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Survival Estimates for the Passage of Spring-Migrating Juvenile Salmonids Through Snake and Columbia River Dams and Reservoirs, 2021

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Daniel L. Widener, James R. Faulkner, Steven G. Smith, and Tiffani M. Marsh

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Fish Ecology Division
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112

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Contents

Executive Summary

In 2021, we completed the 29th year of a study to estimate survival and travel time of juvenile Pacific salmon *Oncorhynchus* spp. passing dams and reservoirs on the Snake and Columbia Rivers. All estimates were derived from detections of fish tagged with passive integrated transponder (PIT) tags.

During the 2021 migration season, field work was restricted by the COVID-19 pandemic. Both the tagging program at Lower Granite Dam and the estuary trawl detection system operated at reduced capacity in 2021. We tagged and released a total of 18,120 hatchery steelhead *O. mykiss,* 4,854 wild steelhead, and 1,770 wild Chinook salmon *O. tshawytscha* at Lower Granite Dam on the Snake River. In addition to detections of these fish, we used detections of yearling Chinook and steelhead tagged by other researchers upstream from Lower Granite Dam and at other hatcheries and traps on the Snake and Columbia Rivers.

In 2021, reduced tagging operations at Lower Granite Dam, combined with very low detection rates in the juvenile bypass system, would have resulted in extremely small sample sizes for survival estimation if not for the spillway detection system. Most survival estimates in 2021 would not have been possible without data from this spillway system, which first became operational in 2020.

In addition to the spillway system at Lower Granite, detection sites in 2021 included the juvenile bypass systems at Lower Granite, Little Goose, Lower Monumental, Ice Harbor, McNary, John Day, and Bonneville Dam, as well as the Bonneville Dam corner collector. Detection data from all of these sites have been used in previous years.

In 2020, the Columbia River estuary trawl detection system was not operated, and we used alternative sources of detection information below Bonneville Dam for survival estimation. In 2021, we continued to use all available data sources downstream of Bonneville Dam, including those from the trawl system. We anticipate continuing this approach in future years, as well as revisiting past years when only data from the trawl was used. Three sources of data downstream from Bonneville Dam were available in 2021:

1) Detections by the estuary trawl
2) Recoveries of tags from multiple avian nesting and roosting areas in the Columbia River estuary

3) Detections of precocious juvenile fish as they ascended the adult fish ladder at Bonneville Dam

Primary research objectives in 2021 were:

1) Estimate reach survival and travel time throughout the migration period of yearling Chinook salmon and steelhead
2) Evaluate relationships between survival estimates and migration conditions
3) Evaluate survival estimation models under prevailing conditions

In 2021, we estimated reach survival and travel time for yearling Chinook salmon, steelhead, and sockeye *O. nerka* of both wild and hatchery origin, and also for coho salmon *O. kisutch* of hatchery origin. Survival estimates were calculated using a statistical model for mark-recapture data from single-release groups.

During most of the migration season, detection probabilities at dams downstream from Lower Granite Dam were extremely low as a result of very high rates of spill and correspondingly low proportions of fish passing via juvenile bypass systems. Due to these low detection probabilities, we were unable to use our customary approach of pooling "virtual" release groups of fish detected or released at Lower Granite Dam during the same daily or weekly period. Instead, we estimated survival and detection probabilities by pooling virtual release groups over biweekly periods.

Additionally, because of low detection rates at McNary Dam, no survival estimates were possible for pooled groups of fish detected passing McNary over any period (daily, weekly, or biweekly). Instead, for survival estimation between McNary and Bonneville Dam, we used the same biweekly groups used for estimates in the reaches from Lower Granite to McNary. This change from customary methods was also necessary in 2020 because of low detection rates.

Hatchery and wild fish were combined in some analyses. Among PIT-tagged fish detected at Lower Granite Dam, 91% of yearling Chinook and 90% of steelhead were of hatchery origin. In the overall runs, which include both tagged and untagged fish, our corresponding estimates of the hatchery-origin component were 91.6% of yearling Chinook and 90.5% of steelhead.

All survival probability estimates between dams refer to the reach from the tailrace of the upstream dam to the tailrace of the downstream dam. Estimates of average survival and associated standard errors are listed by reach in Table E1 for groups of combined wild and hatchery yearling Chinook salmon and steelhead.

Table E1. Average survival estimates by reach for combined hatchery and wild yearling Chinook salmon and steelhead during 2021. Standard errors in parentheses.

	Yearling Chinook salmon	Steelhead
Snake River Smolt Trap to Lower Granite Dam	0.867 (0.108)	0.936 (0.029)
Lower Granite to Little Goose Dam	0.806 (0.067)	1.070 (0.045)
Little Goose to Lower Monumental Dam	1.136 (0.127)	1.089 (0.083)
Lower Monumental to McNary Dam[a]	0.854 (0.146)	0.681 (0.043)
Lower Monumental to Ice Harbor Dam	1.027 (0.137)	0.972 (0.076)
Ice Harbor to McNary Dam	0.781 (0.054)	0.804 (0.096)
McNary to John Day Dam	0.960 (0.077)	0.757 (0.071)
John Day to Bonneville Dam[b]	0.796 (0.096)	0.795 (0.029)
Snake River Smolt Trap to Bonneville Dam[c]	0.471 (0.094)	0.456 (0.028)

[a] Two-project reach, including Ice Harbor Dam and reservoir.
[b] Two-project reach, including The Dalles Dam and reservoir.
[c] Entire hydropower system, including eight dams and reservoirs.

We also estimated average survival through the entire hydropower system from the Snake River Smolt Trap at the head of Lower Granite reservoir to the tailrace of Bonneville Dam (Table E1). These estimates were the product of average survival estimates through the following three reaches: Snake River Smolt Trap to Lower Granite Dam, Lower Granite to McNary Dam, and McNary to Bonneville Dam. For combined wild and hatchery fish from the Snake River, average estimated survival through the entire hydropower system was 0.471 (95% CI 0.286-0.655) for yearling Chinook and 0.456 (0.401-0.511) for steelhead.

We estimated survival for hatchery fish originating upstream from the confluence of the Columbia and Yakima Rivers. For yearling Chinook salmon, estimated survival to Bonneville Dam ranged from 0.903 (SE 0.432) for Methow Hatchery fish released to Twisp Pond—a notably imprecise estimate—to 0.227 (0.048) for Cle Elum Hatchery fish released to Jack Creek Pond. For Upper Columbia River steelhead, estimated survival to McNary Dam ranged from 0.585 (0.153) for Wells Hatchery fish released from Methow Hatchery to 0.133 (0.118) for Wells Hatchery fish released to the Twisp River.

Of the smolt run at large that arrived at Lower Granite Dam, we estimated that 7.9% of yearling Chinook and 7.7% of steelhead were transported from a Snake River collector dam (means of combined wild and hatchery estimates). These estimates were the lowest on record by a wide margin.

Two factors determine the ultimate proportion of fish transported: passage timing of the population relative to the transportation period and the proportion of the population collected during the transportation period. In 2021, proportions of fish collected during transport operations were far below average. For the period of transport operations in 2021, we estimated that the respective proportions collected were only 14.6 and 6.4% for wild and hatchery Chinook and 11.1 and 7.2% for wild and hatchery steelhead. These proportions were far below average. These low collection rates were the primary cause of the substantially below-average proportions transported.

In addition to estimates of survival for yearling Chinook salmon and steelhead, we calculated travel time over individual reaches between dams and over combined reaches between Lower Granite and Bonneville Dam (461 km). Over the last several years, we have noted a trend toward shorter smolt travel times relative to levels of flow and spill. However, we did not see strong evidence of this trend in 2021.

For the majority of the migration season, travel times for both yearling Chinook and steelhead were similar to those in other recent low-flow years. The exceptions were after the start of May for Chinook and from late April through early May for steelhead. During these periods, travel times were slightly shorter than in past low-flow years.

At dams where PIT-tag detection was possible only in the juvenile bypass system, detection probabilities were extremely low in 2021. This reduced the quality of survival estimates and forced us to alter our methods in an attempt to compensate. The quality of survival estimates has suffered from low detection probabilities in other recent years, but the issue was especially acute in 2020 and 2021.

With the exception of Lower Granite and Bonneville, each of which had an additional monitored passage route, every dam had a detection rate less than half of the 2007-2019 average in both 2020 and 2021. These extremely low detection rates resulted in highly imprecise survival estimates for most single-project component reaches.

In recent years, spill levels have been increased in an attempt to boost juvenile salmonid survival through the hydropower system. Unfortunately, the drop in smolt detection rates at Snake and Columbia River dams is a side effect of increased spill since 2006, and extreme increases during the last two years. In 2021, these extremely high spill rates combined with low flow to produce the lowest detection probabilities yet.

Given a fixed number of tagged smolts, lower detection probabilities greatly reduce the precision of survival estimates from PIT-tag data. In light of present operations, we believe the need is increasingly urgent to develop PIT-tag detection capability for passage routes other than bypass systems. Specifically, we recommend that the region place high priority on development and installation of PIT-monitoring systems for conventional spillways, as well as for surface-passage structures.

The spillway detection system at Lower Granite Dam continued to be highly successful at detecting fish in 2021. Without it, survival estimation for Snake River fish would have been impossible. When detection was possible only in the juvenile bypass system at Lower Granite Dam, the overall mean estimated annual percentage detected from 2007 to 2019 was 26.1% for tagged yearling Chinook. In 2021, the estimated overall percentage detected was 40.8%, with only 1.7% detected in the bypass system and 39.1% detected on the spillway system. We urge regional managers to take note of the success of the new system and to prioritize installation of similar systems at other major dams.

As we have suggested in recent years, higher rates of detection are necessary if we are to enhance or even maintain the precision of juvenile survival estimates based on PIT-tag data. Because of its low cost, ease of implantation, low biological impact, and long life, the PIT tag continues to be the preferred marking technique for the Columbia Basin fisheries community. Throughout the basin, nearly 2 million individual fish are PIT-tagged annually.

After tagging, these fish can be monitored through both their juvenile and adult migrations. However, the value of information gathered per tagged fish is proportional to the rate of detection after release. Thus, with reduced detections, the rate of return on investment in the entire PIT-tagging program is reduced.

Aside from these effects on the quality of smolt migration data, at present there is no other tagging method that allows direct comparison of smolt-to-adult return ratios between groups. Therefore, it is critical that we take the necessary steps to maximize the quantity and quality of information already offered by the PIT tag at existing levels of tagging.

Introduction

Accurate and precise estimates of survival are critical for recovery of depressed stocks of Pacific salmon *Oncorhynchus* spp. that migrate through Snake and Columbia River reservoirs, dams, and free-flowing reaches. To develop recovery strategies that will optimize survival of migrating smolts, resource managers need information on the magnitude, locations, and causes of smolt mortality. Such knowledge is necessary for recovery strategies applied under present passage conditions as well as for those applied under conditions projected for the future (Williams and Matthews 1995; Williams et al. 2001, Crawford and Rumsey 2011).

From 1993 through 2021, the National Marine Fisheries Service (NMFS) has estimated annual survival for Pacific salmon stocks as they pass Snake and Columbia River dams and reservoirs (Iwamoto et al. 1994; Muir et al. 1995, 1996, 2001a,b, 2003; Smith et al. 1998, 2000a,b, 2003, 2005, 2006; Hockersmith et al. 1999; Zabel et al. 2001, 2002; Faulkner et al. 2007-2017; Widener et al. 2018-2021). Annual survival estimates are based on data from detections of juvenile salmonids implanted with passive integrated transponder (PIT) tags (Prentice et al. 1990a). Here we report results for smolts that migrated in spring 2021, the 29th year of the study. Research objectives in 2021 were:

1) Estimate reach survival and travel time throughout the yearling Chinook salmon and steelhead migration season.
2) Evaluate relationships between survival estimates and migration conditions.
3) Evaluate the performance of survival estimation models under prevailing operational and environmental conditions.

Survival from Release to Bonneville Dam

Methods

Experimental Design

To estimate survival and detection probability for groups of PIT-tagged Pacific salmon smolts *Oncorhynchus* spp., we used the Cormack-Jolly-Seber (CJS) mark-recapture model for single-release groups, otherwise known as the single-release model (Cormack 1964; Jolly 1965; Seber 1965; Skalski 1998; Skalski et al. 1998; Muir et al. 2001a). In our application of the model, detection of a PIT-tagged fish is equivalent to "recapture." Further background information and underlying statistical theory pertaining to the single-release model is detailed by Iwamoto et al. (1994).

During the 2021 migration season, survival estimates were based on detections of fish released from Lower Granite Dam, from hatcheries and traps in the Snake River Basin, and from hatcheries and dams in the Upper Columbia River. A large number of PIT-tagged yearling Chinook salmon *O. tshawytscha* used in our analyses were released in the Snake River upstream from Lower Granite Dam for the annual multi-agency *Comparative Survival Study* (McCann et al. 2022).

Generally, tagged fish are detected at dams with monitoring facilities only if they are diverted into the juvenile bypass systems at those dams (Figure 1). The exceptions are Lower Granite, which has a spillway detection system (active since 2020) and Bonneville, which has a detection system located in the corner collector of Powerhouse 2 (active since 2006). In 2021, the following ten sites were equipped with automated monitoring facilities or were monitored by hand (Figure 1; Prentice et al. 1990a,b,c):

<u>Dams with detection systems</u>

- Lower Granite Dam (rkm[1] 695)
- Little Goose Dam (rkm 635)
- Lower Monumental Dam (rkm 589)
- Ice Harbor Dam (rkm 538)
- McNary Dam (rkm 470)
- John Day Dam (rkm 347)
- Bonneville Dam (rkm 234)

<u>Estuary sites of detection or recovery</u>

- Astoria-Megler Bridge (rkm 12)
- Avian colonies (rkm 8-32)
- Pair-trawl system (rkm 65-84)

[1] River kilometer from the mouth of the Columbia River

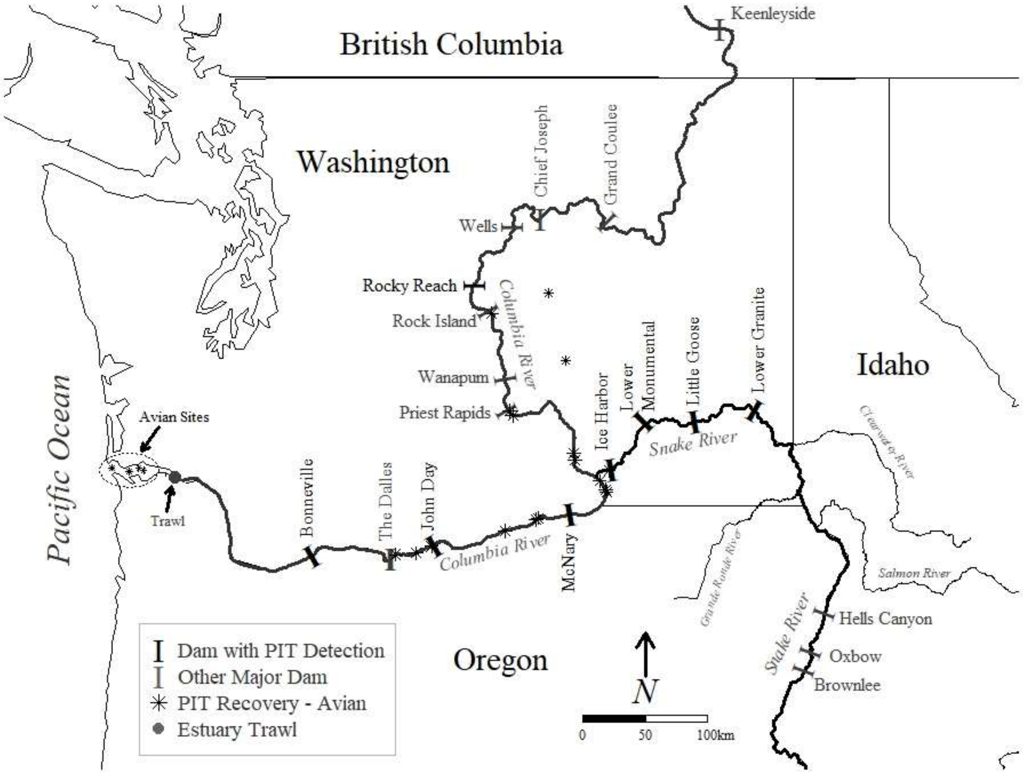

Figure 1. Study area showing PIT-tag detection sites in the Columbia River Basin, 2021. Dams with detection capability are marked with black bars, and those without are marked with gray bars. Other detection sites are marked with gray dots, while sites of recovery from avian nesting and roosting areas are marked with stars.

After juvenile salmonids passed Bonneville Dam heading downstream, there were three sources of detection data that we used in 2021. From the Columbia River estuary, we used detections by the NMFS pair-trawl detection system (Ledgerwood et al. 2004), and recoveries of PIT tags deposited by predaceous birds on several nesting colonies on islands and on the Astoria-Megler Bridge (Evans et al. 2021). The third source of "post-Bonneville" data was detection of precocious juveniles (known as "mini-jacks") migrating upstream through the fish ladders at Bonneville Dam. In 2021, these were all the sources of PIT-tag information after smolts passed Bonneville Dam.

We grouped detections from all three post-Bonneville data sources to form a composite "final detection site." Using the single-release model, for the final detection site in the series, only the joint probability of survival to and detection at the site can be estimated; there is no information that can be used to estimate the parameters separately. Thus, to estimate survival to Bonneville Dam separately from detection probability at the dam, detection at a final site farther downstream is required.

In 2021, detection probabilities were moderate for Bonneville Dam and low for the composite final detection site. Though data were sufficient to estimate survival from John Day to Bonneville Dam for most stocks, the resulting estimates were often imprecise.

At Snake and Columbia River dams, most tagged fish were returned to the river after detection, which allowed for the possibility of additional detection at one or more sites downstream (Marsh et al. 1999). Thus, for fish released in the Snake River Basin upstream from Lower Granite Dam, we estimated survival in the following seven reaches, with all estimates between dams spanning the reach from tailrace to tailrace:

- Point of release to Lower Granite Dam (various distances)
- Lower Granite to Little Goose Dam (60 km)
- Little Goose to Lower Monumental Dam (46 km)
- Lower Monumental to Ice Harbor Dam (51 km)
- Ice Harbor to McNary Dam (68 km)
- McNary to John Day Dam (123 km)
- John Day to Bonneville Dam (112 km)

At Ice Harbor Dam, a PIT-tag detection system was first operated in the juvenile bypass facility in 2005. Since 2006, detections at Ice Harbor have been sufficient to partition the two-project survival estimate from Lower Monumental to McNary Dam. However, in 2021, detections at Ice Harbor and Lower Monumental were extremely low, and detections at McNary were also far below average. These low detection rates resulted in small samples with very poor precision in the resulting survival estimates.

For fish released in the Upper Columbia River, we estimated survival in the following three reaches, with all estimates between dams spanning tailrace to tailrace:

- Point of release to McNary Dam (various distances)
- McNary to John Day Dam (123 km)
- John Day to Bonneville Dam (112 km)

Study Fish

Releases from Lower Granite Dam—During 2021, we collected hatchery and wild steelhead *O. mykiss* and wild yearling Chinook smolts at the Lower Granite Dam juvenile bypass facility. Fish were PIT tagged and released to the tailrace for the express purpose of estimating downstream survival. Numbers of fish were collected in approximate proportion to numbers arriving in the bypass system at Lower Granite Dam except during the early and late periods of the migration season. We tagged relatively more fish during the early and late periods to ensure adequate detection numbers for estimates during these periods.

No hatchery yearling Chinook were tagged specifically for this study because sufficient numbers of these fish had been tagged and released from Snake River Basin hatcheries and traps by other researchers. We used data from these fish to estimate detection probabilities, survival probabilities, and travel time.

For both yearling Chinook salmon and steelhead, we created virtual daily "release groups" from fish tagged and released upstream from Lower Granite Dam and subsequently detected passing the dam. Virtual release groups included fish detected in either the juvenile bypass or spillway detection systems. At Lower Granite Dam, each daily group of fish detected and returned to the river was combined with fish tagged and released from the dam on the same date. These daily groups were then pooled into weekly and biweekly groups.

We estimated survival for biweekly groups in individual reaches between Lower Granite and McNary Dam. We attempted to estimate survival for daily and weekly groups as well; however, extremely poor detection rates at every dam downstream from Lower Granite rendered the results unusable. Additionally, for fish released early and late in the season, some biweekly groups were too small for reliable estimates of either survival or travel time. These groups were excluded from analysis.

We PIT tagged and released 18,120 hatchery steelhead, 4,854 wild steelhead, and 1,770 wild yearling Chinook salmon at Lower Granite Dam from 8 April through 12 June 2021 (Table 1). From these numbers, total tagging mortalities were 64, 4, and 10 for hatchery steelhead, wild steelhead, and wild yearling Chinook salmon, respectively. Each of these mortality rates was well below 1% of the total number of fish handled. Tag codes from mortalities and shed tags were removed from the dataset before analysis.

Table 1. Number by date of hatchery and wild steelhead, and wild yearling Chinook salmon PIT tagged and released at Lower Granite Dam for survival estimates in 2021. Also included are numbers of tagging mortalities and shed tags.

	Hatchery Steelhead			Wild Steelhead			Wild Yearling Chinook		
Release date	Number released	Mortalities	Shed tags	Number released	Mortalities	Shed tags	Number released	Mortalities	Shed tags
8 Apr	616	-	-	113	-	-	43	-	-
9 Apr	407	-	-	106	-	-	75	-	-
14 Apr	711	-	-	98	-	-	76	-	-
15 Apr	703	-	-	65	-	-	106	1	-
23 Apr	875	2	-	100	-	-	66	-	-
24 Apr	865	4	-	103	-	-	103	1	-
27 Apr	888	1	-	113	-	-	95	1	-
28 Apr	693	-	2	51	-	-	25	-	-
29 Apr	692	9	-	46	-	-	25	1	-
30 Apr	573	1	-	34	-	-	10	-	-
1 May	690	8	1	71	-	-	65	-	-
4 May	760	7	-	320	1	-	130	1	-
5 May	745	2	1	303	-	1	127	1	-
6 May	838	7	-	247	-	1	59	-	1
7 May	767	1	-	444	-	-	99	1	-
8 May	581	2	-	321	-	2	134	1	-
11 May	566	1	-	114	-	-	60	-	1
12 May	586	2	-	114	1	-	38	-	-
13 May	1,027	3	1	218	-	-	41	-	-
14 May	800	1	1	288	-	-	22	-	-
15 May	321	1	-	134	-	-	19	-	-
18 May	537	2	-	147	-	-	34	-	-
19 May	441	1	-	248	-	-	50	-	-
20 May	557	2	-	253	-	-	47	-	-
21 May	217	5	-	94	-	-	41	-	-
22 May	562	2	1	280	-	-	12	-	-
25 May	108	-	-	43	-	-	5	-	-
26 May	116	-	-	54	1	-	9	-	-
27 May	139	-	1	42	-	-	5	-	-
28 May	102	-	-	27	1	-	2	-	-
29 May	60	-	1	23	-	-	6	-	-
2 Jun	52	-	1	23	-	-	11	-	-
3 Jun	112	-	-	41	-	-	28	1	-
4 Jun	106	-	-	37	-	-	42	1	-
5 Jun	107	-	1	46	-	-	60	-	-
8 Jun	56	-	-	33	-	-	-	-	-
9 Jun	37	-	-	23	-	-	-	-	-
10 Jun	39	-	-	16	-	-	-	-	-
11 Jun	42	-	-	14	-	-	-	-	-
12 Jun	26	-	-	7	-	1	-	-	-
	18,120	64	11	4,854	4	5	1,770	10	2

At Lower Granite Dam, a total of 105,131 yearling Chinook salmon (96,075 hatchery, 9,056 wild) were either collected, tagged, and released to the tailrace or detected and returned to the tailrace. A total of 117,676 steelhead (105,368 hatchery, 12,308 wild) were tagged and released or detected and returned to the tailrace of Lower Granite Dam.

We estimated that 91.6% of the overall yearling Chinook run was of hatchery origin in 2021. This estimate was based on counts of the run at large (both tagged and non-tagged fish) by the Fish Passage Center (FPC 2021a) and on our own estimates of daily detection probability at Lower Granite Dam (based on tagged fish only). We estimated that 90.5% of the overall steelhead run was of hatchery origin in 2021. The estimate for steelhead was based on unpublished data from the Smolt Monitoring Program (Jerry McCann, Fish Passage Center, personal communication), using fin erosion as a marker to distinguish hatchery-origin fish from wild fish.

For combined hatchery and wild groups used to estimate survival, estimated proportions of hatchery fish were 91% for yearling Chinook and 90% for steelhead. These proportions were very similar to the hatchery/wild composition of the overall run.

When we tag fish at Lower Granite Dam for this study, we intentionally emphasize tagging of wild fish to ensure adequate sample sizes for separate estimates of survival for wild fish. However, due to the small number of wild smolts entering the bypass system at Lower Granite Dam, as well as the reduced tagging capacity due to COVID-19 work protocols, we were unable to meet our tagging goals for wild smolts in 2021.

This resulted in overall sample sizes for wild fish that were lower than average, though not as low as those in 2020. Small numbers in virtual release groups compounded the difficulties imposed by low detection rates at downstream sites. These reductions in sample size ultimately resulted in poor precision of survival estimates for wild fish in 2021.

***Releases from McNary Dam*—**To estimate survival downstream of McNary Dam for yearling Chinook and steelhead released from locations throughout the Snake River Basin, our standard methodology in previous years has been to create virtual daily "release groups" at McNary. Virtual groups were formed according to day of detection at McNary. However, in 2021 detection rates at McNary were too low to generate sample sizes sufficient for survival estimation using this method.

In total, only 9,268 yearling Chinook and 3,370 steelhead of Snake River origin were detected passing McNary Dam in 2021. These detection numbers resulted in small sample sizes that were similar to those in 2020. In both 2020 and 2021, the combination of small sample sizes, low detection rates below Bonneville Dam, and extremely low detection rates at John Day Dam made survival estimation impossible for virtual groups made from fish detected at McNary Dam.

Therefore, in 2021 we again used the alternative method devised in 2020 for survival estimation of Snake River Basin fish between McNary Dam and Bonneville Dam. This alternative method uses virtual release groups based on day of detection at Lower Granite Dam for survival estimation between McNary and Bonneville Dam. This method boosts sample sizes available for survival estimation because far more Snake River fish are detected at Lower Granite than at McNary.

The main drawback of this method is that it results in greater overlap in downstream passage timing among adjacent virtual release groups due to dispersion during migration downstream from Lower Granite. When release groups are followed all the way from Lower Granite to Bonneville Dam, a large degree of overlap is expected in passage timing at the furthest downstream sites. This overlap impairs the ability to distinguish changes in survival that may result from river conditions, which change across the season.

Additionally, dispersal within virtual groups is likely to increase variation among individuals in survival and detection probability at each reach and detection site. This variation presumably increases as fish move downstream, potentially violating the model assumption of homogeneous survival and detection probabilities across individuals within a release group. If this violation is of sufficient magnitude, it can potentially bias survival estimates (Appendix A). Despite this risk, the method is the most stable among available approaches, producing estimates of acceptable quality for comparison with estimates from the method used in previous years.

Releases in the upper Columbia River—Groups of tagged yearling Chinook and steelhead were released from locations throughout the Columbia River Basin upstream from the confluence of the Columbia and Snake Rivers. For these fish, we estimated survival from release to McNary Dam and to dams downstream using release groups based on species, tagging site, and release location. We also pooled fish of a given species from all release locations into a single overall group for the entire year. We used these pooled groups for estimates between McNary and Bonneville Dam.

Releases from Hatcheries and Smolt Traps—In 2021, most hatcheries in the Snake and upper Columbia River Basins released PIT-tagged fish as part of research independent of our survival study. We used data from hatchery releases of PIT-tagged yearling Chinook, sockeye *O. nerka*, coho *O. kisutch*, and steelhead to obtain estimates of survival and detection probability. For fish originating in the Snake River Basin, we provided estimates from release to Lower Granite Dam and to points downstream from Lower Granite Dam. For fish originating in the Upper Columbia River Basin, we provided estimates of survival from release to McNary Dam and to points downstream from McNary Dam.

We also estimated survival to Lower Granite Dam and to points downstream for wild and hatchery yearling Chinook salmon and steelhead and wild sockeye PIT tagged at and released from many smolt traps throughout the Snake River Basin, including the Salmon River (White Bird), Snake River, and Lower Grand Ronde Smolt Traps.

Data Analysis

Tagging and detection data were downloaded from the Columbia Basin PIT Tag Information System (PTAGIS), a regional database maintained by the Pacific States Marine Fisheries Commission (PSMFC 1996-present). Data were first downloaded on 18 August 2021, and we published a memorandum of preliminary survival estimates on 7 October 2021. However, when that memo was published, data from PIT-tag recoveries on avian colonies throughout the basin were not yet available.

By late November 2021, recovery data from the avian colonies had been uploaded to the PTAGIS database, significantly expanding detection data from below Bonneville Dam. Accordingly, on 3 December we again downloaded tagging and detection data for the 2021 migration year. Data were examined for erroneous records, inconsistencies, and anomalies. Records were eliminated where appropriate, and all eliminated PIT-tag codes were recorded with the reasons for their elimination. Very few records were eliminated (<0.1%).

For each remaining PIT-tag code, we constructed a detection history. Each detection history indicated all potential detection locations, whether the tagged fish had been detected or not detected at each location, and disposition of the fish after detection. Methods for data retrieval, database quality assurance/control, and construction of detection histories were the same as those used in past years and are described in detail by Iwamoto et al. (1994).

All analyses reported here were from data downloaded on 3 December 2021. It is possible that data in the PTAGIS database may have been updated or corrected after this date. Thus, estimates we may provide in the future, or data used for future analyses, may differ slightly from those presented here.

Tests of Assumptions—We evaluated assumptions of the single-release model as applied to the detection-history data generated from PIT-tagged juvenile salmonids in the Snake and Columbia Rivers (Burnham et al. 1987). Chi-square contingency tests were used to evaluate model assumptions, with assumption violations indicated by significant differences between observed and expected proportions of fish in different detection-history categories (Appendix A).

In past study years, some sample sizes have been large enough that these tests had sufficient power to detect small violations of model assumptions. However, in 2021 statistical power was likely low for most tests due to small sample sizes and low detection probabilities. Very small violations have only marginal effects on survival estimates, but large violations can result in biased parameter estimates. Appendix A contains a detailed discussion of these tests of assumption, the extent of assumption violations, and implications of and possible reasons for these violations.

Survival Estimates—All of our survival estimates were calculated from a release point or from the tailrace of a dam to the tailrace of a downstream dam. All estimates of survival and detection were computed using the statistical computer program SURPH (Survival with Proportional Hazards) for analyzing mark-recapture data. This program was developed for analyses using the single-release model by researchers at the University of Washington (Skalski et al. 1993; Smith et al. 1994; Lady et al. 2013).

Estimates of survival probability under the single-release model are random variables, subject to sampling variability, and the model does not constrain parameter estimates to below 1.0. When true survival probabilities are close to 1.0 and/or when sampling variability is high, it is possible for estimates of survival probability to exceed 1.0, even when model assumptions are not violated. For practical purposes, these estimates should be considered equal to 1.0 and to represent true survival probabilities that are certainly less than 1.0 by some amount.

When estimates of survival through a particular river section were available for a series of release groups from the same stock, we calculated a weighted average of these estimates over the entire migration season. When a series extended across all or most of the season, we considered this weighted average to be the seasonal average for the year. For each survival estimate in such a series, the weight applied was proportional to the inverse of its estimated relative variance (coefficient of variation squared).

We used the inverse of estimated *relative* variance rather than *absolute* variance because the variance of a survival probability estimate from the single-release model is a function of the estimate itself. Consequently, lower survival estimates tend to have smaller estimated variance. Use of the inverse relative variance prevented the weighted mean from being biased toward the lower estimates.

For various stocks from both the Snake and Upper Columbia Rivers, we estimated survival from point of release to Bonneville Dam, the final dam encountered by seaward-migrating juvenile salmonids. For extended reaches like this, estimates were derived as the product of appropriate estimates for the shorter component reaches.

Estimated survival from the Snake River Smolt Trap to Bonneville Dam provides important information on survival through an extended reach containing eight hydroelectric projects. The Snake River Smolt Trap is located near the head of Lower Granite reservoir, so estimated survival from the trap to Bonneville Dam essentially covers the reservoir, forebay, dam, and tailrace for each of these eight hydropower projects. For yearling Chinook salmon and steelhead, we constructed this estimate from two components:

1) Estimated survival to Lower Granite Dam for fish tagged and released at the Snake River Smolt Trap using a single estimate for all fish pooled across the migration season
2) Weighted mean estimated survival from Lower Granite to Bonneville Dam for virtual biweekly groups of fish released from Lower Granite Dam

In past years, when sizes of virtual release groups at McNary Dam and downstream detection rates were sufficient, we calculated the annual mean estimate for survival from Lower Granite to Bonneville Dam. This estimate was the product of the following two independent weighted means: (1) estimated survival from Lower Granite to McNary Dam and (2) estimated survival from McNary to Bonneville Dam. This method does not produce estimates to Bonneville Dam for virtual groups formed at Lower Granite Dam. However, the alternative method used in 2020 and 2021 does produce such estimates, and we have reported them here.

We performed statistical tests to compare pairs of survival estimates between years or stocks, or to compare an estimate to its estimated long-term mean. For each of these comparisons, we calculated the difference between survival estimates and used the estimated variances of the estimates to calculate a variance of the difference. Resulting variances were then used to calculate a z-statistic, which we compared to a standard normal distribution to obtain two-sided p-values. We considered differences between estimates to be statistically significant at the $\alpha = 0.05$ level.

Results

Snake River Yearling Chinook Salmon

Survival Probabilities—For biweekly groups of yearling Chinook salmon, we estimated survival probability from the tailrace of Lower Granite Dam downstream through multiple Snake River dams over eight consecutive weeks during 6 April-31 May (Table 2). Mean estimated survival was 0.806 (SE 0.067) from Lower Granite to Little Goose, 1.136 (0.127) from Little Goose to Lower Monumental, and 0.854 (0.146) from Lower Monumental to McNary Dam. For the combined reach from Lower Granite to McNary Dam, mean estimated survival was 0.730 (0.026).

Table 2. Survival probability estimates from Lower Granite to McNary Dam for Snake River yearling Chinook in 2021. Daily groups of combined hatchery and wild fish were determined by day of detection at Lower Granite Dam and pooled for biweekly estimates. Weighted means are of independent estimates for biweekly groups. Standard errors in parentheses.

Estimated survival of yearling Chinook salmon groups from Lower Granite Dam (SE)					
Date at Lower Granite Dam	Number released	Lower Granite to Little Goose Dam	Little Goose to Lower Monumental	Lower Monumental to McNary Dam	Lower Granite to McNary Dam
6-19 Apr	4,572	0.994 (0.249)	1.171 (0.824)	0.768 (0.529)	0.895 (0.175)
20 Apr-3 May	38,880	0.880 (0.165)	1.073 (0.330)	0.777 (0.195)	0.734 (0.043)
4-17 May	51,226	0.708 (0.111)	1.332 (0.426)	0.775 (0.220)	0.732 (0.041)
18-31 May	7,746	0.678 (0.229)	0.547 (0.366)	1.679 (0.993)	0.623 (0.082)
Weighted mean		**0.806 (0.067)**	**1.136 (0.127)**	**0.854 (0.146)**	**0.730 (0.026)**

In 2021, detection rates at McNary Dam were too low to create virtual release groups of sufficient sample size from fish detected at the dam. Thus, we estimated survival and detection probabilities downstream of McNary Dam using biweekly groups formed from fish detected or tagged and released at Lower Granite Dam; the same groups that were used for Snake River reaches (Table 3).

While these virtual groups were identified by date of passage at Lower Granite Dam, their dates of passage at McNary were later. Detection probabilities were low at McNary and extremely low at John Day Dam. Consequently, survival estimates were generally imprecise (Table 3). Mean estimated survival was 0.960 (SE 0.077) from

McNary to John Day, 0.796 (0.096) from John Day to Bonneville, and 0.746 (0.112) for the combined reach from McNary to Bonneville Dam.

Table 3. Survival probability estimates for Snake River yearling Chinook over individual reaches from McNary to Bonneville Dam and for the overall reach from Lower Granite to Bonneville Dam 2021. Daily groups of combined hatchery and wild fish were determined by day of detection at Lower Granite Dam and pooled for biweekly estimates. Weighted means are of independent estimates for biweekly groups. Standard errors in parentheses.

Estimated survival of yearling Chinook salmon groups from Lower Granite Dam (SE)					
Date at Lower Granite Dam	Number Released	McNary to John Day Dam	John Day to Bonneville Dam	McNary to Bonneville Dam	Lower Granite to Bonneville Dam
6-19 Apr	4,572	0.615 (0.205)	0.923 (0.352)	0.568 (0.190)	0.508 (0.138)
20 Apr-3 May	38,880	1.014 (0.114)	0.978 (0.156)	0.992 (0.139)	0.728 (0.093)
4-17 May	51,226	1.020 (0.133)	0.657 (0.102)	0.670 (0.077)	0.490 (0.050)
18-31 May	7,746	0.672 (0.164)	0.585 (0.178)	0.393 (0.102)	0.245 (0.055)
Weighted mean		**0.960 (0.077)**	**0.796 (0.096)**	**0.746 (0.112)**	**0.543 (0.085)**

For Snake River yearling Chinook, the overall survival estimate from Lower Granite to Bonneville Dam was 0.543 (SE 0.085) for wild and hatchery fish combined. For wild and hatchery yearling Chinook released from the Snake River Smolt Trap, estimated survival to Lower Granite Dam was 0.867 (0.108). Thus, estimated survival probability through all eight hydropower projects encountered by Snake River yearling Chinook salmon was 0.471 (0.094).

We also estimated separate probabilities of survival from Lower Granite to McNary Dam for hatchery vs. wild yearling Chinook (Table 4). Sample sizes were adequate to estimate survival for biweekly groups of hatchery yearling Chinook, but were too low to estimate survival for wild Chinook. We were able to estimate survival for wild fish only by pooling all wild-origin smolts into a single group. Weighted mean estimated survival across the season was higher for hatchery than for wild Chinook salmon, but the difference was not significant ($P = 0.25$).

Table 4. Survival probability estimates from Lower Granite to McNary Dam for Snake River yearling Chinook salmon in 2021. For hatchery fish, separate daily groups were determined by day of detection at Lower Granite Dam and pooled for biweekly estimates. Weighted means are of the independent estimates for biweekly groups. For wild fish, all detections were pooled into a single group for the full season. Standard errors in parentheses.

Estimated survival of biweekly groups from Lower Granite Dam (SE)					
Date at Lower Granite Dam	Number released	Lower Granite to Little Goose Dam	Little Goose to Lower Monumental Dam	Lower Monumental to McNary Dam	Lower Granite to McNary Dam
			Hatchery yearling Chinook		
6-19 Apr	3,510	1.068 (0.368)	0.562 (0.519)	1.416 (1.266)	0.849 (0.193)
20 Apr-3 May	36,426	0.718 (0.140)	2.387 (1.040)	0.424 (0.167)	0.726 (0.045)
4-17 May	48,487	0.703 (0.122)	1.406 (0.522)	0.744 (0.248)	0.736 (0.043)
18-31 May	6,248	0.988 (0.529)	0.618 (0.644)	1.198 (1.089)	0.731 (0.120)
Weighted mean		**0.766 (0.073)**	**1.643 (0.359)**	**0.706 (0.164)**	**0.735 (0.012)**
			Wild yearling Chinook		
22 Mar-6 Jul	**41,335**	**1.021 (0.150)**	**0.720 (0.179)**	**0.916 (0.197)**	**0.673 (0.053)**

We were unable to estimate survival probabilities for daily groups of yearling Chinook salmon in 2021. Even for pooled biweekly groups, the precision of nearly all survival estimates was poor (Table 2). Consequently, it was impossible to assess any potential within-season trends in survival during 2021.

Detection Probabilities**—**Detection probability estimates in 2021 were extremely low at almost every dam downstream of Lower Granite Dam (Tables 5-7). In marked contrast, because of the spillway detection system, detection probability estimates at Lower Granite Dam were above average (Appendix Tables B4, B8, B10). Detection probability estimates at Snake River dams were generally higher for wild than for hatchery Chinook salmon (Table 7).

Table 5. Detection probability estimates at Little Goose, Lower Monumental, and McNary Dam for Snake River yearling Chinook salmon in 2021. Daily groups of combined hatchery and wild fish were determined by day of detection at Lower Granite Dam and pooled for biweekly estimates. Standard errors in parentheses.

	Detection probability estimates for yearling Chinook salmon groups from Lower Granite Dam (SE)			
Date at Lower Granite Dam	Number released	Little Goose Dam	Lower Monumental Dam	McNary Dam
6-19 Apr	4,572	0.028 (0.007)	0.008 (0.005)	0.045 (0.009)
20 Apr-3 May	38,880	0.009 (0.002)	0.005 (0.001)	0.049 (0.003)
4-17 May	51,226	0.011 (0.002)	0.004 (0.001)	0.050 (0.003)
18-31 May	7,746	0.016 (0.006)	0.005 (0.003)	0.074 (0.010)

Table 6. Detection probability estimates at John Day and Bonneville Dam for Snake River yearling Chinook salmon in 2021. Daily groups of combined hatchery and wild fish were determined by day of detection at Lower Granite Dam and pooled for biweekly estimates. Standard errors in parentheses.

	Detection probability estimates for yearling Chinook salmon groups from Lower Granite Dam (SE)		
Date at Lower Granite Dam	Number released	John Day Dam	Bonneville Dam
6-19 Apr	4,572	0.025 (0.007)	0.172 (0.047)
20 Apr-3 May	38,880	0.021 (0.002)	0.143 (0.018)
4-17 May	51,226	0.013 (0.002)	0.184 (0.019)
18-31 May	7,746	0.035 (0.008)	0.272 (0.062)

Table 7. Detection probability estimates at Little Goose, Lower Monumental, and McNary Dam for Snake River yearling Chinook salmon in 2021. For hatchery fish, separate daily groups were determined by day of detection at Lower Granite Dam and pooled for biweekly estimates. All wild fish were pooled into a single group for the full season. Standard errors in parentheses.

Detection probability estimates for groups from Lower Granite Dam (SE)				
Date at Lower Granite Dam	Number released	Little Goose Dam	Lower Monumental Dam	McNary Dam
	Hatchery yearling Chinook			
6-19 Apr	3,510	0.020 (0.007)	0.013 (0.011)	0.038 (0.009)
20 Apr-3 May	36,426	0.010 (0.002)	0.002 (0.001)	0.046 (0.003)
4-17 May	48,487	0.010 (0.002)	0.004 (0.001)	0.047 (0.003)
18-31 May	6,248	0.009 (0.005)	0.003 (0.003)	0.061 (0.011)
	Wild yearling Chinook			
22 Mar-6 Jul	41,335	0.023 (0.004)	0.012 (0.003)	0.086 (0.007)

Snake River Steelhead

Survival Probabilities—For biweekly groups of steelhead, we estimated survival probabilities from the tailrace of Lower Granite Dam through multiple downstream dams for twelve consecutive weeks during 23 March-14 June (Table 8). Mean estimated survival was 1.070 (SE 0.045) from Lower Granite to Little Goose, 1.089 (0.083) from Little Goose to Lower Monumental, and 0.681 (0.043) from Lower Monumental to McNary Dam. For the combined reach from Lower Granite to McNary Dam, estimated survival averaged 0.788 (0.073).

Table 8. Survival probability estimates from Lower Granite to McNary Dam for Snake River juvenile steelhead in 2021. Daily groups of combined hatchery and wild fish were determined by day of detection at Lower Granite Dam and pooled for biweekly estimates. Weighted means are of independent estimates for biweekly groups. Standard errors in parentheses.

	Estimated survival of steelhead groups from Lower Granite Dam (SE)				
Date at Lower Granite Dam	Number released	Lower Granite to Little Goose Dam	Little Goose to Lower Monumental	Lower Monumental to McNary Dam	Lower Granite to McNary Dam
23 Mar-5 Apr	1,139	1.177 (0.254)	0.563 (0.296)	0.788 (0.417)	0.522 (0.106)
6-19 Apr	26,910	1.001 (0.064)	1.230 (0.201)	0.635 (0.104)	0.781 (0.048)
20 Apr-3 May	34,559	1.154 (0.117)	1.190 (0.284)	0.762 (0.179)	1.046 (0.097)
4-17 May	36,181	1.184 (0.114)	0.905 (0.150)	0.747 (0.117)	0.800 (0.064)
18-31 May	13,499	0.838 (0.196)	1.213 (0.433)	0.443 (0.133)	0.450 (0.059)
1-14 Jun	4,740	0.607 (0.369)	1.556 (1.384)	0.625 (0.429)	0.589 (0.132)
Weighted mean		**1.070 (0.045)**	**1.089 (0.083)**	**0.681 (0.043)**	**0.788 (0.073)**

In 2021, detection rates at McNary Dam were too low to create virtual release groups of sufficient sample size from fish detected at the dam. Thus, we estimated survival and detection probabilities downstream of McNary Dam using biweekly groups formed from fish detected at Lower Granite Dam—the same groups used for estimates in Snake River reaches (Table 9).

While these virtual groups were identified by date of passage at Lower Granite Dam, their dates of passage at McNary were later. Detection probabilities were low at McNary and extremely low at John Day Dam. Consequently, survival estimates were generally imprecise (Table 9). Mean estimated survival was 0.757 (SE 0.071) from McNary to John Day, 0.795 (0.029) from John Day to Bonneville, and 0.602 (0.029) for the entire reach from McNary to Bonneville Dam (Table 9).

Table 9. Survival probability estimates from McNary to Bonneville Dam and for the overall reach from Lower Granite to Bonneville Dam for Snake River juvenile steelhead in 2021. Daily groups of combined hatchery and wild fish were determined by day of detection at Lower Granite Dam and pooled for biweekly estimates. Weighted means are of independent estimates for biweekly groups. Standard errors in parentheses.

		Estimated survival of steelhead groups from Lower Granite Dam (SE)			
Date at Lower Granite Dam	Number Released	McNary to John Day Dam	John Day to Bonneville Dam	McNary to Bonneville Dam	Lower Granite to Bonneville Dam
23 Mar-5 Apr	1,139	0.856 (0.397)	0.736 (0.376)	0.630 (0.227)	0.329 (0.098)
6-19 Apr	26,910	0.750 (0.086)	0.775 (0.089)	0.581 (0.051)	0.454 (0.028)
20 Apr-3 May	34,559	0.653 (0.080)	0.796 (0.076)	0.519 (0.056)	0.544 (0.029)
4-17 May	36,181	0.755 (0.090)	0.831 (0.081)	0.628 (0.056)	0.503 (0.020)
18-31 May	13,499	1.419 (0.415)	0.529 (0.147)	0.751 (0.122)	0.338 (0.032)
1-14 Jun	4,740	0.691 (0.253)	0.956 (0.325)	0.661 (0.189)	0.389 (0.070)
Weighted mean		**0.757 (0.071)**	**0.795 (0.029)**	**0.602 (0.029)**	**0.487 (0.026)**

For wild and hatchery Snake River steelhead, the overall survival estimate from Lower Granite to Bonneville Dam was 0.487 (SE 0.026). For wild and hatchery steelhead released from the Snake River Smolt Trap, estimated survival probability to Lower Granite Dam tailrace was 0.936 (0.029). Thus, estimated survival probability through all eight hydropower projects encountered by Snake River steelhead was 0.456 (0.028).

We also estimated separate probabilities of survival from Lower Granite to McNary Dam for biweekly groups of hatchery vs. wild steelhead (Table 10). Survival from Lower Granite to McNary was not consistently different between hatchery and wild fish for individual biweekly groups. However, weighted mean estimated survival across the season was higher for hatchery than for wild steelhead, though the difference was not statistically significant ($P = 0.08$).

For daily groups of steelhead in 2021, we were unable to estimate survival probabilities. Even for pooled biweekly groups, the precision of nearly all survival estimates was extremely poor (Table 8). Consequently, it was impossible to assess any potential trends in survival within the 2021 migration season.

Table 10. Survival probability estimates from Lower Granite to McNary Dam for Snake River juvenile steelhead in 2021. Separate daily groups of hatchery and wild fish were determined by day of detection at Lower Granite Dam and pooled for biweekly estimates. Weighted means are of independent estimates for biweekly groups. Standard errors in parentheses.

	Estimated survival for groups from Lower Granite Dam (SE)				
Date at Lower Granite Dam	Number released	Lower Granite to Little Goose Dam	Little Goose to Lower Monumental Dam	Lower Monumental to McNary Dam	Lower Granite to McNary Dam
	Hatchery steelhead				
23 Mar-5 Apr	1,102	1.232 (0.287)	0.493 (0.259)	0.851 (0.443)	0.517 (0.105)
6-19 Apr	26,175	1.009 (0.066)	1.212 (0.203)	0.642 (0.107)	0.784 (0.049)
20 Apr-3 May	32,548	1.127 (0.116)	1.242 (0.311)	0.753 (0.187)	1.053 (0.101)
4-17 May	31,075	1.232 (0.133)	0.899 (0.172)	0.737 (0.133)	0.816 (0.071)
18-31 May	10,131	0.944 (0.288)	1.111 (0.500)	0.423 (0.154)	0.444 (0.067)
1-14 Jun	3,764	1.001 (0.909)	0.647 (0.710)	1.044 (0.690)	0.676 (0.170)
Weighted mean		**1.084 (0.042)**	**1.079 (0.087)**	**0.692 (0.049)**	**0.802 (0.071)**
	Wild steelhead				
6-19 Apr	735	0.730 (0.204)	1.466 (1.037)	0.566 (0.431)	0.606 (0.238)
20 Apr-3 May	2,008	2.007 (1.346)	0.501 (0.466)	0.865 (0.641)	0.869 (0.319)
4-17 May	5,106	0.918 (0.191)	0.906 (0.307)	0.787 (0.262)	0.655 (0.129)
18-31 May	3,368	0.659 (0.239)	1.395 (0.824)	0.493 (0.264)	0.453 (0.119)
Weighted mean		**0.875 (0.160)**	**1.045 (0.166)**	**0.708 (0.078)**	**0.624 (0.074)**

***Detection Probabilities*—**For biweekly groups of steelhead, detection probability estimates were very low in 2021 at Little Goose, Lower Monumental, McNary, and John Day Dam (Tables 11-13). Detection probability estimates for steelhead were above average at Bonneville Dam, where fish are detected in the corner collector, and well above average at Lower Granite Dam, with its spillway detection system (Appendix Tables B5, B8, B10). Detection probability estimates at Snake River dams were generally higher for wild than for hatchery steelhead (Table 13).

Table 11. Detection probability estimates at Little Goose Dam, Lower Monumental Dam, and McNary Dam for Snake River juvenile steelhead in 2021. Daily groups of combined hatchery and wild fish were determined by day of detection at Lower Granite Dam and pooled for biweekly estimates. Standard errors in parentheses.

Detection probability estimates for steelhead groups from Lower Granite Dam (SE)				
Date at Lower Granite Dam	Number released	Little Goose Dam	Lower Monumental Dam	McNary Dam
23 Mar-5 Apr	1,139	0.087 (0.020)	0.036 (0.019)	0.114 (0.026)
6-19 Apr	26,910	0.043 (0.003)	0.015 (0.002)	0.042 (0.003)
20 Apr-3 May	34,559	0.020 (0.002)	0.005 (0.001)	0.013 (0.001)
4-17 May	36,181	0.019 (0.002)	0.009 (0.001)	0.015 (0.001)
18-31 May	13,499	0.014 (0.004)	0.012 (0.003)	0.028 (0.004)
1-14 Jun	4,740	0.009 (0.006)	0.008 (0.005)	0.025 (0.006)

Table 12. Detection probability estimates at John Day Dam and Bonneville Dam for Snake River juvenile steelhead in 2021. Daily groups of combined hatchery and wild fish were determined by day of detection at Lower Granite Dam and pooled for biweekly estimates. Standard errors in parentheses.

Detection probability estimates for steelhead groups from Lower Granite Dam (SE)			
Date at Lower Granite Dam	Number released	John Day Dam	Bonneville Dam
23 Mar-5 Apr	1,139	0.029 (0.014)	0.352 (0.107)
6-19 Apr	26,910	0.016 (0.002)	0.366 (0.023)
20 Apr-3 May	34,559	0.016 (0.001)	0.354 (0.019)
4-17 May	36,181	0.011 (0.001)	0.381 (0.016)
18-31 May	13,499	0.008 (0.002)	0.281 (0.027)
1-14 Jun	4,740	0.013 (0.005)	0.309 (0.056)

Table 13. Detection probability estimates at Little Goose Dam, Lower Monumental Dam, and McNary Dam for Snake River juvenile steelhead in 2021. Separate daily groups of hatchery and wild fish were determined by day of detection at Lower Granite Dam and pooled for biweekly estimates. Standard errors in parentheses.

	Estimated detection probability of groups from Lower Granite Dam			
Date at Lower Granite Dam	Number released	Little Goose Dam	Lower Monumental Dam	McNary Dam
		Hatchery steelhead		
23 Mar-5 Apr	1,102	0.080 (0.020)	0.038 (0.019)	0.117 (0.027)
6-19 Apr	26,175	0.042 (0.003)	0.015 (0.002)	0.041 (0.003)
20 Apr-3 May	32,548	0.021 (0.002)	0.005 (0.001)	0.012 (0.001)
4-17 May	31,075	0.018 (0.002)	0.008 (0.001)	0.014 (0.001)
18-31 May	10,131	0.012 (0.004)	0.011 (0.004)	0.026 (0.005)
1-14 Jun	3,764	0.006 (0.005)	0.010 (0.006)	0.022 (0.006)
		Wild steelhead		
6-19 Apr	735	0.089 (0.028)	0.023 (0.016)	0.062 (0.027)
20 Apr-3 May	2,008	0.010 (0.007)	0.008 (0.006)	0.020 (0.008)
4-17 May	5,106	0.026 (0.006)	0.018 (0.005)	0.024 (0.005)
18-31 May	3,368	0.022 (0.009)	0.015 (0.007)	0.033 (0.010)

Survival Between Lower Monumental and Ice Harbor Dam

At Ice Harbor Dam, a PIT-tag detection system became operational in 2005. In most years since then, detection probabilities have been low but sufficient to estimate survival from Lower Monumental to Ice Harbor and from Ice Harbor to McNary Dam. In 2021, detections at Ice Harbor Dam were especially poor and lower than in most recent years (Table 14); detection probabilities were equally low at Lower Monumental and also quite low at McNary.

For yearling Chinook salmon in 2021, mean estimated survival was 1.027 (SE 0.137) from Lower Monumental to Ice Harbor Dam and 0.781 (0.054) from Ice Harbor to McNary Dam. In these same two reaches, mean estimated survival for steelhead was 0.972 (0.076) and 0.804 (0.096), respectively (Table 14).

Table 14. Survival and detection probability estimates from Lower Monumental to McNary Dam, including Ice Harbor Dam, for Snake River yearling Chinook salmon and juvenile steelhead in 2021. Daily groups of combined hatchery and wild fish were determined by day of detection at Lower Granite Dam and were pooled for biweekly estimates. Weighted means are of independent estimates for biweekly groups. Standard errors in parentheses.

	Estimated survival probability			
Date at Lower Granite Dam	Number released	Lower Monumental to Ice Harbor Dam	Ice Harbor to McNary Dam	Detection Probability at Ice Harbor Dam
	Hatchery and wild yearling Chinook salmon			
23 Mar-5 Apr	801	1.768 (1.235)	0.727 (0.397)	0.033 (0.016)
6-19 Apr	4,572	0.666 (0.467)	1.036 (0.314)	0.023 (0.006)
20 Apr-3 May	38,880	0.926 (0.247)	0.792 (0.096)	0.012 (0.001)
4-17 May	51,226	1.092 (0.351)	0.687 (0.116)	0.005 (0.001)
Weighted mean		**1.027 (0.137)**	**0.781 (0.054)**	
	Hatchery and wild steelhead			
23 Mar-5 Apr	1,139	1.042 (0.408)	1.156 (0.341)	0.061 (0.017)
6-19 Apr	26,910	0.934 (0.175)	0.684 (0.090)	0.011 (0.001)
20 Apr-3 May	34,559	0.813 (0.188)	1.011 (0.147)	0.008 (0.001)
4-17 May	36,181	1.007 (0.185)	0.722 (0.106)	0.007 (0.001)
18-31 May	13,499	1.547 (0.736)	0.274 (0.113)	0.004 (0.002)
Weighted mean		**0.972 (0.076)**	**0.804 (0.096)**	

Survival and Detection from Hatcheries and Smolt Traps

***Snake River Hatchery Release Groups*—**Survival estimates varied among stocks and among release sites for fish of the same hatchery stock (Appendix Tables B1-B3), as did estimated detection probabilities among detection sites (Appendix Tables B4-B6).

For yearling Chinook salmon, estimated survival to Lower Granite Dam ranged from 0.957 (SE 0.038) for Clearwater Hatchery fish released to Clear Creek in the Middle Fork Clearwater Basin to 0.287 (0.012) for Pahsimeroi Hatchery fish from Pahsimeroi Pond on the Pahsimeroi River (Appendix Table B1).

For steelhead, estimated survival to Lower Granite ranged from 0.852 (0.018) for Magic Valley Hatchery fish released to the Little Salmon River and 0.852 (0.032) for Dworshak Hatchery fish released to the north fork of the Clearwater River to 0.536 (0.014) for Hagerman Hatchery fish released to the East Fork Salmon River (Appendix Table B2).

For sockeye salmon, only one group of hatchery-reared fish was released in 2021. Estimated survival to Lower Granite Dam was 0.756 (0.010) for Springfield Hatchery fish released in late April from Sawtooth Hatchery (Appendix Table B3).

***Snake River Smolt Trap Release Groups*—**For tagged wild and hatchery juvenile salmonids released from Snake River Basin smolt traps, estimated survival probability to Lower Granite Dam was generally inversely related to distance between the respective traps and the dam (Appendix Table B7). Estimated detection probabilities at dams other than Lower Granite were substantially below average but were similar among groups of the same species and rearing type released from different traps (Appendix Table B8).

We saw no consistent difference in estimated detection probabilities at Lower Granite Dam between wild fish and their hatchery conspecifics released from the same location (e.g., Lower Grande Ronde and Salmon River Smolt Traps). Detection rates at Little Goose, Lower Monumental, and McNary Dam were so low that it was often impossible to generate estimates of detection probability for specific rearing types released from a given trap. Consequently, it was impossible to assess whether there were differences in detection probabilities between wild and hatchery fish at those sites.

Upper Columbia River Hatchery Release Groups—We estimated survival probabilities from release at Upper Columbia River hatcheries to McNary, John Day, and Bonneville Dam for yearling Chinook, coho, and steelhead. These estimates varied among hatcheries and release locations (Appendix Table B9), as did estimates of detection probability (Appendix Table B10).

For Upper Columbia River yearling Chinook salmon, estimated survival from release to Bonneville Dam ranged from 0.903 (SE 0.432) for Methow Hatchery fish released to Twisp Pond to 0.227 (0.048) for Cle Elum Hatchery fish released to Jack Creek Pond.

For Upper Columbia River steelhead, estimated survival from release to Bonneville Dam ranged from 0.585 (0.153) for Wells Hatchery fish released from Methow Hatchery to 0.133 (0.118) for Wells Hatchery fish released to the Twisp River.

For coho salmon, estimated survival from release to Bonneville Dam ranged from 0.408 (0.065) for Yakima Hatchery fish released to the Yakima River to 0.272 (0.096) for Winthrop Hatchery fish released to Early Winters Pond.

Travel Time and Migration Rates

Methods

We calculated travel time of yearling Chinook salmon and steelhead through the following eight reaches:

- Lower Granite to Little Goose Dam (60 km)
- Little Goose to Lower Monumental Dam (46 km)
- Lower Monumental to McNary Dam (119 km)
- Lower Granite to McNary Dam (225 km)
- Lower Granite to Bonneville Dam (461 km)
- McNary to John Day Dam (123 km)
- John Day to Bonneville Dam (113 km)
- McNary to Bonneville Dam (236 km)

Between any two dams, travel time could be calculated only for individual fish detected at both the upstream and downstream dam. We defined travel time as the number of days between last detection at the upstream dam and first detection at the downstream dam. Generally, the last detection at an upstream dam was on a monitor near the juvenile bypass outfall site; fish arrived in the tailrace within a few seconds or minutes after detection near the outfall site.

Our measures of travel time for individual fish included the time required to move through the tailrace of the upstream dam as well as through the reservoir, forebay, and entry to the collection channel of the downstream dam. Thus, travel time encompassed any delays associated with passage at the downstream dam, such as lingering in the forebay, gatewell, or collection channel prior to first detection in the juvenile bypass system.

Migration rate for each individual fish was calculated as length of the reach of interest (km) divided by travel time (d) and included the potential delays noted above. We calculated the 20th percentile, median, and 80th percentile travel time and migration rate for each group.

The true complete set of travel times for tagged fish within a release group would include travel time for both detected and non-detected fish. However, travel time cannot be determined for fish that traverse a reach of river without being detected at both ends. Therefore, travel time statistics were computed only for detected fish, which represent a subsample of the complete tagged release group.

At dams other than Lower Granite and Bonneville, only the juvenile bypass system is monitored for PIT tags. To pass such dams undetected, a tagged fish must utilize a different passage route, such as a turbine, spillway, or sluiceway. Passage times through those routes are typically shorter than through the juvenile bypass system. Thus, at dams other than Lower Granite and Bonneville, passage time for non-detected fish is typically minutes to hours shorter than for detected fish, all of which pass via the juvenile bypass system.

Results

Median travel time decreased over the migration season (Tables 15-20). For both yearling Chinook and steelhead, estimated migration rates were generally highest in the lower river sections. Over the last several years we have noted a trend toward shorter smolt travel times relative to levels of flow and spill. However, we did not see strong evidence that the extremely high levels of spill in 2021 resulted in markedly shorter travel times than in other recent low-flow years.

For the majority of the migration season, travel times for both Chinook and steelhead were similar to those in other low-flow years since 2007 (Figure 2). The exceptions were after the start of May for Chinook and from late April through early May for steelhead, when travel times were slightly shorter than in other low-flow years. These differences in smolt travel time were modest, considering the presence of spill rates that were far higher in 2021 than in past low-flow years.

We calculated an index of Snake River flow exposure for each daily group of PIT-tagged Chinook salmon and steelhead (Appendix C1). We then related flow exposure to travel time for each daily group (Figure 3). For Chinook, the observed decrease in travel time during May appeared to coincide with slightly higher flows. However, travel time for steelhead was slightly shorter in 2021 than in previous low-flow years during most of April and through mid-May, with the exception of 2001, when extreme low flows and a near-complete lack of spill led to exceptionally long travel times (Figure 2).

The period from April to mid-May encompasses both very low and near-average flows; the increase in flow exposure around 25 April did not appear to coincide with any substantial change in travel time (Figure 3). For both species, general decreases in travel time as the season progressed were also presumably related to increased levels of smolt readiness.

Table 15. Travel time from Lower Granite to Bonneville Dam for Snake River yearling Chinook salmon in 2021. Daily groups of combined hatchery and wild fish were determined by day of detection at Lower Granite Dam and pooled for weekly statistics.

Travel time of yearling Chinook salmon tagged or detected at Lower Granite Dam (d)

Date at Lower Granite Dam	Lower Granite to Little Goose Dam				Little Goose to Lower Monumental				Lower Monumental to McNary Dam			
	N	20%	Median	80%	N	20%	Median	80%	N	20%	Median	80%
30 Mar-5 Apr	31	6.3	12.5	20.0	0	-	-	-	0	-	-	-
6-12 Apr	49	6.3	10.7	14.3	1	3.0	3.0	3.0	0	-	-	-
13-19 Apr	78	5.2	6.4	9.8	1	3.3	3.3	3.3	0	-	-	-
20-26 Apr	110	3.5	5.3	7.0	0	-	-	-	1	4.8	4.8	4.8
27 Apr-3 May	199	2.9	3.4	4.3	2	2.0	2.2	2.3	4	4.2	4.6	5.0
4-10 May	304	2.5	3.3	3.6	1	1.9	1.9	1.9	0	-	-	-
11-17 May	87	2.4	2.5	3.2	0	-	-	-	1	2.1	2.1	2.1
18-24 May	77	2.3	2.5	2.7	0	-	-	-	0	-	-	-
25-31 May	9	2.4	3.0	3.4	0	-	-	-	0	-	-	-
1-7 Jun	13	2.3	2.4	2.5	0	-	-	-	0	-	-	-

Date at Lower Granite Dam	Lower Granite to McNary Dam				Lower Granite to Bonneville Dam			
	N	20%	Median	80%	N	20%	Median	80%
30 Mar-5 Apr	32	19.8	26.4	29.6	69	29.3	33.2	36.6
6-12 Apr	60	16.1	22.5	27.4	145	23.4	27.4	31.8
13-19 Apr	120	12.8	15.5	19.4	249	18.1	20.8	23.9
20-26 Apr	451	9.4	11.3	13.8	1,255	13.2	15.2	18.0
27 Apr-3 May	927	7.6	9.1	10.6	2,770	11.5	12.8	14.8
4-10 May	799	7.5	8.4	9.5	2,650	10.8	11.8	12.8
11-17 May	1,061	6.4	7.2	8.1	1,925	9.8	10.6	11.5
18-24 May	315	6.4	7.1	8.1	398	9.7	10.7	11.4
25-31 May	37	6.6	7.1	8.2	112	9.3	10.2	11.0
1-7 Jun	14	4.9	5.8	6.2	77	7.9	8.7	9.4

Table 16. Migration rate from Lower Granite to Bonneville Dam for Snake River yearling Chinook salmon in 2021. Daily groups of combined hatchery and wild fish were determined by day of detection at Lower Granite Dam and pooled for weekly statistics.

Migration rate of yearling Chinook salmon tagged or detected at Lower Granite Dam (km/d)

Date at Lower Granite Dam	Lower Granite to Little Goose Dam				Little Goose to Lower Monumental				Lower Monumental to McNary Dam			
	N	20%	Median	80%	N	20%	Median	80%	N	20%	Median	80%
30 Mar-5 Apr	31	3.0	4.8	9.5	0	-	-	-	0	-	-	-
6-12 Apr	49	4.2	5.6	9.5	1	15.5	15.5	15.5	0	-	-	-
13-19 Apr	78	6.1	9.4	11.6	1	13.9	13.9	13.9	0	-	-	-
20-26 Apr	110	8.5	11.2	17.1	0	-	-	-	1	24.7	24.7	24.7
27 Apr-3 May	199	14.0	17.9	20.6	2	19.7	21.1	22.8	4	23.8	26.1	28.5
4-10 May	304	16.6	18.2	23.9	1	24.5	24.5	24.5	0	-	-	-
11-17 May	87	18.9	24.0	25.1	0	-	-	-	1	55.3	55.3	55.3
18-24 May	77	22.3	24.4	25.6	0	-	-	-	0	-	-	-
25-31 May	9	17.6	20.3	24.7	0	-	-	-	0	-	-	-
1-7 Jun	13	24.5	25.4	26.4	0	-	-	-	0	-	-	-

Date at Lower Granite Dam	Lower Granite to McNary Dam				Lower Granite to Bonneville Dam			
	N	20%	Median	80%	N	20%	Median	80%
30 Mar-5 Apr	32	7.6	8.5	11.4	69	12.6	13.9	15.7
6-12 Apr	60	8.2	10.0	14.0	145	14.5	16.9	19.7
13-19 Apr	120	11.6	14.5	17.6	249	19.3	22.2	25.5
20-26 Apr	451	16.4	19.8	23.8	1,255	25.6	30.4	34.8
27 Apr-3 May	927	21.2	24.8	29.5	2,770	31.3	36.1	40.0
4-10 May	799	23.6	26.7	29.9	2,650	35.9	39.2	42.7
11-17 May	1,061	28.0	31.2	34.9	1,925	39.9	43.5	47.3
18-24 May	315	27.7	31.5	35.3	398	40.3	43.2	47.3
25-31 May	37	27.6	31.6	33.9	112	41.8	45.2	49.5
1-7 Jun	14	36.4	38.8	46.3	77	49.0	52.9	58.4

Table 17. Travel time and migration rate from McNary to Bonneville Dam for Snake River yearling Chinook salmon in 2021. Daily groups of combined hatchery and wild fish were determined by day of detection at Lower Granite Dam and pooled for weekly statistics.

	Hatchery and wild yearling Chinook salmon tagged or detected at Lower Granite Dam											
Date at Lower Granite Dam	McNary to John Day Dam				John Day to Bonneville Dam				McNary to Bonneville Dam			
	N	20%	Median	80%	N	20%	Median	80%	N	20%	Median	80%
	Travel time (d)											
30 Mar-5 Apr	1	5.5	5.5	5.5	3	1.7	1.8	2.1	7	5.2	6.0	6.9
6-12 Apr	1	4.4	4.4	4.4	2	1.6	1.7	1.8	6	5.0	5.6	6.8
13-19 Apr	4	3.5	4.2	4.6	6	1.6	1.7	1.8	10	4.6	4.9	5.5
20-26 Apr	10	3.0	3.5	3.9	32	1.5	1.6	1.8	74	4.0	4.2	5.0
27 Apr-3 May	12	2.8	3.0	3.5	53	1.5	1.6	1.8	130	3.9	4.2	4.9
4-10 May	7	2.9	3.0	3.4	36	1.5	1.7	1.8	104	3.7	3.9	4.3
11-17 May	6	2.8	3.0	3.5	21	1.5	1.7	1.9	132	3.7	4.0	4.5
18-24 May	9	2.8	2.9	3.3	12	1.5	1.6	1.7	27	3.6	4.1	4.5
25-31 May	3	3.0	3.4	6.0	7	1.3	1.4	1.6	4	3.2	3.3	3.6
	Migration rate (km/d)											
30 Mar-5 Apr	1	22.4	22.4	22.4	3	54.6	63.8	65.3	7	34.1	39.6	45.3
6-12 Apr	1	27.8	27.8	27.8	2	62.8	66.5	70.2	6	34.8	42.2	47.3
13-19 Apr	4	26.6	29.4	35.5	6	61.7	65.3	70.6	10	42.9	48.6	51.4
20-26 Apr	10	31.9	34.8	40.3	32	61.4	68.5	74.3	74	47.0	55.5	59.7
27 Apr-3 May	12	35.2	40.5	44.2	53	62.1	71.5	76.9	130	48.1	56.5	61.0
4-10 May	7	36.0	40.9	42.9	36	61.1	66.9	73.9	104	55.3	59.9	63.6
11-17 May	6	35.1	40.3	44.2	21	60.1	65.7	73.4	132	52.7	58.6	63.1
18-24 May	9	36.9	41.8	43.6	12	65.7	72.4	77.4	27	51.9	57.3	65.9
25-31 May	3	20.4	36.7	41.1	7	69.8	78.5	88.3	4	65.0	71.1	74.0

Table 18. Travel times from Lower Granite to Bonneville Dam for Snake River juvenile steelhead in 2021. Daily groups of combined hatchery and wild fish were determined by day of detection at Lower Granite Dam and pooled for weekly statistics.

Travel time of juvenile steelhead tagged or detected at Lower Granite Dam (d)

Date at Lower Granite Dam	Lower Granite to Little Goose Dam				Little Goose to Lower Monumental				Lower Monumental to McNary Dam			
	N	20%	Median	80%	N	20%	Median	80%	N	20%	Median	80%
30 Mar-5 Apr	113	2.9	3.5	4.3	0	-	-	-	2	6.3	10.3	14.3
6-12 Apr	618	3.0	3.8	4.6	13	2.9	4.4	8.4	7	3.6	4.7	6.1
13-19 Apr	546	3.0	3.2	4.1	7	1.8	2.2	2.4	5	4.1	4.4	5.0
20-26 Apr	324	2.7	3.3	4.3	0	-	-	-	0	-	-	-
27 Apr-3 May	485	2.1	2.2	3.1	3	1.6	2.0	3.0	2	3.0	3.1	3.2
4-10 May	526	2.1	2.2	2.4	4	1.8	2.3	2.6	1	2.9	2.9	2.9
11-17 May	289	2.1	2.2	2.8	2	1.8	1.9	2.0	1	2.8	2.8	2.8
18-24 May	126	2.0	2.1	2.3	0	-	-	-	2	3.3	4.2	5.1
25-31 May	35	2.0	2.1	2.4	1	1.5	1.5	1.5	0	-	-	-
1-7 Jun	17	2.0	2.1	2.4	0	-	-	-	0	-	-	-

	Lower Granite to McNary Dam				Lower Granite to Bonneville Dam			
	N	20%	Median	80%	N	20%	Median	80%
30 Mar-5 Apr	64	10.0	12.4	15.4	126	17.4	18.7	20.8
6-12 Apr	365	9.8	11.4	13.6	1,201	15.4	16.8	18.8
13-19 Apr	494	7.9	8.9	10.4	3,168	11.9	13.2	14.8
20-26 Apr	200	7.5	8.5	10.2	2,707	11.8	12.8	14.6
27 Apr-3 May	256	6.3	7.2	8.2	3,856	9.9	10.8	11.9
4-10 May	250	6.1	7.0	7.8	5,125	9.9	10.8	11.8
11-17 May	178	6.0	6.4	7.4	1,710	9.9	10.7	11.9
18-24 May	132	6.0	6.8	7.4	847	9.7	10.4	11.4
25-31 May	35	5.9	6.2	7.1	419	8.6	9.5	10.3
1-7 Jun	41	4.9	6.1	7.2	416	8.2	9.5	11.9

Table 19. Migration rate from Lower Granite to Bonneville Dam for Snake River juvenile steelhead in 2021. Daily groups of combined hatchery and wild fish were determined by day of detection at Lower Granite Dam and pooled for weekly statistics.

Migration rate of juvenile steelhead tagged or detected at Lower Granite Dam (km/d)

Date at Lower Granite Dam	Lower Granite to Little Goose Dam				Little Goose to Lower Monumental				Lower Monumental to McNary Dam			
	N	20%	Median	80%	N	20%	Median	80%	N	20%	Median	80%
30 Mar-5 Apr	113	13.9	17.3	20.8	0	-	-	-	2	8.3	11.6	18.9
6-12 Apr	618	13.1	15.7	19.7	13	5.4	10.5	15.6	7	19.6	25.3	33.1
13-19 Apr	546	14.7	18.8	20.1	7	18.9	20.5	25.1	5	23.8	27.0	28.8
20-26 Apr	324	14.0	18.3	22.5	0	-	-	-	0	-	-	-
27 Apr-3 May	485	19.4	26.7	28.3	3	15.6	22.7	28.6	2	36.7	38.0	39.3
4-10 May	526	24.8	27.5	29.0	4	17.5	19.7	26.1	1	41.6	41.6	41.6
11-17 May	289	21.5	27.5	28.8	2	23.2	24.3	25.6	1	43.0	43.0	43.0
18-24 May	126	26.4	28.0	30.6	0	-	-	-	2	23.2	28.3	36.2
25-31 May	35	25.5	28.4	29.9	1	29.9	29.9	29.9	0	-	-	-
1-7 Jun	17	24.9	28.3	29.7	0	-	-	-	0	-	-	-

Date at Lower Granite Dam	Lower Granite to McNary Dam				Lower Granite to Bonneville Dam			
	N	20%	Median	80%	N	20%	Median	80%
30 Mar-5 Apr	64	14.6	18.1	22.5	126	22.2	24.7	26.5
6-12 Apr	365	16.5	19.8	22.8	1,201	24.5	27.5	30.0
13-19 Apr	494	21.5	25.3	28.5	3,168	31.2	34.9	38.8
20-26 Apr	200	22.0	26.5	30.2	2,707	31.5	35.9	39.2
27 Apr-3 May	256	27.3	31.2	35.7	3,856	38.7	42.5	46.7
4-10 May	250	28.7	32.3	36.7	5,125	39.1	42.8	46.8
11-17 May	178	30.5	35.2	37.4	1,710	38.7	43.0	46.7
18-24 May	132	30.3	33.1	37.8	847	40.3	44.3	47.4
25-31 May	35	31.6	36.6	38.1	419	44.8	48.6	53.7
1-7 Jun	41	31.2	37.0	46.0	416	38.8	48.5	56.3

Table 20. Travel time and migration rates from McNary to Bonneville Dam for Snake River juvenile steelhead in 2021. Daily groups of combined hatchery and wild fish were determined by day of detection at Lower Granite Dam and pooled for weekly statistics.

	Hatchery and wild juvenile steelhead tagged or detected at Lower Granite Dam											
Date at Lower Granite Dam	McNary to John Day Dam				John Day to Bonneville Dam				McNary to Bonneville Dam			
	N	20%	Median	80%	N	20%	Median	80%	N	20%	Median	80%
Travel time (d)												
30 Mar-5 Apr	1	4.3	4.3	4.3	3	2.3	2.6	2.8	12	5.7	6.1	6.9
6-12 Apr	9	3.6	5.0	6.8	15	1.8	2.1	2.3	68	4.7	5.3	6.6
13-19 Apr	13	3.0	3.4	4.4	49	1.8	2.0	2.3	97	4.4	4.7	5.3
20-26 Apr	6	3.0	3.3	4.1	56	1.6	1.8	2.0	29	4.0	4.4	4.9
27 Apr-3 May	7	3.0	3.9	5.0	42	1.6	1.7	2.0	43	3.7	4.1	4.6
4-10 May	2	2.9	2.9	2.9	50	1.6	1.8	2.1	73	3.8	4.2	4.5
11-17 May	0	-	-	-	24	1.7	1.9	2.3	28	4.1	4.5	5.2
18-24 May	3	3.0	3.3	10.8	1	1.2	1.2	1.2	19	3.8	4.1	4.5
25-31 May	3	2.6	2.9	3.1	7	1.2	1.3	1.5	12	3.2	3.5	4.1
Migration rate (km/d)												
30 Mar-5 Apr	1	28.9	28.9	28.9	3	40.5	44.1	48.9	12	34.1	38.6	41.2
6-12 Apr	9	18.1	24.5	34.0	15	49.6	54.1	61.1	68	35.5	44.6	50.0
13-19 Apr	13	28.0	35.9	40.7	49	49.3	56.8	62.4	97	44.9	50.2	54.1
20-26 Apr	6	30.3	36.9	41.4	56	57.1	64.2	72.0	29	48.5	53.5	58.4
27 Apr-3 May	7	24.6	31.5	41.7	42	56.5	65.7	72.9	43	51.4	57.7	63.3
4-10 May	2	42.1	42.1	42.3	50	52.8	62.8	70.2	73	51.9	55.8	62.1
11-17 May	0	-	-	-	24	48.9	59.5	67.3	28	45.5	52.9	57.6
18-24 May	3	11.4	37.4	40.3	1	97.4	97.4	97.4	19	53.0	57.1	62.9
25-31 May	3	39.9	42.1	46.8	7	76.9	88.3	97.4	12	57.1	67.6	73.8

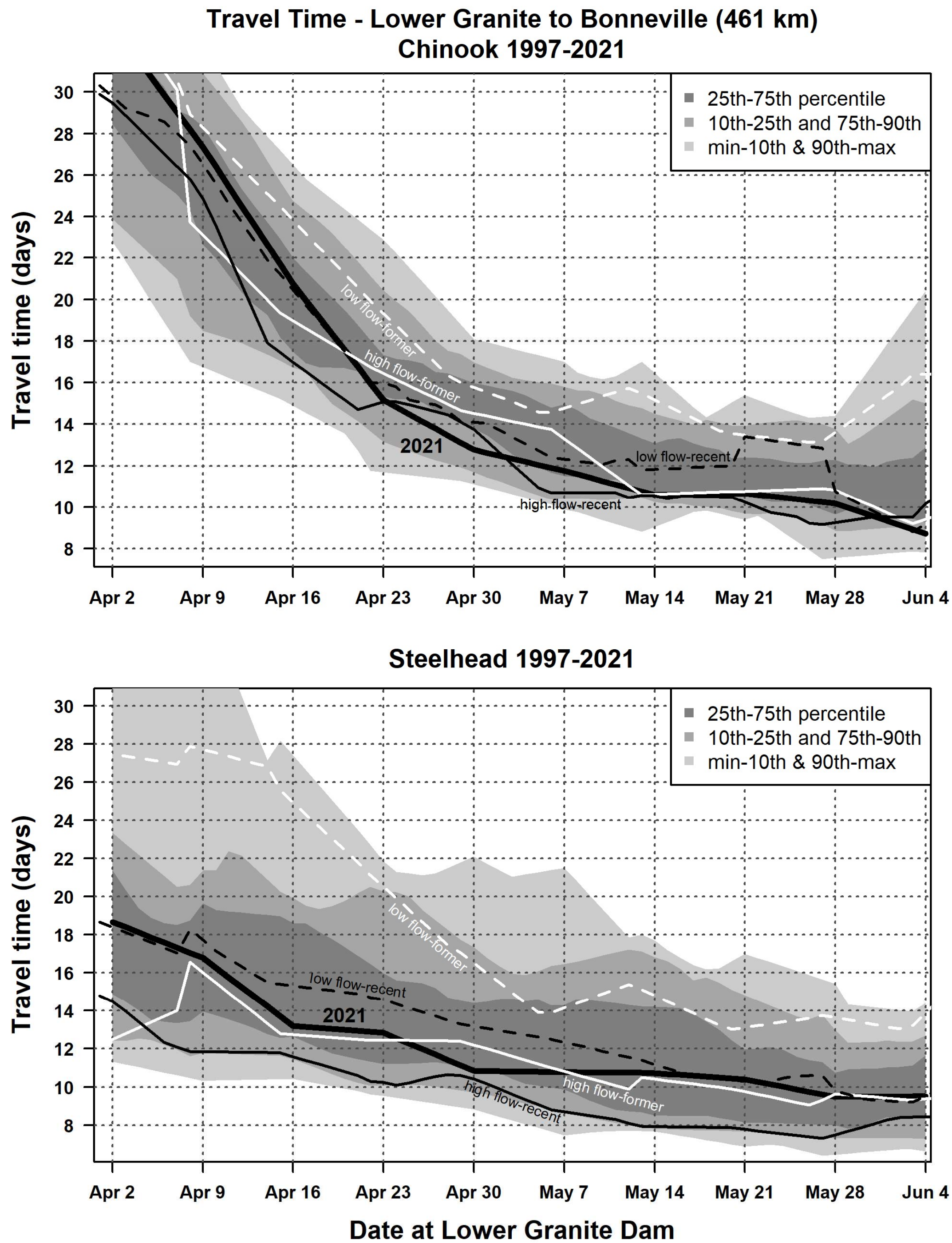

Figure 2. Median travel time (d) from Lower Granite to Bonneville Dam (461 km) vs. date passing Lower Granite Dam for yearling Chinook salmon and juvenile steelhead. Shaded regions show daily quantiles during 1997-2021 (excluding 2001). Lines show daily medians from selected subsets of years: low-flow years during the former (2004-2005) and recent spill regimes (2007, 2010, 2013, 2015, and 2021); high-flow years during the former (1997 and 2006) and recent spill regimes (2011, 2012, 2017, 2018, and 2019).

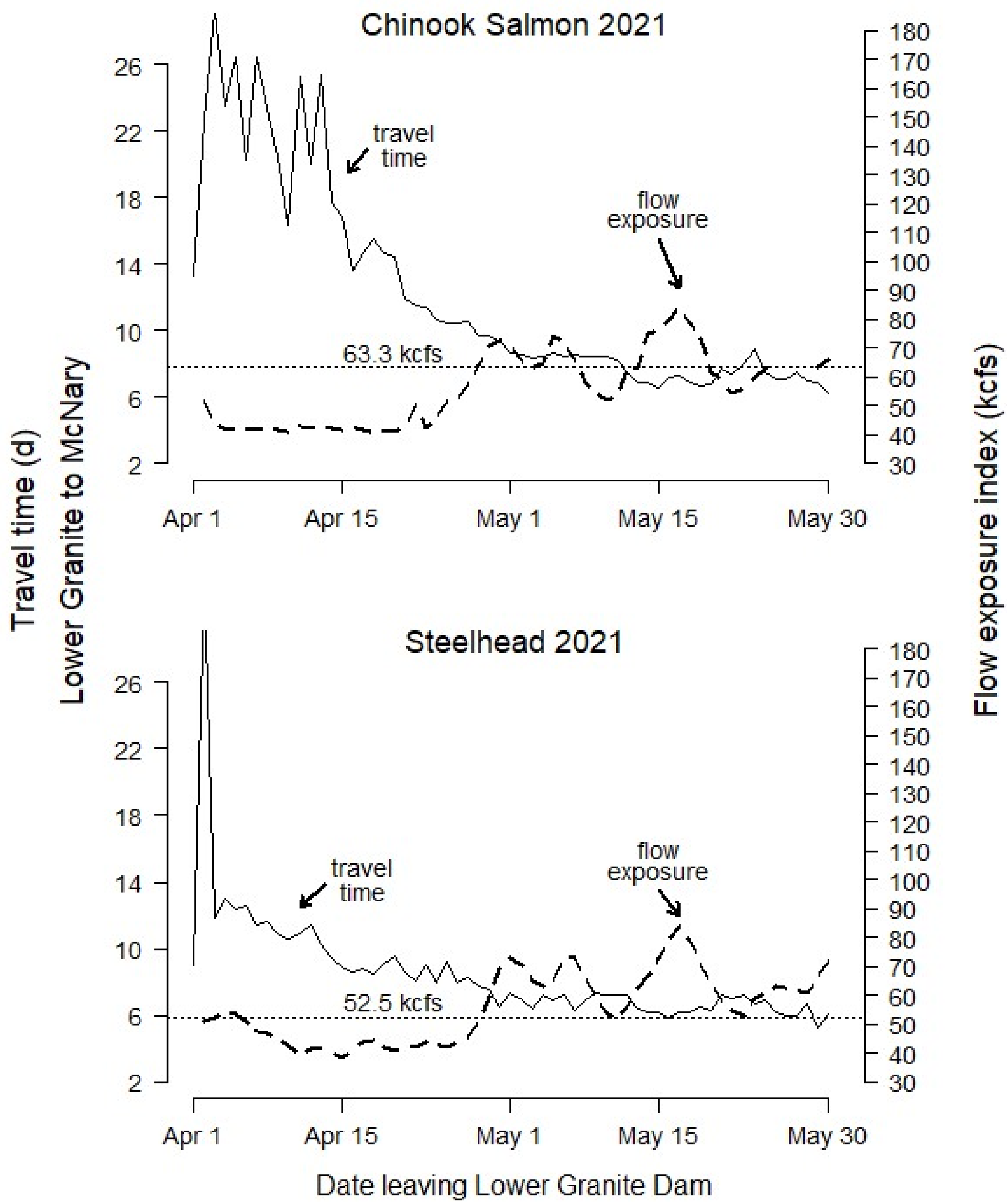

Figure 3. Median travel time (d) from Lower Granite to McNary Dam and index of flow exposure at Little Goose Dam (kcfs) for daily groups of PIT-tagged yearling Chinook salmon and juvenile steelhead during 2021. Dashed horizontal lines represent the mean flow exposure index for the year weighted by the number of PIT-tagged fish in each daily group.

Proportion Transported of Spring Migrants

Methods

To estimate the proportion of non-tagged fish that were transported required estimates of the following quantities:

1. The total number of non-tagged fish passing Lower Granite Dam each day
2. Travel time distributions to, and probabilities of entering juvenile bypass systems at Little Goose and Lower Monumental Dam
3. Proportions of fish collected each day that were transported from each of the three dams

These estimates were then combined to derive the overall estimate of proportion transported across the season.

The process for estimating the proportion transported for a particular stock is detailed step-by-step below. For each of the three types of quantities, steps include data sources, calculations, and elaboration regarding assumptions and other key underlying concepts.

Estimate the total number of non-tagged fish passing Lower Granite Dam each day

1a. Acquire Lower Granite Dam smolt report from the Smolt Monitoring Program (FPC 2021a). Extract daily "collection counts," which estimate the number of fish, tagged and untagged, that entered the juvenile bypass system each day.

1b. Use PIT-tag data to derive daily estimates of the probability of entering the juvenile bypass system at Lower Granite Dam, following the methods of Sandford and Smith (2002).

Since 2020, two passage routes have been monitored for PIT-tagged fish at Lower Granite Dam: the juvenile bypass system and the spillway detection system.[2] These calculations use only juvenile bypass system detections. Because detection efficiency in the juvenile bypass system is nearly 100% (i.e., almost every tagged fish that enters is detected at least once in the system), we assume that the estimated daily detection probability estimates are equivalent to the probability of entering the system.

[2] In the PTAGIS database, the juvenile bypass system is designated as site GRJ and the spillway detection system is site GRS.

1c. For each day, divide the collection count (step 1a) by the estimated probability of entering the juvenile bypass system (step 1b) to get an estimate of the total number of fish (tagged and untagged) that passed Lower Granite Dam on that day. Subtracting the collection count from the estimated total number passing gives an estimate of the number of fish that were not subject to transportation because they passed via routes other than the juvenile bypass system.

Estimate probabilities of entering the juvenile bypass systems at Little Goose and Lower Monumental Dam using travel-time distributions

2. For each daily group arriving at Lower Granite Dam (all passage routes), estimate the proportion of the group that first entered a juvenile bypass system at (i) Lower Granite Dam (ii) Little Goose Dam, (iii) Lower Monumental Dam, or (iv) did not enter the juvenile bypass system at any of the three dams.

   2a. For each daily group of PIT-tagged fish detected in the juvenile bypass system at Lower Granite Dam and directed to the tailrace to continue in-river migration, tabulate the number that were next detected at Little Goose Dam (i.e. next entered a juvenile bypass system) and the number that passed Little Goose undetected and next entered a juvenile bypass at Lower Monumental Dam.

   2b. Translate these counts into Lower Granite *equivalents*. An equivalent is a count at a downstream dam that is adjusted upward to account for mortality that occurred between release at Lower Granite Dam and that downstream site (i.e., the number of fish that had to have left Lower Granite Dam in order to realize the downstream counts at Little Goose and Lower Monumental Dam).

   2c. Assume that for the group of untagged fish arriving at Lower Granite Dam on a given day, the proportion of Lower Granite equivalents first collected at Lower Granite, Little Goose, and Lower Monumental is the same as that of the group of PIT-tagged fish that arrived at Lower Granite on that day. (The number of tagged fish that arrived at Lower Granite but were not detected in the juvenile bypass system is estimated using detection counts and the probability estimates from step 1b.)

Estimate proportions of fish collected each day that were transported

3a. Acquire smolt transportation reports for Lower Granite, Little Goose, and Lower Monumental Dams from the Smolt Monitoring Program (FPC 2021b). For each day at each dam, calculate the proportion of collected smolts that were transported.

3b. For each daily group of fish arriving at Lower Granite Dam, estimate the proportion that entered the juvenile bypass system at each collector dam *and* were transported from that dam.

For groups arriving at Lower Granite Dam after the respective starting dates of the general transportation program at each collector dam, the proportion transported from those that entered the bypass system at each dam is almost always nearly 100% (see step 3a). There can be short, intermittent disruptions, usually resulting from unforeseen circumstances.

For daily groups arriving at Lower Granite Dam before the general transportation starting date, the estimated proportion that is eventually transported depends on travel-time distributions to downstream collector dams. These distributions determine the proportions of the group that arrive at each downstream dam after transportation has started there. Travel-time distributions change throughout the season. For example, fish that arrive earlier at Lower Granite Dam tend to take more time to arrive at downstream dams.

To estimate downstream arrival distributions for a daily group of untagged fish, we assumed they had the same travel-time distributions as those observed for PIT-tagged fish detected at Lower Granite Dam on the same day.

Combine estimates to derive the proportion of smolts transported over entire season

4. For each daily group of the run-at-large, calculate the product of the estimated quantities from steps 1-3:
    - Number of fish in the group passing Lower Granite Dam that day (step 1)
    - Proportion of fish first entering the bypass system at each dam (step 2)
    - Proportion of fish entering the bypass system that were transported (step 3).

    This gives the estimated total equivalents from each daily group at Lower Granite Dam that were transported from each dam.

5. Sum all daily estimated numbers transported and divide by the total population estimate (sum of estimated daily number passing Lower Granite Dam) to derive the overall estimated proportion transported for the season.

Results

In 2021, collection for transportation began on 22 April at Lower Granite Dam, 23 April at Lower Monumental Dam, and 24 April at Little Goose Dam. At each of these dams, the first barge departed on 24 April. Before these dates, smolts in the collection systems at Snake River dams were bypassed to the tailrace of the dam.

Estimated percentages of non-tagged yearling Chinook salmon transported during the entire 2021 season were 9.8% for wild and 5.9% for hatchery smolts. For non-tagged steelhead, estimated percentages transported were 11.1% for wild and 4.3% for hatchery smolts. These estimates represented the proportion of smolts arriving at Lower Granite Dam that were subsequently transported, either from Lower Granite or from one of the downstream collector dams. The proportion of smolts transported in 2021 was the lowest on record and was substantially lower than the previous record lows from 2015 and 2020 (Figure 4; Table 21).

Before 2006, collected fish were transported throughout the season, starting from the first day on which the collection system was supplied with water. Between 2007 and 2013, collected fish were bypassed until a designated date, and the beginning date of transportation was staggered at each downstream dam (e.g., a few days later at Little Goose than at Lower Granite Dam).

Since 2014, transportation has begun simultaneously at all three collector dams. This schedule was followed in 2021 with the exception that the three collector dams began collection one day apart from each other.

In any given year, the percentage of a stock transported is largely determined by a combination of three factors: (1) migration timing, (2) the starting date of general smolt transportation, and (3) the percentage of smolts that enter the collection system during the transportation period.

In 2021, collection for transportation began during 22-24 April at Lower Granite, Little Goose, and Lower Monumental Dams. The transportation program has started on or about 24 April since 2018, so the start date in 2021 was typical of recent years. However, the proportion of smolts transported in 2021 was substantially lower than in any previous year, suggesting that either run timing was earlier in 2021 or collection rates were lower (or both).

The run in 2021 was only slightly early for steelhead and neither early nor late for Chinook. We estimate that 44.3% of wild and 11.7% of hatchery Chinook salmon, and 20.9% of wild and 54.1% of hatchery steelhead passed Lower Granite prior to the start of transportation. These numbers were slightly higher than in most previous years for steelhead, indicating that run timing did reduce steelhead transportation rates slightly in 2021.

In 2021, extremely low proportions of passing smolts were collected after the start of transportation. We estimated that 14.6% of wild and 6.4% of hatchery Chinook and 11.1% of wild and 7.2% of hatchery steelhead that passed during transport operations were collected and transported. These estimates accounted for all fish transported either from Lower Granite or from a downstream collector dam. The difference in proportion of transported fish between rear-types resulted from a difference in the probability of entering the collection system.

Collection rates in 2021 were less than one-half of the already low collection rates from 2020, and less than one-quarter of the collection rates from 2018 or 2019. These extremely low collection rates resulted from the combination of extremely high spill proportions and low flow during the 2021 migration season. Low collection rates were the primary cause of this very low overall transportation rate.

Our survival estimates are based largely on detections of PIT-tagged fish that migrated in the river. These fish were either detected in juvenile bypass systems and returned to the river or they passed dams via turbines or spillways (including surface-passage structures). Detections of fish that were ultimately transported were used for survival information only to the point where they were removed from the river.

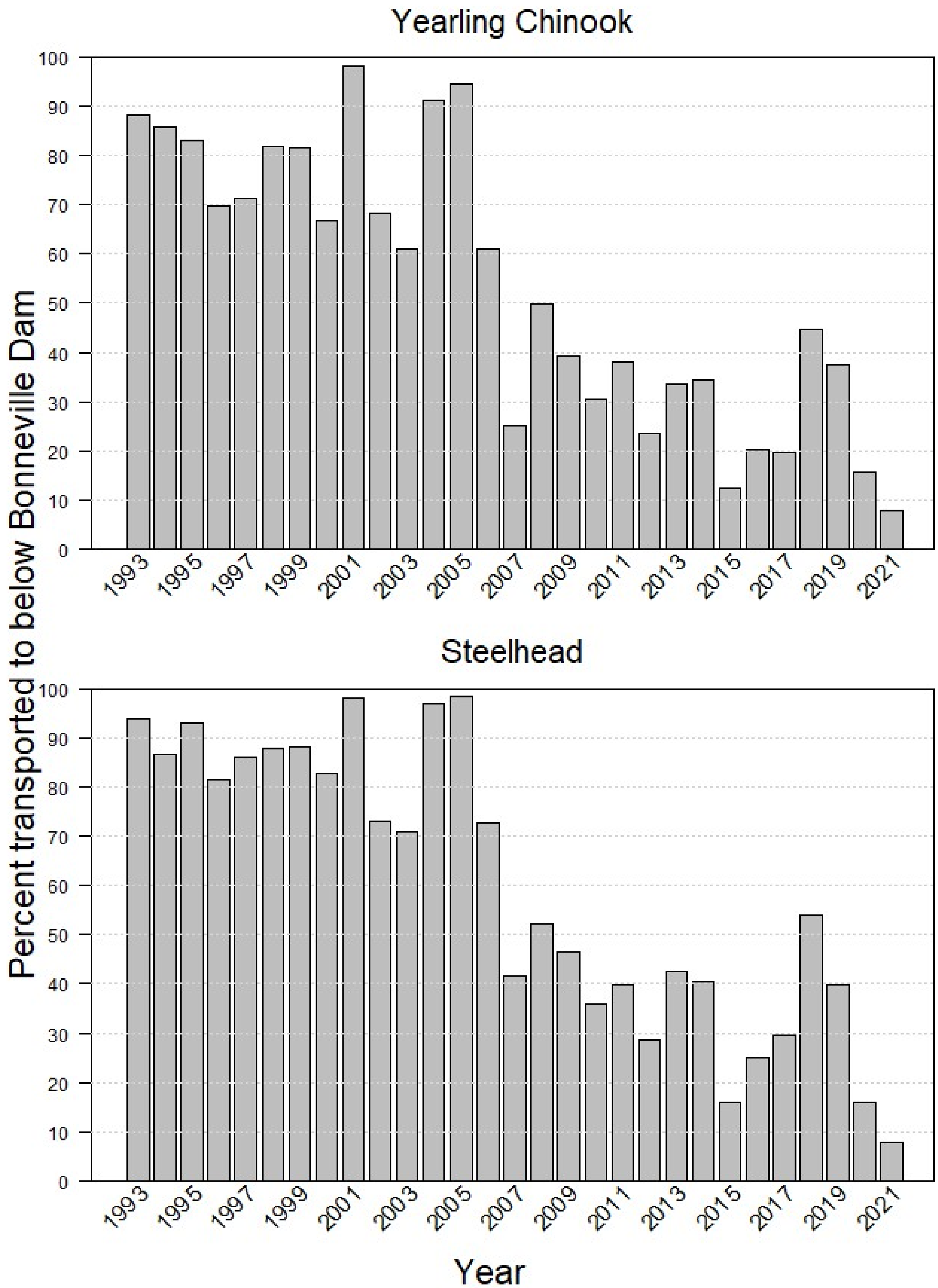

Figure 4. Annual estimated percentages of fish arriving at Lower Granite Dam that were subsequently transported and released downstream of Bonneville Dam, for Snake River yearling Chinook salmon and juvenile steelhead (mean of estimates for hatchery and wild fish), 1993-2021.

Table 21. Annual estimated percentages of fish arriving at Lower Granite Dam that were transported and released downstream of Bonneville Dam. Estimates are for Snake River yearling Chinook and juvenile steelhead (hatchery, wild, and mean), 1993-2021. Simple arithmetic means are given across all years and for periods with similar transportation schedules (1993-2006 and 2007-2021).

	Estimated percentages of fish transported, 1993-2021 (%)					
	Yearling Chinook salmon			**Juvenile steelhead**		
Year	Hatchery	Wild	Mean	Hatchery	Wild	Mean
1993	88.1	88.5	88.3	94.7	93.2	94.0
1994	84.0	87.7	85.9	82.2	91.3	86.8
1995	79.6	86.4	83.0	94.3	91.8	93.0
1996	68.7	71.0	69.9	82.9	79.8	81.4
1997	71.5	71.1	71.3	84.5	87.5	86.0
1998	81.5	82.5	82.0	87.3	88.1	87.7
1999	77.3	85.9	81.6	88.5	87.6	88.1
2000	63.0	70.5	66.8	81.5	84.0	82.8
2001	97.3	99.0	98.2	96.7	99.3	98.0
2002	64.3	72.1	68.2	70.6	75.2	72.9
2003	51.7	70.4	61.1	68.6	72.9	70.8
2004	90.5	92.0	91.3	97.3	96.3	96.8
2005	93.9	95.3	94.6	98.2	98.6	98.4
2006	62.3	59.9	61.1	76.7	68.4	72.6
2007	25.4	24.8	25.1	41.3	41.9	41.6
2008	45.3	54.3	49.8	46.9	57.7	52.3
2009	38.3	40.4	39.4	43.7	49.0	46.4
2010	22.6	38.2	30.4	35.0	36.6	35.8
2011	40.7	35.2	38.0	36.1	43.3	39.7
2012	24.7	22.7	23.7	26.2	31.4	28.8
2013	31.0	36.1	33.6	33.6	51.4	42.5
2014	38.3	30.9	34.6	33.3	47.4	40.4
2015	13.6	11.4	12.5	13.2	18.7	16.0
2016	21.0	19.3	20.2	22.6	27.7	25.2
2017	21.4	17.8	19.6	19.0	40.2	29.6
2018	45.4	44.1	44.8	44.5	63.3	53.9
2019	33.6	41.6	37.6	35.5	44.1	39.8
2020	12.5	18.8	15.7	11.7	20.5	16.1
2021	5.9	9.8	7.9	4.3	11.1	7.7
Mean						
1993-2021	**51.5**	**54.4**	**53.0**	**56.9**	**62.0**	**59.5**
1993-2006	**76.7**	**80.9**	**78.8**	**86.0**	**86.7**	**86.4**
2007-2021	**28.0**	**29.7**	**28.8**	**29.8**	**39.0**	**34.4**

Comparisons Among Annual Estimates

Comparison Among Years

We made two types of comparisons between annual survival estimates from 2021 and those from the previous 28 study years. First, for Snake River hatchery yearling Chinook, we compared estimated survival to Lower Granite Dam with distance of the respective hatcheries from the dam.

Second, for Snake and Columbia River yearling Chinook, steelhead, and sockeye, we compared estimates of mean annual survival through specific reaches during 2021 with estimates of mean annual survival through those same reaches in all previous study years for which these data were available.

We also compared detection probability estimates in 2021 to those from previous study years. For all yearling Chinook salmon released upstream from Lower Granite Dam in 2021, we calculated annual mean detection probability at three major Snake River dams and three major lower Columbia River dams. We compared these estimates to annual mean detection probability estimates for the same stock at the same dams in the years 2000-2020.

Snake River Stocks

Yearling Chinook Salmon—For yearling Chinook salmon, estimated survival to Lower Granite Dam was above average for fish from a majority of hatcheries in 2021, with below-average survival estimated only for fish from Rapid River and Pahsimeroi Hatchery (Table 22). Kooskia, Lookingglass, and McCall Hatchery fish had the highest survival on record for those hatcheries. Pahsimeroi Hatchery fish had extremely poor survival due to an outbreak of bacterial kidney disease at the hatchery.

Over the years of the study, we have consistently observed an inverse relationship between estimated survival and distance from the release site to Lower Granite Dam. This relationship is illustrated in Figure 5 for hatchery yearling Chinook salmon, using mean estimated survival across years ($R^2 = 0.813$, $P = 0.006$).

Table 22. Survival probability estimates from release to Lower Granite Dam for groups of yearling Chinook salmon released from selected Snake River Basin hatcheries, 1993-2021. Distance to Lower Granite Dam is shown for each release site (km). Standard errors in parentheses. Simple arithmetic means across all years are given.

	Estimated survival of hatchery yearling Chinook salmon (SE)							
Year	Dworshak (116 km)	Kooskia (176 km)	Lookingglass* (209 km)	Rapid River (283 km)	McCall (457 km)	Pahsimeroi (630 km)	Sawtooth (747 km)	Mean
1993	0.647 (0.028)	0.689 (0.047)	0.660 (0.025)	0.670 (0.017)	0.498 (0.017)	0.456 (0.032)	0.255 (0.023)	0.554 (0.060)
1994	0.778 (0.020)	0.752 (0.053)	0.685 (0.021)	0.526 (0.024)	0.554 (0.022)	0.324 (0.028)	0.209 (0.014)	0.547 (0.081)
1995	0.838 (0.034)	0.786 (0.024)	0.617 (0.015)	0.726 (0.017)	0.522 (0.011)	0.316 (0.033)	0.230 (0.015)	0.576 (0.088)
1996	0.776 (0.017)	0.744 (0.010)	0.567 (0.014)	0.588 (0.007)	0.531 (0.007)	NA	0.121 (0.017)	0.555 (0.096)
1997	0.576 (0.017)	0.449 (0.034)	0.616 (0.017)	0.382 (0.008)	0.424 (0.008)	0.500 (0.008)	0.508 (0.037)	0.494 (0.031)
1998	0.836 (0.006)	0.652 (0.024)	0.682 (0.006)	0.660 (0.004)	0.585 (0.004)	0.428 (0.021)	0.601 (0.033)	0.635 (0.046)
1999	0.834 (0.011)	0.653 (0.031)	0.668 (0.009)	0.746 (0.006)	0.649 (0.008)	0.584 (0.035)	0.452 (0.019)	0.655 (0.045)
2000	0.841 (0.009)	0.734 (0.027)	0.688 (0.011)	0.748 (0.007)	0.689 (0.010)	0.631 (0.062)	0.546 (0.030)	0.697 (0.035)
2001	0.747 (0.002)	0.577 (0.019)	0.747 (0.003)	0.689 (0.002)	0.666 (0.002)	0.621 (0.016)	0.524 (0.023)	0.653 (0.032)
2002	0.819 (0.011)	0.787 (0.036)	0.667 (0.012)	0.755 (0.003)	0.592 (0.006)	0.678 (0.053)	0.387 (0.025)	0.669 (0.055)
2003	0.720 (0.008)	0.560 (0.043)	0.715 (0.012)	0.691 (0.007)	0.573 (0.006)	0.721 (0.230)	0.595 (0.149)	0.654 (0.028)
2004	0.821 (0.003)	0.769 (0.017)	0.613 (0.004)	0.694 (0.003)	0.561 (0.002)	0.528 (0.017)	0.547 (0.018)	0.648 (0.044)
2005	0.823 (0.003)	0.702 (0.021)	0.534 (0.004)	0.735 (0.002)	0.603 (0.003)	0.218 (0.020)	0.220 (0.020)	0.548 (0.092)
2006	0.853 (0.007)	0.716 (0.041)	0.639 (0.014)	0.764 (0.004)	0.634 (0.006)	0.262 (0.024)	0.651 (0.046)	0.646 (0.071)
2007	0.817 (0.007)	0.654 (0.015)	0.682 (0.010)	0.748 (0.004)	0.554 (0.007)	0.530 (0.038)	0.581 (0.015)	0.652 (0.040)
2008	0.737 (0.011)	0.631 (0.015)	0.694 (0.008)	0.801 (0.004)	0.578 (0.007)	0.447 (0.011)	0.336 (0.012)	0.603 (0.062)
2009	0.696 (0.007)	0.633 (0.012)	0.699 (0.009)	0.728 (0.005)	0.513 (0.005)	0.510 (0.006)	0.367 (0.007)	0.592 (0.050)
2010	0.898 (0.017)	0.744 (0.030)	0.682 (0.025)	0.786 (0.019)	0.566 (0.014)	0.384 (0.023)	0.427 (0.018)	0.641 (0.072)
2011	0.722 (0.006)	0.729 (0.014)	0.572 (0.009)	0.766 (0.006)	0.631 (0.007)	0.498 (0.005)	0.521 (0.007)	0.634 (0.041)
2012	0.743 (0.008)	0.652 (0.013)	0.689 (0.009)	0.718 (0.014)	0.571 (0.006)	0.581 (0.006)	0.473 (0.008)	0.632 (0.036)
2013	0.794 (0.015)	0.609 (0.026)	0.703 (0.019)	0.735 (0.011)	0.656 (0.011)	0.606 (0.016)	0.564 (0.011)	0.667 (0.031)

Table 22. Continued.

Year	Dworshak (116 km)	Kooskia (176 km)	Lookingglass* (209 km)	Rapid River (283 km)	McCall (457 km)	Pahsimeroi (630 km)	Sawtooth (747 km)	Mean
	Estimated survival of hatchery yearling Chinook salmon (SE)							
2014	0.816 (0.009)	0.595 (0.011)	0.673 (0.009)	0.757 (0.008)	0.714 (0.008)	0.794 (0.008)	0.646 (0.008)	0.714 (0.031)
2015	0.768 (0.018)	0.532 (0.027)	0.655 (0.035)	0.811 (0.024)	0.729 (0.030)	0.771 (0.036)	0.696 (0.036)	0.709 (0.035)
2016	0.714 (0.007)	0.684 (0.012)	0.704 (0.007)	0.815 (0.005)	0.654 (0.006)	0.772 (0.008)	0.676 (0.006)	0.717 (0.022)
2017	0.693 (0.013)	0.565 (0.025)	0.585 (0.020)	0.652 (0.010)	0.700 (0.012)	0.746 (0.012)	0.606 (0.010)	0.650 (0.025)
2018	0.744 (0.015)	0.633 (0.030)	0.651 (0.012)	0.651 (0.009)	0.702 (0.011)	0.634 (0.015)	0.519 (0.013)	0.648 (0.026)
2019	0.688 (0.013)	0.571 (0.022)	0.627 (0.024)	0.491 (0.009)	0.616 (0.014)	0.280 (0.008)	0.539 (0.021)	0.545 (0.050)
2020	0.811 (0.011)	0.747 (0.029)	0.629 (0.017)	0.567 (0.010)	0.733 (0.011)	0.559 (0.018)	0.681 (0.020)	0.675 (0.036)
2021	0.784 (0.012)	0.808 (0.041)	0.757 (0.026)	0.631 (0.011)	0.783 (0.012)	0.287 (0.012)	0.637 (0.016)	0.670 (0.069)
Mean	**0.770 (0.013)**	**0.667 (0.016)**	**0.659 (0.010)**	**0.691 (0.019)**	**0.613 (0.015)**	**0.524 (0.032)**	**0.487 (0.030)**	**0.630 (0.011)**

* Released at Imnaha River Weir.

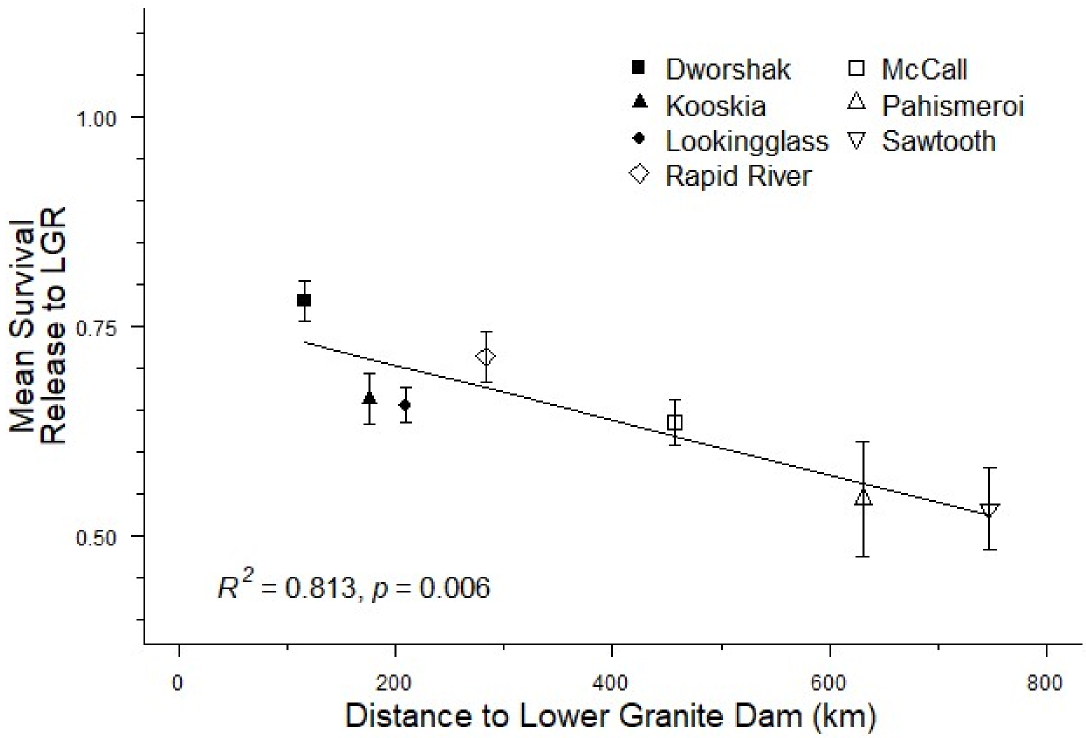

Figure 5. Mean estimated survival probability from release at Snake River Basin hatcheries to Lower Granite Dam tailrace, 1998-2021, vs. distance (km) from release to Lower Granite Dam. The coefficient of determination between survival and migration distance is also shown, along with the *P*-value for a test of the null hypothesis of zero correlation. Whiskers are 95% confidence intervals.

For combined wild and hatchery yearling Chinook salmon in 2021, mean estimated survival was 0.730 (95% CI 0.679-0.781) from Lower Granite to McNary Dam and 0.746 (0.526-0.966) from McNary to Bonneville Dam (Tables 23-24; Figures 6-7). The estimate from Lower Granite to McNary Dam was very close to the long-term mean of 0.735, and the difference was not statistically significant ($P = 0.85$). The estimate from McNary to Bonneville was above the long-term mean of 0.704, but again, the difference was not significant ($P = 0.70$). The overall estimate from Lower Granite to Bonneville Dam was 0.543, which was above, but not significantly different from the long-term mean of 0.524 ($P = 0.82$).

For combined wild and hatchery yearling Chinook salmon from the Snake River Smolt Trap to the tailrace of Bonneville Dam, mean estimated survival was 0.471 (95% CI 0.286-0.655; Table 24) in 2021. Though imprecise, this estimate was close to the 25-year mean of 0.484 as well as the estimate from 2020 of 0.477.

For wild Chinook smolts, we did not have sufficient data to estimate survival for biweekly groups. Instead, we used a single pooled group of all wild fish released upstream from Lower Granite Dam and detected passing the dam plus those tagged at the dam. Using this method, estimated survival for wild yearling Chinook salmon in 2021 was 0.673 (95% CI 0.569-0.777) from Lower Granite to McNary Dam. This estimate was below, but not significantly different from, the long-term average of 0.718 (Table 25; $P = 0.40$).

Estimated survival for wild Chinook salmon from McNary to Bonneville Dam was 0.533 (95% CI 0.304-0.762), which was substantially below the long-term average of 0.649 (Table 25). However, due to the uncertainty in this estimate, the difference was not significant ($P = 0.32$).

Estimated survival for wild Chinook from Lower Granite to Bonneville Dam was 0.359 (95% CI 0.214-0.504), which well was below the long-term average of 0.473 but not significantly different from it due to the poor precision of the estimate ($P = 0.13$). Extremely few wild Chinook were tagged at the Snake River Smolt Trap in 2021, and we were unable to estimate survival for wild Chinook separately for any reach starting at the trap.

Table 23. Annual survival probability estimates from the Snake River Smolt Trap to Bonneville Dam for Snake River yearling Chinook salmon (combined hatchery and wild fish), 1993-2021. Shaded columns are reaches that comprise two dams and reservoirs; the following column gives the square root of the two-project estimate to facilitate comparison with one-project estimates. Standard errors in parentheses. Simple arithmetic means across all available years are given.

Annual survival estimates for hatchery and wild yearling Chinook salmon (SE)								
Year	Trap to Lower Granite Dam	Lower Granite to Little Goose Dam	Little Goose to Lower Monumental	Lower Monumental to McNary Dam	L Monumental to Ice Harbor and Ice Harbor to McNary	McNary to John Day Dam	John Day to Bonneville Dam	John Day to The Dalles and The Dalles to Bonneville Dam
1993	0.828 (0.013)	0.854 (0.012)	NA	NA	NA	NA	NA	NA
1994	0.935 (0.023)	0.830 (0.009)	0.847 (0.010)	NA	NA	NA	NA	NA
1995	0.905 (0.010)	0.882 (0.004)	0.925 (0.008)	0.876 (0.038)	0.936	NA	NA	NA
1996	0.977 (0.025)	0.926 (0.006)	0.929 (0.011)	0.756 (0.033)	0.870	NA	NA	NA
1997	NA	0.942 (0.018)	0.894 (0.042)	0.798 (0.091)	0.893	NA	NA	NA
1998	0.924 (0.009)	0.991 (0.006)	0.853 (0.009)	0.915 (0.011)	0.957	0.822 (0.033)	NA	NA
1999	0.940 (0.009)	0.949 (0.002)	0.925 (0.004)	0.904 (0.007)	0.951	0.853 (0.027)	0.814 (0.065)	0.902
2000	0.929 (0.014)	0.938 (0.006)	0.887 (0.009)	0.928 (0.016)	0.963	0.898 (0.054)	0.684 (0.128)	0.827
2001	0.954 (0.015)	0.945 (0.004)	0.830 (0.006)	0.708 (0.007)	0.841	0.758 (0.024)	0.645 (0.034)	0.803
2002	0.953 (0.022)	0.949 (0.006)	0.980 (0.008)	0.837 (0.013)	0.915	0.907 (0.014)	0.840 (0.079)	0.917
2003	0.993 (0.023)	0.946 (0.005)	0.916 (0.011)	0.904 (0.017)	0.951	0.893 (0.017)	0.818 (0.036)	0.904
2004	0.893 (0.009)	0.923 (0.004)	0.875 (0.012)	0.818 (0.018)	0.904	0.809 (0.028)	0.735 (0.092)	0.857
2005	0.919 (0.015)	0.919 (0.003)	0.886 (0.006)	0.903 (0.010)	0.950	0.772 (0.029)	1.028 (0.132)	1.014
2006	0.952 (0.011)	0.923 (0.003)	0.934 (0.004)	0.887 (0.008)	0.942	0.881 (0.020)	0.944 (0.030)	0.972
2007	0.943 (0.028)	0.938 (0.006)	0.957 (0.010)	0.876 (0.012)	0.936	0.920 (0.016)	0.824 (0.043)	0.908
2008	0.992 (0.018)	0.939 (0.006)	0.950 (0.011)	0.878 (0.016)	0.937	1.073 (0.058)	0.558 (0.082)	0.750
2009	0.958 (0.010)	0.940 (0.006)	0.982 (0.009)	0.855 (0.011)	0.925	0.866 (0.042)	0.821 (0.043)	0.906
2010	0.968 (0.040)	0.962 (0.011)	0.973 (0.019)	0.851 (0.017)	0.922	0.947 (0.021)	0.780 (0.039)	0.883

Table 23. Continued.

Annual survival estimates for hatchery and wild yearling Chinook salmon (SE)								
Year	Trap to Lower Granite Dam	Lower Granite to Little Goose Dam	Little Goose to Lower Monumental	Lower Monumental to McNary Dam	L Monumental to Ice Harbor and Ice Harbor to McNary	McNary to John Day Dam	John Day to Bonneville Dam	John Day to The Dalles and The Dalles to Bonneville Dam
2011	0.943 (0.009)	0.919 (0.007)	0.966 (0.007)	0.845 (0.012)	0.919	0.893 (0.026)	0.766 (0.080)	0.875
2012	0.928 (0.012)	0.907 (0.009)	0.939 (0.010)	0.937 (0.016)	0.968	0.915 (0.023)	0.866 (0.058)	0.931
2013	0.845 (0.031)	0.922 (0.012)	0.983 (0.014)	0.904 (0.022)	0.951	0.931 (0.054)	0.823 (0.036)	0.907
2014	0.905 (0.015)	0.947 (0.005)	0.919 (0.010)	0.894 (0.017)	0.946	0.912 (0.053)	0.752 (0.104)	0.867
2015	0.909 (0.103)	0.928 (0.031)	0.960 (0.057)	0.785 (0.032)	0.886	0.724 (0.069)	0.937 (0.160)	0.968
2016	0.936 (0.015)	0.956 (0.006)	0.912 (0.010)	0.872 (0.013)	0.934	0.796 (0.039)	0.871 (0.047)	0.933
2017	NA	0.916 (0.009)	0.908 (0.013)	0.912 (0.024)	0.956	0.720 (0.041)	0.871 (0.200)	0.933
2018	0.880 (0.022)	0.942 (0.013)	0.917 (0.019)	0.877 (0.036)	0.936	0.770 (0.074)	0.743 (0.100)	0.862
2019	0.785 (0.027)	0.874 (0.015)	0.953 (0.027)	0.792 (0.032)	0.890	1.015 (0.088)	0.798 (0.111)	0.893
2020	0.848 (0.058)	0.811 (0.039)	1.171 (0.128)	0.847 (0.095)	0.920	0.862 (0.039)*	0.865 (0.060)*	0.930*
2021	0.867 (0.108)	0.806 (0.067)	1.136 (0.127)	0.854 (0.146)	0.924	0.960 (0.077)*	0.796 (0.096)*	0.892*
Mean	**0.919 (0.010)**	**0.918 (0.008)**	**0.940 (0.014)**	**0.860 (0.011)**	**0.927 (0.006)**	**0.871 (0.018)**	**0.808 (0.021)**	**0.897 (0.012)**

* Estimates for 2020-2021 in the reaches between McNary Dam and Bonneville Dam used a different method than in previous years.

Table 24. Annual survival probability estimates through the entire hydropower system, and through component river reaches for Snake River yearling Chinook salmon (combined hatchery and wild fish), 1993–2021. Standard errors in parentheses. Simple arithmetic means across all available years are given.

	Annual survival estimates for hatchery and wild yearling Chinook (SE)				
Year	Trap to Lower Granite Dam	Lower Granite to McNary Dam	McNary to Bonneville Dam	Lower Granite to Bonneville Dam	Trap to Bonneville Dam
1993	0.828 (0.013)	NA	NA	NA	NA
1994	0.935 (0.023)	NA	NA	NA	NA
1995	0.905 (0.010)	0.715 (0.031)	NA	NA	NA
1996	0.977 (0.025)	0.648 (0.026)	NA	NA	NA
1997	NA	0.653 (0.072)	NA	NA	NA
1998	0.924 (0.011)	0.770 (0.009)	NA	NA	NA
1999	0.940 (0.009)	0.792 (0.006)	0.704 (0.058)	0.557 (0.046)	0.524 (0.043)
2000	0.929 (0.014)	0.760 (0.012)	0.640 (0.122)	0.486 (0.093)	0.452 (0.087)
2001	0.954 (0.015)	0.556 (0.009)	0.501 (0.027)	0.279 (0.016)	0.266 (0.016)
2002	0.953 (0.022)	0.757 (0.009)	0.763 (0.079)	0.578 (0.060)	0.551 (0.059)
2003	0.993 (0.023)	0.731 (0.010)	0.728 (0.030)	0.532 (0.023)	0.528 (0.026)
2004	0.893 (0.009)	0.666 (0.011)	0.594 (0.074)	0.395 (0.050)	0.353 (0.045)
2005	0.919 (0.015)	0.732 (0.009)	0.788 (0.093)	0.577 (0.068)	0.530 (0.063)
2006	0.952 (0.011)	0.764 (0.007)	0.842 (0.021)	0.643 (0.017)	0.612 (0.018)
2007	0.943 (0.028)	0.783 (0.006)	0.763 (0.044)	0.597 (0.035)	0.563 (0.037)
2008	0.992 (0.018)	0.782 (0.011)	0.594 (0.066)	0.465 (0.052)	0.460 (0.052)
2009	0.958 (0.010)	0.787 (0.007)	0.705 (0.031)	0.555 (0.025)	0.531 (0.025)
2010	0.968 (0.040)	0.772 (0.012)	0.738 (0.039)	0.569 (0.032)	0.551 (0.038)
2011	0.943 (0.009)	0.746 (0.010)	0.687 (0.065)	0.513 (0.049)	0.483 (0.046)
2012	0.928 (0.012)	0.790 (0.016)	0.802 (0.051)	0.634 (0.042)	0.588 (0.040)
2013	0.845 (0.031)	0.781 (0.016)	0.796 (0.064)	0.622 (0.052)	0.525 (0.048)

Table 24. Continued.

Annual survival estimates for hatchery and wild yearling Chinook (SE)					
Year	Trap to Lower Granite Dam	Lower Granite to McNary Dam	McNary to Bonneville Dam	Lower Granite to Bonneville Dam	Trap to Bonneville Dam
2014	0.905 (0.015)	0.784 (0.013)	0.715 (0.107)	0.560 (0.084)	0.507 (0.077)
2015	0.909 (0.103)	0.727 (0.033)	0.629 (0.043)	0.457 (0.037)	0.415 (0.058)
2016	0.936 (0.015)	0.752 (0.011)	0.672 (0.060)	0.505 (0.046)	0.473 (0.043)
2017	NA	0.743 (0.019)	0.643 (0.157)	0.478 (0.117)	NA
2018	0.880 (0.022)	0.733 (0.025)	0.590 (0.045)	0.432 (0.036)	0.381 (0.033)
2019	0.785 (0.027)	0.628 (0.027)	0.825 (0.060)	0.518 (0.044)	0.407 (0.037)
2020	0.848 (0.058)	0.766 (0.018)	0.733 (0.045)*	0.563 (0.039)	0.477 (0.046)
2021	0.867 (0.108)	0.730 (0.026)	0.746 (0.112)*	0.543 (0.085)	0.471 (0.094)
Mean	**0.919 (0.010)**	**0.735 (0.011)**	**0.704 (0.018)**	**0.524 (0.017)**	**0.484 (0.017)**

* The estimates for 2020-2021 for the reach between McNary Dam and Bonneville Dam used a different method than in previous years.

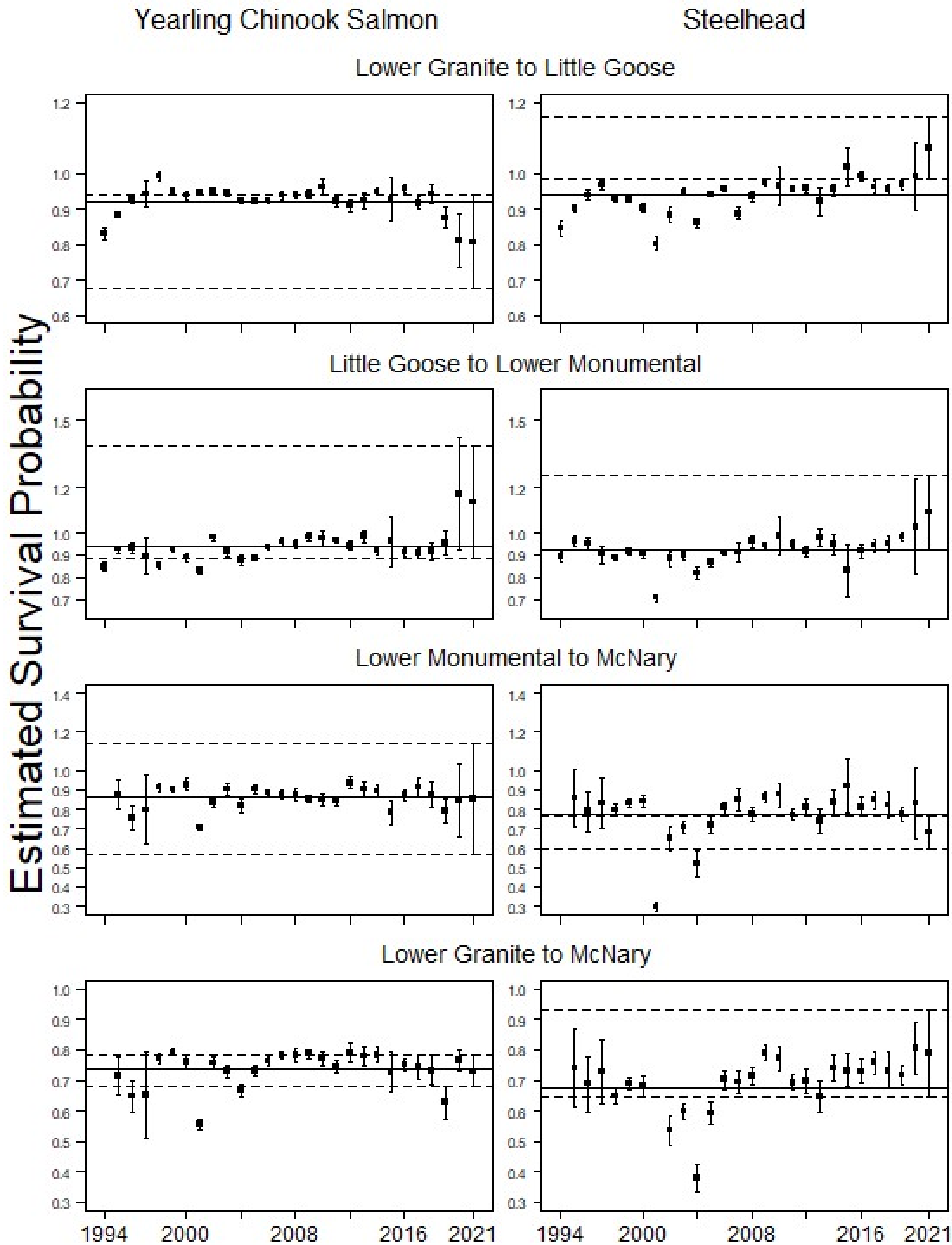

Figure 6. Annual survival probability estimates through Snake River reaches for Snake River yearling Chinook salmon and juvenile steelhead (combined hatchery and wild fish), 1993-2021. Whiskers represent 95% CIs. Dashed horizontal lines indicate 95% CI endpoints for 2021 estimates; solid horizontal lines indicate long-term means (1993-2021).

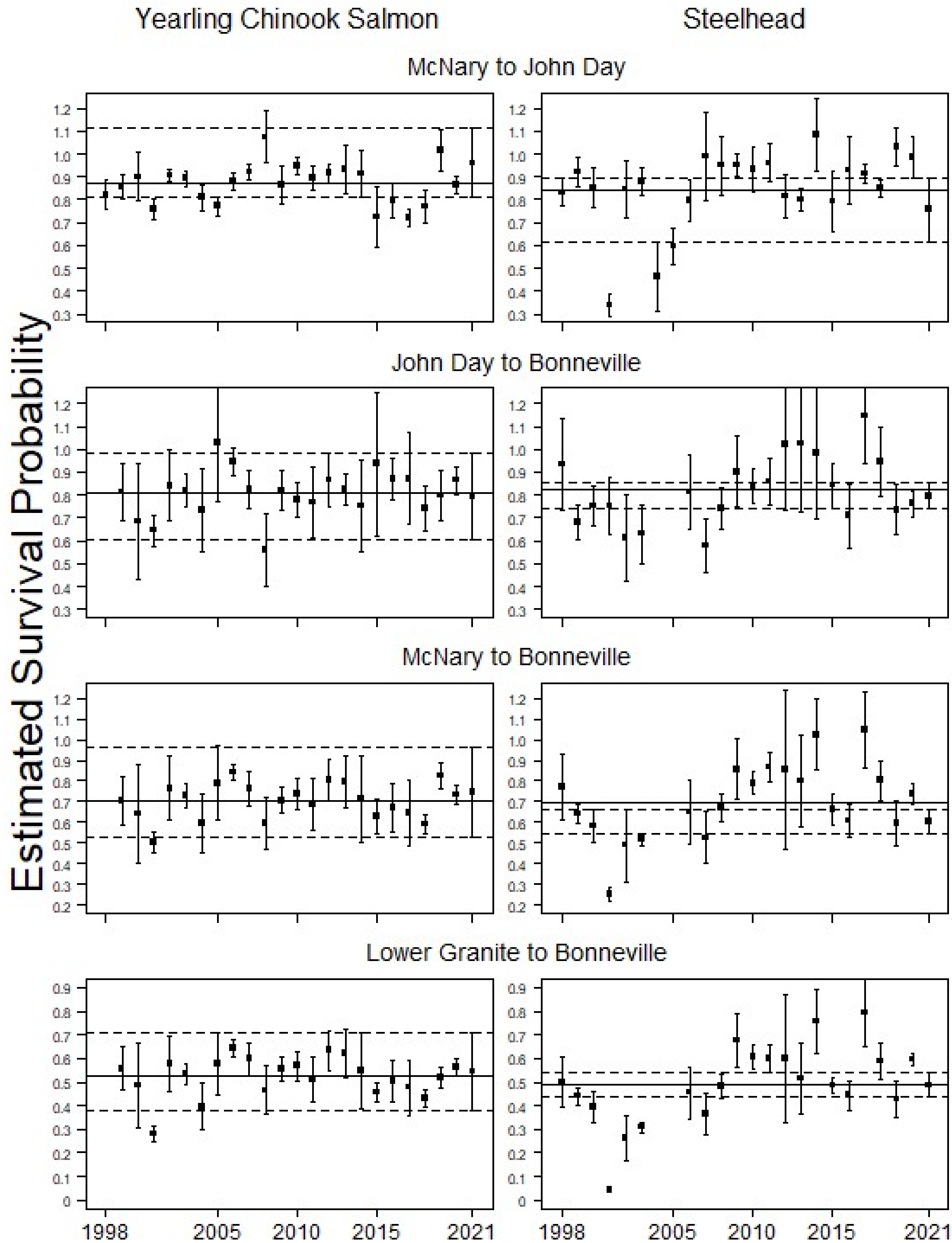

Figure 7. Annual survival probability estimates through Columbia River reaches and from Lower Granite to Bonneville Dam for Snake River yearling Chinook and juvenile steelhead (combined hatchery and wild fish), 1993-2021. Whiskers represent 95% CIs. Dashed horizontal lines indicate 95% CI endpoints for 2021 estimates; solid horizontal lines indicate long-term means (1993-2021).

Table 25. Annual survival probability estimates through the entire hydropower system, and through component river reaches for Snake River yearling Chinook salmon (wild fish only), 1993–2021. Standard errors in parentheses. Simple arithmetic means across all available years are given.

Annual survival estimates for wild yearling Chinook					
Year	Trap to Lower Granite Dam	Lower Granite to McNary Dam	McNary to Bonneville Dam	Lower Granite to Bonneville Dam	Trap to Bonneville Dam
1993	0.847 (0.024)	NA	NA	NA	NA
1994	0.913 (0.036)	NA	NA	NA	NA
1995	0.944 (0.015)	0.697 (0.097)	NA	NA	NA
1996	0.984 (0.039)	0.574 (0.059)	NA	NA	NA
1997	NA	NA	NA	NA	NA
1998	0.915 (0.019)	0.771 (0.015)	NA	NA	NA
1999	0.951 (0.011)	0.791 (0.014)	0.620 (0.099)	0.490 (0.079)	0.466 (0.075)
2000	0.955 (0.023)	0.775 (0.014)	0.575 (0.156)	0.446 (0.121)	0.425 (0.116)
2001	0.921 (0.058)	0.542 (0.028)	0.437 (0.041)	0.237 (0.025)	0.218 (0.027)
2002	0.985 (0.038)	0.768 (0.026)	0.469 (0.120)	0.360 (0.093)	0.355 (0.092)
2003	0.943 (0.033)	0.729 (0.020)	0.757 (0.059)	0.552 (0.046)	0.520 (0.047)
2004	0.862 (0.013)	0.667 (0.023)	0.566 (0.164)	0.377 (0.110)	0.325 (0.095)
2005	0.964 (0.034)	0.661 (0.017)	0.681 (0.243)	0.450 (0.161)	0.434 (0.156)
2006	0.929 (0.019)	0.754 (0.010)	0.827 (0.085)	0.623 (0.064)	0.579 (0.061)
2007	0.903 (0.062)	0.773 (0.013)	0.780 (0.088)	0.603 (0.069)	0.544 (0.072)
2008	0.955 (0.036)	0.786 (0.020)	0.607 (0.127)	0.477 (0.101)	0.456 (0.098)
2009	0.940 (0.012)	0.765 (0.018)	0.606 (0.068)	0.464 (0.053)	0.436 (0.050)
2010	0.821 (0.047)	0.744 (0.021)	0.612 (0.063)	0.455 (0.049)	0.374 (0.045)
2011	0.954 (0.010)	0.743 (0.015)	0.955 (0.197)	0.710 (0.147)	0.677 (0.140)
2012	0.942 (0.013)	0.798 (0.020)	0.831 (0.065)	0.663 (0.054)	0.625 (0.052)
2013	0.791 (0.045)	0.778 (0.018)	0.685 (0.092)	0.553 (0.073)	0.422 (0.062)

Table 25. Continued.

Year	Trap to Lower Granite Dam	Lower Granite to McNary Dam	McNary to Bonneville Dam	Lower Granite to Bonneville Dam	Trap to Bonneville Dam
			Annual survival estimates for wild yearling Chinook		
2014	0.892 (0.017)	0.722 (0.015)	0.577 (0.074)	0.417 (0.054)	0.372 (0.049)
2015	0.867 (0.192)	0.647 (0.058)	0.843 (0.106)	0.545 (0.084)	0.473 (0.127)
2016	0.957 (0.019)	0.703 (0.017)	0.490 (0.095)	0.344 (0.067)	0.330 (0.065)
2017	NA	0.709 (0.020)	0.436 (0.063)	0.309 (0.045)	NA
2018	0.871 (0.030)	0.760 (0.031)	0.762 (0.144)	0.579 (0.112)	0.504 (0.099)
2019	0.868 (0.065)	0.669 (0.028)	0.813 (0.114)	0.544 (0.080)	0.472 (0.078)
2020	0.703 (0.111)*	0.674 (0.073)	0.463 (0.145)	0.312 (0.103)	0.219 (0.081)
2021	NA	0.673 (0.053)	0.533 (0.117)	0.359 (0.074)	NA
Mean	**0.907 (0.013)**	**0.718 (0.013)**	**0.649 (0.031)**	**0.473 (0.026)**	**0.439 (0.026)**

* Based on a sample size of just 69 tagged fish released.

Steelhead—For combined wild and hatchery steelhead, mean estimated survival from Lower Granite to McNary Dam was 0.788 (95% CI 0.645-0.931) in 2021, which was slightly lower than the 2020 estimate of 0.807 but not significantly different from it ($P = 0.82$; Tables 26-27; Figures 6-7). This estimate was also substantially higher than the long-term average of 0.673, but not significantly different from it due to the poor precision of the 2021 estimate ($P = 0.12$).

Mean estimated survival from McNary to Bonneville Dam for Snake River steelhead was 0.602 (0.545-0.659) in 2021, which was much lower than the estimate of 0.738 in 2020, and the difference was significant ($P = 0.02$). The 2021 estimate was also lower than the long-term average of 0.695, and again the difference was significant ($P = 0.04$).

Estimated survival from the Snake River Smolt Trap to Bonneville Dam for combined wild and hatchery steelhead was 0.456 (0.401-0.511; Table 27), which was lower than both the estimate of 0.544 from 2020 and the long-term average of 0.461. The difference between estimates for 2020 vs. 2021 was significant ($P = 0.05$), but the difference between the estimates for 2021 vs. the long-term average was not significant ($P = 0.91$).

Estimated survival for wild steelhead in 2021 was 0.624 (95% CI 0.479-0.769) from Lower Granite to McNary Dam. This estimate was below, but not significantly different from, the long-term average of 0.655 (Table 28; $P = 0.68$). Estimated survival for wild steelhead from McNary to Bonneville Dam was 0.605 (0.462-0.748), which was slightly below the long-term average of 0.623, but the difference was not significant ($P = 0.83$).

Estimated survival for wild steelhead from the Snake River Smolt Trap to Bonneville Dam in 2021 was 0.450 (95% CI 0.296-0.605; Table 28), which was higher than the long-term average of 0.420. However, the difference was not significant ($P = 0.71$).

Table 26. Annual survival probability estimates from Snake River Smolt Trap to Bonneville Dam for Snake River juvenile steelhead (combined hatchery and wild fish), 1993–2021. Shaded columns are reaches that comprise two dams and reservoirs; the following column gives the square root of the two-project estimate to facilitate comparison with one-project estimates. Standard errors in parentheses. Simple arithmetic means across all available years are given.

Annual survival estimates for hatchery and wild steelhead								
Year	Trap to Lower Granite Dam	Lower Granite to Little Goose Dam	Little Goose to Lower Monumental	Lower Monumental to McNary Dam	L Monumental to Ice Harbor and Ice Harbor to McNary	McNary to John Day Dam	John Day to Bonneville Dam	John Day to The Dalles and The Dalles to Bonneville Dam
1993	0.905 (0.006)	NA	NA	NA	NA	NA	NA	NA
1994	0.794 (0.009)	0.844 (0.011)	0.892 (0.011)	NA	NA	NA	NA	NA
1995	0.945 (0.008)	0.899 (0.005)	0.962 (0.011)	0.858 (0.076)	0.926	NA	NA	NA
1996	0.951 (0.015)	0.938 (0.008)	0.951 (0.014)	0.791 (0.052)	0.889	NA	NA	NA
1997	0.964 (0.015)	0.966 (0.006)	0.902 (0.020)	0.834 (0.065)	0.913	NA	NA	NA
1998	0.924 (0.009)	0.930 (0.004)	0.889 (0.006)	0.797 (0.018)	0.893	0.831 (0.031)	0.935 (0.103)	0.967
1999	0.908 (0.011)	0.926 (0.004)	0.915 (0.006)	0.833 (0.011)	0.913	0.920 (0.033)	0.682 (0.039)	0.826
2000	0.964 (0.013)	0.901 (0.006)	0.904 (0.009)	0.842 (0.016)	0.918	0.851 (0.045)	0.754 (0.045)	0.868
2001	0.911 (0.007)	0.801 (0.010)	0.709 (0.008)	0.296 (0.010)	0.544	0.337 (0.025)	0.753 (0.063)	0.868
2002	0.895 (0.015)	0.882 (0.011)	0.882 (0.018)	0.652 (0.031)	0.807	0.844 (0.063)	0.612 (0.098)	0.782
2003	0.932 (0.015)	0.947 (0.005)	0.898 (0.012)	0.708 (0.018)	0.841	0.879 (0.032)	0.630 (0.066)	0.794
2004	0.948 (0.004)	0.860 (0.006)	0.820 (0.014)	0.519 (0.035)	0.720	0.465 (0.078)	NA	NA
2005	0.967 (0.004)	0.940 (0.004)	0.867 (0.009)	0.722 (0.023)	0.850	0.595 (0.040)	NA	NA
2006	0.920 (0.013)	0.956 (0.004)	0.911 (0.006)	0.808 (0.017)	0.899	0.795 (0.045)	0.813 (0.083)	0.902
2007	1.016 (0.026)	0.887 (0.009)	0.911 (0.022)	0.852 (0.030)	0.923	0.988 (0.098)	0.579 (0.059)	0.761
2008	0.995 (0.018)	0.935 (0.007)	0.961 (0.014)	0.776 (0.017)	0.881	0.950 (0.066)	0.742 (0.045)	0.861
2009	1.002 (0.011)	0.972 (0.005)	0.942 (0.008)	0.863 (0.014)	0.929	0.951 (0.026)	0.900 (0.079)	0.949
2010	1.017 (0.030)	0.965 (0.028)	0.984 (0.044)	0.876 (0.032)	0.936	0.931 (0.051)	0.840 (0.038)	0.907

Table 26. Continued.

Annual survival estimates for hatchery and wild steelhead								
Year	Trap to Lower Granite Dam	Lower Granite to Little Goose Dam	Little Goose to Lower Monumental	Lower Monumental to McNary Dam	L Monumental to Ice Harbor and Ice Harbor to McNary	McNary to John Day Dam	John Day to Bonneville Dam	John Day to The Dalles and The Dalles to Bonneville Dam
2011	0.986 (0.017)	0.955 (0.004)	0.948 (0.010)	0.772 (0.014)	0.879	0.960 (0.043)	0.858 (0.051)	0.926
2012	1.001 (0.026)	0.959 (0.006)	0.914 (0.011)	0.811 (0.022)	0.901	0.814 (0.048)	1.021 (0.148)	1.010
2013	0.973 (0.032)	0.921 (0.020)	0.977 (0.020)	0.739 (0.031)	0.860	0.799 (0.025)	1.026 (0.154)	1.013
2014	1.018 (0.028)	0.953 (0.009)	0.947 (0.024)	0.836 (0.032)	0.914	1.082 (0.080)	0.982 (0.147)	0.991
2015	0.874 (0.046)	1.017 (0.028)	0.829 (0.059)	0.923 (0.071)	0.961	0.792 (0.066)	0.842 (0.050)	0.918
2016	0.998 (0.016)	0.990 (0.007)	0.918 (0.016)	0.813 (0.025)	0.902	0.927 (0.074)	0.709 (0.071)	0.842
2017	NA	0.962 (0.008)	0.943 (0.015)	0.849 (0.022)	0.921	0.941 (0.020)	1.145 (0.104)	1.070
2018	0.983 (0.025)	0.953 (0.007)	0.950 (0.016)	0.823 (0.036)	0.907	0.851 (0.039)	0.946 (0.150)	0.973
2019	0.965 (0.027)	0.968 (0.006)	0.981 (0.011)	0.774 (0.019)	0.880	1.029 (0.084)	0.734 (0.110)	0.857
2020	0.914 (0.041)	0.991 (0.049)	1.025 (0.109)	0.834 (0.092)	0.913	0.985 (0.090)*	0.762 (0.057)*	0.873*
2021	0.936 (0.029)	1.070 (0.045)	1.089 (0.083)	0.681 (0.043)	0.825	0.757 (0.071)*	0.795 (0.029)*	0.892*
Mean	**0.950 (0.010)**	**0.939 (0.010)**	**0.922 (0.013)**	**0.773 (0.024)**	**0.876 (0.016)**	**0.844 (0.035)**	**0.821 (0.031)**	**0.903 (0.017)**

* Estimates for 2020-2021 in the reaches between McNary Dam and Bonneville Dam used a different method than in previous years.

Table 27. Annual survival probability estimates through the entire hydropower system, and through component river reaches for Snake River juvenile steelhead (combined hatchery and wild fish), 1993–2021. Standard errors in parentheses. Simple arithmetic means across all available years are given.

	Annual survival estimates for hatchery and wild steelhead				
Year	Snake River Smolt Trap to Lower Granite Dam	Lower Granite to McNary Dam	McNary to Bonneville Dam	Lower Granite to Bonneville Dam	Trap to Bonneville Dam
1993	0.905 (0.006)	NA	NA	NA	NA
1994	0.794 (0.009)	NA	NA	NA	NA
1995	0.945 (0.008)	0.739 (0.066)	NA	NA	NA
1996	0.951 (0.015)	0.688 (0.046)	NA	NA	NA
1997	0.964 (0.015)	0.728 (0.053)	0.651 (0.082)	0.474 (0.069)	0.457 (0.067)
1998	0.924 (0.009)	0.649 (0.013)	0.770 (0.081)	0.500 (0.054)	0.462 (0.050)
1999	0.908 (0.011)	0.688 (0.010)	0.640 (0.024)	0.440 (0.018)	0.400 (0.017)
2000	0.964 (0.013)	0.679 (0.016)	0.580 (0.040)	0.393 (0.034)	0.379 (0.033)
2001	0.911 (0.007)	0.168 (0.006)	0.250 (0.016)	0.042 (0.003)	0.038 (0.003)
2002	0.895 (0.015)	0.536 (0.025)	0.488 (0.090)	0.262 (0.050)	0.234 (0.045)
2003	0.932 (0.015)	0.597 (0.013)	0.518 (0.015)	0.309 (0.011)	0.288 (0.012)
2004	0.948 (0.004)	0.379 (0.023)	NA	NA	NA
2005	0.967 (0.004)	0.593 (0.018)	NA	NA	NA
2006	0.920 (0.013)	0.702 (0.016)	0.648 (0.079)	0.455 (0.056)	0.418 (0.052)
2007	1.016 (0.026)	0.694 (0.020)	0.524 (0.064)	0.364 (0.045)	0.369 (0.047)
2008	0.995 (0.018)	0.716 (0.015)	0.671 (0.034)	0.480 (0.027)	0.478 (0.028)
2009	1.002 (0.011)	0.790 (0.013)	0.856 (0.074)	0.676 (0.059)	0.678 (0.060)
2010	1.017 (0.030)	0.770 (0.020)	0.789 (0.027)	0.608 (0.026)	0.618 (0.032)
2011	0.986 (0.017)	0.693 (0.013)	0.866 (0.038)	0.600 (0.029)	0.592 (0.030)
2012	1.001 (0.026)	0.698 (0.020)	0.856 (0.196)	0.597 (0.138)	0.598 (0.139)
2013	0.973 (0.032)	0.645 (0.026)	0.798 (0.112)	0.515 (0.075)	0.501 (0.075)

Table 27. Continued.

	Annual survival estimates for hatchery and wild steelhead				
Year	Snake River Smolt Trap to Lower Granite Dam	Lower Granite to McNary Dam	McNary to Bonneville Dam	Lower Granite to Bonneville Dam	Trap to Bonneville Dam
2014	1.018 (0.028)	0.740 (0.021)	1.023 (0.088)	0.757 (0.069)	0.771 (0.073)
2015	0.874 (0.046)	0.733 (0.027)	0.663 (0.039)	0.486 (0.034)	0.425 (0.037)
2016	0.998 (0.016)	0.730 (0.020)	0.608 (0.040)	0.444 (0.032)	0.443 (0.032)
2017	NA	0.759 (0.019)	1.045 (0.095)	0.793 (0.075)	NA
2018	0.983 (0.025)	0.733 (0.031)	0.802 (0.098)	0.588 (0.076)	0.578 (0.076)
2019	0.965 (0.027)	0.717 (0.017)	0.595 (0.109)	0.427 (0.079)	0.412 (0.077)
2020	0.914 (0.041)	0.807 (0.043)	0.738 (0.052)*	0.595 (0.027)	0.544 (0.035)
2021	0.936 (0.029)	0.788 (0.073)	0.602 (0.029)*	0.487 (0.026)	0.456 (0.028)
Mean	**0.950 (0.010)**	**0.673 (0.026)**	**0.695 (0.037)**	**0.491 (0.034)**	**0.461 (0.033)**

* The estimates for 2020-2021 for the reach between McNary Dam and Bonneville Dam used a different method than in previous years.

Table 28. Annual survival probability estimates through the entire hydropower system, and through component river reaches for Snake River juvenile steelhead (wild fish only), 1993–2021. Standard errors in parentheses. Simple arithmetic means across all available years are given.

	Annual survival estimates for wild steelhead				
Year	Snake River Smolt Trap to Lower Granite Dam	Lower Granite to McNary Dam	McNary to Bonneville Dam	Lower Granite to Bonneville Dam	Trap to Bonneville Dam
1993	0.898 (0.009)	NA	NA	NA	NA
1994	0.844 (0.011)	NA	NA	NA	NA
1995	0.955 (0.013)	NA	NA	NA	NA
1996	0.973 (0.022)	NA	NA	NA	NA
1997	0.968 (0.051)	NA	NA	NA	NA
1998	0.919 (0.017)	0.698 (0.030)	NA	NA	NA
1999	0.910 (0.024)	0.746 (0.019)	0.634 (0.113)	0.473 (0.085)	0.430 (0.078)
2000	0.980 (0.027)	0.714 (0.028)	0.815 (0.102)	0.582 (0.076)	0.570 (0.076)
2001	0.958 (0.011)	0.168 (0.010)	0.209 (0.046)	0.035 (0.008)	0.034 (0.008)
2002	0.899 (0.023)	0.593 (0.039)	0.574 (0.097)	0.341 (0.062)	0.306 (0.056)
2003	0.893 (0.026)	0.597 (0.022)	0.500 (0.042)	0.299 (0.027)	0.267 (0.026)
2004	0.936 (0.007)	0.383 (0.029)	NA	NA	NA
2005	0.959 (0.008)	0.562 (0.046)	NA	NA	NA
2006	0.976 (0.036)	0.745 (0.040)	0.488 (0.170)	0.363 (0.128)	0.355 (0.125)
2007	1.050 (0.056)	0.730 (0.027)	0.524 (0.064)	0.383 (0.049)	0.402 (0.056)
2008	0.951 (0.029)	0.692 (0.029)	0.713 (0.093)	0.493 (0.068)	0.469 (0.066)
2009	0.981 (0.019)	0.763 (0.029)	0.727 (0.073)	0.555 (0.060)	0.544 (0.059)
2010	1.003 (0.049)	0.773 (0.041)	0.736 (0.110)	0.569 (0.090)	0.571 (0.095)
2011	0.983 (0.037)	0.730 (0.024)	0.660 (0.136)	0.482 (0.101)	0.474 (0.100)
2012	1.107 (0.070)	0.697 (0.047)	NA	NA	NA
2013	0.921 (0.057)	0.621 (0.055)	0.671 (0.142)	0.417 (0.096)	0.384 (0.091)

Table 28. Continued.

		Annual survival estimates for wild steelhead			
Year	Snake River Trap to Lower Granite Dam	Lower Granite to McNary Dam	McNary to Bonneville Dam	Lower Granite to Bonneville Dam	Trap to Bonneville Dam
2014	1.000 (0.047)	0.620 (0.034)	1.057 (0.144)	0.655 (0.096)	0.655 (0.101)
2015	0.867 (0.139)	0.741 (0.080)	0.608 (0.051)	0.451 (0.062)	0.390 (0.082)
2016	0.958 (0.037)	0.644 (0.053)	0.436 (0.043)	0.281 (0.036)	0.269 (0.036)
2017	NA	0.723 (0.039)	0.413 (0.058)	0.299 (0.045)	NA
2018	0.848 (0.060)	0.736 (0.075)	0.822 (0.136)	0.605 (0.118)	0.513 (0.106)
2019	0.973 (0.088)	0.771 (0.044)	0.640 (0.062)	0.493 (0.055)	0.480 (0.069)
2020	0.802 (0.109)[a]	NA	NA	NA	NA
2021	1.079 (0.141)[b]	0.624 (0.074)	0.605 (0.073)[c]	0.389 (0.037)	0.450 (0.079)
Mean	**0.950 (0.013)**	**0.655 (0.029)**	**0.623 (0.042)**	**0.430 (0.033)**	**0.420 (0.034)**

a. Based on a sample size of just 124 fish.

b. Based on a sample size of just 290 fish.

c. The estimate for 2021 for the reach between McNary Dam and Bonneville Dam used a different method than in previous years.

Sockeye Salmon—For pooled groups of wild and hatchery Snake River sockeye salmon, estimated survival from Lower Granite to McNary Dam was 0.817 in 2021 (95% CI 0.653-1.023; Table 29). This estimate was close to the 2020 estimate of 0.803 but substantially higher than the long-term average of 0.651 (1996-2021). The survival estimate from McNary to Bonneville Dam was 0.452 (0.339-0.603), which was well below the long-term average of 0.558. For these fish, estimated survival from Lower Granite to Bonneville Dam was 0.369 (0.308-0.442) in 2021. This estimate was slightly below the long-term average of 0.407.

Table 29. Annual survival probability estimates for juvenile Sockeye salmon (combined hatchery and wild fish) from Lower Granite Dam to Bonneville Dam for Snake River fish and from Rock Island Dam to Bonneville Dam for Columbia River fish, 1996-2021. Standard errors in parentheses. Simple arithmetic means across all available years are given.

	Annual survival estimates for Snake River Sockeye		
Year	Lower Granite to McNary Dam	McNary to Bonneville Dam	Lower Granite to Bonneville Dam
1996	0.283 (0.184)	NA	NA
1997	NA	NA	NA
1998	0.689 (0.157)	0.142 (0.099)	0.177 (0.090)
1999	0.655 (0.083)	0.841 (0.584)	0.548 (0.363)
2000	0.679 (0.110)	0.206 (0.110)	0.161 (0.080)
2001	0.205 (0.063)	0.105 (0.050)	0.022 (0.005)
2002	0.524 (0.062)	0.684 (0.432)	0.342 (0.212)
2003	0.669 (0.054)	0.551 (0.144)	0.405 (0.098)
2004	0.741 (0.254)	NA	NA
2005	0.388 (0.078)	NA	NA
2006	0.630 (0.083)	1.113 (0.652)	0.820 (0.454)
2007	0.679 (0.066)	0.259 (0.084)	0.272 (0.073)
2008	0.763 (0.103)	0.544 (0.262)	0.404 (0.179)
2009	0.749 (0.032)	0.765 (0.101)	0.573 (0.073)
2010	0.723 (0.039)	0.752 (0.098)	0.544 (0.077)
2011	0.659 (0.033)	NA	NA
2012	0.762 (0.032)	0.619 (0.084)	0.472 (0.062)
2013	0.691 (0.043)	0.776 (0.106)	0.536 (0.066)
2014	0.873 (0.054)	0.817 (0.115)	0.713 (0.110)
2015	0.702 (0.054)	0.531 (0.115)	0.373 (0.037)
2016	0.523 (0.047)	0.227 (0.059)	0.119 (0.030)
2017	0.544 (0.081)	0.324 (0.107)	0.176 (0.055)
2018	0.684 (0.061)	0.940 (0.151)	0.643 (0.088)
2019	0.836 (0.053)	0.520 (0.044)	0.434 (0.031)
2020	0.803 (0.111)	0.546 (0.149)	0.439 (0.104)
2021	0.817 (0.094)	0.452 (0.067)	0.369 (0.034)
Mean	**0.651 (0.033)**	**0.558 (0.060)**	**0.407 (0.045)**

Table 29. Continued.

	Annual survival estimates for upper Columbia River Sockeye		
	Rock Island to McNary Dam[a]	McNary to Bonneville Dam[b]	Rock Island to Bonneville Dam[a]
1996	NA	NA	NA
1997	0.397 (0.119)	NA	NA
1998	0.624 (0.058)	1.655 (1.617)	1.033 (1.003)
1999	0.559 (0.029)	0.683 (0.177)	0.382 (0.097)
2000	0.487 (0.114)	0.894 (0.867)	0.435 (0.410)
2001	0.657 (0.117)	NA	NA
2002	0.531 (0.044)	0.286 (0.110)	0.152 (0.057)
2003	NA	NA	NA
2004	0.648 (0.114)	1.246 (1.218)	0.808 (0.777)
2005	0.720 (0.140)	0.226 (0.209)	0.163 (0.147)
2006	0.793 (0.062)	0.767 (0.243)	0.608 (0.187)
2007	0.625 (0.046)	0.642 (0.296)	0.401 (0.183)
2008	0.644 (0.094)	0.679 (0.363)	0.437 (0.225)
2009	0.853 (0.076)	0.958 (0.405)	0.817 (0.338)
2010	0.778 (0.063)	0.627 (0.152)	0.488 (0.111)
2011	0.742 (0.088)	0.691 (0.676)	0.513 (0.498)
2012	0.945 (0.085)	0.840 (0.405)	0.794 (0.376)
2013	0.741 (0.068)	0.658 (0.217)	0.487 (0.155)
2014	0.428 (0.056)	0.565 (0.269)	0.242 (0.111)
2015	0.763 (0.182)	0.446 (0.200)	0.340 (0.130)
2016	0.807 (0.082)	0.545 (0.126)	0.448 (0.144)
2017	0.719 (0.113)	0.611 (0.181)	0.500 (0.332)
2018	0.927 (0.118)	0.560 (0.112)	0.344 (0.124)
2019	0.941 (0.125)	0.701 (0.120)	0.737 (0.191)
2020	0.910 (0.218)	0.288 (0.154)	0.352 (0.325)
2021	0.894 (0.227)	0.533 (0.180)	0.466 (0.169)
Mean	**0.714 (0.033)**	**0.686 (0.067)**	**0.498 (0.048)**

[a] Estimates in these columns use all fish tagged at Rock Island Dam.

[b] Estimates in this column use all fish tagged upstream from the Yakima River.

Upper Columbia River Stocks

Sockeye Salmon—For Upper Columbia River sockeye salmon captured, tagged, and released to the tailrace of Rock Island Dam in 2021, estimated survival to McNary Dam was 0.894 (95% CI 0.548-1.459; Table 29). This (highly imprecise) estimate was higher than the long-term average of 0.714 and similar to the 2020 estimate of 0.910. Estimated survival between McNary and Bonneville Dam for these fish was 0.533 (0.280-1.015), which, while very imprecise, was substantially below the long-term average of 0.686. Estimated survival of sockeye from Rock Island to Bonneville Dam in 2021 was 0.466 (0.234-0.928). This estimate was higher than the 2020 estimate of 0.352, but slightly lower than the long-term average of 0.498. However, this estimate was also very imprecise.

Yearling Chinook Salmon—For pooled groups of yearling Chinook from Upper Columbia River hatcheries, estimated survival in 2021 from McNary to Bonneville Dam was 0.624 (95% CI 0.528-0.737), significantly below the 1999-2021 average of 0.802 ($P = 0.002$; Table 30).

Steelhead—For pooled groups of hatchery steelhead from Upper Columbia hatcheries, estimated survival from McNary to Bonneville Dam in 2021 was 0.564 (95% CI 0.474-0.671). This estimate was also significantly below the long-term average of 0.752 ($P = 0.003$; Table 30).

Table 30. Annual survival probability estimates from release to Bonneville Dam for upper Columbia River yearling Chinook salmon and juvenile steelhead (hatchery-origin only), 1999-2021. Multiple release sites were used in each year, and sites were not the same in all years. Standard errors in parentheses. Simple arithmetic means across all available years are given.

Annual survival estimates upper Columbia River				
Year	Release site to McNary Dam	McNary to John Day Dam	John Day to Bonneville Dam	McNary to Bonneville Dam
	Hatchery yearling Chinook salmon			
1999	0.572 (0.014)	0.896 (0.044)	0.795 (0.129)	0.712 (0.113)
2000	0.539 (0.025)	0.781 (0.094)	NA	NA
2001	0.428 (0.009)	0.881 (0.062)	NA	NA
2002	0.555 (0.003)	0.870 (0.011)	0.940 (0.048)	0.817 (0.041)
2003	0.625 (0.003)	0.900 (0.008)	0.977 (0.035)	0.879 (0.031)
2004	0.507 (0.005)	0.812 (0.019)	0.761 (0.049)	0.618 (0.038)
2005	0.545 (0.012)	0.751 (0.042)	NA	NA
2006	0.520 (0.011)	0.954 (0.051)	0.914 (0.211)	0.871 (0.198)
2007	0.584 (0.009)	0.895 (0.028)	0.816 (0.091)	0.730 (0.080)
2008	0.582 (0.019)	1.200 (0.085)	0.522 (0.114)	0.626 (0.133)
2009	0.523 (0.013)	0.847 (0.044)	1.056 (0.143)	0.895 (0.116)
2010	0.660 (0.014)	0.924 (0.040)	0.796 (0.046)	0.735 (0.037)
2011	0.534 (0.010)	1.042 (0.047)	0.612 (0.077)	0.637 (0.077)
2012	0.576 (0.012)	0.836 (0.035)	1.140 (0.142)	0.953 (0.115)
2013	0.555 (0.013)	0.965 (0.050)	1.095 (0.129)	1.056 (0.117)
2014	0.571 (0.013)	0.974 (0.047)	0.958 (0.122)	0.933 (0.114)
2015	0.512 (0.015)	0.843 (0.043)	1.032 (0.081)	0.870 (0.062)
2016	0.610 (0.009)	0.857 (0.027)	0.942 (0.068)	0.807 (0.055)
2017	0.582 (0.013)	0.853 (0.030)	1.107 (0.142)	0.944 (0.120)
2018	0.608 (0.016)	0.914 (0.044)	0.820 (0.096)	0.749 (0.084)
2019	0.506 (0.018)	0.853 (0.042)	0.920 (0.066)	0.785 (0.056)
2020	0.629 (0.025)	0.867 (0.045)	0.922 (0.094)	0.800 (0.083)
2021	0.529 (0.028)	0.807 (0.066)	0.773 (0.071)	0.624 (0.053)
Mean	**0.559 (0.011)**	**0.892 (0.020)**	**0.895 (0.036)**	**0.802 (0.028)**

Table 30. Continued.

Year	Release site to McNary Dam	McNary to John Day Dam	John Day to Bonneville Dam	McNary to Bonneville Dam
	Annual survival estimates upper Columbia River			
	Hatchery steelhead			
2003	0.471 (0.004)	0.997 (0.012)	0.874 (0.036)	0.871 (0.036)
2004	0.384 (0.005)	0.794 (0.021)	1.037 (0.112)	0.823 (0.088)
2005	0.399 (0.004)	0.815 (0.017)	0.827 (0.071)	0.674 (0.057)
2006	0.397 (0.008)	0.797 (0.026)	0.920 (0.169)	0.733 (0.134)
2007	0.426 (0.016)	0.944 (0.064)	0.622 (0.068)	0.587 (0.059)
2008	0.438 (0.015)	NA	NA	NA
2009	0.484 (0.018)	0.809 (0.048)	0.935 (0.133)	0.756 (0.105)
2010	0.512 (0.017)	0.996 (0.054)	0.628 (0.038)	0.626 (0.033)
2011	0.435 (0.012)	1.201 (0.064)	0.542 (0.101)	0.651 (0.119)
2012	0.281 (0.011)	0.862 (0.047)	1.240 (0.186)	1.069 (0.159)
2013	0.384 (0.020)	0.957 (0.071)	0.974 (0.104)	0.932 (0.099)
2014	0.468 (0.043)	0.883 (0.124)	0.807 (0.153)	0.712 (0.130)
2015	0.351 (0.019)	0.807 (0.084)	0.707 (0.073)	0.570 (0.043)
2016	0.416 (0.011)	0.771 (0.037)	0.633 (0.046)	0.487 (0.032)
2017	0.437 (0.025)	0.880 (0.062)	1.095 (0.210)	0.964 (0.188)
2018	0.416 (0.021)	0.942 (0.062)	1.232 (0.194)	1.161 (0.186)
2019	0.342 (0.016)	0.812 (0.048)	0.746 (0.054)	0.606 (0.047)
2020	0.420 (0.035)	0.879 (0.082)	0.859 (0.084)	0.756 (0.092)
2021	0.324 (0.025)	0.854 (0.100)	0.661 (0.066)	0.564 (0.050)
Mean	**0.410 (0.013)**	**0.889 (0.025)**	**0.852 (0.049)**	**0.752 (0.044)**

Detection Probabilities

Based on our estimates, the probability of detection for PIT-tagged juvenile Chinook salmon in 2021 was extremely low at most dams on the Snake and Columbia Rivers (Figure 8). Detection probability was even lower than in 2020 at Little Goose and Lower Monumental Dam, setting a new record low at those dams.

Detection probabilities were also the lowest ever at John Day and extremely low at McNary Dam in 2021, continuing a trend of declining detection over the past few years (Figure 8). Detection probability at Bonneville Dam has not trended in any consistent direction and in 2021 was near average. The stability of detection probability at Bonneville Dam was likely due to the fact that the dam has detection capability in both the juvenile bypass system and corner collector at Powerhouse Two.

In contrast to the other dams, detection probability was high at Lower Granite Dam in 2021 (Figure 8) as a result of the spillway detection system at that site. Detection in the bypass system at Lower Granite Dam was less than 10% in 2021. Had the bypass system been the only detection site at Lower Granite, as it is at all other dams besides Bonneville, detection probability would have been extremely low in 2021.

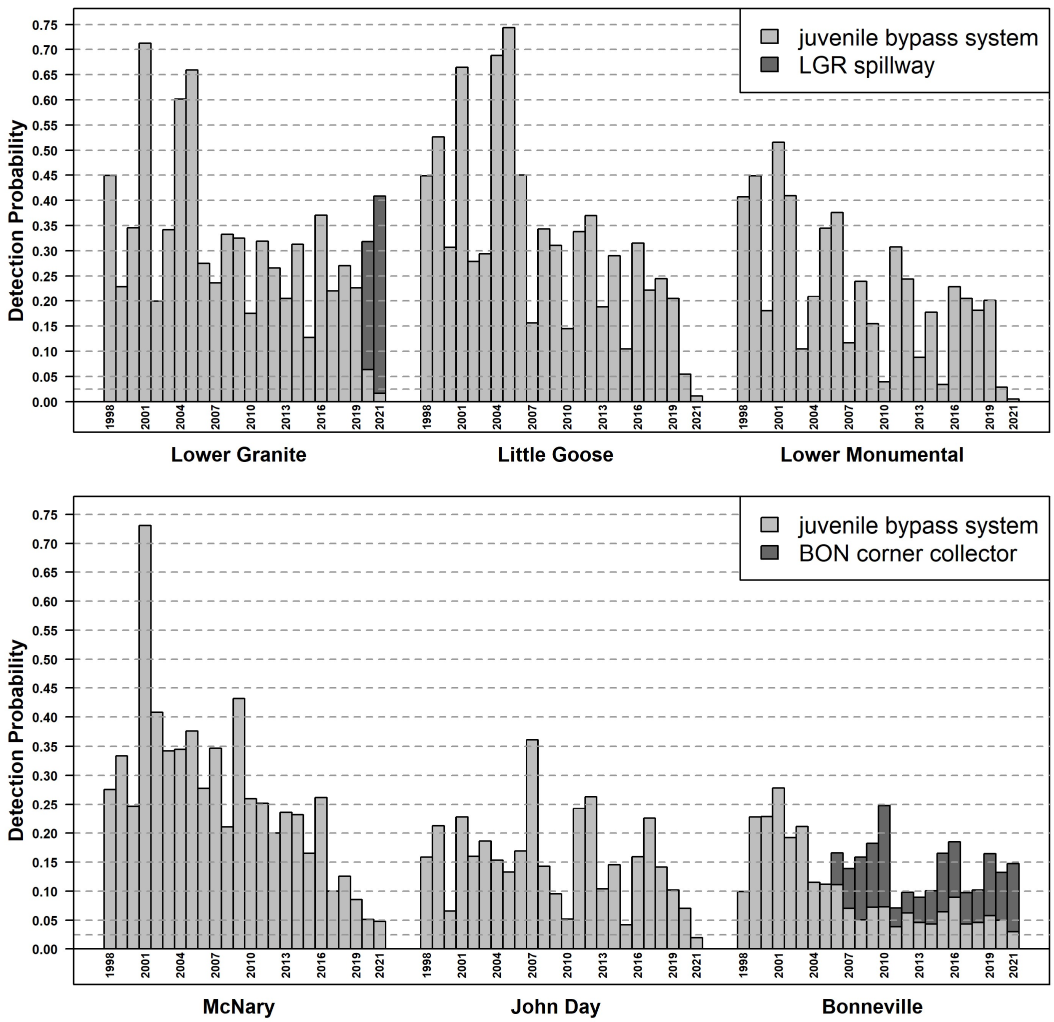

Figure 8. Annual mean detection probability for Snake River yearling Chinook salmon at six major dams on the Snake and Columbia Rivers, 2000-2021. Ice Harbor Dam was excluded because of persistent very low juvenile detection probabilities.

Comparison Between Snake and Columbia River Stocks

In 2021, estimated survival from McNary to Bonneville Dam was higher for hatchery and wild yearling Chinook originating in the Snake River (0.746; 95% CI 0.526-0.966; Table 31) than for those originating in the Upper Columbia River Basin (0.615; 0.515-0.715), but the difference was not statistically significant ($P = 0.29$).

For combined hatchery and wild steelhead migrating from McNary to Bonneville during 2021, estimated survival for Snake River fish was 0.602 (0.545-0.659; Table 31). This was slightly higher than the survival estimate for Upper Columbia River fish (0.554; 0.464-0.644), but the difference was not statistically significant ($P = 0.38$).

For hatchery and wild sockeye, estimated survival from McNary to Bonneville was lower for stocks originating in the Snake (0.452; 0.339-0.603; Table 31) than in the Upper Columbia River Basin (0.533; 0.280-1.015). However, both estimates were very imprecise, and the difference was not statistically significant ($P = 0.65$).

Table 31. Annual survival probability estimates from McNary to Bonneville Dam for various spring-migrating salmonid stocks (hatchery and wild combined) in 2021. In shaded rows, the annual estimates are weighted means of estimates for biweekly groups. In all other rows, all release cohorts were pooled into a single group for the annual estimate. Release numbers for pooled cohorts are from points upstream of McNary Dam. All Chinook salmon are spring/summer run. Standard errors in parentheses.

			Estimated survival (SE)		
Stock	Release location	Number released	McNary to John Day Dam	John Day to Bonneville Dam	McNary to Bonneville Dam
Snake River Chinook	Lower Granite Dam tailrace	102,424	0.960 (0.077)	0.796 (0.096)	0.746 (0.112)
Upper Columbia Chinook	Upper Columbia sites[a]	231,543	0.811 (0.065)	0.758 (0.068)	0.615 (0.051)
Upper Columbia Chinook	Yakima River sites[b]	79,329	0.675 (0.099)	0.657 (0.129)	0.443 (0.084)
Upper Columbia Coho	Upper Columbia sites[a]	37,446	0.966 (0.161)	0.741 (0.127)	0.716 (0.105)
Upper Columbia Coho	Yakima River sites[b]	11,907	0.849 (0.216)	1.237 (0.452)	1.050 (0.359)
Snake River Sockeye	Snake River sites[c]	51,720	1.041 (0.252)	0.434 (0.101)	0.452 (0.067)
Upper Columbia Sockeye	Upper Columbia sites[a]	10,124	1.469 (0.576)	0.363 (0.159)	0.533 (0.180)
Snake River Steelhead	Lower Granite Dam tailrace	117,028	0.757 (0.071)	0.795 (0.029)	0.602 (0.029)
Upper Columbia Steelhead	Upper Columbia sites[a]	98,247	0.801 (0.087)	0.691 (0.064)	0.554 (0.046)

[a] Any release site on the Columbia River or its tributaries upstream from confluence with the Yakima River.
[b] Any release site on the Yakima River or its tributaries.
[c] Any release site on the Snake River or its tributaries upstream from Lower Granite Dam.

Discussion

The work of NOAA Fisheries and other agencies was affected in 2021 by restrictions related to the COVID-19 pandemic. Both the tagging program at Lower Granite Dam and the Columbia River estuary trawl detection system were operated at reduced capacity. The number of tagging personnel was cut by about half, which contributed to a substantial reduction in numbers of fish tagged at Lower Granite Dam compared to past study years (Table 32). The estuary trawl also operated at half capacity, with a reduction in sampling hours of about 50%. Consequently, there were smaller sample sizes available at Lower Granite Dam and lower detection rates below Bonneville Dam. Small sample sizes increased the difficulty of survival estimation in 2021.

Extremely high spill levels combined with low flows in 2021 resulted in extremely low proportions of fish passing via the juvenile bypass systems. Consequentially, there were extraordinarily low detection rates in bypass systems. Very few fish were detected in the bypass system at Lower Granite Dam, and this impacted sample sizes for survival estimates at all downstream sites (Table 32). Low numbers of fish passing via the bypass system also exacerbated the difficulty of tagging operations. On some days, not enough fish were collected to fulfill even the reduced tagging capacity.

However, the large number of fish detected by the spillway detection system at Lower Granite Dam helped compensate for both the low numbers of fish tagged and the very low numbers of fish detected in the juvenile bypass system. The spillway system was installed during winter 2019-2020, and 2021 was its second year of operation. A total of 101,148 yearling Chinook and 91,019 steelhead were detected by the spillway system during the 2021 migration season (Table 32). Of the more than 200,000 smolts used for survival estimation starting at Lower Granite Dam, 85% were detected in the spillway system, 11% were tagged after collection in the bypass system, and just 4% were detected in the bypass system.

Since its installation at the dam, systematic testing has not yet been done to quantify detection efficiency of the spillway detection system (percentage of fish passing that are detected). However, a formal study of spillway system detection efficiency is planned for spring 2022.

Table 32. Total number of PIT-tagged hatchery and wild yearling Chinook salmon and juvenile steelhead used for survival probability estimates from Lower Granite Dam, 2010-2021. Fish are categorized by location of detection or tagging. Only smolts returned to the river after detection or tagging are included.

	Smolt numbers at Lower Granite Dam (n)							
	Detected in spillway system		Detected in juvenile bypass system		Tagged in juvenile bypass system		Total	
Year	Hatchery	Wild	Hatchery	Wild	Hatchery	Wild	Hatchery	Wild
				Yearling Chinook salmon				
2010	-	-	35,402	12,411	47,902	17,008	83,304	29,419
2011	-	-	70,206	17,495	47	16,029	70,253	33,524
2012	-	-	51,282	12,831	46	16,749	51,328	29,580
2013	-	-	43,617	8,550	13	11,773	43,630	20,323
2014	-	-	69,152	15,502	76	17,917	69,228	33,419
2015	-	-	26,210	3,465	33	8,300	26,243	11,765
2016	-	-	87,431	11,964	85	22,145	87,516	34,109
2017	-	-	45,355	8,158	10	14,241	45,365	22,399
2018	-	-	54,989	9,409	0	11,823	54,989	21,232
2019	-	-	38,961	6,376	14	6,349	38,975	12,725
2020	60,290	5,344	14,106	2,295	0	0	74,396	7,639
2021	94,298	6,850	3,768	600	57	1,770	98,123	9,220
				Steelhead				
2010	-	-	33,171	5,035	16,173	11,991	49,344	17,026
2011	-	-	60,961	5,350	22,011	18,001	82,972	23,351
2012	-	-	45,350	7,438	20,121	20,122	65,471	27,560
2013	-	-	29,420	5,400	17,380	7,457	46,800	12,857
2014	-	-	42,082	6,823	20,593	14,493	62,675	21,316
2015	-	-	14,626	1,578	25,278	17,065	39,904	18,643
2016	-	-	55,467	5,625	17,972	14,774	73,439	20,399
2017	-	-	42,253	3,619	22,049	18,422	64,302	22,041
2018	-	-	47,465	5,699	20,249	15,396	67,714	21,095
2019	-	-	47,919	4,249	20,888	14,758	68,807	19,007
2020	60,090	3,442	9,899	1,161	0	0	69,989	4,603
2021	83,846	7,173	4,756	476	18,120	4,854	106,722	12,503

Unfortunately, even with the spillway detection system, sample sizes for both wild Chinook and wild steelhead were well below average in 2021 (Table 32). The shortage of data for wild smolts severely impacted the quality of survival estimates for both stocks.

Using the single-release-model, detection information downstream of Bonneville Dam is required to estimate survival to Bonneville. In 2020 restrictions related to the COVID-19 pandemic caused a complete suspension of estuary detection trawl operations. This suspension resulted in a severe shortage of detection data available below Bonneville Dam in 2020. Therefore, we used alternative sources of detection information below Bonneville Dam in lieu of detection data from the estuary trawl.

The estuary trawl resumed operation in 2021. However, considering the positive results of using alternate data sources for survival estimation in 2020, we decided to continue using these data sources in addition to data from the trawl. For 2021, we identified three sources of evidence that a PIT-tagged smolt had been alive in the tailrace of Bonneville Dam after passing the dam:

1) Tags detected by the estuary trawl
2) Tags deposited by avian predators on colonies in the Columbia River estuary, on the Astoria-Megler Bridge, and at other miscellaneous locations in the estuary
3) Detections of juvenile fish in the adult fish ladder at Bonneville Dam. Some precocious juveniles pass Bonneville Dam in the downstream direction and then forego ocean rearing, instead ascending the ladder to undertake a spawning migration. This behavior is far more common in yearling Chinook than in other species, and such fish are known as "mini-jacks."

We used all of these data sources in 2021 (Table 33), combining all available detections from the three sites below Bonneville Dam into an effective single "final detection site" for survival estimation using the single-release model.

Low detection probabilities resulting from high spill also required use of an alternative method to estimate survival downstream from McNary Dam. Rather than our customary regrouping of fish based on release or detection date at McNary, we followed cohorts defined at Lower Granite Dam throughout the entire hydropower system to Bonneville Dam and the estuary (see methods in *Survival from Release to Bonneville Dam*).

Table 33. Number of PIT tags detected or recovered at various locations downstream from Bonneville Dam, 2021. Only tags that contributed to one or more of the survival estimates in this report are included in this table. That is, these counts do not include tags from stocks for which we do not report survival or tags recovered from avian sites that were from previous smolt migration years.

	Tags detected or recovered in 2021 (n)			
Site	Yearling Chinook	Steelhead	Coho	Sockeye
Columbia River estuary trawl	1,166	1,979	142	199
East Sand Island*	1,031	2,761	126	91
Rice Island*	0	0	0	0
Miller Sands Island*	10	9	1	0
Astoria-Megler Bridge*	647	381	53	65
Bonneville Dam adult ladders	1,524	44	152	1
Total	**4,378**	**5,174**	**474**	**356**

* An avian nesting, loafing, and/or roosting site.

Overall, the use of a combination of alternative methods and data sources introduced a new variable when comparing results from 2020-2021 with those from the time series of smolt migration years prior to 2020. We are conducting a reanalysis of historical data that applies the new approaches used in 2020 and 2021 where possible. We are also investigating consequences of shifting the primary data source at Lower Granite Dam from fish that passed via the juvenile bypass system to fish that passed via the spillway.

Preliminary findings from these investigations have given us no reason to suspect that the alternative methods and data sources used in 2020 and 2021 resulted in systematic bias in estimates. We have found that for a subset of past migration years, the addition of avian-recovery data to sample data from the trawl resulted in higher estimates of survival to Bonneville Dam for yearling Chinook. However, these increases were small, and there was no such systematic effect for steelhead. These investigations are ongoing, and results will be published after completion.

In 2021, the addition of avian-recovery data from the estuary had a greater impact on resulting survival estimates than typical in previous years. We published a memo of preliminary survival estimates on 7 October 2021; many of the estimates published here differ substantially from those published in the memo. Reasons for these differences generally fell into two categories: 1) addition of avian-recovery data directly altered the estimate, or 2) addition of avian-recovery data made possible the use of a preferred estimation method, which was otherwise not available. In the second case, there were differences both in the data used and in the assumptions made. We do not address the details of these differences here, but we can report that very small and variable detection probabilities across the season likely amplified the effect of changes in data and/or methods. We will investigate these matters in the coming months.

In addition to investigating modified methods for traditional CJS survival estimation, we have also been developing and investigating the use of Bayesian formulations of the CJS model. A Bayesian approach to CJS offers several advantages over the traditional frequentist approach, including improvements in precision and in the ability to incorporate additional avian-recovery data from the interior Columbia River Basin. Both of these advantages could be of great value in the current regime of limited detection data.

Appendix D presents an overview and summary of our current investigations into Bayesian CJS modeling, both with and without avian-recovery data from the interior basin. Once these investigations are complete and the Bayesian methods are mature, we intend to employ them in future years of this study.

We observed below-average survival in the reach from McNary to Bonneville Dam for most stocks. Among Snake River stocks, combined hatchery and wild steelhead, wild Chinook, and sockeye all had below-average survival. Among stocks originating in the upper Columbia River, hatchery and wild Chinook, hatchery and wild steelhead, and sockeye all had below-average survival. Some estimates from 2021 were significantly lower than the corresponding long-term mean, while in other cases, poor precision meant we could not be certain about any individual estimate. Nevertheless, low survival of multiple stocks in the McNary-to-Bonneville reach was noteworthy.

Survival upstream from Lower Granite Dam was average or above average in 2021 for most stocks of hatchery Chinook and steelhead and for Chinook and steelhead from most smolt traps (Table 22). The notable exception was yearling Chinook salmon reared at Pahsimeroi Hatchery. These fish displayed extremely poor survival in 2021.

An outbreak of bacterial kidney disease (BKD) occurred at the hatchery in 2021 (Trevor Conder, pers. comm. 2021). Bacterial kidney disease is highly transmissible and known to cause high mortality rates in salmonids (Fryer and Sanders 1981). This BKD outbreak was likely responsible for the poor survival of Pahsimeroi Hatchery smolts in 2021. A similar outbreak occurred at the same hatchery in 2019, which resulted in similar low survival estimates that year.

We have observed a steep decline in the number of Chinook captured and tagged at the Snake River Smolt Trap in recent years. In 2021, a mere 27 wild Chinook smolts were tagged, and we were unable to generate a survival estimate for wild Chinook between the trap and Lower Granite Dam. The number of hatchery Chinook smolts tagged at the trap has also declined significantly, with only 528 tagged there in 2021.

We were able to estimate survival to Lower Granite for hatchery Chinook tagged at the Snake River Trap, but the small sample size impacted the precision of the estimate. If the number of Chinook captured at the trap declines any further, it will call into question the representativeness of the sample, and we may lose the ability to monitor survival through the Lower Granite project for Chinook salmon.

Environmental conditions and management actions in 2021 resulted in a migration season with water temperatures that were slightly warmer than average, flows that were very low, and spill proportions that were extremely high (Appendix Figures C1-C2). Mean flow in the Snake River was far below average for nearly the whole season. Daily water temperature values were consistently about one degree above average for much of the season.

Spill discharge levels, in terms of absolute volume, were about average in 2021. However, because flow volumes were low, spill percentages were extremely high for the entire migration season. Percent spill was the highest on record at lower Snake River dams as well as at John Day and Bonneville Dam. While not record-setting, spill percentages were also very high at McNary Dam.

These high spill proportions were the result of a management program that began in 2020, known as *Flexible Spill Operation*. This program uses 16 h of high spill each day, which is intended to decrease travel time and increase survival of smolts during their downstream migration. These 16 h are combined with two, 4-h periods of reduced spill, which are intended to aid adult upstream passage and allow increased power generation.

To accommodate the new spill program, in 2020 the limit on total dissolved gas (TDG) was increased from 120 to 125% saturation in the tailrace (BPA 2020). This higher limit allowed a much higher proportion of flow to be spilled during hours of peak spill (typically 60-90% of total flow at the dams). During hours of reduced spill, typical spill proportions were 25-45%.

In 2021, these very high spill percentages did not result in above-average levels of TDG, because TDG is most directly affected by spill volume rather than spill percent. Low flow levels in the Snake and Columbia Rivers resulted in spill volumes that were mostly average, and thus levels of TDG were also average at most dams. Daily average TDG values were generally below 120% at both Snake and Columbia River dams for most of the migration season (Appendix Figures C3, C10-C11).

Hourly TDG levels can vary widely within a day due to the *Flexible Spill Operations* program; therefore, daily average TDG values do not reflect the maximum exposure experienced by fish. During the juvenile salmonid migration period, TDG levels were at or above 115% between 53-100% of the time depending on the dam, and above 120% for 0-25% of the time (Table 34). Hourly TDG levels only exceeded 125% briefly below John Day Dam and did not exceed that level at any other site.

Table 34. Summary of total dissolved gas (TDG) levels from monitors below dams in 2021. Measurements include the period of 3 April-15 June at Snake River dams and 10 April-15 June at Columbia River dams. Numbers derived from hourly records. Gas dissipates with distance from the dam, so measurements can depend on monitor location, and all are less than the maximum TDG produced in the immediate tailrace. Distance (km) downstream from the respective tailrace is given for each monitor.

Dam	Distance from tailrace (km)	Total dissolved gas (%) Mean	Max	Percentage (%) of hours with TDG ≥ 115%	≥ 120%	≥ 125%
Snake River (3 April-15 June)						
Lower Granite	1.3	116.0	123.6	65.5	14.0	0.0
Little Goose	1.1	118.5	124.5	95.6	25.2	0.0
Lower Monumental	1.6	116.1	122.8	60.0	6.9	0.0
Ice Harbor	5.8	114.7	118.3	52.8	0.0	0.0
Columbia River (10 April-15 June)						
McNary	2.1	117.1	124.9	91.3	5.7	0.0
John Day	1.3	117.3	125.7	82.5	9.6	0.7
The Dalles	4.0	118.0	122.8	95.5	20.1	0.0
Bonneville	0.4	118.6	122.0	99.9	20.6	0.0

Exposure of fish to high levels of TDG can cause gas bubble trauma (GBT, also known as gas bubble disease), which can result in injury and death (Bouk 1980; Weitkamp and Katz 1980). The disease manifests as bubbles in tissues and blood and affects the eyes, fins, lateral line, body surface, gills, heart, and other internal organs. It can lead to death directly, through physiological mechanisms, or indirectly, through increased susceptibility to pathogens or to predation due to impaired senses and reduced swimming ability. Severity of gas bubble trauma depends on absolute TDG levels and on duration of exposure, temperature, depth, and fish size.

Levels of TDG decrease with increasing depth in the water column, so fish can reduce exposure by swimming deeper. Laboratory researchers examined the effects of TDG supersaturation on yearling Chinook and juvenile steelhead in shallow tanks (0.25 m), assessing the formation of gas bubble trauma and resulting mortality (Dawley and Ebel 1975). They found that exposure to 120% TDG for 1.5 d resulted in over 50% mortality, and mortality was 100% within 3 d for both species. At 115% TDG, steelhead reached 10% mortality in 10 d and 50% mortality in 20 d, while Chinook reached 7% mortality after 33 d.

Dawley et al. (1976) performed a similar experiment with subyearling Chinook and juvenile steelhead exposed to TDG levels ranging 100-127%. In addition to shallow tanks, deeper tanks (2.5 m) were used to allow for depth compensation by fish. They found that the average depth occupied by fish within the deep tanks increased with increasing TDG. They also found that time to 25% mortality of fall Chinook in deep tanks was comparable to that in shallow tanks with approximately 10% lower TDG. However, mortality was still substantial in deep tanks at 127% TDG, with subyearling Chinook having approximately 12% mortality and steelhead having 25% mortality at 7 d.

Beeman and Maule (2006) studied the migration depth of radio-tagged yearling Chinook and steelhead smolts between Ice Harbor and McNary Dam during 1997-1999. They found that mean depths of steelhead ranged from 2.0 m in the Snake River portion of the study area to 2.3 m in McNary Dam forebay, while mean depths of yearling Chinook ranged from 1.5 m in the Snake River to 3.2 m near McNary. Mean TDG at the monitor downstream from Ice Harbor Dam was 114-133% during the study period.

Beeman and Maule (2006) concluded that TDG was an important predictor of migration depth for both species, though the relationship differed. For steelhead, mean migration depth increased by 0.3 m with each 10% increase in TDG, while mean depth actually decreased for Chinook by 0.2 m for every 10% increase in TDG. Despite these differences, they concluded that fish migrating in the hydropower system likely use depth to compensate for increased TDG.

We do not know how TDG affected fish survival in 2021. Levels of TDG in 2021 were generally lower than in many recent years. However, with levels of TDG sustained at over 115% in many reaches for a majority of the migration period, it is not inconceivable that exposure to TDG affected fish. It seems unlikely that the low survival rates we found in the McNary to Bonneville reach in 2021 were the result of direct mortality due to TDG, but effects of sustained TDG exposure, in combination with higher temperatures, may have left some fish more susceptible to predation pressures.

Another possible explanation for poor survival estimates of salmonids in the lower Columbia River is predation by piscivorous fish. Several species of piscivorous fish reside in Snake and Columbia River reservoirs, including northern pikeminnow *Ptychocheilus oregonensis*, walleye *Sander vitreus*, and smallmouth bass *Micropterus dolomieu*.

Northern pikeminnow is the focus of a predator control program that has operated in the Columbia River Basin since 1991 with the objective of reducing predation on salmonid smolts. Since inception of the program, indices of both northern pikeminnow abundance and consumption of juvenile salmon have decreased (Porter 2012; Storch et al. 2014). We have no evidence that this pattern changed in 2021. No predator control program currently exists for walleye or smallmouth bass, but restrictions on recreational fishing, such as bag limits and size limits, were relaxed in 2017.

The population of smallmouth bass in Snake River reservoirs does not appear to have changed in a consistent direction (Table 35; Erhardt et al. 2018). Collection counts at Snake River dams have not been trending in any particular direction in recent years; however, the number of smallmouth bass seen in the bypass at Lower Granite Dam in 2021 was the highest ever observed.

Erhardt et al. (2018) noted that Chinook yearlings are less vulnerable to smallmouth bass predation than subyearlings because yearlings are larger and migrate when the river is cooler. However, Erhardt et al. also found that yearling Chinook were the most common prey item in the stomachs of large smallmouth bass in April. Storch et al. (2014) estimated that spring indices of smallmouth bass predation on salmonids generally increased over the period 1991-2013.

Walleye density and predation rates on juvenile salmon have not been estimated with confidence in the Snake River (Storch et al. 2014), but collection counts of walleye have increased since 2013 (Table 35). In particular, record numbers of walleye were seen in the bypass of both Little Goose and Lower Monumental Dams in 2021.

Table 35. Collection counts of notable incidental species at the juvenile fish bypass facilities of Snake River dams. Counts shown are from the expanded sample plus the total number of individuals observed in the separator. Data from U.S. Army Corps of Engineers Juvenile Fish Collection and Bypass reports. Abbreviation LMN = Lower Monumental Dam.

	Number of individuals seen in juvenile bypass systems at three Snake River dams (n)								
	Smallmouth bass			Walleye			Siberian prawn		
Year	Lower Granite	Little Goose	LMN	Lower Granite	Little Goose	LMN	Lower Granite	Little Goose	LMN
2008	-	15,503	-	-	32	-	-	5,213	-
2009	-	5,092	-	-	19	-	-	6,327	-
2010	1,024	4,150	12,171	0	20	10	11,711	38,676	8,599
2011	682	3,691	393	1	8	19	3,400	15,743	2,818
2012	620	2,442	10,984	1	7	8	3,831	23,183	2,219
2013	445	1,279	428	0	9	9	6,634	45,015	12,969
2014	2,037	3,528	1,457	0	14	92	9,839	81,310	18,388
2015	2,160	2,102	779	1	27	337	20,979	464,586	48,243
2016	4,819	2,992	848	3	65	608	25,848	51,518	10,527
2017	1,604	8,977	1,764	1	110	733	4,148	31,668	9,020
2018	3,625	2,939	1,046	5	170	352	43,434	11,159	1,557
2019	7,781	4,896	1,053	13	101	656	71,565	36,217	2,182
2020	3,037	1,922	-	5	137	-	145,030	87,409	-
2021	15,380	5,933	782	14	743	859	1,179,365	131,109	8,461

These observations suggest the possibility that juvenile salmonids faced increased predation from smallmouth bass and walleye in Snake River reservoirs in 2021, but whether similar patterns are occurring in Columbia River reservoirs is not clear. Smallmouth bass, northern pikeminnow, and walleye are all known to be abundant in McNary and John Day reservoirs (Rieman et al. 1991; Tabor et al. 1993), but recent data on the populations of these predator fish are not available.

Wild smolts are smaller than their hatchery counterparts, which increases their vulnerability to gape-limited predators such as piscivorous fish. However, wild Chinook yearlings are still substantially larger than wild subyearlings, and piscivorous fish in Columbia River reservoirs have been demonstrated to prey primarily on subyearlings (Rieman et al. 1991; Tabor et al. 1993). Predation by piscivorous fish may have been a factor in the below-average survival we found for wild Snake River Chinook in 2021.

Without current data on piscivorous predator populations in the Columbia River, we cannot be certain if the low survival we found for various lower Columbia River stocks was related to piscivorous fish predation. However, environmental conditions in the Snake and Columbia Rivers likely led to increased predation from piscivorous fish in 2021. Warmer-than-average water temperatures increase the metabolic rate and predator activity of piscivorous fish. Low flows and low turbidity increase the vulnerability of prey fish to visual predators (Gregory and Levings 1998). All three of these factors came into play during 2021, when both the Snake and Columbia Rivers had a combination of warm temperatures, low flows, and low turbidity.

Fish are not the only taxa that prey upon migrating smolts. Avian piscivores are abundant along the Columbia River below its confluence with the Snake, and their populations and consumption rates have been intensively monitored (Collis et al. 2002; Ryan et al. 2001, 2003; Roby et al. 2008, 2021; Evans et al. 2012; Collis et al. 2020).

In Lake Wallula (McNary Dam reservoir), Crescent Island recently harbored the second largest Caspian tern *Hydroprogne caspia* colony in North America, with an annual average of about 500 breeding pairs from 2000 through 2014. Other avian piscivores in this area include large populations of gulls *Larus* spp, the American white pelican *Pelecanus erythrorhynchos,* double-crested cormorant *Phalacrocorax auritus*, great egret *Ardea alba*, and the herons *A. herodias* and *Nycticorax nycticorax.*

Starting in 2014 and continuing through 2021, passive and active dissuasion measures were employed on the Crescent Island Caspian tern colony. These efforts have resulted in elimination of nesting at Crescent Island since 2015. However, terns displaced from this colony have attempted to relocate or join other colonies within the mid-Columbia Basin.

Thus, since the start of tern management in 2014, the total number of breeding pairs in the Columbia Plateau region has declined, but not to levels that meet the goal set by regional managers. The combined population size of Caspian tern colonies in the Columbia Plateau region was estimated at about 400 breeding pairs in 2021, which was slightly lower than the 2014-2021 average (Evans et al. 2021).

Consumption rates of Caspian terns on Upper Columbia steelhead were estimated at a moderate rate of ~6.2% across all colonies by Evans et al (2021). Their estimated predation rates on Snake River steelhead were much lower, totaling just over 1.5%. Predation rates on spring Chinook were lower still, with estimates of ~0.8% for Snake River fish and ~0.5% for upper Columbia River fish (Evans et al. 2021).

In addition to Caspian terns, a number of other piscivorous bird colonies were observed in the mid-Columbia Basin in 2021. Several large colonies of gulls were seen in the Blalock Islands complex in John Day reservoir; at Miller Rocks in The Dalles reservoir; at Crescent and Badger Islands in McNary Reservoir; and on Island 20 in the Hanford reach. In McNary Reservoir, a sizable colony of double-crested cormorants was observed on Foundation Island, and a colony of American white pelican was observed on Badger Island (Evans et al. 2021).

All five of the large gull colonies were estimated to have had substantial predation rates on both Snake River and upper Columbia River steelhead, varying from 2.8 to 13.9% per colony. Gull predation rates on Snake River spring Chinook were much lower, but not negligible, varying from 0.5 to 1.9% per colony. The cormorant colony on Foundation Island was estimated to have substantial predation rates of 4.4% on Snake River spring Chinook and 3.0% on Snake River steelhead, but much lower predation on other stocks. The pelican colony on Badger Island was found to have predation rates of 1% for Snake River steelhead and 0.4% for upper Columbia steelhead, but very low predation rates on Chinook stocks. It was not possible to estimate avian predation rates on sockeye in 2021 (Evans et al. 2021).

Environmental conditions also increased the vulnerability of salmonid smolts to avian predation in 2021, as the year was characterized by low flow, high temperature, and low turbidity, which have all been found to be associated with higher bird predation rates (Hostetter et al. 2012; Payton et al. 2016; Hostetter et al. 2021). These mid-Columbia River avian predators almost certainly contributed to the low survival estimated for some steelhead stocks in the lower Columbia River in 2021, and they may have contributed to low survival for sockeye as well.

However, it is less certain whether avian predation was a major contributor to the below-average survival estimated for wild Chinook in 2021. Avian predation rates on yearling Chinook salmon smolts are considerably lower than on steelhead (Evans et al. 2012; Hostetter et al. 2012; Evans et al. 2021, draft report). The combined predation rates on spring Chinook from the cormorant colony on Foundation Island and the major gull colonies in 2021 totals far less than the predation rates on steelhead (Evans et al. 2021, draft report). Furthermore, hatchery smolts tend to be more vulnerable to avian predators than wild smolts (Flagg et al. 2000). If avian predation were the primary cause of low survival for wild Chinook in 2021, we would expect to see similarly low survival for hatchery Chinook, but that was not the case. Avian predation may have contributed to the below-average survival of wild Chinook we observed in 2021, but it seems likely that other factors were also at play.

An exploding population of invasive Siberian prawn *Palaemon modestus* also potentially influenced survival of juvenile salmon in Snake River reservoirs in 2021 and other recent years. This species of prawn was first documented in the Snake River in 1998 (Haskell et al. 2006). Siberian prawns consume the same types of prey as juvenile salmon, and competition with these prawns may depress growth rates of juvenile salmon in Snake River reservoirs (Tiffan et al. 2014; Tiffan and Hurst 2016).

Collection counts of Siberian prawns at Snake River dams were low in the 2000s but have increased significantly. In 2021, the collection count of over 1 million prawns at Lower Granite Dam was eight times that of the collection count in 2020, which, at 145,030, was the highest ever observed there previously. The 2021 count at Lower Granite was also more than double the highest count previously observed anywhere (464,586 at Little Goose Dam in 2015). Collection counts were also above average at Little Goose and Lower Monumental Dams in 2021 (Table 35). This suggests the possibility that salmonids continue to face increased competition from Siberian prawn, at least in Lower Granite reservoir. However, it is not clear whether Siberian prawn were a factor in the low survival of wild Chinook observed in 2021.

It seems doubtful that competition with Siberian prawns would impact wild Chinook but not fish from other stocks, and estimated survival was about average for both hatchery Chinook and hatchery steelhead in 2021. Furthermore, these prawns are rarely observed at lower Columbia River dams, which encompass the reaches where wild Chinook survival was the lowest, and where we observed low survival for several other salmonid stocks.

Court-ordered spill was instituted in 2006, and in subsequent years, surface collectors were installed at Lower Granite and four additional dams. With these changes, average travel time between Lower Granite and Bonneville Dam has generally decreased, more so for steelhead than for Chinook smolts. Fish can linger in the forebay for hours or days before passing a dam. Spilling some amount of water throughout the day, especially when surface weirs are in place, greatly decreases this forebay delay.

As spill targets have repeatedly increased during the past several years, travel time has generally been very short throughout the season. However, any decreases in travel time have been marginal. Beyond a certain level of spill, further increases appear to yield diminishing returns in terms of speeding migration and shortening travel time. Despite very high spill levels, travel times for both Chinook and steelhead were only slightly shorter in 2021 than in other recent low-flow years, and even these small decreases were not sustained for the entire season. In the first half of April for Chinook, and during early April and late May for steelhead, travel times in 2021 were essentially equal to those from previous low-flow years.

High spill volumes such as those in 2021 are likely to induce eddies in the tailrace at some dams. The severity of eddies generated in the tailrace depends on flow and spill conditions, as well as general configuration of the dam (Bellerud 2017; Fredricks 2017). The combination of low flow and extremely high spill in 2021 may have resulted in more severe eddies than in past years. Powerful eddies in the tailrace may increase the time it takes for smolts to exit the tailrace and continue downstream movement, potentially increasing exposure to predation (Roby et al. 2016).

In 2021, estimated percentages of yearling Chinook salmon and steelhead transported from Snake River dams were the lowest on record by a substantial margin. Transportation rates initially dropped during 2015-2017, when the general program began around 1 May. These rates increased in 2018 and 2019, after the program start date was changed to 23 April. However in 2020, and again in 2021, the proportion of fish transported plummeted, despite the earlier start date. This drop in transportation rates has been caused by very low proportions of fish collected due to high rates of spill.

Programs instituted to encourage spillway passage by increasing spill and using surface-passage structures have been successful. However, higher proportions of spillway passage result in lower proportions of tagged fish entering bypass systems. There is evidence that surface spill is disproportionately attractive to fish at lower flow levels. Extremely high levels of spill, combined with low flows, has resulted in extremely low detection rates at all dams except Lower Granite with its new spillway detection system and Bonneville with its corner collector (Figure 8).

For survival estimates based on PIT-tag data, sample size is directly proportional to the number of detected fish, which in turn depends on both detection probability and total number of tagged migrants. Reduced effective sample sizes have become common in recent years, as reliance on spillway and surface passage has increased. Spill is now the primary management strategy used in attempts to increase survival of juvenile fish passing dams within the Federal Columbia River Power System.

At present, the emphasis on spillway passage reduces detection rates by reducing the proportion of fish that enter juvenile bypass systems. At most dams, juvenile bypass systems remain as the only passage route for which PIT-tag monitoring technology is available. While emphasizing spillway passage might indeed increase smolt survival, the quality of information gathered to verify higher rates of survival has been degraded by reduced detection probabilities. Consequences of reduced detection probability include:

1) Reduced certainty in survival estimates: standard errors become larger and confidence intervals wider. Estimates are also more likely to be further from the true survival value and are frequently greater than 100%.

2) Greater negative correlation between survival estimates in consecutive reaches. That is, there is an increased chance that sampling variability will result in estimates that are inversely correlated: high in one reach and low in the next, or vice versa.

3) Insufficient data to estimate survival at all in some cases.

All three consequences are usually most serious for the two furthest downstream reaches within the migration corridor: those from McNary to John Day and from John Day to Bonneville Dam.

Smaller effective sample sizes also heighten uncertainty in estimates of travel time and smolt-to-adult return ratios. Higher uncertainty in turn reduces the quality of predictive models based on these estimates. Ultimately, this uncertainty may weaken the efficacy of management decisions informed by estimates and model predictions, hinder the development of appropriate restoration plans, and impair the ability to monitor and assess restoration plans after they are implemented.

If detection rates remain low, precision in survival estimates can be increased only by releasing larger numbers of tagged fish. This option is not feasible, as it would increase both the cost of monitoring and the burden on an already stressed biological resource. Therefore, assuming the emphasis on spillway passage will continue, the best option for retaining or increasing precision in survival estimates is to increase rates of detection by developing PIT-tag monitoring systems for additional fish-passage routes.

The spillway detection system in the ogee at Lower Granite Dam compensates for the decrease in detection in the juvenile bypass system. The two detection systems combined to result in overall detection probabilities that were not depressed during the 2021 migration season. An additional benefit of having detection capability in more than one passage route is that overall detection probability is far less dependent on fluctuations in spill and flow. Large variations in detection probability within the migration season can have negative effects on the accuracy of survival and detection probability estimates from mark-recapture models and can also introduce bias to estimates of travel time.

Detection capability in multiple passage routes will also advance our understanding of passage-route distributions throughout the migration season, producing valuable insight into fish passage behavior. The spillway detection system allows us to track fish that passed Lower Granite Dam via different routes on the same day. In the future, once sufficient data have been collected, we will be able to directly compare both subsequent downstream survival and smolt-to-adult return rate between the two passage routes.

The success of the spillway detection system at Lower Granite Dam is very encouraging. Because the present management goal is to pass as many juveniles via spill as possible, the spillway is the ideal location for expanded PIT-tag detection. Increased detection rates will pay dividends, not only for survival estimates, but also for all other investments in PIT-tag research within the region.

We believe that the region should prioritize installation of similar spillway systems at other dams on the Snake and Columbia Rivers, particularly McNary and Bonneville Dam. These two dams are of critical importance to survival estimation for listed salmonid stocks. Continued development of new and alternative technologies to boost our abilities to detect PIT-tagged fish should remain a high priority as well.

Further development of new PIT-tag detection methods could lead to other improvements; for example, autonomous detection barges that allow detection in forebays or tailraces of dams. Stationary, removable, or semi-permanent arrays placed below Bonneville Dam could enhance or even supplant data from the estuary pair trawl detection system. These and other alternative methods for increasing detections should be actively pursued.

This study provides information that is essential for monitoring the status and trends of imperiled salmonid stocks as they migrate to the ocean. Without sufficient detections of PIT-tagged fish, our ability to monitor these stocks—and the effects of management actions on their survival—has been severely diminished. Therefore, actions to improve detection of these fish are critical to protect these valuable natural resources and avoid exposing threatened stocks to further harm, which we will no longer be able to measure.

Conclusions and Recommendations

Based on results of survival studies to date, we recommend the following:

1) Develop PIT-tag detection capability in spillways or surface passage structures at Bonneville and McNary Dam. Such capability would immediately improve detection rates and increase certainty in estimates of survival for juvenile salmonids passing Snake and Columbia River dams.

2) Pursue development of alternative PIT-detection technologies that could improve detection downstream of Bonneville Dam and potentially at other dams.

3) Continue to coordinate survival studies with other projects to maximize data-collection effort and minimize study effects on salmonid resources.

4) Continue development and maintenance of instream PIT-detection systems for use in tributaries. Such systems can identify sources of mortality upstream from the Snake and Clearwater River confluence. Estimates of survival from hatcheries to Lower Granite Dam suggest that substantial mortality occurs in these areas.

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Appendix A: Evaluation of Model Assumptions

Background

Using the Cormack-Jolly-Seber (CJS), or single-release model, passage of a single PIT-tagged salmonid through the hydropower system is modeled as a sequence of events. Examples of such events are detection at Little Goose Dam or survival from Lower Granite to Little Goose Dam. Each event has an associated probability of occurrence, and probabilities are considered "conditional," as they are defined only if a certain condition is met. For example, probability of detection at Little Goose Dam *given* that the fish survived to Little Goose Dam.

Thus, the detection history is a record of outcomes in a series of events. It is necessarily an imperfect record, as survival without detection cannot always be distinguished from mortality. For a given group of tagged fish, the single-release model represents detection history data as a multinomial distribution, with each multinomial cell probability (detection history probability) a function of the underlying survival and detection event probabilities. Three key assumptions lead to the multinomial cell probabilities used in the single-release model:

A1) All fish in a single group of tagged fish have common event probabilities (that is, each conditional detection or survival probability is common to all fish in the group).

A2) Event probabilities for each individual fish are independent from those for all other fish.

A3) Each event probability for an individual fish is conditionally independent from all other probabilities.

For a migrating PIT-tagged fish, assumption A3 implies that detection at any particular dam does not affect (or give information regarding) probabilities of subsequent events. For the tagged group as a whole, this further implies the assumption that detected and nondetected fish at a given dam have the same probability of survival in downstream reaches and have the same conditional probability of detection at downstream dams.

Methods

We used the methods presented by Burnham et al. (1987; pp 71-77) to assess goodness-of-fit of the single-release model to observed detection history data. In these tests, we compiled a series of contingency tables from detection history data for each group of tagged fish, and used χ^2 tests to identify systematic deviations from what was expected if the assumptions were met. We applied the tests to biweekly groups of yearling Chinook salmon and steelhead (hatchery and wild combined) leaving Lower Granite Dam during the migration year (Snake River-origin fish only, i.e., the groups used for survival estimates reported in Tables 1-2 and 7-8).

If goodness-of-fit tests for a series of release groups resulted in more significant differences between observed and expected values than expected by chance, we compared observed and expected tables to determine the nature of the violation. While a consistent pattern of violations in assumption testing does not unequivocally pinpoint the cause of the violation, such patterns can be suggestive and may allow us to rule out some hypothesized causes. Potential causes of assumption violations include

1) Inherent differences between individuals in survival or detection probability (e.g., in the propensity to be guided by bypass screens)
2) Differential mortality between a passage route that is monitored for PIT tags (e.g., juvenile collection system) and those that are not (e.g., spillways and turbines)
3) Behavioral responses to bypass and detection
4) Differences in passage timing for detected and non-detected fish if such differences result in exposure to different conditions downstream

However, inherent differences and behavioral responses cannot be distinguished using detection information alone. Conceptually, we make the distinction that inherent traits are those that characterized the fish before any hydropower system experience, while behavioral responses occur as a result of particular hydropower system experiences. For example, a developed preference for a particular passage route is a behavioral response, while a size-related difference in passage-route selection is inherent. Of course, response to passage experience may also depend on inherent characteristics.

To describe each test conducted, we followed the nomenclature of Burnham et al. (1987). For release groups from Lower Granite Dam, we analyzed 6-digit detection histories indicating detection status at Little Goose, Lower Monumental, McNary, John Day, and Bonneville Dams, and the final digit for detection anywhere below Bonneville Dam (estuary trawl, Bonneville adult ladder, or piscivorous bird recovery).

A first series of tests is called Test 2 (Burnham et al. 1987). The first component test in the series for Lower Granite Dam groups is called Test 2.C2, based on the following contingency table:

Test 2.C2	First site detected below Little Goose				
df = 4	Lower Monumental	McNary	John Day	Bonneville	Below Bonneville
Not detected at Little Goose	n_{11}	n_{12}	n_{13}	n_{14}	n_{15}
Detected at Little Goose	n_{21}	n_{22}	n_{23}	n_{24}	n_{25}

In this table, all fish detected below Little Goose Dam were cross-classified according to their detection history at Little Goose and according to their first detection site below Little Goose. For example, n_{11} is the count of fish not detected at Little Goose that were first detected downstream at Lower Monumental Dam.

If all model assumptions are met, counts of fish detected at Little Goose should be in constant proportion to those of fish not detected (i.e., n_{11}/n_{21}, n_{12}/n_{22}, n_{13}/n_{23}, n_{14}/n_{24}, and n_{15}/n_{25} are equal in expectation). Because this table counted only fish detected below Little Goose (i.e., all fish survived passage at Goose), differential *direct* mortality between fish detected and not detected at Little Goose will not cause violations of Test 2.C2 by itself. However, differential *indirect* mortality related to Little Goose passage could cause violations if differences in mortality are expressed below Lower Monumental Dam.

Behavioral response to guidance at Little Goose could also cause violations of Test 2.C2. For example, if fish detected at Little Goose become more likely to be detected downstream, then they will tend to have more first-site downstream detections at Lower Monumental. Conversely, if fish detected at Little Goose become less likely to be detected downstream, they will have fewer first-site downstream detections at Lower Monumental. Inherent differences among fish could also result in violations of Test 2.C2 and would be difficult to distinguish from behavioral responses.

There are three additional component tests of Test 2 (Tests 2.C3, 2.C4, and 2.C5), conditioning on detection status at McNary, John Day, and Bonneville Dams, respectively, and taking analogous form to that of Test 2.C2.

The next series of tests is called Test 3, which has two subseries called Test 3.SR and Test 3.Sm. The first test in the 3.SR subseries is called Test 3.SR3, based on the contingency table:

Test 3.SR3	Detected again at McNary or below?	
df = 1	YES	NO
Detected at Lower Monumental, not detected at Little Goose	n_{11}	n_{12}
Detected at Lower Monumental, detected at Little Goose	n_{21}	n_{22}

In this table, all fish detected at Lower Monumental are cross-classified according to their status at Little Goose and whether or not they were detected again downstream from Lower Monumental. As with the Test 2 series, differential mortality in different passage routes at Little Goose will not be detected by this test if all the mortality is expressed before the fish arrive at Lower Monumental. However, differences in mortality expressed below McNary could cause violations, as could behavioral responses (which could also be somewhat harder to detect because of the conditioning on detection at Lower Monumental) or inherent differences in detectability or survival between fish detected at Little Goose and those not detected there.

The first test in the 3.Sm series is Test 3.Sm3, based on the contingency table:

Test 3.Sm3	First site detected below Lower Monumental			
df = 3	McNary	John Day	Bonneville	Below Bonneville
Detected at Lower Monumental, not detected at Little Goose	n_{11}	n_{12}	n_{13}	n_{14}
Detected at Lower Monumental, detected at Little Goose	n_{21}	n_{22}	n_{23}	n_{24}

This test is sensitive to the same sorts of differences as Test 3.SR3, but tends to have somewhat less power. Because the table classifies only fish detected below Lower Monumental, it is not sensitive to differences in survival between Lower Monumental and McNary.

There are three additional component 3.SR tests (SR4, SR5, SR6), respectively conditioned on detection at McNary, John Day, and Bonneville and analogous to Lower Monumental in Test 3.SR3. Similarly, there are two additional component 3.Sm tests (Sm4 and Sm5), respectively conditioned on detection at McNary and John Day and analogous to Lower Monumental in Test 3.Sm3.

Contingency table tests are not possible when any of the row or column totals are zero. Furthermore, when any of the expected cell counts of a table are less than 5.0, the χ^2 distribution does not sufficiently approximate the sampling distribution of the test statistic. For tables with more than two columns, if any column that was two or more columns from the left had a zero column total, we combined the two rightmost columns to create tables with successively fewer columns until the column totals were no longer zero or until there were only two columns remaining.

No test was possible if a 2 × 2 table had a zero column total. When a test was still possible for a table (regardless of table size) but one or more of the expected cell counts in the table was less than 5, we conducted a Fisher's exact test and reported the *p*-value from that test. We assumed that the assumptions of the χ^2 test were met for all overall tests.

Results

For release groups in 2021, there were more significant overall tests than expected by chance alone for steelhead but not for yearling Chinook salmon (5% are expected by chance alone with $\alpha = 0.05$; Appendix Table A1). There were four biweekly groups of yearling Chinook salmon, and the overall sum of χ^2 test statistics was not significant for any of them. The overall test was significant for 3 of the 6 steelhead groups (50%).

Among all individual component tests (i.e., 2.C2, 3.SR3, etc.), 1 test out of 38 (3%) was significant for yearling Chinook salmon and 6 out of 56 (11%) were significant for steelhead (Appendix Tables A2-A5). There was an 86% chance of 1 or more tests out of 38 being significant if the true test-wise probability of a "false positive" result was $\alpha = 0.05$. Likewise for steelhead, there was a 6% chance of 6 or more significant tests out of 56.

Thus, the number of observed positive tests for Chinook could have been due to chance, but the number of positive tests for steelhead was not likely due to chance, provided there were no true assumption violations. However, due to the very low detection probabilities at most dams, many of the tests were likely under-powered.

Therefore, the tests would not likely detect an assumption violation if one were actually present.

We diagnosed patterns in the contingency tables that led to significant tests, and results were similar to those we reported in past years. For biweekly groups of yearling Chinook, the one significant component test (Test 2.C4) indicated that fish detected at McNary Dam had fewer first detections below Bonneville Dam than fish not detected at McNary Dam.

For steelhead, in each of the significant component tests (Tests 2.C2, 2.C3, 2.C4, and 2.C5), fish detected at the reference dam of the test had more detections at a downstream dam than fish not detected at the reference dam. This suggests that fish detected one dam were more likely than fish not detected at that dam to be detected again at another dam downstream.

Discussion

In 2021, as in previous years, we concluded that inherent differences in detectability (guideability) of fish within a release group was the most likely cause of patterns we observed in contingency table tests. Zabel et al. (2002, 2005) and Faulkner et al. (2019) provided evidence of inherent differences in guidance/detection related to length of fish at tagging, and similar observations were made in evaluating the 2021 data.

Fish size probably does not explain all inherent differences, but it appeared to explain some. Faulkner et al. (2019) found larger fish were less likely to be detected in juvenile bypass systems than smaller fish at most dams, and that relationship held for both yearling Chinook and steelhead. This relationship means that fish detected at one dam will tend to be smaller, and therefore inherently more likely to be detected at a subsequent dam downstream. All of the significant component tests for steelhead in 2021 suggested that fish detected at the reference dam were more likely to be detected again at a dam downstream. This supports the idea that individual heterogeneity in lengths could be the cause of the significant tests. However, this pattern did not hold for the significant contingency table test for Chinook. This offers evidence that size selection is not the only mechanism driving these assumption violations.

Another possibility is that changes in spill level among sequential dams were correlated with one another during passage of a cohort, and this resulted in correlated detection probabilities within subsets of the cohort. The flexible spill operation resulted in wide variation of spill percentage within a given day. These variations in turn may have resulted in wide variation in the proportion of fish entering bypass systems and being detected.

This scenario creates heterogeneity of detection probabilities at each dam and could result in patterns of detection for subsets of fish in a cohort that could lead to fish detected at one dam being more or less likely to be detected at the next dam. This process is complicated, and further research is needed to determine whether such a scenario could have led to the assumption violations observed in 2021.

Although the contingency table tests did well at detecting some violations of CJS model assumptions, there were instances where assumptions could have been violated without resulting in significant tests. A specific example would be in the case of acute differential post-detection mortality, where detected and non-detected fish have different rates of mortality between detection at a point of interest and the subsequent detection point. This mortality would constitute a violation of assumption A3.

However, none of the contingency table tests described here would detect this violation because each test is conditioned on fish with at least one detection, either at the site at which subgroups are defined or at sites downstream. To discern differential post-detection mortality requires knowledge of the fate of individual non-detected fish at the site of interest and downstream. However, the fate of fish not detected at the site of interest is only known for fish detected downstream, and not for those never detected again. Therefore, none of the assumption tests described here can discern differential post-detection mortality between two consecutive detection sites.

Results in previous years (e.g., Zabel et al. 2002) led us to conclude that some amount of heterogeneity in the survival and detection process occurred but did not seriously affect the performance of estimators of survival (see also Burnham et al. 1987 on effects of a small amount of heterogeneity). Further investigation is needed to evaluate the effects of assumption violations under current conditions, with low detection probabilities.

Appendix Table A1. Number of tests of goodness-of-fit to the single-release model conducted, and number of significant ($\alpha = 0.05$) results for groups of Snake River Chinook salmon and juvenile steelhead in 2021. Daily groups of combined hatchery and wild fish, determined by day of detection at Lower Granite Dam, were pooled for biweekly groups for tests.

Test		Species		Total
		Chinook	Steelhead	
Test 2.C2	Tests (n)	4	6	10
	Significant tests (n)	0	1	1
Test 2.C3	Tests (n)	4	6	10
	Significant tests (n)	0	1	1
Test 2.C4	Tests (n)	4	6	10
	Significant tests (n)	1	3	4
Test 2.C5	Tests (n)	4	6	10
	Significant tests (n)	0	1	1
Test 3.SR3	Tests (n)	3	4	7
	Significant tests (n)	0	0	0
Test 3.Sm3	Tests (n)	1	1	2
	Significant tests (n)	0	0	0
Test 3.SR4	Tests (n)	4	6	10
	Significant tests (n)	0	0	0
Test 3.Sm4	Tests (n)	3	5	8
	Significant tests (n)	0	0	0
Test 3.SR5	Tests (n)	4	6	10
	Significant tests (n)	0	0	0
Test 3.Sm5	Tests (n)	3	4	7
	Significant tests (n)	0	0	0
Test 3.SR6	Tests (n)	4	6	10
	Significant tests (n)	0	0	0
Test 2 sum	Tests (n)	4	6	10
	Significant tests (n)	0	3	3
Test 3 sum	Tests (n)	4	6	10
	Significant tests (n)	0	0	0
Test 2 + 3	Tests (n)	4	6	10
	Significant tests (n)	0	3	3

Appendix Table A2. Results of Test 2 and overall tests of goodness-of-fit to the single-release model for groups of Snake River yearling Chinook salmon 2021. Daily groups of combined hatchery and wild fish, determined by day of detection at Lower Granite Dam, were pooled for biweekly groups for tests.

	Overall (2+3)		Test 2 (sum)		Test 2.C2	
Release	χ^2	*P*-value	χ^2	*P*-value	χ^2	*P*-value
6–19 Apr	25.88	0.077	15.55	0.113	4.29	0.261
20 Apr–3 May	19.30	0.312	14.62	0.147	6.72	0.150
4–17 May	19.35	0.435	12.66	0.243	4.33	0.398
18–31 May	10.92	0.618	7.41	0.686	0.70	0.830
Total (df)	75.45 (66)	0.199	50.24 (40)	0.129	16.04 (16)	0.450

	Test 2.C3		Test 2.C4		Test 2.C5	
Release	χ^2	*P*-value	χ^2	*P*-value	χ^2	*P*-value
6–19 Apr	5.88	0.268	2.82	0.191	2.56	0.131
20 Apr–3 May	1.85	0.714	6.00	**0.050**	0.05	0.823
4–17 May	2.62	0.462	5.61	0.060	0.10	0.623
18–31 May	2.12	0.639	3.12	0.191	1.47	0.634
Total (df)	12.47 (12)	0.409	17.55 (8)	**0.025**	4.18 (4)	0.382

Appendix Table A3. Results of Test 3 tests of goodness-of-fit to the single-release model for groups of Snake River yearling Chinook salmon in 2021. Daily groups of combined hatchery and wild fish, determined by day of detection at Lower Granite Dam, were pooled for biweekly groups for tests.

Release	Test 3 (sum)		Test 3.SR3		Test 3.Sm3		Test 3.SR4	
period	χ^2	*P*-value	χ^2	*P*-value	χ^2	*P*-value	χ^2	*P*-value
6–19 Apr	10.33	0.171	0.15	1.000	-	-	5.35	0.075
20 Apr–3 May	4.68	0.699	0.40	1.000	-	-	0.00	1.000
4–17 May	6.69	0.669	5.99	0.145	0.24	1.000	0.08	1.000
18–31 May	3.51	0.319	-	-	-	-	0.31	1.000
Total (df)	25.21 (26)	0.507	6.54 (3)	0.088	0.24 (2)	0.887	5.74 (4)	0.219

	Test 3.Sm4		Test 3.SR5		Test 3.Sm5		Test 3.SR6	
	χ^2	*P*-value	χ^2	*P*-value	χ^2	*P*-value	χ^2	*P*-value
6–19 Apr	1.26	1.000	1.78	0.218	0.92	1.000	0.87	1.000
20 Apr–3 May	0.30	1.000	0.08	1.000	3.60	0.187	0.30	0.593
4–17 May	0.13	1.000	0.02	0.701	0.18	1.000	0.05	0.817
18–31 May	-	-	3.04	0.120	-	-	0.16	0.658
Total (df)	1.69 (6)	0.946	4.92 (4)	0.296	4.70 (3)	0.195	1.38 (4)	0.848

Appendix Table A4. Results of Test 2 and overall tests of goodness-of-fit to the single-release model for groups of Snake River juvenile steelhead in 2021. Daily groups of combined hatchery and wild fish, determined by day of detection at Lower Granite Dam, were pooled for biweekly groups for tests.

	Overall (2+3)		Test 2 (sum)		Test 2.C2	
Release	χ^2	*P*-value	χ^2	*P*-value	χ^2	*P*-value
23 Mar–5 Apr	15.07	0.446	8.54	0.576	2.81	0.443
6–19 Apr	41.98	**0.003**	37.65	**<0.001**	5.08	0.279
20 Apr–3 May	42.25	**0.001**	33.53	**<0.001**	7.64	0.095
4–17 May	23.00	0.149	11.67	0.308	7.26	0.076
18–31 May	35.08	**0.006**	29.79	**0.001**	15.25	**0.011**
1–14 Jun	12.56	0.482	11.71	0.305	3.92	0.422
Total (df)	169.94 (99)	**<0.001**	132.89 (60)	**<0.001**	41.96 (24)	**0.013**

	Test 2.C3		Test 2.C4		Test 2.C5	
Release	χ^2	*P*-value	χ^2	*P*-value	χ^2	*P*-value
23 Mar–5 Apr	1.68	0.689	2.86	0.195	1.19	0.328
6–19 Apr	9.12	**0.032**	18.04	**<0.001**	5.41	**0.039**
20 Apr–3 May	1.75	0.517	20.68	**<0.001**	3.46	0.063
4–17 May	3.21	0.253	0.90	0.737	0.30	0.582
18–31 May	1.08	0.857	9.32	**0.019**	4.14	0.065
1–14 Jun	6.37	0.200	1.16	0.270	0.26	0.475
Total (df)	23.21 (18)	0.183	52.96 (12)	**<0.001**	14.76 (6)	**0.022**

Appendix Table A5. Results of Test 3 tests of goodness-of-fit to the single-release model for groups of Snake River juvenile steelhead in 2021. Daily groups of combined hatchery and wild fish, determined by day of detection at Lower Granite Dam, were pooled for biweekly groups for tests.

Release period	Test 3 (sum) χ^2	Test 3 (sum) *P*-value	Test 3.SR3 χ^2	Test 3.SR3 *P*-value	Test 3.Sm3 χ^2	Test 3.Sm3 *P*-value	Test 3.SR4 χ^2	Test 3.SR4 *P*-value
23 Mar–5 Apr	6.53	0.258	-	-	-	-	0.90	0.668
6–19 Apr	4.33	0.931	1.28	0.378	0.31	1.000	0.40	0.530
20 Apr–3 May	8.72	0.273	0.60	1.000	-	-	1.81	0.245
4–17 May	11.33	0.125	1.34	0.586	-	-	1.50	0.255
18–31 May	5.29	0.625	0.14	1.000	-	-	0.10	1.000
1–14 Jun	0.85	0.837	-	-	-	-	0.30	1.000
Total (df)	37.05 (39)	0.559	3.36 (4)	0.499	0.31 (3)	0.958	5.01 (6)	0.543

Release period	Test 3.Sm4 χ^2	Test 3.Sm4 *P*-value	Test 3.SR5 χ^2	Test 3.SR5 *P*-value	Test 3.Sm5 χ^2	Test 3.Sm5 *P*-value	Test 3.SR6 χ^2	Test 3.SR6 *P*-value
23 Mar–5 Apr	4.62	0.250	0.93	1.000	-	-	0.08	1.000
6–19 Apr	0.86	1.000	0.16	0.686	0.06	1.000	1.26	0.263
20 Apr–3 May	0.75	0.677	1.59	0.207	0.35	1.000	3.62	0.057
4–17 May	1.39	0.366	0.11	1.000	3.77	0.187	3.22	0.073
18–31 May	0.41	1.000	0.72	0.595	1.20	0.515	2.72	0.129
1–14 Jun	-	-	0.49	1.000	-	-	0.06	0.557
Total (df)	8.03 (10)	0.626	4.00 (6)	0.677	5.38 (4)	0.250	10.96 (6)	0.090

Appendix B: Survival and Detection Data from Individual Hatcheries and Traps

Appendix Table B1. Survival probability estimates for yearling Chinook salmon released from Snake River Basin hatcheries in 2021. Standard errors in parentheses.

Hatchery/ Release site	Number released	Release to Lower Granite Dam	Lower Granite to Little Goose Dam	Little Goose to Lower Monumental Dam	Lower Monumental to McNary Dam	Release to McNary Dam
Yearling Chinook salmon						
Clearwater Hatchery						
Clear Creek	9,788	0.957 (0.038)	0.619 (0.219)	NA	NA	NA
Powell Pond	25,476	0.652 (0.013)	0.804 (0.217)	0.558 (0.252)	1.683 (0.635)	0.492 (0.048)
Red River Pond	17,057	0.821 (0.020)	0.884 (0.327)	1.586 (1.211)	0.520 (0.352)	0.599 (0.066)
Selway River	17,087	0.657 (0.015)	0.589 (0.166)	NA	NA	NA
N Fork Clearwater R	19,091	0.878 (0.016)	0.802 (0.217)	0.834 (0.358)	1.147 (0.400)	0.674 (0.070)
Dworshak Hatchery						
N Fork Clearwater R	41,698	0.784 (0.012)	0.802 (0.171)	1.100 (0.475)	0.775 (0.297)	0.536 (0.039)
Kooskia Hatchery						
Kooskia	6,000	0.808 (0.041)	0.698 (0.280)	1.524 (1.555)	0.816 (0.791)	0.701 (0.158)
Lookingglass Hatchery						
Catherine Creek Pond	20,698	0.515 (0.016)	1.062 (0.496)	1.812 (1.946)	0.318 (0.310)	0.315 (0.038)
Grande Ronde Pond	1,928	0.483 (0.058)	0.453 (0.198)	NA	NA	NA
Imnaha River	8,843	0.638 (0.027)	1.093 (0.453)	NA	NA	NA
Imnaha Weir	11,858	0.757 (0.026)	0.675 (0.242)	0.898 (0.555)	1.196 (0.623)	0.549 (0.069)
Lookingglass Hatchery	4,775	0.568 (0.029)	0.904 (0.335)	NA	NA	NA
Lostine Pond	5,961	0.485 (0.025)	1.134 (0.433)	0.926 (0.702)	0.613 (0.419)	0.312 (0.059)
McCall Hatchery						
Knox Bridge	51,881	0.783 (0.012)	0.828 (0.207)	1.047 (0.446)	0.864 (0.302)	0.586 (0.034)
Johnson Creek	2,184	0.552 (0.052)	0.553 (0.347)	0.544 (0.449)	NA	NA
Pahsimeroi Hatchery						
Pahsimeroi Pond	20,582	0.287 (0.012)	1.754 (1.180)	1.036 (1.215)	0.446 (0.436)	0.233 (0.041)
Rapid River Hatchery						
Rapid River Hatchery	51,483	0.631 (0.011)	0.805 (0.188)	0.884 (0.383)	1.166 (0.437)	0.524 (0.041)
Sawtooth Hatchery						
Alturas Lake Creek	999	0.722 (0.086)	1.358 (1.292)	0.294 (0.366)	1.896 (1.831)	0.546 (0.287)
Sawtooth Hatchery	18,868	0.637 (0.016)	1.318 (0.711)	1.053 (0.903)	0.549 (0.372)	0.486 (0.058)
Yankee Fork	8,474	0.391 (0.022)	NA	NA	NA	NA

Appendix Table B2. Survival probability estimates for juvenile steelhead released from Snake River Basin hatcheries in 2021. Standard errors in parentheses.

Hatchery/ Release site	Number released	Release to Lower Granite Dam	Lower Granite to Little Goose Dam	Little Goose to Lower Monumental Dam	Lower Monumental to McNary Dam	Release to McNary Dam
			Juvenile steelhead			
Clearwater Hatchery						
Meadow Creek	10,779	0.800 (0.009)	1.040 (0.158)	1.495 (0.605)	0.604 (0.243)	0.752 (0.105)
Newsome Creek	5,989	0.762 (0.016)	0.500 (0.124)	NA	NA	NA
S Fork Clearwater R	4,693	0.741 (0.014)	1.266 (0.250)	0.688 (0.322)	0.803 (0.366)	0.518 (0.075)
Dworshak Hatchery						
S Fork Clearwater R	12,705	0.747 (0.012)	0.730 (0.085)	1.921 (0.706)	0.511 (0.190)	0.536 (0.062)
N Fork Clearwater R	1,489	0.852 (0.032)	1.347 (0.861)	0.961 (1.069)	0.488 (0.466)	0.538 (0.155)
Mainstem Clearwater R	18,506	0.842 (0.010)	1.377 (0.225)	1.214 (0.503)	0.516 (0.203)	0.727 (0.067)
Hagerman Hatchery						
East Fork Salmon R	8,530	0.536 (0.014)	1.423 (0.754)	0.281 (0.179)	1.573 (0.638)	0.337 (0.068)
Sawtooth Hatchery	11,569	0.732 (0.010)	0.896 (0.200)	1.006 (0.442)	1.061 (0.444)	0.701 (0.123)
Irrigon Hatchery						
Big Canyon Facility	3,980	0.718 (0.018)	1.032 (0.285)	0.746 (0.378)	0.817 (0.408)	0.452 (0.117)
Little Sheep Facility	14,978	0.768 (0.010)	0.969 (0.128)	0.926 (0.232)	0.921 (0.234)	0.635 (0.088)
Wallowa Hatchery	13,517	0.722 (0.009)	1.021 (0.134)	1.189 (0.376)	0.596 (0.188)	0.522 (0.067)
Lyons Ferry Hatchery						
Cottonwood Pond	5,993	0.788 (0.009)	1.221 (0.318)	NA	NA	NA

Appendix Table B2. Continued.

Hatchery/ Release site	Number released	Release to Lower Granite Dam	Lower Granite to Little Goose Dam	Little Goose to Lower Monumental Dam	Lower Monumental to McNary Dam	Release to McNary Dam
			Juvenile steelhead (continued)			
Magic Valley Hatchery						
Little Salmon R	4,377	0.852 (0.018)	1.229 (0.543)	1.179 (1.195)	0.520 (0.506)	0.641 (0.216)
Pahsimeroi R Trap	11,329	0.763 (0.010)	1.041 (0.245)	0.919 (0.444)	0.816 (0.366)	0.596 (0.091)
Sawtooth Hatchery	5,689	0.774 (0.016)	0.695 (0.190)	1.508 (1.011)	1.126 (0.773)	0.914 (0.285)
Yankee Fork	13,212	0.615 (0.011)	0.968 (0.292)	NA	NA	NA
Niagara Springs Hatchery						
Hells Canyon Dam	8,580	0.776 (0.010)	1.801 (0.437)	0.402 (0.160)	1.446 (0.521)	0.812 (0.141)
Little Salmon R	5,086	0.814 (0.019)	0.832 (0.294)	NA	NA	NA
Pahsimeroi R Trap	8,971	0.657 (0.011)	1.993 (1.078)	0.381 (0.262)	1.475 (0.763)	0.736 (0.220)

Appendix Table B3. Survival probability estimates for juvenile Sockeye and Coho salmon released from Snake River Basin hatcheries for migration year 2021. Standard errors in parentheses.

Hatchery/ Release site	Release date	Number released	Release to Lower Granite Dam	Lower Granite to Little Goose Dam	Little Goose to Lower Monumental Dam	Lower Monumental to McNary Dam	Lower Granite to McNary Dam	Release to McNary Dam
				Sockeye salmon				
Springfield Hatchery								
Sawtooth Hatchery	30 April 2021	51,310	0.756 (0.010)	0.693 (0.360)	1.136 (0.727)	1.038 (0.406)	0.817 (0.094)	0.617 (0.071)
				Coho salmon				
Cascade Hatchery								
Lostine River	4 April 2021	1,000	0.406 (0.046)	0.533 (0.437)	1.861 (2.261)	NA	NA	NA
Eagle Creek Hatchery								
Kooskia Hatchery	5 April 2021	4,988	0.581 (0.028)	NA	NA	NA	NA	NA
N Lapwai Valley Pd	30 March 2021	4,999	0.763 (0.030)	NA	NA	NA	NA	NA
Kooskia Hatchery								
Kooskia Hatchery	14 April 2021	3,943	0.669 (0.038)	0.346 (0.152)	NA	NA	NA	NA

Appendix Table B4. Detection probability estimates for yearling Chinook salmon released from Snake River Basin hatcheries in 2021. Standard errors in parentheses.

Hatchery/ Release site	Number released	Lower Granite Dam	Little Goose Dam	Lower Monumental Dam	McNary Dam
Yearling Chinook salmon					
Clearwater Hatchery					
Clear Creek	9,788	0.275 (0.012)	0.015 (0.006)	NA	0.033 (0.005)
Powell Pond	25,476	0.458 (0.010)	0.010 (0.003)	0.010 (0.004)	0.044 (0.005)
Red River Pond	17,057	0.389 (0.010)	0.008 (0.003)	0.003 (0.002)	0.039 (0.005)
Selway River	17,087	0.486 (0.012)	0.012 (0.004)	0.003 (0.002)	0.038 (0.005)
N F Clearwater R	19,091	0.513 (0.010)	0.011 (0.003)	0.006 (0.002)	0.039 (0.004)
Dworshak Hatchery					
N F Clearwater R	41,698	0.435 (0.007)	0.012 (0.003)	0.005 (0.002)	0.045 (0.004)
Kooskia Hatchery					
Kooskia	6,000	0.342 (0.019)	0.023 (0.010)	0.007 (0.006)	0.046 (0.011)
Lookingglass Hatchery					
Catherine Cr Pond	20,698	0.390 (0.013)	0.009 (0.004)	0.003 (0.002)	0.060 (0.008)
Grande Ronde P	1,928	0.340 (0.043)	0.038 (0.018)	NA	0.095 (0.034)
Imnaha Weir	8,843	0.366 (0.016)	0.014 (0.006)	0.002 (0.002)	0.079 (0.012)
Imnaha River	11,858	0.356 (0.013)	0.018 (0.007)	0.010 (0.005)	0.058 (0.008)
Lookingglass H	4,775	0.420 (0.023)	0.015 (0.006)	NA	0.051 (0.013)
Lostine Pond	5,961	0.419 (0.023)	0.016 (0.006)	0.005 (0.004)	0.080 (0.016)
McCall Hatchery					
Knox Bridge	51,881	0.386 (0.006)	0.008 (0.002)	0.004 (0.002)	0.055 (0.004)
Johnson Creek	2,184	0.394 (0.039)	0.014 (0.010)	0.014 (0.010)	0.052 (0.023)
Pahsimeroi Hatchery					
Pahsimeroi Pond	20,582	0.374 (0.016)	0.009 (0.006)	0.004 (0.004)	0.043 (0.008)
Rapid River Hatchery					
Rapid River Hatch	51,483	0.397 (0.007)	0.011 (0.003)	0.005 (0.002)	0.039 (0.003)
Sawtooth Hatchery					
Alturas Lake Cr	999	0.364 (0.046)	0.010 (0.010)	0.010 (0.010)	0.038 (0.022)
Sawtooth H.	18,868	0.402 (0.011)	0.006 (0.003)	0.003 (0.002)	0.036 (0.005)
Yankee Fork	8,474	0.344 (0.021)	NA	0.006 (0.006)	0.034 (0.009)

Appendix Table B5. Detection probability estimates for juvenile steelhead released from Snake River Basin hatcheries in 2021. Standard errors in parentheses.

Hatchery/ Release site	Number released	Lower Granite Dam	Little Goose Dam	Lower Monumental Dam	McNary Dam
Juvenile steelhead					
Clearwater Hatchery					
Meadow Creek	10,779	0.737 (0.009)	0.029 (0.005)	0.009 (0.003)	0.023 (0.004)
Newsome Creek	5,989	0.680 (0.015)	0.028 (0.008)	NA	0.018 (0.004)
S Fork Clearwater R	4,693	0.726 (0.014)	0.038 (0.008)	0.025 (0.011)	0.053 (0.009)
Dworshak Hatchery					
S Fork Clearwater R	12,705	0.625 (0.010)	0.054 (0.007)	0.015 (0.005)	0.041 (0.005)
N Fork Clearwater R	1,489	0.656 (0.027)	0.014 (0.010)	0.008 (0.008)	0.032 (0.011)
Mainstem Clearwater	18,506	0.633 (0.008)	0.016 (0.003)	0.007 (0.003)	0.033 (0.003)
Hagerman Hatchery					
East Fork Salmon R	8,530	0.596 (0.016)	0.011 (0.006)	0.016 (0.006)	0.020 (0.005)
Sawtooth Hatchery	11,569	0.662 (0.010)	0.019 (0.004)	0.008 (0.003)	0.012 (0.002)
Irrigon Hatchery					
Big Canyon Facility	3,980	0.671 (0.018)	0.031 (0.009)	0.017 (0.008)	0.020 (0.006)
Little Sheep Facility	14,978	0.655 (0.009)	0.033 (0.005)	0.017 (0.004)	0.020 (0.003)
Wallowa Hatchery	13,517	0.719 (0.009)	0.038 (0.005)	0.012 (0.004)	0.026 (0.004)
Lyons Ferry Hatchery					
Cottonwood Pond	5,993	0.839 (0.010)	0.031 (0.008)	0.003 (0.003)	0.013 (0.003)
Magic Valley Hatchery					
Little Salmon R	4,377	0.658 (0.015)	0.015 (0.007)	0.004 (0.003)	0.007 (0.003)
Pahsimeroi R Trap	11,329	0.661 (0.010)	0.015 (0.004)	0.004 (0.002)	0.013 (0.002)
Sawtooth Hatchery	5,689	0.602 (0.014)	0.027 (0.008)	0.004 (0.002)	0.007 (0.003)
Yankee Fork	13,212	0.590 (0.011)	0.017 (0.005)	0.002 (0.002)	0.015 (0.003)
Niagara Springs Hatchery					
Hells Canyon Dam	8,580	0.724 (0.010)	0.012 (0.003)	0.008 (0.003)	0.014 (0.003)
Little Salmon R	5,086	0.656 (0.017)	0.029 (0.010)	NA	0.022 (0.006)
Pahsimeroi Trap	8,971	0.697 (0.012)	0.008 (0.004)	0.008 (0.004)	0.008 (0.002)

Appendix Table B6. Detection probability estimates for juvenile Sockeye and Coho salmon released from Snake River Basin hatcheries for migration year 2021. Standard errors in parentheses.

Hatchery/ Release site	Release date	Number released	Detection probability: Lower Granite	Little Goose	Lower Monumental	McNary
			Sockeye salmon			
Springfield Hatchery						
Sawtooth Hatchery	30 April	51,310	0.514 (0.007)	0.002 (0.001)	0.003 (0.001)	0.014 (0.002)
			Coho salmon			
Cascade Hatchery						
Lostine River	4 April	1,000	0.488 (0.058)	0.014 (0.014)	0.015 (0.015)	NA
Eagle Creek Hatchery						
Kooskia Hatchery	5 April	4,988	0.415 (0.022)	NA	NA	0.024 (0.008)
N Lapwai Valley Pd	30 March	4,999	0.431 (0.019)	NA	0.005 (0.005)	0.024 (0.006)
Kooskia Hatchery						
Kooskia Hatchery	14 April	3,943	0.402 (0.025)	0.010 (0.005)	0.003 (0.003)	0.037 (0.010)

Appendix Table B7. Survival probability estimates for juvenile salmonids released from traps in Snake River Basin in 2021. Standard errors in parentheses.

Trap	Release dates	Distance to LGR (km)	Number released	Release to Lower Granite	Lower Granite to Little Goose	Little Goose to Lower Monumental	Lower Monumental to McNary Dam	Release to McNary Dam
				Wild Chinook salmon				
Snake	08 Apr-21 May	52	27	NA	NA	NA	NA	NA
Grande Ronde	11 Mar-25 May	100	1,405	0.832 (0.057)	1.412 (1.316)	NA	NA	NA
Imnaha	09 Feb-31 May	142	3,441	0.852 (0.052)	1.796 (0.858)	1.202 (1.298)	0.294 (0.290)	0.540 (0.108)
Lolo Creek	18 Mar-31 May	159	462	0.451 (0.070)	NA	NA	NA	NA
Salmon	11 Mar-20 May	233	1,105	0.923 (0.077)	0.885 (0.798)	0.633 (0.789)	NA	NA
Lookingglass Cr	01 Feb-26 Apr	235	660	0.574 (0.086)	NA	NA	NA	NA
Minam	17 Mar-13 May	246	734	0.549 (0.074)	NA	NA	NA	NA
Lostine	05 Feb-26 May	274	575	0.694 (0.106)	0.449 (0.360)	0.655 (0.702)	NA	NA
Catherine Creek	02 Feb-29 May	362	597	0.279 (0.052)	NA	NA	NA	NA
U. Grande Ronde	26 Mar-19 May	397	700	0.413 (0.060)	NA	NA	NA	NA
S. Fork Salmon	13 Mar-30 Apr	408	1,440	0.602 (0.058)	NA	NA	NA	NA
Johnson Creek	04 Mar-29 May	436	419	0.487 (0.083)	0.355 (0.199)	NA	NA	NA
Panther Creek	16 Mar-31 May	468	842	0.756 (0.088)	1.367 (1.302)	0.180 (0.212)	1.675 (1.306)	0.311 (0.108)
Big Creek	19 Mar-30 Apr	489	993	0.673 (0.081)	NA	NA	NA	NA
Lower Lemhi R.	19 Mar-31 May	553	3,093	0.742 (0.046)	0.839 (0.759)	0.273 (0.267)	3.140 (1.363)	0.533 (0.128)
Upper Lemhi R.	20 Mar-22 May	595	311	0.468 (0.064)	NA	NA	NA	NA
Pahsimeroi	09 Mar-31 May	621	391	0.399 (0.073)	NA	NA	NA	NA
Marsh Creek	21 Mar-31 May	630	113	0.434 (0.209)	NA	NA	NA	NA
Sawtooth	20 Mar-30 May	747	336	1.246 (0.650)	NA	NA	NA	NA

Appendix Table B7. Continued.

Trap	Release dates	Distance to LGR (km)	Number released	Release to Lower Granite	Lower Granite to Little Goose	Little Goose to Lower Monumental	Lower Monumental to McNary Dam	Release to McNary Dam
				Wild steelhead				
Snake	03 Mar-21 May	52	290	1.079 (0.141)	0.456 (0.270)	NA	NA	NA
Asotin Creek	01 Feb-29 May	64	2,919	0.807 (0.027)	0.751 (0.208)	1.006 (0.484)	1.146 (0.620)	0.699 (0.258)
Grande Ronde	19 Mar-25 May	100	365	0.764 (0.056)	0.419 (0.226)	NA	NA	NA
Imnaha	25 Feb-31 May	142	5,271	0.814 (0.022)	1.144 (0.469)	0.931 (0.624)	0.520 (0.298)	0.450 (0.096)
Lolo Creek	23 Mar-31 May	159	1,040	0.754 (0.065)	NA	NA	NA	NA
Lochsa River	04 Apr-28 May	208	494	1.020 (0.123)	0.406 (0.324)	NA	NA	NA
Salmon	06 Apr-21 May	233	68	0.961 (0.222)	NA	NA	NA	NA
Lookingglass Cr	01 Feb-28 May	235	324	0.602 (0.065)	0.498 (0.392)	0.634 (0.671)	NA	NA
Minam	17 Mar-25 May	246	161	0.791 (0.189)	NA	NA	NA	NA
Lostine	09 Feb-30 May	274	239	0.558 (0.127)	NA	NA	NA	NA
Upper Grande Ronde	26 Mar-24 May	397	600	0.436 (0.048)	0.626 (0.527)	NA	NA	NA
Lower Lemhi R.	21 Mar-31 May	553	871	0.574 (0.038)	NA	NA	NA	NA
Hayden Creek	18 Mar-31 May	596	481	0.243 (0.034)	NA	NA	NA	NA
				Hatchery Chinook Salmon				
Snake	21 Mar-21 May	52	528	0.894 (0.120)	1.241 (1.171)	NA	NA	NA
Grande Ronde	07 Apr-23 May	100	1,359	0.775 (0.080)	0.920 (0.607)	NA	NA	NA
Salmon	17 Mar-21 May	233	3,780	0.793 (0.038)	2.436 (2.358)	0.306 (0.354)	1.008 (0.675)	0.596 (0.134)
				Hatchery steelhead				
Snake	26 Mar-21 May	52	2,406	0.925 (0.030)	1.123 (0.361)	1.012 (0.626)	NA	NA
Grande Ronde	04 Apr-25 May	100	2,832	0.853 (0.021)	0.811 (0.137)	3.111 (2.182)	0.340 (0.256)	0.731 (0.232)
Salmon	08 Apr-21 May	233	1,299	0.866 (0.034)	1.042 (0.457)	0.761 (0.562)	1.384 (1.199)	0.950 (0.598)

Appendix Table B8. Detection probability estimates for juvenile salmonids released from fish traps in Snake River Basin in 2021. Standard errors in parentheses.

Trap	Release dates	Distance to LGR (km)	Number released	Lower Granite Dam	Little Goose Dam	Lower Monumental Dam	McNary Dam
Wild Chinook salmon							
Snake	08 Apr-21 May	52	27	NA	NA	NA	NA
Grande Ronde	11 Mar-25 May	100	1,405	0.466 (0.035)	0.017 (0.016)	NA	NA
Imnaha	09 Feb-31 May	142	3,441	0.321 (0.021)	0.019 (0.009)	0.004 (0.004)	0.100 (0.021)
Lolo Creek	18 Mar-31 May	159	462	0.524 (0.084)	NA	NA	NA
Salmon	11 Mar-20 May	233	1,105	0.426 (0.039)	0.020 (0.019)	0.018 (0.016)	0.045 (0.022)
Lookingglass Cr	01 Feb-26 Apr	235	660	0.378 (0.060)	NA	NA	NA
Minam	17 Mar-13 May	246	734	0.459 (0.065)	NA	NA	NA
Lostine	05 Feb-26 May	274	575	0.371 (0.061)	0.046 (0.039)	0.018 (0.018)	0.031 (0.031)
Catherine Creek	02 Feb-29 May	362	597	0.529 (0.100)	NA	NA	NA
U. Grande Ronde	26 Mar-19 May	397	700	0.415 (0.064)	NA	NA	NA
S. Fork Salmon	13 Mar-30 Apr	408	1,440	0.426 (0.044)	NA	NA	NA
Johnson Creek	04 Mar-29 May	436	419	0.500 (0.088)	0.069 (0.047)	NA	NA
Panther Creek	16 Mar-31 May	468	842	0.418 (0.052)	0.015 (0.015)	0.013 (0.013)	0.107 (0.041)
Big Creek	19 Mar-30 Apr	489	993	0.398 (0.050)	0.085 (0.029)	NA	NA
Lower Lemhi R.	19 Mar-31 May	553	3,093	0.406 (0.027)	0.013 (0.012)	0.027 (0.012)	0.067 (0.017)
Upper Lemhi R.	20 Mar-22 May	595	311	0.583 (0.082)	NA	NA	NA
Pahsimeroi	09 Mar-31 May	621	391	0.500 (0.094)	NA	NA	NA
Marsh Creek	21 Mar-31 May	630	113	0.510 (0.250)	NA	NA	NA
Sawtooth	20 Mar-30 May	747	336	0.124 (0.067)	NA	NA	NA

Appendix Table B8. Continued.

Trap	Release dates	Distance to LGR (km)	Number released	Lower Granite Dam	Little Goose Dam	Lower Monumental Dam	McNary Dam
Wild steelhead							
Snake	03 Mar-21 May	52	290	0.514 (0.074)	0.065 (0.043)	NA	NA
Asotin Creek	01 Feb-29 May	64	2,919	0.646 (0.023)	0.026 (0.008)	0.016 (0.007)	0.018 (0.007)
Grande Ronde	19 Mar-25 May	100	365	0.782 (0.058)	0.053 (0.035)	NA	NA
Imnaha	25 Feb-31 May	142	5,271	0.612 (0.018)	0.017 (0.007)	0.012 (0.007)	0.028 (0.007)
Lolo Creek	23 Mar-31 May	159	1,040	0.484 (0.044)	NA	NA	NA
Lochsa River	04 Apr-28 May	208	494	0.449 (0.059)	0.046 (0.039)	NA	NA
Salmon	06 Apr-21 May	233	68	0.612 (0.153)	NA	NA	NA
Lookingglass Cr	01 Feb-28 May	235	324	0.698 (0.076)	0.062 (0.054)	0.051 (0.045)	NA
Minam	17 Mar-25 May	246	161	0.479 (0.121)	NA	NA	NA
Lostine	09 Feb-30 May	274	239	0.547 (0.128)	0.133 (0.088)	NA	NA
Upper Grande Ronde	26 Mar-24 May	397	600	0.639 (0.070)	0.050 (0.045)	NA	NA
Lower Lemhi R.	21 Mar-31 May	553	871	0.724 (0.047)	NA	NA	NA
Hayden Creek	18 Mar-31 May	596	481	0.780 (0.097)	NA	NA	NA
Hatchery Chinook salmon							
Snake	21 Mar-21 May	52	528	0.392 (0.057)	0.017 (0.017)	NA	NA
Grande Ronde	07 Apr-23 May	100	1,359	0.364 (0.040)	0.016 (0.012)	NA	NA
Salmon	17 Mar-21 May	233	3,780	0.447 (0.023)	0.002 (0.002)	0.005 (0.003)	0.044 (0.011)
Hatchery steelhead							
Snake	26 Mar-21 May	52	2,406	0.646 (0.023)	0.022 (0.008)	0.010 (0.005)	NA
Grande Ronde	04 Apr-25 May	100	2,832	0.738 (0.019)	0.062 (0.012)	0.005 (0.004)	0.022 (0.008)
Salmon	08 Apr-21 May	233	1,299	0.659 (0.028)	0.017 (0.008)	0.009 (0.006)	0.008 (0.006)

Appendix Table B9. Survival probability estimates for yearling Chinook, steelhead, and Coho salmon released from upper-Columbia River hatcheries in 2021. Standard errors in parentheses.

Hatchery/ Release site	Number released	Release to McNary Dam	McNary to John Day Dam	John Day to Bonneville Dam	McNary to Bonneville Dam	Release to Bonneville Dam
Yearling Chinook salmon						
Chiwawa Hatchery						
Chiwawa Pond	9,388	0.712 (0.280)	0.469 (0.248)	0.675 (0.390)	0.316 (0.191)	0.225 (0.103)
Cle Elum Hatchery						
Clark Flat Pond	16,003	0.343 (0.066)	0.587 (0.184)	0.698 (0.281)	0.410 (0.153)	0.140 (0.045)
Easton Pond	11,998	0.235 (0.063)	0.616 (0.250)	0.840 (0.514)	0.518 (0.308)	0.122 (0.065)
Jack Creek Pond	12,005	0.227 (0.048)	0.729 (0.271)	0.705 (0.388)	0.514 (0.258)	0.117 (0.053)
East Bank Hatchery						
Carlton Pond	5,235	0.808 (0.265)	0.600 (0.246)	NA	NA	NA
Chelan River	10,427	0.628 (0.127)	1.132 (0.396)	0.496 (0.201)	0.562 (0.197)	0.353 (0.101)
Dryden Pond	20,363	0.846 (0.129)	0.724 (0.168)	0.763 (0.194)	0.553 (0.132)	0.468 (0.086)
Nason Acclimation F.	31,914	0.357 (0.071)	0.844 (0.237)	0.720 (0.214)	0.608 (0.181)	0.217 (0.048)
Entiat Hatchery						
Entiat Hatchery	19,875	0.790 (0.150)	0.837 (0.214)	0.693 (0.149)	0.580 (0.133)	0.458 (0.060)
Leavenworth Hatchery						
Leavenworth NFH	19,964	0.505 (0.055)	0.751 (0.130)	1.001 (0.278)	0.752 (0.201)	0.380 (0.093)
Methow Hatchery						
Chewuch Pond	4,990	0.402 (0.113)	NA	NA	NA	NA
Goatwall Pond	4,933	0.610 (0.215)	0.618 (0.331)	1.002 (0.550)	0.619 (0.317)	0.377 (0.140)
Methow Hatchery	4,894	0.613 (0.233)	NA	NA	NA	NA
Twisp Pond	4,987	0.903 (0.432)	0.308 (0.199)	0.966 (0.480)	0.298 (0.160)	0.269 (0.065)
Wells Hatchery						
Wells Hatchery	10,966	0.626 (0.187)	0.534 (0.199)	1.717 (1.024)	0.917 (0.577)	0.574 (0.318)
Winthrop Hatchery						
Winthrop NFH	19,905	0.568 (0.084)	1.219 (0.330)	0.711 (0.218)	0.867 (0.219)	0.492 (0.101)

Appendix Table B9. Continued.

Hatchery/ Release site	Number released	Release to McNary Dam	McNary to John Day Dam	John Day to Bonneville Dam	McNary to Bonneville Dam	Release to Bonneville Dam
			Steelhead			
Chiwawa Hatchery						
Chiwawa River	20,145	0.269 (0.041)	0.499 (0.111)	0.965 (0.184)	0.482 (0.089)	0.130 (0.014)
Wells Hatchery						
Antoine Creek	4,996	0.359 (0.121)	0.399 (0.165)	1.020 (0.291)	0.407 (0.151)	0.146 (0.023)
Methow Hatchery	4,975	0.585 (0.153)	NA	NA	NA	NA
Salmon Creek	4,996	0.346 (0.117)	0.834 (0.463)	0.495 (0.235)	0.413 (0.157)	0.143 (0.025)
Similkameen Pond	4,991	0.350 (0.157)	0.615 (0.378)	0.779 (0.362)	0.479 (0.236)	0.167 (0.034)
St. Marys Pond	4,998	0.381 (0.154)	0.576 (0.305)	0.713 (0.278)	0.410 (0.183)	0.156 (0.030)
Twisp River	2,486	0.133 (0.118)	0.394 (0.446)	NA	NA	NA
Wells Hatchery	4,990	0.440 (0.078)	1.438 (0.448)	0.395 (0.114)	0.568 (0.124)	0.250 (0.032)
Winthrop NFH	2,428	0.489 (0.460)	0.522 (0.590)	0.513 (0.349)	0.268 (0.261)	0.131 (0.035)
Winthrop Hatchery						
Twisp Pond	4,445	0.251 (0.153)	1.121 (0.890)	0.768 (0.448)	0.861 (0.579)	0.216 (0.062)
Winthrop NFH	28,333	0.278 (0.038)	1.202 (0.262)	0.634 (0.122)	0.762 (0.124)	0.212 (0.019)

Appendix Table B9. Continued.

Hatchery/ Release site	Number released	Release to McNary Dam	McNary to John Day Dam	John Day to Bonneville Dam	McNary to Bonneville Dam	Release to Bonneville Dam
			Coho salmon			
Leavenworth Hatchery						
Leavenworth NFH	9,899	0.398 (0.064)	0.901 (0.228)	0.843 (0.259)	0.760 (0.219)	0.303 (0.072)
Wells Hatchery						
Twisp Pond	2,498	0.345 (0.174)	1.084 (0.778)	1.420 (1.052)	1.540 (1.130)	0.532 (0.285)
Willard Hatchery						
Eightmile Pond	4,992	0.303 (0.094)	1.218 (0.668)	0.560 (0.304)	0.682 (0.292)	0.207 (0.062)
Winthrop Hatchery						
Early Winters Pond	4,981	0.272 (0.096)	1.191 (0.674)	0.676 (0.362)	0.805 (0.370)	0.219 (0.065)
Midvalley Pond	4,974	0.296 (0.073)	1.283 (0.877)	0.872 (0.629)	1.120 (0.467)	0.331 (0.112)
Winthrop NFH	4,953	0.402 (0.100)	0.868 (0.370)	0.796 (0.317)	0.691 (0.219)	0.278 (0.055)
Yakima Hatchery						
Yakima River, rkm 256	9,610	0.408 (0.065)	0.827 (0.212)	1.236 (0.451)	1.022 (0.351)	0.417 (0.127)

Appendix Table B10. Detection probability estimates for yearling Chinook salmon, steelhead, and Coho salmon released from upper-Columbia River hatcheries in 2021. Standard errors in parentheses.

Hatchery/ Release site	Number released	McNary Dam	John Day Dam	Bonneville Dam
		Yearling Chinook salmon		
Chiwawa Hatchery				
Chiwawa Pond	9,388	0.015 (0.006)	0.020 (0.008)	0.154 (0.071)
Cle Elum Hatchery				
Clark Flat Pond	16,003	0.046 (0.009)	0.034 (0.009)	0.164 (0.053)
Easton Pond	11,998	0.043 (0.012)	0.040 (0.013)	0.143 (0.076)
Jack Creek Pond	12,005	0.064 (0.014)	0.039 (0.013)	0.149 (0.069)
East Bank Hatchery				
Carlton Pond	5,235	0.015 (0.005)	0.028 (0.008)	0.068 (0.033)
Chelan River	10,427	0.027 (0.006)	0.017 (0.005)	0.167 (0.048)
Dryden Pond	20,363	0.023 (0.004)	0.019 (0.004)	0.139 (0.026)
Nason Acclimation F.	31,914	0.017 (0.004)	0.020 (0.004)	0.149 (0.033)
Entiat Hatchery				
Entiat Hatchery	19,875	0.013 (0.003)	0.017 (0.003)	0.164 (0.022)
Leavenworth Hatchery				
Leavenworth NFH	19,964	0.046 (0.005)	0.036 (0.005)	0.158 (0.039)
Methow Hatchery				
Chewuch Pond	4,990	0.027 (0.008)	0.006 (0.004)	0.118 (0.045)
Goatwall Pond	4,933	0.020 (0.008)	0.016 (0.007)	0.154 (0.058)
Methow Hatchery	4,894	0.017 (0.007)	NA	NA
Twisp Pond	4,987	0.012 (0.006)	0.012 (0.006)	0.206 (0.051)
Wells Hatchery				
Wells Hatchery	10,966	0.017 (0.005)	0.034 (0.008)	0.073 (0.041)
Winthrop Hatchery				
Winthrop NFH	19,905	0.023 (0.004)	0.011 (0.003)	0.148 (0.030)
		Steelhead		
Chiwawa Hatchery				
Chiwawa River	20,145	0.035 (0.006)	0.027 (0.005)	0.300 (0.032)
Wells Hatchery				
Antoine Creek	4,996	0.020 (0.008)	0.026 (0.009)	0.423 (0.068)
Methow Hatchery	4,975	0.016 (0.005)	0.004 (0.003)	0.435 (0.060)
Salmon Creek	4,996	0.023 (0.008)	0.013 (0.007)	0.382 (0.069)
Similkameen Pond	4,991	0.013 (0.006)	0.014 (0.007)	0.327 (0.067)
St. Marys Pond	4,998	0.016 (0.007)	0.019 (0.008)	0.362 (0.070)
Twisp River	2,486	0.015 (0.015)	0.015 (0.015)	0.154 (0.100)
Wells Hatchery	4,990	0.035 (0.007)	0.020 (0.006)	0.441 (0.057)
Winthrop NFH	2,428	0.008 (0.008)	0.016 (0.011)	0.333 (0.091)
Winthrop Hatchery				
Twisp Pond	4,445	0.007 (0.005)	0.011 (0.006)	0.251 (0.072)
Winthrop NFH	28,333	0.017 (0.003)	0.012 (0.002)	0.341 (0.031)

Appendix Table B10. Continued.

Hatchery/ Release site	Number released	McNary Dam	John Day Dam	Bonneville Dam
		Coho salmon		
Leavenworth Hatchery				
Leavenworth NFH	9,899	0.034 (0.006)	0.025 (0.006)	0.250 (0.060)
Wells Hatchery				
Twisp Pond	2,498	0.015 (0.009)	0.016 (0.009)	0.125 (0.068)
Willard Hatchery				
Eightmile Pond	4,992	0.025 (0.009)	0.013 (0.006)	0.277 (0.083)
Winthrop Hatchery				
Early Winters Pond	4,981	0.018 (0.007)	0.012 (0.006)	0.276 (0.083)
Midvalley Pond	4,974	0.034 (0.010)	0.006 (0.004)	0.190 (0.065)
Winthrop NFH	4,953	0.025 (0.007)	0.013 (0.005)	0.316 (0.063)
Yakima Hatchery				
Yakima River, rkm 256	9,610	0.044 (0.008)	0.029 (0.006)	0.153 (0.047)

Appendix C: Environmental Conditions and Salmonid Passage Timing

Methods

In August 2021 we obtained data on daily flow, temperature, spill, and dissolved gas saturation (TDG) at Snake River dams from Columbia River DART (1996-present). We also obtained collection counts of yearling Chinook salmon and steelhead (hatchery and wild combined) compiled by the Smolt Monitoring Program (FPC 2021a). We created plots to compare daily measures of flow, temperature, spill, and TDG in 2021 vs. in selected recent years. We plotted conditions in 2021 against long-term daily quantiles using values from 1989-2021 for flow and temperature and from 2006-2021 for spill and TDG. Periods selected for flow and temperature quantiles were based on available data. For spill and TDG we used only the period since the first year of court-ordered spill.

We combined collection count data with daily estimates of the proportion of fish using the juvenile bypass system (equivalent to daily estimates of PIT-tag detection probabilities) to calculate daily estimates of the number of smolts passing Lower Granite Dam. For visual comparison, we normalized the daily estimates by dividing by the annual total and created plots of these daily passage proportions to compare with those during selected recent years and with long-term daily quantiles

In addition, for each daily group of PIT-tagged yearling Chinook salmon and steelhead detected at or released from Lower Granite Dam, we calculated an index of Snake River flow exposure. For each daily group, the index was equal to the average daily flow at Lower Monumental Dam during the period between the 25th and 75th percentiles of PIT-tag detection at Lower Monumental Dam for the daily group. We then investigated the relationship between this index and estimates of travel time from Lower Granite Dam to McNary Dam tailrace (results shown in Figure 3).

Results

Environmental conditions and management actions in 2021 resulted in a year with low flows, warmer than average water temperatures, and extremely high spill percentages for the whole migration season. During the main migration period of 1 April-15 June 2021, mean flow at Little Goose Dam was 56.1 kcfs, which was far below the long-term mean of 92.0 kcfs (1993-2021), and was the third lowest flow year in that time series.

Daily flow values were far below long-term daily medians except for a few pulses in flow during late April and early May. During those brief pulses, flow was nearer, but still below, the long-term daily median (Appendix Figure C1).

Mean water temperature at Little Goose Dam during the 2021 migration period was 11.6°C, which was slightly above the long-term mean (1993-2021) of 11.2°C. Daily water temperatures were about one degree higher than average from 23 April to 7 May, from 19 to 24 May, and from 4-15 June. Daily temperature was essentially average otherwise (Appendix Figure C1).

Mean spill discharge at Snake River dams during the 2021 migration was 38.1 kcfs, which was similar to the 2006-2021 mean of 35.6 kcfs. Daily spill discharge was moderately above average in late April and early May and close to average for the rest of the migration period (Appendix Figure C2).

Spill as a percentage of flow at Snake River dams averaged 63.2% in 2021, considerably greater than the long-term mean of 38.0% (2006-2021). In fact, spill proportions in 2021 surpassed those in 2020 to produce the highest recorded mean spill percent on record. Daily mean spill percentages in 2021 were very consistent and extremely high for the entire migration period (Appendix Figure C2).

Daily mean percent dissolved gas saturation was slightly above the long-term median in 2021, but much lower than in 2020, likely due to the lower levels of total spill discharge in 2021 (Appendix Figure C3). Daily mean percent dissolved gas saturation remained fairly consistently between 116 and 118% for the majority of the migration season, but hourly values fluctuated between approximately 114 and 125% (data not shown).

The increase in flow from 30 April to 10 May 2021 may have been associated with the large increase in Chinook passage and a smaller increase in steelhead passage around that time (Appendix Figure C4). However, the major spike in steelhead smolt passage around 20 April occurred during a period when both flow and temperature were very consistent; thus this spike was likely related to some other factor.

Daily water temperature and flow values are typically highly correlated across all four federal dams in the lower Columbia River, and we illustrate the patterns using data from The Dalles Dam (Appendix Figure C5). Daily flow values at these dams in 2021 were below the long-term median for nearly the entire migration period. In early April, daily flows were among the lowest recorded in the past three decades. Daily flows increased somewhat in mid-April, but were still far below the long-term median except for brief periods in early May and early June, during which daily flow values were only slightly below the median.

Daily water temperature values in 2021 were above average in the lower Columbia River for nearly the entire migration period (Appendix Figure C5). Water temperature was between one-half and one degree above the median, except for an extremely brief period around 12 April and during the second week of June, when water temperature was essentially equal to the median.

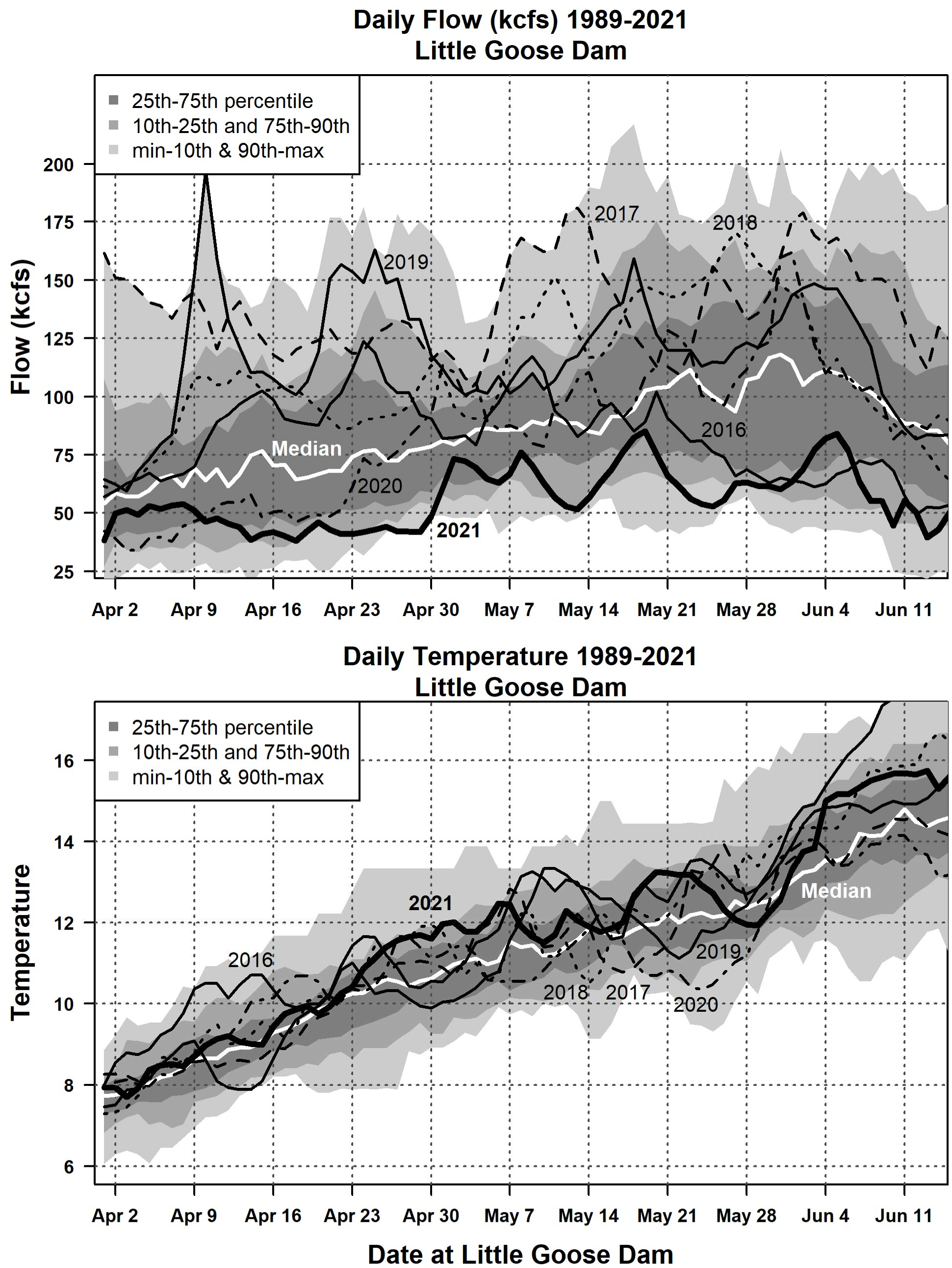
Daily and seasonal spill patterns varied widely among the four dams on the lower Columbia River. At McNary Dam in 2021, spill volume was about average overall, but daily spill volumes varied from moderately below average during early April and late May to slightly above average during late April and early June (Appendix Figure C6). However, spill as a percentage of flow at McNary Dam was far above average for the entire migration period, with only 2017 and 2020 having higher spill percentages in recent years.

At John Day Dam in 2021, spill volume was slightly above average overall. Daily spill volumes varied from near-average in early April and late May to moderately above average in early May and early June (Appendix Figure C7). However, spill as a percentage of flow was extremely high for the entire migration season in 2021, even more so at John Day than at McNary. The 2021 migration season had the highest spill percentages ever recorded at John Day.

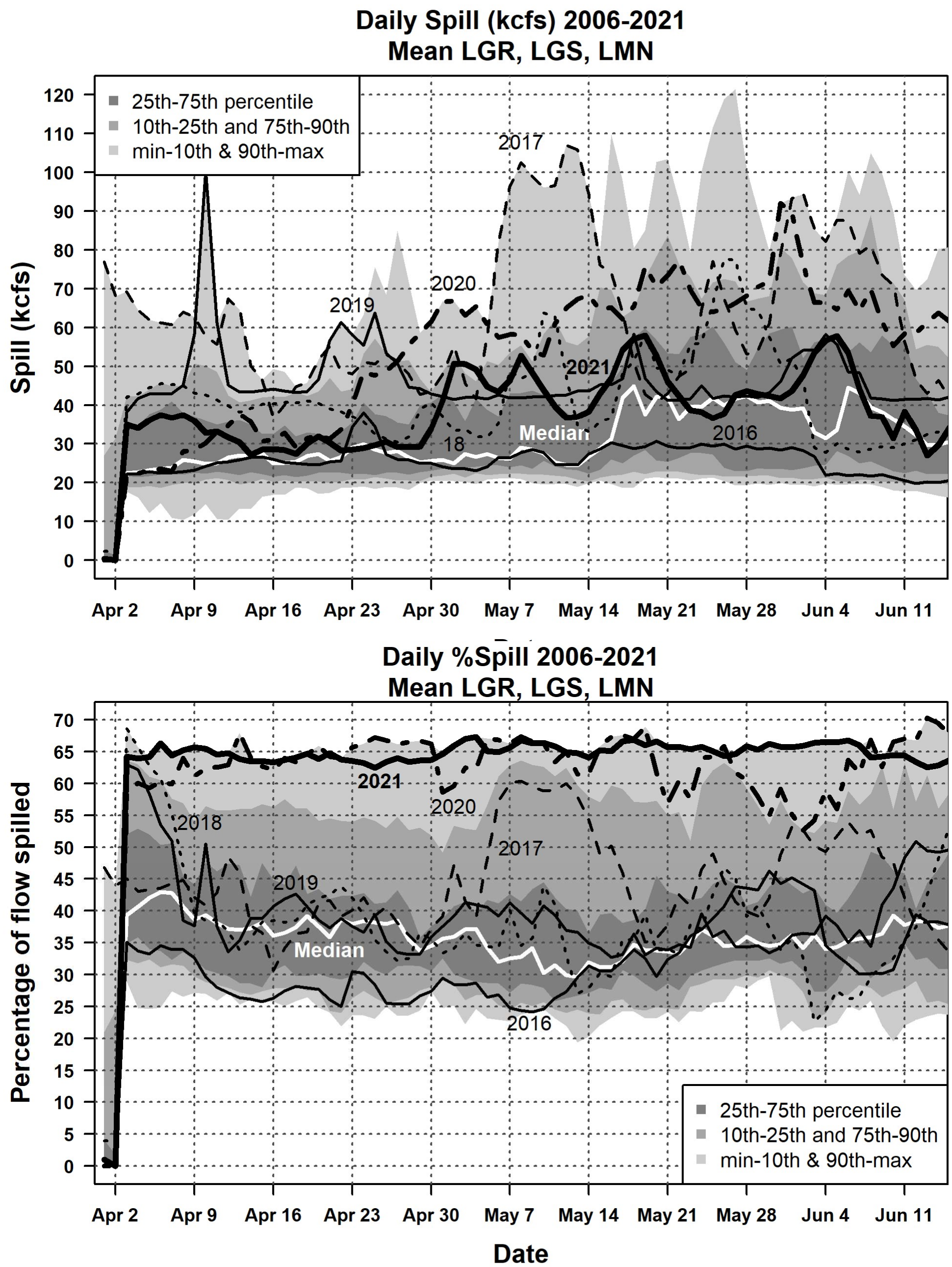
Spill operations at The Dalles Dam are less variable from year to year than at other dams, primarily to match a constant target of 40% spill. This spill percentage was matched almost exactly for the full migration season at The Dalles Dam (Appendix Figure C8). However, because flow was well below average, this resulted in spill volumes that were far below average in 2021 at The Dalles.

At Bonneville Dam in 2021, overall spill volume was essentially average. Daily spill volumes were average in early April, slightly above average in late April and early May, and average again for the rest of May and into June (Appendix Figure C9). However, similar to John Day, spill as a percentage of flow was extremely high at Bonneville Dam for nearly the whole migration season. During April and May 2021, spill percentage was higher at Bonneville than in any previous year.

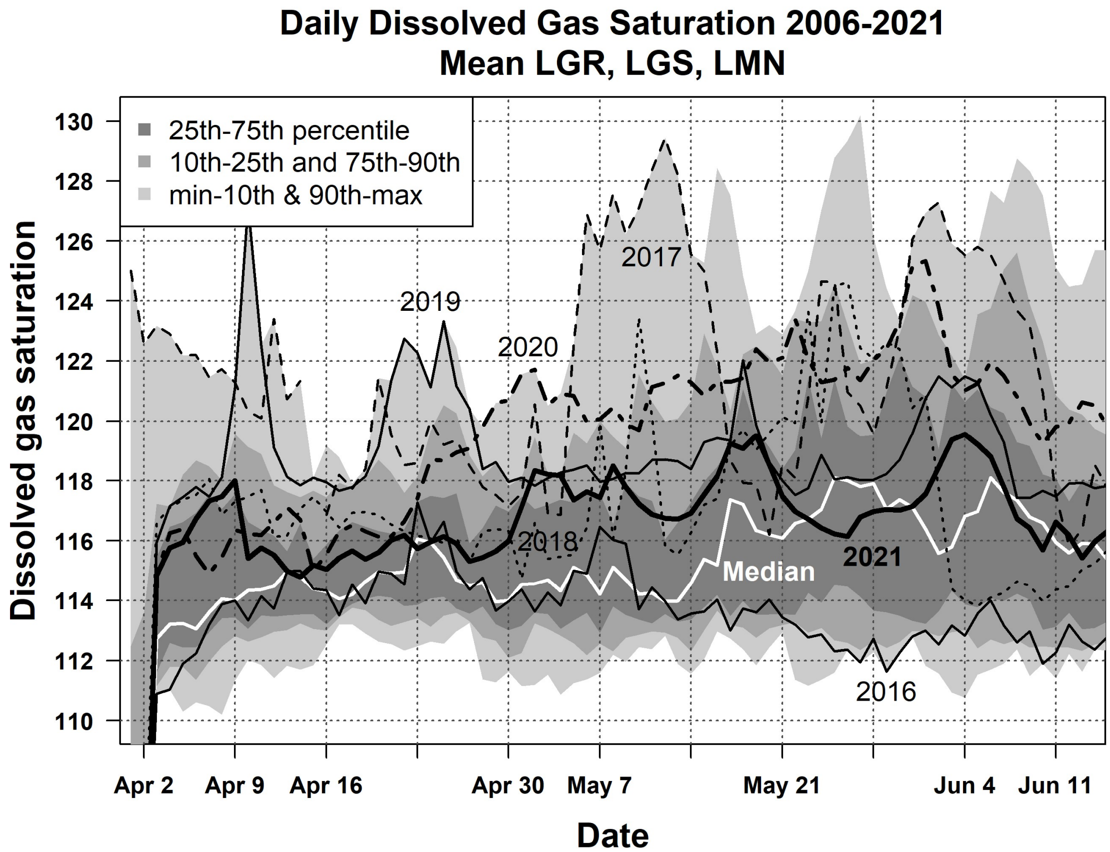
Daily mean percent dissolved gas saturation stayed close to the long-term median in 2021 at McNary, John Day, and Bonneville Dam (Appendix Figures C10-C11). Daily mean percent dissolved gas saturation remained fairly consistently between 116 and 120% for the majority of the migration season at all three dams. However, daily dissolved gas saturation was frequently above the long-term median at The Dalles Dam in 2021, with significantly greater fluctuation than at the other lower Columbia River dams. Daily dissolved gas concentrations peaked during early May, mid-May, and late May at The Dalles, with each peak reaching between 120 and 122% total dissolved gas.



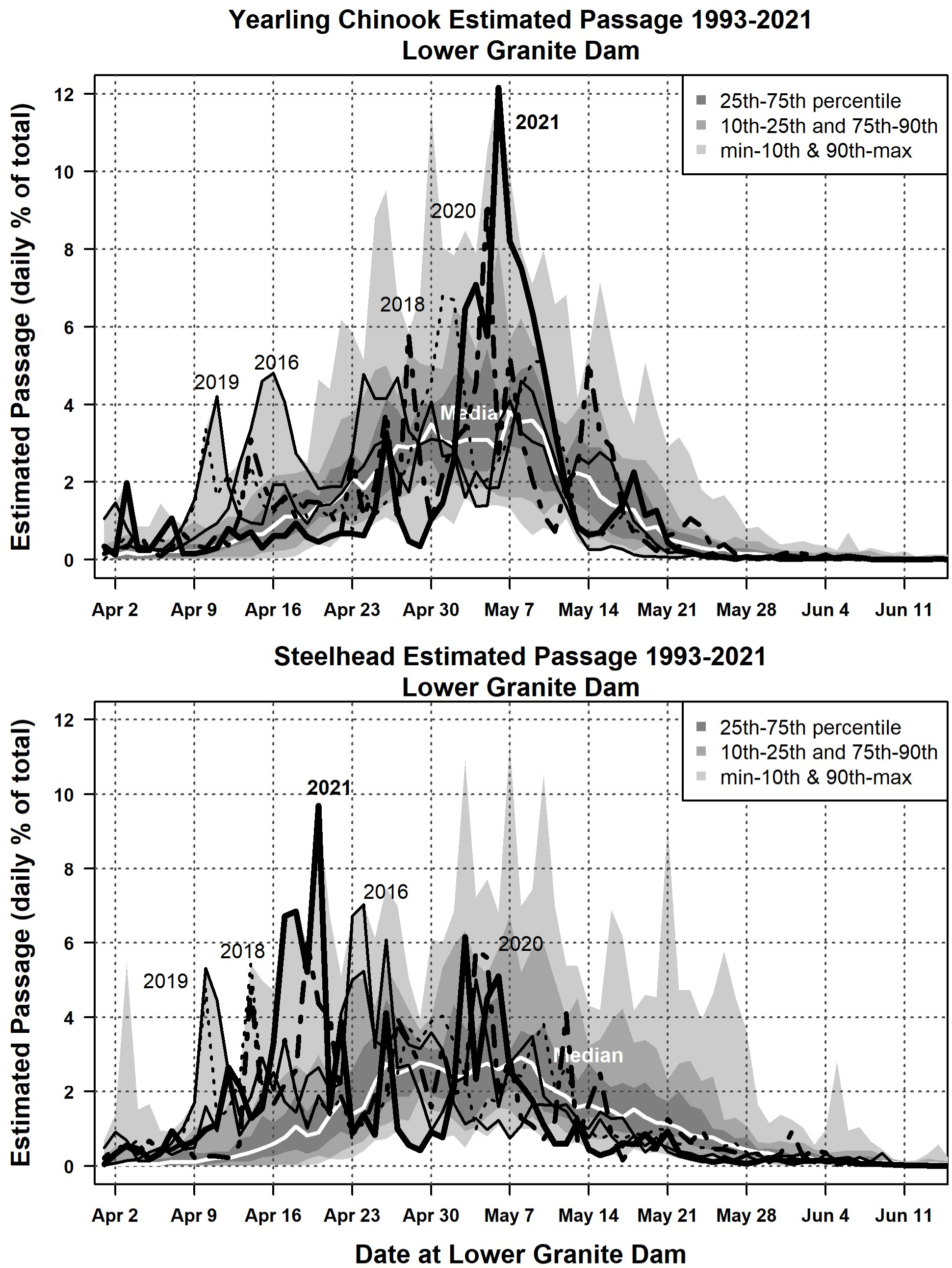
Appendix Figure C1. Upper panel shows daily mean flow at Little Goose Dam from April to mid-June. Lines show daily mean flows for 2021 and selected recent years and long-term median. Shaded areas illustrate daily quantiles for 1989-2021. Lower panel uses the same format to show daily mean temperature at Little Goose Dam. Quantiles for daily temperature are calculated from 1989 to 2021.



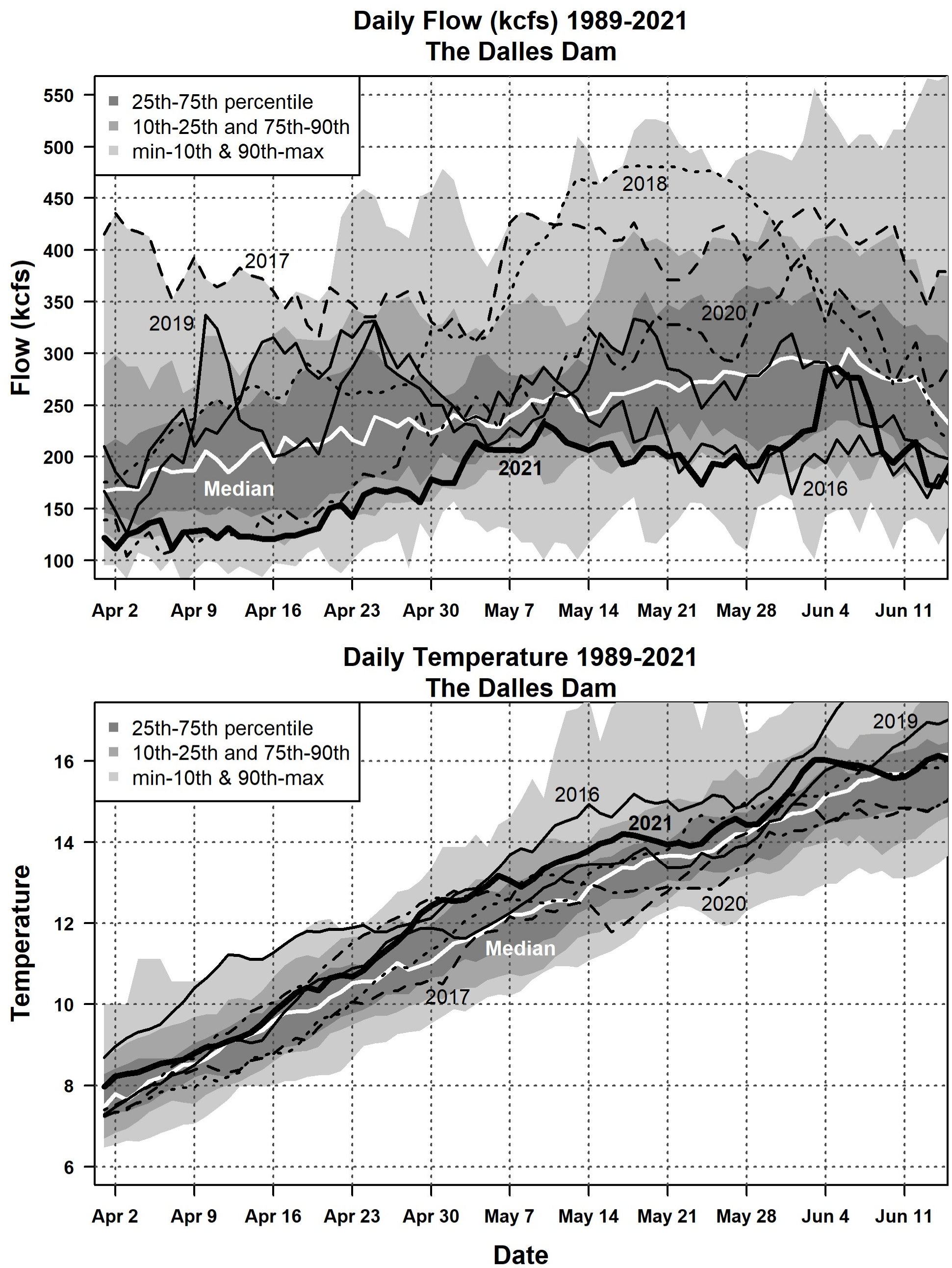
Appendix Figure C2. Upper panel shows daily mean Snake River spill (kcfs) from April to mid-June, averaged across Lower Granite, Little Goose and Lower Monumental Dams. Lower panel shows daily spill as a percentage of total flow. Lines show daily values for 2021, selected recent years, and the long-term median. Shaded areas indicate daily quantiles for 2006-2021.



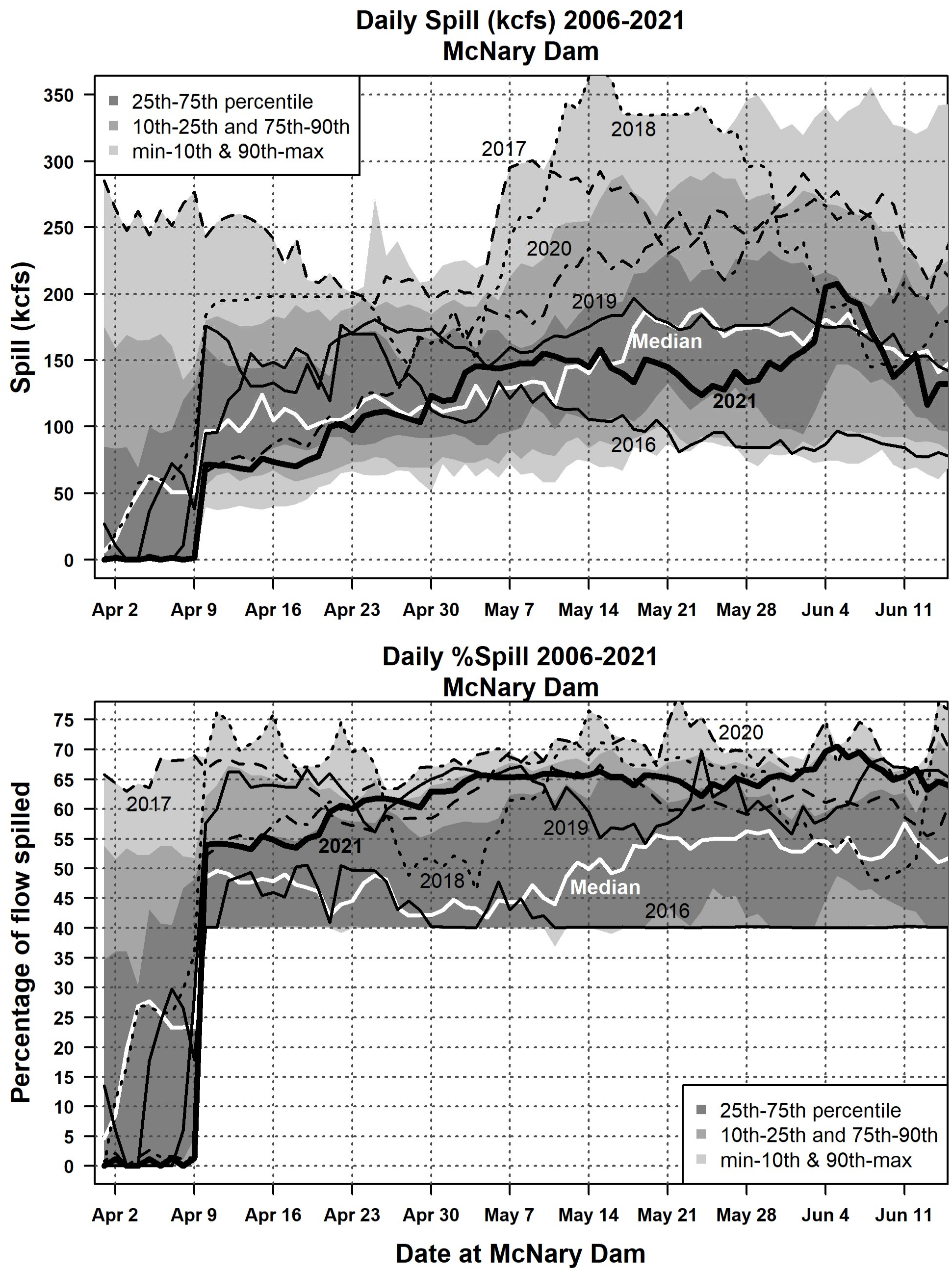
Appendix Figure C3. Daily mean percentage of dissolved gas averaged across Lower Granite, Little Goose and Lower Monumental Dam from April to mid-June 2021. Lines show daily percentage for 2021, selected recent years, and the long-term median. Shaded areas indicate daily quantiles for 2006-2021.



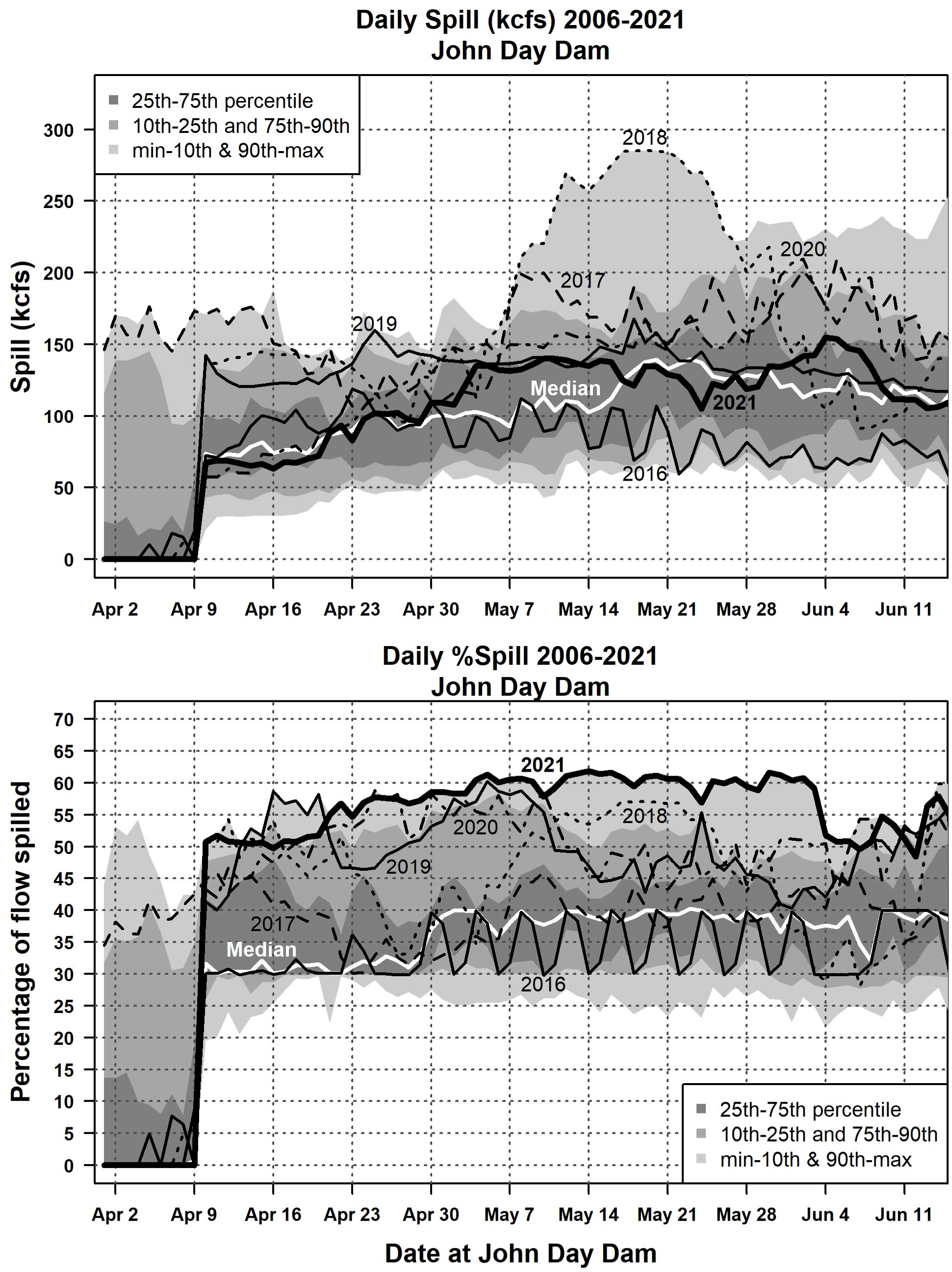
Appendix Figure C4. Estimated daily smolt passage at Lower Granite Dam for yearling Chinook salmon and steelhead. Daily passage is expressed as percentage of the yearly total. Lines indicate daily values for 2021, the long term median, and selected recent years. Shaded areas indicate smolt-passage quantiles from 1993 to 2021.



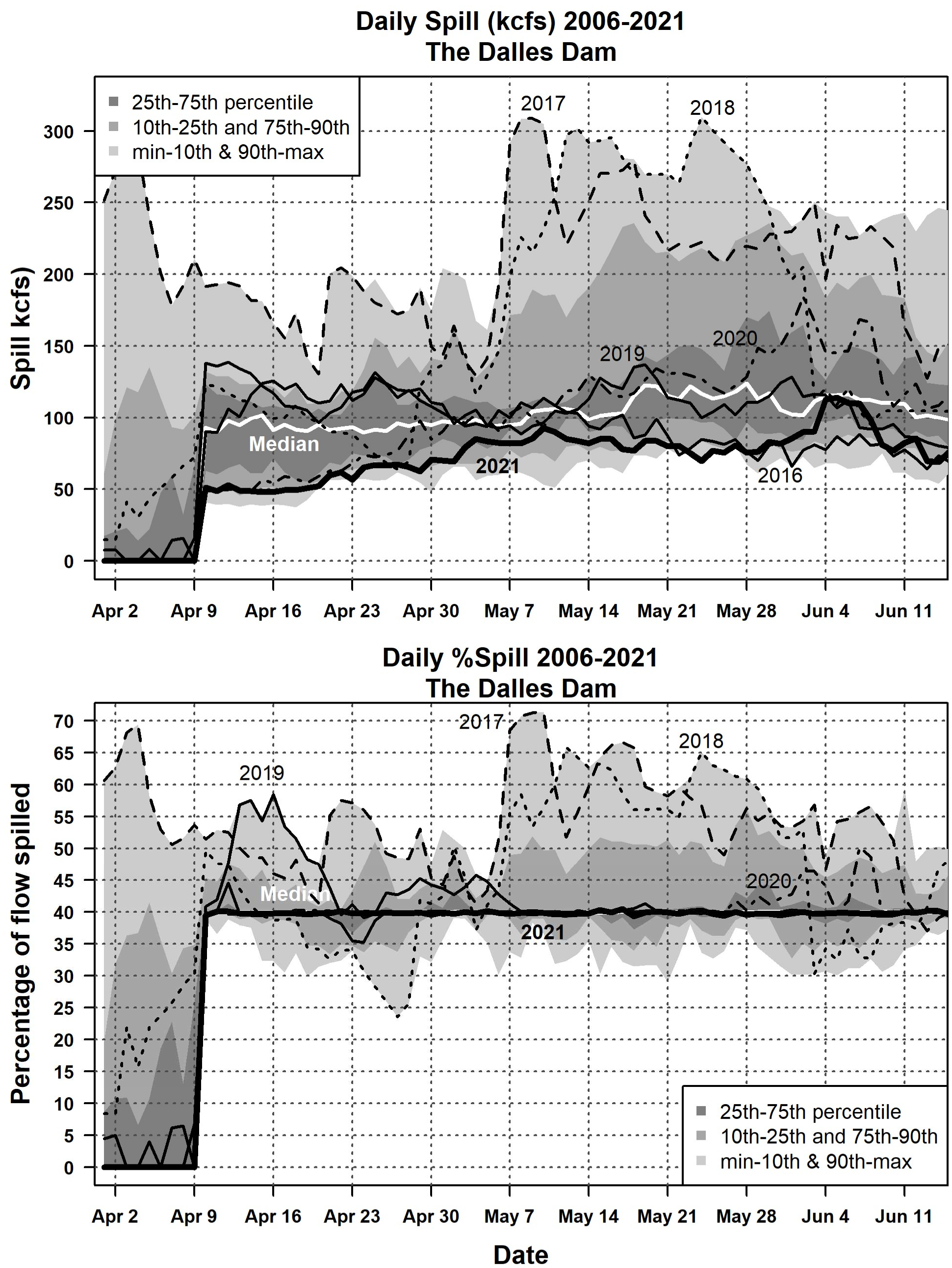
Appendix Figure C5. Upper panel shows daily mean flow at The Dalles Dam from April to mid-June. Lines show daily mean flows for 2021, selected recent years, and the long-term median. Shaded areas illustrate daily quantiles from 1989 to 2021. Lower panel uses the same format to show daily mean temperature at The Dalles Dam. Quantiles for daily temperature are calculated from 1989 to 2021.



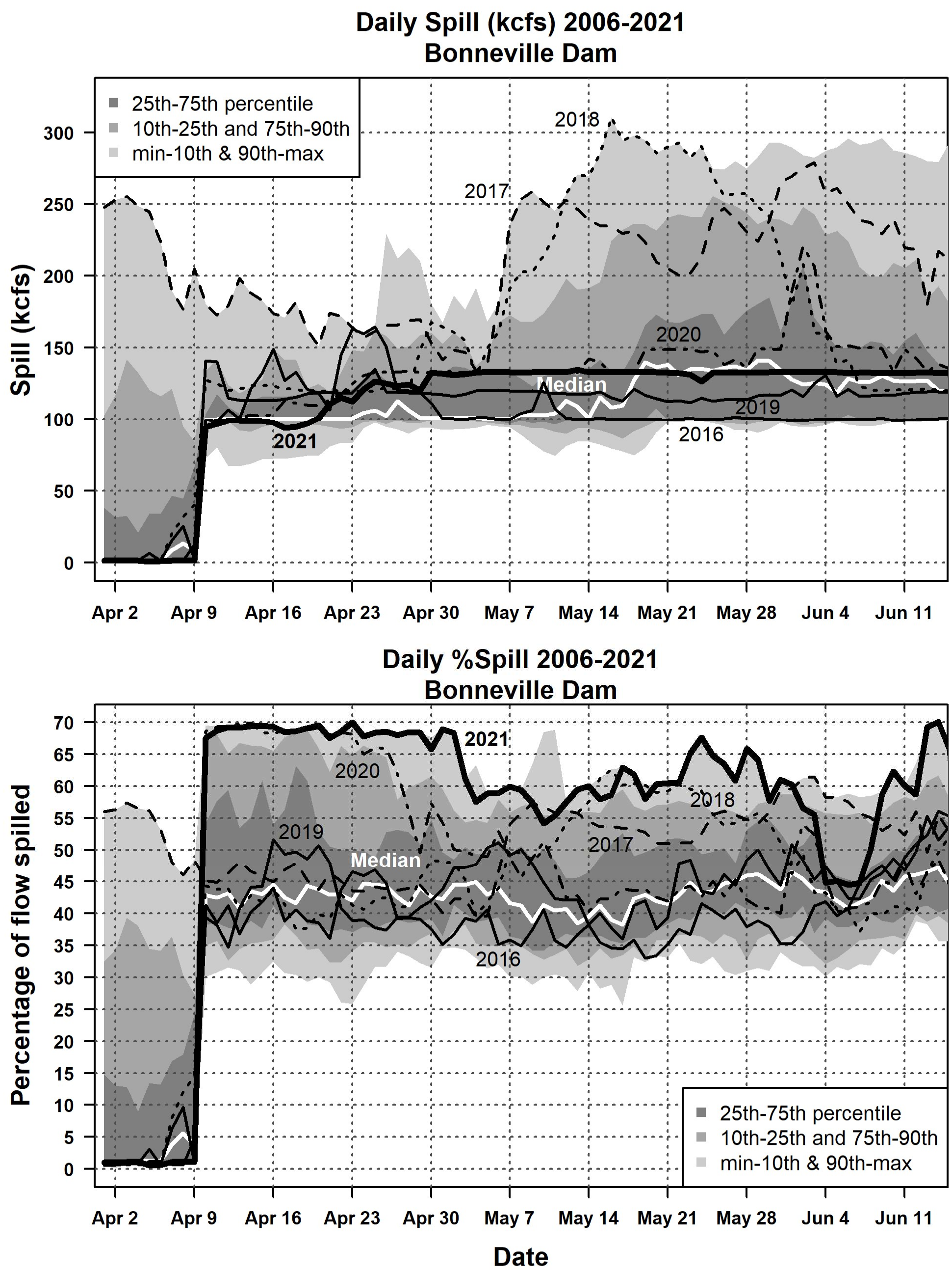
Appendix Figure C6. Upper panel shows daily mean spill (kcfs) from April to mid-June at McNary Dam. Lower panel shows daily spill as a percentage of total flow. Lines show daily values for 2021, selected recent years, and the long-term median. Shaded areas indicate daily quantiles for 2006-2021.



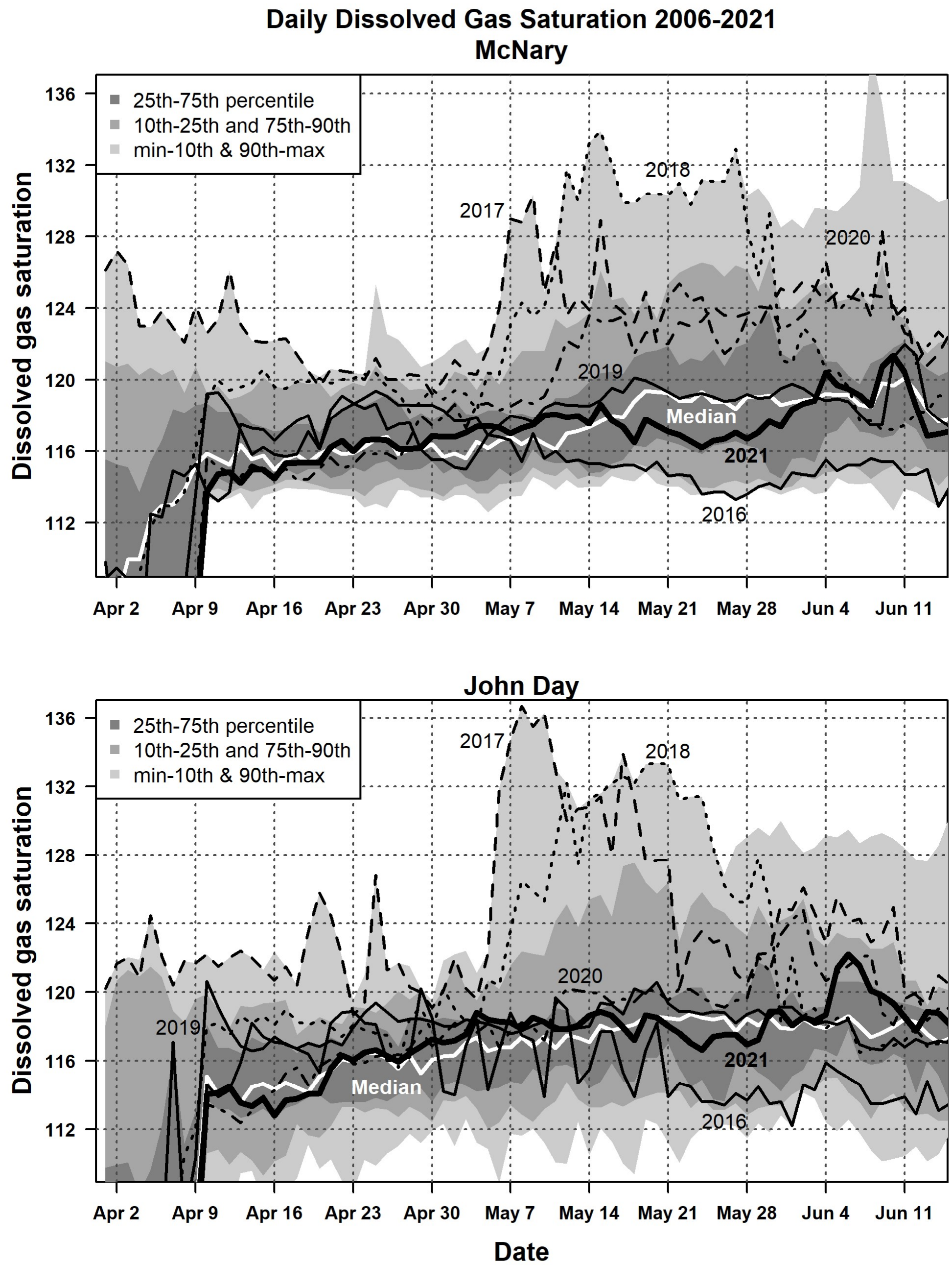
Appendix Figure C7. Upper panel shows daily mean spill (kcfs) from April to mid-June at John Day Dam. Lower panel shows daily spill as a percentage of total flow. Lines show daily values for 2021, selected recent years, and the long-term median. Shaded areas indicate daily quantiles for 2006-2021.



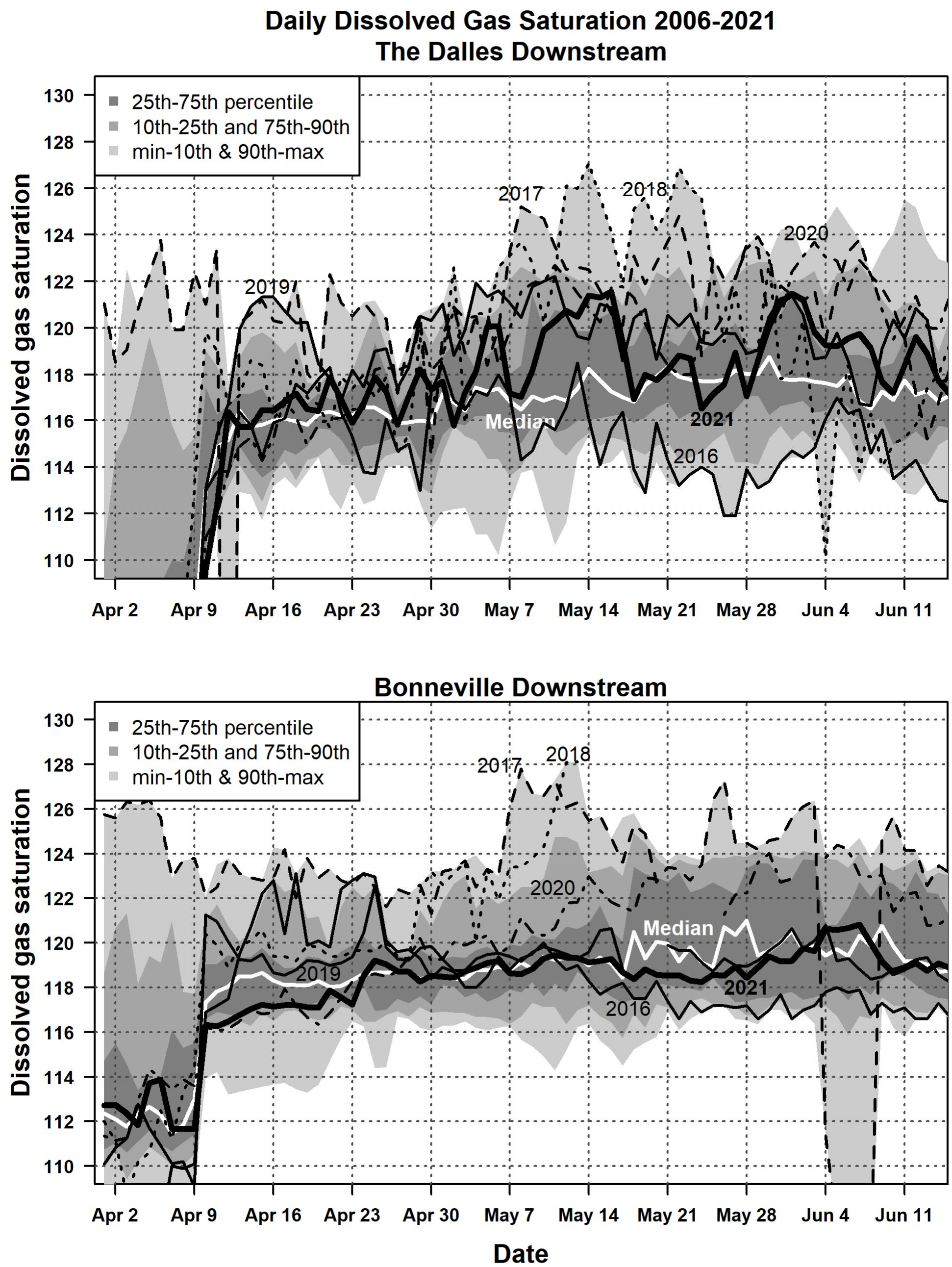
Appendix Figure C8. Upper panel shows daily mean spill (kcfs) from April to mid-June at The Dalles Dam. Lower panel shows daily spill as a percentage of total flow. Lines show daily values for 2021, selected recent years, and the long-term median. Shaded areas indicate daily quantiles for 2006-2021.



Appendix Figure C9. Upper panel shows daily mean spill (kcfs) from April to mid-June at Bonneville Dam. Lower panel shows daily spill as a percentage of total flow. Lines show daily values for 2021, selected recent years, and the long-term median. Shaded areas indicate daily quantiles for 2006-2021.



Appendix Figure C10. Daily mean percentage of dissolved gas at McNary and John Day Dam from April to mid-June 2021. Lines show daily percentage for 2021, selected recent years, and the long-term median. Shaded areas indicate daily quantiles for 2006-2021.



Appendix Figure C11. Daily mean percentage of dissolved gas at The Dalles and Bonneville Dam from April to mid-June 2021. Lines show daily percentage for 2021, selected recent years, and the long-term median. Shaded areas indicate daily quantiles for 2006-2021.

Appendix D: Use of Bayesian Methods and Tag Recoveries from Interior Columbia Avian Colonies

Introduction

The quality of our survival estimates for migrating juvenile salmon has been degraded in recent years by a substantial reduction in detection probability at most dams. For some stocks, there has been a corresponding reduction in the number of fish tagged at Lower Granite Dam. This degradation of data quality prompted us to review the data sources and statistical methods we have customarily used and to explore potential additional data, as well as alternative methods and models, for survival estimation.

Until 2020, we made use of data from the Columbia River estuary, downstream of Bonneville Dam, exclusively from detections of live fish by the estuary trawl detection system. In 2020, operation of the trawl was canceled under COVID-19 restrictions. Therefore, instead of data from trawl detections, we used data from recoveries of PIT tags deposited by predaceous birds at various sites in the estuary. As detailed in the *Survival from Release to Bonneville Dam* section of this report, we used both sources of data in 2021, and will continue to do so in the future.

Thus, in 2021 we began estimating survival to Bonneville using data from both live fish detected in the estuary and recoveries of tags from dead fish taken by birds and deposited at sites in the estuary. Using the data in this way did not require modifications to our statistical models. Using the data in this way did not require modifications to our statistical models, because live detections and dead recoveries in the estuary provide equivalent information with respect to using the CJS model to estimate survival to Bonneville Dam.

We have not previously made use of data from avian colonies in the interior Columbia Basin, where recovered tags are from dead fish that were taken by birds upstream of Bonneville Dam. In both the estuary and the interior Columbia, tags are deposited during the annual period when avian nesting and smolt migration coincide. Tags are recovered later in the fall after birds have dispersed.

However, in contrast to the estuary data, interior-colony recoveries represent mortalities that occurred within river reaches for which we estimate survival. Because the interior dead-recovery sites intervene between sites of live detection, the standard CJS model is not a valid representation of the data; mark-recapture-recovery models are required. We developed such models to incorporate data from interior avian colonies, and investigated whether this approach would result in survival estimates of improved quality. Here we present results of these efforts.

Bayesian statistical methods are well-suited to accommodate the use of recoveries from dead fish in survival estimation. They offer a number of potential advantages over our customary approach:

- Bayesian methods are generally better suited for complex models, as they more completely represent underlying data-generating processes.
- When information from data is low, parameter estimation using Bayesian methods can use prior information—which can come from previous studies.
- Bayesian posterior distributions of estimated parameters are more flexible and accurate than the sampling distributions employed under a frequentist approach, leading to better characterization of the uncertainty in estimation.
- For models in which estimated survival probabilities are constrained between zero and one, estimates from Bayesian models are better behaved. In frequentist mark-recapture models with such constraints, biased estimates can result, and uncertainty in the estimates can be underestimated or not estimable at all (standard error equal to zero).

The Cormack-Jolly-Seber (CJS) mark-recapture model (Cormack 1964; Jolly 1965; Seber 1965) is widely used among the fisheries community, and it has been our customary statistical tool for smolt survival estimation. Other researchers have adapted the CJS model to a Bayesian framework (Brooks et al. 2000; Poole 2002; Bonner and Schwarz 2006; Gimenez et al. 2007; Muthukumarana et al. 2008; Schofield et al. 2009), and these adaptations have included applications for estimating survival of salmon.

Muthukumarana et al. (2008) developed a method to jointly estimate survival, detection, and travel time of salmon, where survival was dependent on travel time, and unobserved travel times were estimated as parameters. Perry et al. (2018) built on the methods of Muthukumarana et al. (2008), extending the Bayesian approach to a multistate framework, which captured temporal variation in detection and survival that other methods could not. Hance et al. (2020) developed a method of jointly estimating survival, detection, and travel time that integrated over unobserved travel times, thus improving computational efficiency. Hance et al. (2022) extended those models to a multistate framework.

Mark-recapture models that include recoveries from dead fish (i.e., mark-recapture-recovery models) were originally developed in the frequentist setting (Burnham

1993; Barker 1997; Catchpole et al. 1998). These models were later adapted to the Bayesian setting (e.g., King and Brooks 2002; King 2012). For estimation of salmon survival, Hostetter et al. (2018) and Payton et al. (2020) developed Bayesian mark-recapture-recovery models that take advantage of PIT-tag recoveries from avian colonies. Hostetter et al. (2018) use a state-space model formulation that operates on the level of individual fish and requires the use of discrete latent-state parameters to model the unobserved states of the survival process. Their approach is similar to the method described by King (2012).

The model of Payton et al. (2020) does not require latent-state variables and has the advantage of estimating different sources of mortality separately, drawing on an approach proposed by Schaub and Pradel (2004). However, the Payton et al. model requires additional data on tag-deposition rates and detection efficiency of tag-recovery efforts, either or both of which may not be available. Both the Hostetter et al. (2018) and Payton et al. (2020) models built on the general recovery model of Catchpole et al. (2001) to account for the possibility that a tag could be transported and deposited outside the reach where the predation event occurred.

Here we present a modeling framework similar to that of Payton et al. (2020), but without the explicit modeling of separate sources of mortality and without the need for data on tag-deposition rates and detection efficiency of recovery efforts. Instead, we modeled the joint probability of being taken by a bird *and* having the tag deposited and detected on a colony, given that the fish died in a particular reach. This framework requires only live-detection and dead-recovery data.

We developed this approach so that results could be directly compared to those from the standard frequentist CJS model. We are developing an extension of the model of Hance et al. (2020) to utilize dead-recovery data from interior avian colonies. Although we expect to use this extended model as our standard approach in the future, at present we confine our reporting to the initial comparison using the simpler model.

This appendix is intended to (1) introduce our use of Bayesian methods for survival estimation in the familiar context of the type of data used in this and previous annual reports, and (2) establish proof-of-concept for the incorporation of data from tags recovered on avian colonies in the interior Columbia Basin. We provide Bayesian estimates for a few key stocks of interest in the 2021 migration year and compare them to estimates from the standard frequentist CJS model. We also compare Bayesian estimates between models that incorporate recoveries from interior avian colonies and those that use only detection data from live fish passing dams.

Methods

We created Bayesian CJS models that either did or did not account for recoveries of tags from avian colonies in the interior Columbia Basin. We use the abbreviation "BCJS" for the Bayesian CJS model that does not include interior island dead recoveries and "BCJS-DR" for the model that does.

We provide estimates from both models for comparison, with the same temporal groupings used for standard CJS estimates reported in the *Survival from Release to Bonneville Dam* section of this report. Full statistical details of the Bayesian models and inference methods are not provided here, but will be included in future reports, after the approach has been adopted to our annual survival estimates. Here we explain the crucial components of how the BCJS-DR model handles mortality and tag recovery data.

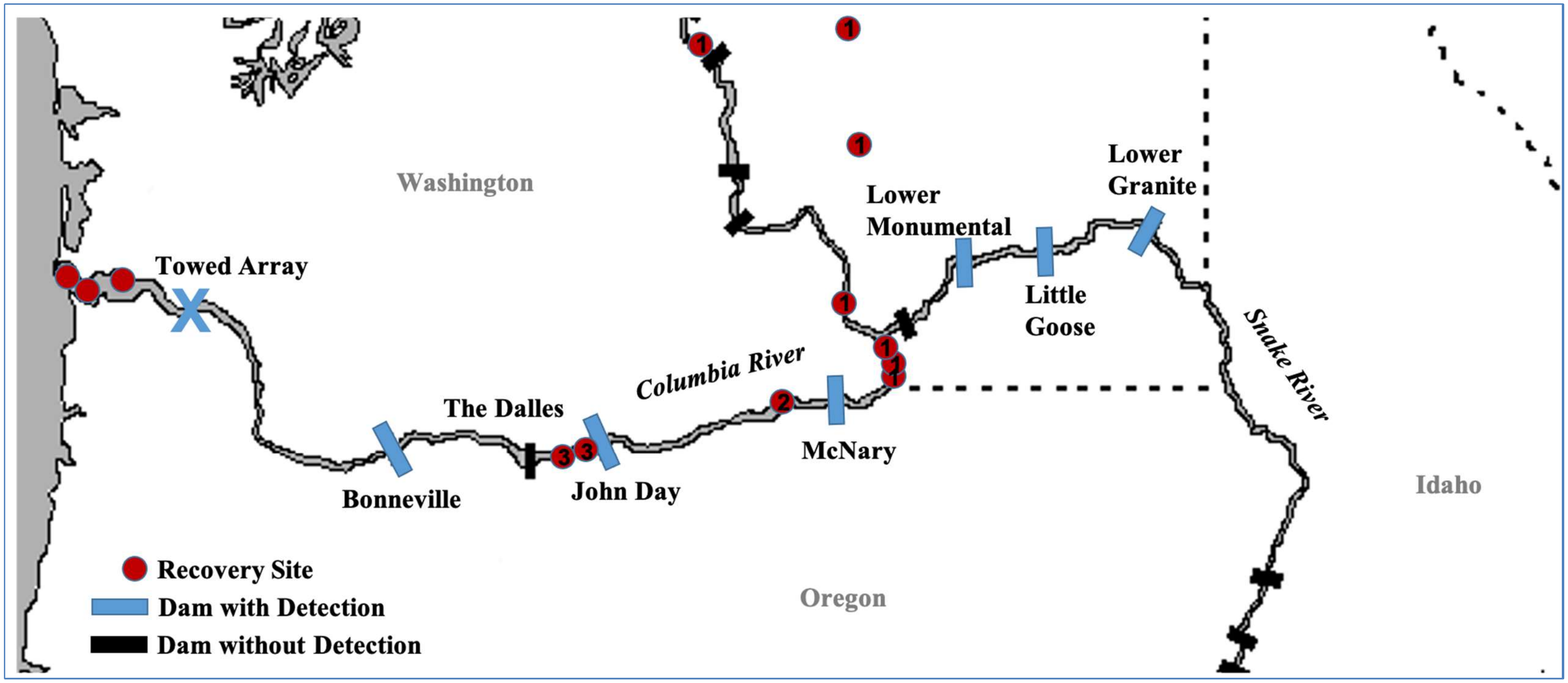
There were ten tag-recovery locations in the interior Columbia Basin and three recovery locations in the Columbia River estuary in 2021. Each location had one or more avian colonies represented by different bird species (see Evans et al. 2016 for details on species and locations). We pooled dead recoveries from the estuary with live detections that occurred there, treating all as a single detection site, just as we did for the CJS model in the *Survival from Release to Bonneville Dam* section of this report.

For both standard CJS and the Bayesian models, data from the estuary serve only to identify fish that survived to pass Bonneville Dam. None of the models allows separate estimation of survival, detection, and recovery probabilities downstream of Bonneville Dam. With respect to these models, all live detections and dead recoveries in the estuary provide equivalent information. However, this is not the case for detections and recoveries from the interior sites, and for the data upstream of Bonneville Dam the two types of data cannot be pooled.

To formulate the BCJS-DR model, we combined recoveries from interior colonies for all bird species from the various locations into a set of three synthetic "pooled recovery sites," based on their physical location relative to specific dams in the migration corridor (Appendix Table D1; Appendix Figure D1). First, all colonies located upstream of McNary Dam were pooled into a single recovery site due to the proximity of most sites to each other and to the relatively concentrated foraging locations of colonies between Lower Monumental and McNary Dam or on the upper Columbia River (Evans et al. 2016; Payton et al. 2020).

Appendix Table D1. Sites with avian colonies with PIT-tag recoveries for smolt migration year 2021 and designated pooled recovery sites. Colonies and sites were pooled across bird species and based on colony location for those in the interior Columbia Basin.

Colony site name	Site location	Location (rkm)	Pooled site no.
Sites upstream from McNary Dam			
Lenore Lake	Banks Lake subbasin	-	1
Potholes Reservoir	Lower Crab subbasin	-	1
Rock Isl Forebay Waterbird Colony	Upper Columbia, Rock Island Pool	730	1
Richland Island	Upper Columbia, Hanford Reach	545	1
Foundation Island	Middle Columbia, Lake Wallula	518	1
Badger Island	Middle Columbia, Lake Wallula	512	1
Crescent Island	Middle Columbia, Lake Wallula	510	1
McNary Dam		**470**	
Central Blalock Island	Mid-Columbia, Lake Umatilla	440	2
John Day Dam		**347**	
Preacher's Island	Middle Columbia, Lake Celilo	345	3
Little Miller Island	Middle Columbia, Lake Celilo	331	3
The Dalles Dam		**308**	
Bonneville Dam		**234**	
Miller Sands Island	Estuary	38	-
Astoria-Megler Bridge	Estuary	12	-
East Sand Island	Estuary	8	-



Appendix Figure D1. Location of individual recovery sites (red circles) comprising one or more avian colonies with PIT-tag recoveries in 2021. Recovery sites are labeled with the pooled recovery site numbers shown in Appendix Table D1 and Appendix Figure D2. Also shown are dams with PIT-tag detection, dams without PIT-tag detection, and the location of the towed array in the estuary.

Similarly, we designated a second pooled recovery site comprising all recoveries from colonies between McNary and John Day Dam (only Central Blalock Island in 2021), and a third for all recoveries from colonies between John Day and Bonneville Dam. Combining individual colonies into pooled sites reduced the number of parameters necessary in the models and reduced sparsity in the recovery data. Hereafter, we will refer to these synthetic sites simply as “recovery sites.”

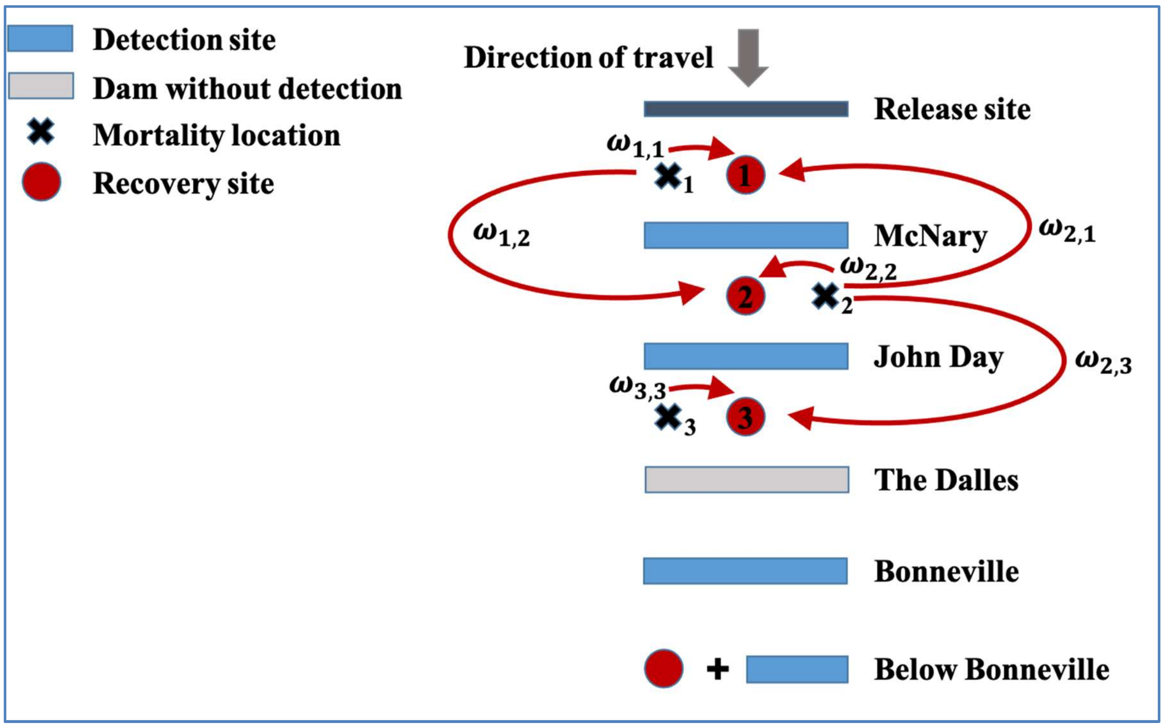
It is important to accurately account for the processes that generated the data in our models, including the fact that a bird from a colony located in one river segment may deposit a tag from a fish that was captured in a different segment. For example, a bird might capture a fish in the tailrace of McNary Dam and carry it back to its colony upstream of McNary Dam; another bird might capture a fish in the forebay of John Day Dam but move downstream and deposit the tag on its colony in The Dalles Reservoir.

The BCJS-DR model includes specific conditional joint probabilities to account for this behavior. Given that a fish died within a particular river segment, each such parameter was the joint probability that mortality was caused by a bird *and* that the tag was transported to, deposited on, and eventually recovered at each of the possible pooled recovery sites (Appendix Figure D2). For example, for Upper Columbia River fish not surviving from release to McNary Dam, the model included probabilities of fish being captured by birds in the reach *and* the tags being recovered on either the recovery site in Lake Wallula (McNary reservoir; site 1), the recovery site in Lake Umatilla (John Day reservoir; site 2), or not recovered at all. We did not include a parameter for recovery on recovery site 3 because data suggests that tags from fish captured upstream of McNary Dam are very rarely deposited downstream of John Day Dam. The set of probabilities associated with fish captured in a particular river segment sum to one. To determine which parameters to include in our model, we used information from Evans et al. (2016) and Payton et al. (2020) regarding the most likely combinations of foraging sites and colony deposition sites.

Consider the reach from release in the upper Columbia River to McNary Dam (Appendix Figure D2). We denote this reach 1 and define three possible sources of mortality for the reach. Let $\theta_{A1,1}$ be mortality due to avian predation in reach 1 by birds from recovery site 1 (i.e., tags will be deposited on recovery site 1), let $\theta_{A1,2}$ be mortality due to avian predation in reach 1 by birds from recovery site 2, and let θ_{O1} be mortality due to all other sources in reach 1. Further, let total mortality in reach 1 be $\theta_{T1} = \theta_{A1,1} + \theta_{A1,2} + \theta_{O1}$. If we denote the probability of survival from release to McNary Dam as ϕ_1, then:

$$(1 - \phi_1) = \theta_{T1} = \theta_{A1,1} + \theta_{A1,2} + \theta_{O1}.$$

For the purpose of building the model, we are interested in the proportion of total mortality that is due to each source of avian predation, although these proportions are not directly estimable with our model (see below). Following concepts in Schaub and Pradel (2004) and Payton et al. (2020), we let $\alpha_{j,k}$ be the conditional probability that a fish died by mortality source k, given it died in reach j, where $j = 1, \dots, J-1$ and $k = 1, \dots, K$.



Appendix Figure D2. Diagram of combinations of mortality location and recovery site allowed by the BCJS-DR model for fish released from Upper Columbia or Yakima River sites. Blue bars indicate dams with capability to detect live fish passing, black exes indicate general locations between detection or release sites where fish may encounter predation mortality, and red circles represent pooled recovery sites (Appendix Table D1). Arrows indicate possible routes of tag transfer from mortality locations to recovery sites, and arrows are labeled with their associated recovery parameters. Detections of live fish downstream of Bonneville Dam were combined with recoveries of tags on estuary nesting sites (dead fish).

Here J is the total number of reaches, and we assume there is no mortality due to avian predation from the interior colonies in the final reach. The first $K-1$ mortality sources are avian predation by birds from recovery site k, while mortality source K represents all other sources of mortality combined.

For the example of fish released in the upper Columbia River, $J=4$ and $K=4$. Note that $\alpha_{j,k} \in [0,1]\ \forall j,k$ and $\sum_{k=1}^{K} \alpha_{j,k} = 1$. We assume $\alpha_{1,3} = 0$ in this example. It follows that $\alpha_{1,1}(1-\phi_1) = \theta_{A1,1}$, $\alpha_{1,2}(1-\phi_1) = \theta_{A1,2}$, and $\alpha_{1,4}(1-\phi_1) = \theta_{O1}$. Likewise, $\alpha_{1,1} = \theta_{A1,1}/\theta_{T1}$ and $\alpha_{1,2} = \theta_{A1,2}/\theta_{T1}$, so the $\alpha_{j,k}$ parameters represent the respective proportions of total mortality due to each source of mortality within reach j.

For a tag to be recovered from a recovery site, given the fish was predated on by birds from a colony represented by that site, it must first be deposited on the site and then be detected by tag-recovery efforts. Both of these steps can be assigned a probability, but such conditional probabilities are confounded if data specific to each step are not available to allow estimation. Rather than modeling the probabilities separately, we define $\delta_{j,k}$ to be the joint conditional probability of the tag from a dead fish being deposited ***and*** detected on recovery site *k*, given it was taken by a bird from recovery site *k* in reach *j*. We assume tags are not recovered from fish dying by causes other than avian predation; thus $\delta_{j,K} = 0$ for all *j*.

Thus, the probability of a fish being taken by birds from recovery site 1 in reach 1 and having its tag recovered on recovery site 1 is $\alpha_{1,1}\delta_{1,1}(1-\phi_1)$, or equivalently, $\delta_{1,1}\theta_{A1,1}$. The probability of a fish being taken by birds from recovery site 1 in reach 1 and not having its tag recovered is $\alpha_{1,1}\left(1-\delta_{1,1}\right)(1-\phi_1)$, or equivalently, $(1-\delta_{1,1})\theta_{A1,1}$. Similar notation follows for probabilities associated with other mortality sources and with other recovery sites. We can now partition the total mortality in reach 1 as:

$$\begin{aligned}(1-\phi_1) = {} & \alpha_{1,1}\delta_{1,1}(1-\phi_1) + \alpha_{1,2}\delta_{1,2}(1-\phi_1) \\ & + \left[\alpha_{1,1}\left(1-\delta_{1,1}\right)(1-\phi_1) + \alpha_{1,2}\left(1-\delta_{1,2}\right)(1-\phi_1) \right. \\ & \left. + \alpha_{1,4}\left(1-\delta_{1,4}\right)(1-\phi_1)\right],\end{aligned}$$

where the brackets separate mortalities that are not recovered from those that are recovered. After using the substitutions $\alpha_{1,4} = \left(1-\alpha_{1,1}-\alpha_{1,2}\right)$ and $\delta_{1,4} = 0$ and reducing terms within the brackets, the partition of mortality in reach 1 becomes:

$$(1-\phi_1) = \alpha_{1,1}\delta_{1,1}(1-\phi_1) + \alpha_{1,2}\delta_{1,2}(1-\phi_1) + \left[\left(1-\alpha_{1,1}\delta_{1,1}-\alpha_{1,2}\delta_{1,2}\right)(1-\phi_1)\right].$$

Without further data that would allow us to uniquely identify the pairs of $\delta_{j,k}$ and $\alpha_{j,k}$ parameters, those parameters are confounded and not separately estimable. Payton et al. (2020) provide methods for separately estimating these parameters, and they describe the additional data required. However, we opted instead to define new parameters $\omega_{j,k} = \alpha_{j,k}\delta_{j,k}$ for $j = 1, \ldots, J-1$ and $k = 1, \ldots, K-1$, and $\omega_{j,K} = 1 - \sum_{k=1}^{K-1} \omega_{j,k}$, where $\omega_{j,k} \in [0,1]\ \forall j, k$. For $k < K$, the $\omega_{j,k}$ represent the conditional joint probability that a fish is taken by a bird from recovery site k ***and*** its tag is deposited and later detected on that recovery site, given the fish died in reach j. Thus, the parameter $\omega_{j,K}$ represents the conditional probability that a fish is either taken by birds from some recovery site and its tag is never recovered, or it dies due to a mortality source other than avian predation from one of the represented recovery sites, given it dies in reach j.

We refer to the $\omega_{j,k}$ parameters generically as "recovery" probabilities, where the "recovery" process is understood to include predation by birds, deposition of tags, and detection of deposited tags. These joint probabilities are estimable using data on live detections and dead recoveries, avoiding the need for auxiliary data on deposition and tag detection rates on separate colonies.

In our example for reach 1, we assume $\omega_{1,3} = 0$ (tags from fish taken in reach 1 are not recovered on recovery site 3). After substituting the remaining $\omega_{j,k}$ parameters into the above partitioning of mortality, the partitioning becomes:

$$(1-\phi_1) = \omega_{1,1}(1-\phi_1) + \omega_{1,2}(1-\phi_1) + \omega_{1,4}(1-\phi_1).$$

Mortality in each other reach where avian predation occurs is partitioned in a similar manner, depending on the number of possible recovery sites associated with the reach. These partitions of mortality are then entered into the likelihood equation for the model in an appropriate manner with the dead-recovery and live-detection data for estimation of parameters.

Failure to account for likely combinations of predation in reach j and recovery on recovery site k can result in mortality apportioned to the incorrect reach and biased reach survival estimates. We confirmed this using simulation (not shown) and by testing simplified models that omitted some of the recovery parameters. However, when specific $\omega_{j,k}$ parameters are very close to zero, it is better to assume they are equal to zero in order to reduce the number of parameters in the model.

For the recovery probabilities, we used a weakly informative Dirichlet prior distribution for each reach, accounting for all the pertinent mortality sources. The multivariate Dirichlet distribution ensures that the vector of probabilities across mortality sources within each reach sums to one. The prior distribution for each reach was parameterized with a vector of means and a vector of variances, each with dimension equal to the number of non-zero mortality sources for the reach. For data sets consisting of multiple bi-weekly cohorts, the prior distributions for the recovery probabilities within a reach had the same multivariate mean and variance for each cohort. This allowed the posterior values to differ across cohorts within a reach while keeping the prior distributions the same.

We assumed that recovery probabilities were fairly low, based on estimates by Evans et al. (2016) and Payton et al. (2020). We parameterized their prior distributions so that most of the mass was less than 0.5 and so that means for probabilities of recovery on sites outside of the mortality reach were approximately half of the mean probability of recovery within the mortality reach, on average.

For probabilities of survival and detection, we used weakly informative beta prior distributions, parameterized based on historical estimates. For data sets consisting of multiple bi-weekly cohorts, we allowed survival and detection probabilities to vary by cohort and river reach, with different means and variances by river reach, but with shared means and variances across cohorts within a reach.

The BCJS and BCJS-DR models share the standard assumptions of the CJS mark-recapture model (Appendix A). In addition, the following assumptions apply to recovery probabilities from the BCJS-DR model:

1. All fish have the same probability of having their tag recovered on a particular colony, given they died in a particular reach (homogeneity of recovery probabilities);
2. Detection history does not affect recovery probability (recovery probabilities are conditionally independent of detection probabilities).

We conducted tests of model assumptions for the BCJS-DR model (McCrea et al. 2014). We conducted posterior predictive checks on both the BCJS and BCJS-DR models to assess model performance (Gelman et al. 1996; Gelman and Shalizi 2013; Chambert et al. 2014). Posterior predictive checks create a posterior distribution of predicted values by first drawing parameter values from the joint posterior distribution and then generating detection and recovery histories using those parameter values within the model structure. Summaries of the observed data are then compared to the posterior predictive distributions of generated data to assess goodness of fit. Detailed results of the assumptions tests and posterior predictive checks are not presented here, but some general results are covered in the *Discussion* section below.

We processed all data and results using the program *R* (R Core Team 2019) and conducted parameter inference using Hamiltonian Monte Carlo (Neal 2011; Hoffman and Gelman 2014) with the program *Stan* via the *rstan* package (Stan Development Team 2020). For each model, we ran eight parallel chains, each with 2,000 adaptation iterations (burn-in) followed by 2,500 sampling iterations thinned to retain every fourth iteration, for a total of 5,000 posterior samples retained across all chains. We assessed convergence and mixing of chains by visually inspecting trace plots of the posterior samples and by assessing associated values of the Gelman-Rubin statistic (Gelman and Rubin 1992) and effective sample sizes (Gelman et al. 2013).

We report posterior means and posterior standard deviations of reach survival estimates in the tables of results, consistent with reporting of means and standard errors in the main text for the standard CJS model. Posterior standard deviations will typically be smaller than standard errors from the standard CJS model due to the model form we used, especially for models of data from multiple cohorts. We plotted posterior medians and associated 0.025 and 0.975 quantiles of the posterior distributions (i.e., 95% credible intervals), shown in the figures below. These two complementary sets of posterior summaries provided more information than any single approach. The means and medians of parameter estimates are typically close in value unless their associated marginal posterior distribution is skewed. Medians provide a better estimate of central tendency whether distributions are skewed or not.

Tabular results for data sets comprising multiple bi-weekly cohorts included posterior means for each river reach. For each reach, this was the weighted mean across cohorts, with weights proportional to the respective expected number of fish from each cohort remaining alive and not removed (censored) at the start of the reach. Expected numbers of fish remaining were calculated as the initial number of fish released in a cohort multiplied by the product of the probabilities of not being removed at previous dams and cumulative survival to the start of the reach.

Results

For Chinook, sockeye, and coho salmon, the number of tags recovered from interior basin avian colonies was very small, around 1% of the number released, totaled across all sites (Appendix Table D2). A higher percentage of tags from steelhead were recovered, but these totaled only about 4%. For reference, Table 33 provides numbers of tags recovered at estuary avian colonies by species.

Our results are presented in a series of tables giving detailed reach-by-reach survival estimates from BCJS and BCJS-DR models. We also present a series of figures illustrating estimates for longer river stretches with comparison to estimates from the CJS model. Results are given for the following:

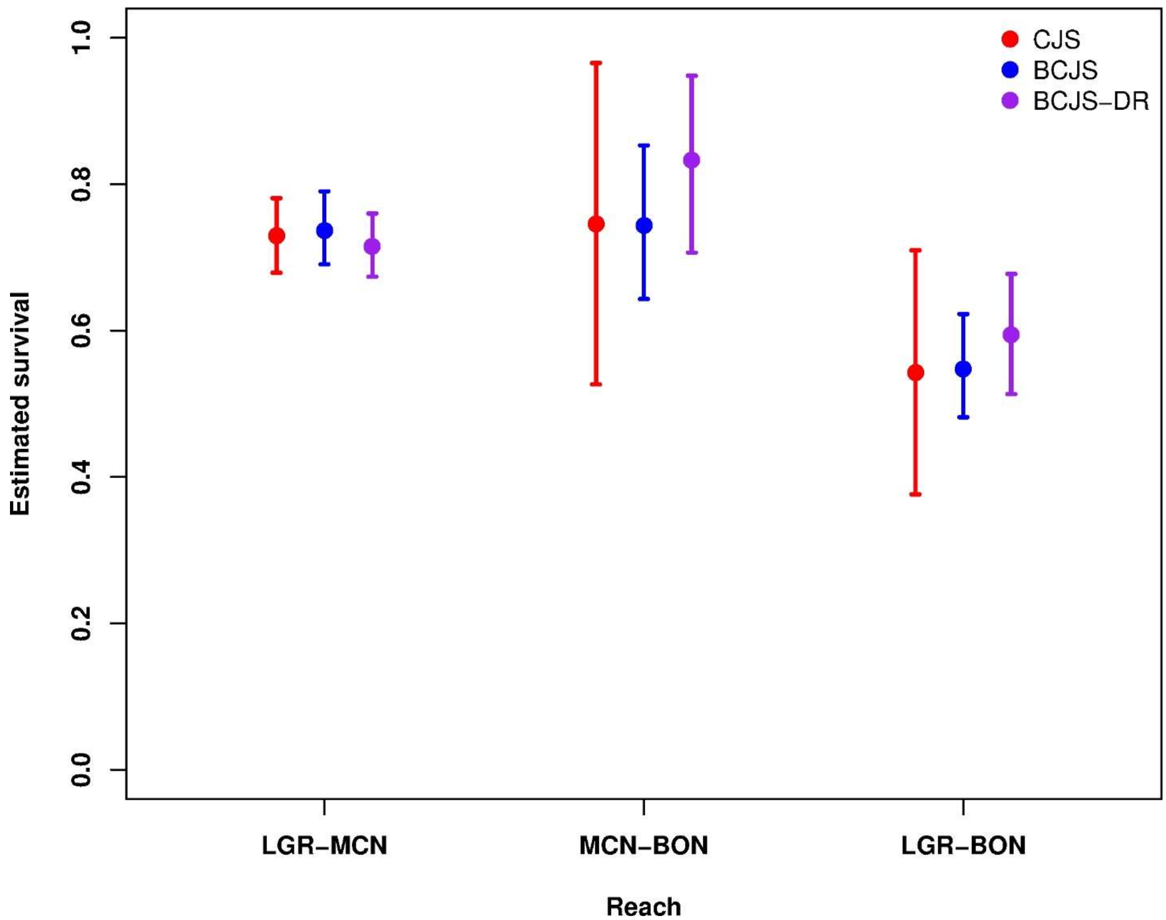
- Hatchery + wild Snake River Chinook (Appendix Table D3; Appendix Figure D3)
- Wild-only Snake River Chinook (Appendix Table D4; Appendix Figure D4)
- Hatchery + wild Upper Columbia and Yakima River Chinook (Appendix Table D5; Appendix Figures D5 and D6)
- Hatchery + wild Snake River steelhead (Appendix Table D6; Appendix Figure D7)
- Wild Snake River steelhead (Appendix Table D7; Appendix Figure D8)
- Hatchery + wild Upper Columbia River steelhead (Appendix Table D8; Appendix Figure D9)
- Hatchery + wild Snake River sockeye (Appendix Table D9; Appendix Figure D10)
- Hatchery + wild Upper Columbia River sockeye (Appendix Table D10; Appendix Figure D11)
- Hatchery + wild Upper Columbia and Yakima River coho (Appendix Table D11; Appendix Figures D12 and D13)

Appendix Table D2. Number and percentage of PIT tags recovered on interior Columbia Basin avian colonies, by stock and pooled recovery site (Appendix Table D1). Percentages are relative to total number released by row. Abbreviation HW = hatchery and wild stocks combined.

		Total	Tags recovered from interior basin avian colonies							
	Rearing	released	Site 1		Site 2		Site 3		Total	
Stock	type	(n)	(n)	(%)	(n)	(%)	(n)	(%)	(n)	(%)
Chinook salmon										
Snake River	HW	102,424	820	0.8	21	0.02	186	0.20	1,027	1.0
Snake River	Wild	41,335	160	0.4	7	0.02	21	0.05	187	0.5
Upper Columbia R	HW	231,548	511	0.2	63	0.03	414	0.20	988	0.4
Yakima River	HW	79,329	813	1.0	11	0.01	39	0.05	863	1.1
Total Chinook	HW	413,301	2,144	0.5	95	0.02	639	0.20	**2,878**	**0.7**
Steelhead										
Snake River	HW	117,027	3,673	3.1	620	0.53	944	0.8	5,237	4.5
Snake River	Wild	11,217	286	2.5	35	0.31	91	0.8	412	3.7
Upper Columbia R	HW	98,249	2,927	3.0	281	0.29	518	0.5	3,726	3.8
Total steelhead	HW	215,276	6,600	3.1	901	0.42	1,462	0.7	**8,963**	**4.2**
Sockeye salmon										
Snake River	HW	51,720	392	0.8	14	0.03	204	0.4	610	1.2
Upper Columbia R	HW	10,124	7	0.1	4	0.04	55	0.5	66	0.7
Total sockeye	HW	61,844	399	0.6	18	0.03	259	0.4	**676**	**1.1**
Coho salmon										
Upper Columbia R	HW	37,450	184	0.5	46	0.12	157	0.4	387	1.0
Yakima Rive	HW	11,907	88	0.7	12	0.10	12	0.1	112	0.9
Total coho	HW	49,357	272	0.6	58	0.12	169	0.3	**499**	**1.0**

Appendix Table D3. Bayesian survival probability estimates (posterior means) for Snake River yearling Chinook in 2021. Daily groups of combined hatchery and wild fish were determined by day of detection at Lower Granite Dam and pooled for biweekly estimates. Posterior standard deviations in parentheses.

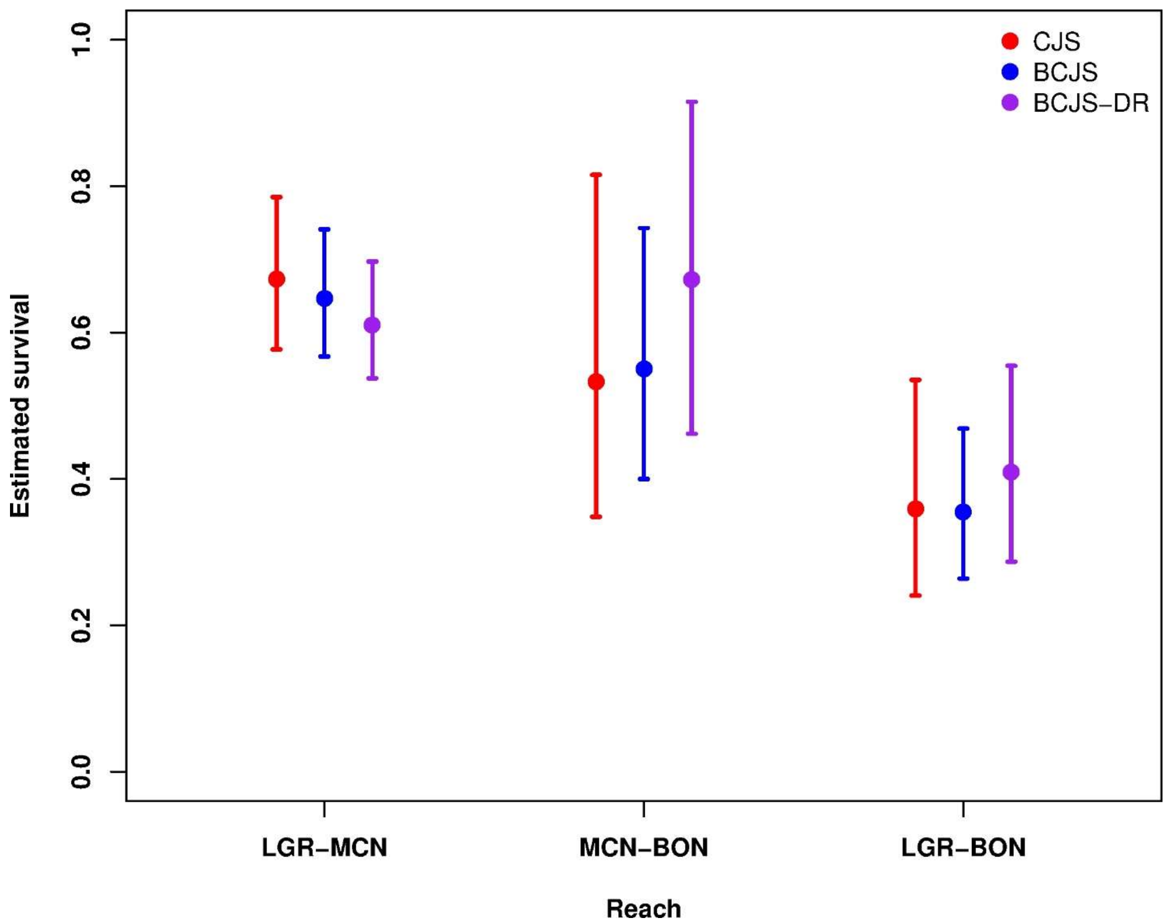
		Estimated survival of Snake River yearling Chinook salmon groups from Lower Granite Dam (SD)							
Date at Lower Granite Dam	Number released	Lower Granite to Little Goose	Little Goose to Lower Monumental	Lower Monumental to McNary	Lower Granite to McNary	McNary to John Day	John Day to Bonneville	McNary to Bonneville	Lower Granite to Bonneville
Bayesian CJS model ***excluding*** tags from interior avian colonies (BCJS)									
6-19 Apr	4,572	0.897 (0.066)	0.954 (0.054)	0.884 (0.069)	0.753 (0.050)	0.903 (0.071)	0.807 (0.081)	0.727 (0.080)	0.546 (0.059)
20 Apr-3 May	38,880	0.896 (0.063)	0.957 (0.050)	0.891 (0.063)	0.760 (0.033)	0.941 (0.044)	0.849 (0.065)	0.798 (0.063)	0.606 (0.045)
4-17 May	51,226	0.876 (0.071)	0.953 (0.055)	0.881 (0.068)	0.730 (0.032)	0.917 (0.056)	0.790 (0.073)	0.723 (0.065)	0.527 (0.043)
18-31 May	7,746	0.840 (0.100)	0.933 (0.080)	0.857 (0.086)	0.665 (0.069)	0.839 (0.119)	0.750 (0.108)	0.624 (0.103)	0.411 (0.056)
Posterior mean		0.882 (0.064)	0.953 (0.052)	0.883 (0.063)	0.738 (0.026)	0.920 (0.046)	0.811 (0.061)	0.745 (0.054)	0.549 (0.036)
Bayesian CJS model ***including*** tags from interior avian colonies (BCJS-DR)									
6-19 Apr	4,572	0.862 (0.060)	0.942 (0.052)	0.901 (0.061)	0.728 (0.048)	0.991 (0.018)	0.849 (0.085)	0.841 (0.084)	0.612 (0.066)
20 Apr-3 May	38,880	0.866 (0.052)	0.950 (0.047)	0.907 (0.053)	0.743 (0.030)	0.996 (0.007)	0.883 (0.068)	0.880 (0.067)	0.653 (0.050)
4-17 May	51,226	0.841 (0.056)	0.945 (0.050)	0.896 (0.055)	0.708 (0.030)	0.995 (0.012)	0.810 (0.079)	0.805 (0.079)	0.569 (0.051)
18-31 May	7,746	0.796 (0.084)	0.900 (0.088)	0.873 (0.080)	0.618 (0.063)	0.975 (0.066)	0.774 (0.116)	0.753 (0.119)	0.462 (0.068)
Posterior mean		0.848 (0.049)	0.943 (0.046)	0.898 (0.051)	0.716 (0.022)	0.994 (0.010)	0.837 (0.064)	0.832 (0.063)	0.595 (0.042)



Appendix Figure D3. Survival probability estimates for Snake River yearling Chinook salmon in 2021 from Lower Granite Dam using different estimation methods. Methods are standard CJS (CJS), Bayesian CJS (BCJS), and Bayesian CJS with dead recoveries from interior avian colonies (BCJS-DR). Estimates for CJS include maximum likelihood estimate and associated 95% confidence interval, while Bayesian methods show posterior median with 95% credible intervals.

Appendix Table D4. Bayesian survival probability estimates (posterior means) for wild Snake River yearling Chinook in 2021. All wild fish tagged upstream of Lower Granite Dam were pooled into a single group for the full season and were combined with wild fish tagged at Lower Granite Dam. Posterior standard deviations in parentheses.

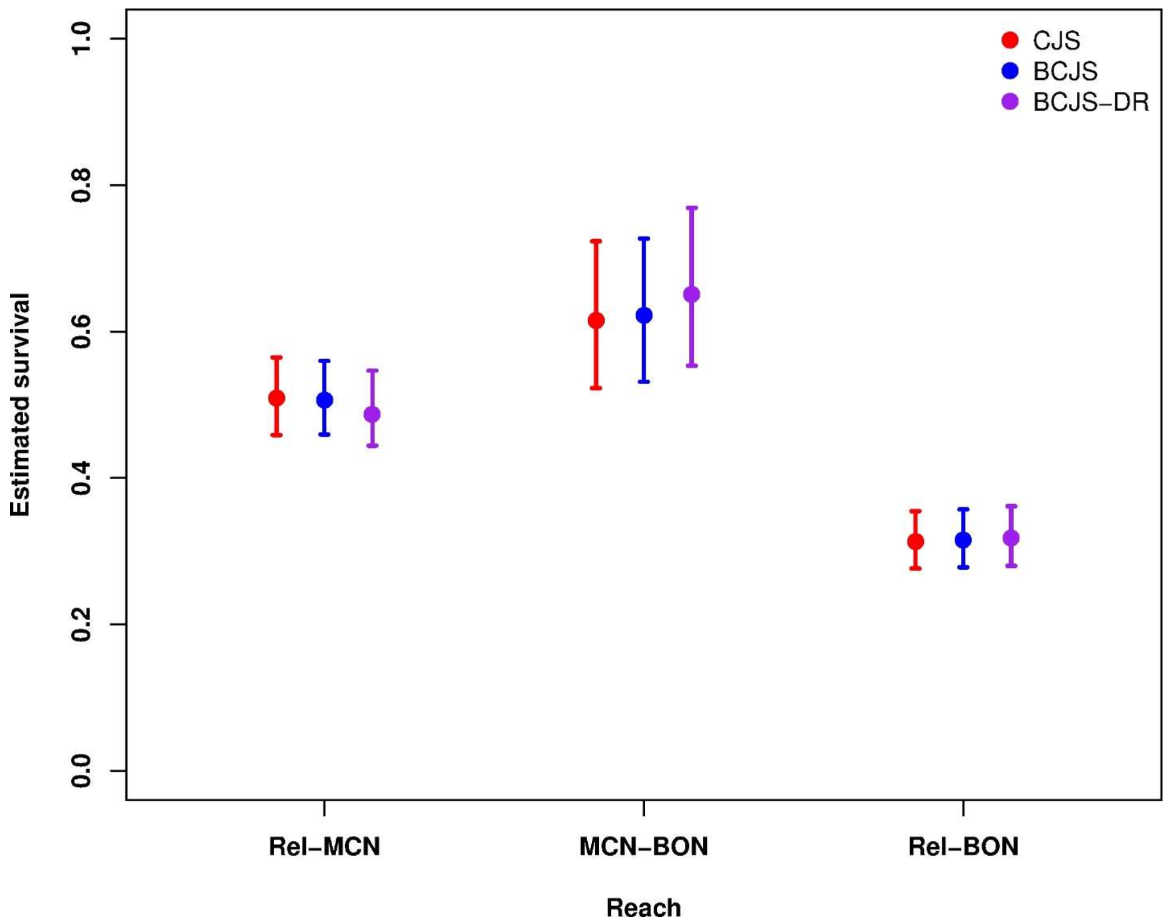
Estimated survival of wild Snake River yearling Chinook salmon groups from Lower Granite Dam (SD)									
Date at Lower Granite Dam	Number released	Lower Granite to Little Goose	Little Goose to Lower Monumental	Lower Monumental to McNary	Lower Granite to McNary	McNary to John Day	John Day to Bonneville	McNary to Bonneville	Lower Granite to Bonneville
Bayesian CJS model ***excluding*** tags from interior avian colonies (BCJS)									
22 Mar-6 Jul	41,335	0.899 (0.055)	0.846 (0.072)	0.860 (0.070)	0.649 (0.044)	0.710 (0.087)	0.784 (0.106)	0.554 (0.088)	0.358 (0.053)
Bayesian CJS model ***including*** tags from interior avian colonies (BCJS-DR)									
22 Mar-6 Jul	41,335	0.903 (0.054)	0.801 (0.076)	0.852 (0.068)	0.612 (0.041)	0.936 (0.094)	0.727 (0.123)	0.677 (0.119)	0.413 (0.070)



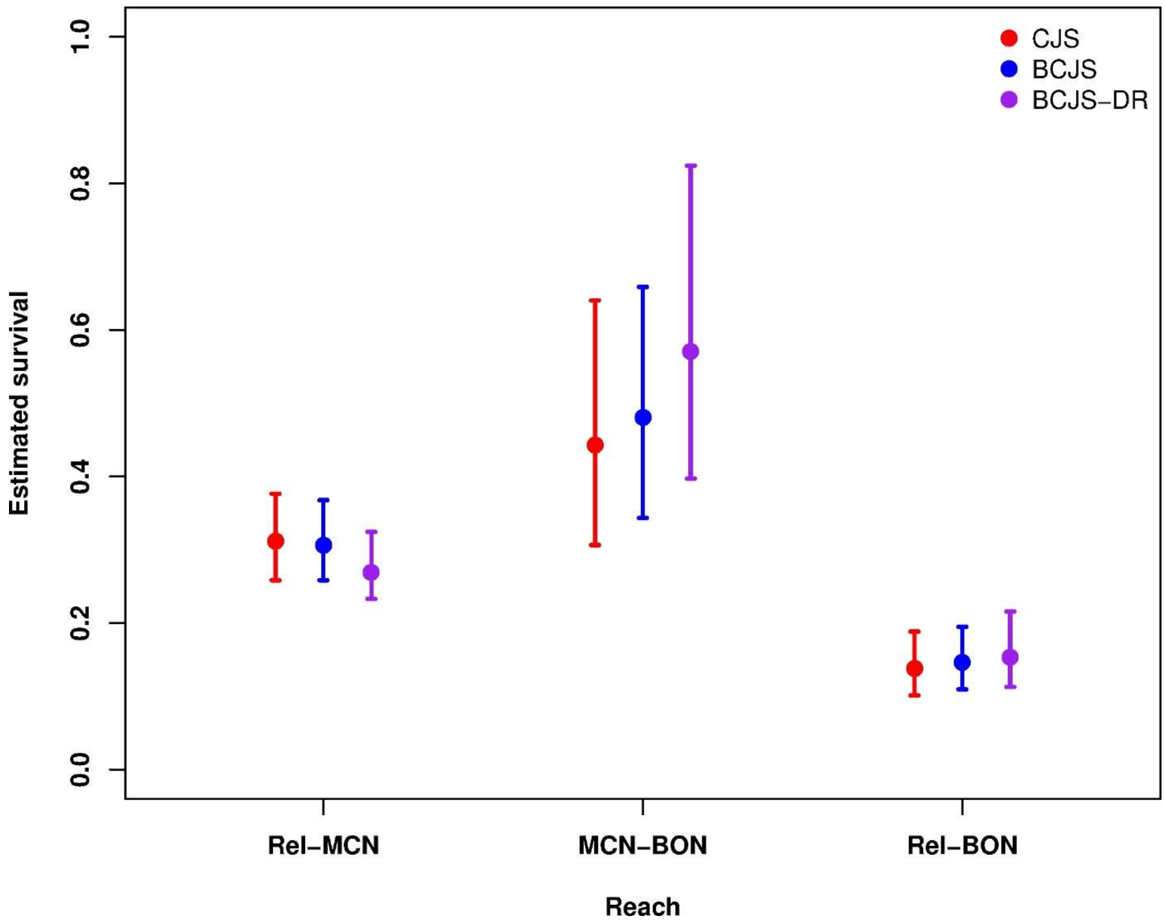
Appendix Figure D4. Survival probability estimates Snake River wild yearling Chinook salmon in 2021 from Lower Granite Dam using different estimation methods. Methods are standard CJS (CJS), Bayesian CJS (BCJS), and Bayesian CJS with dead recoveries from interior avian colonies (BCJS-DR). Estimates for CJS include maximum likelihood estimate and associated 95% confidence interval, while Bayesian methods show posterior median with 95% credible intervals.

Appendix Table D5. Bayesian survival probability estimates (posterior means) for yearling Chinook from the Upper Columbia River in 2021. All fish tagged upstream of McNary Dam were pooled into a single group for the full season. Posterior standard deviations in parentheses.

Estimated survival of yearling Chinook salmon groups from the Upper Columbia River (SD)						
Pooled release group	Number released	Release to McNary	McNary to John Day	John Day to Bonneville	McNary to Bonneville	Release to Bonneville
Bayesian CJS model ***excluding*** tags from interior avian colonies (BCJS)						
Upper Columbia R	231,548	0.507 (0.025)	0.812 (0.058)	0.771 (0.064)	0.624 (0.050)	0.316 (0.020)
Yakima River	79,329	0.308 (0.028)	0.694 (0.087)	0.703 (0.111)	0.485 (0.082)	0.148 (0.022)
Bayesian CJS model ***including*** tags from interior avian colonies (BCJS-DR)						
Upper Columbia R	231,548	0.489 (0.026)	0.909 (0.077)	0.722 (0.067)	0.653 (0.055)	0.319 (0.021)
Yakima River	79,329	0.272 (0.023)	0.925 (0.104)	0.633 (0.117)	0.581 (0.107)	0.157 (0.026)



Appendix Figure D5. Survival probability estimates for yearling Chinook salmon from sites in the upper Columbia River in 2021 using different estimation methods. Methods are standard CJS (CJS), Bayesian CJS (BCJS), and Bayesian CJS with dead recoveries from interior avian colonies (BCJS-DR). Estimates for CJS include maximum likelihood estimate and associated 95% confidence interval, while Bayesian methods show posterior median with 95% credible intervals.

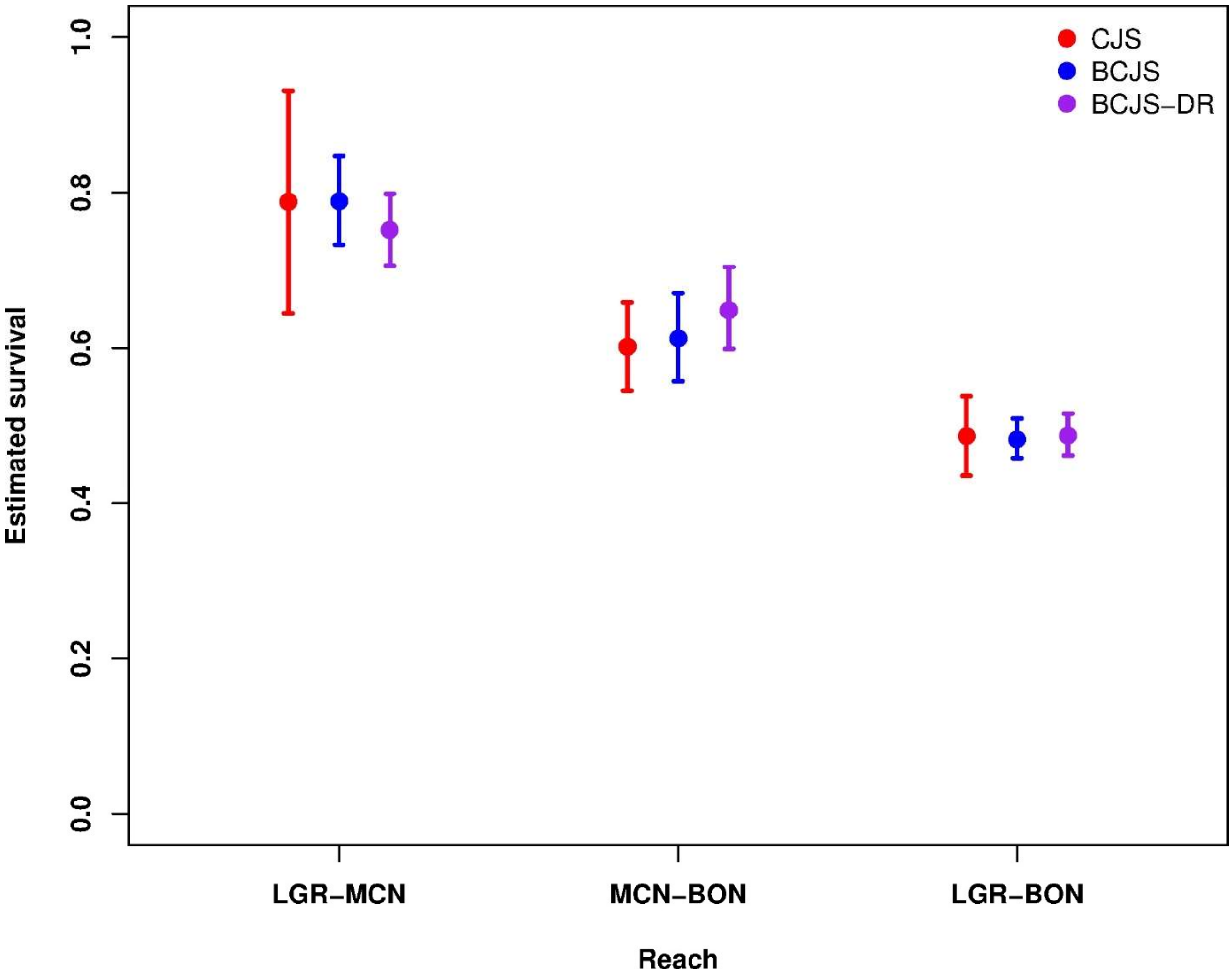


Appendix Figure D6. Survival probability estimates for yearling Chinook salmon from sites in the Yakima River Basin in 2021 using different estimation methods. Methods are standard CJS (CJS), Bayesian CJS (BCJS), and Bayesian CJS with dead recoveries from interior avian colonies (BCJS-DR). Estimates for CJS include maximum likelihood estimate and associated 95% confidence interval, while Bayesian methods show posterior median with 95% credible intervals.

Appendix Table D6. Bayesian survival probability estimates (posterior means) for Snake River steelhead in 2021. Daily groups of combined hatchery and wild fish were determined by day of detection at Lower Granite Dam and pooled for biweekly estimates. Posterior standard deviations in parentheses.

Estimated survival of Snake River steelhead groups from Lower Granite Dam (SD)

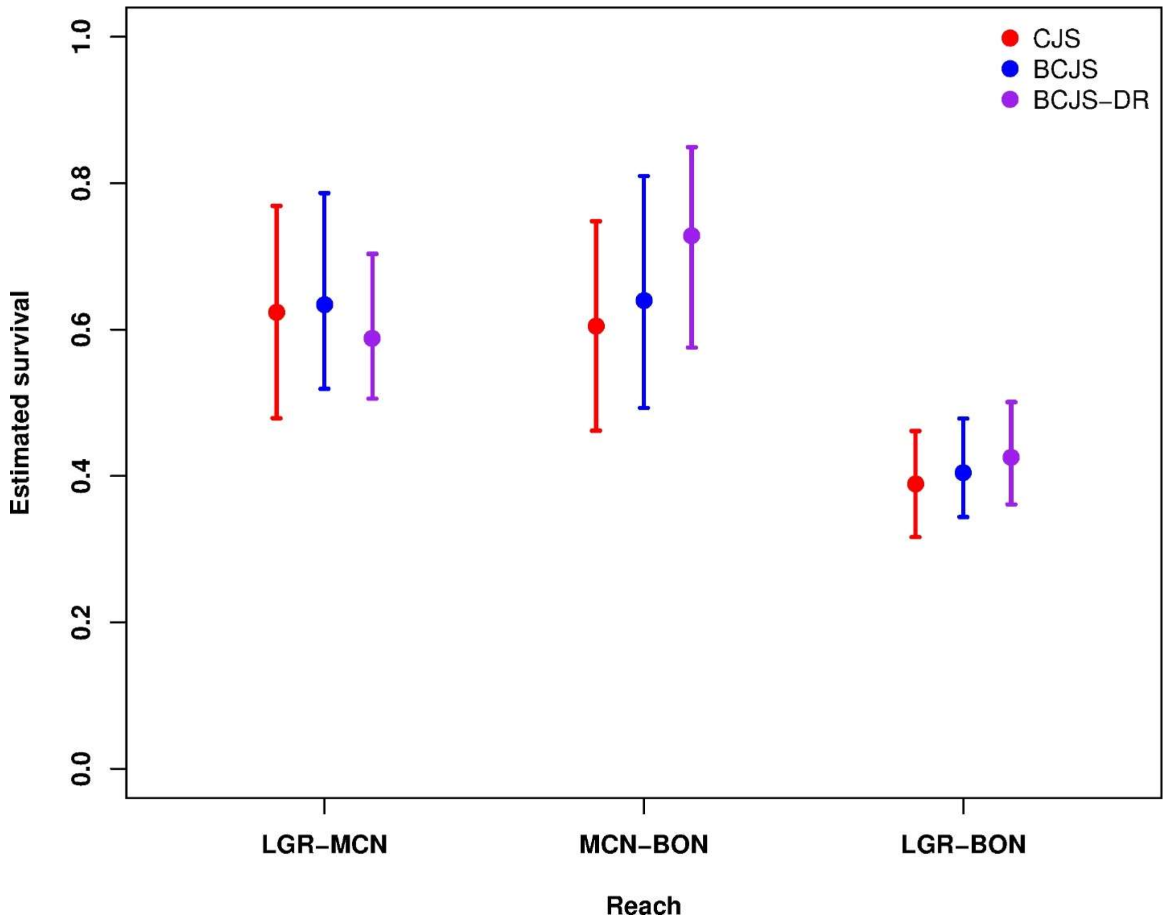
Date at Lower Granite	Number released	Lower Granite to Little Goose	Little Goose to Lower Monumental	Lower Monumental to McNary	Lower Granite to McNary	McNary to John Day	John Day to Bonneville	McNary to Bonneville	Lower Granite to Bonneville
Bayesian CJS model results ***excluding*** tags from interior avian colonies (BCJS)									
23 Mar-5 Apr	1,139	0.990 (0.019)	0.979 (0.038)	0.697 (0.094)	0.674 (0.087)	0.768 (0.065)	0.773 (0.067)	0.592 (0.059)	0.397 (0.051)
6-19 Apr	26,909	0.992 (0.011)	0.986 (0.021)	0.796 (0.045)	0.779 (0.040)	0.770 (0.053)	0.783 (0.052)	0.601 (0.039)	0.467 (0.023)
20 Apr-3 May	34,559	0.994 (0.009)	0.988 (0.016)	0.914 (0.046)	0.898 (0.044)	0.777 (0.051)	0.789 (0.049)	0.611 (0.037)	0.548 (0.024)
4-17 May	36,181	0.993 (0.011)	0.985 (0.022)	0.826 (0.052)	0.808 (0.047)	0.782 (0.054)	0.805 (0.049)	0.628 (0.040)	0.506 (0.018)
18-31 May	13,499	0.980 (0.046)	0.974 (0.053)	0.586 (0.079)	0.555 (0.055)	0.782 (0.059)	0.781 (0.060)	0.609 (0.052)	0.336 (0.027)
1-14 Jun	4,740	0.979 (0.050)	0.974 (0.050)	0.657 (0.088)	0.623 (0.073)	0.766 (0.064)	0.785 (0.060)	0.600 (0.056)	0.371 (0.036)
Posterior mean		0.991 (0.011)	0.985 (0.019)	0.810 (0.034)	0.790 (0.029)	0.776 (0.046)	0.791 (0.043)	0.613 (0.029)	0.483 (0.013)
Bayesian CJS model results ***including*** tags from interior avian colonies (BCJS-DR)									
23 Mar-5 Apr	1,139	0.991 (0.015)	0.973 (0.042)	0.652 (0.084)	0.628 (0.077)	0.831 (0.062)	0.774 (0.065)	0.641 (0.055)	0.401 (0.050)
6-19 Apr	26,909	0.993 (0.010)	0.983 (0.022)	0.759 (0.038)	0.741 (0.034)	0.826 (0.055)	0.775 (0.054)	0.638 (0.038)	0.472 (0.024)
20 Apr-3 May	34,559	0.994 (0.009)	0.984 (0.019)	0.871 (0.041)	0.852 (0.038)	0.832 (0.053)	0.783 (0.050)	0.650 (0.036)	0.553 (0.025)
4-17 May	36,181	0.994 (0.009)	0.982 (0.022)	0.790 (0.042)	0.771 (0.038)	0.834 (0.053)	0.796 (0.049)	0.662 (0.037)	0.509 (0.019)
18-31 May	13,499	0.989 (0.021)	0.971 (0.045)	0.567 (0.060)	0.543 (0.047)	0.828 (0.057)	0.770 (0.059)	0.637 (0.049)	0.345 (0.028)
1-14 Jun	4,740	0.984 (0.035)	0.969 (0.052)	0.607 (0.072)	0.576 (0.060)	0.824 (0.059)	0.786 (0.059)	0.646 (0.051)	0.371 (0.035)
Posterior mean		0.993 (0.008)	0.981 (0.020)	0.773 (0.028)	0.752 (0.024)	0.830 (0.047)	0.784 (0.044)	0.649 (0.027)	0.488 (0.014)



Appendix Figure D7. Survival probability estimates Snake River steelhead in 2021 from Lower Granite Dam using different estimation methods. Methods are standard CJS (CJS), Bayesian CJS (BCJS), and Bayesian CJS with dead recoveries from interior avian colonies (BCJS-DR). Estimates for CJS include maximum likelihood estimate and associated 95% confidence interval. Bayesian methods show posterior median with 95% credible intervals. Abbreviations: LGR, Lower Granite; MCN, McNary; BON, Bonneville.

Appendix Table D7. Bayesian survival probability estimates (posterior means) for wild Snake River steelhead in 2021. Daily groups were determined by day of detection at Lower Granite Dam and pooled for biweekly estimates. Posterior standard deviations in parentheses.

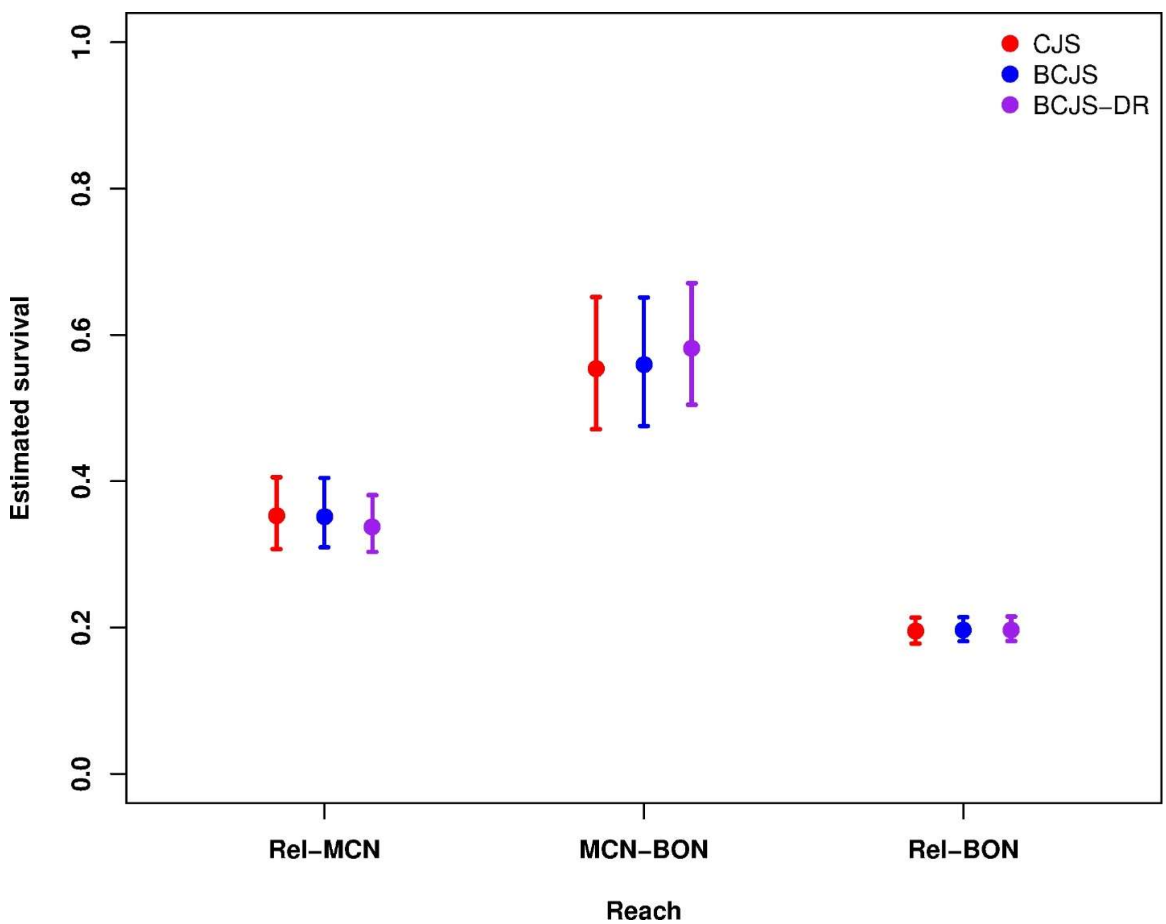
Estimated survival of wild Snake River steelhead groups from Lower Granite Dam (SD)										
Date at Lower Granite Dam	Number Released	Lower Granite to Little Goose	Little Goose to Lower Monumental	Lower Monumental to McNary	Lower Granite to McNary	McNary to John Day	John Day to Bonneville	McNary to Bonneville	Lower Granite to Bonneville
Bayesian CJS model ***excluding*** tags from interior avian colonies (BCJS)									
6-19 Apr	735	0.908 (0.078)	0.911 (0.090)	0.781 (0.109)	0.640 (0.085)	0.795 (0.117)	0.761 (0.111)	0.600 (0.104)	0.379 (0.058)
20 Apr-3 May	2,008	0.913 (0.074)	0.914 (0.087)	0.801 (0.101)	0.662 (0.078)	0.820 (0.101)	0.795 (0.094)	0.648 (0.090)	0.425 (0.047)
4-17 May	5,106	0.912 (0.073)	0.914 (0.085)	0.796 (0.101)	0.657 (0.073)	0.824 (0.099)	0.814 (0.088)	0.667 (0.086)	0.434 (0.040)
18-31 May	3,368	0.884 (0.098)	0.897 (0.103)	0.761 (0.117)	0.594 (0.086)	0.800 (0.112)	0.771 (0.104)	0.612 (0.098)	0.359 (0.050)
Posterior mean		0.904 (0.075)	0.909 (0.087)	0.786 (0.099)	0.638 (0.068)	0.814 (0.098)	0.794 (0.086)	0.643 (0.081)	0.406 (0.034)
Bayesian CJS model ***including*** tags from interior avian colonies (BCJS-DR)									
6-19 Apr	735	0.890 (0.076)	0.864 (0.091)	0.774 (0.103)	0.588 (0.073)	0.893 (0.085)	0.785 (0.101)	0.699 (0.098)	0.409 (0.061)
20 Apr-3 May	2,008	0.895 (0.073)	0.870 (0.086)	0.800 (0.093)	0.616 (0.064)	0.905 (0.073)	0.813 (0.084)	0.733 (0.081)	0.449 (0.050)
4-17 May	5,106	0.890 (0.073)	0.874 (0.085)	0.795 (0.087)	0.612 (0.056)	0.903 (0.071)	0.826 (0.078)	0.744 (0.074)	0.453 (0.041)
18-31 May	3,368	0.877 (0.083)	0.851 (0.098)	0.747 (0.102)	0.550 (0.067)	0.890 (0.084)	0.780 (0.091)	0.692 (0.091)	0.378 (0.051)
Posterior mean		0.887 (0.071)	0.865 (0.084)	0.780 (0.085)	0.593 (0.051)	0.899 (0.070)	0.808 (0.074)	0.724 (0.070)	0.427 (0.036)



Appendix Figure D8. Survival probability estimates for wild Snake River steelhead in 2021 from Lower Granite Dam using different estimation methods. Methods are standard CJS (CJS), Bayesian CJS (BCJS), and Bayesian CJS with dead recoveries from interior avian colonies (BCJS-DR). Estimates for CJS include maximum likelihood estimate and associated 95% confidence interval. Bayesian methods show posterior median with 95% credible intervals.

Appendix Table D8. Bayesian survival probability estimates (posterior means) for steelhead from the upper Columbia River in 2021. All fish tagged upstream of McNary Dam were pooled into a single group for the full season. Posterior standard deviations in parentheses.

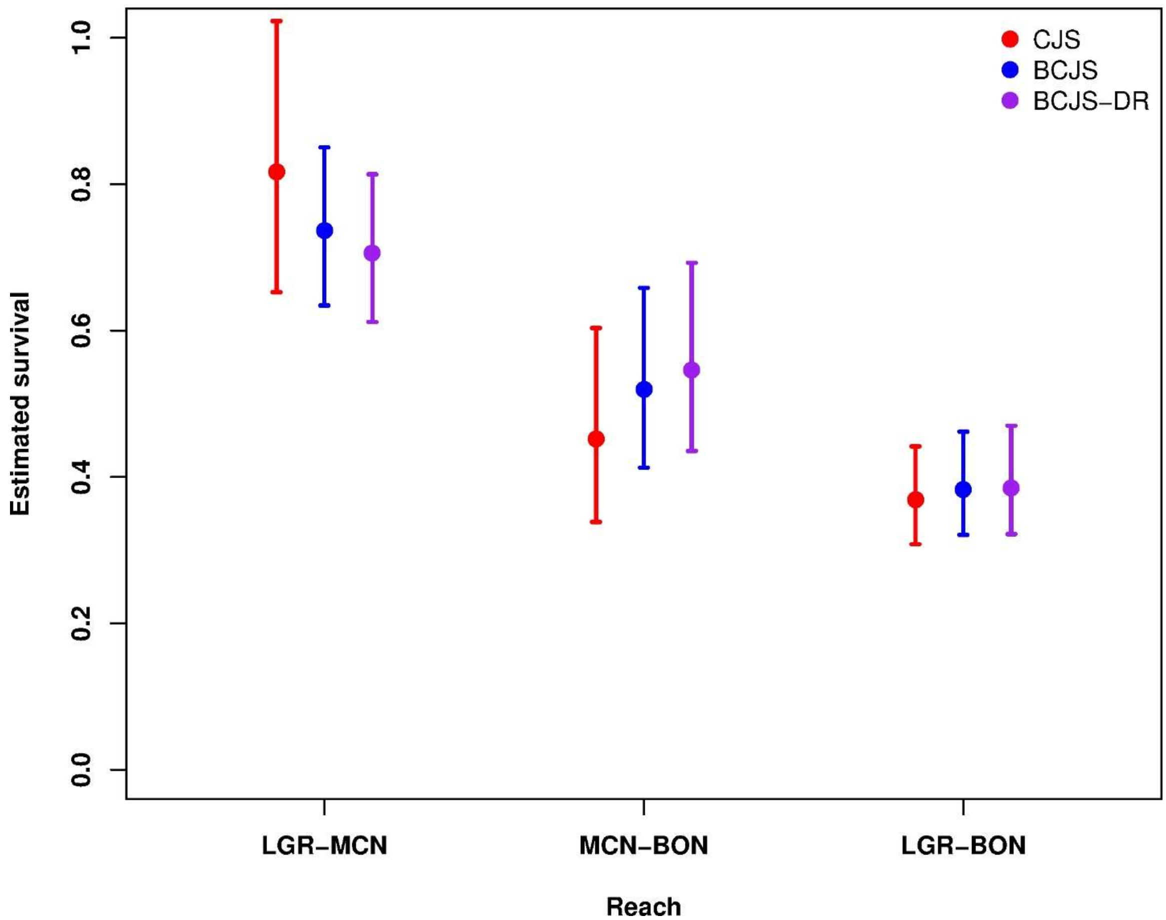
		Estimated survival of steelhead groups from the Upper Columbia River (SD)				
Pooled release group	Number released	Release to McNary	McNary to John Day	John Day to Bonneville	McNary to Bonneville	Release to Bonnevie
Bayesian CJS model ***excluding*** tags from interior avian colonies (BCJS)						
Upper Columbia R	98,249	0.353 (0.024)	0.793 (0.072)	0.709 (0.059)	0.560 (0.044)	0.197 (0.008)
Bayesian CJS model ***including*** tags from interior avian colonies (BCJS-DR)						
Upper Columbia R	98,249	0.339 (0.020)	0.852 (0.067)	0.688 (0.055)	0.584 (0.042)	0.197 (0.008)



Appendix Figure D9. Survival probability estimates for steelhead from upper Columbia River sites in 2021 using different estimation methods. Methods are standard CJS (CJS), Bayesian CJS (BCJS), and Bayesian CJS with dead recoveries from interior avian colonies (BCJS-DR). Estimates for CJS include maximum likelihood estimate and associated 95% confidence interval. Bayesian methods show posterior median with 95% credible intervals.

Appendix Table D9. Bayesian survival probability estimates (posterior means) for Snake River sockeye (hatchery and wild) in 2021. All fish tagged upstream of Lower Granite Dam were pooled into a single group for the full season. Posterior standard deviations in parentheses.

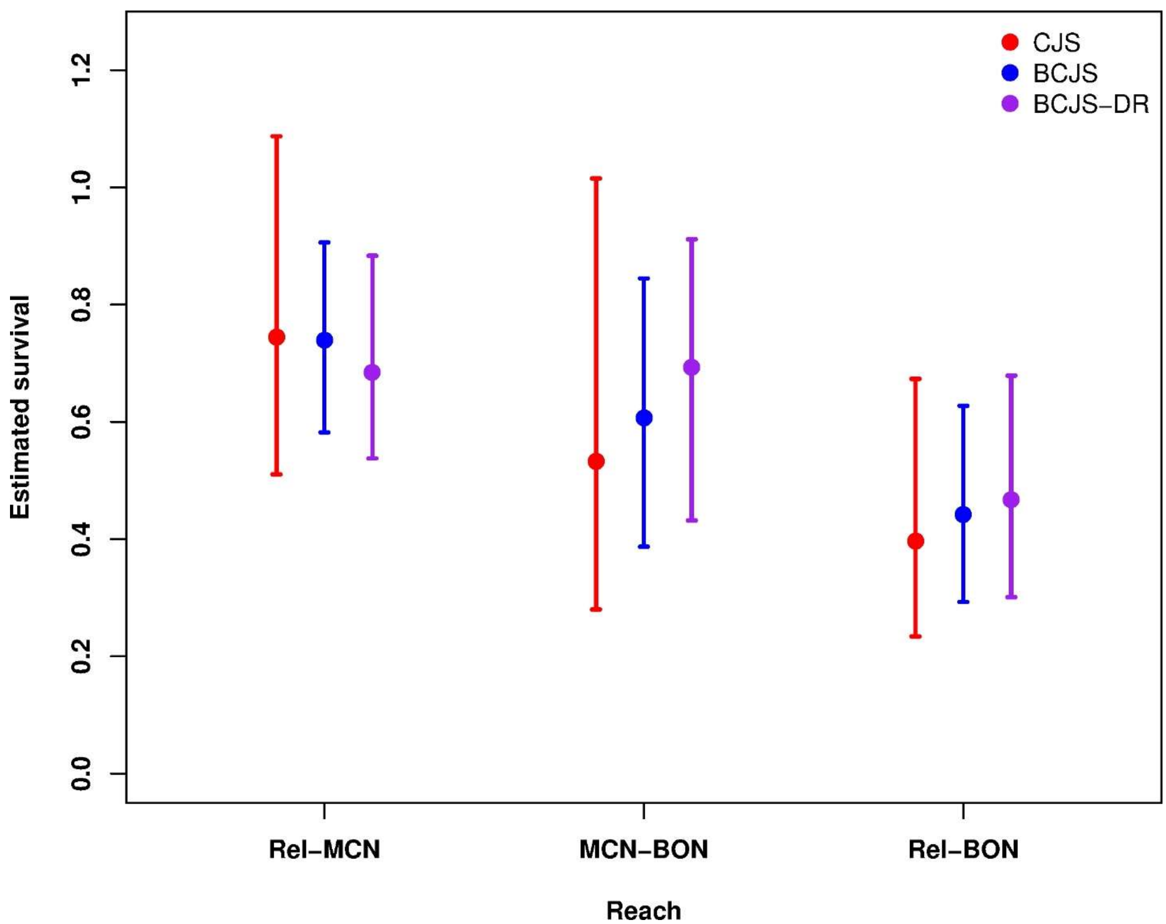
		Estimated survival of Snake River sockeye groups from Lower Granite Dam (SD)							
Date at Lower Granite Dam	Number Released	Lower Granite to Little Goose Dam	Little Goose to Lower Monumental	Lower Monumental to McNary Dam	Lower Granite to McNary Dam	McNary to John Day Dam	John Day to Bonneville Dam	McNary to Bonneville Dam	Lower Granite to Bonneville Dam
Bayesian CJS model ***excluding*** tags from interior avian colonies (BCJS)									
6 May–23 Jun	51,720	0.898 (0.058)	0.906 (0.055)	0.911 (0.053)	0.739 (0.056)	0.855 (0.078)	0.617 (0.085)	0.524 (0.063)	0.385 (0.037)
Bayesian CJS model ***including*** tags from interior avian colonies (BCJS-DR)									
6 May–23 Jun	51,720	0.888 (0.060)	0.895 (0.058)	0.894 (0.049)	0.708 (0.051)	0.980 (0.028)	0.562 (0.069)	0.551 (0.066)	0.388 (0.038)



Appendix Figure D10. Survival probability estimates for Snake River sockeye in 2021 from Lower Granite Dam using different estimation methods. Methods are standard CJS (CJS), Bayesian CJS (BCJS), and Bayesian CJS with dead recoveries from interior avian colonies (BCJS-DR). Estimates for CJS include maximum likelihood estimate and associated 95% confidence interval. Bayesian methods show posterior median with 95% credible intervals.

Appendix Table D10. Bayesian survival probability estimates (posterior means) for sockeye (hatchery and wild) from the upper Columbia River in 2021. All fish tagged upstream of McNary Dam were pooled into a single group for the full season. Posterior standard deviations in parentheses.

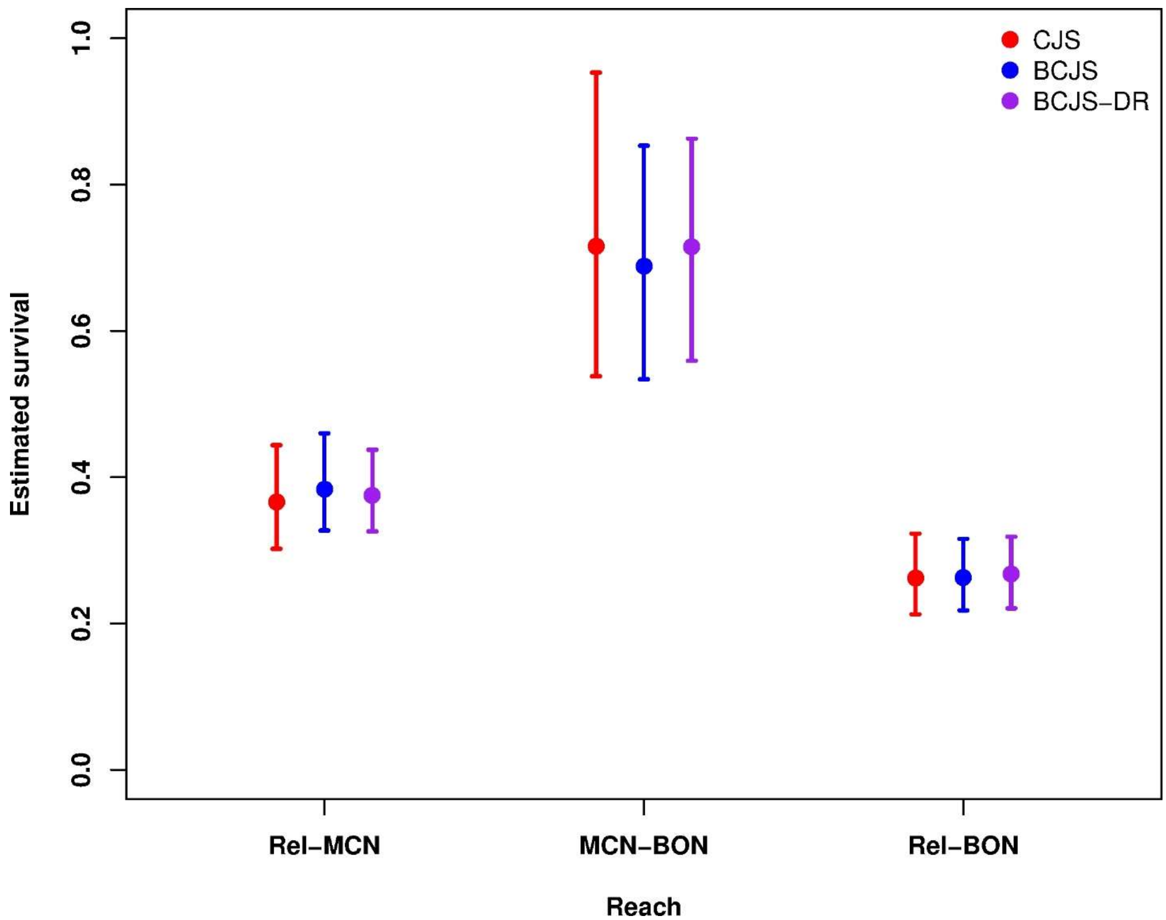
		Estimated survival of sockeye groups from the Upper Columbia River (SD)				
Pooled release group	Number released	Release to McNary	McNary to John Day	John Day to Bonneville	McNary to Bonneville	Release to Bonnevie
Bayesian CJS model ***excluding*** tags from interior avian colonies (BCJS)						
Upper Columbia R	10,124	0.740 (0.084)	0.854 (0.085)	0.715 (0.132)	0.609 (0.119)	0.447 (0.087)
Bayesian CJS model ***including*** tags from interior avian colonies (BCJS-DR)						
Upper Columbia R	10,124	0.691 (0.089)	0.979 (0.028)	0.702 (0.132)	0.687 (0.130)	0.472 (0.097)



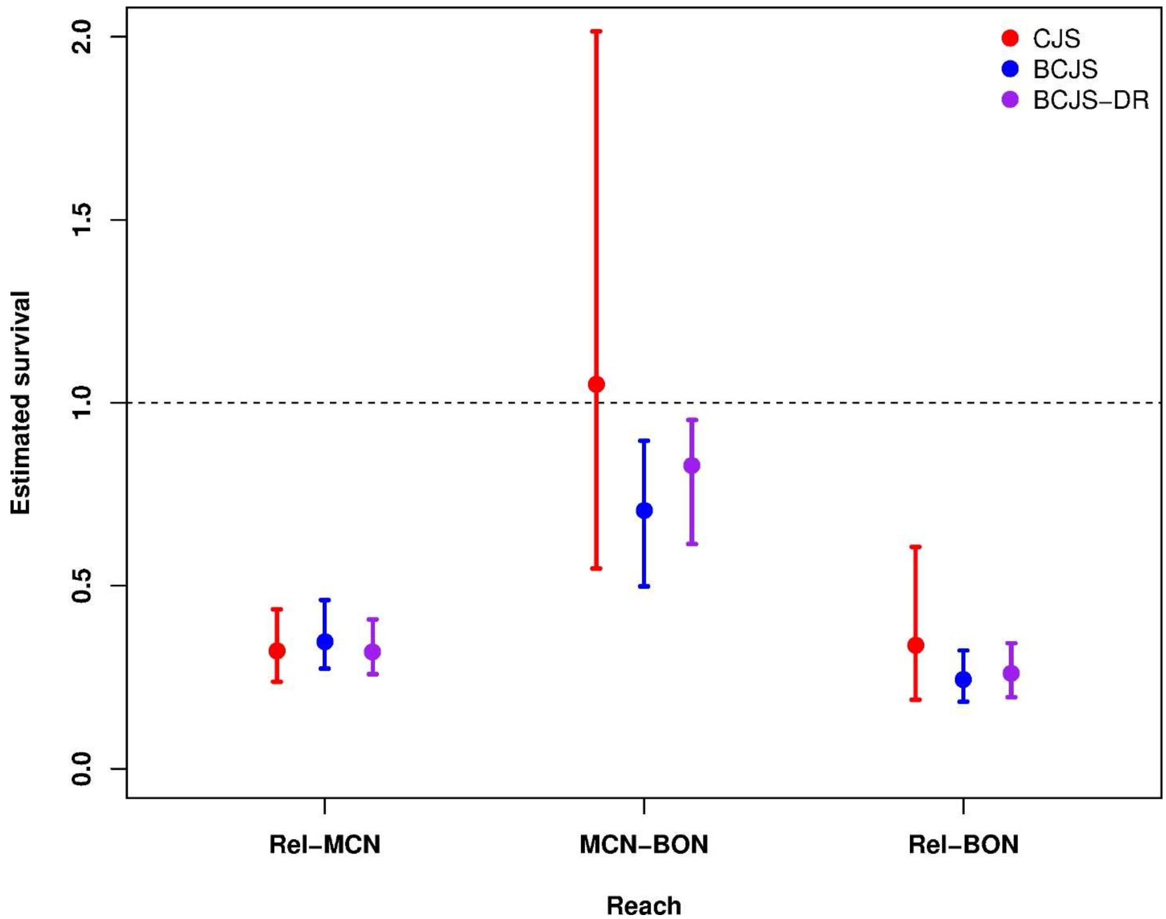
Appendix Figure D11. Survival probability estimates for sockeye from upper Columbia River sites in 2021 using different estimation methods. Methods are standard CJS (CJS), Bayesian CJS (BCJS), and Bayesian CJS with dead recoveries from interior avian colonies (BCJS-DR). Estimates for CJS include maximum likelihood estimate and associated 95% confidence interval. Bayesian methods show posterior median with 95% credible intervals.

Appendix Table D11. Bayesian survival probability estimates (posterior means) for coho from the upper Columbia River in 2021. All fish tagged at sites upstream of McNary Dam were pooled into a single group for the full season. Posterior standard deviations in parentheses.

		Estimated survival of coho groups from the upper Columbia River (SD)				
Pooled release group	Number released	Release to McNary	McNary to John Day	John Day to Bonneville	McNary to Bonneville	Release to Bonneville
Bayesian CJS model ***excluding*** tags from interior avian colonies (BCJS)						
Upper Columbia R	37,450	0.386 (0.034)	0.861 (0.074)	0.802 (0.086)	0.689 (0.082)	0.264 (0.025)
Yakima River	11,907	0.353 (0.048)	0.829 (0.096)	0.850 (0.088)	0.703 (0.104)	0.246 (0.036)
Bayesian CJS model ***including*** tags from interior avian colonies (BCJS-DR)						
Upper Columbia R	37,450	0.377 (0.029)	0.931 (0.048)	0.767 (0.082)	0.713 (0.078)	0.268 (0.025)
Yakima River	11,907	0.323 (0.038)	0.952 (0.045)	0.858 (0.087)	0.817 (0.089)	0.263 (0.037)



Appendix Figure D12. Survival probability estimates for coho from upper Columbia River sites in 2021 using different estimation methods. Methods are standard CJS (CJS), Bayesian CJS (BCJS), and Bayesian CJS with dead recoveries from interior avian colonies (BCJS-DR). Estimates for CJS include maximum likelihood estimate and associated 95% confidence interval, while Bayesian methods show posterior median with 95% credible intervals.



Appendix Figure D13. Survival probability estimates for coho from Yakima River sites in 2021 using different estimation methods. Methods are standard CJS (CJS), Bayesian CJS (BCJS), and Bayesian CJS with dead recoveries from interior avian colonies (BCJS-DR). Estimates for CJS include maximum likelihood estimate and associated 95% confidence interval, while Bayesian methods show posterior median with 95% credible intervals.

Discussion

We believe that the Bayesian approach to survival estimation offers many advantages over the frequentist CJS approach. These advantages include a likely reduction in uncertainty of estimates, the ability to include prior information, and the constraint of probability estimates between zero and one. We also believe that including recoveries of tags from avian colonies will often lead to more precise reach survival estimates when the number of recoveries is sufficient to overcome the loss of precision related to estimation of additional parameters needed in those models.

However, we found that the number of recovered tags from interior avian colonies was often very small in 2021, and gains in precision from incorporating recovery data were minimal. We were also concerned that some survival estimates may be subject to bias due to violations of the additional model assumptions, especially in the presence of very low detection probabilities. Caution is needed when using recovery data from interior basin avian colonies under these conditions.

A main interest in this investigation was the potential increase in precision (decrease in uncertainty) of survival estimates from the incorporation of recovery data from interior avian colonies. For all stocks from the Snake River except wild Chinook, precision was greater for estimates from the BCJS-DR model than from the BCJS model for both the reach from Lower Monumental to McNary Dam and the combined reach from Lower Granite to McNary Dam.

Likewise, for all stocks from the Upper Columbia or Yakima River except sockeye, precision of survival estimates from release to McNary Dam was increased using recovery data from the interior avian colonies. Increases in precision upstream of McNary Dam were likely due to the fact that the highest proportion of recoveries came from colonies upstream of McNary.

In contrast, for survival estimates downstream of McNary Dam, precision was increased less frequently. Precision was increased for estimates from McNary to Bonneville Dam for all steelhead, all coho, and sockeye from Upper Columbia sites. However, increases in precision were not observed in this reach for any Chinook stocks, nor for sockeye from the Snake River Basin.

More importantly, the BCJS-DR estimates had decreased precision (increased uncertainty) for the combined reach from Lower Granite to Bonneville Dam for all stocks except steelhead and coho from Upper Columbia River sites. For those exceptions, precision was essentially equal between the BCJS and BCJS-DR estimates. Given that the combined reach from Lower Granite to Bonneville Dam is of most interest, one could conclude that the BCJS-DR model did not provide meaningfully improved precision compared to the BCJS model.

In addition to precision, the actual values of the survival estimates themselves were of interest. Inclusion of recoveries from the interior basin resulted in some distinctive and fairly consistent patterns in the survival estimates across reaches for the stocks investigated. In particular, for every stock investigated, estimated survival from McNary to John Day Dam was higher using the BCJS-DR model than using the BCJS model—in some cases, remarkably higher. Furthermore, for all Snake River stocks except wild Chinook, estimated survival from Lower Granite to McNary Dam was lower for the BCJS-DR model than for BCJS.

Likewise, for all stocks from Upper Columbia or Yakima River sites, estimated survival from release to McNary Dam was lower for BCJS-DR than for BCJS. With the exception of hatchery and wild Chinook from the Snake River, wild steelhead from the Snake River, and coho from the Yakima River, estimated survival from John Day to Bonneville Dam was also lower for BCJS-DR than for BCJS models. Despite lower estimated survival between John Day and Bonneville Dam, estimated survival for all stocks through the combined reach from McNary to Bonneville Dam was higher for BCJS-DR than for BCJS. This was because of the large increases in estimated survival between McNary and John Day Dam.

These consistent patterns in changes to the survival estimates when interior recoveries were included suggest two possible explanations: 1) the BCJS-DR model was somehow mis-specified or had errors; or 2) the data did not meet the assumptions of the BCJS-DR model, resulting in biased survival estimates. We considered both explanations.

To evaluate the first explanation, we performed simulations to test both Bayesian models when assumptions were met. These simulations would ensure that the models were operating as expected and uncover any potential errors in implementation. We generated data under combinations of low or high detection probabilities and low or high recovery probabilities, where fish were released upstream of Lower Granite Dam and followed to below Bonneville Dam. We generated 500 simulated data sets under each scenario. The scenario with low detection and low recovery probabilities (low-low) had parameter values similar to those estimated for 2021.

We do not provide detailed simulation results here; the crucial result was that survival estimates from both models were essentially unbiased under all scenarios. There was a slight bias (1.3%) in the survival estimate from McNary to John Day Dam for the low-low scenario under the BCJS-DR model. In this scenario, bias was measured by comparing the posterior medians to the mean values used to generate the data. This was the largest bias for any survival estimate from either model for that scenario.

However, under the low-low scenario, precision of all survival estimates was higher using the BCJS-DR model than using BCJS. Furthermore, root mean squared error (a combined measure of precision and bias) was lower (better) for all survival and detection probabilities from BCJS-DR. Results indicated that both Bayesian models were working as expected when model assumptions were met. Under no simulated scenario did survival estimates exhibit the patterns that concerned us in the 2021 data. Thus, we suspect that the patterns in the estimates for 2021 were most likely caused by properties in the observed data that violated of assumptions of the BCJS-DR model.

The BCJS-DR model adds another layer of model complexity and introduces additional model assumptions that must be met. One assumption is that the probability of being recovered on an avian colony is conditionally independent of live-detection probabilities. We suggest a few mechanisms by which this assumption could be violated. One possibility is that birds at a particular dam target their foraging efforts on the powerhouse side of the tailrace differently than the spillway side, so that detected (bypassed) fish have different recovery probabilities than undetected fish.

Another possibility relates to dam operations. Flexible spill operations resulted in widely varying spill levels within each day, with fairly consistent patterns at some dams (e.g., John Day Dam). These spill operations translate directly into patterns in detection probability. If hours of high or low detection correlate with hours of high avian predation activity, then detection history could be correlated with recovery probability.

A third possibility is if detection and recovery probabilities are both related to an individual characteristic such as fish size or condition, resulting in correlation between individual detection and recovery probabilities. Various studies have found associations between fish size or condition and bypass probability (e.g., Zabel et al. 2005; Hostetter et al. 2015a; Faulkner et al. 2019), and between fish size and condition and avian predation (Hostetter et al. 2012).

A second assumption specific to the BCJS-DR model is that all fish in a cohort share the same values of the recovery probabilities (homogeneity). We suggest a few mechanisms by which this assumption could be violated. First, fish passing through a reservoir at night have very little chance of being taken by diurnal avian predators. This would result in unequal recovery probabilities across individuals based on time of passage.

A second possibility is that predation rates of birds change through the season (Hostetter et al. 2022), as do tag deposition rates (Hostetter et al. 2015b). Furthermore, tag-detection probabilities on avian colonies generally increase with date of deposition (Evans et al. 2012); thus, joint recovery probabilities will also vary through the season. Models that pool all observations through the season will not account for this heterogeneity in recovery probabilities.

A third possibility is that joint recovery probability is associated with some characteristic of individual fish, such as size or condition, which would lead to heterogeneity in recovery probabilities across individuals. Hostetter et al. (2012) found that both fish size and condition were associated with susceptibility to avian predation for Snake River steelhead.

These are not exhaustive lists of possible causes of assumption violations, but they clarify that one or more of the assumptions could be violated by patterns in operations, animal behavior, or individual fish characteristics. It is reasonable to suspect that one or more of these violations occurred in 2021.

We devised and performed a limited set of tests of model assumptions for the BCJS-DR model, but most tests were not significant, and we did not find consistent patterns in those tests that would explain the consistent increase in survival from McNary to John Day Dam. In most cases, the jump in survival was associated with a decrease in estimated detection probability at John Day Dam.

There could have been insufficient power of the assumption tests to detect violations due to very low detection probabilities, or there could be violations that the tests could not detect. Further investigation of assumption violations is needed to understand what could cause the observed patterns in survival estimates when recoveries from interior avian colonies were included. We plan to conduct more extensive simulations to further investigate these questions.

We performed posterior predictive checks to compare observed counts of fish detections and tag recoveries to counts predicted by the fitted models. These checks allowed an assessment of how well the models and estimated parameters were able to reproduce the observed data, and therefore provided a measure of goodness of fit. Posterior predictive checks could also be used to assess some model assumptions. The checks often indicated that data generated from the BCJS model were more consistent with observed count data than data generated from the BCJS-DR model, although differences were often small.

There is a risk of misrepresentative posterior distributions when model assumptions are not met, and low detection and recovery probabilities compounded that problem. We will conduct further research to address the effects of various model assumption violations so that we can identify causes of such violations. Further investigation will also clarify when models using interior Columbia recoveries should not be used or when modifications to these models are needed.

For data sets consisting of bi-weekly cohorts of fish passing Lower Granite Dam, cohort-level posterior estimates and standard deviations from the BCJS model were sometimes very different from the corresponding quantities from standard CJS (for example, compare the upper portion of Appendix Table D3 with results in Tables 2-3). In particular, for BCJS there was less variation in posterior estimates across cohorts within a reach, and standard deviations of individual reach estimates were much smaller than corresponding estimates from standard CJS.

The primary cause of these differences was the form of the model used. Under our BCJS model, estimates for the various cohorts within a particular reach shared a prior distribution. In contrast, corresponding estimates from the standard CJS model were assumed independent; not sharing a common distribution. The shared prior distribution had the effect of "shrinking" individual Bayesian estimates toward their mean when information from the data was weak, such as when sample sizes were small and/or detections were low.

A similar effect occurs in the frequentist setting when variation among cohort-level estimates is represented as "random effects" around a common mean (Franklin et al. 2002). We have not used such models in past years of this study, and for simplicity did not entertain them for this appendix. For data sets consisting of a single pooled group for the entire season, most reach estimates and associated uncertainty from the BCJS model were close to those from the standard CJS, with uncertainty of estimates often smaller for BCJS.

We concluded that the BCJS model is preferable to standard CJS because of gains in precision, the ability to use prior information, and the constraint of estimates to the unit interval. We plan to use some form of Bayesian CJS in future estimates. We did not find that the BCJS-DR model provided clear benefits over BCJS for 2021, despite what we perceived as its potential for gains in precision. For such gains in precision to be realized, sufficient numbers of avian colony recoveries are needed; apparently, recoveries were not sufficient for most stocks in 2021, with the possible exception of steelhead.

Furthermore, there were many plausible ways for assumptions of the BCJS-DR model to be violated, and such violations can lead to biased survival estimates. Until we have more definitive answers about how potential assumption violations affect survival estimates, we do not recommend use of BCJS-DR survival estimates for 2021.

We plan to expand our methods to include the model of Hance et al. (2020), including a modified version that uses tag recovery data from interior avian colonies where appropriate. These models will allow joint estimation of survival and travel time over finer time scales and will have the ability to estimate the proportion of smolts transported. They will also allow for survival and abundance estimates for the tagged and untagged run at large. Our goal is to use the most advanced statistical tools in conjunction with all appropriate data sources to produce survival estimates that are as accurate and precise as possible. With this in mind, we plan to transition to these new statistical methods and will ultimately apply them to past years so that we will have a catalog of estimates using consistent methodology.

U.S. Secretary of Commerce
Gina M. Raimondo

Under Secretary of Commerce for
Oceans and Atmosphere
Dr. Richard W. Spinrad

Assistant Administrator for Fisheries
Janet Coit

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fisheries.noaa.gov

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National Marine
Fisheries Service
Northwest Fisheries Science Center
2725 Montlake Boulevard East
Seattle, Washington 98112