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Survival of Juvenile Salmonids Passing through Bypass Systems, Turbines, and Spillways with and without Flow Deflectors at Snake River Dams

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Abstract.—Using yearling chinook salmon *Oncorhynchus tshawytscha* and steelhead *O. mykiss* tagged with passive integrated transponders (PITs), we estimated passage survival through bypass systems, turbines, and spill bays with and without flow deflectors at Snake River dams relative to survival of fish released into the tailrace below the dam. Actively migrating fish were collected and marked with PIT tags at Snake River dam smolt collection facilities. Groups of tagged fish were then released through hoses into different passage routes; releases were coincident with a tailrace release approximately 1–2 km below the dam. Relative survival was estimated by the use of tag–recapture models for paired releases from detections of individual PIT-tagged fish at juvenile collection or detection facilities at downstream dams. Detection sites included Little Goose, Lower Monumental, McNary, John Day, and Bonneville dams, depending on the release location and year. Standard errors of relative survival probability estimates were generally less than 3.0% through all potential passage routes. The estimated relative survival was highest through spill bays without flow deflectors (98.4–100%), followed by spill bays with flow deflectors (92.7–100%), bypass systems (95.3–99.4%), and turbines (86.5–93.4%). These estimates of relative survival, which include both the direct and indirect effects of passage, are generally higher than past estimates but similar to other recent estimates determined with modern techniques under present dam configurations and operating conditions.

Up-to-date estimates of the survival of juvenile salmonids (smolts) passing through juvenile bypass systems, turbines, and spillways at main-stem dams on the Snake and Columbia rivers are needed to determine the optimal operations to maximize smolt survival. Many present operational decisions are based on fish passage models that use data collected many years ago with outdated techniques and under operational conditions that are no longer relevant.

Juvenile salmonid passage facilities at Lower Granite and Little Goose dams were recently upgraded to include extended submersible bar screens, modified balanced-flow vertical barrier screens, and raised operating gates. Numerous improvements have also been made within the bypass systems at these and other Snake River dams; these improvements include enlarged orifices from gate wells into bypass systems, enlarged transport flumes, fish separators, and relocated bypass outfalls (Merchant and Barila 1998). Fish guidance efficiency (FGE) research (Whitney et al. 1997) has shown that in the absence of spill, the majority of migrant yearling spring or summer chinook salmon *Oncorhynchus tshawytscha* and steelhead *O. mykiss* that enter the powerhouse turbine intakes at Snake River dams are guided into bypass systems (69–78% of yearling chinook salmon and 82–92% of steelhead).

Beginning in midseason 1994, voluntary spill has been used in an effort to increase the survival of smolts passing dams on the Snake and Columbia rivers. The spill program reduced the number of smolts passing through turbines and bypass systems and increased the number passing through spillways. Historically, high spill levels at dams caused water in tailraces below dams to become supersaturated with dissolved atmospheric gases, which decreased the survival of downstream migrant fish (Williams 1989). As a result, spillways at most dams on the Snake and Columbia rivers were retrofitted with flow deflectors to reduce entrainment of atmospheric gases. Although flow de-

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[1] U.S. National Marine Fisheries Service (USNMFS). 1995. Endangered Species Act—Section 7 Consultation. Biological opinion. Reinitiation of consultation on 1994–1998 operation of the federal Columbia River power system and juvenile transportation program in 1995 and future years. USNMFS, Northwest Region, Seattle, Washington.

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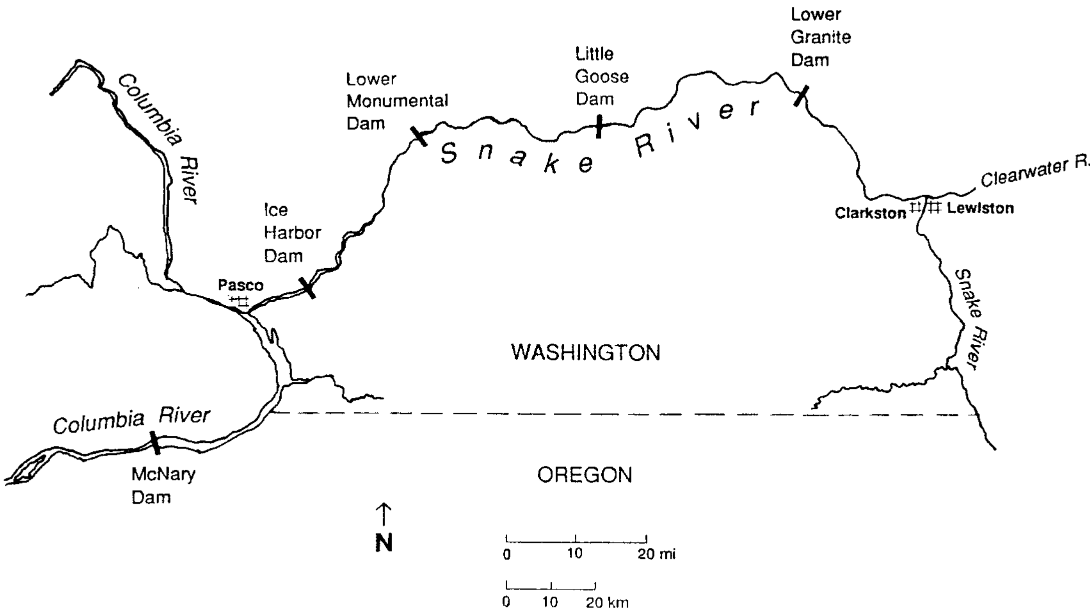

FIGURE 1.—Locations of Snake River dams (Lower Granite, Little Goose, and Lower Monumental dams) where route-specific survival was estimated in 1993–1997.

flectors were effective in reducing dissolved gas levels (Weitkamp and Katz 1980), the effects of the modified spillways on smolt survival have not been thoroughly evaluated.

Previous studies indicated that among the different passage routes through dams, direct passage survival for juvenile salmonids was generally highest for spillways, followed by bypass systems and then turbines. Spillway survival estimates have ranged from 73% to 100%, and turbine survival estimates are from 81% to 98% (Schoeneman et al. 1961; Whitney et al. 1997). Bypass survival was evaluated in only a few studies and usually not through the entire bypass system (Whitney et al. 1997). Dawley et al. (1994) reported that the overall recovery percentage of subyearling chinook salmon for bypass-released groups was 7.6% less than that for turbine-released groups and 8.3% less than that for tailrace-released groups at the Bonneville Dam Second Powerhouse over 4 years of study. However, this estimate of relative survival did not include any mortality or injury incurred before entering the collection channel (i.e., from passage along the submersible traveling screen into the gate well or passage through the orifice).

Our objective was to estimate survival through various passage routes at Snake River dams, including juvenile bypass systems, turbines, and spill bays with and without flow deflectors, and to compare the survival of dam-passage groups with fish released downstream from the dams. At Little Goose Dam in 1997, all passage routes were evaluated simultaneously, and reach survival estimates were also available (Muir et al., in press). By combining these estimates, we partitioned overall mortality estimates into reservoir- and dam-related components.

Study Site

Lower Granite, Little Goose, and Lower Monumental dams are the uppermost dams in the Snake River–Columbia River system that have passage and collection facilities for juvenile fish (Figure 1). Each of the three dams has six Kaplan turbine units (six blades) with about 30 m of head differential between forebay and tailrace that operate in flow ranges from about 340 to 623 m^3/s per turbine, eight spill bays with a capacity of about 815 m^3/s each (six with flow deflectors to reduce entrainment of atmospheric gas), and a juvenile bypass and/or collection system. Bypass systems include extended-length submersible bar screens (Lower Granite and Little Goose dams) or standard-length submersible traveling screens (Lower Monumental Dam), which guide smolts away from turbine intakes in all turbine units. Orifices in the gate wells lead to collection channels that pass smolts to the tailrace or to holding or loading facilities for eventual transport by truck or barge

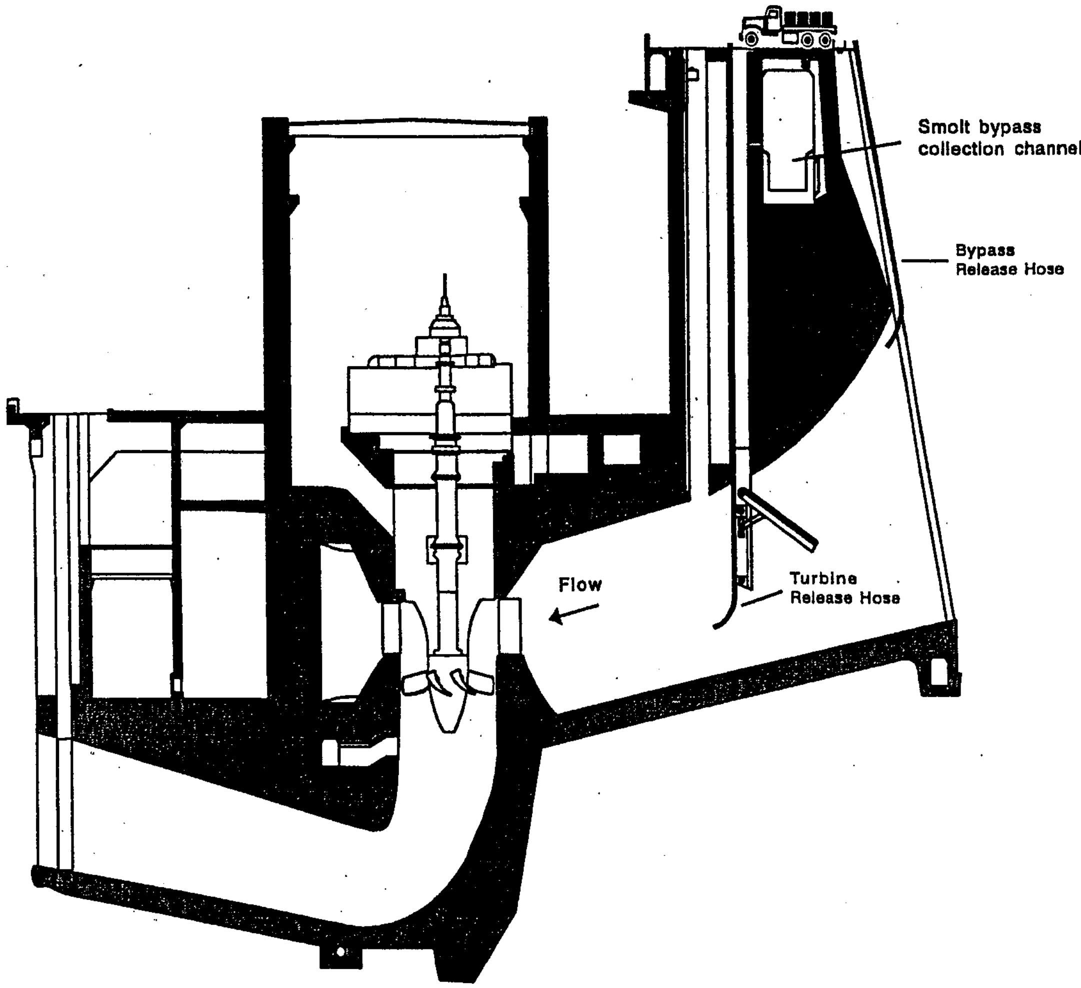

FIGURE 2.—Cross section of a typical Snake River dam turbine unit showing locations of the bypass collection channel hose, the bypass release hose, and the turbine release hose that were used for juvenile salmonid releases in 1993–1997.

(Figure 2; Matthews et al. 1977; Merchant and Barila 1998). Bypass systems at most dams on the Snake and Columbia rivers are equipped with passive integrated transponder (PIT) tag detection systems, where fish are passively interrogated for PIT tags as they pass (Prentice et al. 1990b; Muir et al., in press).

Methods

Tagging procedures.—Actively migrating fish were collected for PIT tagging (Prentice et al. 1990a) at Snake River dam juvenile collection facilities. We used only fish clearly identifiable as hatchery-reared (i.e., fin-clipped) yearling chinook salmon or steelhead that were not previously PIT tagged. Fish were transferred in water from the collection tank or raceway into a preanesthetizer (tricaine methanesulfonate [MS-222]), sorted, and PIT tagged by the use of 12-gauge hypodermic syringes (Prentice et al. 1990c). Fish were sorted and tagged in recirculating MS-222 anesthetic systems. Emptied syringes were sterilized in ethyl alcohol for a minimum of 10 min before reloading with tags. Groups of fish for paired releases were generally tagged simultaneously, and tagging personnel were rotated among tagging stations when half of each release group was tagged. Tagged fish were transferred through water-filled pipes to 1,300-L aluminum tanks mounted on trucks. The tanks were supplied with flow-through water for a minimum 24-h recovery period from anesthesia and to determine post-tagging mortality. The tanks

TABLE 1.—Test conditions and equipment for estimating survival through turbines, bypass systems, and spillways at Lower Granite (LGR), Little Goose (LGO), and Lower Monumental (LMO) dams in 1993–1997.

Release location	Dam	Year	Species	Release hose	Locations and conditions
Spillway	LGR	1996	Steelhead	10.2 cm × 24.3 m	Bay 1, 110 m^3/s
(no deflector)	LGO	1997	Steelhead	10.2 cm × 21 m	Bay 1, 139–283 m^3/s
	LMO	1994	Yearling chinook	7.6 cm × 24.4 m	Bay 8, 125–136 m^3/s
Spillway	LGO	1993	Yearling chinook	7.6 cm × 25.0 m	Bay 3, 108 m^3/s
(deflector)	LGO	1997	Steelhead	10.2 cm × 21 m	Bay 3, 139–283 m^3/s
	LMO	1994	Yearling chinook	7.6 cm × 24.4 m	Bay 7, 125–136 m^3/s
Bypass	LGR	1994	Yearling chinook	7.6 cm × 12.2 m	Unit 6A, collection channel
	LGR	1995	Yearling chinook	7.6 cm × 12.2 m	Unit 6A, collection channel
	LGR	1995	Steelhead	7.6 cm × 12.2 m	Unit 6A, collection channel
	LGO	1994	Yearling chinook	7.6 cm × 12.4 m	Unit 6C, collection channel
	LGO	1995	Steelhead	7.6 cm × 12.4 m	Unit 6C, collection channel
	LGO	1997	Steelhead	10.2 cm × 27.4 m	Unit 6B, trash rack
	LMO	1995	Yearling chinook	7.6 cm × 23.8 m	Unit 6C, collection channel
	LMO	1995	Steelhead	7.6 cm × 23.8 m	Unit 6C, collection channel
Turbine	LGR	1995	Yearling chinook	10.2 cm × 53.3 m	Unit 4B, 135 MW
	LGO	1993	Yearling chinook	7.6 cm × 30.5 m	Unit 6B, 135 MW
	LGO	1997	Steelhead	10.2 cm × 56.4 m	Unit 6B, 135 MW
	LMO	1994	Yearling chinook	10.2 cm × 53.3 m	Unit 6B, 135 MW

were aerated with oxygen during transport to release sites. Holding density did not exceed 750 fish per tank. Prerelease mortality (handling and tagging mortality combined) averaged less than 1.0%. Before release, PIT tag data files for each group were uploaded to the PIT Tag Information System (PTAGIS) maintained by the Pacific States Marine Fisheries Commission.

Release procedures.—After the minimum recovery period, fish for turbine, bypass system, and spillway releases were transported in their tanks to the designated release areas on the forebay deck and released via hoses into their respective passage routes (Table 1; Figure 3). For all hose releases, sufficient water was added to ensure that all fish exited the hose at the time of release. All fish were released during daylight hours. To stabilize conditions, spill pattern, flow level, and powerhouse loading were kept constant for 30 min before beginning and 30 min after completing all releases. However, the total discharge, volume of spill, and number of turbine units operating varied among releases.

Turbine-release groups were released through a hose attached to the bottom of the submersible traveling screen or extended-length bar screen (Figure 2). The end of the hose passed through a gently sweeping (61-cm radius) 90° bracket that directed fish into the center of the turbine intake below the screen. At Lower Granite Dam in 1995, turbine-release groups were held and released from 120-L plastic containers (rather than from tanks) at hourly intervals throughout the day by means of the release system and turbine hose used by RMC Environmental Services for turbine survival research with balloon-tagged fish (Normandeau Associates, Inc., et al. 1995).

Bypass-release groups were released either through a hose directly into the collection channel (1993–1995 at all three dams) or through a gently sweeping (61-cm radius) 90° bracket attached to the first trash rack section, where fish were guided into the bypass system by the bar screen (1997 at Little Goose Dam).

Spillway-release groups were released through a hose mounted to the center of each spill bay, either through a bracket mounted on the Tainter gate (1993–1994 at Little Goose and Lower Monumental dams) or through a steel tube anchored to the upstream wall of the spill bay (1997 at Little Goose Dam). During evaluations of spill bays with and without flow deflectors, flow was kept equal between the two spill bays during releases; spill level was dependent on total project discharge. Spillway-release groups at Lower Granite Dam (1996) were released at the terminus of a prototype surface bypass collector connected to Spill Bay 1, which did not have a flow deflector.

Tailrace-release groups were transferred through a hose to partially filled 1,300-L tanks mounted on a barge. The tanks were supplied with either oxygen or flow-through water during transport to a release site in the tailrace 1–2 km downstream from the dam (Figure 3). Tailrace-release groups were timed to best match arrival times at downstream dams with fish released through other passage routes.

To minimize effects on relative survival, release

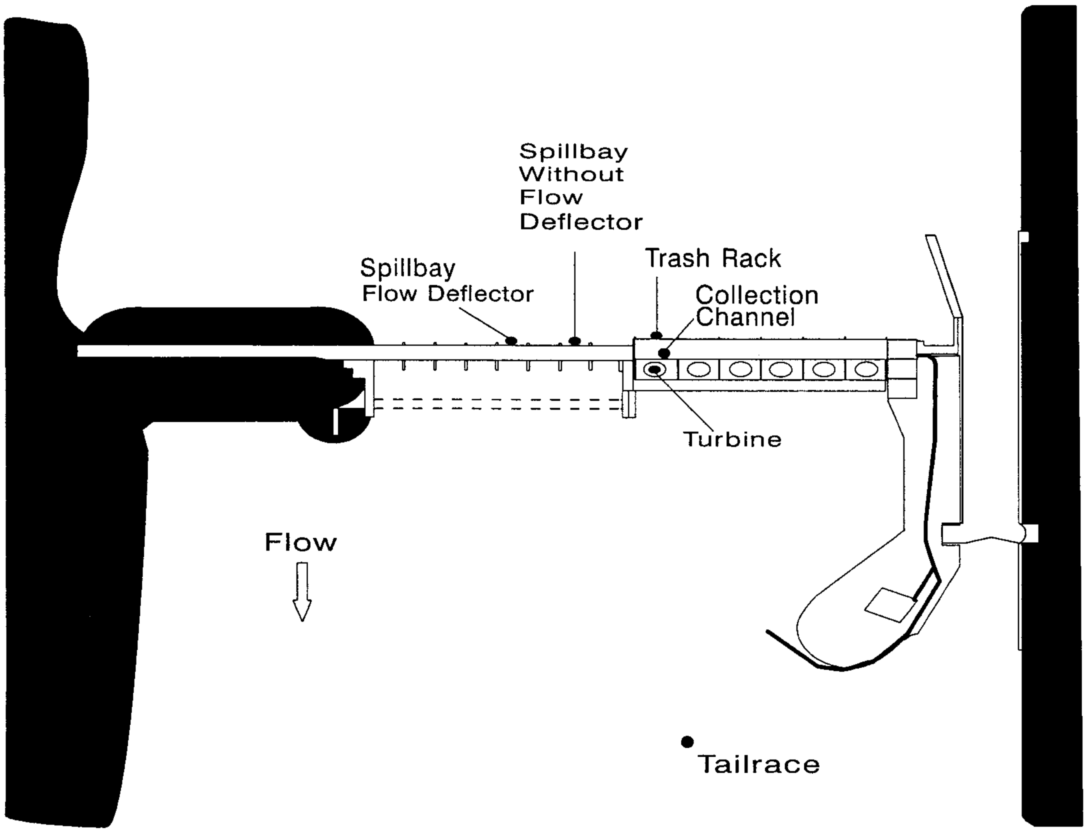

FIGURE 3.—Release sites at Little Goose Dam on the Snake River where route-specific survival was estimated from 1993 through 1997.

procedures for all groups were standardized as much as possible. The holding tanks were the same size, fish densities in tanks were the same, release hoses (including those for tailrace groups) were of the same diameter (but different lengths), flow-through water was provided during holding, and oxygen was provided during transport to release sites. Any fish that died were removed from all tanks before release.

Statistical analyses.—PIT tag detection data at downstream dams were retrieved from PTAGIS for all release groups and checked for erroneous records, inconsistencies, and data anomalies. Records were eliminated where appropriate, mostly due to mortality before release (see annual contract reports footnoted in Table 2 for details). For groups released in bypass systems, fish were removed from analysis if records indicated that they were not diverted back to the river at the release dam (i.e., they were collected and transported). For trash-rack-release groups, only fish detected in the bypass facility were included in the analysis to exclude smolts that swam out of the turbine unit and passed the dam through a turbine or spillway. Other reasons for eliminating records (e.g., tag code reported as detected before the release date; detection recorded at a particular dam on an earlier date than a detection at a dam farther upstream) resulted in elimination of much less than 1% of all records and almost none in recent years.

An assumption of statistical models for paired-release groups is that the groups are mixed as they move downstream. Distributions of daily detections at downstream dams for paired-release groups were tested for proportionality by the use of chi-square tests (see annual reports footnoted in Table 2 for complete methods for testing assumptions).

Two different methods for paired releases were used to estimate relative survival. In most cases, there were multiple detection sites downstream from the release sites, so that estimation of survival probabilities was possible by the use of multiple-recapture models for single releases (the

TABLE 2.—Number of replicates, number of tagged fish released with passive integrated transponder tags, and survival estimates for turbine, bypass, and spillway releases at Lower Granite (LGR), Little Goose (LGO), and Lower Monumental (LMO) dams in 1993–1997. The percentages detected for the combined replicates by use of the relative recovery (RR) method and the relative survival (RS) method estimates of survival are also shown for the treatment and control releases. All relative survival estimates shown are weighted averages of the independent (replicate) estimates; weights are inversely proportional to the respective relative variances.

Release location	Dam	Year	Species	Replicates (N)	Fish released	
					Treatment	Control
Spillway	LGR	1996[a]	Steelhead	5	7,491	7,468
(no deflector)	LGO	1997[b]	Steelhead	14	6,736	6,953
	LMO	1994[c]	Yearling chinook	3	4,157	4,243
Spillway	LGO	1993[d]	Yearling chinook	3	2,328	2,201
(deflector)	LGO	1997[b]	Steelhead	15	7,494	7,453
	LMO	1994[c]	Yearling chinook	3	4,206	4,243
Bypass	LGR	1994[e]	Yearling chinook	3	3,896	2,194
	LGR	1995[f]	Yearling chinook	4	3,130	3,021
	LGR	1995[f]	Steelhead	5	3,747	3,763
	LGO	1994[e]	Yearling chinook	3	3,407	2,225
	LGO	1995[f]	Steelhead	5	3,097	3,653
	LGO	1997[b]	Steelhead	12	6,847	5,953
	LMO	1995[f]	Yearling chinook	5	4,197	3,783
	LMO	1995[f]	Steelhead	5	4,120	3,746
Turbine	LGR	1995[f]	Yearling chinook	2	3,236	1,581
	LGO	1993[d]	Yearling chinook	3	2,236	2,201
	LGO	1997[b]	Steelhead	13	6,215	6,505
	LMO	1994[e]	Yearling chinook	2	2,838	2,841

[a] Smith et al. 1998.
[b] Muir et al. 1998.
[c] Muir et al. 1995.
[d] Iwamoto et al. 1994.
[e] Muir et al. 1995.
[f] Muir et al. 1996.
[g] Model estimates. Absolute survival does not exceed 1.00.

''complete capture history'' protocol of Burnham et al. [1987]). For each release group in the pair, the single-release model was applied independently, resulting in a suite of estimated survival probabilities in downstream reaches and estimates of detection probabilities at downstream detection sites (dams with detection facilities). The relative survival probability for each passage route was estimated as the ratio of the estimated probability of survival to the next downstream dam for the test group to that for the reference group. We used the computer program SURPH (Smith et al. 1994) to calculate the estimated probabilities. We refer to this paired-release method as ''relative survival.'' We used the relative-survival method where possible for all paired releases from 1993 through 1996.

Survival estimates were not possible when there was only a single detection site that detected a sufficient number of tagged fish downstream from the release site. This was the case for releases at Lower Monumental Dam in all years and for Little Goose Dam in 1993. In this case, the recovery proportion (proportion of fish in a release group detected at least once downstream after release) was calculated for each release group in the pair. The relative survival probability for the passage route was estimated as the ratio of the recovery proportion for the test group to that for the reference group. We refer to this paired-release method as ''relative recovery.''

When paired-release groups are mixed downstream and when tests do not indicate that survival and detection probabilities downstream of the first reach are unequal for test and reference groups, then the relative-recovery method may be used even in cases in which the relative-survival method is possible. In these cases, the relative-recovery method will typically result in more precise estimates, because the total number of estimated parameters is decreased (Burnham et al. 1987). On the basis of results of mixing tests, we used the relative-recovery method for paired releases from Little Goose Dam in 1997.

Fish were released at more than two release sites at Lower Monumental Dam in 1994 (two spillway types and the tailrace) and at Little Goose Dam in 1997 (all passage routes and the tailrace). In these

TABLE 2.—Extended.

Release location	Model used	Detection (%)		Survival (%)		Relative survival (SE)
		Treatment	Control	Treatment	Control	
Spillway	RS			95.3	94.1	1.010 (0.019)[g]
(no deflector)	RR	55.4	55.4			1.004 (0.015)[g]
	RR	49.5	50.4			0.984 (0.033)
Spillway	RR	53.5	52.6			1.021 (0.026)[g]
(deflector)	RR	54.0	55.7			0.972 (0.015)
	RR	46.7	50.4			0.927 (0.023)
Bypass	RS			84.0	82.6	0.994 (0.030)
	RS			86.5	88.2	0.976 (0.036)
	RS			89.4	91.1	0.983 (0.019)
	RS			84.0	85.8	0.994 (0.023)
	RS			92.1	91.1	0.979 (0.031)
	RR	55.1	57.8			0.953 (0.016)
	RR	25.0	25.9			0.954 (0.034)
	RR	18.2	19.2			0.929 (0.060)
Turbine	RS			82.6	88.6	0.927 (0.027)
	RR	49.6	52.6			0.920 (0.025)
	RR	52.1	55.8			0.934 (0.016)
	RR					0.865 (0.018)

cases, analysis of variance (ANOVA, $P < 0.05$) was used to compare recovery proportions among release sites. For the Lower Monumental Dam releases in 1994, proportions were compared among the three release sites (including the tailrace), with release day used as a block effect. For the 1997 Little Goose Dam releases, proportions relative to the tailrace proportion were compared for the four passage routes. Dividing by the reference group proportion accounted for temporal differences in average detection probabilities and eliminated the need for blocking by release day in the ANOVA design. Treatment means of significant F-tests were ranked by Fisher's protected-least-significant-difference procedure.

Estimates presented in Results are weighted averages of multiple independent (replicate) estimates; weights are inversely proportional to respective relative variances (coefficient of variation squared). When the relative survival estimate (or recovery proportion) for the treatment group exceeded that for the reference group, we reported the actual ratio (greater than 100%). Of course, absolute survival through a passage route cannot exceed 100%. Because conditions varied, no statistical comparisons were made among survival estimates from different years or different dams.

Because tailrace groups were released 1–2 km downstream from each dam and data were detections at downstream dams, estimates of relative survival obtained in this study include both the direct and indirect effects of passage through each route of passage. Direct effects include immediate mortality, whereas indirect effects include mortality caused by disorientation or injury leading to mortality before arrival at downstream dams.

Partitioning reach survival estimates into reservoir and dam components.—During 1997, hatchery steelhead were PIT tagged and released 5 d/week at Lower Granite Dam as part of a reach survival study (Muir et al., in press). Survival was estimated through various reaches, including from the tailrace of Lower Granite Dam to the tailrace of Little Goose Dam. Using detection probability estimates from the single-release model for these steelhead arriving at Little Goose Dam (P_{cjs}; cjs = Cormack–Jolly–Seber), FGE estimates for Little Goose Dam from Whitney et al. (1997), and Little Goose Dam route-specific survival estimates (for the spill bay [S_{sp}], bypass [S_{byp}], and turbine [S_{turb}]; Table 2), we estimated the proportion of hatchery steelhead passing via the spill bays (P_{sp}). We could then partition dam passage-related survival (S_{dam}) from the overall survival (for both reservoir and dam [$S_{res+dam}$]) for hatchery steelhead passing through this reach. The formula used for these calculations was $P_{cjs} = (1 - P_{sp}) \cdot \text{FGE}$. P_{cjs} is also the estimate of the proportion through the bypass system, so P_{turb} (proportion through the turbine) $= 1 - P_{cjs} - P_{sp}$. For survival, $S_{dam} = P_{cjs} \cdot S_{byp}$

$+ P_{turb} \cdot S_{turb} + P_{sp} \cdot S_{sp}$, and $S_{res} = S_{res+dam}/S_{dam}$, where $S_{res+dam}$ was estimated from groups released from Lower Granite Dam between 13 and 30 April.

By estimating the proportion of fish that used each route of passage during the study period, we were able to estimate several measures of fish passage, including spill efficiency (the proportion of fish that used the spillway), spill effectiveness (the proportion of fish spilled divided by the proportion of water spilled), and fish passage efficiency (the proportion of fish that used nonturbine routes of passage). The proportion of water spilled was calculated from daily average project spill and discharge levels during the study period obtained from the University of Washington Web site at http://www.cbr.washington.edu/dart/dart.html.

Results

In general, passage conditions at downstream dams (e.g., the proportion of water spilled, total discharge levels, and turbine loads) were relatively constant during the period in which fish from paired releases were passing. In most cases in which chi-square tests were significant, distributions of arrival times at downstream dams were not so different that fish from different groups experienced substantially different conditions at the dam, and the effect on survival probabilities was presumably minimal. Furthermore, estimates of reach survival through Snake River dams and reservoirs have exhibited little temporal variation within a migration season (Skalski 1998; Skalski et al. 1998; Muir et al., in press). Results of assumption tests and plots of arrival distributions for all individual releases can be found in the annual contract reports footnoted in Table 2.

Overall detection proportions varied each year depending on the number of detection sites operating downstream and the amount of spill. Detection proportions were lowest for fish released at Lower Monumental Dam in 1995 (Table 2).

Survival Estimates

Relative survival estimates varied significantly among release locations for steelhead at Little Goose Dam in 1997 (F = 3.79, df = 3, 50; P = 0.016). For yearling chinook salmon at Lower Monumental Dam in 1994, relative survival estimates were not significantly different (F = 3.80, df = 2, 4; P = 0.119).

Relative survival estimates were highest (98.4–100%) for yearling chinook salmon and steelhead released into spill bays without flow deflectors (Table 2; Figure 4). Although relative survival estimates were generally lower for spill bays with flow defectors (92.7–100%), survival through the two types of spill bays was not significantly different at Little Goose Dam for steelhead in 1997 (F = 3.79, df = 3, 50; P = 0.016; Fisher's protected least significant difference) or at Lower Monumental Dam for yearling chinook salmon in 1994 (F = 3.80, df = 2, 4; P = 0.119).

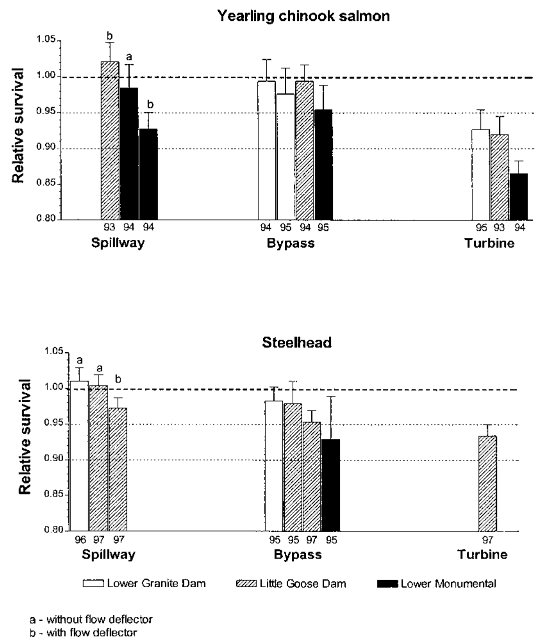

FIGURE 4.—Estimates of the relative survival and SEs for yearling chinook salmon and steelhead passing through spillways (with and without flow deflectors), bypasses, and turbines at Lower Granite, Little Goose, and Lower Monumental dams on the Snake River in 1993–1997 (year of release shown below bars).

Estimated survival through bypass systems ranged from 95.4% to 99.4% for yearling chinook salmon and from 92.9% to 98.3% for steelhead for groups released into the collection channel (Table 2; Figure 4). Estimated survival was 95.3% for steelhead that passed through the entire bypass system at Little Goose Dam in 1997. Estimated turbine survival ranged from 86.5% to 92.7% for yearling chinook salmon and was 93.4% for steelhead at Little Goose Dam in 1997 (Table 2; Figure 4).

For releases at Little Goose Dam in 1997, estimated survival was highest for PIT-tagged hatchery steelhead released into the spill bay without a flow deflector, followed by those released into a spill bay with a flow deflector, the bypass system, and the turbine (Table 2; Figure 4). Survival was significantly higher for fish released into the spill bay without a flow deflector than for those released in the bypass and turbine locations ($F = 3.79$, df $= 3, 50$; $P = 0.016$; Fisher's protected least significant difference). No other contrasts of means were significant.

Partitioning Reach Survival Estimates into Reservoir and Dam Components

Using FGE = 90% and $P_{\text{cjs}} = 0.532$ during the study period, we estimated the proportion of hatchery steelhead passing via the spill bays at Little Goose Dam in 1997 as follows: P_{sp} (proportion through the spillway) $= 1 - 0.0532/0.90 = 0.409$. Thus, P_{turb} (proportion through the turbine) $= 1 - 0.532 - 0.409 = 0.059$, and $S_{\text{dam}} = 0.532 \cdot 0.953 + 0.059 \cdot 0.934 + 0.409 \cdot 0.972 = 0.960$. $S_{\text{res+dam}} = 0.954$ during the study period, so $S_{\text{res}} = 0.954/0.960 = 0.994$.

The estimated fish passage efficiency was 94% (proportion of fish passing via nonturbine routes). The estimated spill efficiency at Little Goose Dam was 40.9% (proportion of fish passing via spill) for hatchery steelhead during the study period. We estimated that 33.0% of the flow at Little Goose Dam was spilled during the study period, so the estimated spill effectiveness was $0.409/0.33 = 1.24$.

Discussion

Decisions on how best to operate Snake and Columbia River dams requires accurate estimates of survival through each potential passage route as well as overall estimates of project and reservoir survival. This study provides such estimates for hatchery yearling chinook salmon and steelhead at Snake River dams. During periods when juvenile salmonids are not collected for transport, spill provides the safest means of passage at Snake River dams. During these periods, spill volumes should be set at the maximum level that does not result in excessive nitrogen supersaturation. Our results agree with the generally high survival of fish that pass through spillways measured in studies since the 1940s (Schoeneman et al. 1961; Whitney et al. 1997). Bypass systems provide the next safest route of passage, and efforts aimed at improving bypass efficiency and survival should continue. These results support the measures for juvenile fish passage prescribed for the listed Snake River fish in the 1995 biological opinion for the Endangered Species Act.

Our estimates of turbine survival are similar to those found in recent turbine survival studies at Snake and Columbia River dams that used HI-Z Turb'N tags (balloon tags; Normandeau Associates, Inc., et al. 1995; Mathur et al. 1996) but are generally higher than those reported in past studies that used other marking methods (Schoeneman et al. 1961; Whitney et al. 1997). Turbine survival (48 h) for balloon-tagged yearling chinook salmon was estimated at 93.0% at Rocky Reach Dam (Mathur et al. 1996) and 94.8% at Lower Granite Dam (Normandeau Associates, Inc., et al. 1995), values similar to our Lower Granite Dam survival estimate through the same turbine unit determined with PIT tags (92.7%).

Spillway deflectors did not significantly affect survival through spill bays in our studies at Little Goose and Lower Monumental dams with the sample sizes used, although point estimates of survival were higher without a flow deflector than with a flow deflector (100% versus 97.2% at Little Goose Dam and 98.6% versus 93.0% at Lower Monumental Dam, respectively). In balloon-tag studies in 1997, the estimated survival of hatchery steelhead through the two spillway types was significantly different in the same spill bays we studied at Little Goose Dam; point estimates were nearly identical to our estimates determined with PIT tags. Survival (48 h) through the spill bay without a flow deflector was estimated at 100%, whereas survival through the spill bay with a deflector was significantly lower at 98% at a spill volume of 158 m^3/s (Normandeau Associates, Inc., et al. 1997). Estimated survival through the two spill bays was more similar for other spill volumes tested (Normandeau Associates, Inc., et al. 1997). Balloon-tag studies give direct estimates of survival (up to 48 h) and do not include mortality farther downstream from injuries sustained during passage, whereas PIT tag evaluations include both direct and indirect mortality. These results indicate that although the installation of flow deflectors reduces the entrainment of atmospheric gases, it may also reduce juvenile salmonid survival. However, the small reduction in survival is acceptable, considering the potential losses from gas supersaturation that could occur during times of high forced spill if flow defectors were not present (Weitkamp and Katz 1980).

Few studies have evaluated survival through bypass systems or through the entire system (Whitney et al. 1997). Our studies at Little Goose Dam in 1997 were the first to estimate mortality for fish that passed along the submersible traveling screen, into the gate well, through the orifice into the collection channel, and into the bypass outfall area, where predation rates can be especially high (Reiman et al. 1991; Dawley et al. 1994). For hatchery steelhead released in front of the bar screen at Little Goose Dam, survival was estimated at 95.3% in 1997. This estimate was lower than the estimates of 99.4% for hatchery chinook salmon (1994) and 97.9% for hatchery steelhead (1995), estimates obtained when fish were released into the collection channel and did not pass through the entire bypass system at this dam. Survival is often assumed to be 97–98% through bypass systems (Whitney et al. 1997), but results from our studies suggest that it may be lower.

Recent studies evaluating survival through Snake River and Columbia River dams have generally found higher survival than previous studies. Possible reasons for improved survival include the use of different tagging methods (PIT tags and HI-Z Turb'N tags versus nitrogen freeze brands, coded-wire tags, and fin clips), differences in location of control or reference releases, and improved passage conditions at dams. PIT tags and HI-Z Turb'N tags provide more precise estimates of survival than do methods used in previous studies because of their high recapture rates and reliability. Previous studies relied on releases of large batches of marked fish for recapture in subsampling at downstream dams (often requiring expansion of recoveries by sampling efficiency estimates) or on returns of adults many years later. Passage conditions at dams have improved considerably over the past 20 years (Williams and Matthews 1995), probably leading directly to increases in survival.

In addition to physical changes at dams, the conditions that smolts face in tailraces may also have improved (Dawley et al. 1994) due to a predator control program that removed about 900,000 northern pikeminnow *Ptychocheilus oregonensis* from reservoirs between 1990 and 1995 (Beamesderfer et al. 1996); the use of bird wires across tailraces to discourage avian predation; the positioning of bypass outfall exits in areas unattractive to predators (Shively et al. 1996); and the voluntary spill program, which could also reduce predation by pushing predators farther downstream (Faler et al. 1988). Together, these efforts have probably increased survival of smolts through all passage routes by discouraging predation when smolts are most vulnerable because of stress and disorientation caused by dam passage (Matthews et al. 1986; Maule et al. 1988; Sigismondi and Weber 1988; Olla and Davis 1992; Mesa 1994).

The lowest estimates of survival observed through each route of passage were from Lower Monumental Dam. These estimates were also generally the least precise. Why survival through this dam would be lower is unknown, although the fact that survival for all passage routes was lower suggests a common effect, perhaps related to the conditions that smolts face immediately below the dam in the tailrace (i.e., above the zone in which they mixed with tailrace-released fish).

The high fish passage efficiency (94%) estimated for steelhead passing Little Goose Dam during the study period in 1997 indicates that current operations at that dam, which use extended-length bar screens and spill, keep most smolts from encountering turbines (<6% passed through turbines). Partitioning the estimate of reach survival for steelhead passing through Little Goose Reservoir and Dam during the study period indicated that most of the mortality in this reach occurred during passage through the dam (4%); little mortality was detected in the 60-km reservoir (<1%). Substantially increasing survival through this reservoir and dam beyond that estimated during 1997 would be difficult because mortality occurs through all potential passage routes including spillways and bypass systems.

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