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Survival and Migration Behavior of Juvenile Salmonids at Lower Granite Dam, 2006

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Survival and Migration Behavior of Juvenile Salmonids at Lower Granite Dam, 2006

Final Report of Research

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Summary

We described behavior and estimated passage and survival parameters of juvenile salmonids during spring and summer migration periods at Lower Granite Dam in 2006. During the spring, the study was designed to examine the effects of the Behavioral Guidance Structure (BGS) by using a randomized-block BGS Stored / BGS Deployed treatment design. The summer study was designed to compare passage and survival through Lower Granite Dam using a randomized-block design during two spill treatments while the BGS was in the stored position. We used the Route Specific Survival Model to estimate survival and passage probabilities of hatchery yearling Chinook salmon, hatchery juvenile steelhead, and hatchery and wild subyearling Chinook salmon. We also estimated fish guidance efficiency (FGE), fish passage efficiency (FPE), Removable Spillway Weir passage effectiveness (RPE), spill passage effectiveness (SPY), and combined spill and RSW passage effectiveness.

The analysis was based on 1,677 hatchery yearling Chinook salmon, 1,985 hatchery juvenile steelhead and 2,078 hatchery and wild subyearling Chinook salmon surgically implanted with radio tags. About 60% of the radio-tagged fish were released at Blyton Landing, Washington (18 km upstream of the dam) to serve as a treatment group, and the remainder were released 500 m below the dam as a control group.

There were no significant differences in survival probabilities between treatments within the species studied, but several significant differences in passage probabilities were present (Summary Tables 1, 2, and 3). Yearling Chinook salmon FPE was greater during the BGS Deployed treatment due to greater passage probabilities through the spillway, lower probabilities through the bypass, and greater FGE than during the BGS stored treatment. The probability of passage through the RSW was similar in each treatment (0.281 deployed, 0.312 stored). For juvenile steelhead, only the passage probability through the RSW was significantly different with a slightly greater probability during the stored (0.285) than the deployed (0.245) treatment. The FPE of subyearling Chinook salmon was significantly greater during the 1-stop treatment than during the 4-stop treatment. This was a result of a significantly greater RSW passage

probability during the 1-stop treatment (0.620) than the 4-stop treatment (0.522). Diel differences in passage probabilities were evident in most groups. The greatest passage probabilities were generally through the RSW during the day and through the spillway, bypass, and turbines during the night.

Survival probabilities of yearling Chinook salmon and juvenile steelhead were greater than those of subyearling Chinook salmon. Survival probabilities of yearling Chinook salmon and juvenile steelhead through routes other than the turbines within each treatment were high (greater than 0.952) and similar to one another. Their survival though the turbines (0.815 to 0.952) were lower than the other routes, but few fish passed via this location and no significant differences between treatments were detected. Survival probabilities of subyearling Chinook salmon showed a similar trend among routes as in spring migrants, but the probabilities were on average about 0.06 lower.

The BGS had little effect on passage routes during the spring. Approximately 25% of the fish detected in the forebay were detected near the BGS (within about 6 m). The first detections of these fish were distributed along the entire length of the BGS, but 53% of the juvenile steelhead and 37% of the yearling Chinook salmon were first detected near the BGS within 75 m of the dam. The BGS diversion coefficient (the reduction in powerhouse passage through units 1-5 with the BGS deployed; P_b) was 7% of yearling Chinook salmon and 16% of juvenile steelhead. A correction for fish passing through the gap between the BGS and the shore and those passing under the BGS ($P_{b\ corrected}$) was biased due to limited detection of fish passing under the structure.

Most fish detected with 6 m of the RSW passed via that route. Nearly one third of yearling Chinook salmon and juvenile steelhead and two thirds of subyearling Chinook salmon detected in the forebay were detected within 6 m of the RSW. Of these fish, at least 84% passed via the RSW (84 to 98% depending on treatment and species). The RSW continued to be an effective passage route, with passage effectiveness (percent fish passed divided by percent water passed) of 4.2 to 6.4, depending on treatment and species.

Summary Table 1.— Summary of the estimated survival, lambda, passage estimates, standard error (SE) and the estimated fish passage and guidance efficiencies for yearling Chinook salmon passing through Lower Granite Dam during spring 2006. Treatments consisted of the Behavior Guidance Structure (BGS) being deployed or stored. Asterisks indicate significant differences (two-tail *z*-test, $\alpha = 0.05$) between BGS stored and BGS deployed treatments.

	Dam Treatments					
	BGS Stored		BGS Deployed		Overall (Stored and Deployed)	
Parameters	Probability(SE)	95% CI	Probability(SE)	95% CI	Probability(SE)	95% CI
S pool	0.989 (0.006)	0.974,0.997	0.987 (0.006)	0.971,0.996	0.988 (0.004)	0.978,0.995
S forebay	0.991 (0.007)	0.974,1.003	0.999 (0.004)	0.987,1.005	0.996 (0.003)	0.987,1.001
S dam	0.967 (0.012)	0.939,0.989	0.966 (0.014)	0.936,0.992	0.975 (0.008)	0.957,0.990
S spillway	0.970 (0.018)	0.923,0.999	0.985 (0.019)	0.931,1.014	0.982 (0.013)	0.951,1.002
S RSW	0.985 (0.016)	0.941,1.009	0.979 (0.019)	0.929,1.009	0.992 (0.010)	0.966,1.009
S turbine	0.815 (0.086)	0.619,0.943	0.935 (0.042)	0.826,0.994	0.909 (0.039)	0.817,0.968
S bypass	0.987 (0.014)	0.947,1.009	0.951 (0.026)	0.887,0.993	0.976 (0.014)	0.944,0.998
λ	0.994 (0.005)	0.980,0.999	0.989 (0.006)	0.972,0.997	0.991 (0.004)	0.982,0.997
*Pr spillway**	0.331 (0.026)	0.281,0.383	0.253 (0.025)	0.206,0.304	0.294 (0.018)	0.259,0.331
*Pr RSW**	0.281 (0.006)	0.235,0.331	0.312 (0.010)	0.261,0.365	0.295 (0.006)	0.260,0.331
*Pr turbine**	0.081 (0.016)	0.053,0.115	0.158 (0.021)	0.119,0.203	0.117 (0.013)	0.093,0.144
Pr bypass	0.308 (0.025)	0.260,0.359	0.277 (0.026)	0.229,0.329	0.294 (0.018)	0.260,0.331
FPE*	0.919 (0.016)	0.885,0.947	0.842 (0.021)	0.797,0.881	0.883 (0.013)	0.856,0.907
FGE*	0.793 (0.037)	0.714,0.860	0.637 (0.042)	0.552,0.717	0.716 (0.029)	0.658,0.770
SPY [a]	1.001		0.711		0.857	
RPE [a]	5.640		6.449		6.004	
CPE [a]	1.609		1.398		1.502	

[a]-No standard error or confidence interval presented.

Summary Table 2. — Summary of the estimated survival, lambda, passage estimates, standard error (SE) and the estimated fish passage and guidance efficiencies for juvenile steelhead passing through Lower Granite Dam during spring 2006. Treatments consisted of the Behavior Guidance Structure (BGS) being deployed or stored. Asterisks indicate significant differences (two-tail *z*-test, α = 0.05) between BGS stored and BGS deployed treatments.

	Dam Treatments					
	BGS Stored		BGS Deployed		Overall (Stored and Deployed)	
Parameters	Probability(SE)	95% CI	Probability(SE)	95% CI	Probability(SE)	95% CI
S pool	0.998 (0.002)	0.990,1.001	0.998 (0.002)	0.990,1.001	0.998 (0.002)	0.993,1.001
S forebay	0.994 (0.005)	0.981,1.004	0.990 (0.005)	0.976,0.998	0.992 (0.004)	0.983,0.998
S dam	0.958 (0.011)	0.934,0.977	0.981 (0.009)	0.960,0.999	0.976 (0.007)	0.961,0.988
S spillway	0.985 (0.013)	0.949,1.003	0.989 (0.013)	0.954,1.010	0.991 (0.008)	0.970,1.004
S RSW	0.952 (0.022)	0.897,0.985	0.989 (0.013)	0.952,1.010	0.981 (0.011)	0.954,0.997
S turbine	0.879 (0.082)	0.670,0.981	0.875 (0.072)	0.685,0.973	0.900 (0.049)	0.780,0.971
S bypass	0.955 (0.017)	0.915,0.981	0.986 (0.013)	0.953,1.007	0.972 (0.010)	0.948,0.989
λ	0.997 (0.003)	0.989,1.000	0.994 (0.004)	0.981,0.999	0.996 (0.002)	0.989,0.999
Pr spillway	0.282 (0.022)	0.239,0.327	0.295 (0.024)	0.250,0.346	0.288 (0.016)	0.257,0.320
*Pr RSW**	0.245 (0.003)	0.204,0.288	0.285 (0.004)	0.241,0.333	0.263 (0.002)	0.233,0.295
Pr turbine	0.058 (0.012)	0.037,0.086	0.063 (0.018)	0.034,0.096	0.060 (0.009)	0.043,0.080
Pr bypass	0.416 (0.025)	0.368,0.464	0.357 (0.024)	0.312,0.405	0.389 (0.017)	0.355,0.423
FPE	0.942 (0.012)	0.914,0.963	0.937 (0.018)	0.904,0.966	0.940 (0.009)	0.920,0.957
FGE	0.877 (0.025)	0.822,0.921	0.849 (0.038)	0.779,0.915	0.866 (0.020)	0.825,0.903
SE [a]	0.852		0.830		0.839	
RPE [a]	4.910		5.886		5.364	
CPE [a]	1.384		1.436		1.405	

[a]-No standard error or confidence interval presented.

Summary Table 3.— Summary of the estimated survival, lambda, passage estimates, standard error, and the estimated fish passage and guidance efficiencies for subyearling Chinook salmon at Lower Granite Dam during 2006. Treatments consisted of 1 stop and 4 stop spill treatments. Asterisks indicate significant differences (two-tail *z*-test, $\alpha = 0.05$) between BGS stored and BGS deployed treatments.

	Dam Treatments					
	RSW/1-Stop		RSW/4-Stops		Overall RSW/1-and 4-Stops)	
Parameters	Probability(SE)	95% CI	Probability(SE)	95% CI	Probability(SE)	95% CI
S *pool*	0.926 (0.014)	0.896,0.951	0.928 (0.013)	0.900,0.951	0.927 (0.009)	0.907,0.944
S *forebay*	0.958 (0.012)	0.929,0.978	0.941 (0.013)	0.914,0.963	0.949 (0.009)	0.930,0.965
S *dam*	0.918 (0.021)	0.830,0.991	0.906 (0.018)	0.869,0.942	0.914 (0.014)	0.886,0.942
S *spillway*	0.844 (0.073)	0.681,0.962	0.934 (0.039)	0.839,0.996	0.894 (0.040)	0.805,0.961
S RSW	0.969 (0.021)	0.925,1.009	0.916 (0.023)	0.867,0.959	0.945 (0.016)	0.913,0.975
S turbine	0.683 (0.121)	0.436,1.004	0.872 (0.063)	0.727,0.969	0.846 (0.054)	0.728,0.936
S bypass	0.863 (0.045)	0.766,0.941	0.882 (0.036)	0.803,0.945	0.875 (0.028)	0.815,0.927
λ	0.959 (0.011)	0.933,0.977	0.977 (0.009)	0.954,0.991	0.967 (0.007)	0.950,0.980
Pr spillway	0.108 (0.017)	0.030,0.144	0.137 (0.017)	0.106,0.172	0.104 (0.011)	0.084,0.127
*Pr RSW**	0.620 (0.004)	0.569,0.669	0.522 (0.007)	0.474,0.570	0.568 (0.005)	0.533,0.603
*Pr turbine**	0.049 (0.012)	0.029,0.167	0.099 (0.015)	0.072,0.131	0.094 (0.011)	0.074,0.117
Pr bypass	0.223 (0.022)	0.152,0.305	0.242 (0.021)	0.202,0.284	0.234 (0.015)	0.205,0.264
FPE*	0.951 (0.012)	0.833,0.971	0.901 (0.015)	0.869,0.928	0.906 (0.011)	0.883,0.926
FGE	0.819 (0.041)	0.527,0.889	0.709 (0.039)	0.629,0.781	0.713 (0.029)	0.653,0.768
SPY [a]	0.504		0.623		0.481	
RPE [a]	5.034		4.243		4.614	
CPE [a]	2.158		1.925		1.978	

[a]-No standard error or confidence interval presented.

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Introduction

As the operator of hydroelectric dams on the Lower Snake and Columbia rivers, the U.S. Army Corps of Engineers (USACE) has been required to evaluate the recovery of anadromous fish within the framework of the Nation Marine Fisheries Service's 2004 Biological Opinion Remand. This Biological Opinion defined objectives to evaluate and improve the survival of Snake River salmon and steelhead over the next decade.

Surface bypass is one option being tested by the USACE as an alternative passage route to conventional spill, turbines, and bypass systems, which may improve juvenile salmonid survival. Observations at several Columbia River dams have shown that migrating fish pass through surface water passage structures at higher percentages per percent of water discharge than relatively deeper spillway or turbine routes. At Wells Dam, Washington, where spill bays are located above the turbines, 90% of fish passed through spillway intake baffles that used 7% of the total discharge (Skalski et al. 1996). Research at other dams corroborates the effectiveness of surface-oriented routes of passage. In a review of passage studies, Giorgi and Stevenson (1995) reported that 40 to 50% of juvenile salmonids approaching The Dalles Dam passed through the ice and trash sluiceway (a surface passage route) during non-spill conditions. Swan et al. (1995) discovered that about 50% of radio-tagged juvenile Chinook salmon passed via the sluiceway at Ice Harbor Dam while considerable spill occurred. Based on the vertical distribution of fish in the Lower Granite forebay and the success of surface-oriented passage routes at other dams, many resource managers have concluded that near-surface flows may be an effective non-turbine passage route.

During the summer of 2001, the USACE installed a removable spillway weir (RSW) at Lower Granite Dam. Based on the surface bypass concept, the RSW discharges water at a much shallower depth than conventional spill bays or turbine intakes. In the spring of 2002 and 2003, the performance of the RSW was evaluated and compared to the current management strategy of spilling water to the "gas cap". These evaluations indicated that the RSW was an effective and efficient passage structure (Anglea 2003; Plumb et al. 2004). These studies found that the RSW discharged just 8.5% of the total discharge through the dam, but on average passed 56-62% of radio-tagged fish passing Lower Granite Dam. Although spill to the gas cap passed comparable percentages of fish (54-66%) as the RSW, spilling to the gas cap discharged about 35% of the total discharge through the project. The RSW passed higher percentages of fish per unit volume of water discharged than spill to the gas cap making the RSW an attractive management option. During 2003, Plumb et al. (2004) also found that survival though the RSW was favorable at 98%.

A floating wall intended to guide fish toward surface spill devices has also been used at Lower Granite Dam. In 1998 this wall, known as the behavioral guidance structure (BGS) was affixed to the powerhouse as an aid in directing fish away from the powerhouse and into a surface bypass collector. The BGS at that time was 335 m long and ranged in depth from 17 to 30 m to generally follow the river bottom in the powerhouse forebay. This BGS was shown to divert about 60% of the fish otherwise bound for powerhouse passage toward the collector (Adams et al. 2001). In 2006 a shallower version (17 m deep throughout its 335 m length) was tested as an aid in directing fish toward the RSW and spillway.

During 2006, we used radio telemetry to determine differences in behavior, passage and survival of fish migrating past Lower Granite Dam. Our objectives were to: 1) assess fish passage relative to spill, powerhouse, RSW, and BGS operations, 2) estimate route-specific passage and survival for juvenile steelhead, yearling and subyearling Chinook salmon, and 3) examine relations between dam operations, fish behavior, passage and survival. Specifically, during the spring, our study design was to test passage, survival, and behavior during BGS treatments. During the summer our study design was to test passage, survival, and behavior during 1-stop and 4-stop spill treatments.

Methods

Study Area

Lower Granite Lock and Dam is located in eastern Washington on the Snake River at river kilometer (rkm) 173. The drainage area supported by Lower Granite Lock and Dam is 267,287 square kilometers containing, most significantly, the Snake River above Clarkston, Washington, Clearwater River, Salmon River, Imnaha River, and Grande Ronde River (Figure 1). The lock and dam are used primarily for power generation and inland navigation and perform secondary uses of flood control and recreation. The study area was from the uppermost release location at Blyton Landing (rkm 192.4) to Lower Monumental Lock and Dam (rkm 65; Figure 2).

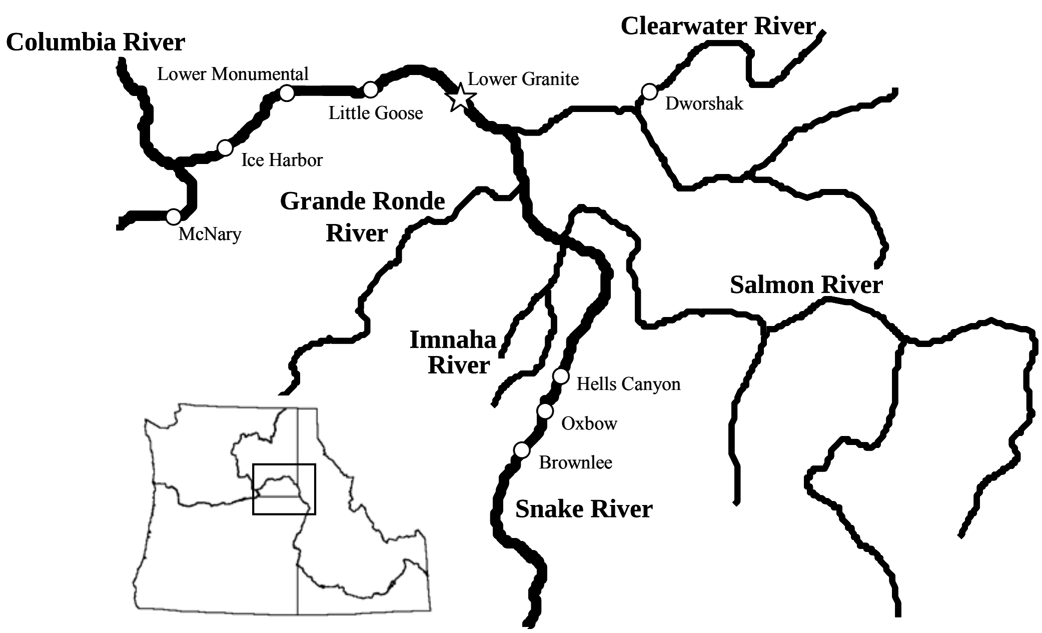

Figure1. — Overview of the Snake River and its major tributaries, Lower Granite Dam is shown relative to other major hydroelectric projects in the region.

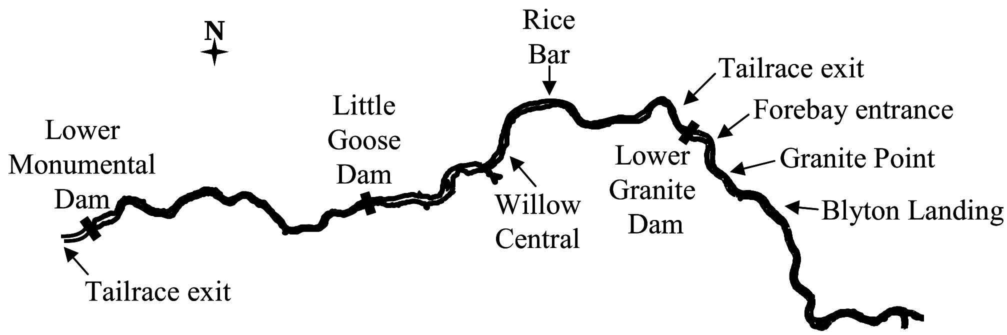

Figure 2. — Overview of study area during 2006. Key locations include Blyton Landing rkm 192.4, Granite Point rkm 182, forebay entrance rkm 175, Lower Granite Dam rkm 173, tailrace exit rkm 171, Rice Bar rkm 150, Willow Central rkm 136, Little Goose Dam rkm 113, and Lower Monumental Dam rkm 65.

The overall width of the project is 975 m, comprising of a 437 m earthen dam, a navigation lock, an eight-bay spillway, and a six-unit powerhouse. Incorporated within the project are fish facilities consisting of an adult ladder for upstream migrants, an adult fish trap and handling facility, downstream migrants bypass system, juvenile holding and sampling facility, and juvenile transport facilities (Figure 3).

The spillway consists of eight bays with a maximum design capacity of 850 kcfs. Spill bays two thru eight are controlled by tainter gates and discharge water at a depth of 16 m at the normal operating pool elevation of 223.4 m. Spill bay one contains a removable spillway weir (RSW) allowing for surface discharge which is initiated by the tainter gate and controlled by forebay elevation (3 m deep at normal operating pool).

The powerhouse consists of six 6-blade Kaplan turbines capable of 810 megawatt plant capacity. Each unit draws water through three induction slots. The slots are outfitted with extended-length submerged bar screens (ESBS) and vertical barrier fish screens for fish guidance to the bypass system.

A unique structure at Lower Granite Lock and Dam is the behavioral guidance structure (BGS). The BGS is a 335 m long, 18 m deep barrier wall suspended from floating pontoons. The structure can be attached to the powerhouse at an anchor frame while deployed (during 2006, the attachment point was between unit 5 and unit 6) or anchored in the powerhouse forebay when stored (Figure 3).

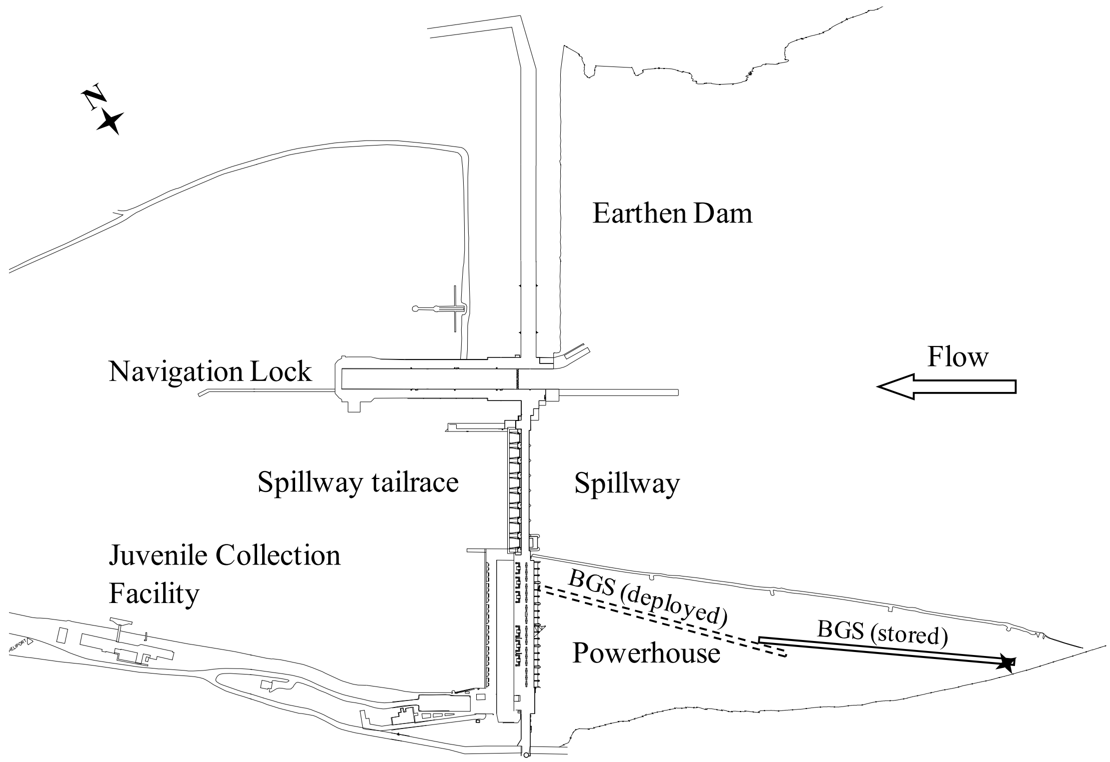

Figure 3. — Overview of Lower Granite Lock and Dam structures and features. The Behavioral Guidance Structure (BGS) is shown as deployed and stored. The BGS was in the stored position during the summer study period 2006

Radio Telemetry System

The radio telemetry system consisted of aerial and underwater antennas monitored by data collection equipment. All remote area antennas (those away from the dam) were monitored using Lotek SRX_400-W16 receivers (Lotek Wireless, Inc., Newmarket, Ontario, Canada). The dams and nearby areas were monitored using a combination of Lotek SRX_400-W16 receivers and Multi-protocol Integrated Telemetry Acquisition Systems (MITAS, Grant Systems Engineering (GSE), King City, Ontario, Canada).

Antennas and receivers were deployed to evaluate fish behavior in the reaches upstream of and near the dam to determine route-specific passage and survival through all routes at the dam. Arrays used to describe fish behavior consisted of aerial antennas monitored by SRX. These were deployed at Granite Point (rkm 182), the forebay entrance (rkm 175), Lower Granite Lock and Dam (earthen dam, spillway, and powerhouse), spillway tailrace, a tailrace exit (rkm 171), and at Lower Monumental Lock and Dam (rkm 65).

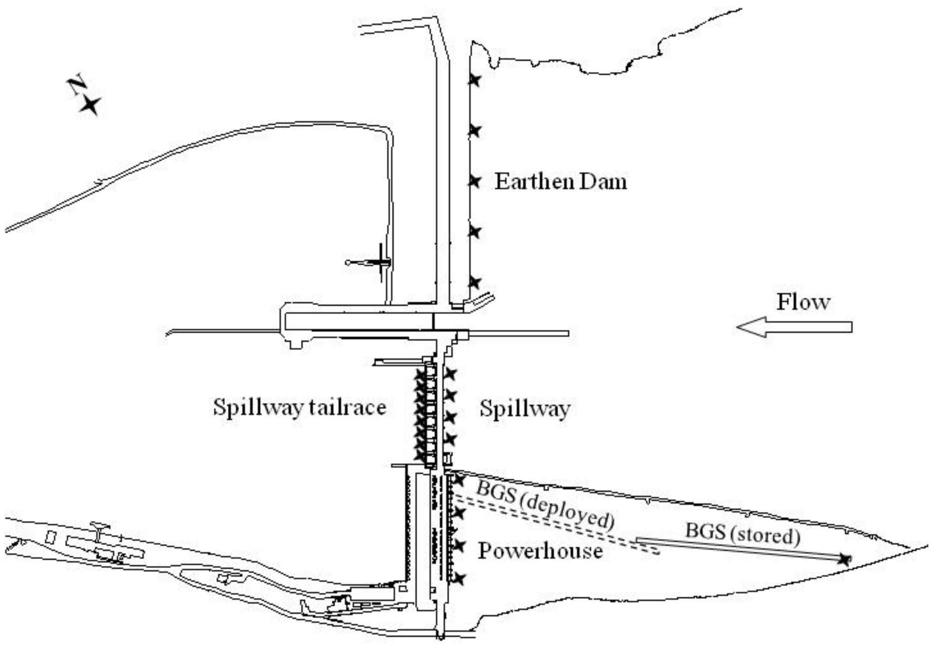

Figure 4. — Detail of Lower Granite Dam behavioral arrays during spring and summer study periods. Aerial arrays were located at the abutment embankment, spillway, powerhouse, and the Removable Spillway Weir (RSW).

Arrays used to assign route-specific passage consisted of underwater dipole antennas monitored using independent MITAS systems. These antennas were deployed in all spill bays (Figure 5), the RSW (Figure 6), turbine unit intake slots (Figure 7), and the juvenile bypass collection channel. All passage routes were monitored with multiple detection arrays and monitoring devices.

A series of underwater dipole antennas and a single corner-reflector aerial antenna were used to detect tagged fish near the BGS. We installed a total of 82 underwater dipole antennas on the north and south sides of the BGS. On modules 1 (closest to the dam) through 11 (furthest upstream), we installed three antennas on the north side of each module at a 5 m depth and three antennas at an 18 m depth on the south side. In addition on modules 1 and 2, we installed three antennas on the south side at a depth of 5 m. To better measure fish traveling around the end of the BGS, we installed one underwater dipole antenna each at depths of 4 m, 10 m, and 16 m on the upstream end of module 11. On the BGS anchor frame attached between turbine units five and six, we installed two antennas each at depths of 6 m and 18 m on the north and south side for a total of eight antennas. North and south antennas were combined for behavior analysis by modules 1, 2, 3-5, 6-7, 9-11 and by depth (5 m and 18 m). The three antennas on the end module 11 were also combined. Lastly, a corner-reflector aerial antenna was mounted near the upstream end of module 11 to detect fish passing through the gap between the BGS and the shore.

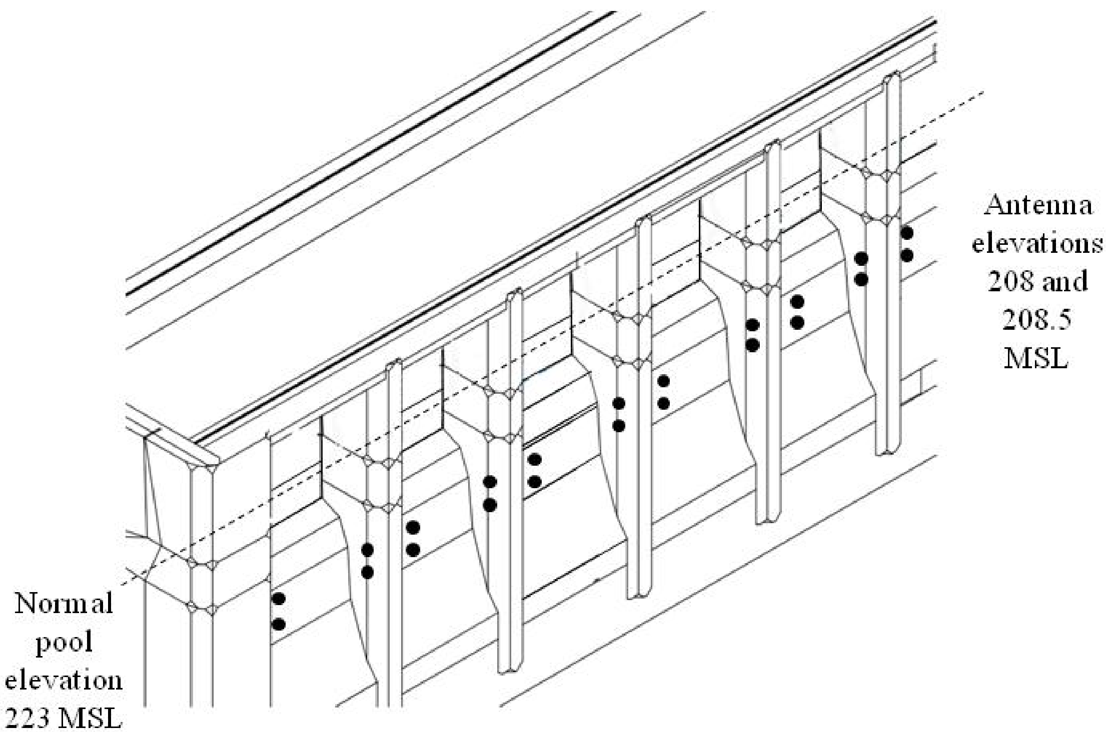

Figure 5. — Schematic of spill bay underwater passage arrays during 2006. Antennas were located in spill bays two-eight at Lower Granite Dam.

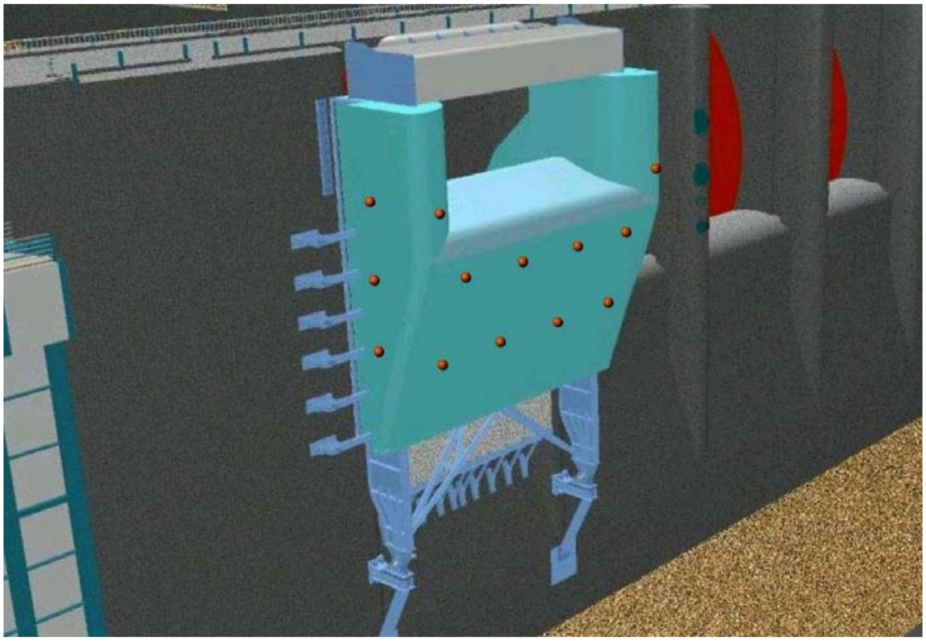

Figure 6. — Details of Removable Spillway Weir (RSW) underwater antenna array during 2006. The RSW is located in spill bay one at Lower Granite Dam.

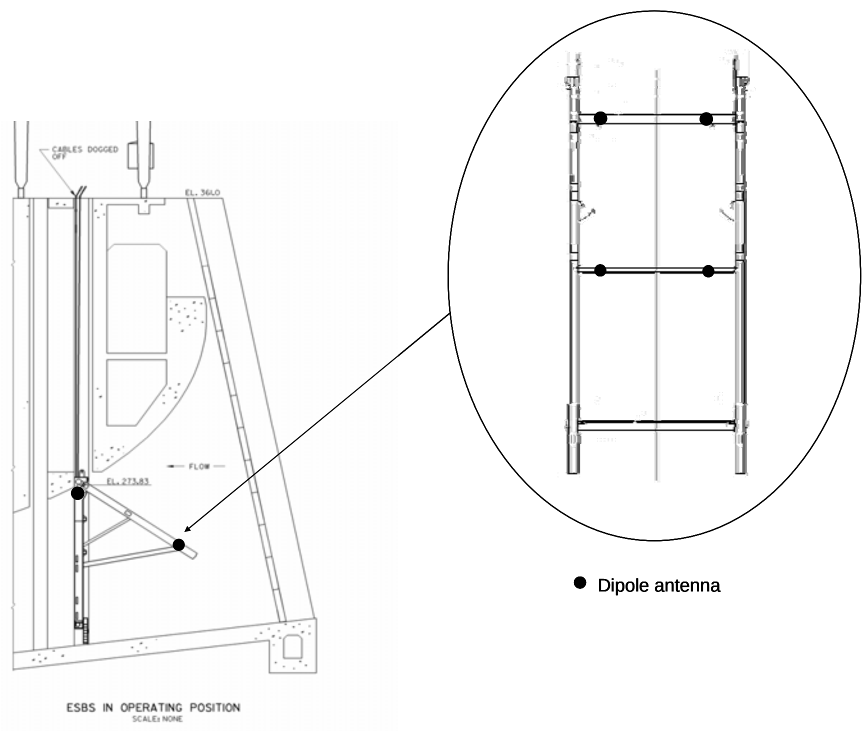

Figure 7. — Detail of powerhouse Extended-Length Submerged Bar Screen passage arrays during spring and summer study periods. The antennas were combined to provide two independent underwater arrays.

In-river arrays used in survival analysis were deployed at Rice Bar Habitat Management Unit (rkm 150), between Willow Landing and Central Ferry Bridge (rkm 136), and Little Goose Lock and Dam (earthen dam, spillway, and powerhouse) and Lower Monumental Dam. All sites for survival detection contained multiple data logging receivers for redundant detection. Survival arrays consisted of aerial antennas monitored by Lotek SRX receivers. In addition, Little Goose Dam passage arrays monitored by the MITAS system were also used as detection arrays for survival.

Sites were maintained throughout the study period for sufficient power supply and data logging capability. Lotek SRX data was collected using Allegro handheld computers (Juniper Systems, Logan, Utah) and laptop computers in conjunction with MaxStream wireless 900 MHz modems (MaxStream, Inc., Orem, Utah). The MITAS systems wrote directly to a computer hard drive.

Radio Transmitters

We used 1.5-volt digitally encoded radio transmitters in addition to passive integrated transponder (PIT) tags. The digitally encoded radio transmitters, manufactured by Lotek Wireless, Inc. (Newmarket, Ontario), were operated at frequencies between 150.330 and 150.600 MHz and used the Lotek "2003 code set". The code set is a digital encoding scheme with 521 unique codes per frequency allowing the ability to identify individuals. Partitioning transmitter codes among frequencies reduces the potential for radio signal collisions and increases the probability of detection. The radio transmitters used in the spring study were model NTC-3-1 and emitted a radio signal every 2 s, resulting in an expected minimum battery life of 16 days (Table 1). The radio transmitters used in the summer study were model NTC-M-2, and emitted a radio signal every 2.5 s, resulting in an expected minimum battery life of 16 days (Table 1). The PIT-tags, provided by Biomark, Inc. (Boise, Idaho; model TX1400ST), emitted a unique digitally coded signal at 134.2 kHz when activated by an electromagnetic field at a PIT-tag detector. The PIT-tags were 2.1 mm in diameter x 12 mm long and weighed 0.07 g in air.

Table 1. — Specifications for radio transmitters used at Lower Granite Dam as supplied by the manufacturer. Minimum fish weight is based on a maximum tag-to-fish weight ratio of 5%.

Species	Transmitter model	Minimum battery life (d)	Dimensions (mm)	Minimum fish weight (g)
Yearling Chinook salmon	NTC-3-1	16	6.3 x 14.5	14.2
Juvenile steelhead	NTC-3-1	16	6.3 x 14.5	14.2
Subyearling Chinook salmon	NTC-M-2	16	5.3 x 13.5	10.0

Fish Tagging

Yearling hatchery spring Chinook salmon, juvenile hatchery steelhead, and subyearling Chinook salmon were obtained from the juvenile fish facility sampled by the Washington Department of Fish and Wildlife at Lower Granite Dam. Fish were held at the juvenile fish facility in 127 L perforated holding containers at a density of < 20 g / 1 L water per container. The containers were held inside a 3.7 m X 1.2 m insulated metal holding tank supplied with flowing river water for approximately 24 h prior to tagging. Fish were considered suitable for tagging if they were free of major injuries, had no external signs of gas bubble trauma, were ≤ 20% descaled, and had no other abnormalities. We alternated the order of tagging treatment and control groups to minimize any possible bias in selecting fish that could result in different mortality rates between the two groups.

To implant transmitters, fish were first anesthetized using buffered tricane methanosulfate (MS-222) at a dosage of 65-70 mg/L. Fish were weighed to the nearest 0.1 g and measured to the nearest mm. Transmitters were surgically implanted using methods described by Adams et al (1998). A PIT tag was placed in the body cavity with the radio transmitter. All weighing, measuring, and containment equipment was treated with a 0.25 ml\L concentration of Stress Coat (Aquarium Pharmaceuticals, Inc.) to minimize handling-related stress to the fish.

Immediately following the tagging procedure, fish were placed in a 19-L perforated bucket filled with 7 L of river water and dissolved oxygen levels between 120-150%. Each bucket held three Chinook salmon or two juvenile steelhead. To fully recover from tagging, the perforated buckets with tagged fish inside fish were placed in 3.7 m X 1.2 m or 4.9 m X 1.2 m insulated metal tanks and held for about 24 h before release. The perforated buckets ensured water circulation.

Fish Releases

To estimate survival and monitor fish behavior, we conducted replicate releases of treatment and control groups of radio-tagged yearling Chinook salmon and juvenile steelhead during the spring and subyearling Chinook salmon during the summer. Treatment groups consisted of radio-tagged fish released approximately 19 km upstream of Lower Granite Dam at Blyton Landing, and control groups were released in the dam tailrace approximately 0.5 km downstream from the dam. Although daily release sizes varied, we maintained a ratio of 1.5:1 between treatment and control groups. The transportation routes of treatment and control fish from the dam to the release sites were adjusted to result in similar transportation times of both groups.

Release techniques were similar for all treatment, control, and euthanized groups. Buckets were transferred from transportation tanks onto a boat and transported to the release location. Fish were released by gently submerging the recovery buckets into the water and tipping the buckets.

Data Analysis

Data proofing

All data collected were examined for completeness and accuracy prior to analysis. Prior to analysis, release and telemetry detections were checked for quality assurance and quality control. Data was then imported into SAS (version 8.1, SAS Institute Inc., Cary, North Carolina, USA) for more detailed proofing and analysis. Release data was merged with telemetry data to create a single dataset that could be scrutinized by an automated proofing program. This program removed non-valid records (environmental noise), duplicate records, and records collected prior to a known release date and time. It flagged records as invalid if they failed to meet the following set of nested criteria:

1. Minimum signal strength.
2. Records collected before the maximum tag life (see Appendix B).
3. A minimum of two detections within a 20-min period within a geographic area.
4. If there were only two detections within an hour at one area of the dam, then there must have been ≥ 2 detections at a different area of the dam within a 3-h period.

After flagging invalid records, the program flagged suspect records for manual proofing based on travel time, residence time, and geographic criteria. Travel times were calculated as the elapsed time between the first detection at one array and the first detection at all subsequent downstream arrays. Residence time was calculated as the elapsed time between the first and last detection at each geographic area. For travel time and residence time criteria, we estimated the probability of each fish's travel or residence time at, or between, each location. To estimate this probability, we fit the cumulative inverse Gaussian distribution to the observed travel time distributions (Zabel 1994; Zabel and Anderson 1997). If the probability of a fish's travel time or residence time was ≤ 0.005 or ≥ 0.995 then these records were flagged for manual proofing. The travel time criterion was effective in identifying noise records that passed other criteria. The geographic criterion flagged records for manual proofing based on inconsistencies in the timing and geographic location of detections. For example, detections at the dam after fish had been detected downstream were flagged for manual inspection. In addition, all instances were manually proofed when detections occurred at a later time upriver from previous downstream detections.

The automated proofing program was also used to assign dam passage routes and times. The passage route of each fish was determined based on the location of its last valid detection at the dam. For example, fish last detected in the juvenile fish collection channel were assigned bypass passage, but fish last detected at underwater antennas on ESBS were assigned to the turbines. Likewise, fish last detected by an underwater antenna or aerial antenna on the spillway were assigned spillway passage. Fish not detected at the dam or last detected by aerial antennas on the navigation wall, powerhouse, or earthen dam were initially assigned an "unknown" passage route.

To refine the effectiveness and validate the accuracy of the automated proofing program all telemetry data collected during the spring and summer study period were filtered through the automated proofing program. Logic errors causing discrepancies between the automated and manual proofing processes were corrected in the program. During the spring and summer studies, the automated proofing program was run on all data. The program flagged 13% of the spring data and 14% of the summer data for manual proofing, and successfully assigned passage routes to 99% during the spring and 97% during the summer. Furthermore 11% of the data for spring and summer assigned a passage route by the automated proofing program was randomly selected and manually inspected to validate the automated passage route assignment.

Treatments and environmental conditions

Treatments were different during the spring and summer study periods. During the spring, treatments were conducted to assess behavior, passage, and survival associated with the Behavioral Guidance Structure (BGS) at Lower Granite Dam. Two treatments, BGS In (deployed) and BGS Out (stored), were implemented using a randomized-block study design (Table 2). During the summer, two treatments were implemented to compare the performance of the RSW during two spill regimes. Using a randomized-block design, two 1-d treatments, 1-stop (one stop open on all spill bays) or 4-stop (4-stops on spill bays 3 and 4 and 1-stop on bays 6-8 with 2, 4, and 5 closed), were assigned within 20, 2-d blocks during the summer study period (Table 3). The BGS was in the stored position during the summer study period.

Table 2. — Randomized block treatments for Behavior Guidance Structure (BGS) at Lower Granite Dam during the spring, 17 April to 27 July 2006. BGS In (BGS is anchored between turbine units 5 and 6). BGS Out (BGS is anchored in the stored position in the forebay).

Date	Block	Treatment	Date	Block	Treatment
17-Apr	1	BGS In	8-May	5	BGS Out
18-Apr	1	BGS In	9-May	5	BGS Out
19-Apr	1	Move out	10-May	5	Move in
20-Apr	1	BGS Out	11-May	5	BGS In
21-Apr	1	BGS Out	12-May	5	BGS In
22-Apr	2	Move in	13-May	6	BGS In
23-Apr	2	BGS In	14-May	6	BGS In
24-Apr	2	BGS In	15-May	6	Move out
25-Apr	2	Move out	16-May	6	BGS Out
26-Apr	2	BGS Out	17-May	6	BGS Out
27-Apr	2	BGS Out	18-May	7	BGS Out
28-Apr	3	BGS Out	19-May	7	BGS Out
29-Apr	3	BGS Out	20-May	7	Move in
30-Apr	3	Move in	21-May	7	BGS In
1-May	3	BGS In	22-May	7	BGS In
2-May	3	BGS In	23-May	8	BGS In
3-May	4	BGS In	24-May	8	BGS In
4-May	4	BGS In	25-May	8	Move out
5-May	4	Move out	26-May	8	BGS Out
6-May	4	BGS Out	27-May	8	BGS Out
7-May	4	BGS Out			

To document the environmental condition that juvenile salmonids experienced during their outmigration, project discharge, total dissolved gas, forebay elevation, tailwater elevation, and water temperature data were summarized for spring and summer study periods.

Forebay behavior

We calculated travel times of radio-tagged fish to understand how environmental conditions and operations at Lower Granite Dam affected the migration timing of juvenile salmonids. Travel times from Blyton Landing, Washington, to the forebay of Lower Granite Dam were calculated as the elapsed time from release to the first detection at the forebay entrance array 2 km upstream of the dam. The forebay entrance array at

Table 3. — Randomized block spill treatments at Lower Granite during summer study period (8 June to 17 July 2006). 1-stop (Removable Spillway Weir open plus one stop at all other spill bays), 4-stop (Removable Spillway Weir open plus 4 stops at spill bays 1 and 3, 1 stop at spill bays 6, 7, and 8, and spill bays 2, 4, and 5 closed).

Date	Block	Treatment	Date	Block	Treatment
8-Jun	1	1 stop	28-Jun	11	4 stops
9-Jun	1	4 stops	29-Jun	11	1 stop
10-Jun	2	4 stops	30-Jun	12	4 stops
11-Jun	2	1 stop	1-Jul	12	1 stop
12-Jun	3	4 stops	2-Jul	13	1 stop
13-Jun	3	1 stop	3-Jul	13	4 stops
14-Jun	4	1 stop	4-Jul	14	1 stop
15-Jun	4	4 stops	5-Jul	14	4 stops
16-Jun	5	1 stop	6-Jul	15	4 stops
17-Jun	5	4 stops	7-Jul	15	1 stop
18-Jun	6	4 stops	8-Jul	16	1 stop
19-Jun	6	1 stop	9-Jul	16	4 stops
20-Jun	7	1 stop	10-Jul	17	1 stop
21-Jun	7	4 stops	11-Jul	17	4 stops
22-Jun	8	1 stop	12-Jul	18	1 stop
23-Jun	8	4 stops	13-Jul	18	4 stops
24-Jun	9	4 stops	14-Jul	19	1 stop
25-Jun	9	1 stop	15-Jul	19	4 stops
26-Jun	10	4 stops	16-Jul	20	4 stops
27-Jun	10	1 stop	17-Jul	20	1 stop

Lower Granite Dam has fixed antennas on the north and south shores and a barge located near the thalweg. The detection range of the fixed antenna locations is approximately 100 m. Approach distributions, arrival locations, residence time, and movements near the BGS and RSW were used to examine behaviors of juvenile salmon at Lower Granite Dam. For approach distributions, we calculated the percent of fish detected as they entered the forebay and arrival locations at the dam. To estimate arrival locations in the forebay we used aerial detections to determine if fish arrived north or south of the barge or middle. To estimate arrival locations across the dam we used fish detections at both aerial and underwater antennas. For residence time, we used the time of first detection at the forebay entrance to time of passage. For BGS behavior we calculated first contact location at the structure, passage through the upstream gap, and fish traveling under the BGS. Several BGS diversion coefficients were calculated during BGS deployed treatments (Table 4). For BGS behavior, guided would be fish passing through the juvenile bypass system and unguided would be fish passing through the turbines. Movement near the RSW was used to calculate discovery efficiency (DE) and entrance efficiency (EE; Table 4).

Table 4. — Definitions of metrics used to evaluate behavior of juvenile salmonids near the Behavioral Guidance Structure (BGS) and the Removable Spillway Weir (RSW) at Lower Granite Dam during spring and summer study period.

Parameter	Description
BGS Diversion Coefficient (P_b)	The observed performance of the BGS. P_b = 1- ((# fish guided units 1-5 when BGS in + # fish unguided units 1-5 when BGS in / total # fish passing dam when BGS in) / (# fish guided units 1-5 when BGS out + # fish unguided when BGS out/ total # fish passing dam when BGS out))).
$P_{b\ corrected}$	Estimated performance of the BGS assuming that the upstream gap could effectively closed to downstream migrants. $P_{b\ corrected} = P_b + (1-P_b)$ * (# fish through upstream gap/ (# fish through gap + # fish under BGS))).
RSW discovery efficiency (DE)	Proportion of fish detected within 6 m of the RSW entrance of the total number of fish in the forebay during RSW operations.
RSW entrance efficiency (EE)	Proportion of fish passing the RSW of fish detected within 6 m of the RSW entrance during RSW operations.

Tailrace egress time was calculated as the time elapsed between the time of passage and the time of detection at the tailrace exit site located about 2 km downriver of the dam. Egress times for bypassed fish were calculated from the last PIT detection in the bypass system to the time of detection 2 km downriver to exclude residence time of fish in the juvenile fish bypass system.

Estimating passage and survival parameters

We estimated passage and survival parameters for yearling and subyearling Chinook salmon and hatchery juvenile steelhead using the Route-Specific Survival Model (RSSM; Skalski et al. 2002). The foundation of this model is based on the classical single release-recapture models of Cormack (1964), Jolly (1965), and Seber (1965; CJS model) and the paired release-recapture model of Burnham et al. (1987). The RSSM partitions survival of fish among reservoir and route-specific components (Table 5). The model also estimates passage probabilities by using a branching process to estimate conditional probabilities of passing through each route (Figure 8).

We utilized the USER software program (User Specified Estimation Routine) to implement the RSSM and estimate passage and survival probabilities (Lady et al. 2003). To prepare the data for input into USER, records for each fish were summarized into detection histories to indicate the route of passage of each fish and whether fish were detected at antenna arrays at the entrance to the forebay and downriver of the dam. For determining whether fish survived to arrays below the dam, we used valid detections from telemetry arrays downriver of Rice Bar (rkm 150) and from all PIT-tag detectors at dams downriver of Lower Granite Dam. Detection histories of each fish form the basis of mark-recapture models and allow for the estimation of survival and detection probabilities. In general, survival and detection probabilities are estimated by:

1. Creating detection histories for each fish.
2. Estimating the probability of each possible detection history from the number of fish with that detection history (i.e., from the observed frequencies of each detection history).
3. Using maximum likelihood methods to find parameter estimates of survival, passage, and detection probabilities that were most likely, given the observed data set of detection histories.

The RSSM uses a primary likelihood to estimate survival and passage probabilities and a secondary likelihood to estimate route-specific detection probabilities. The detection history for the primary likelihood is composed of 4 digits indicating 1) the release site (1 = upstream, 0 = tailrace), 2) whether fish were detected at the forebay entrance site (1=detected, 0=not detected), 3) the route of passage for each fish coded by numbers ranging from 0 to 5 (see Appendix Table A1), and 4) whether fish were detected (1) or not detected (0) at arrays below the dam. For example, the detection history 1030 indicates a fish that was released upstream of the dam, not detected at the forebay entrance site, guided into the juvenile fish bypass system, but not subsequently detected by downriver arrays. The secondary likelihood uses within-route detection histories to calculate the detection probability of each route.

Each unique detection history has a probability of occurrence that can be completely specified in terms of the survival, passage, and detection probabilities (Appendix Table A1). For example, if a fish was detected in the juvenile fish bypass system then it must have survived through the preceding reach. Thus, the probability of this event is the joint probability that it survived through the reservoir (S_{Pool}), survived through the forebay (S_{Fb}), passed into the juvenile fish bypass system (PR_{By}), and was detected in the juvenile fish bypass system (P_{By}). However, if this fish was not subsequently detected at an array downriver of the dam, then two possibilities arise, 1) the fish died ($1\text{-}S_{\mathrm{By}}$, the probability of not surviving through the bypass), or 2) the fish survived the bypass but was not detected by downriver arrays, $S_{\mathrm{By}}(1\text{-}\lambda)$, the joint probability of surviving and not being detected. Therefore, the probability of detection history 1030 can be specified as $S_{\mathrm{Pool}}\, S_{\mathrm{Fb}}\, PR_{\mathrm{By}}\, P_{\mathrm{By}}(1\text{-}S_{\mathrm{By}} + S_{\mathrm{By}}(1\text{-}\lambda))$.

Table 5. — Definition of passage, survival, and detection parameters estimated by route-specific survival models (maximum likelihood estimates, MLE) or derived as functions of MLEs for Lower Granite Dam.

Parameter	Source	Definition
S_{Pool}	MLE	Survival probability of treatment group from release site at Blyton Landing to the point of detection at the forebay entrance site at Lower Granite Dam.
S_{Fb}	MLE	Survival probability of treatment group from point of detection at forebay entrance site to point of detection within passage routes at Lower Granite Dam. In other words, probability of surviving to just downstream of the dam, given that a fish survived to the forebay entrance site.
S_{Sp}	MLE	Spillway survival probability from detection in the spillway to the point of release of control groups in the tailrace.
S_{By}	MLE	Bypass survival probability from detection in the juvenile bypass to the point of release of control groups in the tailrace.
S_{Tu}	MLE	Turbine survival probability from detection in the turbines to the point of release of control groups in the tailrace.
S_{Sw}	MLE	RSW survival probability from detection in the RSW to the point of release of control groups in the tailrace.
P_{Fb}	MLE	Detection probability of the forebay entrance site.
P_{Sp1}	MLE	Detection probability of first spillway array.
P_{Sp2}	MLE	Detection probability of second spillway array.
P_{By1}	MLE	Detection probability for the first bypass array.
P_{By2}	MLE	Detection probability for the second bypass array.
P_{Tu1}	MLE	Detection probability for the first turbines array.
P_{Tu2}	MLE	Detection probability for the second turbines array.
P_{Sw1}	MLE	Detection probability for the first RSW array.
P_{Sw2}	MLE	Detection probability for the second RSW array.
SP	MLE	Probability of passing through the spillway.
SW	MLE	Conditional probability of passing through the RSW given that fish did not pass through the spillway.
BY	MLE	Conditional probability of passing through the juvenile bypass system given that fish did not pass through the spillway or RSW.
λ	MLE	Joint probability of surviving and being detected by all detection arrays downriver of Lower Granite Dam.
S_{Dam}	Derived	Average survival probability of dam passage through all routes weighted by the probability of passing each route.
S_{Fb_Dam}	Derived	Probability of survival from the forebay entrance site to the point of release of control groups of fish in tailrace.
PR_{Sp}	MLE	Probability of spill passage (same as *SP* above).
PR_{By}	Derived	Probability of bypass passage.
PR_{Tu}	Derived	Probability of turbine passage.
PR_{Sw}	Derived	Probability of RSW passage.
FGE	Derived	Fish guidance Efficiency. Probability of passing via the juvenile bypass system out of all fish that were passing through the powerhouse.
FPE	Derived	Fish Passage Efficiency. Probability of passing through non-turbine routes.
SPY	Derived	Spill Passage Effectiveness. Ratio of spill passage probability to proportion of total water volume passed through the spillway
RPE	Derived	RSW Passage Effectiveness. Ratio of RSW passage probability to proportion of total water volume passed through the RSW.
CPE	Derived	Combined Passage Effectiveness. Ratio of RSW + spill passage probability to proportion of total water volume passed through the RSW and spillway.

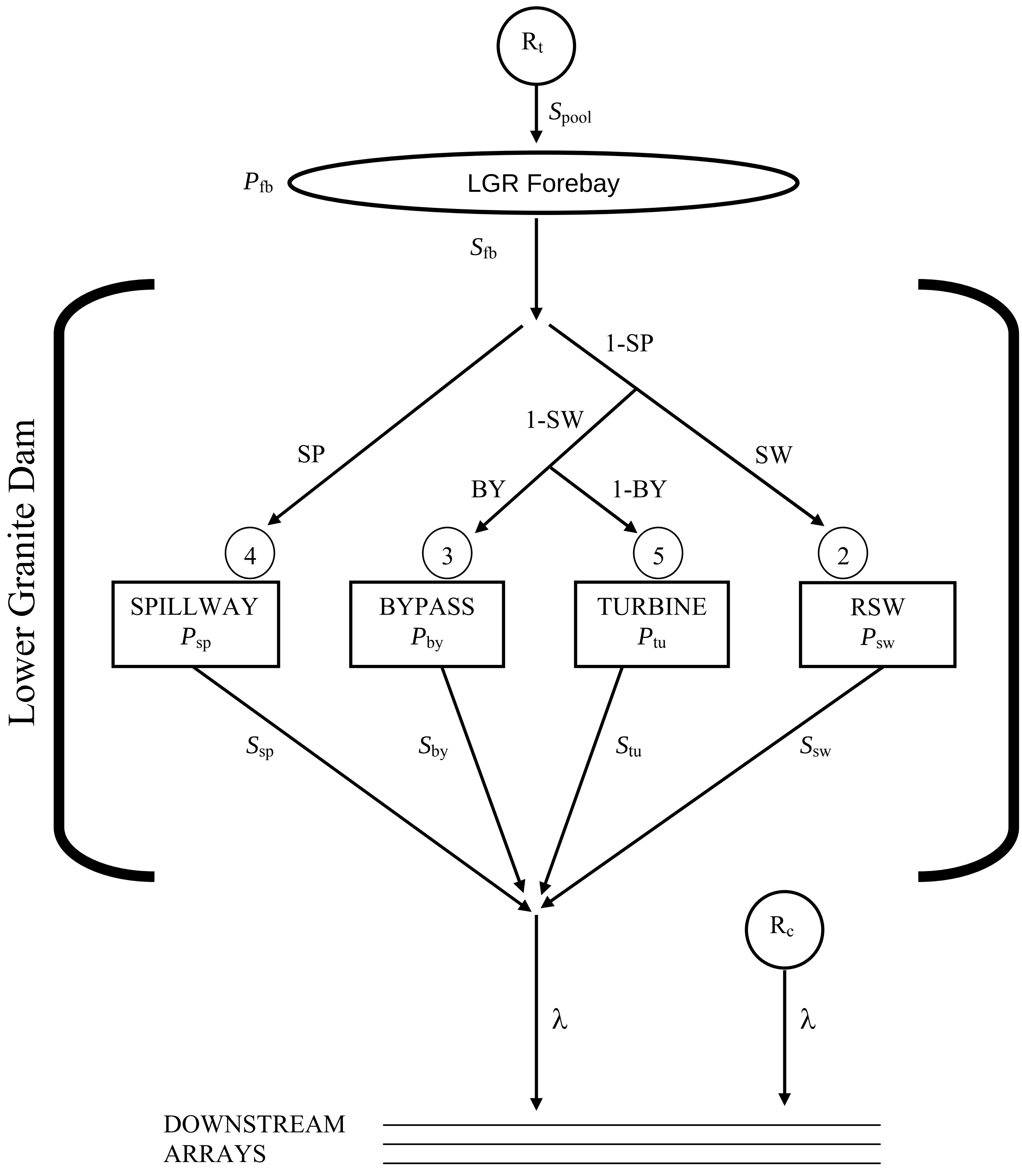

Figure 8. — Schematic of the route-specific survival model for juvenile salmonids passing Lower Granite Dam during Removable Spillway Weir operations. Shown are fish releases and passage, detection, and survival probabilities. Circled numbers show coding used in detection histories to indicate the route of passage of each fish. Lambda (λ) is the joint probability of surviving and being detected by telemetry arrays downriver of Lower Granite Dam.

The expected probability of each detection history is then estimated from the observed frequencies of fish with that detection history. Given the expected probability of each detection history and its probability function in terms of survival, passage, and detection probabilities (Appendix Table A1), likelihood methods were used to find the combination of survival, passage, and detection probabilities that were most likely to occur, given the data set of detection histories. The maximum likelihood function to be maximized is simply the joint probability of all possible detection histories. Sampling variances for parameters estimated by maximum likelihood were calculated using the inverse Hessian matrix provided by the USER software. Further details on the maximum likelihood methods for estimating survival and detection probabilities, including estimation of theoretical variances, can be found in Burnham et al. (1987), Lebreton et al. (1992), and Skalski et al. (2001).

After estimating model parameters using maximum likelihood methods, additional parameters were estimated as functions of model parameters (Table 6). Variances for these parameters were calculated using the Delta method (Seber 1982). Confidence intervals for all model parameters were calculated using likelihood profile methods as supplied in USER software.

Table 6. — Equations for parameters estimated as functions of maximum likelihood estimates for the route-specific survival model at Lower Granite Dam.

Parameter	Equation
S_{Dam}	$(S_{Sp}SP)+(S_{Tu}(1-SP)(1-SW)(1-BY))+(S_{By}(1-SP)(1-SW)BY)+(S_{Sw}(1-SP)SW)$
PR_{Sp}	SP
PR_{By}	(1-SP)(1-SW)BY
PR_{Tu}	(1-SP)(1-SW)(1-BY)
PR_{Sw}	(1-SP)SW
FGE	BY
FPE	SP+((1-SP)SW)+((1-SP)(1-SW)BY)
SPY	PR_{Sp}÷proportion of total water volume spilled
RPE	PR_{Sw}÷proportion of total water volume passing RSW
CPE	(PR_{Sp}+ PR_{Sw}) ÷proportion of total water volume passing spillway and RSW
P_{Sp}	$1-(1-P_{Sp1})(1-P_{Sp2})$
P_{By}	$1-(1-P_{By1})(1-P_{By2})$
P_{Tu}	$1-(1-P_{Tu1})(1-P_{Tu2})$
P_{Sw}	$1-(1- P_{Sw1})(1- P_{Sw2})$
P_{Dam}	$(P_{Sp}\ SP)+(P_{By}(1-SP)(1-SW)BY)+(P_{Tu}(1-SP)(1-BY))+(1-SP)SW$

Assumptions of survival models

Survival and detection probabilities from the RSSM model are subject to eleven assumptions. The first seven of these assumptions relate to inferences to the population of interest, error in interpreting radio signals, and statistical fit of the data to the model's structure:

1. Tagged individuals are representative of the population of interest. For example, if the target population is subyearling Chinook salmon then the sample of tagged fish should be drawn from that population.
2. Survival probabilities of tagged fish are the same as that of untagged fish. For example, the tagging procedures or detection of fish at downstream telemetry arrays should not influence survival or detection probabilities. If the tag negatively affects survival, then single-reach estimates of survival rates will be biased accordingly.
3. All sampling events are instantaneous. That is, sampling should take place over a short distance relative to the distance between telemetry arrays so that

the chance of mortality at a telemetry array is minimized. This assumption is necessary to correctly attribute mortality to a specific river reach. This assumption is usually satisfied by the location of telemetry arrays and the downstream migration rates of juvenile salmonids.

4. The fate of each tagged fish is independent of the fate of other tagged fish. In other words, survival or mortality of one fish has no affect on that of others.
5. The prior detection history of a tagged fish has no effect on its subsequent survival. This assumption could be violated if there are portions of the river that are not monitored for tagged fish. For example, some PIT-tagged fish may repeatedly pass through fish bypasses where PIT-tag readers are located, whereas other fish may consistently pass through spillways, which are not monitored. If fish passing through these routes have different survival rates, then this assumption could be violated. For radio telemetry, this assumption is usually satisfied by the passive nature of detecting radio tags, by monitoring all routes of passage at a dam, and by monitoring the entire channel cross-section of the river.
6. All tagged fish alive at a sampling location have the same detection probability. This assumption could also be violated as described in assumption 5, but is usually satisfied with radio telemetry by monitoring the entire channel cross-section.
7. All tags are correctly identified and the status of tagged fish (i.e., alive or dead) is known without error. This assumes fish do not lose their tags and that the tag is functioning while the fish is in the study area. Additionally, this assumes that all detections are of live fish and that dead fish are not detected and interpreted as live (i.e., false positive detections).
8. Survival for the treatment group (R_t) from its release point to the release point of control group (R_c) is conditionally dependent on survival of the control group (R_c) from its release point to the first downstream telemetry array.
9. Survival is equal for R_t and R_c between the release point of R_c and the first downstream telemetry array.

10. The two detection arrays within each route are independent. This assumption is necessary to obtain valid estimates of route-specific detection probabilities. To fulfill this assumption, fish detected in one array should have the same probability of detection in the second array compared to fish not detected in the first array.
11. Passage routes of radio-tagged fish are known without error. This assumption is important to avoid bias in passage and survival probabilities.

Assumptions 5 and 6 can be formally tested using χ^2 Goodness of Fit tests known as Test 2 and Test 3 (Burnham et al. 1987). Both Test 2 and 3 are implemented as a series of contingency tables for time-specific release groups. Test 2 is informally known as the "recapture test" because it assesses whether detection at an upstream array affects detections at subsequent downstream arrays (assumption 6). Test 3 is known as the "survival test" because it assesses assumption 5 that fish alive at array *i* have the same probability of surviving to array *i*+1. We omit results for Test 2 and 3 because survival and detection probabilities are so high that statistics for contingency tables are typically incalculable, providing little information for assessing assumptions 5 and 6.

We formally tested assumption 7 to test for false positive detections and to ensure that tags did not fail prior to fish exiting the study area. We released a subsample of euthanized tagged fish to estimate the probability of false positive detections. We also conducted a controlled tag life study to estimate the probability of tag failure at any point in time after tags were turned on. We then used the methods of Townsend et al. (2006) to estimate the average probability that a tag was alive while fish were in the study area (See Appendix B: Tag Life Study). If tags fail prior to exiting the study area, then information from the tag life study can be used to correct survival estimates for the probability of tag failure.

The assumptions 8 and 9 imply that effects of the treatment (i.e., dam passage) on survival occur in the first reach only and that delayed mortality due to the treatment is not expressed below the release point of the control group. These assumptions can be satisfied if the two groups (R_t and R_c) are mixed during their downstream migration, suggesting that factors influencing survival are similar among the two release groups.

However, these assumptions may also be satisfied if factors affecting survival are stable over the course of migration. We formally tested assumption 11 for the route-specific survival model by conducting a Chi-square test to compare downstream detection rates of within-route detection histories.

Results

Spring Migration Period

Dam operations and environmental conditions

This section describes discharge, water temperatures, water elevations, and total dissolved gas during the spring study period, 16 April to 13 June. Discharge through Lower Granite Dam was high relative to the previous ten years (Figure 9). During the spring study, the mean daily discharge through Lower Granite Dam was 130.3 kcfs and ranged from 72.9 to 204.1 kcfs. Daily average discharge was greatest through the powerhouse (63.2%) followed by spillway (31.5%) and the RSW (5.3%). Forebay water temperatures (Figure 10) at Lower Granite Dam during the spring study period ranged from 8.4º C to 14.8º C. Forebay elevations during the spring study period ranged from 223.1 to 223.7 m (732 to 734 ft) with a mean of 223.4 m (733 ft). Tailrace elevations during the spring study period varied little form the mean daily elevations. The mean daily percent gas saturation of total dissolved gas (TDG) during the spring study period were 105.8% in the forebay and 119.0% in the tailrace.

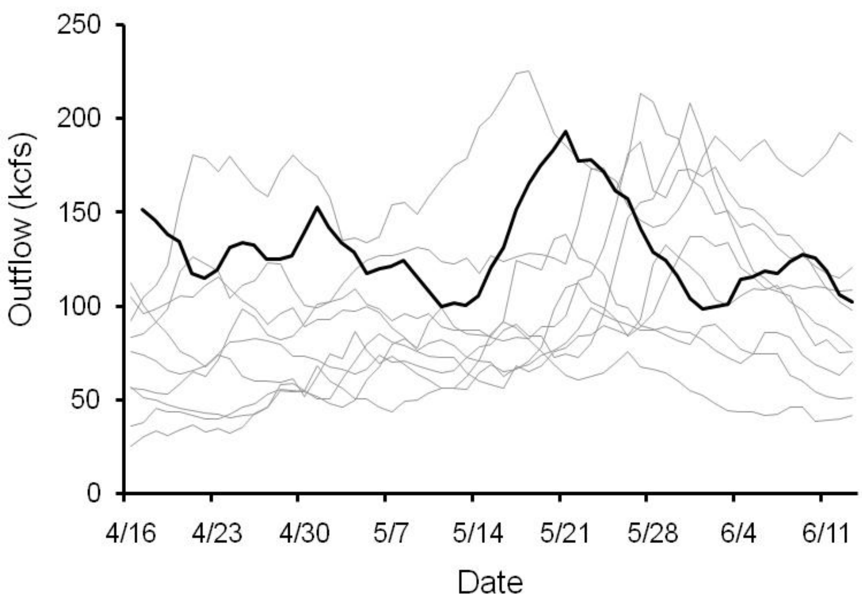

Figure 9. — Outflow at Lower Granite Dam during the 2006 spring study period (16 April to 13 June) relative to previous ten years. Spring outflow current year 2006 bold; 1997-2005 grey scale. Data obtained from the Columbia River DART website: http://www.cqs.washington.edu/dart/river.html.

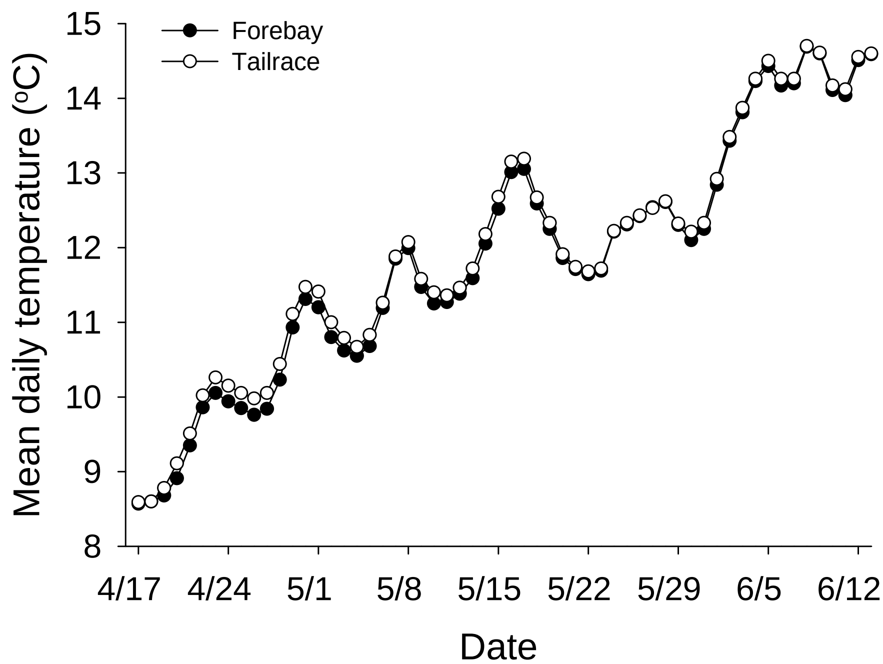

Figure 10. — Mean daily water temperatures in the forebay and tailrace areas of Lower Granite Dam during the spring study period (16 April to 13 June). Data obtained from the Columbia River DART website: http://www.cqs.washington.edu/dart/hgas.com.html.

Fish tagging and releases

We radio-tagged and released 1,667 yearling Chinook salmon and 1,981 juvenile steelhead from 16 April to 24 May 2006 (Table 7). The post-tagging mortality rate during the 24-h recovery period was 0.6% (10 of 1,677) for yearling Chinook salmon and 0.2% (4 of 1,985) for juvenile steelhead. The mortality rates at the Lower Granite Dam juvenile fish bypass facility during the same time period were 0.3% for yearling Chinook salmon, and 0.0% for juvenile steelhead (data from http://www.fpc.org).

Table 7. — Summary of yearling Chinook salmon and juvenile steelhead radio-tagged and released at Lower Granite Dam from 16 April to 24 May 2006. Fish removed from data analysis due to barging, protocol breach, or tag malfunction.

Species	Tagged	Live released	Euthanized (released)	Mortalities	Removed from data
Yearling Chinook salmon	1,677	1,617	50	10	18
Juvenile steelhead	1,985	1,931	50	4	12

For yearling Chinook salmon, the mortality rate of the treatment group was 0.7% (7 of 971) and was not significantly different (chi-square test of proportions, χ_1^2=0.604, *P* = 0.437) than the control group mortality rate of 0.4% (3 of 706). For juvenile steelhead, the mortality rate of the treatment group was 0.2% (2 of 1,174) and was not significantly different (χ_1^2=0.139, *P* = 0.710) than the control group mortality rate of 0.2% (2 of 811). Tagging mortality rates were within the range of other studies using surgical implantation methods (Plumb et al. 2004).

Fish tagged for this study were representative of the run at large. For yearling Chinook salmon, the run percentile was 5% when our study period began and 100% when it ended, representing 95% of the run; for juvenile steelhead the run percentile was 4% when the study began and 99% when it ended, representing 95% of the run. The average size of radio-tagged yearling Chinook salmon and juvenile steelhead was comparable to the population sampled at the fish facility (Figure 11). Ninety-eight percent of yearling Chinook salmon and 100% of juvenile steelhead at the juvenile fish bypass facility during the study period were of suitable size.

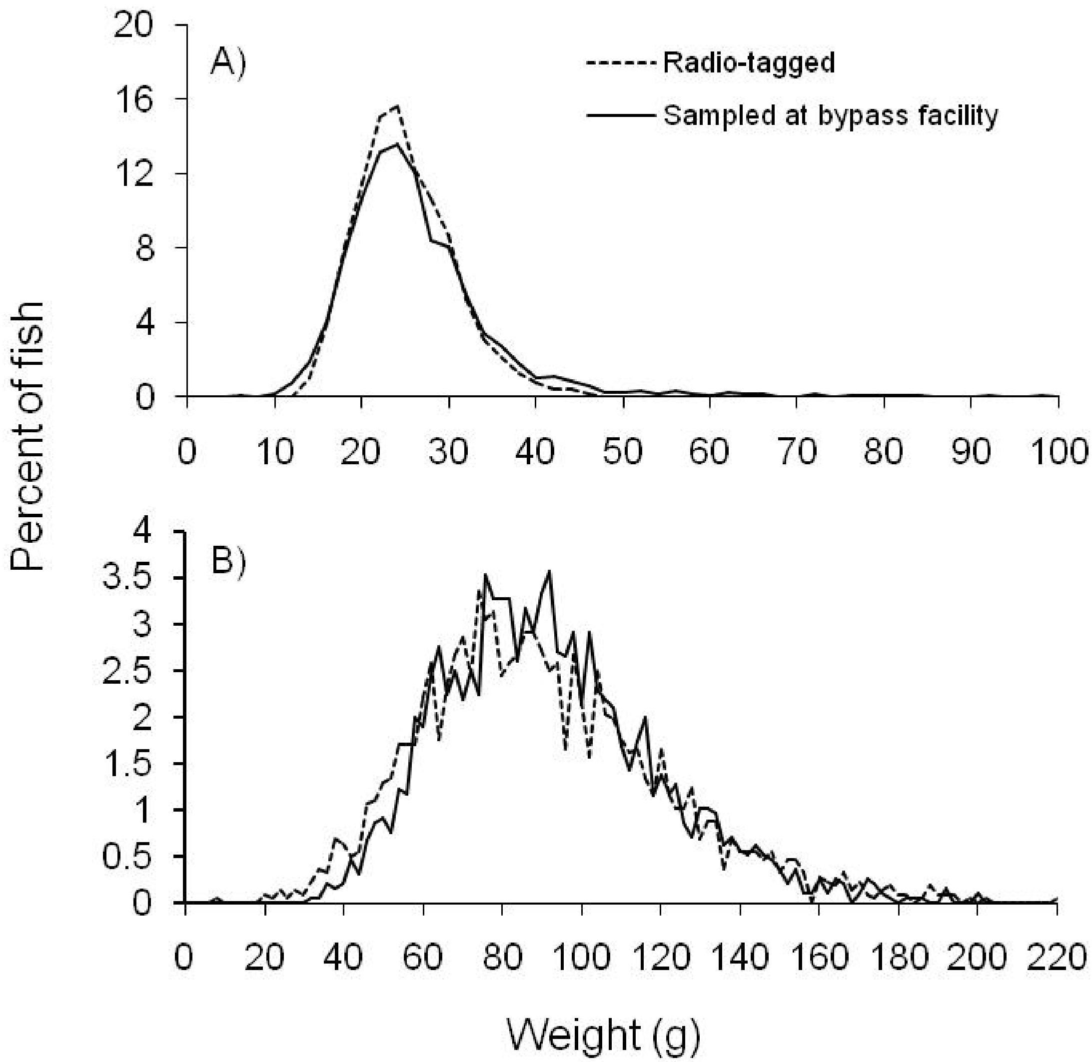

Figure 11. — Frequency distributions of body weight for A) yearling Chinook salmon and B) juvenile steelhead collected at the Lower Granite juvenile fish bypass facility compared to the frequency distribution of fish radio-tagged during the spring tagging period 16 April to 23 May 2006. Note the different Y-axes scales between species.

The sizes of treatment and control fish were similar and we adhered to the 1.5:1 ratio of treatment to control release numbers (Table 8). We released an average of 26.0 yearling Chinook (standard deviation, SD = 2.8) per treatment group and 17.6 yearling Chinook salmon (SD = 2.1) per control release over 37 consecutive days for a total sample size of 1,617 radio-tagged fish. Average release numbers for juvenile steelhead were 31.7 (SD = 5.7) per treatment release and 20.5 (SD = 4.2) for control release for 37 consecutive days for a total sample size of 1,931 radio-tagged fish.

We released euthanized radio-tagged fish to estimate the probability of false detections at telemetry arrays downstream of the dam. Euthanized fish were released with the control group fish. We released an average of six euthanized yearling Chinook salmon and six euthanized juvenile steelhead for a total sample size of 99. Eight euthanized fish releases were made between 18 April and 18 May 2006.

Table 8. — Summary statistics of fork length (mm) and weight (g) for radio-tagged yearling hatchery Chinook salmon and juvenile steelhead released to estimate route-specific survival, passage proportions, and behavior through Lower Granite Dam during the spring study period.

Species	Release group	*n*	Fork Length			Weight		
			Mean	SD	Range	Mean	SD	Range
Yearling Chinook salmon	Control	653	136.6	9.3	112 – 167	25.5	5.3	14.7 – 45.0
	Treatment	964	137.9	9.5	113 – 169	26.3	5.6	15.0 – 47.0
	Euthanized	50	136.9	9.4	111 – 155	25.8	5.3	15.0 – 39.0
Juvenile steelhead	Control	749	216.2	19.9	162 – 283	92.5	26.6	33.2 – 200.6
	Treatment	1,163	216.6	19.8	164 – 275	93.1	27.3	34.8 – 201.4
	Euthanized	49	216.7	19.2	163 – 255	92.5	25.8	38.0 – 142.4

Travel times and approach distributions

A total of 64% of yearling Chinook salmon (610 of 952) and 65% of juvenile steelhead (757 of 1,163) released above Lower Granite Dam were detected by aerial antennas at the forebay entrance. Travel times from release to forebay entrance for yearling Chinook salmon ranged from 7.5 to 345.5 h with a median travel time of 33.9 h. Travel times for juvenile steelhead ranged from 6.4 to 357.2 h with a median travel time of 17.1 h.

Spring migrants were predominantly detected entering the forebay along the north and south areas of the forebay detection array (Figure 12). We found that 41-55%, of yearling Chinook salmon were detected on the north side and south side of the forebay detection array. A small proportion (3%) of yearling Chinook salmon, were detected by the middle antennas in the forebay detection array. Juvenile steelhead (45-51%), were detected entering the forebay either on the north side or south side of the forebay array with a small percentage (3%) detected on the middle antennas.

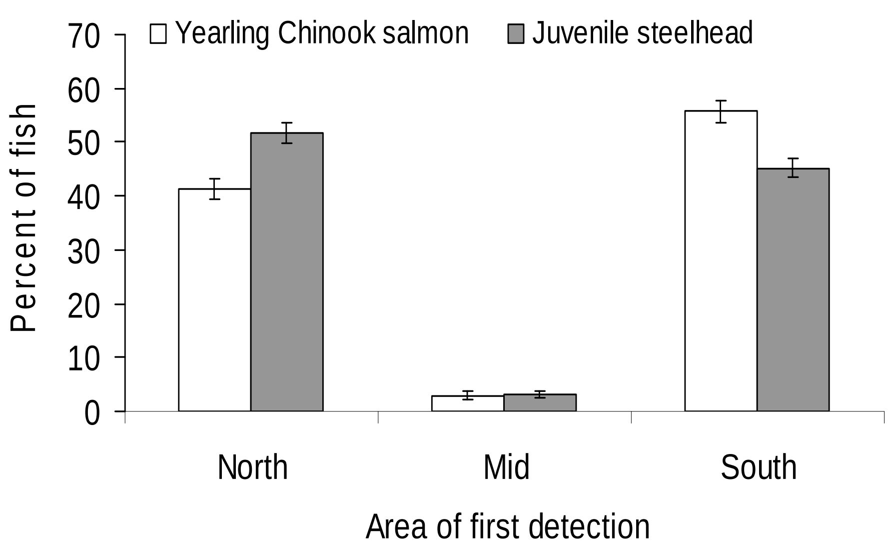

Figure 12. — Location of first aerial antenna detection at the Lower Granite Dam forebay entrance, 2 km upstream of the dam, for radio-tagged yearling Chinook salmon and juvenile steelhead during spring study period. Error bars represent standard errors of a proportion.

Time of arrival at the forebay entrance was similar for yearling Chinook salmon and juvenile steelhead. Yearling Chinook salmon arrived most frequently between 0000 and 0500 h, while juvenile steelhead showed a slight bimodal distribution with fish arriving most frequently between 0300 and 0500 h and 1200 and 1400 h (Figure 13). Arrival at the forebay during the day and night was similar for yearling Chinook salmon with 50.3% arriving during the day and 49.7% arriving at night. A higher percentage of hatchery steelhead arrived at the forebay during the day (62.2%) than during the night (37.8%).

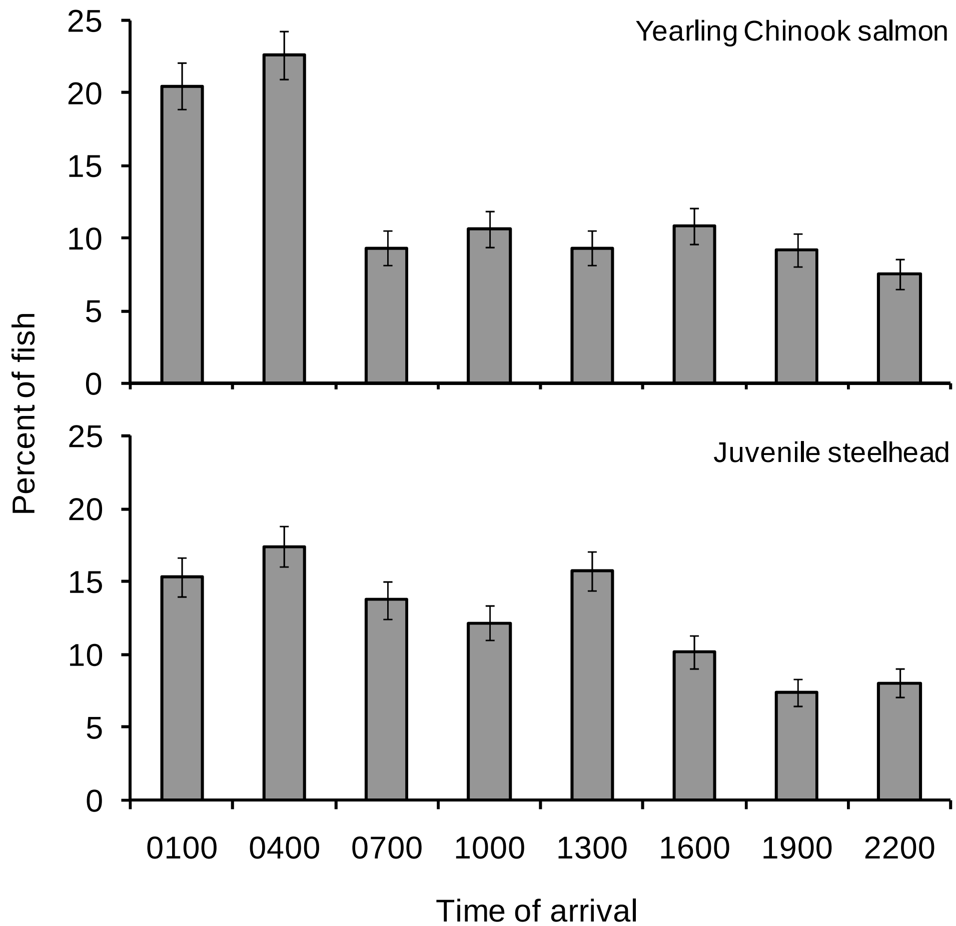

Figure 13. — Time of first detection in the Lower Granite Forebay for radio-tagged yearling Chinook salmon and juvenile steelhead. Data is grouped into 3-h time blocks. Error bars represent the standard error of a proportion.

Arrival locations near Lower Granite dam were similar for yearling Chinook salmon and juvenile steelhead. We found that most radio-tagged fish first arrive near the spillway followed by the earthen dam and powerhouse (Table 9) and were distributed near all areas of the dam regardless of treatment. We found that greater than 49% of yearling Chinook salmon and juvenile steelhead first arrive near the spillway during BGS treatments stored and deployed (Table 9).

Table 9. — Arrival locations of radio-tagged yearling Chinook salmon and juvenile steelhead near Lower Granite Dam during spring study period.

Species	Treatment	Earthen Dam	Spillway	Powerhouse
Yearling Chinook salmon	Overall	30% (151 of 511)	50% (255 of 511)	20% (105 of 511)
	BGS Stored	26% (69 of 269)	59% (135 of 269)	24% (65 of 269)
	BGS Deployed	34% (82 of 242)	49% (120 of 242)	16% (40 of 242)
Hatchery steelhead	Overall	24% (147 of 625)	56% (350 of 625)	20% (128 of 625)
	BGS Stored	21% (66 of 316)	55% (174 of 316)	24% (76 of 316)
	BGS Deployed	26% (81 of 309)	57% (176 of 309)	17% (52 of 309)

Forebay residence time and behavior

Residence times of juvenile Chinook salmon in the forebay were similar during BGS treatments and diel period but varied by passage routes. During BGS deployed and stored treatments median residence times were 5.3 h and 5.0 h. Median residence times during the day were 6.4 h and 5.3 h during the night. Median residence times for juvenile Chinook salmon arriving in the forebay and passing were quite variable and were generally similar among passage routes (Table 10).

Trends in forebay residence times of juvenile steelhead were similar to those of yearling Chinook salmon during BGS treatments and diel periods. The median residence times of juvenile steelhead were 3.5 h when the BGS was deployed and 3.3 h when it was stored. We found that median residence times for juvenile steelhead during the day, 4.4 h, were slightly higher than during the night, 3.7 h. Median residence times for juvenile steelhead entering the forebay, and passing, were quite variable among passage routes (Table 10).

Table 10. — Descriptive statistics of residence time (h) for radio-tagged yearling Chinook salmon and juvenile steelhead at Lower Granite Dam, spring 2006. Residence time was measured from the first detection at the forebay array to the last detection at a known passage route.

Species	Passage route	*n*	Mean	Median	Standard deviation	Minimum	Maximum	Mode
Yearling Chinook salmon	Spill	174	8.0	4.5	10.4	1.3	103.6	2.3
	RSW	178	7.6	5.1	7.9	1.0	56.2	2.8
	Bypass	186	11.7	7.3	14.0	0.0	136.1	4.5
	Turbine	51	11.2	7.9	9.4	1.7	39.7	2.9
Juvenile steelhead	Spill	207	5.1	3.0	9.2	1.3	112.3	2.0
	RSW	203	7.4	3.9	18.2	1.0	250.3	2.2
	Bypass	295	8.2	5.9	7.5	0.1	66.6	0.7
	Turbine	30	5.1	4.0	4.7	1.6	26.4	4.5

Behavior relative to the BGS and RSW

We evaluated behavior of yearling Chinook salmon and juvenile steelhead near the BGS when it was deployed. During that time, 25.7% (73 of 284) of yearling Chinook salmon and 24.5% (92 of 376) juvenile steelhead were detected at the structure. First detection locations for both species were distributed along the entire length of the BGS, but the numbers of fish first detected near the BGS decreased with distance from the dam (Table 11). The largest proportion of radio-tagged fish, yearling Chinook salmon (37%; 42 of 79), and juvenile steelhead (53%; 42 of 79), first detected near the BGS were within 75 m of the powerhouse.

Table 11. — First detection locations at the Behavioral Guidance Structure at Lower Granite Dam during spring 2006. The distances from the dam were measured to include multiple modules of the BGS. The numbers of fish are fish detected on the north side of the BGS.

Distance from dam	Yearling Chinook salmon	Juvenile steelhead
0 – 75 m	22	42
75 – 166 m	17	14
166 – 258 m	10	13
258 – 349 m	11	10

Deployment of the BGS affected the proportion of fish passing via powerhouse routes. The difference in passing through the powerhouse between treatments (P_b) was

7% for yearling Chinook salmon and 16% for juvenile steelhead (Table 13). We also estimated the diversion that may be theoretically possible if the BGS were extended to the shoreline ($P_{b\ corrected}$). This is based on the assumptions that fish detected passing through the gap between the upstream end of the BGS and the shoreline and those passing under the BGS would be diverted. Given these assumptions, this approach indicated that 84% of juvenile Chinook salmon and 54% of juvenile steelhead would be theoretically diverted from powerhouse passage routes if the BGS extended to the shoreline (Table 12).

Table 12. — Behavioral Guidance Structure diversion coefficients at Lower Granite Dam during spring study period, 2006. Guided + unguided are fish passing through the powerhouse turbines or juvenile bypass system during BGS treatments. Total passage is fish passing all known routes during BGS treatments. Gap and under are fish moving through the gap or under the BGS during the deployed treatment.

	BGS Deployed		BGS Stored					
Species	Guided + unguided	Total passage	Guided + unguided	Total passage	Gap	Under	P_b	$P_{b\ corrected}$
Yearling Chinook salmon	58	253	70	283	14	3	0.07	0.84
Juvenile steelhead	94	359	106	331	13	16	0.16	0.54

Fish detected near the RSW opening were used to describe the behavior of fish that were deemed to be within the "discovery area". The discovery efficiency (the percentage of tagged fish detected in the forebay also detected within 6 m of the RSW; DE) and the entrance efficiency (the percentage of these fish passing via the RSW; EE) were estimated. Discover efficiency of yearling Chinook salmon was 30% (88 of 289) during the BGS-Deployed treatment and 28% (90 of 321) during the BGS-Stored treatment. Similarly the DE of juvenile steelhead was 29% (112 of 383) during the BGS-Deployed treatment and 25% (95 of 374) during the BGS-Stored treatment. The EE of yearling Chinook salmon was 90% (80 of 88) and 88% (80 of 90) during the BGS-Deployed and Stored treatments, respectively. The corresponding EE estimates from detections of juvenile steelhead were 84% (94 of 112) and 84% (80 of 95).

Passage and survival estimates for spring migrants using the RSSM

We evaluated the assumptions that 1) fish exited the study area prior to expiration of transmitter batteries and 2) dead radio-tagged fish were not detected by telemetry arrays used to estimate survival. We found that most radio-tagged juvenile salmonids were likely to have exited the study area prior to expiration of transmitter batteries. The probability of a tag being operational at downstream detection arrays was > 99.9%; suggesting that survival estimates were not negatively biased due to non-detection of live fish with non-functioning transmitters (See Appendix B: Tag Life Study). We did detect dead radio-tagged fish at the downstream arrays during 2006. A disproportionate number of dead radio-tagged fish were detected at the second downstream array. Consequently, we excluded this array from the analyses to eliminate any potential bias caused by false-positive detections at this array. Dead radio-tagged fish (two yearling Chinook salmon and two juvenile steelhead) were also detected at other detection arrays but had disproportionately long travel times (≥ 97th percentile). Thus, we assigned fish with travel times equal to or greater than those of the dead radio-tagged fish as non-detections at those arrays. After these adjustments were made, one dead radio-tagged yearling Chinook salmon detected at the third downstream array remained which could not be discounted based on travel time or evidence of patterns such as predation. We thus estimated the probability of detecting a dead radio-tagged yearling Chinook salmon at our downstream arrays to be 0.020 (95% confidence interval [0.0005, 0.1065]). Analyses were conducted 1) with all fish and downstream arrays included and 2) with the removal of the second downstream array and adjustments to capture histories for fish based on travel times from the dead radio-tagged fish contacts. The differences in the estimates generated from the two analyses were minimal, so we are presenting the more conservative estimates that were adjusted as stated above by assumptions made from the radio-tagged dead fish contacts.

The spring study was designed to evaluate the survival and passage probabilities of yearling Chinook salmon and juvenile steelhead during 24 h spill of 20 kcfs, with the RSW in operation and two BGS treatments. We estimated survival and passage probabilities for BGS deployed and BGS stored treatments combined (excluding any BGS move periods), BGS deployed, and BGS stored treatments. We also estimated survival and passage probabilities during diel periods for each treatment (BGS deployed and stored). Lastly, we estimated survival and passage probabilities over smaller time blocks (approximately 8 days) to investigate temporal trends.

We determined a passage route for 95% (611 of 643) of the radio-tagged yearling Chinook salmon and 96% (781 of 811) of the juvenile steelhead released upriver of and passing Lower Granite Dam during BGS deployed and BGS stored treatments. For yearling Chinook salmon, slightly more fish passed the dam during the BGS stored (52%) treatment versus the BGS deployed (48%) treatment, while 50% of juvenile steelhead passed during each operation. For the analyses that evaluated the data for both treatments combined, yearling Chinook salmon passed through the RSW, bypass, and spillway equally (29% through each route), with few fish passing through the turbines (8%; Appendix Table A2). This pattern shifted slightly between the two treatments (BGS deployed and stored). During the BGS deployed treatment the majority of the yearling Chinook salmon passed through the RSW (31%), followed by the bypass (27%), and the spillway (25%), and few fish passing through the turbines (11%; Appendix Table A3). During the BGS stored treatment the majority of the yearling Chinook salmon passed through the spillway (32%), followed by the bypass (30%), and the RSW (27%), with very few fish passing through the turbines (6%; Appendix Table A4). For juvenile steelhead passing during both treatments combined, the majority of the fish passed via the bypass system (38%), followed by the spillway (28%), and the RSW (26%) with only 4% passing via the turbines (Appendix Table A5). This pattern was consistent for steelhead passing during both the BGS deployed (Appendix Table A6) and stored (Appendix Table A7) treatments.

During the route specific evaluation we found significant differences between many of the passage probabilities between the BGS deployed and stored treatments. During the combined treatments passage probabilities between the spillway, RSW, and bypass routes were approximately equal (≈ 0.294, Table 13). However, during the BGS deployed treatment the probability of passing via the spillway decreased (0.253, SE = 0.025) and the probability of passing via the RSW (0.312, SE = 0.010) increased while during the BGS stored treatment the spillway passage probability (0.331, SE = 0.026) increased and the RSW passage probability (0.281, SE = 0.006) decreased. The spillway routes of passage for yearling Chinook salmon and hatchery steelhead were similar during BGS treatments with the majority of fish passing the spillway via the RSW (Figure 14). The probability of passing via the turbine route also increased during the BGS deployed treatment (0.158, SE = 0.021) treatment versus the stored treatment (0.081, SE = 0.016). The different passage probabilities between the treatments were significant using the two-tailed z-test for the spillway ($z = 2.170$, $P = 0.030$), RSW ($z = 2.599$, $P = 0.009$), and the turbine route ($z = 2.918$, $P = 0.004$). The FPE and FGE estimates were significantly lower during the BGS deployed than the BGS stored treatment ($z = 2.918$, $P = 0.004$ for FPE and $z = 2.758$, $P = 0.006$ for FGE). The RPE was higher during the BGS deployed treatment while the SPY and CPE were lower during the BGS stored treatment.

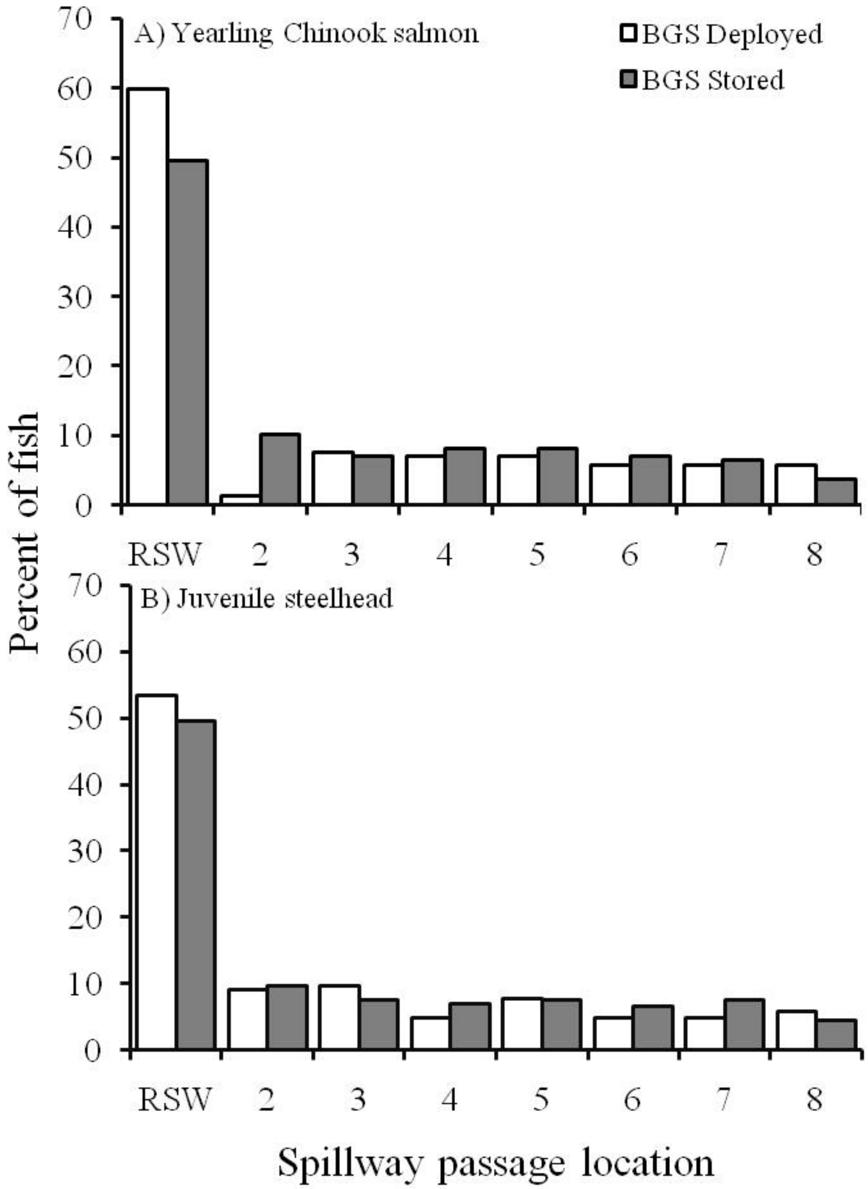

Figure 14. — Spillway passage locations for yearling Chinook salmon and juvenile steelhead during BGS treatments stored and deployed at Lower Granite Dam during spring 2006.

The survival probabilities for yearling Chinook salmon passing during both treatments (deployed and stored combined) were high (≥ 0.975; Table 13), with the exception of the turbine route (0.909). There were no significant differences found for survival probabilities between the two dam treatments. In general the survival probabilities were very similar; with the exception of the turbine route where survival was higher when the BGS was deployed (0.935, SE = 0.042) than stored (0.815, SE = 0.086).

Table 13. — Overall passage and survival estimates for yearling Chinook salmon at Lower Granite Dam during, 2006. Probabilities, standard errors (SE) and confidence intervals (CI) are presented. Treatments consisted of the Behavioral Guidance Structure (BGS) being deployed or stored. Asterisks indicate significant differences (two-tail z-test, α = 0.05) between BGS stored and BGS deployed treatments.

	Dam Treatments					
	BGS Stored		BGS Deployed		Overall (Stored and Deployed)	
Parameters	Probability(SE)	95% CI	Probability(SE)	95% CI	Probability(SE)	95% CI
S pool	0.989 (0.006)	0.974,0.997	0.987 (0.006)	0.971,0.996	0.988 (0.004)	0.978,0.995
S forebay	0.991 (0.007)	0.974,1.003	0.999 (0.004)	0.987,1.005	0.996 (0.003)	0.987,1.001
S dam	0.967 (0.012)	0.939,0.989	0.966 (0.014)	0.936,0.992	0.975 (0.008)	0.957,0.990
S spillway	0.970 (0.018)	0.923,0.999	0.985 (0.019)	0.931,1.014	0.982 (0.013)	0.951,1.002
S RSW	0.985 (0.016)	0.941,1.009	0.979 (0.019)	0.929,1.009	0.992 (0.010)	0.966,1.009
S turbine	0.815 (0.086)	0.619,0.943	0.935 (0.042)	0.826,0.994	0.909 (0.039)	0.817,0.968
S bypass	0.987 (0.014)	0.947,1.009	0.951 (0.026)	0.887,0.993	0.976 (0.014)	0.944,0.998
λ	0.994 (0.005)	0.980,0.999	0.989 (0.006)	0.972,0.997	0.991 (0.004)	0.982,0.997
*Pr spillway**	0.331 (0.026)	0.281,0.383	0.253 (0.025)	0.206,0.304	0.294 (0.018)	0.259,0.331
*Pr RSW**	0.281 (0.006)	0.235,0.331	0.312 (0.010)	0.261,0.365	0.295 (0.006)	0.260,0.331
*Pr turbine**	0.081 (0.016)	0.053,0.115	0.158 (0.021)	0.119,0.203	0.117 (0.013)	0.093,0.144
Pr bypass	0.308 (0.025)	0.260,0.359	0.277 (0.026)	0.229,0.329	0.294 (0.018)	0.260,0.331
FPE*	0.919 (0.016)	0.885,0.947	0.842 (0.021)	0.797,0.881	0.883 (0.013)	0.856,0.907
FGE*	0.793 (0.037)	0.714,0.860	0.637 (0.042)	0.552,0.717	0.716 (0.029)	0.658,0.770
SPY[a]	1.001		0.711		0.857	
RPE [a]	5.640		6.449		6.004	
CPE [a]	1.609		1.398		1.502	

[a]-No standard error or confidence interval presented.

There were differences in passage proportions through the various routes during the day and night. During the BGS stored treatment, passage probabilities were also higher during the day through the spillway and the RSW, while at night the bypass and turbine routes were higher (Table 14). The FGE and FPE were higher during the day as were the SPY, RPE, and CPE during the BGS stored treatment.

During the BGS deployed treatment, passage probabilities through the spillway and the RSW were higher during the day while bypass and turbine routes were higher during the night (Table 15). The FGE and FPE were higher during the day as were the SE, RPE, and CPE. The survival probabilities were very similar between day and night hours, with the day hours being slightly higher for all survival probabilities except the turbine route, which was higher at night. The survival probabilities were generally higher during day hours with the exception of the pool and survival through the turbines. Throughout the spring release season, no apparent temporal trends were observed in data from yearling Chinook salmon. Overall (BGS stored and deployed) survival probability estimates were similar within routes and had a fairly consistent pattern over time; the turbine route had the lowest survival probability (Figure 15). During BGS deployed treatments in the first half of the spring season (17 April – 7 May), passage probability estimates were similar for the spillway, RSW, and bypass and had similar patterns among the various routes over time. Bypass passage probability estimates decreased in the last quarter of the season (18 May – 27 May), while more fish passed through the spillway.

For both treatments (overall, BGS stored, and BGS deployed), juvenile steelhead had the highest probability of passing via the bypass system, followed by the spillway, RSW, and the turbines (Table 15). In general the route specific passage probabilities during the BGS deployed treatment were slightly higher for juvenile steelhead passing via the spillway, RSW, and the turbines and slightly lower passing via the bypass than during the BGS stored treatment (Table 15). However, the only passage probability that was found to be significantly different was the RSW ($z = 7.727$, $P < 0.0001$), which was higher during the BGS deployed (0.285, SE = 0.004) than the BGS stored (0.245, SE = 0.003) treatment.

Table 14. — Overall passage and survival estimates for yearling Chinook salmon passing through Lower Granite Dam during the day (approximately 0500 to 2000) and night hours during spring study period. Probability, standard error (SE), and confidence interval (CI) presented. Treatments consisted of the Behavioral Guidance Structure (BGS) being deployed or stored.

	BGS Stored			
	Day		Night	
Parameters	Probability (SE)	95% CI	Probability (SE)	95% CI
S pool	0.987 (0.008)	0.965,0.997	0.995 (0.008)	0.970,1.005
S forebay	0.999 (0.006)	0.981,1.014	0.975 (0.017)	0.932,1.008
S dam	0.959 (0.017)	0.920,0.991	0.925 (0.028)	0.862,0.976
S spillway	0.982 (0.021)	0.925,1.015	0.909 (0.049)	0.790,0.983
S RSW	0.981 (0.022)	0.921,1.014	0.935 (0.052)	0.796,1.006
S turbine	0.671 (0.137)	0.391,0.890	0.837 (0.111)	0.569,0.982
S bypass	0.976 (0.025)	0.907,1.012	0.966 (0.032)	0.879,1.016
λ	0.990 (0.007)	0.970,0.998	0.990 (0.009)	0.959,0.999
Pr spillway	0.337 (0.032)	0.276,0.403	0.307 (0.041)	0.232,0.391
Pr RSW	0.322 (0.006)	0.261,0.386	0.209 (0.012)	0.145,0.286
Pr turbine	0.066 (0.018)	0.036,0.108	0.132 (0.032)	0.077,0.202
Pr bypass	0.275 (0.031)	0.218,0.338	0.352 (0.042)	0.273,0.436
FPE	0.934 (0.018)	0.892,0.964	0.868 (0.032)	0.798,0.923
FGE	0.807 (0.049)	0.700,0.891	0.728 (0.059)	0.604,0.834
SPY[a]	0.886		0.796	
RPE[a]	6.556		2.366	
CPE[a]	1.633		1.000	

	BGS Deployed			
	Day		Night	
Parameters	Probability (SE)	95% CI	Probability (SE)	95% CI
S pool	0.995 (0.005)	0.977,1.001	0.978 (0.013)	0.942,0.995
S forebay	0.997 (0.006)	0.977,1.008	0.995 (0.009)	0.966,1.009
S dam	0.953 (0.019)	0.911,0.988	0.936 (0.026)	0.878,0.990
S spillway	0.971 (0.028)	0.893,1.012	0.940 (0.050)	0.805,1.013
S RSW	0.967 (0.026)	0.900,1.007	0.940 (0.050)	0.805,1.013
S turbine	0.899 (0.075)	0.705,0.994	0.922 (0.061)	0.761,1.007
S bypass	0.940 (0.040)	0.837,0.997	0.941 (0.041)	0.837,1.007
λ	0.990 (0.007)	0.968,0.998	0.989 (0.011)	0.950,0.999
Pr spillway	0.276 (0.033)	0.214,0.343	0.224 (0.038)	0.156,0.303
Pr RSW	0.372 (0.012)	0.304,0.443	0.225 (0.018)	0.157,0.305
Pr turbine	0.122 (0.025)	0.078,0.176	0.214 (0.038)	0.143,0.293
Pr bypass	0.231 (0.031)	0.174,0.295	0.338 (0.042)	0.260,0.423
FPE	0.878 (0.025)	0.824,0.922	0.786 (0.038)	0.707,0.857
FGE	0.655 (0.060)	0.533,0.766	0.613 (0.060)	0.494,0.726
SPY[a]	0.758		0.929	
RPE[a]	7.678		3.432	
CPE[a]	1.583		1.230	

[a]– No standard error or confidence interval presented.

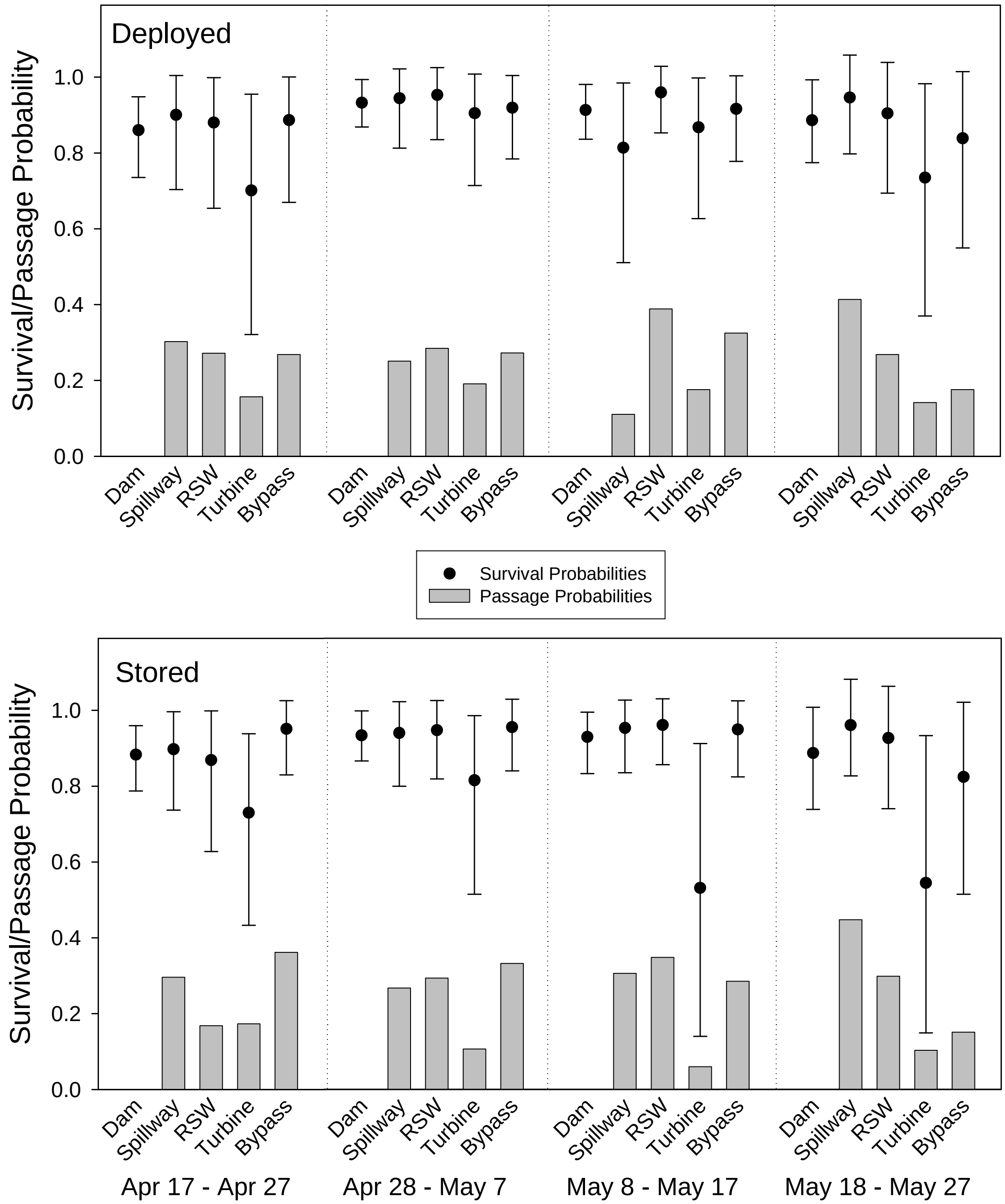

Figure 15. — Overall passage and survival probabilities for yearling Chinook salmon at Lower Granite Dam during BGS stored and deployed treatments. Error bars represent 95% profile likelihood confidence intervals.

Table 15. — Overall survival estimates and passage probabilities for juvenile steelhead passing through Lower Granite dam during spring study period. Standard error and confidence intervals (CI) presented. Treatments consisted of the Behavioral Guidance Structure (BGS) being deployed or stored. Probability and guidance efficiencies definitions are given in Tables 5 and 6. Asterisks indicate significant differences (two-tail z-test, α = 0.05) between BGS stored and BGS deployed treatments.

	Dam Treatments					
	BGS Stored		BGS Deployed		Overall (Stored and Deployed)	
Parameters	Probability(SE)	95% CI	Probability(SE)	95% CI	Probability(SE)	95% CI
S pool	0.998 (0.002)	0.990,1.001	0.998 (0.002)	0.990,1.001	0.998 (0.002)	0.993,1.001
S forebay	0.994 (0.005)	0.981,1.004	0.990 (0.005)	0.976,0.998	0.992 (0.004)	0.983,0.998
S dam	0.958 (0.011)	0.934,0.977	0.981 (0.009)	0.960,0.999	0.976 (0.007)	0.961,0.988
S spillway	0.985 (0.013)	0.949,1.003	0.989 (0.013)	0.954,1.010	0.991 (0.008)	0.970,1.004
S RSW	0.952 (0.022)	0.897,0.985	0.989 (0.013)	0.952,1.010	0.981 (0.011)	0.954,0.997
S turbine	0.879 (0.082)	0.670,0.981	0.875 (0.072)	0.685,0.973	0.900 (0.049)	0.780,0.971
S bypass	0.955 (0.017)	0.915,0.981	0.986 (0.013)	0.953,1.007	0.972 (0.010)	0.948,0.989
λ	0.997 (0.003)	0.989,1.000	0.994 (0.004)	0.981,0.999	0.996 (0.002)	0.989,0.999
Pr spillway	0.282 (0.022)	0.239,0.327	0.295 (0.024)	0.250,0.346	0.288 (0.016)	0.257,0.320
*Pr RSW**	0.245 (0.003)	0.204,0.288	0.285 (0.004)	0.241,0.333	0.263 (0.002)	0.233,0.295
Pr turbine	0.058 (0.012)	0.037,0.086	0.063 (0.018)	0.034,0.096	0.060 (0.009)	0.043,0.080
Pr bypass	0.416 (0.025)	0.368,0.464	0.357 (0.024)	0.312,0.405	0.389 (0.017)	0.355,0.423
FPE	0.942 (0.012)	0.914,0.963	0.937 (0.018)	0.904,0.966	0.940 (0.009)	0.920,0.957
FGE	0.877 (0.025)	0.822,0.921	0.849 (0.038)	0.779,0.915	0.866 (0.020)	0.825,0.903
SE [a]	0.852		0.830		0.839	
RPE [a]	4.910		5.886		5.364	
CPE [a]	1.384		1.436		1.405	

[a]-No standard error or confidence interval presented.

Juvenile steelhead survival probabilities were ≥ 0.972 for both treatments combined with the exception of survival through the turbines (0.900, SE = 0.049). In general, the survival estimates were slightly higher during the BGS deployed versus the BGS stored treatment. However, there were no significant differences found in survival probabilities between the two dam treatments (two-tail *z*-test, α = 0.05). More steelhead passed Lower Granite Dam during day (0500 to 2000) hours for both the BGS deployed (59% day/41% night) and stored (61% day/39% night) treatments than during the night. The passage probability through the RSW during the day hours with the BGS deployed was more than double the RSW passage probability at night, while all other passage probabilities were lower during the day than at night (Table 16). It should be noted that the passage probability estimates themselves are not affected by the absolute numbers of fish passing in day or night, only the error about them. Consequently, the RPE was almost double during the day (7.678) than at night (3.432) during the BGS deployed treatment. The FPE, FGE, and CPE were all higher during day hours than at night while the BGS was deployed. The survival probabilities were very similar between day and night, with the RSW and turbine routes having the largest difference between diel periods. The survival estimate through the RSW was higher and the turbine survival was lower during the day than at night and the dam survival was higher during the day (0.975, SE = 0.013).

During the BGS stored treatment the probability of passing via the RSW was also more than double during the day than at night, resulting in a much higher RPE during the day as well (Table 16). At night the bypass route had the highest passage probability, thus the FPE and FGE were also higher at night. The survival probabilities were very similar between day and night periods, with estimates slightly higher during the day. Overall (BGS deployed and stored) survival probability estimates were similar within routes and had a fairly consistent pattern over time for juvenile steelhead during the spring season. In general, survival and passage probability estimates were lowest for the turbine route overall (Figure 16). We observed a few minor trends for the passage probability. During the BGS stored treatment, bypass passage probability estimates decreased over time on average, while passage probabilities increased for the RSW and spillway combined. During the BGS deployed treatment in the latter half of the season, RSW passage probability estimates decreased while estimates for the spillway increased.

Table 16. — Overall survival estimates and passage probabilities for juvenile steelhead during the day (approximately 0500 to 2000) and night hours at Lower Granite Dam during spring study period. Standard error (SE) and 95% profile likelihood confidence intervals (CI) presented. Treatments consisted of the Behavioral Guidance Structure (BGS) being deployed or stored.

	BGS Stored			
	Day		Night	
Parameters	Probability (SE)	95% CI	Probability (SE)	95% CI
S pool	0.996 (0.004)	0.983,1.001	0.996 (0.006)	0.975,1.003
S forebay	1.001 (0.006)	0.985,1.020	0.989 (0.010)	0.960,1.006
S dam	0.955 (0.015)	0.917,0.981	0.931 (0.023)	0.881,0.973
S spillway	0.976 (0.020)	0.921,1.003	0.961 (0.033)	0.870,1.010
S RSW	0.955 (0.024)	0.894,0.991	0.902 (0.071)	0.715,0.994
S turbine	0.824 (0.114)	0.549,0.972	0.732 (0.165)	0.375,0.957
S bypass	0.965 (0.022)	0.905,0.997	0.942 (0.027)	0.878,0.988
λ	0.996 (0.004)	0.983,1.000	0.992 (0.008)	0.966,1.000
Pr spillway	0.292 (0.029)	0.237,0.350	0.264 (0.035)	0.201,0.336
Pr RSW	0.327 (0.006)	0.271,0.387	0.117 (0.003)	0.074,0.173
Pr turbine	0.074 (0.018)	0.043,0.115	0.053 (0.019)	0.023,0.098
Pr bypass	0.307 (0.029)	0.252,0.366	0.566 (0.039)	0.488,0.641
FPE	0.926 (0.018)	0.885,0.957	0.947 (0.019)	0.902,0.977
FGE	0.806 (0.044)	0.711,0.882	0.915 (0.030)	0.844,0.963
SPY[a]	0.886		0.796	
RPE[a]	6.556		2.366	
CPE[a]	1.633		1.000	

	BGS Deployed			
	Day		Night	
Parameters	Probability (SE)	95% CI	Probability (SE)	95% CI
S pool	0.997 (0.004)	0.983,1.002	0.995 (0.006)	0.976,1.001
S forebay	0.991 (0.006)	0.973,0.999	0.990 (0.009)	0.964,1.005
S dam	0.975 (0.013)	0.946,1.001	0.961 (0.020)	0.917,1.007
S spillway	0.978 (0.022)	0.916,1.011	0.974 (0.028)	0.900,1.025
S RSW	0.986 (0.017)	0.940,1.014	0.939 (0.050)	0.804,1.011
S turbine	0.812 (0.126)	0.512,0.974	0.865 (0.096)	0.623,0.991
S bypass	0.982 (0.020)	0.928,1.013	0.982 (0.023)	0.923,1.029
λ	0.991 (0.006)	0.973,0.999	0.989 (0.011)	0.953,0.999
Pr spillway	0.271 (0.029)	0.217,0.331	0.326 (0.038)	0.257,0.405
Pr RSW	0.372 (0.004)	0.312,0.435	0.165 (0.008)	0.114,0.226
Pr turbine	0.043 (0.014)	0.022,0.079	0.097 (0.026)	0.049,0.153
Pr bypass	0.313 (0.030)	0.257,0.374	0.411 (0.038)	0.339,0.486
FPE	0.957 (0.014)	0.921,0.978	0.903 (0.026)	0.847,0.951
FGE	0.879 (0.037)	0.788,0.938	0.809 (0.047)	0.710,0.897
SPY[a]	0.758		0.929	
RPE[a]	7.678		3.432	
CPE[a]	1.583		1.230	

[A] – No standard error or confidence interval presented.

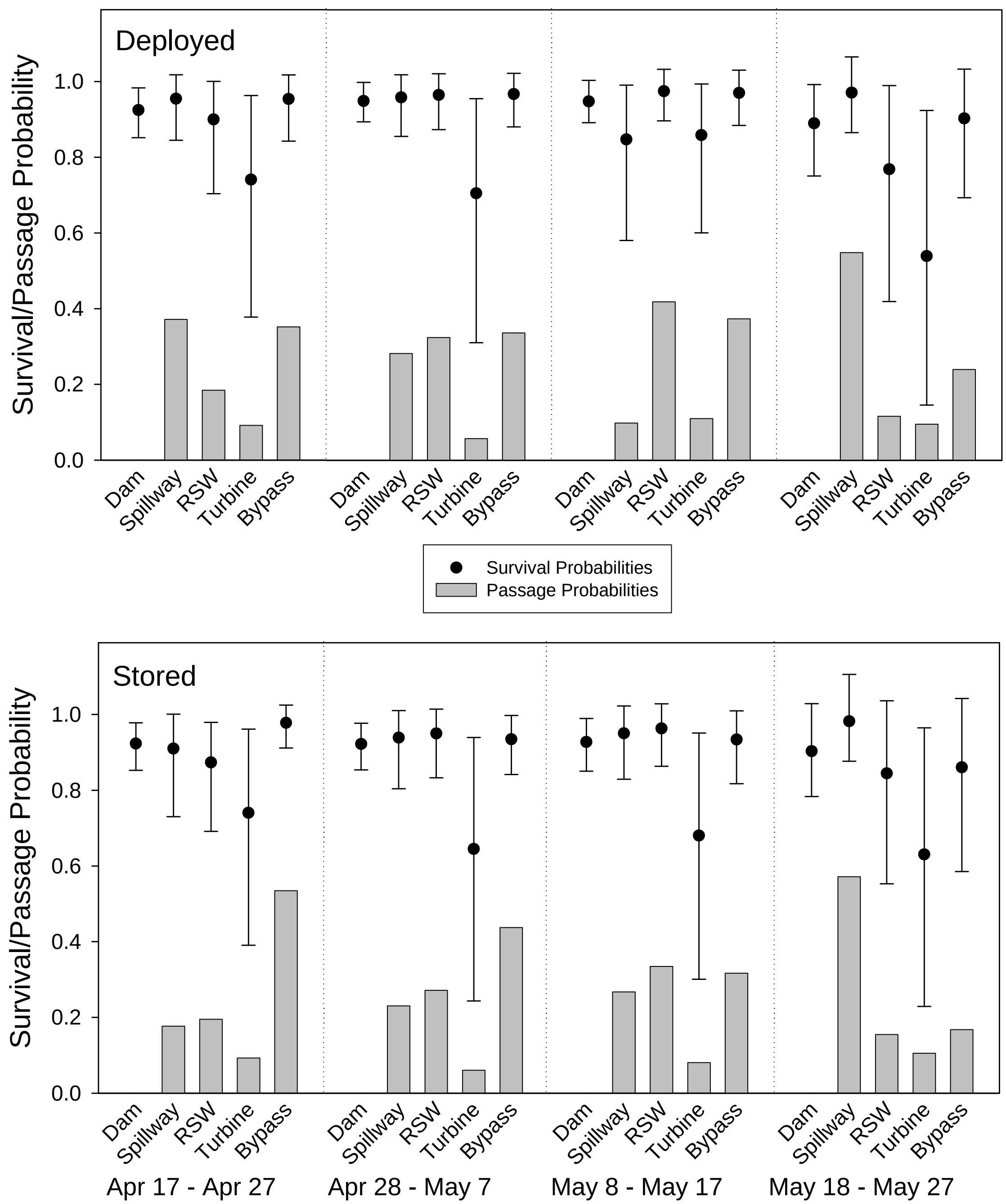

Figure 16. — Estimates of survival and passage probabilities and fish passage and guidance efficiencies (error bars are 95% profile likelihood confidence intervals) for juvenile steelhead passing Lower Granite Dam during stored and deployed BGS treatments, spring 2006.

Tailrace egress

Tailrace egress times varied between species and passage routes at Lower Granite Dam during the 2006 spring study. Overall, we observed median egress times were shortest for fish passing through the spillway and RSW (Table 17). Egress times of yearling Chinook salmon passing the spillway were more variable than those passing the RSW but the opposite was true in the data from juvenile steelhead. The longest median egress time for yearling Chinook salmon was for fish passing through the bypass; for juvenile steelhead the longest median egress time was for fish passing the turbines.

Table 17. — Descriptive statistics of egress time (min) for radio-tagged yearling Chinook salmon and juvenile steelhead at Lower Granite Dam, spring 2006. Tailrace egress time was measured from the time of passage to the last time of detection at the tailrace exit site (about 2 km downriver).

Species	Passage route	*n*	Mean	Median	STD	Minimum	Maximum
Yearling Chinook salmon	Bypass	279	154.4	39.9	675.6	20.0	9,823.8
	Turbine	49	91.9	35.1	341.0	21.4	2,420.8
	Spillway	182	52.3	26.7	251.3	15.8	3,397.1
	RSW	181	50.9	31.4	92.5	16.1	771.0
Juvenile steelhead	Bypass	424	105.1	34.8	623.0	18.8	11,683.0
	Turbine	28	508.8	35.2	2,314.6	25.9	12,293.0
	Spillway	220	30.1	25.2	20.9	16.8	219.2
	RSW	202	72.2	31.9	177.2	13.7	1,891.4

Summer Migration Period

Dam operations and environmental conditions

Discharge through Lower Granite Dam during 2006 summer study period was average relative to the past nine years (Figure 17). During this period, the mean daily discharge through Lower Granite Dam was 60.5 kcfs and ranged from 26.3 to139.0 kcfs. Daily operations at the powerhouse account for about 60.2%, of the total water volume passing Lower Granite Dam with the remaining 26.7% and 13.1% passing through the spillway and the RSW. Mean daily water temperatures ranged from 13.9 ° to 21.1 °C (Figure 18). Mean dissolved gas levels in the tailrace ranged from 105.8% to 145.9% during the summer study period. Forebay elevations ranged from 223.4 to 223.7 m with a mean of 223.5 m. Tailrace elevations ranged from 192.6 to 193.9 m with a median of 193.0 m. Date were obtained from the Columbia River Dart website: http://ww.cqs.washington.edu/dart/river.html.

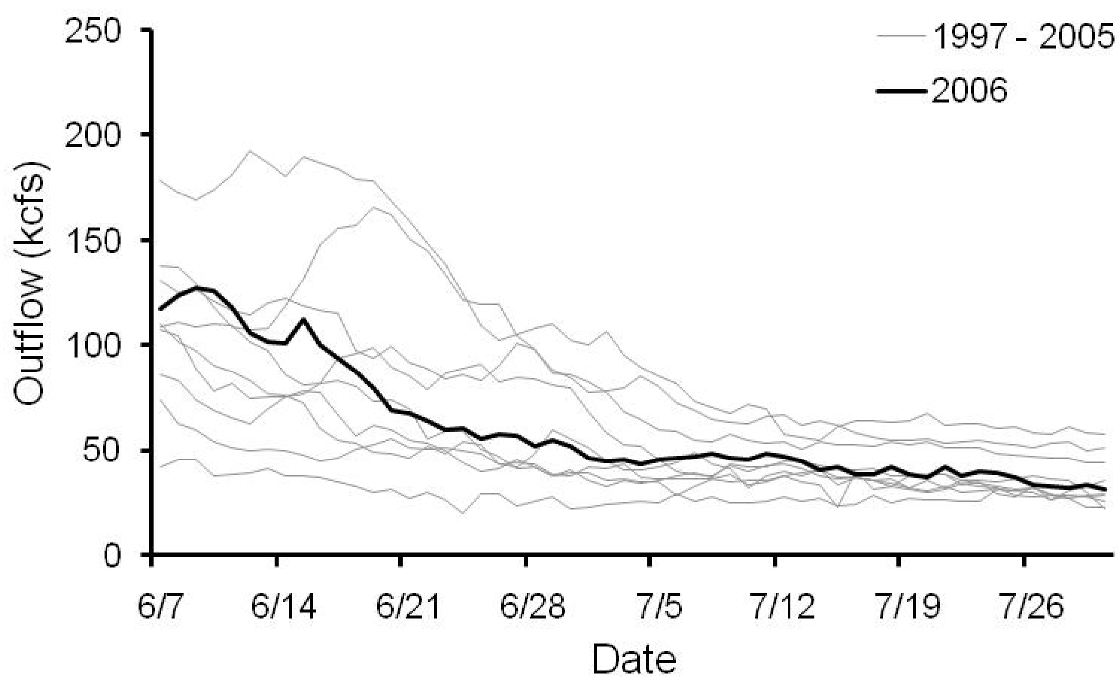

Figure 17.— Discharge at Lower Granite Dam during 2006 summer study period (6 June to 30 July) relative to the previous nine years. Outflow for current year (2006) in bold; 1997-2005 grey scale. Data obtained from the Columbia River DART website: http://ww.cqs.washington.edu/dart/river.html.

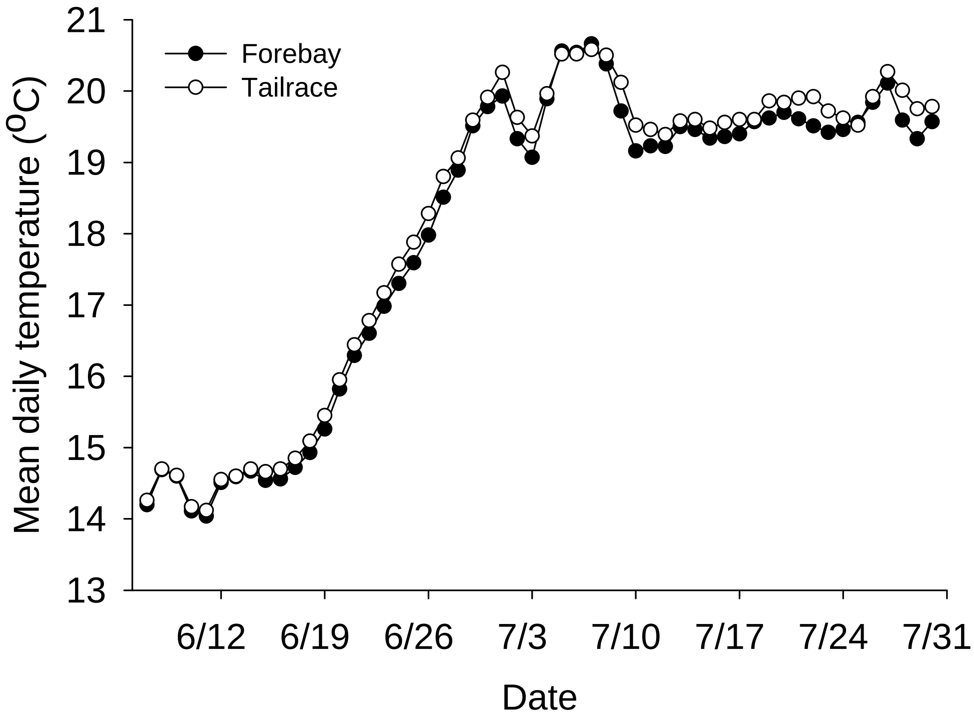

Figure 18.— Mean daily water temperatures in the forebay and tailrace areas of Lower Granite Dam during the summer study period (7 June to 30 July). Data obtained from the Columbia River DART website: http://www.cqs.washington.edu/dart/hgas.

Fish tagging and releases

We radio-tagged and released 2,063 subyearling Chinook salmon from 7 June to 3 July 2006 (Table 18). The post-tagging mortality rate during the 24-h recovery period was 0.7% (15 of 2,078) for subyearling Chinook salmon. The mortality rates at the Lower Granite Dam juvenile fish bypass facility during the same time period was 0.2% for subyearling Chinook salmon (data from http://www.fpc.org). The mortality rate of the treatment group fish was 0.8% (10 of 1,206) and was not significantly different (chi-square test of proportions, χ_1^2 =0.462, P = 0.497) than the control group mortality rate of 0.6% (5 of 872).

Table 18. — Summary of subyearling Chinook salmon radio-tagged and released at Lower Granite Dam, summer 2006. Fish were removed from data analysis due to barging.

Species	Tagged	Live released	Sacrificed (released)	Mortalities	Removed from data
Subyearling Chinook salmon	2,078	2,014	49	15	3

The size of radio-tagged fish was slightly larger than the population sample at the juvenile bypass facility and they represented the latter run timing. The average size of radio-tagged subyearling Chinook salmon was slightly larger than the population due to our minimum size restriction of 10.0 g. However, lengths and weights differed little between treatment and control groups (Table 19). Eighty-four percent of subyearling Chinook salmon collected at the juvenile fish bypass facility were of suitable size for tagging. The run percentile of subyearling Chinook salmon was 56% when our study period began and 97% when it ended, representing 41% of the run (Figure 19).

Table 19. — Summary statistics of fork length (mm) and weight (g) for radio-tagged subyearling Chinook salmon released to estimate route-specific survival, passage proportions, and behavior through Lower Granite Dam, summer 2006.

Species	Release group		Fork Length			Weight		
		N	Mean	SD	Range	Mean	SD	Range
Subyearling Chinook salmon	Control	818	112.0	6.7	98 – 140	14.4	3.0	10.0 – 30.6
	Treatment	1,196	111.4	6.9	97 – 140	14.0	2.8	10.0 – 26.8
	Euthanized	49	111.0	7.2	102 – 129	13.5	2.9	10.1 – 22.1

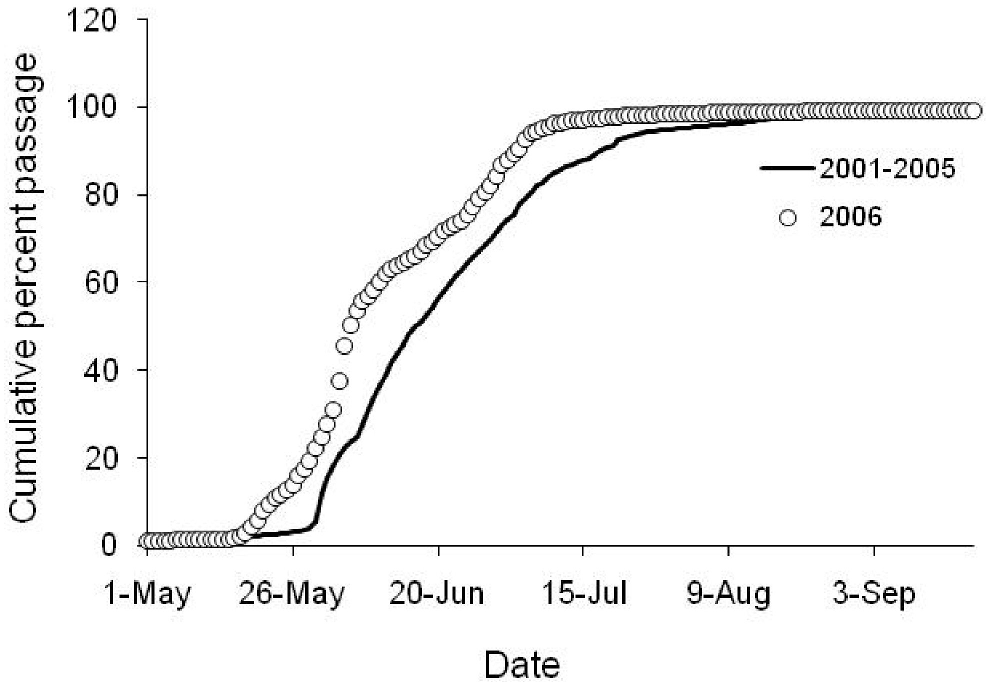

Figure 19. — Cumulative passage distribution of subyearling Chinook salmon at Lower Granite Dam. Shown are the historical 5 year average, 2001-2005, and the current year, 2006. Data from www.fpc.org.

Replicate releases of control and treatment fish were conducted from 8 June to 4 July. Average release numbers for subyearling Chinook salmon were 56.9 (SD = 8.5) per treatment release during 21 consecutive days and 32.7 (SD = 5.9) per control group for a total sample size of 2,014 radio-tagged fish.

We released euthanized fish to estimate the probability of false positive detections at our downstream telemetry arrays. Euthanized fish were released with the control fish. We released an average of six euthanized, radio-tagged subyearling Chinook salmon for a total sample size of 49. Eight releases were made from 6 June to 30 June 2006.

Travel times and approach distributions

A total of 81% of subyearling Chinook salmon (929 of 1,145) released above Lower Granite Dam during the summer study were detected by aerial antennas at the forebay entrance. Travel times from release to the forebay entrance ranged from 8.0 to 442.3 h with a median of 38.3 h. Time of arrival at the forebay entrance was distributed throughout the day with subyearling Chinook salmon arriving most frequently between 0300 and 0500 h (Figure 20).

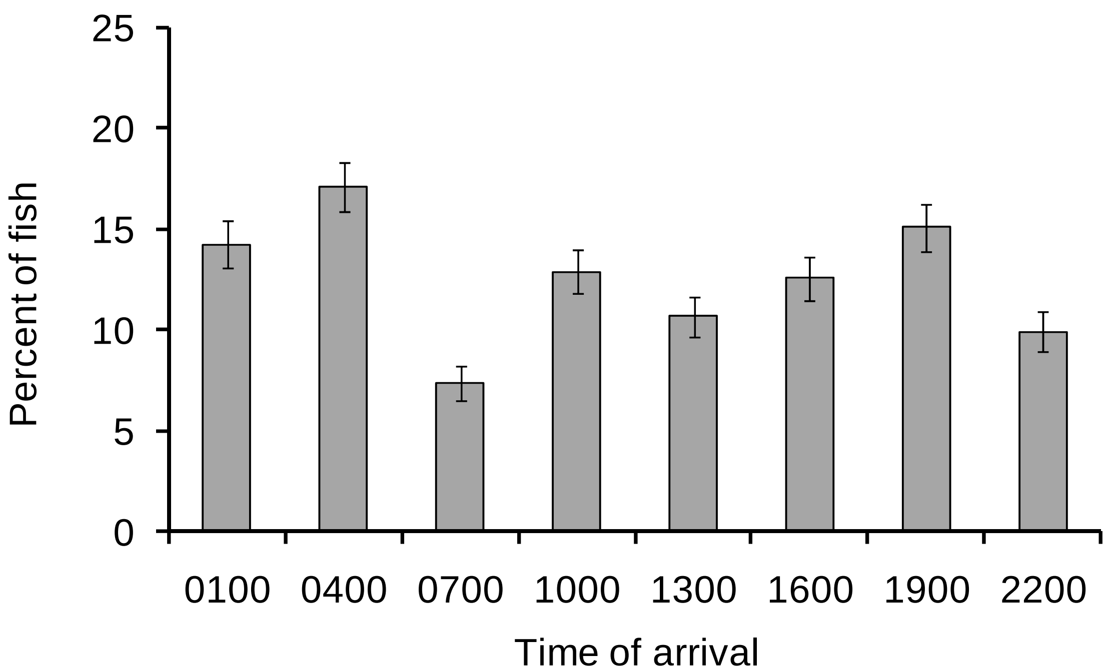

Figure 20. — Time of first detection in the Lower Granite Forebay for radio-tagged subyearling Chinook salmon, during 2006. Data is grouped into 3-h blocks. Error bars represent the standard error of a proportion.

Subyearling Chinook salmon were predominantly detected entering the forebay along the north and south areas of the forebay detection array. We found that slightly more of them entered the forebay between the mid antennas and the south shore antennas than between the mid antennas and the north shore antennas (Figure 21). Few fish were detected on the mid antennas of the array (Figure 21).

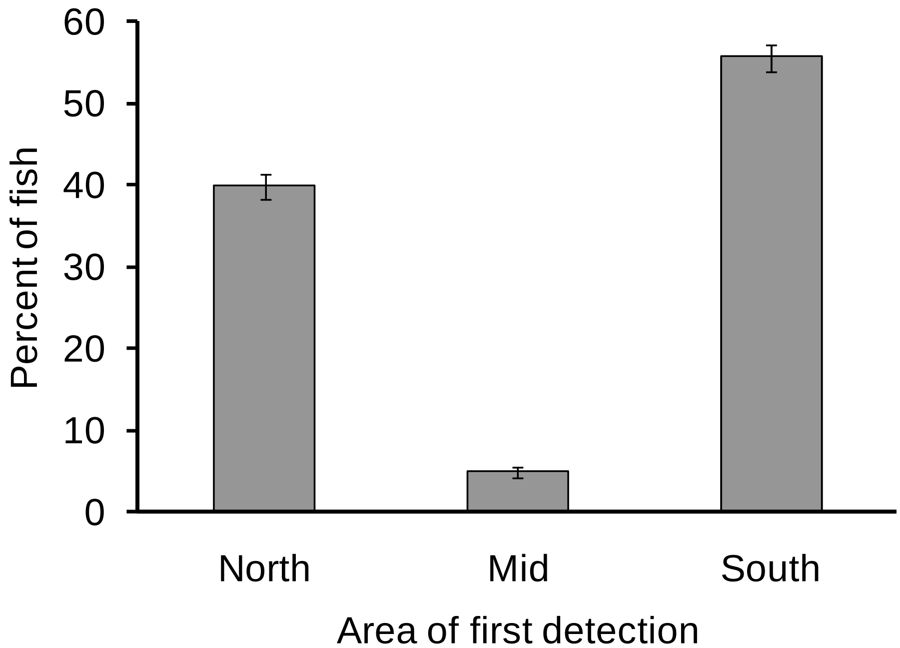

Figure 21. — Location of first aerial antenna detection for radio-tagged subyearling Chinook salmon at the Lower Granite Dam lower forebay entrance, 2 km upstream of the dam, summer 2006. Error bars represent standard errors of a proportion.

Radio-tagged subyearling Chinook salmon arrival near Lower Granite Dam was distributed among all areas. We found that the majority (46.1%) of subyearling Chinook salmon first arrived near the spillway followed by the powerhouse and earthen dam (Table 20). Area of first arrival of radio-tagged fish at Lower Granite Dam during the 1-stop and 4-stop spill treatments varied little between treatments. During the 1-stop spill treatment, a slightly larger proportion (45.7%) of subyearling Chinook salmon were first detected at the spillway than during the 4-stop spill treatment (40.0%), while the proportion of fish first detected at the powerhouse and earthen dam were slightly larger during the 4-stop spill treatment (Table 21).

Table 20.— Arrival locations of radio-tagged subyearling Chinook salmon near Lower Granite Dam during summer study period.

Species	Earthen Dam	Spillway	Powerhouse
Subyearling Chinook salmon	23.1% (200 of 864)	46.1% (398 of 864)	30.8% (266 of 864)

Table 21. — Arrival locations of subyearling Chinook salmon during spill treatments 1-stop and 4-stop at Lower Granite Dam, during 2006.

Treatment	Earthen Dam	Spillway	Powerhouse
1-stop	23.2% (68 of 293)	45.7% (134 of 293)	31.1% (91 of 293)
4-stops	24.5% (76 of 310)	40.0% (124 of 310)	35.5% (110 of 310)

Forebay residence time and behavior

The median forebay residence times of subyearling Chinook salmon varied by spill treatment, diel period, and passage route. Overall median residence times were 13.9 h and 9.8 h during 1 stop and 4 stop spill treatments. Median residence times during 1-stop spill treatment were 14.5 h during the day and 9.4 h during the night. During 4-stop spill treatments median residence times were 12.5 h during the day and 10.4 h during the night. Residence times by passage routes varied by spill treatment and passage route (Table 22).

Table 22. — Summary statistics for residence time (h) by passage route for subyearling Chinook salmon during 1-stop and 4-stop spill treatments at Lower Granite Dam during 2006.

Treatment	Passage route	n	Mean	Median	STD	Minimum	Maximum	Mode
1 stop	Spill	27	36.4	23.1	42.0	1.6	159.1	-
	RSW	167	34.7	11.6	56.4	0.8	347.0	4.2
	Turbine	17	24.1	14.4	32.0	4.4	121.6	-
	Bypass	60	26.3	14.7	33.5	0.03	159.8	0.03
	Overall	271	32.4	13.9	49.5	0.03	347.0	19.5
4 stops	Spill	35	31.0	7.3	60.6	1.6	253.2	1.3
	RSW	178	28.9	10.6	46.2	0.9	325.5	2.4
	Turbine	18	11.5	6.1	9.6	2.6	34.5	-
	Bypass	62	16.7	9.6	18.2	0.04	72.5	-
	Overall	293	25.5	9.8	42.8	0.04	325.5	-

Behavior relative to the RSW

Fish detected near the RSW were used to describe the behavior of fish that were deemed to be within the "discovery area". This area is defined by detections of fish with underwater antennas mounted on the RSW, which have a range of approximately 6 m. The discovery efficiency (fish detected within 6 m of the RSW; DE) and the entrance efficiency (the percent of those fish that pass via the RSW; EE) were estimated. Subyearling Chinook salmon DE was 75% (224 of 300) during 1-stop spill and 61% (200 of 329) during 4-stop spill. The EEs for subyearling Chinook salmon were 94% (211 of 224) and 98% (195 of 200) during 1-stop and 4-stop spill treatments, respectively.

Passage and survival estimates for subyearling Chinook salmon using the RSSM

During the summer, a tag-life study was also performed and radio-tagged euthanized fish were released to test for assumptions that 1) fish exited the study area prior to expiration of transmitter batteries and 2) dead radio-tagged fish were not detected by telemetry arrays used to estimate survival. We found that the probability of a tag being operational at downstream detection arrays was > 99.9% for subyearling Chinook salmon, suggesting that survival estimates were not negatively biased due to non-detection of live fish with non-functioning transmitters (See Appendix B: Tag-Life Study). We did detect radio-tagged dead fish at the second downstream array during the summer, as we did in the spring. This in-river site was the only array where euthanized fish were detected during the summer. Consequently, as in the spring analysis we excluded this gate from the analyses to eliminate any potential bias caused by false-positive detections at this array.

The summer study was designed to evaluate the survival and passage probabilities of subyearling Chinook salmon during two different spill bay configurations while spilling 18 kcfs and operating the RSW 24 h a day; 1-stop versus 4-stops. During the first quarter (8 June to 15 June) of the summer study the treatments did not fit these configurations and fish passing during this time were not included in our analyses. Due to the variability in the prescribed versus observed dam treatments, sample sizes of fish passing during individual spill treatments were considerably less than we proposed; thus we were not able to meet our stated precision goals.

We assigned a passage route to 85% (749 of 886; Appendix Table A8) of the radio-tagged subyearling Chinook salmon released upriver of and passing Lower Granite Dam during the prescribed RSW operations with 1-stop and 4-stop dam treatments. When the data for both dam treatments were evaluated, the majority of the subyearling Chinook salmon passed the dam via the RSW (50%), followed by the bypass (21%), the spillway (9%), and the turbines (5%). This pattern was consistent for the two treatments (i.e., 1-stop, 4-stops; Appendix Table A9 and A10). However, there was a higher percentage of subyearling Chinook salmon passing via the RSW (55%) during the 1-stop treatment than fish passing via the spillway (6%) than during the 4-stop treatment (45% RSW and 12% spillway). Passage locations for subyearling Chinook salmon during the summer showed that the majority of fish passing through the spillway passed via the RSW during 1-stop and 4-stop spill treatments (Figure 22).

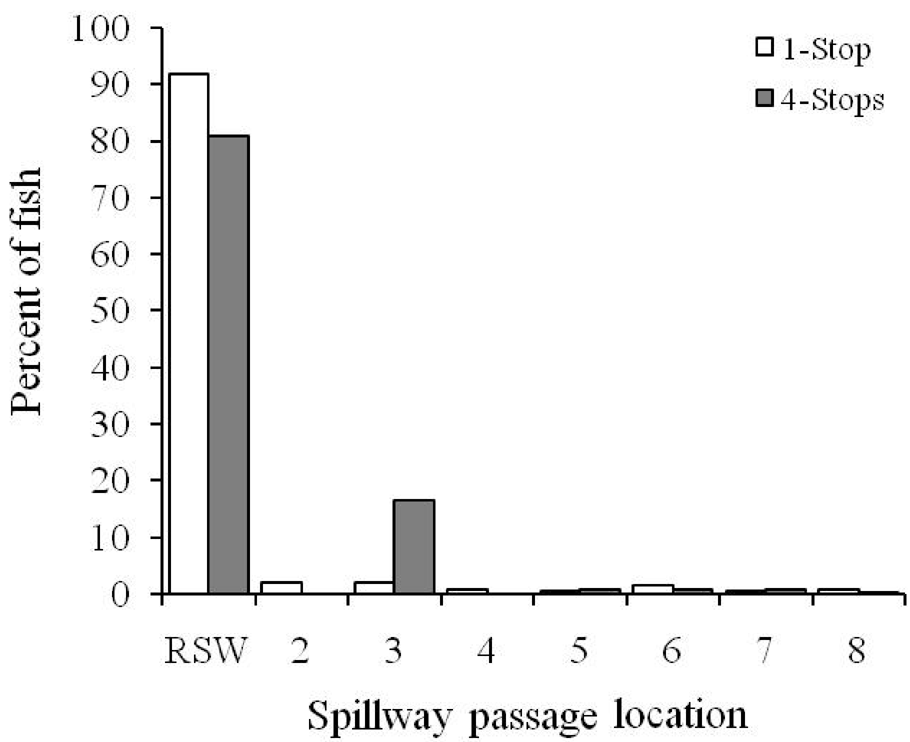

Figure 22. — Spillway passage locations for subyearling Chinook salmon during 1-stop and 4-stop spill treatments at Lower Granite Dam during summer 2006.

We used the capture history data to estimate route specific survival and passage probabilities for subyearling Chinook salmon during the two dam treatments. When data for both treatments were evaluated (1-stop and 4-stop combined), the highest passage probability was via the RSW, followed by the bypass, spillway, and turbine routes (Table 23). This pattern was also consistent within the two treatments. The probability of RSW passage was significantly higher (z = 12.077, P <0.0001) and the probability of turbine passage was significantly lower (z = 2.579, P = 0.010) during 1-stop treatment than during the 4-stop treatment. Consequently, the FPE (0.951) was also significantly higher (z =2.579, P = 0.010) during the 1-stop treatment. There were no significant differences in the survival probabilities between the treatments. The RSW had the highest survival probability (0.969, SE = 0.021) during the 1-stop treatment while the spillway was the highest during the 4-stop treatment (0.934, SE = 0.039). These survival probabilities in conjunction with the higher passage probabilities through the RSW resulted in a slightly higher dam survival for the 1-stop treatment (0.918, SE = 0.021) versus the 4-stop treatment (0.906, SE = 0.018).

More fish passed during the day (approximately 0502 to 2046 hrs) than during the night during both treatments (69% day / 31% night for 1-stop and 63% day / 37% night for 4-stops; Appendix Table A9-A10). The passage probabilities through the RSW were much higher during the day than during the night for both treatments and had the highest survival probability of all routes (Table 24). As a result the overall dam survival was higher during the day for both treatments. The FPE, FGE, RPE, and CPE were all higher during the day versus the night for both treatments, while SPY was similar between diel periods.

Throughout the summer season, no major temporal trends were observed in subyearling Chinook salmon survival and passage probabilities. The RSW passage probabilities steadily increased during the summer study period and leveled off toward the end of the study period. The passage probability estimates for the bypass were higher earlier during the study period than during the latter (Figure 23).

Table 23. — Overall survival estimates and passage probabilities for subyearling Chinook salmon passing through Lower Granite Dam during summer study period. Standard error (SE) and 95% profile likelihood confidence intervals (CI) presented. Treatments consisted of the RSW operating with 1-or 4-stop spill treatments. Asterisks indicate significant differences between 1-stop and 4-stop treatments (two-tail z-test, α = 0.05).

	Dam Treatments					
	RSW/1-Stop		RSW/4-Stops		Overall RSW/1-and 4-Stops)	
Parameters	Probability(SE)	95% CI	Probability(SE)	95% CI	Probability(SE)	95% CI
Spool	0.926 (0.014)	0.896,0.951	0.928 (0.013)	0.900,0.951	0.927 (0.009)	0.907,0.944
S forebay	0.958 (0.012)	0.929,0.978	0.941 (0.013)	0.914,0.963	0.949 (0.009)	0.930,0.965
S dam	0.918 (0.021)	0.830,0.991	0.906 (0.018)	0.869,0.942	0.914 (0.014)	0.886,0.942
S spillway	0.844 (0.073)	0.681,0.962	0.934 (0.039)	0.839,0.996	0.894 (0.040)	0.805,0.961
S RSW	0.969 (0.021)	0.925,1.009	0.916 (0.023)	0.867,0.959	0.945 (0.016)	0.913,0.975
S turbine	0.683 (0.121)	0.436,1.004	0.872 (0.063)	0.727,0.969	0.846 (0.054)	0.728,0.936
S bypass	0.863 (0.045)	0.766,0.941	0.882 (0.036)	0.803,0.945	0.875 (0.028)	0.815,0.927
λ	0.959 (0.011)	0.933,0.977	0.977 (0.009)	0.954,0.991	0.967 (0.007)	0.950,0.980
Pr spillway	0.108 (0.017)	0.030,0.144	0.137 (0.017)	0.106,0.172	0.104 (0.011)	0.084,0.127
*Pr RSW**	0.620 (0.004)	0.569,0.669	0.522 (0.007)	0.474,0.570	0.568 (0.005)	0.533,0.603
*Pr turbine**	0.049 (0.012)	0.029,0.167	0.099 (0.015)	0.072,0.131	0.094 (0.011)	0.074,0.117
Pr bypass	0.223 (0.022)	0.152,0.305	0.242 (0.021)	0.202,0.284	0.234 (0.015)	0.205,0.264
FPE*	0.951 (0.012)	0.833,0.971	0.901 (0.015)	0.869,0.928	0.906 (0.011)	0.883,0.926
FGE	0.819 (0.041)	0.527,0.889	0.709 (0.039)	0.629,0.781	0.713 (0.029)	0.653,0.768
SPY [a]	0.504		0.623		0.481	
RPE [a]	5.034		4.243		4.614	
CPE [a]	2.158		1.925		1.978	

[a]-No standard error or confidence interval presented.

Table 24. — Overall survival estimates and passage probabilities for subyearling Chinook salmon passing through Lower Granite Dam during the day (approximately 0502 to 2046) and night hours, summer 2006. Standard error (SE) and 95% profile likelihood confidence intervals (CI) presented. Treatments consisted of the RSW 1-stop vs. 4-stop treatments.

	RSW/1-Stop			
	Day		Night	
Parameters	Probability (SE)	95% CI	Probability (SE)	95% CI
Spool	0.957 (0.013)	0.928,0.980	0.863 (0.033)	0.792,0.921
S forebay	0.992 (0.026)	0.951,1.128	0.937 (0.034)	0.862,1.027
S dam	0.905 (0.035)	0.787,0.966	0.861 (0.044)	0.758,0.940
S spillway	0.830 (0.099)	0.605,0.982	0.678 (0.197)	0.294,0.962
S RSW	0.959 (0.027)	0.904,1.011	0.982 (0.035)	0.891,1.045
S turbine	0.609 (0.235)	0.194,0.962	0.644 (0.125)	0.394,0.857
S bypass	0.858 (0.060)	0.727,0.960	0.867 (0.067)	0.712,0.976
λ	0.951 (0.015)	0.916,0.975	0.973 (0.016)	0.931,0.993
Pr spillway	0.070 (0.016)	0.044,0.105	0.108 (0.037)	0.049,0.208
Pr RSW	0.673 (0.010)	0.581,0.732	0.430 (0.017)	0.336,0.527
Pr turbine	0.075 (0.028)	0.038,0.193	0.156 (0.036)	0.094,0.237
Pr bypass	0.182 (0.024)	0.138,0.231	0.305 (0.046)	0.222,0.399
FPE	0.925 (0.028)	0.807,0.962	0.844 (0.036)	0.763,0.906
FGE	0.707 (0.089)	0.445,0.840	0.661 (0.069)	0.520,0.785
SPY[a]	0.347		0.453	
RPE[a]	5.785		3.102	
CPE[a]	2.328		1.425	

	RSW/4-Stops			
	Day		Night	
Parameters	Probability (SE)	95% CI	Probability (SE)	95% CI
Spool	0.949 (0.014)	0.918,0.973	0.895 (0.025)	0.842,0.938
S forebay	0.945 (0.015)	0.911,0.971	0.935 (0.022)	0.883,0.970
S dam	0.916 (0.021)	0.871,0.957	0.874 (0.037)	0.801,0.958
S spillway	0.960 (0.042)	0.845,1.019	0.864 (0.081)	0.677,0.998
S RSW	0.917 (0.026)	0.862,0.964	0.896 (0.054)	0.779,0.999
S turbine	0.836 (0.117)	0.556,0.990	0.901 (0.075)	0.721,1.025
S bypass	0.907 (0.045)	0.803,0.978	0.841 (0.062)	0.708,0.956
λ	0.980 (0.010)	0.954,0.994	0.966 (0.024)	0.899,0.994
Pr spillway	0.126 (0.020)	0.090,0.169	0.160 (0.030)	0.107,0.225
Pr RSW	0.618 (0.006)	0.559,0.675	0.346 (0.015)	0.272,0.424
Pr turbine	0.057 (0.015)	0.032,0.091	0.177 (0.032)	0.119,0.244
Pr bypass	0.199 (0.024)	0.155,0.250	0.317 (0.038)	0.247,0.394
FPE	0.943 (0.015)	0.909,0.968	0.823 (0.032)	0.756,0.881
FGE	0.778 (0.052)	0.666,0.868	0.642 (0.057)	0.528,0.748
SPY[a]	0.613		0.638	
RPE[a]	5.324		2.480	
CPE[a]	2.315		1.294	

[a] – No standard error or confidence interval presented

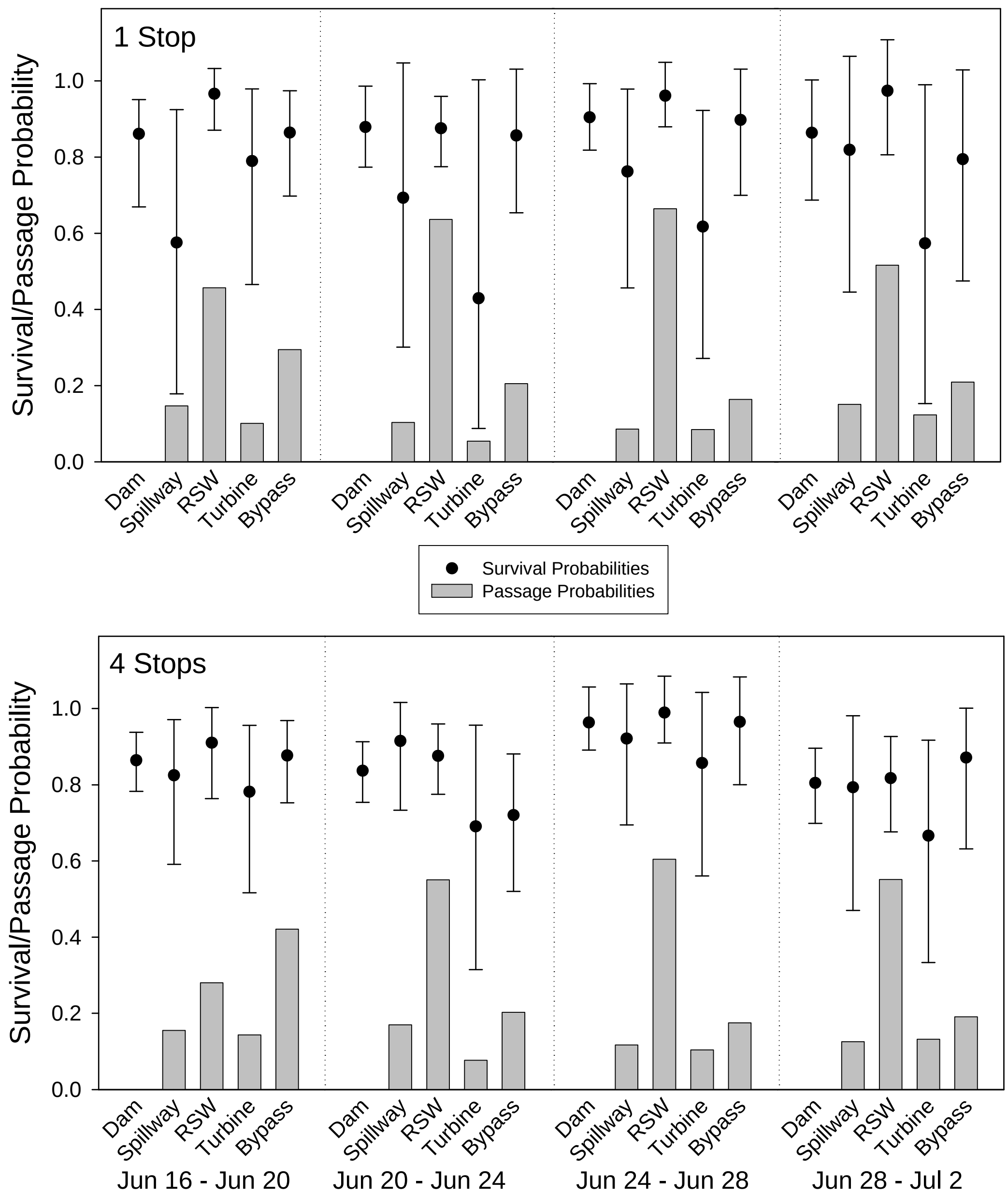

Figure 23. — Estimates of survival and passage probabilities and fish passage and guidance efficiencies (error bars are 95% profile confidence intervals) for subyearling Chinook salmon passing Lower Granite Dam during 1-stop and 4-stop treatments, summer 2006.

Tailrace egress

Tailrace egress times of subyearling Chinook salmon varied slightly between passage routes at Lower Granite Dam. Fish passing through the spillway had the shortest median egress time (33.5 min) while fish passing through the RSW had the longest (52.1 min) but there was considerable variation in the data (Table 25). Fish passing through the powerhouse had similar median egress times though bypassed fish had much greater variation in egress times than fish passing through the turbines (Table 25). Overall median egress times during 1-stop (56.7 min) and 4-stop (56.1 min) spill treatments were similar during the summer study period.

Table 25. — Descriptive statistics of egress time (min) for radio-tagged subyearling Chinook salmon at Lower Granite Dam, summer 2006. Tailrace egress time was measured from the time of passage to the last time of detection at the tailrace exit site (about 2 km downriver).

Species	Passage route	*n*	Mean	Median	STD	Minimum	Maximum	Mode
Subyearling Chinook salmon	Bypass	224	101.1	44.0	302.4	22.5	3,785.4	28.1
	Turbine	50	67.2	42.3	90.0	26.2	632.0	-
	Spillway	141	96.2	33.5	242.8	21.3	1,996.0	22.6
	RSW	437	79.1	52.1	156.2	20.9	2,585.2	30.7

Discussion

This study was one of many evaluations of fish passage at Lower Granite Dam since the mid-1980s. The number of fish passage studies conducted at Lower Granite Dam are too many to mention here, but include studies of radio-tagged fish beginning in 1985 (Stuehrenberg et al. 1986) and nearly annual studies using that method since 1994 (beginning with Rondorf and Banach, 1996); studies of 3-D positions of fish implanted with acoustic tags in 2000, 2002, and 2003 (Cash et al. 2002, 2005a, 2005b); and many studies based on hydroacoustics beginning in 1985 (Kuehl 1986). The purpose of these studies has been to evaluate a myriad of structures and operations designed to increase passage survival, including a surface bypass collector, behavioral guidance structure, and the current RSW (see review of surface bypass studies by Dauble et al. 1999). The results of these studies have guided the development of the BGS and RSW structures at Lower Granite Dam, but the optimal operations when using them are still in question. This study was conducted to evaluate passage and survival with and without use of a modified BGS in the spring and to evaluate two spill patterns and RSW operation without the BGS in use during the summer.

Passage survival was high at Lower Granite Dam in 2006. This was a result of the combination of low probabilities of turbine passage and high survival probabilities in all other routes. Survival probabilities of yearling Chinook salmon and juvenile steelhead were similar to one another through the pool, forebay, and each dam passage route. Survival probabilities of subyearling Chinook salmon were generally about 0.06 lower than the spring migrants, but the trends among routes were similar. As at other dams, the lowest survival probabilities were for the turbine route (0.90 for spring migrants and 0.85 for subyearling Chinook salmon). Perry et al. (2007) reported turbine survivals at Lower Granite Dam during spill and RSW operation in 2005 of 0.961 for yearling Chinook salmon and 0.842 for subyearling Chinook salmon. Turbine survival at Lower Granite Dam is similar to other Snake River Dams. Turbine survival estimates at Little Goose Dam in 2006 were 0.839 for yearling Chinook salmon, 0.918 for juvenile steelhead, and 0.862 for subyearling Chinook salmon (Beeman et al. 2007). Hockersmith et al. (2005)

reported turbine survival of 0.881 for yearling Chinook salmon at Lower Monumental Dam in 2004.

A report by Brown et al. (2007) suggests that injury and mortality of tagged fish passing through turbines could be higher than untagged fish. They exposed fish tagged with transmitter models used in this study to a “worst case” scenario of pressure change to determine if presence of a tag affected injury or mortality. They found an effect due to barotrauma, but acknowledged that they could not extrapolate the results to the real world, because they lacked data on the pressures fish experienced during turbine passage. Thus, their findings at this point serve as a proof of a concept, rather than proof of a true effect. They also found an effect of prior depth compensation, which may have implications on the effects on shallow-oriented migrants vs. deeper-oriented ones. This raises an interesting question about the mechanism(s) of the effects of turbine passage on juvenile salmonids, particularly subyearling Chinook salmon relative to other species. Turbine passage survival estimates of subyearling Chinook salmon are generally lower than for yearling Chinook salmon or juvenile steelhead.

The results from this study indicate the use of the BGS in the spring had several statistically significant effects on passage of the juvenile salmonids studied, but no differences were detected in survival probabilities. Reductions in FGE and spillway passage and increases in turbine and RSW passage of yearling Chinook salmon with the BGS in use resulted in a statistically significant reduction in FPE between treatments (0.842 with the BGS and 0.919 without). The passage probability of juvenile steelhead through the RSW was significantly greater with the BGS in operation (0.285 vs. 0.245), but there were no other significant passage or survival measures of this species between treatments. The use of the BGS also resulted in slightly greater effectiveness of the spillway, RSW, and their combination in passing yearling Chinook salmon and juvenile steelhead.

One of the questions about BGS operation is what the effect would be if the gap between the upstream end of the BGS and the shoreline was closed. This was evaluated by comparing the BGS-specific measures P_b and $P_{b\ corrected}$, however, we are not confident in the results of the $P_{b\ corrected}$ metric in 2006. These BGS-specific measures are meant to describe the difference in powerhouse passage when the BGS is deployed relative to when it is not. The P_b is based on the numbers of fish passing the powerhouse routes relative to all routes during each treatment. The $P_{b\ corrected}$ is a correction for the proportion of fish that got past the BGS by going through the gap versus the total number that got past it (i.e., passage through the gap plus passage underneath). A key assumption in this correction is that fish passing through the gap and under the BGS are detected with equal probability. We do not feel this assumption was met in 2006. The number of antennas mounted under the BGS was limited due to concerns about the safety of divers to affix underwater antennas to the ageing device. Thus, we feel the great apparent influence of closing the gap from this study (e.g., yearling Chinook salmon P_b of 0.07 and their $P_{b\ corrected}$ of 0.84) is an artifact of our poor detection probability under the BGS. If no fish were detected passing under the BGS the $P_{b\ corrected}$ would be 1.0. The true effect of closing the gap is some amount less than what we present, but we have no way to estimate it.

Perhaps the best assessment of the effects of the BGS in 2006 is to look at the results of this study and those of the concurrent hydroacoustic evaluation of fish passage by Ham et al. (2007). Both studies found a statistically significant difference in FGE with lower FGE when the BGS was in use. Ham et al. (2007) discussed this effect based on their data indicating the vertical distributions of fish and concluded that the BGS primarily diverted fish from the upper portion of the water column, thereby reducing the numbers of fish likely to enter the bypass system. Both studies indicate some changes in spillway passage, RSW passage, and turbine passage between treatments, but the statistical significance of these comparisons differs between studies. We found statistical differences were primarily in passage measures of yearling Chinook salmon and not juvenile steelhead. Ham et al. (2007) found few statistical differences, but their results were based on a composite of all species migrating during the spring study period. We also found spillway passage to be lower when the BGS was in use, and Ham et al. (2007) reported slightly higher spillway passage during this treatment. Thus, the specific findings of the two studies are somewhat different, but this may be expected based on differences between the species specificity of the two methods. Both studies found statistical evidence for a reduction in FGE with the BGS in use and both had higher estimates of RSW passage with the BGS in use. The hydroacoustic method found similar turbine passage during both treatments, whereas we found greater turbine passage of yearling Chinook salmon when the BGS was in use and little difference in turbine passage of juvenile steelhead. Thus, when both studies are considered, the effects of the BGS in 2006 appeared to have a species-specific component, with a greater effect on yearling Chinook salmon than juvenile steelhead; resulted in a reduction in FGE, with the magnitude of the effect dependent on species; resulted in a general increase in RSW passage; and may have been more effective if it were extended closer to the shoreline and perhaps to the river bottom. One cannot discount that fish approach to the dam may have been shifted northward when the BGS was in the stored position. If so, turbine passage during the stored condition may be underestimated and spill or RSW passage overestimated in 2006 from conditions with no structure in the forebay.

The BGS was less effective in diverting fish from powerhouse passage in 2006 than the BGS evaluated in 1998. We estimated the P_b of yearling Chinook salmon was 0.07 and that of juvenile steelhead was 0.16, representing a diversion of 7% and 16% of the fish from powerhouse passage. Adams et al. (2001) estimated P_b of 0.56 for yearling Chinook salmon and 0.72 for juvenile steelhead. There are several differences between the studies that may account for these differences. The depth of the BGS in 1998 ranged from 17 to 30 m deep, increasing in the downstream direction and the BGS in 2006 was 17 m deep throughout its length. The shallower BGS may have been less effective. In 1998 the BGS was attached to the dam between turbine units 3 and 4, a surface bypass collector was affixed to the dam above the turbine intakes of units 4, 5, and 6, and only two units were operating behind the BGS. In 2006 it was attached between units 5 and 6, the surface bypass collector was absent, and all turbine units were operating. The increased turbine discharge downstream from the BGS in 2006 (due to the greater number of turbines present and operating) likely increased the flow net under the BGS and may have decreased its effectiveness alone, or in combination with the shallower design. The reduced proportion of total discharge passing via the powerhouse may have also altered the flow net near the BGS and reduced its effectiveness. In 1998 the average discharge during the study period was 115 kcfs and spill, when present, averaged 26% of total discharge. In 2006 the average discharge was 130 kcfs, spill occurred throughout the study period and averaged 32%, and an RSW was in operation passing another 5% of total discharge through the spillway.

The effects of the two spill treatments on subyearling Chinook salmon during the summer were generally limited to the probabilities of passage through the RSW, turbines, and in FPE. A higher probability of passing the RSW, lower probability of passing via the turbines, and higher FPE occurred during the 1-stop spill treatment that during the 4-stop treatment. Other differences include a slightly greater proportion of fish first detected at the spillway during the 1-stop treatment (46% vs. 40%), a slightly longer forebay residence time during the 1-stop treatment (median 13.9 h vs. 9.8 h), and a slightly greater RSW discovery efficiency during the 1-stop treatment (75% vs. 61%). The latter difference may be related to the difference in the proportion of fish first detected at the spillway, as this would place more fish in the general area of the RSW. These differences between treatments did not result in statistically significant differences in any survival measures.

The results of this study from the summer period and those of the hydroacoustic-based study of Ham et al. (2007) differ. Both studies indicate the RSW was more effective during the 1-stop treatment, but the study results differ along most other measures of passage between treatments. We concluded that FPE was higher during the 1-stop treatment (0.951 vs. 0.709) and Ham et al. (2007) found them to be similar, but different statistically (97.8% 1-stop, 98.8% 4-stop; note their results were expressed in percentages, ours were expressed as probabilities). Both studies found the RSW passage to be greater during the 1-stop treatment, presumably due to the opening of spill bay 3 to 4 stops, similar to the RSW opening (equivalent to 3.5 stops). The magnitude of this difference was greater in the hydroacoustic study (90.1% vs. 63.0%) than in this study (0.620 vs. 0.522). Based on similarities in results of this study and those of Ham et al. (2007) the effects of the 4-stop spill treatment relative to the 1-stop treatment during the summer were a decrease in RSW passage efficiency and effectiveness. The hydroacoustic method indicates little difference in FPE between treatments, whereas this study indicates greater FPE during the 1-stop treatment. The reasons for these differences may be in the time periods used for each study. We used data from radio-tagged fish passing the dam between June 8 and July 9 (summer blocks 1-16) and Ham et al. (2007) used data from all fish passing in blocks 4 through 20. We chose to use all blocks available to us due to the shorter time window available for our work (our summer tag and release dates included fish from the 56th to the 96th percentile of passage) whereas the hydroacoustic study omitted the first four blocks due to spill treatment violations and continued much later than we did. Total and spill discharges were greatest during the early part of the summer season, and appeared to affect spill effectiveness, FGE, and RSW efficiency and effectiveness (Ham et al. 2007). These effects appear to account for many of the differences between the two studies during the summer period.

There were several trends in RSW passage in the spring and summer apart from the treatments studied. The greatest probability of RSW passage was during the day in spring and summer. This diel trend was apparent in data from each of the three groups studied. For example, the probabilities of RSW passage of yearling Chinook salmon were 0.32 day / 0.21 night during the BGS Deployed treatment and 0.37 day / 0.22 night during the BGS Stored treatment. The overall (treatments and diel periods pooled) probability of RSW passage was much greater during the summer than during the spring. The probabilities were 0.295, 0.263, and 0.568 for yearling Chinook salmon, juvenile steelhead, and subyearling Chinook salmon, respectively. This was likely affected by species-specific behaviors and the proportion of water passing the various routes at the dam. The proportion of total dam discharge passing through the RSW was 5% during the spring and 13% during the summer, due to the similarity of water volume through the RSW during the varying total discharges (131 kcfs spring, 60 kcfs summer). The survivals of fish passing through the RSW were among the highest of any route during spring (0.992) and summer (0.945).

The operation of the spillway and RSW at Lower Granite Dam for fish passage have little effect on dam passage survival of yearling Chinook salmon and juvenile steelhead, but their operation is important to the dam passage survival of subyearling Chinook salmon. Given the current FGE and survival probabilities at Lower Granite Dam, changes in the location of passage have little or no bearing on the dam passage survival of spring migrants. For example, using a simple model based on FGE, turbine survival and bypass survival of yearling Chinook salmon in 2006 when the BGS was stored, predicted dam survival would be 0.95 without any spill or RSW operation (80%

bypass passage, 20% turbine passage). The estimated dam survival during that treatment in 2006, which included 33% spill passage and 28% RSW passage, was 0.967 (SE 0.012). The similarity with and without RSW and spill passage is due to the similarity in survivals through all non-turbine routes of passage. The results of simulations with data from subyearling Chinook salmon are much different, because their survival through spill (0.844 SE 0.073) and the bypass (0.863 SE 0.045) were much lower than their survival through the RSW (0.969 SE 0.021). In the case of summer operations, the use of the RSW does increase dam survival, particularly during the operations in 2006. Predicted dam survival of subyearling Chinook salmon with only bypass and turbine passage (based on 2006 FGE and survivals through these routes) is 0.830 vs. 0.918 (SE 0.021) during the 1-stop treatment in 2006. These simulations do not account for changes in forebay behavior that can occur with and without spill.

The impacts of operations on fish survival should be considered relative to the entire salmon life cycle. The use of spill and the RSW at Lower Granite Dam has been shown to reduce forebay residence times of juvenile salmonids (Plumb et al. 2004). Delay in dam passage is generally believed to have a negative impact on smolt-to-adult returns by altering the time of ocean entry (Zabel and Williams 2002; Muir et al. 2006), though survival within an individual dam forebay can be quite high (≥ 0.95 in this study). The use of spill is also used as a management strategy to "spread the risk" of passage, by allowing some fish to migrate in-river while others are transported to sites downstream from Bonneville Dam. The support for this strategy is generally three-fold: timing of ocean entry, size selectivity of bypass systems, and effects of passing multiple bypass systems. Muir et al. (2006) suggested that transporting fish results in lower overall survival by altering the timing of ocean entry, size-selective predation, or both. Zabel et al. (2005) reported that juvenile bypass systems preferentially selected smaller fish from the populations in dam forebays, and that small fish returned at lower rates as adults. Williams et al. (2005) described similar size-selectivity in bypass systems of Columbia and Snake River Dams, with the exception of the system at Lower Granite Dam, which had no size-selectivity. They reported that fish collected in the bypass system at Lower Granite Dam had higher adult return rates than those that were never detected in a bypass system, but found no specific mechanism for it.

The optimal spring and summer operation of the spillway and RSW at Lower Granite Dam are still in question. Given the small impact of spill and RSW passage on dam survival of spring migrants, the most beneficial dam operation for fish passage with the RSW for spring migrants may be one in which training spill is at the minimum needed to result in a) passage without delay and b) acceptable passage survival. This minimum does not appear to have been reached yet. Operations during the summer could be different than during the spring, given the impact of the RSW on passage survival during this time. In addition, the optimal training spill required may be different during day and night conditions, because the effectiveness of the RSW as well as total dam discharge are affected by these conditions during the spring and summer.

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Appendix

Appendix A – Route-Specific Survival Model

Appendix Table A1. — Probability functions of detection histories used in the route-specific survival model for juvenile salmonids through Lower Granite Dam, spring 2006.

Detection history	Probability function
1001	$S_{pool}(1-P_{Fb})S_{Fb}(SP(1-P_{Sp})S_{Sp}\lambda+(1-SP)(1-SW)BY(1-P_{By})S_{By}\lambda+(1-SP)(1-SW)(1-BY)(1-P_{Tu})S_{Tu}\lambda+(1-SP)SW(1-P_{Sw})S_{Sw}\lambda)$
1101	$S_{pool}P_{Fb}S_{Fb}(SP(1-P_{Sp})S_{Sp}\lambda+(1-SP)(1-SW)BY(1-P_{By})S_{By}\lambda+(1-SP)(1-SW)(1-BY)(1-P_{Tu})S_{Tu}\lambda+(1-SP)SW(1-P_{Sw})S_{Sw}\lambda)$
1000	$1-S_{pool}+S_{pool}(1-P_{Fb})(1-S_{Fb}+S_{Fb}(SP(1-P_{Sp})(1-S_{Sp}+S_{Sp}(1-\lambda))+(1-SP)(1-SW)BY(1-P_{By})(1-S_{By}+S_{By}(1-\lambda))+(1-SP)(1-SW)(1-BY)(1-P_{Tu})(1-S_{Tu}+S_{Tu}(1-\lambda))+(1-SP)SW(1-P_{Sw})(1-S_{Sw}+S_{Sw}(1-\lambda))))$
1100	$S_{pool}P_{Fb}(1-S_{Fb}+S_{Fb}(SP(1-P_{Sp})(1-S_{Sp}+S_{Sp}(1-\lambda))+(1-SP)(1-SW)BY(1-P_{By})(1-S_{By}+S_{By}(1-\lambda))+(1-SP)(1-SW)(1-BY)(1-P_{Tu})(1-S_{Tu}+S_{Tu}(1-\lambda))+(1-SP)SW(1-P_{Rs})(1-S_{Sw}+S_{Sw}(1-\lambda))))$
1021	$S_{pool}(1-P_{Fb})S_{Fb}(1-SP)SWP_{Sw}S_{Sw}\lambda$
1121	$S_{pool}P_{Fb}S_{Fb}(1-SP)SWP_{Sw}S_{Sw}\lambda$
1020	$S_{pool}(1-P_{Fb})S_{Fb}(1-SP)SWP_{Sw}(1-S_{Sw}+S_{Sw}(1-\lambda))$
1120	$S_{pool}P_{Fb}S_{Fb}(1-SP)SWP_{Sp}(1-S_{Sw}+S_{Sw}(1-\lambda))$
1031	$S_{pool}(1-P_{Fb})S_{Fb}(1-SP)(1-SW)BYP_{By}S_{By}\lambda$
1131	$S_{pool}P_{Fb}S_{Fb}(1-SP)(1-SW)BYP_{By}S_{By}\lambda$
1030	$S_{pool}(1-P_{Fb})S_{Fb}(1-SP)(1-SW)BYP_{By}(1-S_{By}+S_{By}(1-\lambda))$
1130	$S_{pool}P_{Fb}S_{Fb}(1-SP)(1-SW)BYP_{By}(1-S_{By}+S_{By}(1-\lambda))$
1041	$S_{pool}(1-P_{Fb})S_{Fb}SPP_{Sp}S_{Sp}\lambda$
1141	$S_{pool}P_{Fb}S_{Fb}SPP_{Sp}S_{Sp}\lambda$
1040	$S_{pool}(1-P_{Fb})S_{Fb}SPP_{Sp}(1-S_{Sp}+S_{Sp}(1-\lambda))$
1140	$S_{pool}P_{Fb}S_{Fb}SPP_{Sp}(1-S_{Sp}+S_{Sp}(1-\lambda))$
1051	$S_{pool}(1-P_{Fb})S_{Fb}(1-SP)(1-SW)(1-BY)P_{Tu}S_{Tu}\lambda$
1151	$S_{pool}P_{Fb}S_{Fb}(1-SP)(1-SW)(1-BY)P_{Tu}S_{Tu}\lambda$
1050	$S_{pool}(1-P_{Fb})S_{Fb}(1-SP)(1-SW)(1-BY)P_{Tu}(1-S_{Tu}+S_{Tu}(1-\lambda))$
1150	$S_{pool}P_{Fb}S_{Fb}(1-SP)(1-SW)(1-BY)P_{Tu}(1-S_{Tu}+S_{Tu}(1-\lambda))$
0010	$1-\lambda$
0011	λ

Appendix Table A2. — Counts of detection histories of radio-tagged yearling Chinook salmon used in the route-specific survival model for deployed and stored Behavioral Guidance Structure (BGS) treatments at Lower Granite Dam, 2006. The detection histories, composed of 4 digits, indicates 1) the release site (1 = Blyton Landing, 0 = tailrace), 2) whether fish were detected (1) or not detected (0) at the forebay entrance array 3) the route of passage for each fish coded from 0 to 5[a], 4) and whether fish were detected at telemetry arrays downriver of Lower Granite Dam.

				Counts of within-route histories					
		Counts		BGS Deployed			BGS Stored		
n for release/route	Detection history [a]	BGS Deployed	BGS Stored	01	10	11	01	10	11
Blyton (R_t) = 643	1000	4	4						
	1100	0	4						
	1001	2	1						
	1101	11	6						
RSW= 186	1020	0	0	2	14	78	0	12	80
	1120	2	0						
	1021	6	2						
	1121	86	90						
Bypass = 186	1030	0	0	3	0	81	1	9	92
	1130	4	1						
	1031	2	9						
	1131	78	92						
Spillway = 185	1040	0	0	16	0	60	19	3	87
	1140	1	3						
	1041	7	4						
	1141	68	102						
Turbine = 54	1050	0	0	0	18	17	0	13	6
	1150	2	3						
	1051	2	1						
	1151	31	15						
Tailrace (R_c) = 587	0010	3	2						
	0011	276	306						

[a] Coding for third digit of detection history: 0 = not detected in passage route, 1 = released in tailrace, 2 = RSW passage, 3 = juvenile bypass passage, 4 = spillway passage, 5 = turbine passage.

Appendix Table A3. — Counts of detection histories of radio-tagged yearling Chinook salmon used in the route-specific survival model for deployed Behavioral Guidance Structure (BGS) treatments during the day (0515 to 2017 hours) and at night at Lower Granite Dam, 2006. The detection histories, composed of 4 digits, indicates 1) the release site (1 = Blyton Landing, 0 = tailrace), 2) whether fish were detected (1) or not detected (0) at the forebay entrance array 3) the route of passage for each fish coded from 0 to 5[a], 4) and whether fish were detected at telemetry arrays downriver of Lower Granite Dam.

				Counts of within-route histories					
BGS Deployed		Counts		Day			Night		
n for release/route	Detection history [a]	Day	Night	01	10	11	01	10	11
Blyton (R_t) = 306	1000	1	3						
	1100	0	0						
	1001	0	2						
	1101	6	5						
RSW = 94	1020	0	0						
	1120	2	0	2	7	59	0	7	19
	1021	5	1						
	1121	61	25						
Bypass = 84	1030	0	0						
	1130	2	2	0	0	42	3	0	39
	1031	1	1						
	1131	39	39						
Spillway = 76	1040	0	0						
	1140	1	0	10	0	40	6	0	20
	1041	4	3						
	1141	45	23						
Turbine = 35	1050	0	0						
	1150	1	1	0	7	8	0	11	9
	1051	1	1						
	1151	13	18						
Tailrace (R_c) = 279	0010	2	1						
	0011	190	86						

[a] Coding for third digit of detection history: 0 = not detected in passage route, 1 = released in tailrace, 2 = RSW passage, 3 = juvenile bypass passage, 4 = spillway passage, 5 = turbine passage.

Appendix Table A4. — Counts of detection histories of radio-tagged yearling Chinook salmon used in the route-specific survival model for stored Behavioral Guidance Structure (BGS) treatments during day (0515 to 2017 hours) and night at Lower Granite Dam, 2006. The detection histories, composed of 4 digits, indicates 1) the release site (1 = Blyton Landing, 0 = tailrace), 2) whether fish were detected (1) or not detected (0) at the forebay entrance array 3) the route of passage for each fish coded from 0 to 5[a], 4) and whether fish were detected at telemetry arrays downriver of Lower Granite Dam.

				Counts of within-route histories					
BGS Stored		Counts		Day			Night		
n for release/route	Detection history [a]	Day	Night	01	10	11	01	10	11
Blyton (R_t) = 337	1000	3	1						
	1100	0	4						
	1001	0	1						
	1101	1	5						
RSW = 92	1020	0	0	0	6	61	0	6	19
	1120	0	0						
	1021	1	1						
	1121	66	24						
Bypass = 102	1030	0	0	0	6	52	1	3	40
	1130	1	0						
	1031	7	2						
	1131	50	42						
Spillway = 109	1040	0	0	12	2	56	7	1	31
	1140	0	3						
	1041	2	2						
	1141	68	34						
Turbine = 19	1050	0	0	0	7	3	0	6	3
	1150	3	0						
	1051	0	1						
	1151	7	8						
Tailrace (R_c) = 308	0010	2	0						
	0011	202	104						

[a] Coding for third digit of detection history: 0 = not detected in passage route, 1 = released in tailrace, 2 = RSW passage, 3 = juvenile bypass passage, 4 = spillway passage, 5 = turbine passage.

Appendix Table A5. — Counts of detection histories of radio-tagged juvenile steelhead used in the route-specific survival model for deployed and stored Behavioral Guidance Structure (BGS) treatments at Lower Granite Dam, 2006. The detection histories, composed of 4 digits, indicates 1) the release site (1 = Blyton Landing, 0 = tailrace), 2) whether fish were detected (1) or not detected (0) at the forebay entrance array 3) the route of passage for each fish coded from 0 to 5[a], 4) and whether fish were detected at telemetry arrays downriver of Lower Granite Dam.

				Counts of within-route histories					
		Counts		BGS Deployed			BGS Stored		
n for release/route	Detection history [a]	BGS Deployed	BGS Stored	01	10	11	01	10	11
Blyton (R_t) = 811	1000	1	1						
	1100	4	3						
	1001	3	4						
	1101	8	6						
RSW= 209	1020	0	0						
	1120	0	4	4	17	90	1	18	79
	1021	3	3						
	1121	108	91						
Bypass = 312	1030	0	1						
	1130	2	7	8	0	136	4	18	146
	1031	10	18						
	1131	132	142						
Spillway = 230	1040	1	0						
	1140	1	1	23	3	91	18	1	94
	1041	11	11						
	1141	104	101						
Turbine = 30	1050	0	0						
	1150	2	1	0	4	14	0	6	6
	1051	0	0						
	1151	16	11						
Tailrace (R_c) = 697	0010	2	0						
	0011	314	381						

[a] Coding for third digit of detection history: 0 = not detected in passage route, 1 = released in tailrace, 2 = RSW passage, 3 = juvenile bypass passage, 4 = spillway passage, 5 = turbine passage.

Appendix Table A6. — Counts of detection histories of radio-tagged juvenile steelhead used in the route-specific survival model for deployed Behavioral Guidance Structure (BGS) treatments during day (0515 to 2017 hours) and night at Lower Granite Dam, 2006. The detection histories, composed of 4 digits, indicates 1) the release site (1 = Blyton Landing, 0 = tailrace), 2) whether fish were detected (1) or not detected (0) at the forebay entrance array 3) the route of passage for each fish coded from 0 to 5[a], 4) and whether fish were detected at telemetry arrays downriver of Lower Granite Dam.

				Counts of within-route histories					
BGS Deployed		Counts		Day			Night		
n for release/route	Detection history [a]	Day	Night	01	10	11	01	10	11
Blyton (R_t) = 406	1000	0	1						
	1100	2	2						
	1001	1	2						
	1101	4	4						
RSW = 111	1020	0	0						
	1120	0	0	4	15	66	0	2	24
	1021	2	1						
	1121	83	25						
Bypass = 144	1030	0	0						
	1130	1	1	5	0	70	3	0	66
	1031	9	1						
	1131	65	67						
Spillway = 117	1040	1	0						
	1140	1	0	14	0	51	9	3	40
	1041	8	3						
	1141	55	49						
Turbine = 18	1050	0	0						
	1150	1	1	0	1	7	0	3	7
	1051	0	0						
	1151	7	9						
Tailrace (R_c) = 316	0010	2	0						
	0011	224	90						

[a] Coding for third digit of detection history: 0 = not detected in passage route, 1 = released in tailrace, 2 = RSW passage, 3 = juvenile bypass passage, 4 = spillway passage, 5 = turbine passage.

Appendix Table A7. — Counts of detection histories of radio-tagged juvenile steelhead used in the route-specific survival model for stored Behavioral Guidance Structure (BGS) treatments during the day (0515 to 2017 hours) and at night at Lower Granite Dam, 2006. The detection histories, composed of 4 digits, indicates 1) the release site (1 = Blyton Landing, 0 = tailrace), 2) whether fish were detected (1) or not detected (0) at the forebay entrance array 3) the route of passage for each fish coded from 0 to 5[a], 4) and whether fish were detected at telemetry arrays downriver of Lower Granite Dam.

				Counts of within-route histories					
BGS Stored		Counts		Day			Night		
n for release/route	Detection history [a]	Day	Night	01	10	11	01	10	11
Blyton (R_t) = 405	1000	1	0						
	1100	1	2						
	1001	3	1						
	1101	5	1						
RSW = 98	1020	0	0						
	1120	3	1	1	16	64	0	2	15
	1021	3	0						
	1121	75	16						
Bypass = 168	1030	0	1						
	1130	2	5	1	10	65	3	8	81
	1031	11	7						
	1131	63	79						
Spillway = 113	1040	0	0						
	1140	1	0	13	0	59	5	1	35
	1041	4	7						
	1141	67	34						
Turbine = 12	1050	0	0						
	1150	0	1	0	4	3	0	2	3
	1051	0	0						
	1151	7	4						
Tailrace (R_c) = 381	0010	0	0						
	0011	255	126						

[a] Coding for third digit of detection history: 0 = not detected in passage route, 1 = released in tailrace, 2 = RSW passage, 3 = juvenile bypass passage, 4 = spillway passage, 5 = turbine passage.

Appendix Table A8. — Counts of detection histories of radio-tagged subyearling Chinook salmon used in the route-specific survival model for RSW operating with 1-and 4-stop spill configurations at Lower Granite Dam, 2006. The detection histories, composed of 4 digits, indicates 1) the release site (1 = Blyton Landing, 0 = tailrace), 2) whether fish were detected (1) or not detected (0) at the forebay entrance array 3) the route of passage for each fish coded from 0 to 5[a], 4) and whether fish were detected at telemetry arrays downriver of Lower Granite Dam.

				Counts of within-route histories					
		Counts		RSW/1-Stop			RSW/4-Stops		
n for release/route	Detection history [a]	RSW/1-Stop	RSW/4-Stops	01	10	11	01	10	11
Blyton (R_t) = 886	1000	34	39						
	1100	14	23						
	1001	9	6						
	1101	6	6						
RSW= 442	1020	1	0						
	1120	15	22	2	15	208	2	23	192
	1021	43	26						
	1121	166	169						
Bypass = 182	1030	5	4						
	1130	9	10	1	7	73	0	3	98
	1031	12	12						
	1131	55	75						
Spillway = 81	1040	2	2						
	1140	4	3	4	0	20	5	0	52
	1041	3	9						
	1141	15	43						
Turbine = 44	1050	0	2						
	1150	5	3	1	3	11	3	8	18
	1051	0	4						
	1151	10	20						
Tailrace (R_c) = 574	0010	13	5						
	0011	303	253						

[a] Coding for third digit of detection history: 0 = not detected in passage route, 1 = released in tailrace, 2 = RSW passage, 3 = juvenile bypass passage, 4 = spillway passage, 5 = turbine passage.

Appendix Table A9. — Counts of detection histories of radio-tagged subyearling Chinook salmon used in the route-specific survival model for the 1-stop Removable Spillway Weir (RSW) treatment during the day (0502 to 2046 hours) and at night at Lower Granite Dam, summer 2006. The detection histories, composed of 4 digits, indicates 1) the release site (1 = Blyton Landing, 0 = tailrace), 2) whether fish were detected (1) or not detected (0) at the forebay entrance array 3) the route of passage for each fish coded from 0 to 5[a], 4) and whether fish were detected at telemetry arrays downriver of Lower Granite Dam.

RSW/1 stop		Counts		Counts of within-route histories					
				Day			Night		
n for release/route	Detection history [a]	Day	Night	01	10	11	01	10	11
Blyton (R_t) = 408	1000	14	20						
	1100	7	7						
	1001	6	3						
	1101	4	2						
RSW = 225	1020	1	0						
	1120	15	0	1	11	170	1	4	38
	1021	35	8						
	1121	131	35						
Bypass = 81	1030	4	1						
	1130	5	4	0	5	44	1	2	29
	1031	6	6						
	1131	34	21						
Spillway = 24	1040	1	1						
	1140	3	1	1	0	18	3	0	2
	1041	1	2						
	1141	14	1						
Turbine = 15	1050	0	0						
	1150	0	5	0	0	1	1	3	10
	1051	0	0						
	1151	1	9						
Tailrace (R_c) = 316	0010	10	3						
	0011	196	107						

[a] Coding for third digit of detection history: 0 = not detected in passage route, 1 = released in tailrace, 2 = RSW passage, 3 = juvenile bypass passage, 4 = spillway passage, 5 = turbine passage.

Appendix table A10. — Counts of detection histories of radio-tagged subyearling Chinook salmon used in the route-specific survival model for RSW operating with the 4-stop spill treatment during day (0502 to 2046 hours) and night at Lower Granite Dam, 2006. The detection histories, composed of 4 digits, indicates 1) the release site (1 = Blyton Landing, 0 = tailrace), 2) whether fish were detected (1) or not detected (0) at the forebay entrance array 3) the route of passage for each fish coded from 0 to 5[a], 4) and whether fish were detected at telemetry arrays downriver of Lower Granite Dam.

RSW/4 stops		Counts		Counts of within-route histories					
				Day			Night		
N for release/route	Detection history [a]	Day	Night	01	10	11	01	10	11
Blyton (R_t) = 478	1000	18	21						
	1100	14	9						
	1001	3	3						
	1101	2	4						
RSW = 217	1020	0	0	2	16	148	0	7	44
	1120	16	6						
	1021	20	6						
	1121	130	39						
Bypass = 101	1030	4	0	0	1	53	0	2	45
	1130	2	8						
	1031	5	7						
	1131	43	32						
Spillway = 57	1040	1	1	2	0	31	3	0	21
	1140	0	3						
	1041	5	4						
	1141	27	16						
Turbine = 29	1050	1	1	0	5	4	3	3	14
	1150	1	2						
	1051	0	4						
	1151	7	13						
Tailrace (R_c) = 258	0010	3	2						
	0011	196	57						

[a] Coding for third digit of detection history: 0 = not detected in passage route, 1 = released in tailrace, 2 = RSW passage, 3 = juvenile bypass passage, 4 = spillway passage, 5 = turbine passage.

Appendix B - Tag Life Study

Introduction

We conducted a tag-life study to test assumption seven that all tags are correctly identified and marks are not lost during the study. In the case of radio telemetry, when a transmitter fails the mark is essentially lost. Significant premature failure of transmitters can negatively bias survival estimates, since survival models will interpret tag failure as mortality. However, if the rate of tag failure is known, survival estimates can be adjusted to correct for tag failure (Townsend et al. 2006; Cowen and Schwartz 2005). Therefore, it is important to conduct a tag life study as a measure of insurance. If a tag life study is not conducted, there is little recourse for accurately adjusting survival estimates after conducting a study and finding that tags failed prematurely. Premature tag failure may occur through a number of mechanisms including batch-specific manufacturer defects or long travel times of fish due to low discharge. Thus it is important to conduct a tag life study using a random sub-sample of transmitters that will be implanted in fish and under ambient field conditions during the study period. We used the methods of Townsend et al. (2006) to achieve the following goals of the tag life study 1) estimate the probability that a tag was alive at any point in time after it was turned on, 2) estimate the probability of tags being in the study area at any given point in time after release, and 3) estimate the average probability of a tag being alive when passing downstream telemetry arrays. Given this information, we then determined whether the tag failure rate was high enough to warrant correction of survival estimates.

Methods

The tag life study was conducted in situ during the study period of radio-telemetry releases in the spring and summer at Lower Granite Dam during 2006 which will be used for survival evaluations at Little Goose and Lower Granite Dams. Prior to conducting the tag life study, we randomly selected 50 model NTC-3-1 tags (used with yearling Chinook salmon and juvenile steelhead), and 46 model NTC-M-2 tags (used with subyearling Chinook salmon) from the tags to be used for the survival study. The tags were held in large (approximately 4-ft diameter) circular tanks at the Lower Granite Dam and supplied with a constant flow of ambient river water. At the beginning of the spring and summer survival studies, one-third of the transmitters were turned on, the date and time was recorded, and the tags were placed inside small perforated aluminum garbage cans to shield the signal. Another one-third of the tags were turned on midway through the survival study, and the remaining tags were turned on in the latter portion of the season. Tags were monitored with a Lotek SRX data logging receiver until all tags ceased operation.

Next, we estimated the probability of a tag being alive at any given point in time. The lifetime of each tag was calculated as the elapsed time between the time the tag was turned on and the time of the last detection recorded by the data-logging receiver. Any tag that ceased operation in <1 d was excluded from the analysis because we normally discover tags that malfunction within the 24-h recovery period of tagged fish. We then fit a survival distribution function to the tag life data to estimate the probability of a tag operating for a given amount of time. Although many forms of survival distribution functions can be fit to this data, we chose to use the Gompertz distribution (Elandt-Johnson and Johnson 1980, Townsend et al. 2006) as this distribution fit the tag life data well. The Gompertz survival distribution function takes the form

$$S(t) = e^{\frac{\beta}{\alpha}\left(1-e^{\alpha t}\right)}$$

where $S(t)$ is the probability of a tag surviving to time t, and α and β are parameters to be estimated by fitting the model to the tag life data. We used nonlinear least squares methods to fit the Gompertz survival distribution function to the empirical tag survival data. The empirical survival distribution function is simply the proportion of tags surviving to time t.

The probability that a tag is alive when it arrives at a detection array is dependent on the travel time of the tag to each detection array used in the survival analysis. For the route specific survival model, the travel times of interest are from time of release of the treatment group to the time of detection at Lower Granite Dam, and from the release of both treatment and control groups to the time of first detection at any one of the downriver arrays used for survival analysis. In addition to fish travel time, the travel time of the tag must include all elapsed time that the transmitter was operating prior to fish release. Therefore, we recorded dates and times of all instances where transmitters were turned on or off, calculated the total elapsed time, and added this to the travel time of fish to each detection array. We then plotted the empirical cumulative travel time distribution, which is simply the proportion of fish arriving at a given detection array at time *t*, against the survival distribution function to understand whether most fish passed the detection arrays prior to tag failure.

To quantify the rate of tag failure we calculated the average probability that the tag was operational for the *i*th release group to the *j*th detection array (Townsend et al. 2006):

$$\hat{P}(L_{ij}) = \frac{1}{k_{ij}} \sum_{x=1}^{k_{ij}} \hat{S}(t_{ijx})$$

Where $\hat{P}(L_{ij})$ = average probability that a tag is alive at the *j*th detection array (1 = Lower Granite Dam, 2 = first detection at any downriver array) from the *i*th release group (1 = treatment released at Blyton Landing, 2 = control released in the Lower Granite Dam tailrace).

$\hat{S}(h_{ijx})$ = the estimated probability that a tag is alive at time t_{ijx} for the *x*th fish arriving at the *j*th detection array for the *i*th release group. $\hat{S}(h_{ijx})$ is calculated simply by substituting into the survival distribution function the travel time of each tag to each detection array.

k_{ij} = the total number of fish detected at the *j*th detection array for the *i*th release group.

Results

For spring, two tags expired prematurely around days eight and ten. This tag-life is much less than the minimum tag-life (16 days) specified by the manufacturer (Lotek). Most tags expired between days 16 and 20; all tags were expired after 21 days (Appendix Figure B1). For the summer tag-life study, the majority of radio-tags (model NTC-M-2) began to fail between 18-24 days and continued to day 27. There were three tags that expired prematurely (<16 days) one expiring at day 4, day 8, and one after 12 days (Appendix Table B1).

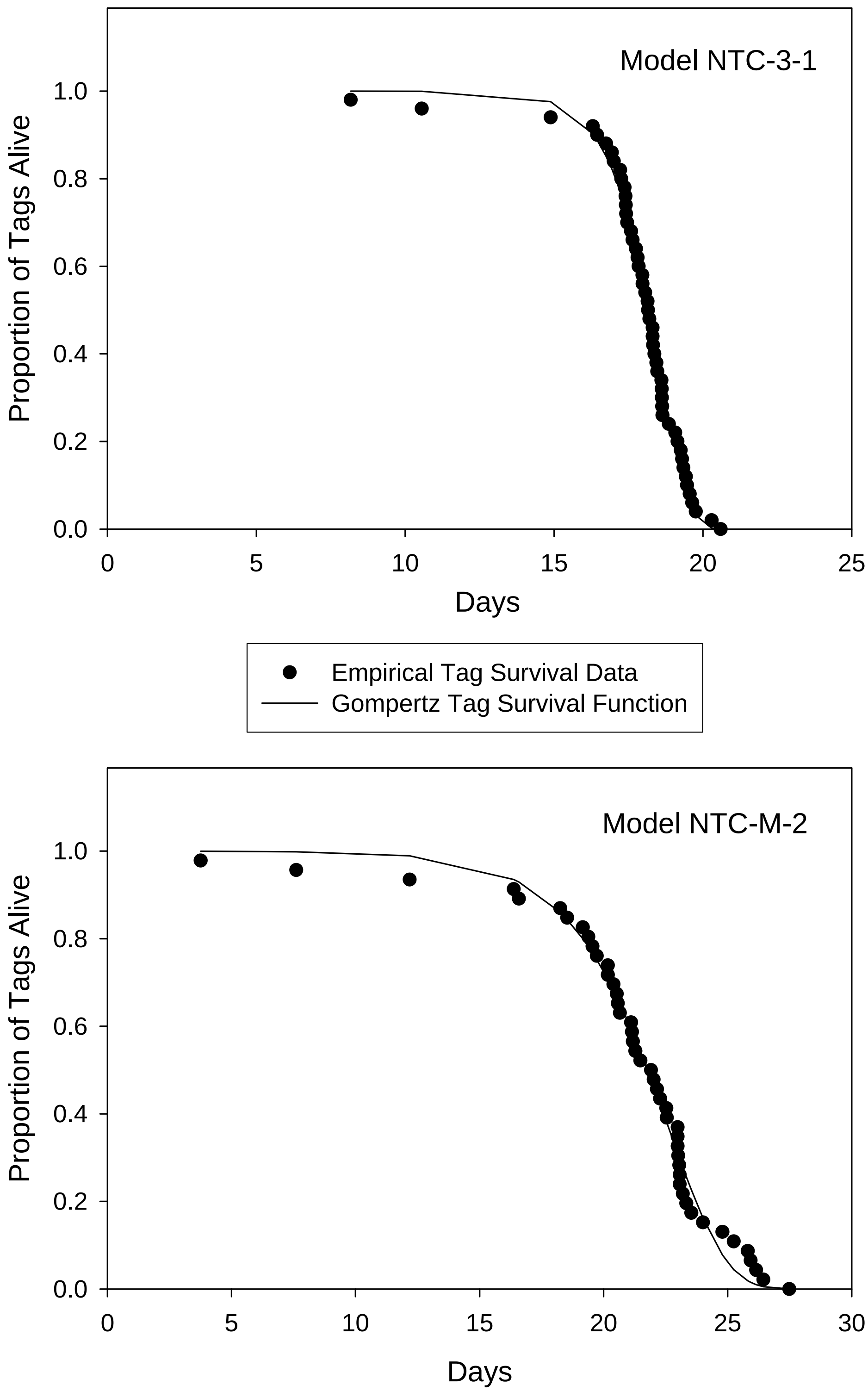
The empirical tag-life data for spring and summer was used for generating model parameters of the Gompertz distribution and calculating probabilities radio-tags were alive at detection arrays. Our tag-life data fit well with the Gompertz distribution for both the spring and summer tag-life studies allowing us to use this model for calculating probabilities (Appendix Figure B2).

Appendix Table B1. — Descriptive statistics of transmitter life (d) measured during tag life studies conducted at Lower Granite Dam during the 2006 study periods. Transmitter model NTC-3-1 was used in yearling Chinook salmon and juvenile steelhead; model NTC-M-2 was used in subyearling Chinook salmon. Also shown are the parameter estimates for α and β from fitting the Gompertz survival distribution function to the tag life data.

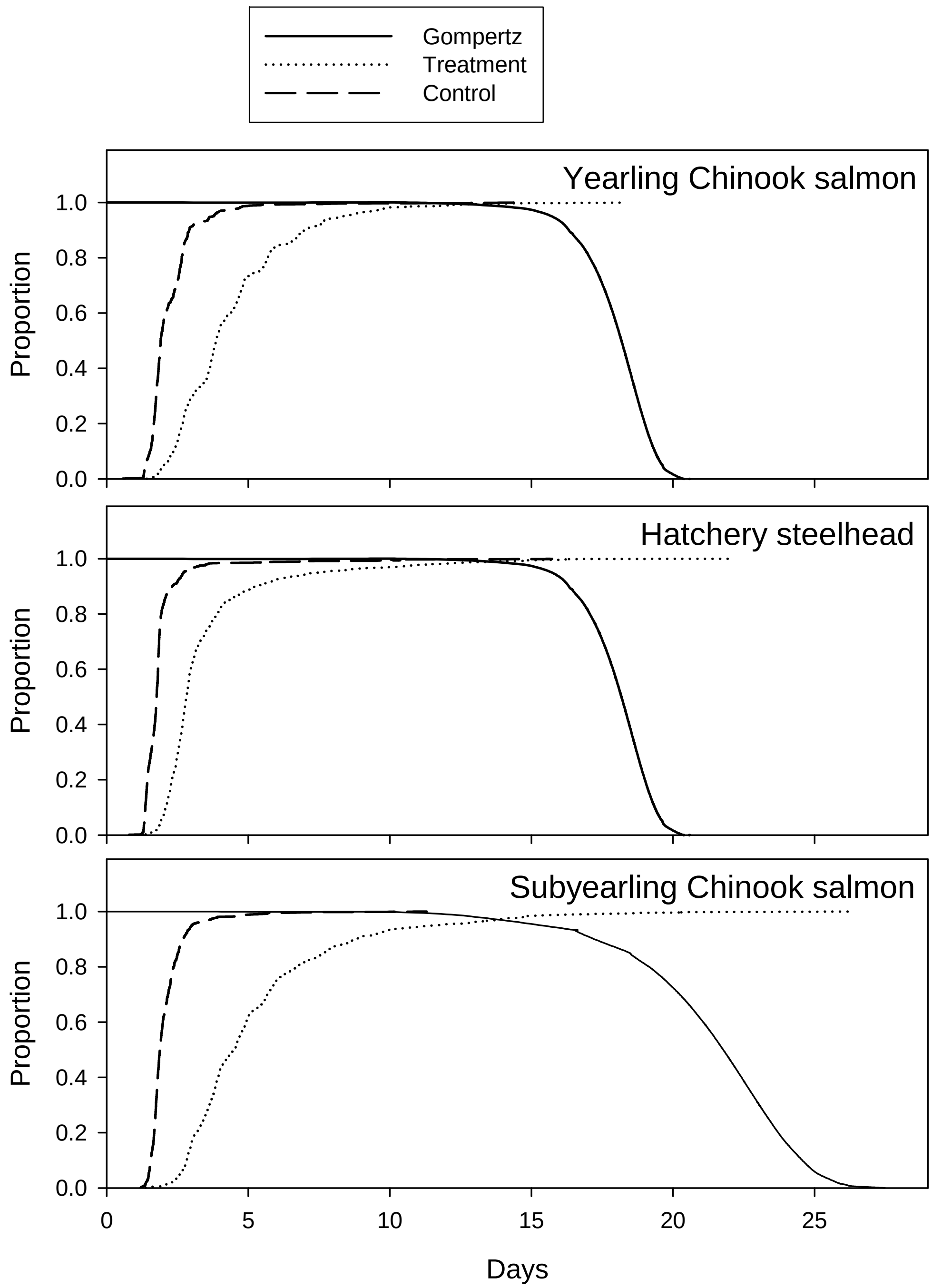
Transmitter model	Number of tags	Mean tag-life (SD)	Min. tag-life	Max. tag-life	α	β
NTC-3-1	50	17.9 (2.06)	8.1	20.6	1.0195	6.30×10^{-9}
NTC-M-2	46	21.1 (4.38)	3.8	27.5	0.4329	2.42×10^{-5}

By comparing the survival distribution function to the cumulative travel time distributions of the transmitters, we found that nearly all transmitters passed detection arrays before tag failure became substantial, especially for yearling Chinook salmon and juvenile steelhead (Appendix Table B2). For subyearling Chinook salmon, most arrived at downstream survival arrays before substantial tag failure occurred, however, several fish released above the dam (treatment) arrived near the time threshold where substantial tag failure occurs.

Townsend et al. (2006) found that the probability of a tag being operational at downstream detection arrays was quite high (>98%), therefore, the adjusted survival estimate (0.9387) changed very little from the unadjusted estimate (0.9339) having a difference of just 0.0048. Our probabilities being greater than this indicates our survival estimates would change even less after correction; therefore we did not adjust our estimates.



Appendix Figure B1. — The Gompertz survival distribution function fit to the tag-life data from tag life studies conducted during the spring (model NTC-3-1) and summer (model NTC-M-2) at Lower Granite Dam during 2006.



Appendix Figure B2. — Cumulative travel time distributions at downstream arrays for the Lower Granite Dam survival evaluation, 2006, compared with the tag survival function. Transmitter model NTC-3-1 was used in yearling Chinook salmon and juvenile steelhead and model NTC-M-2 was used in subyearling Chinook salmon. Travel time distributions include the total elapsed time that the transmitter was operational prior to the release of the fish.

Appendix Table B2. — Mean probability of transmitters being operational when passing telemetry arrays used to calculate survival at Lower Granite Dam during 2006.

Species	Reach	Mean (SD)
Yearling Chinook salmon	Blyton Landing to dam	0.9999 (0.0020)
	Blyton Landing to downriver arrays	0.9990 (0.0195)
	Tailrace to downriver arrays	1.000 (0.0009)
Juvenile steelhead	Blyton Landing to dam	0.9998 (0.0037)
	Blyton Landing to downriver arrays	0.9985 (0.0305)
	Tailrace to downriver arrays	0.9999 (0.0020)
Subyearling Chinook salmon	Blyton Landing to dam	0.9994 (0.0073)
	Blyton Landing to downriver arrays	0.9950 (0.0445)
	Tailrace to downriver arrays	0.9999 (0.0003)

Appendix C - Study Summary

Year: 2006

Study Site:

Lower Granite Lock and Dam (rkm 173) and the surrounding reservoir from 67 rkm to 192.4 rkm.

Study Objectives:

Assess fish passage relative to spill, powerhouse, RSW, and BGS operations. Estimate route specific survival for juvenile salmonids. Determine how BGS treatments, spill treatments and dam operations affect fish behavior, passage and survival at Lower Granite Dam.

Fish:

Species:

Yearling hatchery spring Chinook salmon (*Oncorhynchus tshawytcha*), juvenile steelhead (*O. mykiss*), and hatchery and wild subyearling Chinook salmon (*O. tshawytcha*).

Source:

Fish were obtained from the Juvenile Fish Facility sampled by the Washington Department of Fish and Wildlife at Lower Granite Dam.

Size:

Summary statistics of fork length (mm) and weight (g) for radio-tagged yearling Chinook salmon, juvenile steelhead, and subyearling Chinook salmon tagged at Lower Granite Dam during 2006.

Species	Release group	N	Length (mm)			Weight (g)		
			Mean	SD	Range	Mean	SD	Range
Yearling Chinook salmon	Control	653	136.6	9.3	112-167	25.5	5.3	14.7-45.0
	Treatment	964	137.9	9.5	113-169	26.3	5.6	15.0-47.0
	Sacrifice	50	136.9	9.4	111-155	25.8	5.3	15.0-39.0
Juvenile steelhead	Control	749	216.2	19.9	162-283	92.5	26.6	33.2-200.6
	Treatment	1163	216.6	19.8	164-275	93.1	27.3	34.8-201.4
	Sacrifice	49	216.7	19.2	163-255	92.5	25.8	38.0-142.4

Species	Release group	N	Length (mm)			Weight (g)		
			Mean	SD	Range	Mean	SD	Range
Subyearling Chinook salmon	Control	818	112.0	6.7	98-140	14.4	3.0	10.0-30.6
	Treatment	1196	111.4	6.9	97-140	14.0	2.8	10.0-26.8
	Sacrifice	49	111.0	7.2	102-129	13.5	2.9	10.1-22.1

Tag:

Season	Type	Model	Weight (g)
Spring	Radio	NTC-3-1	0.64
Summer	Radio	NTC-M-2	0.43
Spring and summer	PIT	TX1411BE	0.07

Implant procedure:

Surgical

Survival Estimate:

Value & SE:

Summary of estimated survival, passage probability, and standard errors for radio-tagged yearling Chinook salmon at Lower Granite Dam during, spring 2006.

	BGS Stored		BGS Deployed		Overall	
Parameters	Probability	SE	Probability	SE	Probability	SE
S *pool*	0.989	0.006	0.987	0.006	0.988	0.004
S *forebay*	0.991	0.007	0.999	0.004	0.996	0.003
S *dam*	0.967	0.012	0.966	0.014	0.975	0.008
S *spillway*	0.970	0.018	0.985	0.019	0.982	0.013
S *RSW*	0.985	0.016	0.979	0.019	0.992	0.010
S *turbines*	0.815	0.086	0.935	0.042	0.909	0.039
S *bypass*	0.987	0.014	0.951	0.026	0.976	0.014
λ	0.994	0.005	0.989	0.006	0.991	0.004
Pr spillway	0.331	0.026	0.253	0.025	0.294	0.018
Pr RSW	0.281	0.006	0.312	0.010	0.295	0.006
Pr turbine	0.081	0.016	0.158	0.021	0.117	0.013
Pr bypass	0.308	0.025	0.277	0.026	0.294	0.018

Summary of estimated survival, passage probability, and standard errors for radio-tagged juvenile steelhead at Lower Granite Dam during, spring 2006.

	BGS Stored		BGS Deployed		Overall	
Parameters	Probability	SE	Probability	SE	Probability	SE
S *pool*	0.998	0.002	0.998	0.002	0.998	0.002
S *forebay*	0.994	0.005	0.990	0.005	0.992	0.004
S *dam*	0.958	0.011	0.981	0.009	0.976	0.007
S *spillway*	0.985	0.013	0.989	0.013	0.991	0.008
S *RSW*	0.952	0.022	0.989	0.013	0.981	0.011
S *turbines*	0.879	0.082	0.875	0.072	0.900	0.049
S *bypass*	0.955	0.017	0.986	0.013	0.972	0.010
λ	0.997	0.003	0.994	0.004	0.996	0.002
Pr spillway	0.282	0.022	0.295	0.024	0.288	0.016
Pr RSW	0.245	0.003	0.285	0.004	0.263	0.002
Pr turbine	0.058	0.012	0.063	0.018	0.060	0.009
Pr bypass	0.416	0.025	0.357	0.024	0.389	0.017

Summary of estimated survival, passage probability, and standard errors for radio-tagged subyearling Chinook salmon at Lower Granite Dam during, summer 2006.

	1 stop		4 stops		Overall	
Parameters	Probability	SE	Probability	SE	Probability	SE
S *pool*	0.926	0.014	0.928	0.013	0.927	0.009
S *forebay*	0.958	0.012	0.941	0.013	0.949	0.009
S *dam*	0.918	0.021	0.906	0.018	0.914	0.014
S *spillway*	0.844	0.073	0.934	0.039	0.894	0.040
S *RSW*	0.969	0.021	0.916	0.023	0.945	0.016
S *turbines*	0.683	0.121	0.872	0.063	0.846	0.054
S *bypass*	0.863	0.045	0.882	0.036	0.875	0.028
λ	0.959	0.011	0.977	0.009	0.967	0.007
Pr spillway	0.108	0.017	0.137	0.017	0.104	0.011
Pr RSW	0.620	0.004	0.522	0.007	0.568	0.005
Pr turbines	0.049	0.012	0.099	0.015	0.094	0.011
Pr bypass	0.223	0.022	0.242	0.021	0.234	0.015

Analytical Model:

Route –specific survival model

Environmental/Operating conditions:

Relevant discharge indices:

Discharge for Lower Granite during spring and summer 2006 (all values in kcfs).

Season	Treatment	Dam area	Mean	Median	Minimum	Maximum	STD
Spring	BGS stored	Project	134.8	129.2	91.0	184.5	19.0
		Spillway	51.2	45.0	8.4	100.1	18.6
		RSW	6.7	6.7	0.0	6.8	0.2
		Powerhouse	83.6	84.5	58.3	86.9	3.1
	BGS deployed	Project	139.0	134.9	87.2	204.1	29.4
		Spillway	56.1	50.2	6.9	100.1	28.8
		RSW	6.7	6.7	6.6	6.7	0.1
		Powerhouse	82.8	84.2	61.8	88.8	3.8
Summer	1-stop	Project	54.7	49.5	31.2	109.5	16.9
		Spillway	18.4	17.9	17.1	39.7	1.4
		RSW	6.7	6.7	6.7	6.8	0.1
		Powerhouse	36.2	31.7	13.3	83.2	16.0
	4-stops	Project	54.6	51.2	31.3	94.2	16.5
		Spillway	18.7	18.3	15.3	39.8	1.6
		RSW	6.7	6.7	6.7	6.8	0.1
		Powerhouse	35.9	32.7	13.2	73.9	16.0

Forebay and tailrace elevations (ft) at Lower Granite during spring and summer 2006.

Season	Treatment	Dam area	Mean	Median	Minimum	Maximum	STD
Spring	BGS stored	Forebay	733.4	733.4	732.9	734.2	0.2
		Tailrace	636.1	635.8	634.5	638.5	0.7
	BGS deployed	Forebay	733.4	733.3	732.9	733.9	0.2
		Tailrace	636.2	635.9	634.2	639.5	1.2
Summer	1-stop	Forebay	733.5	733.5	732.9	734.0	0.2
		Tailrace	633.4	633.2	631.9	635.6	0.6
	4-stops	Forebay	733.4	733.4	732.9	734.0	0.2
		Tailrace	633.3	633.2	632.0	635.3	0.6

Temperature & TDG:

Summary stats for temperature and total dissolved gas during spring and summer 2006.

Season	Measurement	Mean	Median	Minimum	Maximum	SD
Spring	Temperature	11.8	11.9	8.4	14.9	1.65
	TDG	105.8	105.8	103.0	110.0	1.41
Summer	Temperature	18.0	19.3	13.0	21.1	2.20
	TDG	102.9	103.0	99.0	106.5	1.38

Treatment(s):

Randomized block treatments for spring and summer 2006.

Date	Block	Treatment	Date	Block	Treatment
17-Apr	1	BGS In	8-May	5	BGS Out
18-Apr	1	BGS In	9-May	5	BGS Out
19-Apr	1	Move Out	10-May	5	Move In
20-Apr	1	BGS Out	11-May	5	BGS In
21-Apr	1	BGS Out	12-May	5	BGS In
22-Apr	2	Move In	13-May	6	BGS In
23-Apr	2	BGS In	14-May	6	BGS In
24-Apr	2	BGS In	15-May	6	Move Out
25-Apr	2	Move Out	16-May	6	BGS Out
26-Apr	2	BGS Out	17-May	6	BGS Out
27-Apr	2	BGS Out	18-May	7	BGS Out
28-Apr	3	BGS Out	19-May	7	BGS Out
29-Apr	3	BGS Out	20-May	7	Move In
30-Apr	3	Move In	21-May	7	BGS In
1-May	3	BGS In	22-May	7	BGS In
2-May	3	BGS In	23-May	8	BGS In
3-May	4	BGS In	24-May	8	BGS In
4-May	4	BGS In	25-May	8	Move Out
5-May	4	Move Out	26-May	8	BGS Out
6-May	4	BGS Out	27-May	8	BGS Out
7-May	4	BGS Out			

8-Jun	1	1-Stop	28-Jun	11	4-Stops
9-Jun	1	4-Stops	29-Jun	11	1-Stop
10-Jun	2	4-Stops	30-Jun	12	4-Stops
11-Jun	2	1-Stop	1-Jul	12	1-Stop
12-Jun	3	4-Stops	2-Jul	13	1-Stop
13-Jun	3	1-Stop	3-Jul	13	4-Stops
14-Jun	4	1-Stop	4-Jul	14	1-Stop
15-Jun	4	4-Stops	5-Jul	14	4-Stops
16-Jun	5	1-Stop	6-Jul	15	4-Stops
17-Jun	5	4-Stops	7-Jul	15	1-Stop
18-Jun	6	4-Stops	8-Jul	16	1-Stop
19-Jun	6	1-Stop	9-Jul	16	4-Stops
20-Jun	7	1-Stop	10-Jul	17	1-Stop
21-Jun	7	4-Stops	11-Jul	17	4-Stops
22-Jun	8	1-Stop	12-Jul	18	1-Stop
23-Jun	8	4-Stops	13-Jul	18	4-Stops
24-Jun	9	4-Stops	14-Jul	19	1-Stop
25-Jun	9	1-Stop	15-Jul	19	4-Stops
26-Jun	10	4-Stops	16-Jul	20	4-Stops
27-Jun	10	1-Stop	17-Jul	20	1-Stop