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MANAGEMENT BRIEF

Survival of Juvenile Chinook Salmon during Barge Transport

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Abstract
To estimate survival during barge transport over a distance of 470 km from Lower Granite Dam on the Snake River to a release area downstream of Bonneville Dam (the lowermost dam on the Columbia River), we used a novel adaptation of a release–recapture model with 1,494 acoustic-tagged yearling Chinook salmon *Oncorhynchus tshawytscha* smolts. Smolts were collected at Lower Granite Dam, received surgically implanted acoustic transmitters, and were divided into three groups: (1) a barge group (R_B) that was released into the raceway with fish that were later loaded into transportation barges (general barge population); (2) a control group (R_A) that was held in a net-pen suspended within the barge hold containing the general barge population until 5–6 h prior to barge evacuation (i.e., fish release into the river), at which time they were confirmed to be alive and then released into the barge hold; and (3) a dead group (R_D) that was euthanized and then released into the barge hold 5–6 h prior to barge evacuation in order to validate a model assumption. Six replicates of each group were loaded onto fish transport barges that departed from Lower Granite Dam between 29 April and 13 May 2010. Detections on acoustic receiver arrays between 70 and 220 km downstream of the barge evacuation site served as the basis for estimation of survival within the barge. The ratio of $R_B : R_A$ survival from release to river kilometer 153 provided the estimate of within-barge survival. The replicate survival estimates ranged from 0.9503 ($\widehat{\text{SE}} = 0.0253$) to 1.0003 ($\widehat{\text{SE}} = 0.0155$). The weighted average of the replicate estimates of survival during the barge transportation experience was 0.9833 ($\widehat{\text{SE}} = 0.0062$). This study provides the first active telemetry documentation that the assumed survival rate of 98% during the barge transportation experience appears to be justified for yearling Chinook salmon smolts.

Efforts to recover anadromous salmonid populations often rely on the development of models that are intended to evaluate the influence of a variety of mitigation scenarios. Inherent within these models are assumptions regarding the relative influence of mitigation actions on the population's recovery. Parameterization of these models often requires assumptions. Model predictions are typically very sensitive to estimated parameters (Ellner and Fieberg 2003). Peters and Marmorek (2001) presented a model to evaluate recovery actions for Snake River spring and summer Chinook salmon *Oncorhynchus tshawytscha* and highlighted the importance of parameterization assumptions for determining the effects of mitigation strategies.

Anadromous salmonid populations in the Columbia River basin have been affected by construction and operation of the dams that form the Federal Columbia River Power System (Nehlsen et al. 1991; Myers et al. 1998). One management strategy that has been developed to mitigate for these impacts is the juvenile fish transportation program. This transportation program was initiated in the 1970s (McCabe et al. 1979; Ebel 1980) and was fully implemented by 1981 (Ward et al. 1997); the program involves the placement of juvenile salmonids into barges that are specifically designed and built to transport these fish from four upstream dams to a release site between river kilometer (rkm) 222 and rkm 227 (Columbia River mouth = rkm 0), roughly 9–14 km downstream of Bonneville Dam (Figure 1). Transported fish are subjected to a variety of stressors and potential sources of injury during the initial collection process as they are routed past screens, through pipes, past

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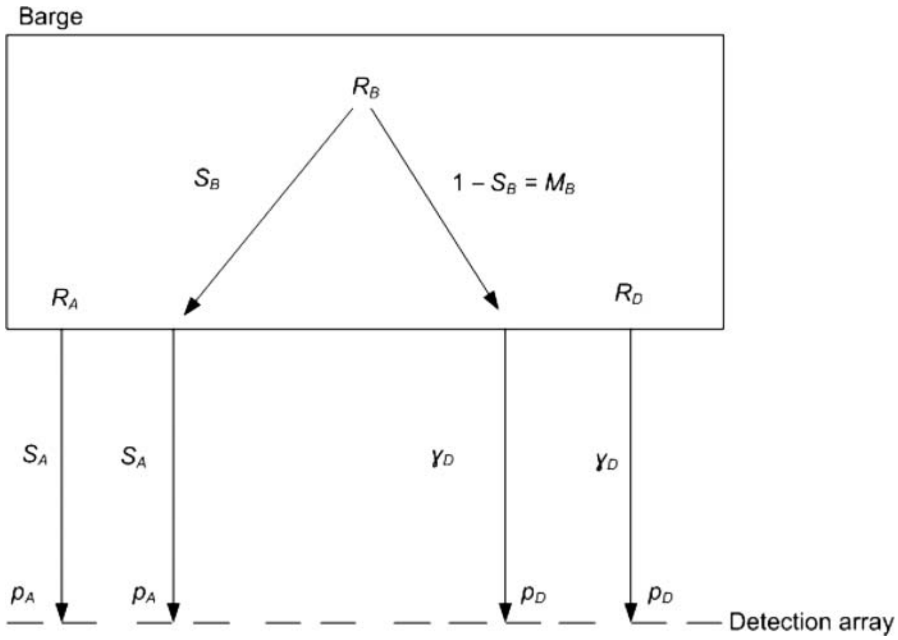

FIGURE 1. Schematic of the barge release–recapture design, which used three groups of yearling Chinook salmon smolts (R_B = barged tagged fish; R_A = tagged live controls; R_D = tagged dead fish; see Methods) to estimate within-barge mortality ($M_B = 1 - S_B$, where S_B is the probability of an R_B smolt surviving in the barge during transportation). Survival of a live fish (R_A or R_B) between barge evacuation and the downstream receiver array (S_A) and the probability of a live fish (R_A or R_B) being detected (p_A) are not separately estimable (i.e., $\theta_A = S_A p_A$) in the case of a single downstream detection array. Similarly, the probability of a dead fish (R_D or R_B) arriving at the receiver array (γ_D) and the probability of a dead fish (R_D or R_B) being detected (p_D) are not separately estimable (i.e., $\theta_D = \gamma_D p_D$) with a single downstream array. With multiple downstream detection arrays, parameters S_A and p_A are separable, as are γ_D and p_D.

dewatering devices, into fish sorting devices and raceways, and then through flumes during loading onto barges (Maule et al. 1988; Congleton et al. 2000). Cumulative stress or injury during the transportation process could reduce fish survival. Several studies have evaluated the relative survival rates of transported fish versus their cohorts that migrated through the hydroelectric system without being transported (e.g., Ward et al. 1997; Buchanan et al. 2006; Clemens et al. 2009); however, we were not able to find direct estimates of fish survival during the transportation process. Muir et al. (2006) indicated that they expected the survival inside a barge to be nearly 100% and cited Budy et al. (2002). Budy et al. (2002) assumed that direct mortality of fish inside a barge was always low (about 2%). However, Budy et al. (2002) did not provide a reference for the 2% mortality estimate and did not explain how it was derived. In modeling efforts to estimate delayed mortality in the Columbia River basin, Peters and Marmorek (2001) assumed a constant survival rate of 98% inside a barge during transportation. Bouwes et al. (1999) pointed out that this assumption could introduce substantial error into recovery modeling efforts if the actual survival during barge transport was different for any reason. Bouwes et al. (1999) also stated that the survival of barged smolts from the point of collection to release downstream of Bonneville Dam had never been formally estimated.

To address the need for direct estimates of the survival of juvenile salmonids transported by barge past the Federal Columbia River Power System in the Snake and Columbia rivers, we developed a release–recapture survival model design and used acoustic telemetry. Our objective was to estimate the survival of yearling Chinook salmon smolts that were transported by barge from Lower Granite Dam (rkm 695) on the Snake River to the typical release area downstream of Bonneville Dam. Specifically, we wanted to quantify the survival of fish during the transportation process from the point of their release into a temporary holding raceway (i.e., after being collected in a juvenile bypass facility) to the time immediately prior to their release from the barge into the Columbia River.

METHODS

Release–recapture design.—We studied Chinook salmon smolts that were barged from Lower Granite Dam because this is the upstream-most dam from which fish are transported. The study examined three separate groups of acoustic-tagged fish that were released into the barges (Figure 2). Barged fish (R_B) were placed into the barge at the beginning of transportation from Lower Granite Dam. However, their release below Bonneville Dam included both live and dead fish—the result of the transportation process. To differentiate the probability of downstream detection for tagged live fish versus tagged dead fish, live (control; R_A) and dead (dead; R_D) acoustic-tagged fish were released into the barge just prior to barge

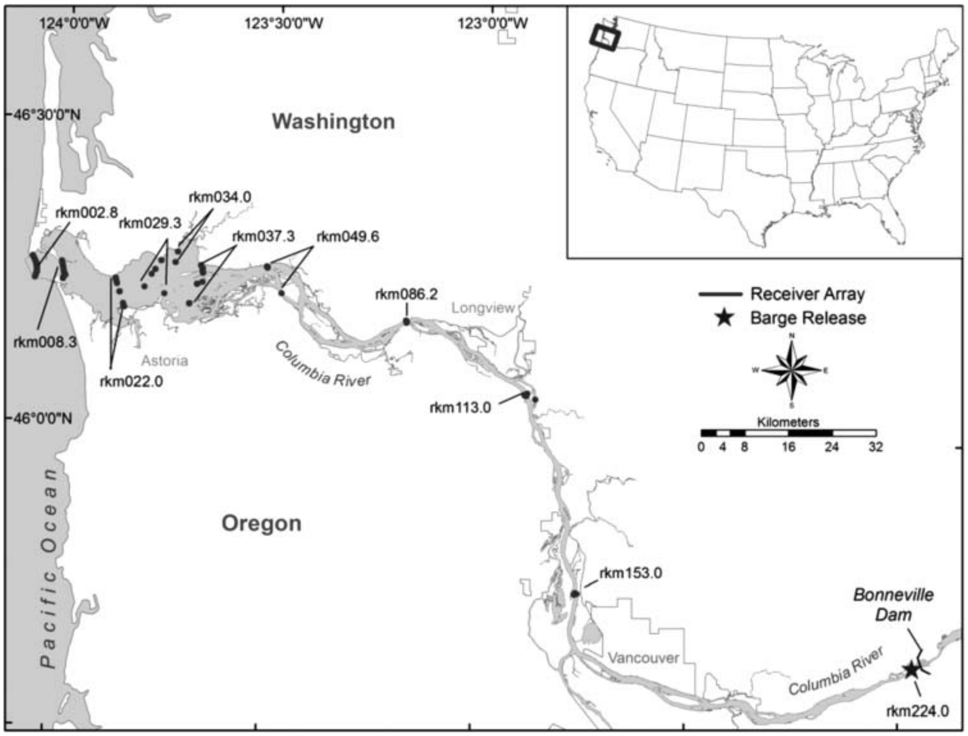

FIGURE 2. Map of the lower Columbia River, showing the barge release area (star) and the locations of the Juvenile Salmonid Acoustic Telemetry System receiver arrays (rkm = river kilometers above the Columbia River mouth).

evacuation (i.e., fish release from the barge into the Columbia River).

Downstream receiver array(s) were used to detect tagged smolts from the three release groups in order to estimate within-barge mortality ($M_B = 1 - S_B$, where S_B is the probability of an R_B smolt surviving in the barge during transportation). To improve the precision of the M_B estimate, the first downstream receiver array was located 71 km downstream of the barge evacuation site to decrease the probability of detecting the R_D fish. Multiple downstream receiver arrays were used to increase the detection probability for all tagged live fish. Multiple downstream arrays were used to test whether R_B and R_A fish had equal downstream survival (i.e., assumption A4 in the Statistical Analysis section below).

The study used approximately 1,500 acoustic-tagged fish distributed across the three release types (R_B, R_A, and R_D). These tagged fish were distributed across six different barge trials over the 2010 out-migration season (i.e., $6 \times 250 = 1{,}500$). The separate estimates of within-barge survival were used to estimate a weighted average based on sampling precision.

Fish collection, tagging, and releases.—Yearling Chinook salmon were obtained from the smolt collection facility at Lower Granite Dam between 27 April and 11 May 2010. Untagged smolts meeting the length criterion (≥95 mm fork length) were held overnight in two rectangular, stainless-steel tanks (184 L each) that were supplied with flow-through river water (temperature range = 9.3–10.9°C) and supplemental oxygen. Eight fish (0.5%) were rejected during the tagging process based on their extremely poor condition (typically fungal infections on the gills or caudal fin) and the expectation that they would not survive the tag implantation surgery. Fish that enter the juvenile fish bypass at Lower Granite Dam are randomly sampled for length measurement. To determine whether the fish we tagged represented the run-at-large, we obtained length data for yearling Chinook salmon collected in these random samples during our study period (Washington Department of Fish and Wildlife, unpublished data).

The morning after collection, a Juvenile Salmonid Acoustic Telemetry System (JSATS; McMichael et al. 2010) acoustic transmitter (weight = 0.43 g in air; pulse repetition interval = 3 s; expected life = 25 d) and a Destron-Fearing passive integrated transponder (PIT) tag (Model TX1411ST; weight = 0.10 g in air) were surgically implanted into the body cavity of each study fish according to protocols described by McMichael et al. (2010) except that in the current study, incisions were made on the linea alba. The PIT tags were used to determine which acoustic-tagged fish died during recovery or in net-pens during transport; data from PIT tags were not analyzed as part of this study. All fish of each experimental group used within a replicate day were tagged on the same day (with systematically even distribution among groups throughout the tagging day) and were then handled differently (i.e., according to release type) until immediately prior to release. All fish were allowed to recover from surgery in three 76-L plastic containers supplied with flow-through river water and supplemental oxygen. After every approximately 100 fish were tagged and had regained equilibrium, they were transferred to three more perforated holding containers (38 L for the R_D group; 76 L each for the R_B and R_A groups), which were then placed into a concrete temporary holding raceway at the facility. All R_B fish spent a recovery period of at least 4 h in the perforated containers within the raceway before being released into the raceway with fish that were to be loaded into barge holds the next morning (hereafter, "general barge population," primarily consisting of Chinook salmon, steelhead *O. mykiss*, and coho salmon *O. kisutch*). All R_A and R_D fish were held in the perforated containers for a minimum of 14 h prior to barge loading. Treatment fish (i.e., R_B) were held in the raceway for a total of approximately 14 h, whereas the general barge population may be held in raceways for as long as 27 h or as little as 15 min when fish are being transported daily. During periods when transportation (barge or truck) occurs every other day, fish may be held in raceways for as long as 50 h.

The morning after tagging, the containers holding the R_A and R_D fish were examined and any overnight mortalities were removed (one R_A fish died overnight during the entire study period). The R_A fish were then transferred into a plastic-mesh net-pen with a stainless-steel frame (0.9 × 0.9 × 1.2 m), which was suspended in the right rear barge hold (94,635 L) of a standard barge (total capacity = 567,811 L). The container holding the R_D fish was floated inside the net-pen, and the container's lid was secured. At approximately the same time, the R_B fish along with the general barge population from the raceway were loaded into the right rear barge hold via a 25-cm-diameter polyvinyl chloride pipe. Shortly after fish from all raceways were loaded, the barge departed from Lower Granite Dam on its way to the release site. After approximately 33 h in transit, the net-pen was lifted from the barge hold in order to examine the R_A group. Any R_A fish that died during transport ($n = 3$) or that could not maintain equilibrium ($n = 1$) were noted and reclassified as R_D fish. At this time, all fish from the R_D group were euthanized with tricaine methanesulfonate at a dose of 250 mg/L of water. The R_A and R_D fish were then released from the net-pen into the barge hold to mix with the general barge population for the remainder of the trip (~6 h). When the barge was approximately 9–14 km downstream of Bonneville Dam, all six barge holds were opened and fish were released into the river. Barge evacuations took place an average of 39 h after initial barge loading and occurred between 2050 and 0045 hours Pacific Daylight Time.

Receiver arrays.—The JSATS autonomous receivers were deployed in arrays at rkm 153 (five receivers), rkm 113 (10 receivers), and rkm 86 (six receivers). Additional receiver arrays in the Columbia River and estuary downstream of rkm 86 were used to improve estimates of detection probability at rkm 153 and 113 (Figure 2). The JSATS autonomous receivers and their operation and use are described by McMichael et al. (2010) and Titzler et al. (2010). In brief, each self-contained receiver held batteries for 30-d deployments, signal processing, and data storage inside waterproof housing and was equipped with a hydrophone, temperature sensor, and pressure sensor on the outside of the waterproof housing. Receivers were deployed 2–5 m above the riverbed by tethering them to anchors via the protocols described by Titzler et al. (2010).

Acoustic-telemetry data processing and filtering were consistent with methods described by McMichael et al. (2010), wherein all candidate transmissions were analyzed to determine whether there were at least four detections of each tag code in a short period of time (12 × the pulse repetition interval) and multipath signals (those that arrived within 0.16 s after the same code) were removed. Valid detections on each receiver were then used to generate detection histories for each tagged fish on each receiver array to be used in the statistical analyses described below.

Statistical analyses.—Three groups of acoustic-tagged smolts were used in the barge mortality study. For purposes of statistical analyses, R_B was the number of acoustic-tagged smolts placed into the barge prior to transportation from Lower Granite Dam (i.e., the barged group), b was the number of R_B smolts detected at hydrophone arrays downriver after evacuation of the barge, R_A was the number of live acoustic-tagged smolts placed into the barge just prior to barge evacuation (i.e., the control group), a was the number of R_A smolts detected at hydrophone arrays downriver after barge evacuation, R_D was the number of dead acoustic-tagged smolts placed into the barge just prior to barge evacuation (i.e., dead group), and d was the number of R_D smolts detected at hydrophone arrays downriver after barge evacuation.

A joint likelihood model was created to analyze the recovery data (i.e., b, a, and d) based on the following parameters: S_B was the probability of an R_B smolt surviving in the barge during transportation, S_A was the probability of a tagged live smolt (R_A or R_B) surviving from the point of barge evacuation to one or more downstream receiver arrays, p_A was the probability of a tagged live fish (R_A or R_B) being detected at a downstream receiver array given that it survived to the array, γ_D was the probability of a tagged dead fish (R_D or R_B) arriving at one or more of the downstream receiver arrays, and p_D was the probability of a tagged dead fish (R_D or R_B) moving downstream and being detected at the downstream array.

Treating each of the releases as independent binomial random variables, the joint likelihood (L) model can be written as follows:

$$\begin{aligned} L = \binom{R_B}{b}\left[S_B S_A p_A + 1(1 - S_B)\gamma_D p_D\right]^{b} \\ \cdot\left[1 - S_B S_A p_A - (1 - S_B)\gamma_D p_D\right]^{R_B - b} \\ \cdot\binom{R_D}{d}(\gamma_D p_D)^{d}(1 - \gamma_D p_D)^{R_D - d} \\ \cdot\binom{R_A}{a}(S_A p_A)^{a}(1 - S_A p_A)^{R_A - a}. \end{aligned} \quad (1)$$

In the case of a single downstream receiver array, the parameters S_A and p_A cannot be separately estimated—only their product can be estimated: $\theta_A = S_A p_A$. Similarly, only the product $\theta_D = \gamma_D p_D$ can be estimated with a single downstream receiver array. The maximum likelihood estimators of the parameters are as follows:

$$\hat{\theta}_D = \frac{d}{R_D},$$

$$\hat{\theta}_A = \frac{a}{R_A}, \text{ and}$$

$$\hat{S}_B = \frac{\left(\frac{b}{R_B} - \frac{d}{R_D}\right)}{\left(\frac{a}{R_A} - \frac{d}{R_D}\right)} \tag{2}$$

with associated variance

$$\begin{aligned}\operatorname{var}(\hat{S}_B) = & \frac{1}{(\theta_A - \theta_D)^2} \\ & \times \left\{ \frac{[S_B(\theta_A - \theta_D) + \theta_D][1 - S_B(\theta_A - \theta_D) - \theta_D]}{R_B} \right. \\ & \left. + \frac{\theta_A(1-\theta_A)S_B^2}{R_A} + \frac{\theta_D(1-\theta_D)(1-S_B)}{R_D} \right\}. \end{aligned} \tag{3}$$

After the study was completed, it was found that no R_D fish were detected at the first downstream detection location. In this case, because d was equal to zero, the estimator of within-barge survival was reduced to the following:

$$\hat{S}_B = \frac{\left(\frac{b}{R_B}\right)}{\left(\frac{a}{R_A}\right)} = \frac{bR_A}{R_B a}. \tag{4}$$

Equation (4) is the Ricker (1958) relative recovery estimator for a paired-release design with only one downstream detection location. With multiple downstream detection sites (Figure 3), the study generalizes to the paired release–recapture design of Burnham et al. (1987). The estimate of within-barge survival is then calculated as

$$\hat{S}_B = \frac{\hat{\theta}_1}{\hat{\theta}_2} \tag{5}$$

with associated variance

$$\operatorname{var}\left(\hat{S}_B\right) = S_B^2 \left[\frac{\operatorname{var}\left(\hat{\theta}_1\right)}{\theta_1} + \frac{\operatorname{var}\left(\hat{\theta}_2\right)}{\theta_2}\right]. \tag{6}$$

The estimate of within-barge survival for the separate trials was calculated based on equations (5) and (6). The overall estimate of within-barge survival across the replicate trials was computed as

$$\hat{\hat{S}}_B = \frac{\sum_{i=1}^{6} \hat{S}_{Bi} W_i}{\sum_{i=1}^{6} W_i} \tag{7}$$

with associated variance

$$\widehat{\operatorname{var}}\left(\hat{S}_B\right) = \frac{\sum_{i=1}^{6}\left(\hat{S}_{Bi} - \hat{\hat{S}}_B\right)^2 W_i}{(6-1)\sum_{i=1}^{6} W_i}, \tag{8}$$

where $\hat{S}_{Bi}$ is the estimate of within-barge survival for the ith trial ($i = 1, \ldots, 6$) and W_i are the weights:

$$W_i = \frac{1}{\left[\operatorname{var}\left(\hat{S}_{Bi}\right)/\hat{S}_{Bi}^2\right]} = \frac{1}{\operatorname{CV}\left(\hat{S}_{Bi}\right)^2} \tag{9}$$

(CV = coefficient of variation). The W_i were based on equation (9) to allow them to be independent of the survival estimates.

The assumptions of the barge mortality model are:

A1. The numbers of fish in all release groups (i.e., R_B, R_A, and R_D) are known without error.
A2. All fish within a release group have an independent and equal probability of recovery.
A3. All tagged dead fish, whether from the R_D or R_B release group, have an equal probability of moving downriver and being detected by the receiver array(s).
A4. All tagged live fish, whether from the R_B or R_A release group, have an equal probability of surviving from the point of barge evacuation to the downstream receiver array(s) and an equal probability of being detected by the array(s).
A5. There is no handling mortality among the fish in either the R_B release group or the R_A release group.
A6. The R_A fish do not die between the time of their release into the barge and the time of barge evacuation.
A7. The tagged fish, whether alive or dead, are drawn from the same population as the barged fish.

The release–recapture design could be reduced to a paired release–recapture model (Burnham et al. 1987) provided that none of the R_D fish released into the barge just prior to evacuations is detected at a downriver receiver array. In this case, the reach between the barge evacuation location and the first downstream receiver array (rkm 153) could be used to estimate within-barge mortality. Subsequent receiver arrays at rkm 113.0, 86.2, 49.6, 37.3, 22.0, 8.3, and 2.8 could be used to increase the rate of detection of the tagged fish and to increase the precision of the estimates. Our statistical analyses would underestimate survival if some tags failed before live fish passed one or more receiver arrays. We conducted a tag life study that monitored 49 tags from the time of tag initiation to the time of tag failure. To test tag life, tags were activated and then placed in perforated plastic bags suspended in a 2-m-diameter, circular fiberglass tank that was supplied with flow-through Columbia River water. Two directional hydrophones (90° × 180°) and two omnidirectional hydrophones were positioned within the tank and were cabled to a quad-channel amplifier. All acoustic signals were decoded and analyzed to determine the time to failure (nearest 0.01 d) for all 49 tags. The

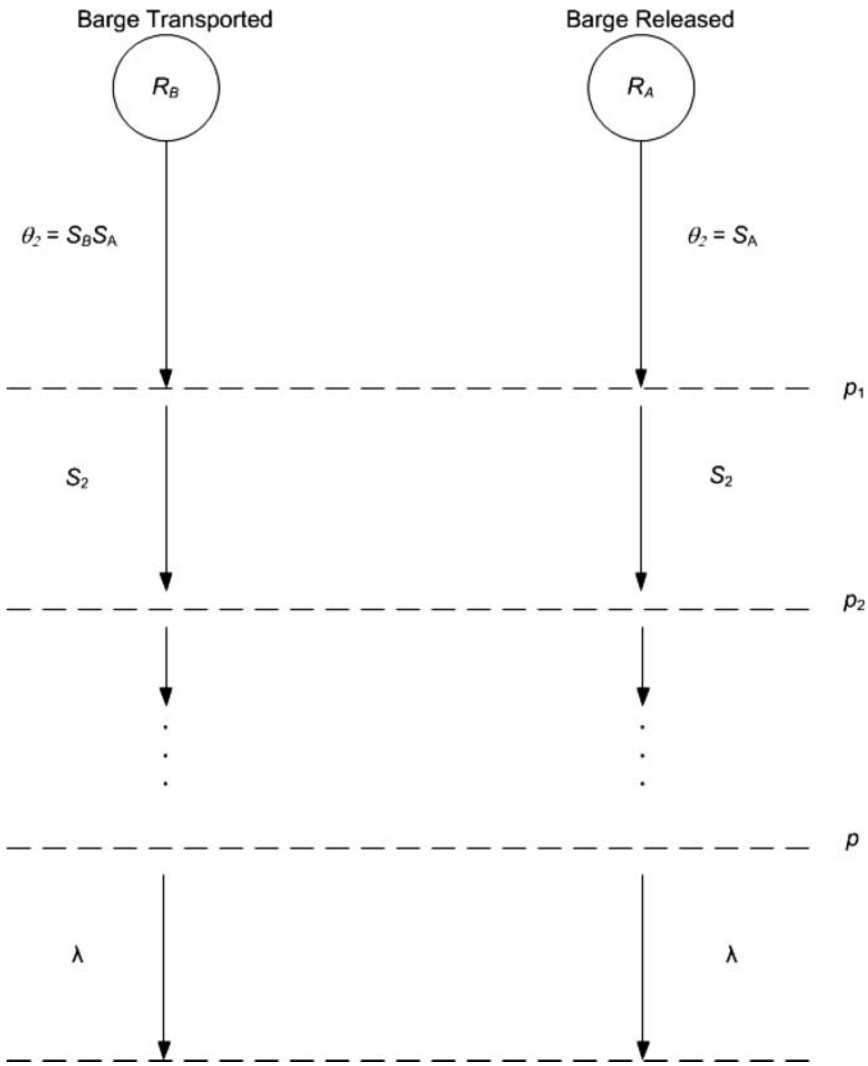

FIGURE 3. Schematic of the paired-release design with barged tagged fish (R_B) and tagged live controls (R_A) used to estimate within-barge mortality ($M_B = 1 - S_B$, where S_B is the probability of an R_B smolt surviving in the barge during transportation). Both releases are assumed to have the same survival from the time of barge evacuation to the first downstream receiver array (S_A) and the same survival (S) and detection probability (p) downstream. Survival and detection probabilities could not be differentiated for the last reach (i.e., $\lambda = Sp$).

probability of the acoustic tags being active at each downstream receiver site was calculated by integrating the tag life curve over the distribution of arrival times at each receiver site. Tag-life-corrected survival estimates (Townsend et al. 2006) were generated by incorporating the probabilities of the acoustic tags being active at the downstream receiver sites into the likelihood equation.

RESULTS

In total, 1,494 yearling Chinook salmon received JSATS acoustic transmitters and PIT tags. These fish were divided among six dates, each consisting of three different experimental groups (Table 1). Tagged fish in the experimental groups were similar in size and tag burden. The tagged fish provided a good representation of the run-at-large, as fewer than 0.5% of the yearling Chinook salmon sampled at Lower Granite Dam were smaller than 95 mm. Figure 4 shows the length frequency distributions of the yearlings tagged for this study and of their cohorts sampled in the same facility during routine fish sampling activities. The total time for which R_A fish were held in net-pens ranged from 31.0 to 34.7 h, and the total barge travel time from Lower Granite Dam to the release location downstream of Bonneville Dam ranged from 37.1 to 40.9 h (Table 1). The release locations varied from rkm 222 to rkm 227 (average ~ rkm 224; Table 1); the release location is intentionally varied so as to reduce the likelihood that predators will be conditioned to congregate at the barge evacuation site.

Fitting the tag life data to the four-parameter vitality model of Li and Anderson (2009) showed that the expected

TABLE 1. Descriptive statistics (SE in parentheses) by date of fish transportation barge departure from Lower Granite Dam on the Snake River in 2010 (each date is a replicate; 6 replicates total). Experimental group, mean fork length (FL), mean weight, tag burden (combined weight of the Juvenile Salmonid Acoustic Telemetry System tag and passive integrated transponder tag [0.53 g in air] expressed as a percentage of fish weight in air), total time for which the control fish were held in the net-pen, total transport time (applies to all groups within a replicate), and the river kilometer (rkm; Columbia River mouth = rkm 0) where fish were released from the barge are shown.

Barge departure date	Group	*N*	FL (mm)	Weight (g)	Tag burden (%)	Total time in net-pen (h)	Total barge travel time (h)	Release rkm
29 Apr	Barge	92	139 (1.3)	25.7 (0.69)	2.2 (0.07)		40.2	225
	Control	92	138 (1.3)	25.9 (0.72)	2.2 (0.07)	33.8		
	Dead	12	137 (3.1)	26.2 (2.01)	2.2 (0.17)			
1 May	Barge	141	135 (1.3)	24.4 (0.73)	2.5 (0.09)		38.7	222
	Control	143	135 (1.3)	24.4 (0.69)	2.5 (0.08)	33.3		
	Dead	23	133 (3.1)	23.7 (1.61)	2.5 (0.20)			
4 May	Barge	116	132 (1.2)	22.1 (0.60)	2.6 (0.08)		40.9	227
	Control	115	136 (1.6)	25.1 (0.89)	2.5 (0.11)	34.7		
	Dead	18	130 (2.7)	21.3 (1.33)	2.7 (0.22)			
7 May	Barge	89	132 (1.6)	21.3 (0.71)	2.8 (0.11)		37.9	225
	Control	91	136 (1.7)	23.6 (0.95)	2.6 (0.12)	31.5		
	Dead	14	138 (2.4)	25.6 (1.23)	2.1 (0.11)			
10 May	Barge	102	134 (1.4)	22.9 (0.73)	2.6 (0.10)		37.3	224
	Control	104	134 (1.3)	22.8 (0.64)	2.5 (0.08)	31.0		
	Dead	14	134 (3.7)	23.1 (1.66)	2.5 (0.24)			
13 May	Barge	155	136 (1.2)	23.9 (0.67)	2.5 (0.07)		37.1	222
	Control	152	132 (1.3)	22.0 (0.62)	2.7 (0.09)	31.1		
	Dead	21	131 (3.1)	21.8 (1.43)	2.7 (0.19)			

tag life was generally about 30 d (Figure 5). Output from the four-parameter model indicated that in all cases, the probability of a tag being active at the downstream detection sites exceeded 0.98 (Table 2). None of the 102 R_D fish that were released into the barge just before evacuations was detected at a downriver array. This finding supported the assumption that detection at downstream receiver arrays indicates that the tagged fish are alive. As such, the

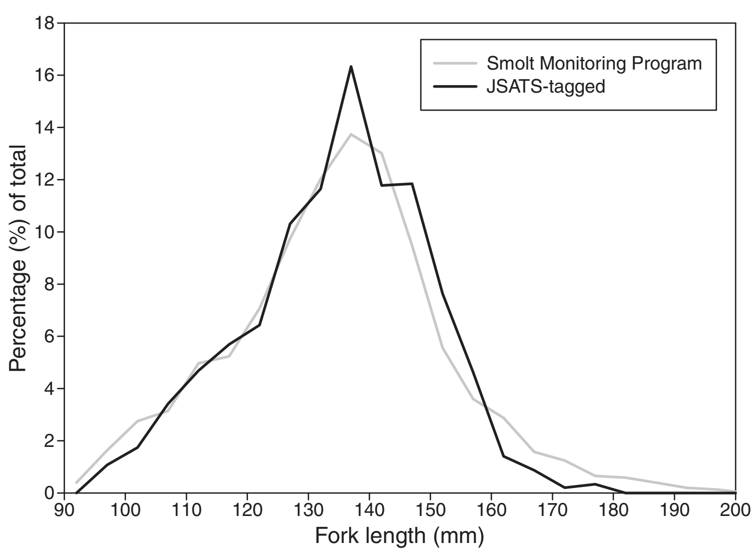

FIGURE 4. Length distributions (fork length, mm) of yearling Chinook salmon that were collected by the Smolt Monitoring Program and yearlings that were tagged (with Juvenile Salmonid Acoustic Telemetry System [JSATS] tags) to estimate survival during barge transport.

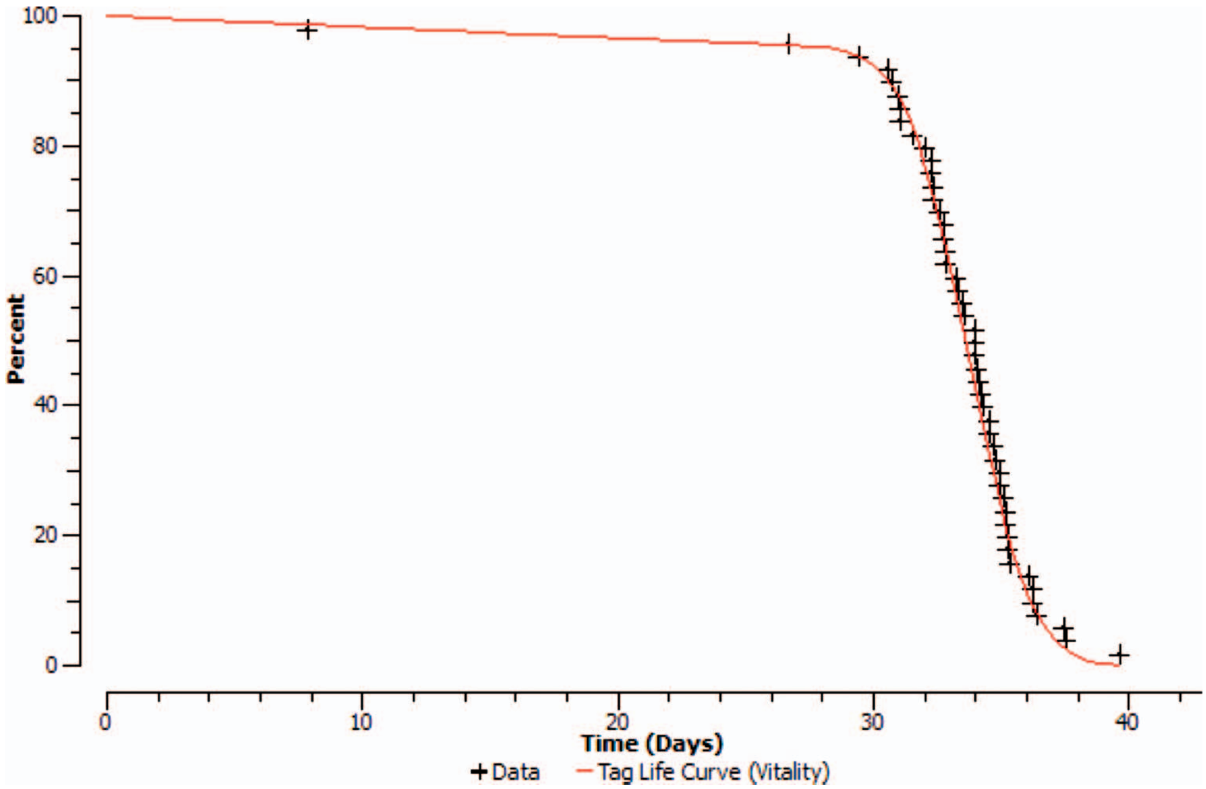

FIGURE 5. Individual failure times for the 49 acoustic tags used in the tag life study, presented with the fitted four-parameter vitality model of Li and Anderson (2009).

release–recapture design was reduced to a paired release–recapture model (Burnham et al. 1987) consisting of R_B and R_A fish.

Tag-life-corrected estimates of reach survival for R_B and R_A fish in five of the six replicates showed that R_A fish survived at a higher rate than R_B fish between barge evacuation and the receiver array at rkm 153 (Table 3). The ratio of survival from release to rkm 153 for R_B fish relative to R_A fish provided estimates of within-barge survival ranging from 0.9503 ($\widehat{\text{SE}}$ = 0.0253) to 1.0003 ($\widehat{\text{SE}}$ = 0.0155; Table 4). The weighted average of the replicate estimates of within-barge survival ($\hat{\bar{S}}$) was 0.9833 ($\widehat{\text{SE}} = 0.0062$). Thus, the estimated mortality due to the transportation experience between the time of fish placement into raceways for temporary holding at Lower Granite Dam and the time immediately before fish release into the Columbia River below Bonneville Dam was about 2% for these yearling Chinook salmon.

The loading densities or species composition in the barge hold where the tagged fish were kept (i.e., right rear hold) did

TABLE 2. Estimated probabilities (SE in parentheses) of an acoustic tag being active at each of the downstream detection sites (by river kilometer [rkm]) in the Columbia River for barge-transported and control Chinook salmon smolts.

Release group	rkm 153	rkm 113	rkm 86.2
Barge	0.9864 (0.0065)	0.9853 (0.0070)	0.9845 (0.0074)
Control	0.9864 (0.0065)	0.9852 (0.0071)	0.9843 (0.0075)

TABLE 3. Estimated survival ($\widehat{\text{SE}}$ in parentheses) for barge-transported and control releases of yearling Chinook salmon smolts between release downstream of Bonneville Dam and the acoustic receiver array at river kilometer (rkm) 153 on the Columbia River for the six replicate trials.

Trial	Release group	Survival ($\widehat{\text{SE}}$) to rkm 153
1	Barge	1.0001 (0.0121)
	Control	0.9999 (0.0121)
2	Barge	0.9569 (0.0209)
	Control	1.0000 (0.0122)
3	Barge	0.9954 (0.0137)
	Control	1.0134 (0.0064)
4	Barge	1.0084 (0.0146)
	Control	1.0185 (0.0091)
5	Barge	0.9527 (0.0242)
	Control	1.0026 (0.0113)
6	Barge	0.9684 (0.0181)
	Control	0.9940 (0.0133)

TABLE 4. Estimates of within-barge survival ($\hat{S}$) of yearling Chinook salmon smolts by replicate trial along with associated release sample sizes. Densities (g/L) of Chinook salmon and steelhead in the right rear barge hold where study fish were held are also shown for each replicate.

Barge departure date	Trial	$\hat{S}$	$\widehat{SE}$	Number of fish released: Barged	Number of fish released: Control	Chinook salmon density	Steelhead density
29 Apr	1	1.0003	0.0155	92	92	3.8	4.4
1 May	2	0.9569	0.0219	141	143	3.8	1.1
4 May	3	0.9823	0.0121	116	115	9.7	8.5
7 May	4	0.9901	0.0113	89	91	8.1	6.9
10 May	5	0.9503	0.0253	102	104	1.3	2.0
13 May	6	0.9742	0.0204	155	152	4.6	2.0

not appear to be related to the estimated survival rates of the replicate groups (Table 4).

DISCUSSION

Attention to tagging protocols and quality assurance procedures ensured that release sizes in our study were known without error (assumption A1). The assumption of independent and identically distributed probabilities of success can be relaxed to assume only independence—in which case, the model presented as equation (1) will overestimate the true sampling variances (assumption A2). The R_D fish were placed into the barge hold prior to barge evacuation with sufficient time for these tagged dead fish to settle in a manner similar to that of the actual mortalities on the barge (assumption A3). The model assumed that survival in the barge was conditionally independent of survival from the time of barge evacuation to the downstream receiver array(s) (assumption A4). Similar handling of R_B and R_A fish was used to ensure that assumption A5 was met. The R_A fish releases were placed into the barge with enough time for the fish to equilibrate but not enough time for mortality to operate (assumption A6). All of the acoustic-tagged fish, regardless of release group (i.e., R_B, R_D, and R_A), were drawn from the same population of fish that was entering the barges, thus allowing us to make inferences back to the general barge population (assumption A7).

Based on the yearling Chinook salmon smolts tagged in 2010, the weighted average of our within-barge survival estimates was slightly over 98% ($\widehat{SE} = 0.06\%$), which comports well with the assumed 98% survival value that had been presented in previous literature (e.g., Bouwes et al. 1999; Peters and Marmorek 2001; Budy et al. 2002).

We do not know whether the transportation experience was the proximate cause of the 2% mortality we measured. It is possible that fish health and physiological condition prior to collection, the routing of fish through structures at the dam prior to barge transportation, or the density or species composition within the barge holds may have been factors in the mortality (Maule et al. 1988; Congleton et al. 2000). Maule et al. (1988) reported that the loading experience was stressful for transported juvenile Chinook salmon. Fish density within the barge hold in which tagged fish were transported did not appear to influence the estimated survival over the density ranges observed during our study. However, the barge hold densities in the present study were relatively low in comparison with densities during some of the transportation dates examined by Congleton et al. (2000). Congleton et al. (2000) found that barge-transported juvenile Chinook salmon showed higher values of stress indices when the densities of steelhead were higher. The density of juvenile steelhead in the barge hold was considerably lower in our study (1.1–8.5 g/L) than in the study conducted by Congleton et al. (2000; 5.4–60.8 g/L).

We observed 2% mortality of yearling Chinook salmon smolts during the barge transportation experience from Lower Granite Dam to downstream of Bonneville Dam in 2010, whereas Muir et al. (2001) estimated mortality of 41–69% for PIT-tagged yearling Chinook salmon migrating from Lower Granite Dam to the Bonneville Dam tailrace. Despite the large differences in mortality between barged fish and in-river migrants, the smolt-to-adult return rates of barged fish are typically not drastically higher than those for fish that migrate in the river (Buchanan et al. 2006). Some researchers have proposed that delayed mortality occurring after the transportation experience may offset the immediate survival advantage afforded by transportation (e.g., Budy et al. 2002; Muir et al. 2006; Schreck et al. 2006).

In all situations where scientists endeavor to increase the understanding of how mitigation measures influence the recovery of imperiled species, it is critical that the effectiveness of these management strategies be clearly understood. Population modeling based on inaccurate assumptions will yield inaccurate results and may jeopardize species recovery. The new method we developed to estimate mortality of yearling Chinook salmon during the barge transportation experience might provide some guidance to others conducting survival studies that require the holding and transport of fish prior to release. We did not evaluate other species or stocks (e.g., steelhead, sockeye salmon *O. nerka*, or subyearling Chinook salmon) or the influence of barge loading location on survival within the barge during transport. We also did not examine the survival of fish transported via trucks, as often occurs during portions of the season when emigrating smolts are less abundant. Finally, survival inside the barge may vary seasonally or annually, and our focused effort in 2010 was not intended to examine the influence of these other factors on juvenile salmonid survival during the transportation experience. If future modeling efforts or recovery planning requires precise estimates of survival for different fish species or stocks or for other operational conditions, then this model and telemetry approach can be used to provide the necessary information.

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