Turbine passage survival estimation for chinook salmon smolts (*Oncorhynchus tshawytscha*) at a large dam on the Columbia River

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Abstract: The short-term survival rate of hatchery-reared fall yearling chinook salmon smolts (*Oncorhynchus tshawytscha*) introduced at 3.1 m below the turbine intake ceiling ($N = 350$) at a large Columbia River hydroelectric dam relative to the survival rate of controls (released in the discharge) was estimated at 93.0% (90% profile CI = 90.1–95.5%); among those introduced at 9.3 m depth ($N = 250$) the survival rate was 94.7% (90% CI = 91.9–97.0%). Differences were not significant, and the pooled estimate of 93.9% (90% CI = 91.9–95.7%) is higher than is generally assumed or reported (70– 89%) for salmonids. Unlike the prevailing models based on recovery ratios of alive fish only, our likelihood model included the capture probabilities of both the alive and dead fish for estimation of parameters and their standard errors. Survival rates reported herein refer to the direct effects of turbine passage; those reported in the literature, however, do not make a clear distinction between direct (immediately upon turbine passage) and indirect effects that may occur over time. The types of fatal injuries observed suggested that a reduction or elimination of gaps between the hub and runner blades may enhance fish survival.

Résumé : On a estimé à 93,0% (profil à 90% : IC = 90,1–95,5%) le taux de survie à court terme de smolts de saumons quinnats d'automne (*Oncorhynchus tshawytscha*) élevés en pisciculture, introduits à 3,1 m sous la partie supérieure d'une prise d'eau de turbine ($N = 350$) d'un important barrage hydro-électrique du fleuve Columbia, par rapport à celui de témoins (libérés dans le déversoir); chez les smolts introduits à une profondeur de 9,3 m ($N = 250$), le taux de survie était de 94,7% (profil à 90% : IC = 91,9–97,0%). Les différences n'étaient pas significatives, et la valeur estimée combinée, de 93,9% (profil à 90 % : IC = 91,9–95,7%), est supérieure à celles qui sont généralement supposées ou signalées (70–89%) pour les salmonidés. À la différence des modèles les plus courants basés sur les rapports de récupération des poissons vivants seulement, notre modèle de vraisemblance prévoit les probabilités de prise des poissons vivants ou morts pour l'évaluation des paramètres et de leur écart-type. Les taux de survie signalés ici correspondent aux effets directs du passage dans la turbine; toutefois, ceux qui sont indiqués dans la littérature ne font pas une distinction très nette entre les effets directs (immédiatement après le passage dans la turbine) et les effets indirects qui surviennent plus tard. Les types de blessures mortelles observés laissent croire que la réduction (ou l'élimination) des espaces vides entre l'axe et les pales mobiles pourrait améliorer les chances de survie des poissons.
[Traduit par la Rédaction]

Introduction

Successful downstream passage of emigrating juvenile salmonids at large hydro dams in the Columbia River Basin is necessary to sustain, increase, or restore the salmon stocks. Of the several causes of mortality to juvenile salmonids on their seaward journey, passage through hydro turbines has been of major concern. Although this concern spans decades, the literature contains little information on survival estimates for chinook salmon smolts, *Oncorhynchus tshawytscha*, particularly at large hydro dams immediately upon turbine passage (Bell 1981; Eicher Associates, Inc. 1987). The available estimates are associated with much uncertainty and were derived under system configurations and operational conditions that were significantly different from those presently used. The tag–recapture methodologies (e.g., branding, fin clipping, or tattooing and subsequent recapture up to 160 km downstream over several days or months with the variable effect of flow on capture efficiencies) suffered low recapture rates and did not allow a clear distinction between immediate and delayed effects of turbine passage (Schoeneman et al. 1961). However, despite much uncertainty, generalized turbine passage survival rates of 70 to 85% at each dam have been assumed in fish passage models (Northwest Power Planning Council 1987; Reiman et al. 1991). At present, major decisions are pending regarding selection of permanent mitigative measures to

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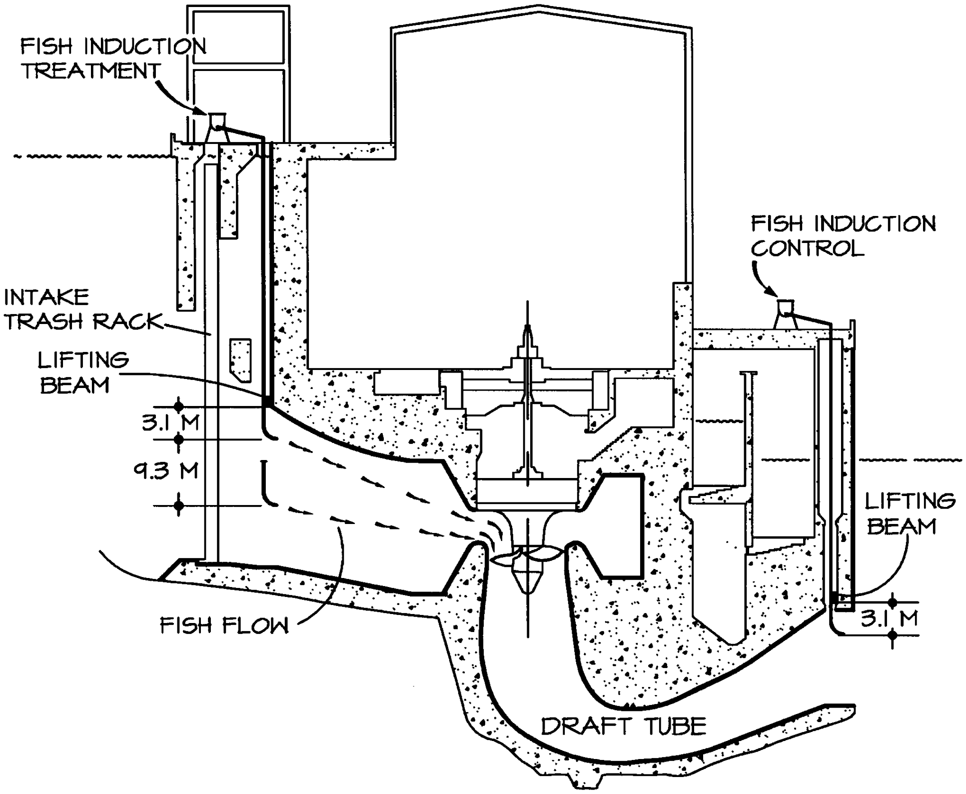
Fig. 1. Schematic of the studied turbine and fish introduction locations.



improve the survival of juvenile salmonids at many hydro dams in the Pacific Northwest. Consequently, precise estimates of turbine passage survival are necessary both to select the best combination of methods for enhancing survival of emigrating salmon smolts and as input in fishery models to improve predictions.

Our study had the following objectives: (*i*) estimation of 1- and 48-h survival (within ±5%, 90% of the time) of yearling fall chinook salmon smolts immediately upon turbine passage; and (*ii*) detection of differences in survival of smolts released at two depths, 3.1 and 9.3 m, below the ceiling of the turbine intake. The two turbine release depths were chosen because Raemhild et al. (1985) reported that approximately 80% of the emigrating salmon smolts enter within 6.1 m of the turbine intake ceiling, while the remainder enter at greater depths (Fig. 1). Hydraulic model studies for some large hydro dams have shown that ceiling-mounted intake guidance screens installed to exclude fish from transport through turbines cause flow to redistribute downward toward the intake floor and accelerate (Turner et al. 1993). Fish entrained in the accelerated, redistributed flow will tend to pass near the turbine blade tip area rather than the hub. Passage of fish through the blade tip region may be more detrimental than passage through the hub because of a higher probability of strike (Eicher Associates, Inc. 1987; Ferguson 1993). The flow redistribution may also increase fish mortality by exposing fish to more severe changes in pressure conditions (Turner et al. 1993). Furthermore, it has been suspected that the gaps between the turbine hub and runner blades pose additional risks to fish survival because flows from the upper area of the turbine intake may draw entrained fish to the hub area (Eicher Associates, Inc. 1987). However, these hypotheses have not been tested in the field.

Site description

The Rocky Reach Dam (river kilometre 752) is located on the Columbia River 11.2 km north of Wenatchee, Washington. The powerhouse, equipped with 11 vertical shaft propeller-type turbines, has a hydraulic capacity of 6125 $m^3 \cdot s^{-1}$ when there is no spillage. With spillage, the total hydraulic capacity of the project is 34 278 $m^3 \cdot s^{-1}$.

All tests were run on a single turbine that had six adjustable blades and was operated at its routine power load production (40–116 MW, 171–457 $m^3 \cdot s^{-1}$) along with other turbines during the study. Tests were run from mid-April through early May, the normal outmigration period of fall chinook salmon smolts at this site. The turbine runner speed is 90 revolutions per minute (rpm), the runner diameter is 7.1 m, and the net head was about 30 m.

Methods

Source of chinook smolts

Yearling fall chinook salmon smolts were obtained from the Rocky Reach Fish Hatchery, Wenatchee, Washington. Fish were either trucked to raceways located onshore across from the powerhouse or to the tagging site and released into holding tanks continuously supplied with ambient river water. Smolts were held for a minimum of 24 h prior to tagging and release to acclimate them to the ambient conditions. The size of chinooks (99–201 mm, average 161 mm fork length) was somewhat larger than the average size of typical emigrants (about 140 mm) generally observed at this site. Fish were randomly allocated to the treatment (turbine exposed) and control (released in discharge) groups and the resulting length distributions were similar ($P > 0.05$) for both groups.

Sample size calculation

One of the main considerations was the number of fish needed to obtain an estimate of survival ($\hat{\tau}$) within a specified precision level. We needed a sample size such that the survival estimate will have a precision (ε) of $\leq \pm 0.05$ at the $P = 0.90$ level $(1 - \alpha)$.

The precision of the estimate was defined as

$$P(|(1 - \hat{\tau}) - (1 - \tau)| < \varepsilon = 1 - \alpha$$

or equivalently

$$P(-\varepsilon < |\hat{\tau} - \tau| < \varepsilon) = 1 - \alpha$$

where the absolute error in estimation, i.e., $|\hat{\tau} - \tau|$, is $< \varepsilon(1 - \alpha)$, when τ is the true value of turbine passage survival and $\hat{\tau}$ is the estimated survival in passage through turbine. The value of ε corresponds to the expected half-width of a $(1 - \alpha)$ confidence interval for $\hat{\tau}$ or $1 - \hat{\tau}$. A precision of ±5%, 90% of the time, is expressed as the probability

$$P(|\hat{\tau} - \tau| < 0.05) = 0.90$$

The following terms are used in the equations and likelihood functions that follow: R_C is the number of control fish released, R_T is the number of treatment fish released into the turbine, a_C is the number of control fish recaptured alive, d_C is the number of control fish recaptured dead or assumed dead, a_T is the number of treatment fish recaptured alive, d_T is the number of treatment fish recaptured dead or assumed dead, S is the probability that fish survive from the release point of the controls to recapture, P_A is the probability an alive fish is recaptured, P_D is the probability a dead fish is recaptured, τ is the probability a treatment fish survives through the turbine, and $1 - \tau$ is turbine-related mortality.

Using the above definition of precision, the required sample sizes for paired control and treatment releases were calculated assuming normality of $\hat{\tau}$ as follows:

$$P\left(\frac{-\varepsilon}{\mathrm{Var}(\hat{\tau})} < Z < \frac{\varepsilon}{\mathrm{Var}(\hat{\tau})}\right) = 1 - \alpha$$

$$\varphi\left(\frac{-\varepsilon}{\mathrm{Var}(\hat{\tau})}\right) = \alpha/2$$

$$\mathrm{Var}(\hat{\tau}) = \frac{\varepsilon^2}{z_{1-\alpha/2}^2}$$

where $\mathrm{Var}(\hat{\tau})$ is the variance of estimate for $\hat{\tau}$, Z is a standard normal deviate satisfying the relationship $P(Z > Z_{1-\alpha/2}) = \alpha/2$, and ϕ is the cumulative distribution function for a standard normal deviate.

Letting $R_C = R_T = R$,

$$R = \frac{\tau}{SP_A}(1 + \tau - 2S\tau P_A)\frac{z_{1-\alpha/2}^2}{\varepsilon^2}$$

By rearranging, this expression can be solved to determine the anticipated precision given the number of fish available when planning a study; this may be of particular value for species targeted for restoration or in short supply.

The sample size (R) is a function of the recapture probabilities (P), expected turbine passage survival (τ) or mortality $(1 - \tau)$, survival probability of controls (S), and the desired precision (ε) at a given significance level (α). Initially, we assumed a combination of recapture, control survival, and turbine passage survival (τ) probabilities of 0.90 or 0.95 for calculating sample sizes. These values had been observed in some recent studies (e.g., Heisey et al. 1992). It was calculated that a paired release of approximately 530 each of treatment and control fish would be needed to achieve the desired precision ($\varepsilon = 0.05$, $1 - \alpha = 0.90$) with the combination of control survival, recapture, and turbine passage survival probabilities of 0.90 for each condition to be tested. However, as our study progressed it became evident that recapture and control survival probabilities exceeded 0.95, and passage survival (τ) probability was >0.90. A combination of these observed values indicated that the sample size could be truncated substantially and still maintain the desired level of precision.

Tagging

Heisey et al. (1992) described the HI-Z Turb'N Tag and recapture technique (U.S. Patent 4 970 988 and Canada Patent 2 016 607) used in the study to estimate direct effects of turbine passage. We emphasized the separation of direct effects, which are manifested immediately after turbine passage as instantaneous fish mortality, injury, and loss of equilibrium, from indirect effects (e.g., predation, disease, physiological stress) that may occur over an extended period and distance. Indirect effects may act individually or in synergism to cause additional mortality. The HI-Z tag effectively estimates direct effects of turbine passage without causing mortality or injury during recapture (Heisey et al. 1992; Mathur et al. 1994).

Fish were anesthetized in 0.5% MS-222, held in a 15-L tub, and tagged upon sedation. Additionally, each fish was given a unique numbered visual implant (VI; Northwest Marine Technology, Inc., Shaw Island, Wash.) tag in the adipose eyelid (postocular tissue) for tracking survival of individual smolts.

When smolts fully recovered from anesthesia, as evident from active swimming behavior, tags were activated and the fish were released through an induction system. The induction system consisted of a small holding basin attached to a 10 cm diameter PVC reinforced flexible delivery hose; the induction system was supplied with river water to ensure that fish were transported quickly within a continuous flow of water (Heisey et al. 1992). Treatment smolts were introduced into the penstock through the delivery hose at the desired depth of 3.1 or 9.3 m below the turbine intake ceiling (Fig. 1). The delivery hose was threaded through a metal pipe that was attached to a steel lifting beam. A 75 cm radius 90° elbow at the end of the metal pipe ensured that the delivery hose remained in position at the desired depths and that the delivery hose, water, and fish were discharged nearly parallel to the entrained flow. The delivery hose was lowered to the desired depths by an overhead crane.

An identical induction system, located on the powerhouse gallery, was deployed in the draft tube exit via a stoplog slot for control fish release (Fig. 1). The end of the delivery hose was positioned approximately 3.1 m beneath the ceiling of the draft tube. The lifting beam was firmly positioned above the draft tube ceiling so that treatment fish concurrently exposed to the turbine did not strike the steel beam frame. An equal number of smolts, as controls, were released at a depth where the treatment fish were expected to enter the tailrace. The control fish provided estimates on handling and tagging mortality and additional data on recapture probabilities.

Initially, two separate trials of 50 treatment and 50 control smolts each equipped with a single HI-Z tag and a miniature radio tag attached to the musculature anterior to the dorsal fin were released nearly simultaneously (Table 1). However, the use of a single HI-Z tag proved inadequate as a higher than expected recovery of inflated tags without fish attached was observed (7% of treatment and 1% of control fish lost tags). These tag recaptures were conservatively assumed dead in the analysis. However, evidence from later trials suggested that recovery of inflated tags without fish did not necessarily indicate immediate mortality. Consequently, in subsequent trials two HI-Z tags (Tables 1 and 2) were applied, with the additional tag attached near the base of the caudal fin. The use of two HI-Z tags increased the probability of fish recapture if one of the tags separated from the fish or malfunctioned.

Recapture

Shortly after release (generally 2–5 min) fish were buoyed to the surface and retrieved in a water sanctuary net and transferred to a

Table 1. Tag–recapture data (1 h) for treatment (turbine exposed) and control (released in turbine discharge) yearling fall chinook salmon smolts released 3.1 m below the intake ceiling of turbine unit 3 at the Rocky Reach Dam, April–May 1993.

	Trial							
	1[a]	2[a]	3	4	5	6	7	Total
Treatment								
No. released	50	50	50	50	50	50	50	350
No. recaptured alive	46	44	46	48	45	49	47	325
No. recaptured dead	1	0	1	2	1	0	2	7
Tags only	2	5	3	0	3	1	1	15
Unknowns	1	1	0	0	1	0	0	3
Control								
No. released	50	50	50	50	50	50	50	350
No. recaptured alive	50	49	49	49	50	50	49	346
No. recaptured dead	0	0	0	0	0	0	0	0
Tags only	0	1	0	0	0	0	0	1
Unknowns	0	0	1	1	0	0	1	3

Note: Homogeneity in recapture probabilities was tested by χ^2 analysis. The χ^2 values (with 12 degrees of freedom) were 7.84 ($P = 0.798$) and 9.07 ($P = 0.697$) for the treatment and control groups, respectively.

[a] Fish equipped with one HI-Z tag.

Table 2. Tag–recapture data (1 h) for treatment (turbine exposed) and control (released in turbine discharge) yearling fall chinook salmon smolts released 9.3 m below the intake ceiling of turbine unit 3 at the Rocky Reach Dam, April–May 1993.

	Trial					
	1	2	3	4	5	Total
Treatment						
No. released	50	50	50	50	50	250
No. recaptured alive	47	50	46	47	44	234
No. recaptured dead	3	0	1	1	2	7
Tags only	0	0	3	2	2	7
Unknowns	0	0	0	0	2	2
Control						
No. released	50	50	50	50	50	250
No. recaptured alive	49	50	49	50	49	247
No. recaptured dead	0	0	0	0	0	0
Tags only	1	0	0	0	0	1
Unknowns	0	0	1	0	1	2

Note: Homogeneity in recapture probabilities was tested by χ^2 analysis. The χ^2 values (with 8 degrees of freedom) were 12.26 ($P = 0.14$) and 7.024 ($P = 0.534$) for the treatment and control groups, respectively.

19-L bucket by crews in the recovery boats; none of the crews was specifically assigned to recapture control or treatment fish groups.

Upon recapture, the tag(s) was (were) removed and the fish carefully examined for type and extent of physical injuries. Injuries resulting from collision with turbine blades or other structural components were classified as mechanical (Eicher Associates, Inc. 1987): severed body, bruises or hemorrhaging, lacerations, missing eye(s), major scale loss, and stress (loss of equilibrium, stunning, abnormal swimming behavior). Injuries probably attributable to hydraulic (pressure change) forces are embolism, bulging eye(s), and air bladder rupture. All injured fish (dead and alive) were measured to establish a relationship, if any, between length and injury rate. The criteria given by Mathur et al. (1994) were used to classify the status of each fish (i.e., alive, dead, preyed upon, or unknown).

All fish recaptured alive were transferred to onshore holding tanks for estimating 48-h survival. Tanks were continuously supplied with ambient river water and covered to prevent fish escapement and potential predation.

Survival estimation

Turbine passage survival rates of fishes are estimated using paired release–recapture methods (Ricker 1975; Burnham et al. 1987). Unlike earlier investigations, however, recaptures of both alive and dead fish are possible with the HI-Z tag–recapture technique (Heisey et al. 1992). Thus, parameters associated with the recapture of both alive and dead fish can be incorporated into the construction of a statistical model. This, along with high recapture probabilities, can be used to estimate precisely turbine passage survival rates.

Maximum likelihood techniques were used to calculate the parameter estimates and their variances for each experiment. The likelihood model was based on the following assumptions: (*i*) the fate of each fish is independent; (*ii*) the control and treatment fish come from the same population of inference and share the same natural survival probability, S; (*iii*) all alive fish have the same probability, P_A, of recapture; (*iv*) all dead fish have the same probability, P_D, of recapture; and (*v*) turbine passage survival (τ) and natural survival (S) to the recapture point are conditionally independent. Additionally, we tested these assumptions: (*i*) handling, tagging, and release do not differentially affect survival probabilities of treatment and control groups; (*ii*) both groups are equally vulnerable to recapture; (*iii*) recapture crews do not differentially select retrieval of either group; and (*iv*) release and recapture of both groups occur over similar time periods (i.e., equality in exposure to tailrace conditions).

The joint likelihood (L) for turbine-related mortality or survival is

$$L(S,\tau,P_A,P_D|R_C,R_T,a_C,d_C,a_T,d_T) =$$

$$\binom{R_C}{a_C,d_C}(SP_A)^{a_C}((1-S)P_D)^{d_C}\,(1-SP_A-(1-S)P_D)^{R_C-a_C-d_C}$$

$$\times\binom{R_T}{a_T,d_T}(S\tau P_A)^{a_T}((1-S\tau)P_D)^{d_T}\,(1-S\tau P_A-(1-S\tau)P_D)^{R_T-a_T-d_T}$$

The generalized likelihood model (unequal recapture probabilities of alive, P_A, and dead fish, P_D) has four parameters (P_A, P_D, S, τ) and four minimum sufficient statistics (a_C, d_C, a_T, d_T). The maximum likelihood estimates are as follows:

$$\hat{\tau} = \frac{a_T R_C}{R_T a_C}$$

$$\hat{S} = \frac{R_T d_C a_C - R_C d_T a_C}{R_C d_C a_T - R_C d_T a_C}$$

$$\hat{P}_A = \frac{d_C a_T - d_T a_C}{R_T d_C - R_C d_T}$$

$$\hat{P}_D = \frac{d_C a_T - d_T a_C}{R_C a_T - R_T a_C}$$

The variance (Var) of the estimated turbine passage survival ($\hat{\tau}$) or mortality ($1 - \hat{\tau}$) is

$$\mathrm{Var}(\hat{\tau}) = \mathrm{Var}(1-\hat{\tau}) = \frac{\hat{\tau}}{SP_A}\left(\frac{(1-S\hat{\tau}P_A)}{R_T} + \frac{(1-SP_A)\hat{\tau}}{R_C}\right)$$

and associated standard error (SE),

$$\mathrm{SE}(\hat{\tau}) = \mathrm{SE}(1-\hat{\tau}) = (\mathrm{Var}(\hat{\tau}))^{1/2} = (\mathrm{Var}(1-\hat{\tau}))^{1/2}$$

An alternative likelihood with three parameters (P, S, τ) was also similarly constructed assuming that the recapture probabilities for alive and dead fish are equal ($P_A = P_D$). Iterative procedures were

Table 3. Pooled tag–recapture data (1 h) for yearling fall chinook salmon smolts released at 3.1 and 9.3 m below the intake ceiling of turbine unit 3 at the Rocky Reach Dam, April–May 1993.

	Treatment	Control
No. released	$R_T = 600$	$R_C = 600$
No. recaptured alive	$a_T = 559$ (0.932)	$a_C = 593$ (0.988)
No. recaptured dead	14 (0.023)	0 (0.0)
Inflated tags only	22 (0.037)	2 (0.003)
Unknowns	5 (0.008)	5 (0.008)

Note: Recapture probabilities are given in parentheses. Homogeneity in recapture probabilities was tested by χ^2 analysis. The last three values in each column (number of recaptured dead, inflated tags only, and unknowns) constitute d_T and d_C for the treatment and control groups, respectively. The χ^2 values (with 22 degrees of freedom) were 19.3 ($P = 0.59$) and 17.1 ($P = 0.76$) for the treatment and control trials, respectively. Symbols are defined in the text.

used to estimate the parameters for this reduced model. Likelihood ratio tests ($P = 0.05$) were used to test the null hypothesis (H_0: $P_A = P_D$) versus the alternative (H_A: $P_A \neq P_D$).

An alternative model using the assumption ($P_A = P_D = 1.0$) in survival estimation from radio telemetry studies was proposed by Pollock et al. (1995). However, this model was not applicable to our study because the assumption $P_A = P_D = 1.0$ was not met in our balloon tag–recapture studies (Heisey et al. 1992; Mathur et al. 1994; present study). The assumption of $P_A = P_D = 1.0$ would underestimate the variance, thereby falsely inflating the perceived precision level and bias the estimates of $\hat{\tau}$.

The 90% confidence intervals on the estimated turbine passage survival were calculated using the profile likelihood method (Hudson 1971). This method of constructing confidence intervals does not assume $\hat{\tau}$ to be normally distributed.

Results

Recapture rates

A paired release of 350 treatment and 350 control fish was made in seven trials of 50 per trial each day, at 3.1 m depth, and 250 treatment and 250 control fish in five trials of 50 per trial each day, at 9.3 m depth (Tables 1 and 2). Recapture probabilities of treatment and control fish were high (≥0.95) in both experiments, though some variation occurred particularly among 3.1 m depth treatment trials. Some of the variation was due to recovery of inflated tags without fish in trials 1 and 2 in which fish were equipped with only one tag (Table 1). However, recapture and survival probabilities between trials of both treatment and control groups were homogeneous (χ^2, $P > 0.05$) in the 3.1 m depth experiment as well as the 9.3 m depth test (Tables 1 and 2). This allowed pooling of individual trial data within the treatment and control groups. Homogeneity (χ^2, $P > 0.05$) among trials for the treatment and control groups was also seen for the entire data set (Table 3). The overall recapture probabilities of treatment and control groups (both alive and dead) were 0.955 and 0.988, respectively (Table 3). Likelihood ratio tests indicated that the recapture probabilities for alive (P_A) and dead (P_D) fish were equal ($P > 0.05$) for each depth as well as the pooled data (Table 4). Although the parameter values from both models are shown in Table 4, the reduced model provided slightly lower standard errors of the estimates.

Because of high recapture probabilities of alive fish, the proportion of fish classified in other categories was low for the entire study (Table 3). None of the control fish were dead at capture while 14 of 600 (2.3%) treatment fish were recaptured dead (Table 3). The percentages of fish classified as unknown were identical (0.8%) for both the treatment and control groups. However, a greater percentage of detached tags was retrieved for the treatment group than for controls (22 of 600 = 3.7% for treatment versus 2 of 600 = 0.3% for control). We recaptured 16 of 23 (69.6%) treatment fish that had lost one tag and the other tag buoyed the fish, suggesting tag separation or tag malfunction. It is likely that tag separation may have also occurred on fish tagged with only one HI-Z tag in the first two trials of the 3.1 m depth experiment (Table 1). This would inflate the proportion of fish assumed dead in the analysis.

Recapture times (time from release through the induction system until the fish or inflated detached tags were retrieved) for both groups were short and statistically similar ($P > 0.05$). The average recapture time for the treatment group was 4.8 ± 3.9 min (mean ± standard deviation) and for the control group it was 4.6 ± 4.6 min.

Survival rates

The estimated survival rates were high (≥93%) for treatment fish released at both depths and little mortality occurred over the 48-h period (Tables 5 and 6). The immediate (1 h) survival rate at 3.1 m depth was 93.9%; the 48-h survival rate was 93.0%. The survival rate at the 9.3 m depth was slightly higher; the immediate and 48-h survival rates were 95.5 and 94.7%, respectively. The slight increase in the calculated 48-h survival rate at the 9.3 m depth is a result of one additional control mortality. However, the 48-h survival was established at 94.7% because, intuitively, it cannot exceed immediate survival (Table 6). The differences in survival between the two depths were not significant ($P > 0.05$).

The homogeneity ($P > 0.05$) in recapture and survival probabilities enabled pooling of the two data sets (Table 7). The overall immediate and 48-h survival was estimated at 94.3 and 93.9%, respectively (Table 7). The precision was <±3% at the $1 - \alpha = 0.90$ level.

Injury

Observed injuries appeared to be caused by mechanical damage (e.g., collision with turbine blades and other structural components). Of the 332 treatment fish available for examination from the 3.1 m depth experiment (Table 1), 19 (5.7%) had severe injuries (severed body, lacerations, bruises and hemorrhaging, or major scale loss). Of the 241 treatment fish available for examination from the 9.3 m depth experiment (Table 2), 10 (4.1%) had severe injuries. However, these differences were not significant ($P > 0.05$). Also, injury rates for treatment fish ≥160 mm long (6.1%) were not significantly different from those of fish <160 mm long.

Discussion

A turbine passage survival estimate can be considered valid with the fulfillment of some of the critical assumptions. These assumptions were met to a large extent during the study, producing valid short-term survival estimates. The assumption of homogeneity ($P > 0.05$) in recapture probabilities both within

Table 4. Maximum likelihood parameter estimates (1 h) and associated standard errors for the reduced (H_0: $P_A = P_D$) and generalized (H_A: $P_A \neq P_D$) models for the yearling fall chinook salmon smolts released at 3.1 and 9.3 m below the intake ceiling of turbine unit 3 at the Rocky Reach Dam, April–May 1993.

	Parameter					
Model	S	$\hat{P}_A$	$\hat{P}_D$	P	$\hat{\tau}$	Log likelihood (ln$L$)
3.1 m depth						
H_0: P_A=P_D	0.997±0.003	—	—	0.991±0.004	0.939±0.013	–123.348
H_A: P_A≠P_D	0.997±0.003	0.991±0.005	0.991±0.111	—	0.939±0.015	–123.348
9.3 m depth						
H_0: P_A=P_D	0.996±0.004	—	—	0.992±0.004	0.947±0.015	–83.647
H_A: P_A≠P_D	0.996±0.004	0.992±0.006	0.992±0.148	—	0.947±0.017	–83.647
Pooled 3.1 and 9.3 m depths						
H_0: P_A=P_D	0.997±0.002	—	—	0.992±0.003	0.943±0.010	–207.090
H_A: P_A≠P_D	0.997±0.002	0.992±0.004	0.992±0.089	—	0.943±0.011	–207.090

Note: Symbols are defined in the text.

Table 5. Immediate (1 h) and 48-h maximum likelihood estimates of survival ($\hat{\tau}$) of yearling fall chinook salmon smolts released at 3.1 m below the intake ceiling of turbine unit 3 at the Rocky Reach Dam, April–May 1993.

	Group		
	Treatment	Control	Analysis
Immediate survival (1 h)			
No. released	$R_T = 350$	$R_C = 350$	
No. recaptured alive	$a_T = 325$	$a_C = 346$	
No. dead or assumed dead	$d_T = 25$	$d_C = 4$	
Estimated turbine survival, $\hat{\tau}$ (%)			93.9±1.34[a]
90% CI			91.5–96.0
Reduced model estimates			
$\hat{S}$			0.997 (0.003)
$\hat{P}$			0.9914 (0.004)
$\hat{\tau}$			0.939 (0.013)
48-h survival			
No. held	$R_T = 324$[b]	$R_C = 346$	
No. alive (48 h)	$a_T = 317$	$a_C = 342$	
No. dead or assumed dead	$d_T = 32$	$d_C = 8$	
Estimated turbine survival, $\hat{\tau}$ (%)			93.0±1.63[a]
90% CI			90.1–5.5
Reduced model estimates			
$\hat{S}$			0.986 (0.006)
$\hat{P}$			0.991 (0.004)
$\hat{\tau}$			0.93 (0.016)

Note: The profile 90% confidence intervals (CI) on survival estimates ($\hat{\tau}$) are based on the reduced model (H_0: $P_A = P_D$). Estimated turbine survival rates are given as the mean ± SE. Symbols are defined in the text.

[a] Adjusted for tag separation the immediate survival rate is 95.1% and the 48-h survival rate is 93.9%.

[b] One alive fish escaped during transfer and was excluded from the 48-h survival analysis; thus, $N = 349$ for the treatment group.

Table 6. Immediate (1 h) and 48-h maximum likelihood estimates of survival ($\hat{\tau}$) of yearling fall chinook salmon smolts released at 9.3 m below the intake ceiling of turbine unit 3 at the Rocky Reach Dam, April–May 1993.

	Group		
	Treatment	Control	Analysis
Immediate survival (1 h)			
No. released	$R_T = 250$	$R_C = 250$	
No. recaptured alive	$a_T = 234$	$a_C = 247$	
No. dead or assumed dead	$d_T = 16$	$d_C = 3$	
Estimated turbine survival, $\hat{\tau}$ (%)			94.7±1.48
90% CI			91.9–97.0
Reduced model estimates			
$\hat{S}$			0.996 (<0.001)
$\hat{P}$			0.992 (<0.001)
$\hat{\tau}$			0.947 (0.015)
48-h survival			
No. held	$R_T = 234$	$R_C = 247$	
No. alive (48 h)	$a_T = 234$	$a_C = 246$	
No. dead or assumed dead	$d_T = 16$	$d_C = 4$	
Estimated turbine survival, $\hat{\tau}$ (%)			95.1±1.53
90% CI			92.3–97.6
Reduced model estimates			
$\hat{S}$			0.992 (0.006)
$\hat{P}$			0.992 (0.004)
$\hat{\tau}$			0.951 (0.016)

Note: The profile 90% confidence intervals (CI) on survival estimates ($\hat{\tau}$) are based on the reduced model (H_0: $P_A = P_D$). Symbols are defined in the text.

and between control and treatment groups was satisfied. The assumption of homogeneity in recapture probabilities of alive and dead fish was also supported by statistical similarity. This in turn allowed fitting of a reduced model ($P_A = P_D$) to the data, resulting in greater precision.

The effect of recapture crew bias was minimized; no boat crew was specifically assigned to retrieve control or treatment fish. Through two-way radio communication the available boat crew was notified of a fish release throughout the study. The fish were nonselectively recaptured with minimal stress and injury. The average recapture times for the treatment and control groups were similar, thus satisfying the assumption of equality of the time both groups were exposed to tailrace conditions (i.e, common S). Although insertion of the tag, induction, and tag removal require fish handling and may result in some injury or mortality, these processes had minimal effects over the 48-h period and the mortality was quantifiable. The pooled 48-h survival of controls was 99.2% (588 of 593).

The inclusion of inflated tag recoveries without fish attached among the dead fish category appears to be a conservative assumption and may have slightly underestimated survival. Sixteen of 23 treatment fish (69.6%) equipped with two HI-Z tags but recovered with one tag were alive, suggesting that tag separation occurred. Fish stripped of a tag that lived for 48 h appeared to be healthy. Thus, if the inflated tag recaptures for fish with single tags are proportionally allocated to the alive and dead categories, the revised overall immediate and 48-h survival estimates for the study are 95.0 and 94.4%, respectively.

A combination of high recapture and high control survival probabilities allowed the use of relatively small sample sizes without sacrificing precision. The precision on the overall 48-h survival estimate was ≤±2.0%, 90% of the time ($N = 600$ treatment and control fish). The precision was equally high (<±3%, 90% of the time) with a paired treatment and control release of 250 fish. Thus, in planning a similar study elsewhere, a paired release of as few as 250 treatment and control fish should be adequate if these control survival and capture probabilities hold.

Past studies provide information on the relationship between recapture probabilities and the sample size requirements to achieve similar precision levels on survival estimates (Schoeneman et al. 1961; Olson and Kaczynski 1980). Schoeneman et al. (1961) reported a precision of ±2%, 95% of the time ($N =$ 300 000 chinook salmon fingerlings), at McNary Dam on the Columbia River; the recapture probabilities were less than 0.05. Olson and Kaczynski (1980) released over 500 000 juveniles of two species (coho salmon, *Oncorhynchus kisutch*, and steelhead trout, *Oncorhynchus mykiss*) at Rock Island Dam on the Columbia River; the recapture probabilities were less than 0.20 and the precision on the survival estimates was variable (±2.6–8.9%, 95% of the time). The present concern for protecting salmonid stocks may make it nearly impossible to use such large sample sizes for solving practical problems.

Our direct survival estimate of about 94% is higher than that often assumed or reported (70–89%) for chinook salmon smolts in passage through large hydro dams on the Columbia River Basin (Schoeneman et al. 1961; Bell 1981; Eicher Associates, Inc. 1987; Northwest Power Planning Council 1987; Reiman et al. 1991). The differences may be explained to a large degree by differences in experimental protocols, the most important being the time and location of fish recapture after releases were made. The recapture process generally occurred over many days and up to 160 km downstream of the powerhouse after fish were released into turbines (e.g., Schoeneman et al. 1961). Longer recapture times at distant locations expose fish, both treatment and controls, to other sources of mortality that may or may not be turbine induced. Consequently, it is likely that the estimates derived from such an experimental protocol include the effects of direct, indirect, and other sources of mortality (e.g., predation, disease, physiological stress). We emphasized separation of direct effects that are manifested immediately after turbine passage as instantaneous fish mortality, injury, and loss of equilibrium from indirect effects that may occur over an extended period and distance individually or synergistically. It is also likely that the differences in survival estimates may be due to differences in system configurations and operating conditions between the two time periods. However, to provide uniformity in the future it is important that in reporting estimates of turbine passage survival, investigators provide a clear distinction as to what effects those estimates portray (direct, indirect, or both). Our estimates represent only the direct effects of turbine passage and should be compared with those derived using rapid recapture methodologies.

Table 7. Immediate (1 h) and 48-h maximum likelihood estimates of survival ($\hat{\tau}$) of yearling fall chinook salmon smolts (pooled 3.1 and 9.3 m data) in passage through turbine unit 3 at the Rocky Reach Dam, April–May 1993.

	Group		
	Treatment	Control	Analysis
Immediate survival (1 h)			
No. released	$R_T = 600$	$R_C = 600$	
No. recaptured alive	$a_T = 559$	$a_C = 593$	
No. dead or assumed dead	$d_T = 41$	$d_C = 7$	
Estimated turbine survival, $\hat{\tau}$ (%)			94.3±1.01[a]
90% CI			92.5–95.8
Reduced model estimates			
$\hat{S}$			0.997 (0.002)
$\hat{P}$			0.992 (0.003)
$\hat{\tau}$			0.943 (0.010)
48-h survival			
No. held	$R_T = 599$[b]	$R_C = 600$	
No. alive (48 h)	$a_T = 551$	$a_C = 588$	
No. dead or assumed dead	$d_T = 48$	$d_C = 12$	
Estimated turbine survival, $\hat{\tau}$ (%)			93.9±1.15[a]
90% CI			91.9–95.7
Reduced model estimates			
$\hat{S}$			0.988 (0.004)
$\hat{P}$			0.992 (0.003)
$\hat{\tau}$			0.939 (0.012)

Note: The profile 90% confidence intervals (CI) on survival estimates ($\hat{\tau}$) are based on the reduced model (H_0: $P_A = P_D$). Symbols are defined in the text.

[a] Adjusted for tag separation the immediate survival rate is 95% and the 48-survival rate is 94.4%.

[b] One alive fish escaped during transfer and was excluded from the 48-h survival estimation; thus, $N = 599$ for the treatment group and 600 for the control group.

Our higher survival estimates were not attributed to chinook salmon size. Chinook salmon in the Schoeneman et al. (1961) study were smaller (40–60 mm total length) than ours (99–201 mm); theoretically, smaller fish are less likely to contact the turbine runner blades or other structural components (Bell 1981). Our estimates of direct effects of turbine passage, however, appear to be similar to those for juveniles of many other species including sensitive clupeids (Heisey et al. 1992; Mathur and Heisey 1992; Mathur et al. 1994).

The hypothesis that survival may be lower for fish entrained at greater depth (Eicher Associates, Inc. 1987; Ferguson 1993) within the turbine could not be supported by our findings. The immediate survival was 0.8% higher (though nonsignificant) for smolts introduced where flow would pass nearer the blade tips (9.3 m) than for those fish introduced in flow passing nearer the hub (3.1 m). At 48 h this difference increased to 1.7%. While these differences may seem quite small they are magnified when viewed from the perspective of improving total survival of emigrants encountering multiple dams.

The tested turbine configuration may explain the slightly lower fish survival at the shallower depth. These turbine types have clearances of about 13 to 38 mm between the runner blades and the hub to allow blade pitch adjustment. Water leaks through clearances at high velocity, thus potentially exposing fish passing through these gaps to scraping, grinding, or hydraulic shear. These gaps have been suspected of being one of the sources of fish injury and mortality (Eicher Associates, Inc. 1987; Ferguson 1993). Consequently, an effort to eliminate or reduce these gaps in turbines for future installations or existing ones may further enhance fish survival.

Although many troubling problems related to turbine passage still remain to be resolved, from a practical standpoint of turbine design improvements at the present time, precise estimation of the direct effects embodied in the turbine configuration is needed. The present study, in our view, quantified the direct effects of turbine passage and identified a potential area for turbine design improvements. On the basis of the present findings, the Public Utility District No. 1 of Chelan County in the state of Washington is proceeding with the development and model testing of a prototype turbine that all but eliminates the gaps between the hub and runner blades. However, the efficacy of any turbine design modification(s) would need to be evaluated in the field. Data from the present study can form a bench mark for relevant comparisons.

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