (Release V_1)



b. LGR Tailrace (Release R_2)



c. Mid-Reservoir (Release R_3)



d. ROR

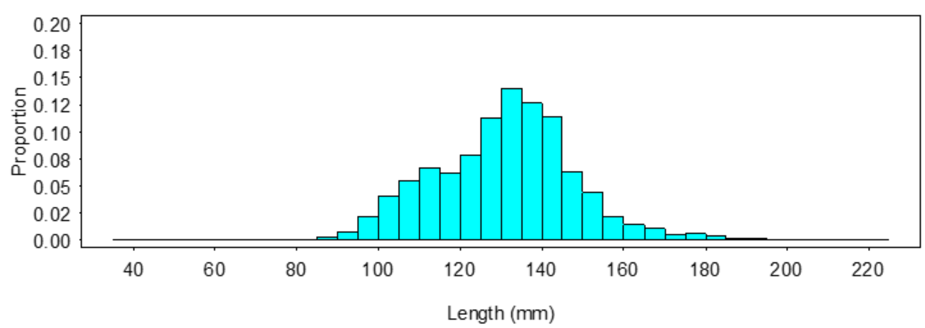
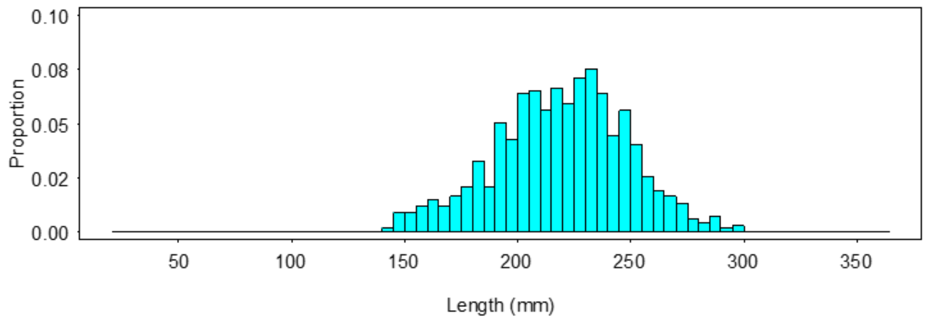
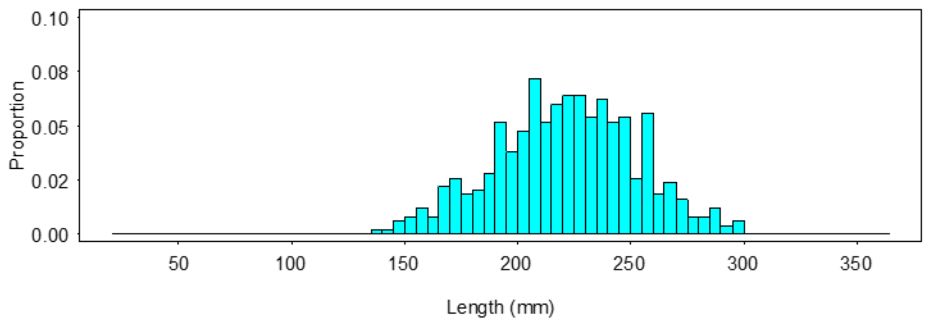


Figure 4.3. Relative Frequency Distributions for Fish Lengths of Yearling Chinook Salmon Used in Release V_1, Release R_2, Release R_3, and ROR Fish Sampled at LGR by the Smolt Monitoring Program in 2018.

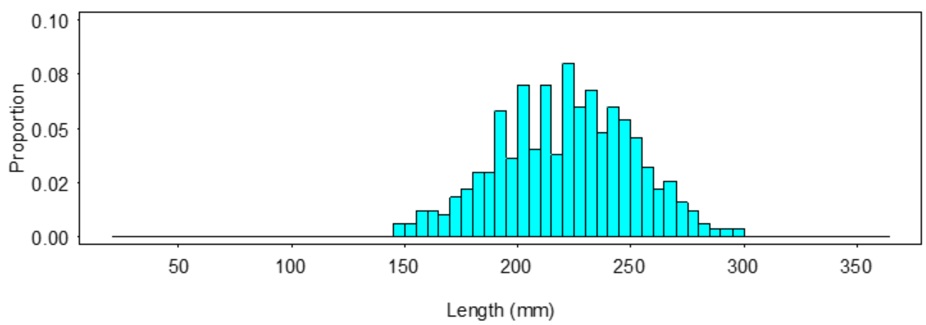
a. LGR (Release V_1)



b. LGR Tailrace (Release R_2)



c. Mid-Reservoir (Release R_3)



d. ROR

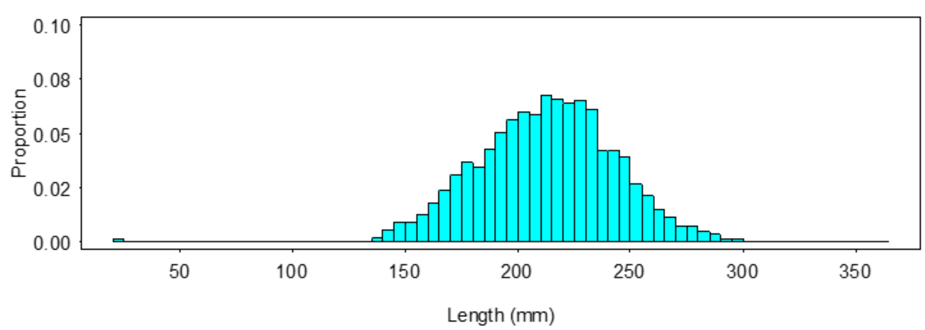
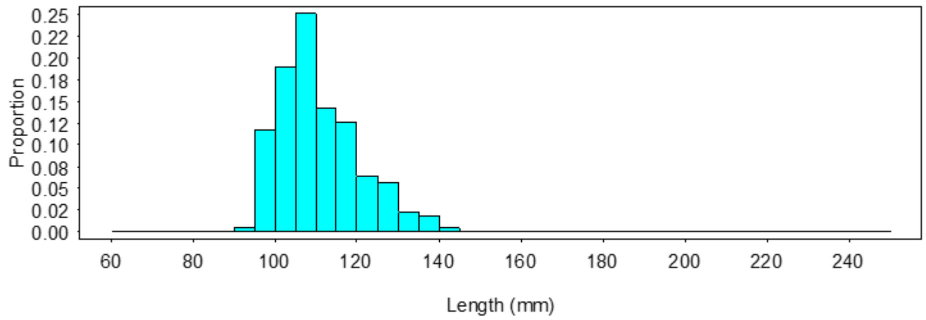
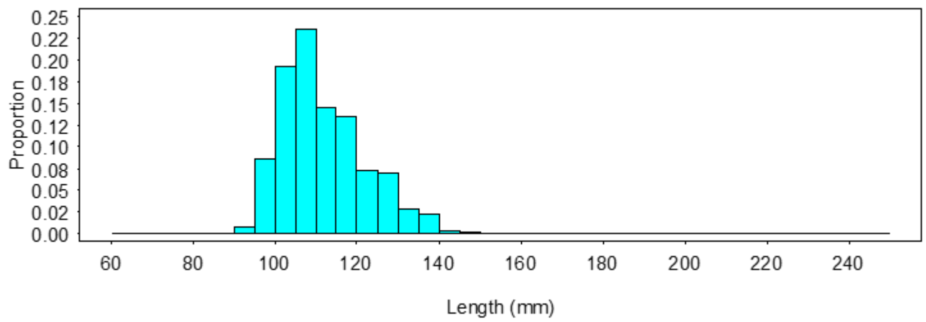


Figure 4.4. Relative Frequency Distributions for Fish Lengths of Juvenile Steelhead Used in Release V_1, Release R_2, Release R_3, and ROR Fish sampled at LGR by the Smolt Monitoring Program in 2018

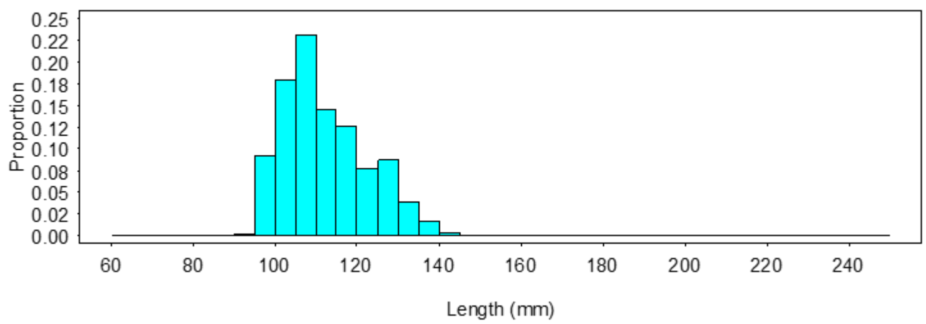
a. LGR (Release V_1)



b. LGR Tailrace (Release R_2)



c. Mid-Reservoir (Release R_3)



d. ROR

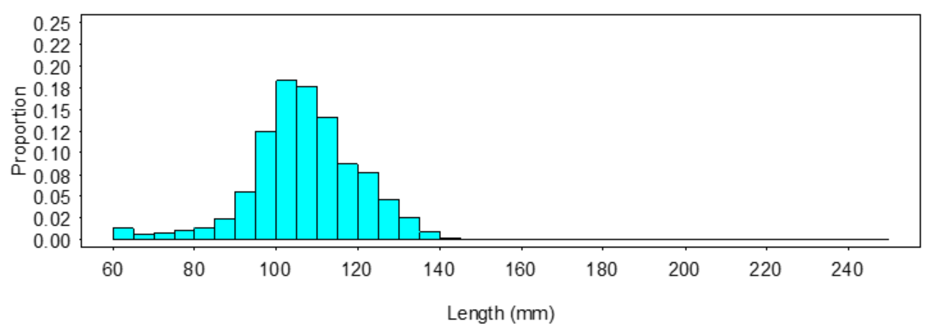


Figure 4.5. Relative Frequency Distributions for Fish Lengths of Subyearling Chinook Salmon Used in Release V_1, Release R_2, Release R_3, and ROR Fish Sampled at LGR by the Smolt Monitoring Program in 2018

4.1.6 Passage Timing

From 17 April, when the first fish in spring were released, through the end of the spring study on 26 May 2018, 80.1% of the yearling Chinook salmon and 70.8% of juvenile steelhead passed LGR (Figure 4.6). By the end of the study on 26 May 2018, 99.4% of the yearling Chinook salmon run and 96.6% of the juvenile steelhead run had passed LGR. From 31 May, when the first fish in summer were released through 7 July 2018, 41.4% of subyearling Chinook salmon passed LGR (Figure 4.6). By the end of the study on 7 July 2018, 90.0% of the subyearling Chinook salmon run had passed LGR.

a. Spring

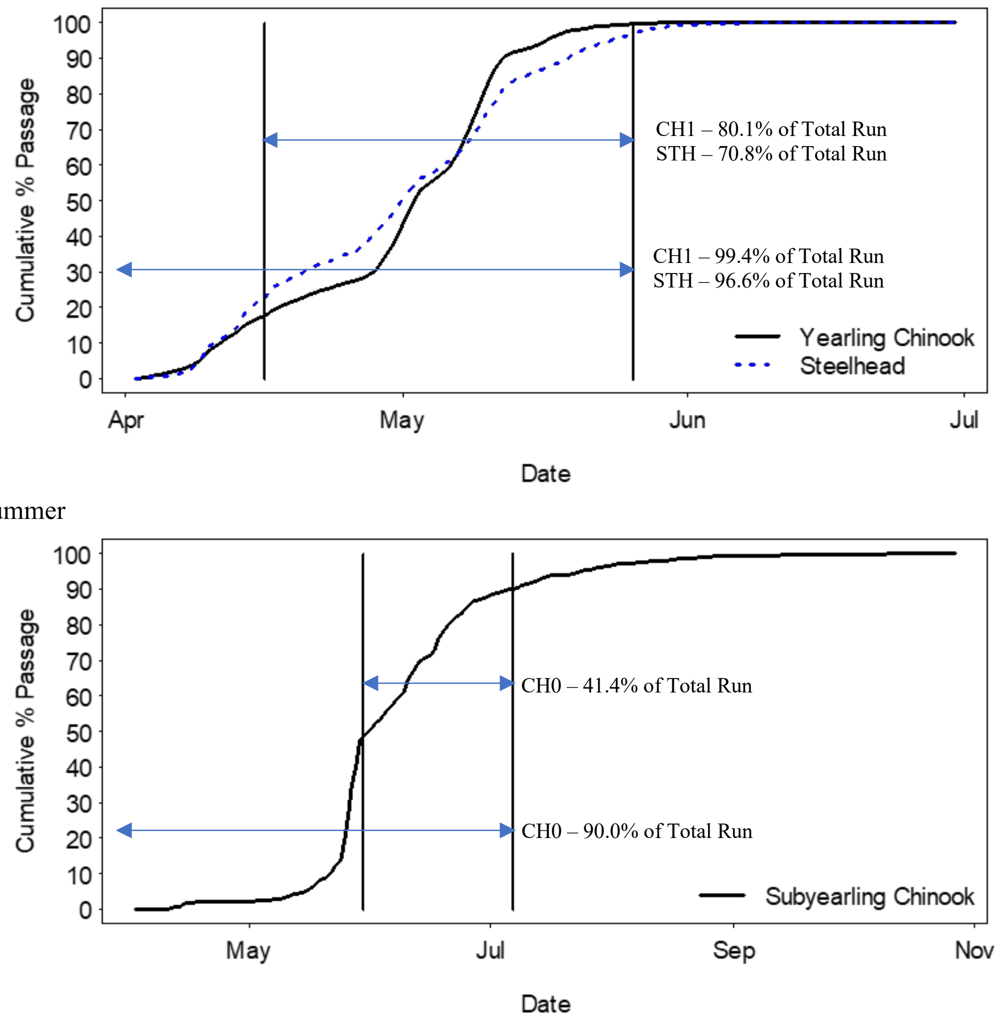


Figure 4.6. Plots of the Cumulative Percent of Yearling Chinook Salmon and Steelhead and Subyearling Chinook Salmon that Passed LGR in 2018 Based on Smolt Monitoring Program Data and Begin and End Dates for the Spring and Summer Tagging Stocks

4.1.7 Discharge and Spill Condition

From the onset of the spring study on 17 April 2018 through 26 May 2018, the percent spill at LGR ranged from 23% to 50% (Figure 4.7). For the summer study (31 May through 9 July 2018), the percent spill ranged from 24% to 76% (Figure 4.7).

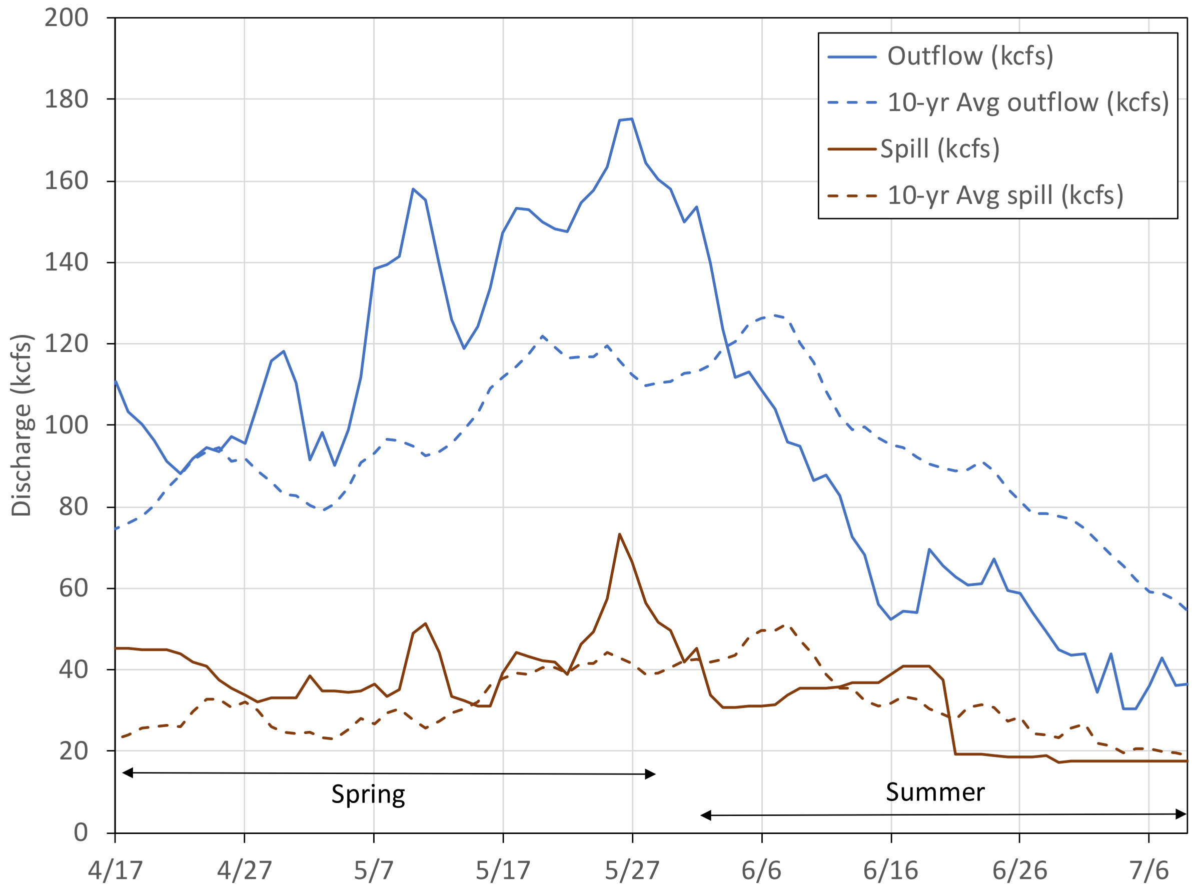


Figure 4.7. Daily Average Total Discharge and Percent Spill at LGR During the Spring and Summer JSATS Survival Studies in 2018 with 10-Year Average Values

4.2 Estimates of Dam Passage Survival

For each fish stock, estimates of dam passage survival were generated by the VIPRE and ViRDCt models (Table 4.4). The estimates of dam passage survival from the two alternative models were consistent within a fish stock. Weighted averages of the survival estimates were 0.9272, 0.9837, and 0.9939 for subyearling Chinook salmon, yearling Chinook salmon, and steelhead, respectively. In general, the ViRDCt estimates were all within 1 $\widehat{\text{SE}}$ from the VIPRE model. In two of the three fish stocks, the VIPRE model produced an estimate higher than that of the ViRDCt model and, in one case, the VIPRE model produced a lower estimate. All six estimates of dam passage survival had standard error estimates < 0.025, the precision goal of the study. As expected, the standard errors from the ViRDCt model were lower than those from the VIPRE model. In calculating dam passage survival for subyearling Chinook salmon, fish arriving at LGR dam after 10 July 2018 were excluded from the V_1 group because they arrived after the last R_2 and R_3 releases.

Table 4.4. Comparison of Estimates of Dam Passage Survival from the Virtual/Paired-Release and the Virtual Release/Dead Fish Correction Models by Fish Stocks at LGR, 2018. Standard errors in parentheses. Subyearling Chinook salmon detected after 10 July 2018 at LGR face were excluded from analysis.

	Yearling Chinook salmon		**Steelhead**		**Subyearling Chinook salmon**	
	VIPRE	ViRDCt	VIPRE	ViRDCt	VIPRE	ViRDCt
	0.9726 (0.0159)	0.9877 (0.0062)	0.9959 (0.0099)	0.9936 (0.0037)	0.9422 (0.0217)	0.9242 (0.0098)
Weighted Average	0.9857 (0.0051)		0.9939 (0.0008)		0.9272 (0.0068)	

4.3 Estimates of Forebay-to-Tailrace Survival

By forming the virtual release, V_1, at the forebay hydrophone array instead of the dam-face array, forebay-to-tailrace survival can be estimated using both the VIPRE and ViRDCt models (Table 4.5). For spring stocks, every fish detected at the forebay array was also detected at the dam face and vice versa. Consequently, the estimates of forebay-to-tailrace survival are nearly identical to the estimates of dam passage survival. The slight differences are due to very small corrections in tag life. Not all subyearling Chinook salmon entering the forebay array were detected at the dam face, so forebay-to-tailrace survival was a few percentage points lower than dam passage survival.

Table 4.5. Comparison of Estimates of Forebay-to-Tailrace Survival from the Virtual/Paired-Release and the Virtual Release/Dead Fish Correction Models by Fish Stocks at LGR, 2018. Standard errors in parentheses. Subyearling Chinook salmon detected at forebay array on or after 10 July 2018 were excluded from the analysis.

	Yearling Chinook salmon		**Steelhead**		**Subyearling Chinook salmon**	
	VIPRE	**ViRDCt**	**VIPRE**	**ViRDCt**	**VIPRE**	**ViRDCt**
	0.9728 (0.0159)	0.9877 (0.0062)	0.9961 (0.0099)	0.9936 (0.0037)	0.8837 (0.0211)	0.9097 (0.0106)
Weighted Average	0.9857 (0.0050)		0.9939 (0.0008)		0.9045 (0.0104)	

4.4 Survival Estimation Components

Each estimate of survival and its precision is based on parameters estimated from tag detection histories. The calculations for estimating survivals with VIPRE are presented in Figure 2.1 and equation 3.1 in section 3.1.1,and those for use with ViRDCt are presented in Figure 2.3 and equations 3.2 and 3.3 in section 3.1.2. The values for the parameters used in those calculations are presented in Table 4.6.

Table 4.6. Parameters for Computing VIPRE and ViRDCt Estimate of Survival for Yearling Chinook Salmon, Steelhead, and Subyearling Chinook Salmon at LGR, 2018. See Figure 2.1, Figure 2.3 and equations 3.1, 3.2. and 3.3 for detail on parameters. Standard errors are presented in parentheses. Bolded entries are dam survival estimates.

Parameter	Yearling Chinook salmon	Steelhead	Subyearling Chinook salmon
		ViRDCt model	
p_1	1.0000 (<0.0001)	1.0000 (<0.0001)	0.9988 (0.0012)
λ	0.9790 (0.0075)	0.9899 (0.0043)	0.9847 (0.0060)
ω	0.2877 (0.0311)	0.3005 (0.0339)	0.1315 (0.0199)
p_D	1.0000 (<0.0001)	1.0000 (<0.0001)	1.0000 (<0.0001)
Ψ	0.0328 (0.0228)	0.0727 (0.0350)	0.0263 (0.0260)
$\hat{S}_D$	**0.9877 (0.0062)**	**0.9936 (0.0037)**	**0.9242 (0.0098)**
		VIPRE model	
$\hat{S}_1$	0.9710 (0.0081)	0.9850 (0.0049)	0.9133 (0.0097)
p_1	0.9954 (0.0032)	1.0000 (<0.0001)	1.0000 (<0.0001)
λ_1	0.9515 (0.0103)	0.9740 (0.0062)	0.7869 (0.0153)
$\hat{S}_2$	0.9756 (0.0102)	0.9805 (0.0070)	0.8707 (0.0137)
p_2	1.0000 (<0.0001)	0.9979 (0.0021)	0.9939 (0.0035)
λ_2	0.9375 (0.0143)	0.9691 (0.0078)	0.8236 (0.0158)
$\hat{S}_3$	0.9771 (0.0095)	0.9913 (0.0050)	0.8983 (0.0124)
p_3	1.0000 (<0.0001)	0.9958 (0.0029)	0.9957 (0.0030)
λ_3	0.9514 (0.0127)	0.9693 (0.0078)	0.7668 (0.0171)
$\hat{S}_D$	**0.9726 (0.0159)**	**0.9959 (0.0099)**	**0.9422 (0.0217)**

4.5 Travel Times

4.5.1 Forebay Residence Times

Using the R_1 releases, forebay residence times from first detection at the forebay array to the last detection at the dam-face array were calculated (Table 4.7, Figure 4.8). Yearling Chinook salmon and steelhead had similar mean times of 10.13 ($\widehat{\mathrm{SE}}(\bar{t}) = 0.62$) and 13.42 ($\widehat{\mathrm{SE}}(\bar{t}) = 1.34$) hours, respectively. Median forebay residence times were 4.92 hours for yearling Chinook salmon and 4.07 hours for steelhead. In contrast, subyearling Chinook salmon had a mean forebay residence time almost six times longer, with a mean of 62.10 hours ($\widehat{\mathrm{SE}}(\bar{t}) = 4.03$) and a median of approximately two times longer (Table 4.7).

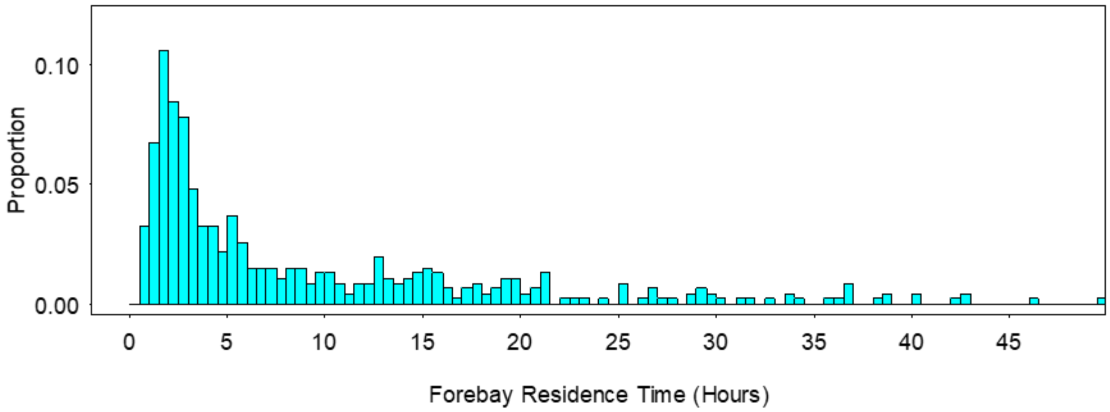
Table 4.7. Forebay Residence Times and Tailrace Egress Times for Yearling Chinook Salmon, Steelhead, and Subyearling Chinook Salmon at LGR, 2018

	Forebay residence time (hours)				Tailrace egress time (hours)			
Stock	$\bar{t}$	$\widehat{\mathrm{SE}}(\bar{t})$	**Median**	**Range**	$\bar{t}$	$\widehat{\mathrm{SE}}(\bar{t})$	**Median**	**Range**
Yearling Chinook salmon	10.13	0.62	4.92	0.53 – 135.25	2.00	0.86	0.27	0.17 – 313.65
Steelhead	13.42	1.34	4.07	0.60 – 453.43	2.93	2.27	0.27	0.17 – 1519.17
Subyearling Chinook salmon	62.10	4.03	8.96	0.55 – 942.43	2.15	0.29	0.62	0.20 – 539.48

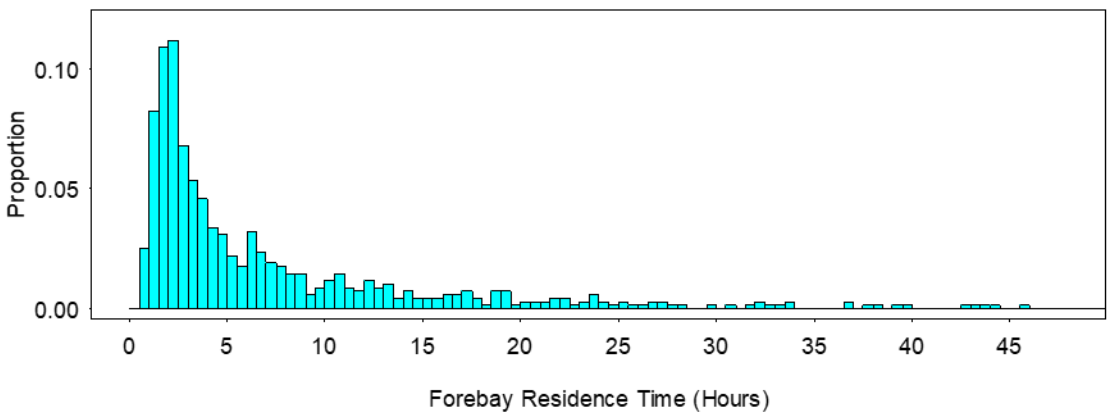
4.5.2 Tailrace Egress Time

The intervening time from last detection at the dam face or juvenile bypass to the last detection at the tailrace array were calculated for yearling Chinook salmon, steelhead, and subyearling Chinook salmon (Table 4.6, Figure 4.9). Mean egress times were relatively consistent across species, with mean values ranging from 2.00 h ($\widehat{\mathrm{SE}}(\bar{t}) = 0.86$) to 2.93 h ($\widehat{\mathrm{SE}}(\bar{t}) = 2.27$). Median egress times in summer (for subyearling Chinook) at 0.62 h were approximately double that of the spring stocks at 0.27 h for both (Table 4.6).

1. Yearling Chinook salmon



b. Steelhead



c. Subyearling Chinook salmon

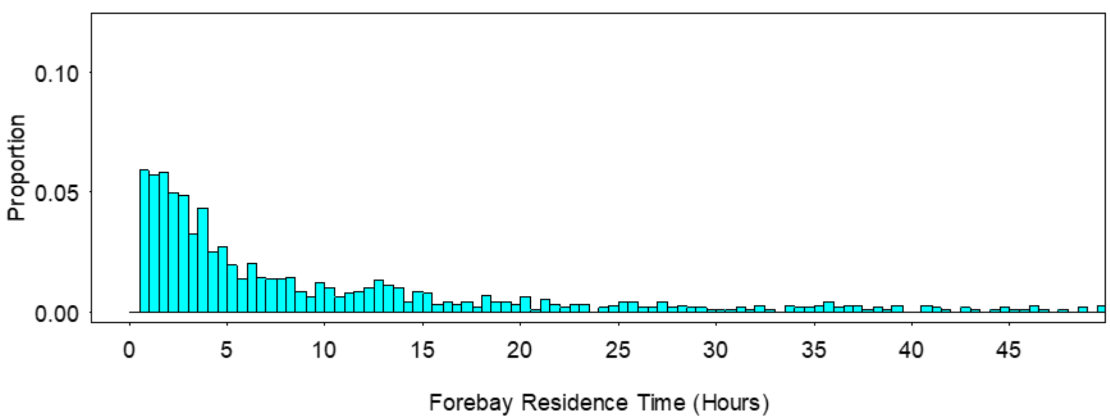


Figure 4.8. Distribution of Forebay Residence Times for Yearling Chinook Salmon, Steelhead, and Subyearling Chinook Salmon at LGR, 2018

4.5.3 Project Passage Time

The intervening time from first detection at the forebay array (1 km upstream of the dam) to the last detection at the tailrace array was calculated for yearling Chinook salmon, steelhead, and subyearling

Chinook salmon (Table 4.7). Again, yearling Chinook salmon and steelhead had similar mean passage times of 12.16 h ($\widehat{\text{SE}}(\bar{t}) = 1.10$) and 15.84 h ($\widehat{\text{SE}}(\bar{t}) = 2.58$), respectively. Mean passage times for subyearling Chinook salmon were roughly4 times longer, consistent with their protracted forebay residence time. Median project passage times were similar for yearling Chinook salmon and steelhead at 5.49 h and 4.53 h, respectively, with subyearling Chinook salmon taking twice as long at 10.67 h.

Table 4.8. Project Passage Times for Yearling Chinook Salmon, Steelhead, and Subyearling Chinook Salmon at LGR, 2018

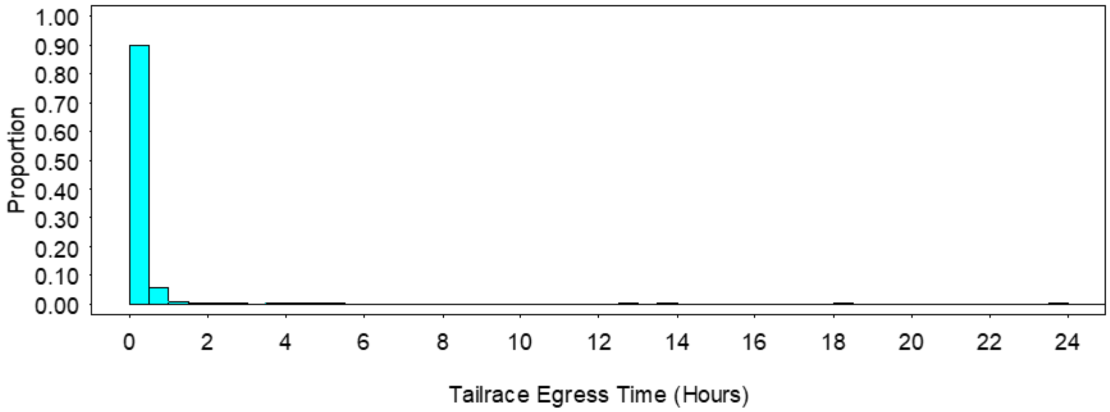
	Project passage time			
Stock	$\bar{x}$	$\widehat{\text{SE}}(\bar{x})$	**Median**	**Range**
Yearling Chinook salmon	12.16	1.10	5.49	0.80 – 329.42
Steelhead	15.84	2.58	4.53	0.85 – 1520.63
Subyearling Chinook salmon	55.83	3.84	10.67	1.17 – 945.47

4.6 Route-specific Passage Proportions

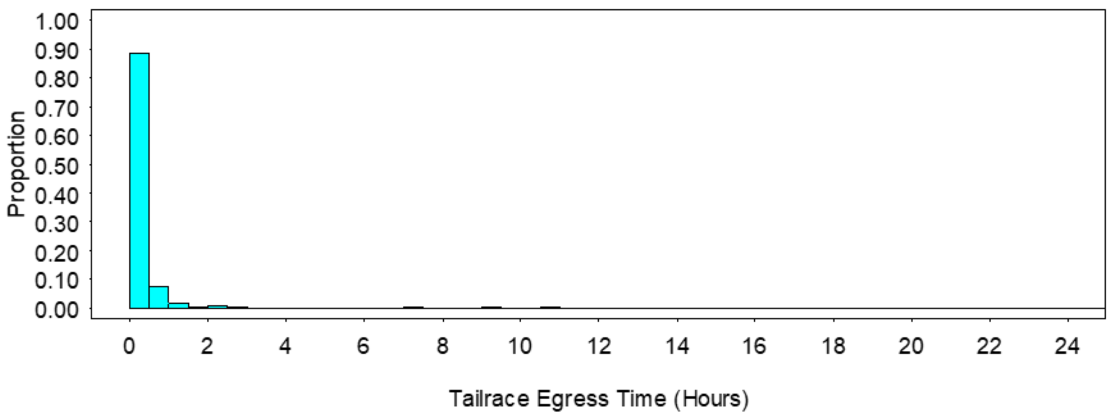
4.6.1 Passage Distributions

Based on the upstream release R_1, passage proportions through the various routes of LGR were calculated using the last detections at the dam-face array (or PIT-tag detectors in the juvenile bypass). Routes of passage delineated were spillway (SPL), removable spillway weir (RSW), juvenile bypass system (JBS), and turbines (TUR). Because detection rates were near 100% for all routes, passage proportions were based on binomial sampling (Table 4.8). All three fish stocks used the regular spillway similarly with about 25% passage. However, subyearling Chinook salmon used the RSW substantially more than the other two fish stocks. Conversely, subyearling Chinook salmon used the JBS only one-third as much as the other two fish stocks (Table 4.8).

a. Yearling Chinook salmon



b. Steelhead



c. Subyearling Chinook salmon

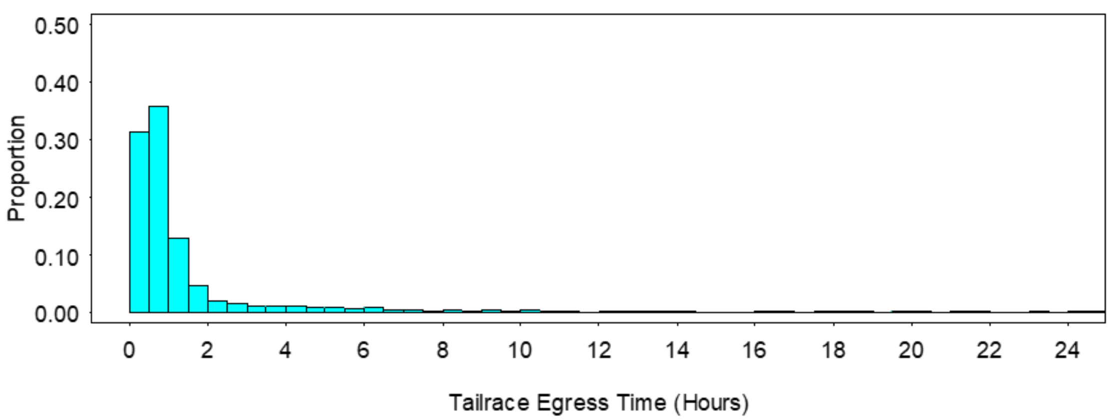


Figure 4.9. Distribution of Tailrace Egress Times for Yearling Chinook Salmon, Steelhead, and Subyearling Chinook Salmon at LGR, 2018

Table 4.9. Route-Specific Passage Proportions for Yearling Chinook Salmon, Steelhead, and Subyearling Chinook Salmon at the Spillway, Removable Spillway Weir, Juvenile Bypass System, and Turbines

Fish stock	Sample size (n)	SPL ($\hat{P}$)	SPL $\widehat{\text{SE}}(\hat{P})$	RSW ($\hat{P}$)	RSW $\widehat{\text{SE}}(\hat{P})$	JBS ($\hat{P}$)	JBS $\widehat{\text{SE}}(\hat{P})$	TUR ($\hat{P}$)	TUR $\widehat{\text{SE}}(\hat{P})$
Yearling Chinook salmon	462	0.2554	0.0203	0.3658	0.0224	0.3074	0.0215	0.0714	0.0120
Steelhead	680	0.2544	0.0167	0.3191	0.0179	0.3926	0.0187	0.0338	0.0069
Subyearling Chinook salmon	891	0.2469	0.0144	0.5499	0.0167	0.1156	0.0107	0.0875	0.0095

4.6.2 Spill Passage Efficiency (SPE)

SPE, defined as the fraction of fish going through the SPL or RSW, was calculated by fish stock (Table 4.10). Yearling Chinook salmon and steelhead had similar values around 60%, while subyearling Chinook salmon had a much higher value near 80%.

4.6.3 Fish Passage Efficiency (FPE)

FPE, defined as the fraction of fish going through non-turbine routes, was calculated by fish stock (Table 4.10). FPE exceeded 90% for all three fish stocks.

Table 4.10. Estimates of Spill Passage Efficiency and Fish Passage Efficiency for Yearling Chinook Salmon, Steelhead, and Subyearling Chinook Salmon at LGR, 2018

Fish stock	$\widehat{\text{SPE}}$	$\widehat{\text{SE}}(\widehat{\text{SPE}})$	$\widehat{\text{FPE}}$	$\widehat{\text{SE}}(\widehat{\text{FPE}})$
Yearling Chinook salmon	0.6212	0.0226	0.9286	0.0120
Steelhead	0.5735	0.0190	0.9662	0.0069
Subyearling Chinook salmon	0.7969	0.0135	0.9125	0.0095

4.7 Route-specific Passage Survival

Treating the tagged fish going through the various passage routes as separate virtual releases, the VIPRE model was used to estimate route-specific passage survival by fish stock (Table 4.10). Regardless of fish stock, the JBS had the highest passage survival of any route at LGR, with survival probability values essentially equaling 1.0. The removable spillway weir had the next highest values of route-specific survival, with values ranging from 0.9655–0.9853. A surprising result was the relatively low survival of subyearling Chinook salmon through the spillway, with an estimated value of 0.8456 ($\widehat{\text{SE}} = 0.0321$). Conversely, subyearling Chinook salmon had much higher turbine passage survival than the other two fish stocks, with an estimated value of 0.9949 ($\widehat{\text{SE}} = 0.0306$) (Table 4.10).

Table 4.11. Route-Specific Passage Survival Estimates Through the Spillway, Removable Spillway Weir, Juvenile Bypass System, and Turbines for Yearling Chinook Salmon, Steelhead, and Subyearling Chinook Salmon

	SPL		RSW		JBS		TUR	
Fish stock	$(\hat{S})$	$\widehat{\mathrm{SE}}(\hat{S})$	$(\hat{S})$	$\widehat{\mathrm{SE}}(\hat{S})$	$(\hat{S})$	$\widehat{\mathrm{SE}}(\hat{S})$	$(\hat{S})$	$\widehat{\mathrm{SE}}(\hat{S})$
Yearling Chinook salmon	0.9521	0.0244	0.9855	0.0172	0.9961	0.0158	0.8779	0.0599
Steelhead	1.0003	0.0119	0.9843	0.0141	1.0111	0.0087	0.8804	0.0715
Subyearling Chinook salmon	0.8456	0.0321	0.9655	0.0230	1.0023	0.0277	0.9949	0.0306

5.0 Discussion

5.1 Comparison of VIPRE vs. ViRDCt Model Estimates

For each of the three fish stocks, there was an opportunity to compare estimates of dam passage survival generated by the alternative VIPRE and ViRDCt models. The estimates of survival from the two alternative release-recapture models comported well within and across fish stocks (Table 4.4). Estimates from the two models were generally within 1 SE of each other, as estimated by the VIPRE model. No one model appeared to systematically have higher or lower survival estimates than the other. Within the limits of the field trial, it appears both models were attempting to estimate the same values of dam passage survival.

On the other hand, the ViRDCt model produced survival estimates with lower standard error (SE). The SEs from the ViRDCt model were less than half the size of the SEs from the VIPRE model. This improvement in precision was accomplished by the ViRDCt model using less than half the number of acoustic tags used by the VIPRE model. These results strongly suggest that future studies to monitor dam passage survival could generate more precise estimates with greater cost-effectiveness using the ViRDCt approach.

5.2 Comparison of the LGR 2018 Estimates with Prior Studies

The 2018 study to estimate dam passage survival at LGR was the first at that location. Consequently, there is no direct reference to compare the 2018 LGR results with earlier values. However, the 2018 LGR results can be compared to the estimates of dam passage survival reported by Skalski et al. (2016) collected during compliance studies at other FCRPS hydroprojects, 2010–2014.

Nine estimates of dam passage survival using the VIPRE model were generated for yearling Chinook salmon at other FCRPS projects, with a range of 0.9597 ($\widehat{\text{SE}} = 0.0176$) to 0.9868 ($\widehat{\text{SE}} = 0.0090$) and a mean value of 0.9678 (Skalski et al. 2016). The survival value of 0.9726 ($\widehat{\text{SE}} = 0.0159$) for yearling Chinook salmon generated at LGR in 2018 comports well with these historical values elsewhere.

Nine estimates of dam passage survival using the VIPRE model were generated for juvenile steelhead at other FCRPS projects, with a range of 0.9534 ($\widehat{\text{SE}} = 0.0097$) to 0.9952 ($\widehat{\text{SE}} = 0.0083$) and a mean value of 0.9792 (Skalski et al. 2016). The 2018 estimate of dam passage survival for steelhead at LGR of 0.9959 ($\widehat{\text{SE}} = 0.0099$) is on the high side of the historical range observed elsewhere.

Eleven estimates of dam passage survival using the VIPRE model were generated for subyearling Chinook salmon at other FCRPS projects, with a range of 0.9076 ($\widehat{\text{SE}} = 0.0139$) to 0.9789 ($\widehat{\text{SE}} = 0.0079$) and a mean value of 0.9441 (Skalski et al. 2016). The 2018 estimate of dam passage survival for subyearling Chinook salmon at LGR of 0.9422 ($\widehat{\text{SE}} = 0.0217$) is very similar to the mean of historical values observed elsewhere.

The two estimates of dam passage survival for the spring migrants at LGR in 2018 exceed the 2008 BiOp survival standard of ≥ 0.96. Similarly, the VIPRE survival estimate for subyearling Chinook salmon at LGR in 2018 exceeded the 2008 BiOp survival standard of ≥ 0.93 for summer migrants.

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Appendix A

Capture Histories Used in Survival Analyses

Appendix A

Capture Histories Used in Survival Analyses

Table A.1. Capture history data for V_1, R_2, and R_3 used in estimated dam passage survival based on the VIPRE model.

	Yearling Chinook salmon	**Steelhead**	**Subyearling Chinook salmon**
V_1			
1 1 1	411	637	565
0 1 1	1	0	0
1 0 1	0	0	8
0 0 1	0	0	0
1 2 0	4	3	5
0 2 0	0	0	0
1 1 0	20	17	153
0 1 0	1	0	0
2 0 0	0	0	0
1 0 0	4	7	71
0 0 0	14	11	79
R_2			
1 1	270	471	481
0 1	0	1	3
2 0	1	2	6
1 0	18	15	103
0 0	9	12	97
R_3			
1 1	274	473	467
0 1	0	2	2
2 0	2	4	2
1 0	14	15	142
0 0	8	6	77

Table A.2. Dam survival estimates—ViRDCt model.

Detection history.	Live yearling (V_1)	Dead yearling (D_1)	Live steelhead (V_1)	Dead steelhead (D_1)	Live subyearling (V_1)	Dead subyearling (D_1)
1 1	439	2	664	3	801	1
0 1	0	0	0	0	1	0
1 0	12	59	8	52	21	37
0 0	4	151	3	128	58	251

For yearling Chinook salmon and steelhead, the capture histories for forebay-to-tailrace survival are the same as for the dam survival estimates since all those detected at the forebay were detected at the dam face, and vice versa. Capture histories for estimating forebay-to-tailrace survival for subyearling Chinook salmon are given in Table A.3 and Table A.4.

Table A.3. Capture history data for V_1, R_2, and R_3 used in estimating forebay-to-tailrace survival based on the VIPRE model.

	Subyearling Chinook salmon
V_1	
1 1 1	671
0 1 1	0
1 0 1	10
0 0 1	0
1 2 0	5
0 2 0	0
1 1 0	235
0 1 0	0
2 0 0	0
1 0 0	85
0 0 0	175
R_2	
1 1	481
0 1	3
2 0	6
1 0	103
0 0	97
R_3	
1 1	467
0 1	2
2 0	2
1 0	142
0 0	77

Table A.4. ViRDCt model—forebay-to-tailrace.

	Live subyearling (V_1)	**Dead subyearling (D_1)**
1 1	800	1
0 1	1	0
1 0	21	37
0 0	70	251

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