North American Journal of Fisheries Management 29:670–679, 2009

DOI: 10.1577/M07-227.1

[Article]

A Multiple-Release Model to Estimate Route-Specific and Dam Passage Survival at a Hydroelectric Project

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Abstract.—Previous methods of estimating route-specific passage and survival probabilities for anadromous salmonids past hydroelectric dams have often failed because of faulty assumptions. We present a robust, multiple-release model that combines release–recapture methods that are known to solve parts of the overall problem. Release 1 allows estimation of route-specific passage proportions and relative route-specific survival probabilities. Releases 2 and 3 provide an estimate of absolute survival through a particular route, which gives estimates of absolute route-specific survival probabilities and dam survival when combined with release 1. Releases 1 and 4 together provide an estimate of project (dam and pool) survival. Combining information from all four releases gives estimates of pool survival. The method is demonstrated through a 2006 study of sockeye salmon *Oncorhynchus nerka* passing Rocky Reach Dam on the Columbia River in Washington State. We estimate that the majority of tagged smolts passed via the powerhouse (51.41%, $\widehat{\mathrm{SE}} = 2.31\%$) and the fewest over the spillway (1.71%, $\widehat{\mathrm{SE}} = 0.60\%$). Estimates of route-specific survival ranged from 0.9657 ($\widehat{\mathrm{SE}} = 0.0220$) through the powerhouse to 1.0301 ($\widehat{\mathrm{SE}} = 0.0160$) over the spillway and through the bypass system. The estimated overall survival was 0.9794 ($\widehat{\mathrm{SE}} = 0.0264$) past the dam and 0.9527 ($\widehat{\mathrm{SE}} = 0.0285$) through the pool, so estimated survival through the Rocky Reach Project was 0.9331 ($\widehat{\mathrm{SE}} = 0.0121$).

Hydropower offers the promise of clean energy and is a common source of electricity, with more than 79,000 hydroelectric projects in the United States and many more worldwide. Along with their benefits, however, hydroelectric projects (i.e., dams) may block passage of both migratory and resident fish species. Dams that provide fish passage may nevertheless contribute to mortality in several ways, including direct mortality from passage and indirect mortality from increased predators and temperatures in the dam's reservoir (Raymond 1988). Hydroelectric projects that affect populations listed as endangered or threatened under the Endangered Species Act of 1973 (U.S. Code, title 16, chapter 35, sections 1531–1544) must be operated so they do not jeopardize the survival of those populations. Each ESA-listed population has a habitat conservation plan. For populations that pass a dam, the plan requires estimates of survival through the dam's pool (reservoir), past the dam itself, past the overall project (i.e., pool and dam together), and through each available passage route. Statistical release–recapture methods are necessary for producing these survival estimates. In this paper, we present a multiple-release study design for estimating these various survival probabilities for sockeye salmon *Oncorhynchus nerka* smolts migrating past Rocky Reach Dam on the Columbia River in Washington State (Figure 1) in 2006. The methods developed here may also be used for other species for which survival past hydroelectric projects must be estimated.

Several attempts have been made to address these passage survival questions for salmonids in the Pacific Northwest. For example, Skalski et al. (1998) developed a single-release, multiple-recapture model that used a release of tagged smolts at the top of the dam's pool (i.e., in the tailrace of the next dam upstream). The single-release model can be used to estimate the overall project survival, but does not allow separate estimation of pool and dam survival or estimation of survival through the different passage routes. Furthermore, estimates of project survival will be negatively biased in the presence of mortality that is caused by handling but occurs after release (postrelease mortality). Skalski et al. (2002) developed a paired-release model using radiotelemetry data for an upstream release in the

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Received December 19, 2007; accepted September 2, 2008

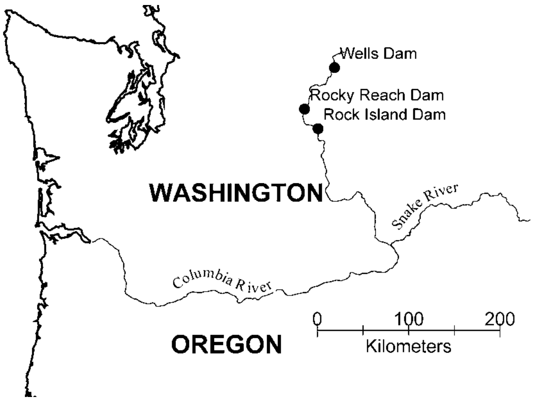

FIGURE 1.—Map of the Columbia River basin showing the locations of Wells, Rocky Reach, and Rock Island dams.

tailrace of the previous dam and a downstream release in the tailrace of the dam in question. Fish in the upstream release group were detected via radio antennae at the entrances to the dam. These detected fish were treated as a "virtual release group" and were compared with fish in the downstream release group. The virtual release group enabled estimation of passage probabilities through the different routes. Using it to also estimate route-specific survival probabilities depends on the assumption of a common survival probability of the virtual release group and the downstream release group. This assumption is often violated because the downstream release group experiences postrelease mortality in the monitored stretch of river, whereas the upstream release group experiences postrelease mortality in the tailrace of the previous dam. This violation of a key assumption results in positively biased estimates of dam passage survival.

A variation on the paired-release model of Skalski et al. (2002) places the upstream release in the forebay of the dam in question (Eppard et al. 1999). When smolts are released immediately upstream of the dam, it is reasonable to assume that the treatment (upstream release) and control (downstream release) groups experience the same tailrace mortality (including postrelease handling mortality). However, it is unlikely that smolts from a forebay release are distributed at the various dam passage routes in the same way as smolts that naturally approach the dam from upstream. A biased passage route distribution will produce an estimate of dam passage survival that is biased in an unknown way.

Although a complete and satisfactory statistical approach has not previously been developed to estimate route-specific survival as well as dam and pool survival, approaches have been developed for solving parts of this problem. In particular, a release from the top of the pool combined with double detection arrays at the entrances of the different routes through the dam can be used to determine the proportions of smolts entering the different passage routes (Skalski et al. 2002). Combining this design with arrays downstream of the dam enables estimation of the relative passage survival probabilities through the different routes. A release directly into a particular passage route, combined with a release in the tailrace downstream of that passage route, will provide an estimate of absolute survival through that passage route (Burnham et al. 1987). The estimate of absolute survival at one route and the estimates of relative survival through the other routes can be combined to give estimates of absolute survival through all routes and, thus, when combined with estimated passage probabilities, an estimate of dam passage survival. Finally, a paired release using the upstream release from the top of the pool and a downstream release in the tailrace of the dam will provide an estimate of project survival (Burnham et al. 1987). Pool survival can be estimated by dividing project survival by dam survival. Thus, by combining multiple approaches known to address different aspects of the estimation problem, a multiple-release model can be derived to estimate all desired quantities.

In this paper, we present a statistical model and estimators using a quadratic-release study design to estimate (1) route-specific passage and survival probabilities, (2) dam survival, and (3) pool survival. The model is demonstrated with acoustic release–recapture data of sockeye salmon from a tagging study designed to estimate passage, dam, and pool survival probabilities for Rocky Reach Dam (Chelan County, Washington) on the Columbia River in 2006.

Methods

Study site.—Rocky Reach Dam is a hydroelectric project on the middle Columbia River (river kilometer [rkm] 762.3, measuring from the mouth of the Columbia River) operated by Public Utility District No. 1 of Chelan County (Chelan PUD) in north-central Washington State (Figure 1). Rocky Reach has 11 hydraulic turbines, providing a combined hydraulic capacity through the powerhouse of 6,229.7 m^3/s. There are 12 spillway gates through which smolts may pass during spill operations. Alternatively, smolts may pass through a surface collector, the juvenile bypass system, or the powerhouse (turbines). Both the surface collector and the bypass system divert smolts around the dam to the tailrace through a system of tubes. Rocky Reach's reservoir, Lake Entiat, extends upriver 66.7 rkm to the tailrace of Wells Dam.

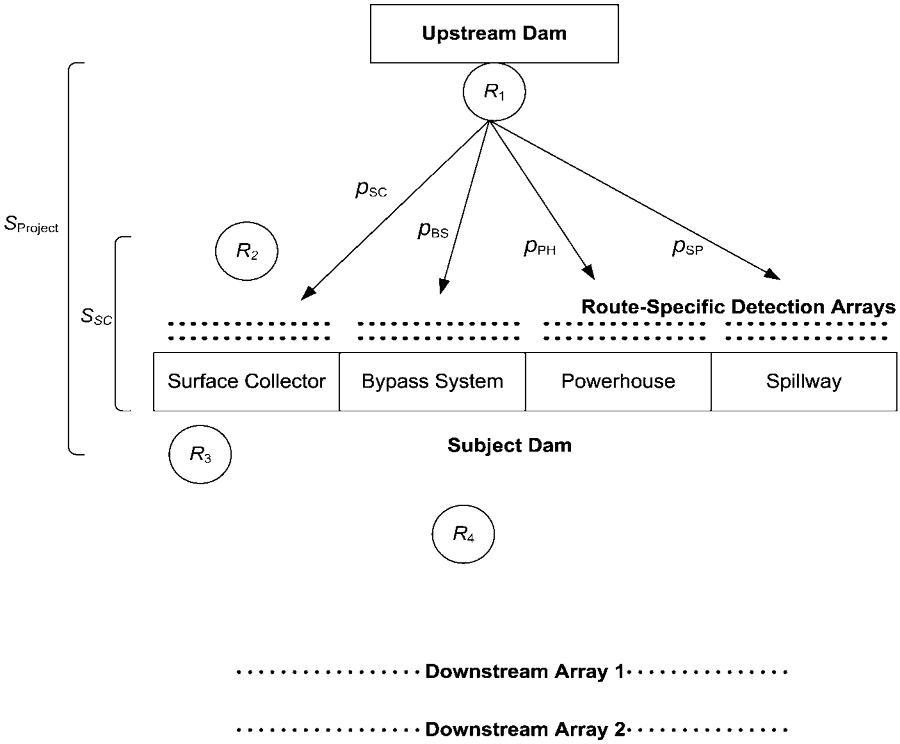

FIGURE 2.—Schematic of the quadruple-release study design using release groups R_1, R_2, R_3, and R_4. The proportion of R_1 passing the subject dam by route i is denoted by p_i, where i = SC (surface collector), BS (bypass system), PH (powerhouse), or SP (spillway). Project survival from the tailrace of the upstream dam to the tailrace of the subject dam is denoted S_{Project}; absolute survival through the surface collector is denoted S_{SC}. Double detection arrays are placed at each passage route at the subject dam, and two detection arrays are located downstream of the subject dam's tailrace.

Tagging and release of smolts.—Emigrating run-of-river sockeye salmon smolts were collected from the juvenile bypass collector at Rocky Reach Dam. Acoustic transmitter tags were surgically implanted in each smolt at least 95 mm in fork length. Fish were first anesthetized with tricaine methanesulfonate (MS-222) at 100-mg/L of water and inspected for injuries, deformations, and extreme scale loss before tagging. Fish were held for 48 h after tagging to allow for recovery and identification of post-tagging mortality, tag loss, or premature tag failure.

The tags used were HTI Model 795m Acoustic Tags. These tags were approximately 6.8 mm in diameter × 16.5 mm long, weighed 0.75 g in air (about 2.7–8.4% of fish body weight), and had an average operating life of 15–21 d. The HTI Model 290 Acoustic Tag Receiver (ATR) system was used to detect tagged fish at various downriver sites. This ATR system supports up to 16 hydrophones and operates at 307 kHz. For more information on the acoustic tag methods used, see Steig et al. (2004).

A quadruple-release study design was used (Figure 2) to estimate dam and route-specific passage and survival probabilities. An upstream release at Wells Dam tailrace (R_1) was paired with a tailrace release at Rocky Reach (R_4) to estimate project passage survival. The release pair R_2 and R_3 was used to estimate absolute survival through the juvenile surface collector. In this study, the location of the surface collector outfall in the Rocky Reach tailrace meant that the optimal release locations for R_3 and R_4 were the same, so only a single release (R_3') was made in the Rocky Reach tailrace in place of both R_3 and R_4. In general, releases R_3 and R_4 need to be unique. To estimate the numbers of tagged smolts entering each passage route, double hydroacoustic arrays were placed at the entrances to each of the four routes that smolts use to pass the dam. Downstream detection arrays were placed at the Rock Island Hydropark (rkm 743.5) and the Rock Island Dam boat restriction zone (rkm 730.6).

Statistical model.—A generic quadruple-release model will be used to illustrate the estimation of route-specific passage and survival probabilities as well as dam and pool survival probabilities. As a result of the unique layout at Rocky Reach Dam, this quadruple-release model was simplified to a triple-release model, where release R_3' was used in place of both R_3 and R_4. The possible routes through Rocky Reach Dam include the powerhouse (PH), spillway (SP), bypass system (BS), and surface collector (SC). Formulae of estimators are presented first, followed by a discussion of the necessary assumptions. The likelihood model is presented in the Appendix.

The first release (R_1; Figure 2) is at the top of the reservoir and is used to estimate the proportions of fish entering the different dam passage routes, the relative survival through each route, and project survival. The double hydroacoustic array at each route entry was used to estimate the number of tagged smolts passing by each route. For each passage route, let n_{10} be the number of tagged smolts detected at the first array but not the second, n_{01} the number detected at the second array but not the first, and n_{11} the number detected at both arrays. Under the assumption of no mortality between the two arrays, the number of tagged smolts estimated to have entered that passage route is then (Chapman 1951)

$$\hat{N} = \frac{(n_1 + 1)(n_2 + 1)}{n_{11} + 1} - 1, \tag{1}$$

where $n_1 = n_{10} + n_{11}$ and $n_2 = n_{01} + n_{11}$; the associated variance estimator (Seber 1982: 60) is

$$\widehat{\text{Var}}(\hat{N}) = \frac{(n_1 + 1)(n_2 + 1)n_{10}n_{01}}{(n_{11} + 1)^2(n_{11} + 2)}. \tag{2}$$

Using equation (1) for each passage route, $\hat{N}_{\text{SC}}$, $\hat{N}_{\text{PH}}$, $\hat{N}_{\text{SP}}$, and $\hat{N}_{\text{BS}}$ can be estimated. The proportion of tagged smolts that passed through the surface collector (i.e., the passage probability through the surface collector, p_{SC}) is estimated by

$$\hat{p}_{\text{SC}} = \frac{\hat{N}_{\text{SC}}}{\hat{N}_{\text{SC}} + \hat{N}_{\text{PH}} + \hat{N}_{\text{SP}} + \hat{N}_{\text{BS}}}. \tag{3}$$

The variance of $\hat{p}_{\text{SC}}$ can be estimated using the delta method (Seber 1982:7–9), as follows:

$$\begin{aligned}
&\widehat{\text{Var}}(\hat{p}_{\text{SC}}) \\
&= \frac{\hat{p}_{\text{SC}}(1 - \hat{p}_{\text{SC}})}{(\hat{N}_{\text{SC}} + \hat{N}_{\text{PH}} + \hat{N}_{\text{SP}} + \hat{N}_{\text{BS}})2} + \hat{p}_{\text{SC}}^2(1 - \hat{p}_{\text{SC}})^2 \\
&\quad \times \left[\frac{\widehat{\text{Var}}(\hat{N}_{\text{SC}})}{\hat{N}_{\text{SC}}^2} + \frac{\widehat{\text{Var}}(\hat{N}_{\text{PH}}) + \widehat{\text{Var}}(\hat{N}_{\text{SP}}) + \widehat{\text{Var}}(\hat{N}_{\text{BS}})}{(\hat{N}_{\text{PH}} + \hat{N}_{\text{SP}} + \hat{N}_{\text{BS}})^2}\right].
\end{aligned} \tag{4}$$

The proportions p_{PH}, p_{SP}, and p_{BS} and their respective variances are estimated analogously.

Release R_1 also gives information to estimate relative route-specific survival in terms of the survival through a particular passage route, say the surface collector. For example, to estimate the relative survival of smolts through the powerhouse compared with the surface collector ($R_{\text{PH/SC}}$), let M_{PH} be the number of smolts known to have passed through the powerhouse (i.e., the number of smolts actually detected at the powerhouse entry), and let m_{PH} be the number of these smolts later detected downstream. Additionally, define S_{PH} to be the survival probability through the powerhouse, and define M_{SP}, M_{BS}, M_{SC}, m_{SP}, m_{BS}, m_{SC}, S_{SP}, S_{BS}, and S_{SC} analogously. Then $R_{\text{PH/SC}} = S_{\text{PH}}/S_{\text{SC}}$ and is estimated as

$$\hat{R}_{\text{PH/SC}} = \frac{(m_{\text{PH}}/M_{\text{PH}})}{(m_{\text{SC}}/M_{\text{SC}})}, \tag{5}$$

and the associated variance estimator (Burnham et al. 1987:84) is

$$\widehat{\text{Var}}(\hat{R}_{\text{PH/SC}}) = \hat{R}_{\text{PH/SC}}^2\left(\frac{1}{m_{\text{PH}}} - \frac{1}{M_{\text{PH}}} + \frac{1}{m_{\text{SC}}} - \frac{1}{M_{\text{SC}}}\right). \tag{6}$$

The relative survival probabilities $R_{\text{SP/SC}}$ and $R_{\text{BS/SC}}$ are estimated analogously.

Releases R_2 and R_3 (Figure 2) are used to estimate absolute survival through the surface collector via a paired release–recapture model. Under the assumption of homogeneous detection processes for releases R_2 and R_3, survival through the surface collector ($\hat{S}_{\text{SC}}$) is estimated as the relative recovery ratio of R_2 compared with R_3. More precisely, let t be the number of smolts from R_2 detected downstream and c be the number from R_3 detected downstream. Then S_{SC} is estimated as

$$\hat{S}_{\text{SC}} = \left(\frac{t}{R_2}\right) / \left(\frac{c}{R_3}\right), \tag{7}$$

and the associated variance estimator is

$$\widehat{\text{Var}}(\hat{S}_{\text{SC}}) = \hat{S}_{\text{SC}}^2\left(\frac{1}{t} - \frac{1}{R_2} + \frac{1}{c} - \frac{1}{R_3}\right). \tag{8}$$

Equation (7) is based on model $H_{1\phi}$ of Burnham et al. (1987). Should downstream detection processes be heterogeneous for releases R_2 and R_3, alternative survival estimators may be necessary.

The estimate of survival through the surface collector ($\hat{S}_{\text{SC}}$) can be combined with the estimates of the relative route-specific survival probabilities $\hat{R}_{\text{PH/SC}}$, $\hat{R}_{\text{SP/SC}}$ and $\hat{R}_{\text{BS/SC}}$ to estimate absolute survival through the powerhouse, spillway, and bypass routes. For example, powerhouse survival (S_{PH}) is estimated as

$$\hat{S}_{\text{PH}} = \hat{R}_{\text{PH/SC}} \cdot \hat{S}_{\text{SC}} = \left(\frac{m_{\text{PH}}/M_{\text{PH}}}{m_{\text{SC}}/M_{\text{SC}}}\right) \cdot \left(\frac{t/R_2}{c/R_3}\right). \tag{9}$$

The estimates $\hat{R}_{\mathrm{PH/SC}}$ and $\hat{S}_{\mathrm{SC}}$ are derived from separate release groups, so these estimates are independent, resulting in the following variance estimator for $\hat{S}_{\mathrm{PH}}$ (Goodman 1960):

$$\widehat{\mathrm{Var}}(\hat{S}_{\mathrm{PH}}) = \widehat{\mathrm{Var}}(\hat{R}_{\mathrm{PH/SC}})\cdot\hat{S}^2_{\mathrm{SC}} + \widehat{\mathrm{Var}}(\hat{S}_{\mathrm{SC}})\cdot\hat{R}^2_{\mathrm{PH/SC}} - \widehat{\mathrm{Var}}(\hat{R}_{\mathrm{PH/SC}})\cdot\widehat{\mathrm{Var}}(\hat{S}_{\mathrm{SC}}). \tag{10}$$

The estimators of S_{SP} and S_{BS} and their associated variances are defined analogously.

Overall dam survival can be estimated by combining the estimates of route-specific passage and survival probabilities as follows:

$$\hat{S}_{\mathrm{Dam}} = \hat{S}_{\mathrm{SC}}(\hat{p}_{\mathrm{PH}}\cdot\hat{R}_{\mathrm{PH/SC}} + \hat{p}_{\mathrm{SP}}\cdot\hat{R}_{\mathrm{SP/SC}} + \hat{p}_{\mathrm{BS}}\cdot\hat{R}_{\mathrm{BS/SC}} + \hat{p}_{\mathrm{SC}}). \tag{11}$$

The variance of $\hat{S}_{\mathrm{Dam}}$ can be estimated via the delta method as

$$\begin{aligned}\widehat{\mathrm{Var}}(\hat{S}_{\mathrm{Dam}}) &= \hat{S}^2_{\mathrm{SC}}\Big[\hat{R}^2_{\mathrm{PH/SC}}\widehat{\mathrm{Var}}(\hat{p}_{\mathrm{PH}}) + \hat{R}^2_{\mathrm{SP/SC}}\widehat{\mathrm{Var}}(\hat{p}_{\mathrm{SP}}) \\ &\quad + \hat{R}^2_{\mathrm{BS/SC}}\widehat{\mathrm{Var}}(\hat{p}_{\mathrm{BS}}) + \widehat{\mathrm{Var}}(\hat{p}_{\mathrm{SC}}) + \hat{p}^2_{\mathrm{PH}}\widehat{\mathrm{Var}}(\hat{R}_{\mathrm{PH/SC}}) \\ &\quad + \hat{p}^2_{\mathrm{SP}}\widehat{\mathrm{Var}}(\hat{R}_{\mathrm{SP/SC}}) + \hat{p}^2_{\mathrm{BS}}\widehat{\mathrm{Var}}(\hat{R}_{\mathrm{BS/SC}})] \\ &\quad + (\hat{S}_{\mathrm{Dam}}/\hat{S}_{\mathrm{SC}})^2\widehat{\mathrm{Var}}(\hat{S}_{\mathrm{SC}}).\end{aligned} \tag{12}$$

The variance estimator in equation (12) ignores the negative correlation among the passage proportion estimates $\hat{p}_{\mathrm{SC}}$, $\hat{p}_{\mathrm{BS}}$, $\hat{p}_{\mathrm{PH}}$, and $\hat{p}_{\mathrm{SP}}$. The effect of this correlation is to lower the variance of $\hat{S}_{\mathrm{Dam}}$ by a negligible amount.

Releases R_1 and R_4 (Figure 2) with downstream detections provide information for estimating overall project (dam and pool) survival by using the paired release–recapture methods of Burnham et al. (1987). Rocky Reach project survival, S_{RR}, is the product of survival through Rocky Reach's pool (S_{Pool}) and past Rocky Reach Dam itself (S_{Dam}). This allows estimation of survival through the pool as follows:

$$\hat{S}_{\mathrm{Pool}} = \hat{S}_{\mathrm{RR}}/\hat{S}_{\mathrm{Dam}}, \tag{13}$$

with estimated variance

$$\widehat{\mathrm{Var}}(\hat{S}_{\mathrm{Pool}}) = \hat{S}^2_{\mathrm{Pool}}\left[\frac{\widehat{\mathrm{Var}}(\hat{S}_{\mathrm{RR}})}{\hat{S}^2_{\mathrm{RR}}} + \frac{\widehat{\mathrm{Var}}(\hat{S}_{\mathrm{Dam}})}{\hat{S}^2_{\mathrm{Dam}}}\right]. \tag{14}$$

Assumptions.—The following assumptions are used: (1) at each passage route at the subject dam, detections at the two arrays are independent; (2) all smolts within a release group have equal and independent survival and detection probabilities; (3) all smolts in releases R_1 and R_4 have the same magnitude of postrelease mortality and tag loss by the time they arrive at the downstream detection sites; (4) releases R_1 and R_4 have the same downstream natural survival probabilities below the release location of R_4; (5) all smolts in releases R_2 and R_3 have the same magnitude of postrelease mortality and tag loss by the time they arrive at the downstream detection sites; (6) releases R_2 and R_3 have the same downstream natural survival probabilities below the release location of R_3; and (7) all smolts known to have passed through the hydroproject have the same downstream detection probabilities.

Assumption (1) is necessary to correctly estimate the absolute passage numbers at the different passage routes. Violations of this assumption will result in biased estimates of absolute passage numbers, route-specific survival, and dam passage survival. Along with assumption (1), assumptions (2), (3), (4), and (7) are necessary to estimate the relative route-specific survival probabilities. Assumptions (2), (5), (6), and (7) are necessary to estimate absolute survival through the specific dam passage route. Assumptions (2), (3), (4), and (7) are necessary to estimate project survival. With extra detection arrays downstream, it may be possible to relax assumptions (4) and (6) (Burnham et al. 1987).

Results

For the Rocky Reach study in 2006, releases R_3 and R_4 were combined to form a single release (R_3') in the Rocky Reach tailrace below the surface collector. A total of 481 acoustically tagged sockeye smolts were released (R_1) in the Wells Dam tailrace (Table 1); releases made above and below the surface collector at Rocky Reach Dam included R_2 (479 smolts) and R_3' (478; Table 2). A total of 467 smolts from R_1 were detected at the entrances to the Rocky Reach passage routes (Tables 1, 3) and monitored for detection downriver at the Rock Island acoustic arrays. We estimated that the powerhouse passed the highest proportion of fish (0.5141; $\widehat{\mathrm{SE}} = 0.0231$), followed closely by the surface collector (0.4345; $\widehat{\mathrm{SE}} = 0.0229$; Table 4). The fewest numbers of fish were passed at the bypass system (0.0342; $\widehat{\mathrm{SE}} = 0.0084$) and spillway (0.0171; $\widehat{\mathrm{SE}} = 0.0060$). The average percent spill during the course of the study was 14.4%.

Survival through the surface collector was estimated to be 0.9895 ($\widehat{\mathrm{SE}} = 0.0062$). Survival estimates through the other routes ranged from 0.9657 ($\widehat{\mathrm{SE}} = 0.0220$) for the powerhouse to 1.0301 ($\widehat{\mathrm{SE}} = 0.0160$) for both the bypass system and spillway. Overall dam passage

TABLE 1.—Detection histories for the 481 acoustic-tagged sockeye salmon smolts released (R_1) in the tailrace of Wells Dam of the Columbia River in Washington. Detection locations were downstream, where smolts were initially enumerated as detections or nondetections at Rocky Reach Dam and then detected (d) or not detected (n) at the Rock Island Hydropark (HP) and boat restriction zone (BR) acoustic arrays.

Rocky Reach Dam		Rock Island Dam			
Detection site	Number detected	HP_d–BR_d	HP_d–BR_n	HP_n–BR_d	HP_n–BR_n
Powerhouse	240	225	0	0	15
Spillway	8	8	0	0	0
Bypass system	16	16	0	0	0
Surface collector	203	194	1	0	8
Not detected	14	3	0	0	11

survival was estimated at 0.9794 ($\widehat{\mathrm{SE}} = 0.0264$). Pool passage survival was estimated to be 0.9527 ($\widehat{\mathrm{SE}} = 0.0285$), and overall project survival was estimated to be 0.9331 ($\widehat{\mathrm{SE}} = 0.0121$).

The estimated numbers of smolts from R_1 that entered each detection route were nearly identical to the total detected at each route (Table 3), indicating that the overall detection probability at the double arrays at Rocky Reach was nearly 1.0. Combined with the estimated survival through the pool, this gave an expectation that less than 1 of the 481 smolts in R_1 would pass the dam undetected, with subsequent detection downstream. Of the 14 smolts from R_1 that were not detected at Rocky Reach Dam (Table 1), 3 smolts were detected at downstream arrays at Rock Island and 11 were never detected. The low number of fish passing Rocky Reach undetected empirically confirms the implied nearly perfect detection probabilities at the double arrays we used in estimating route-specific passage proportions in this study (Table 3).

Discussion

Estimating route-specific survival and survival past a dam is similar to the old problem of measuring weights with only a pan balance and four rocks: How should the rocks be arranged on the two pans in order to measure the desired weight? In this paper, we present a method of arranging our four rocks (i.e., releases) and our balance (i.e., acoustic arrays) to estimate (1) route-specific passage proportions, (2) route-specific survival, (3) project survival, (4) dam survival, and (5) pool survival. Although the single- and double-release methods used in the past (e.g., Skalski et al. 1998) can be used to estimate project survival, they are insufficient for estimating route-specific parameters or for separating project survival into pool and dam survival. Typically, a quadruple release–recapture design is needed to partition project survival into dam and pool components. For the 2006 sockeye salmon study, the unique geometry of Rocky Reach Dam made it possible to combine the two tailrace releases (R_3 and R_4), so that a triple-release design could be used.

Analytical Considerations

Analysis of the multiple releases could be written as a joint likelihood model (Appendix), using maximum likelihood methods to estimate parameters. We chose instead to focus on more easily described closed-form estimators with variance estimators derived via the delta method to better illustrate the design elements of the study in this paper. The closed-form estimators are all method-of-moments estimators that are bias-adjusted when necessary. Thus, the closed-form estimators presented here are unbiased to a first-order approximation, whereas the maximum likelihood estimators (MLEs) derived from the likelihood model may exhibit considerable bias for small sample sizes. However, the likelihood model may be useful for model selection or model averaging under alternative hypotheses, such as common detection probabilities at the entrance arrays or common passage survival probabilities across routes.

All unbiased estimators of probability parameters whose true values are at or near 1.0 may yield estimates that are greater than 1.0. This occurred for the 2006 sockeye salmon study, where point estimates of both survival over the spillway and survival through the bypass system were equal to 1.0301. In such cases it may be reasonable to truncate the out-of-range estimates at 1.0. However, estimates of other param-

TABLE 2.—Detection histories for acoustic-tagged sockeye salmon smolts in releases above (R_2) and below (R_3') the surface collector at Rocky Reach Dam, Columbia River, Washington. Detection locations were downstream, where smolts were detected (d) or not detected (n) at the Rock Island Hydropark (HP) and boat restriction zone (BR) acoustic arrays.

			Rock Island Dam			
Release group	Release site	Number released	HP_d–BR_d	HP_d–BR_n	HP_n–BR_d	HP_n–BR_n
R_2	Above surface collector	479	470	2	0	7
R_3'	Below surface collector	478	473	3	0	2

TABLE 3.—Detection histories at Rocky Reach Dam for the 467 acoustic-tagged sockeye salmon smolts released (R_1) in the tailrace of Wells Dam that were detected (d) or not detected (n) at Rocky Reach Dam, as well as the number estimated to have passed via each of four routes ($\hat{N}$). Detection locations were at the first (A1) and then second (A2) acoustic arrays at the entrances to the Rocky Reach Dam powerhouse, spillway, bypass system, and surface collector.

Rocky Reach detection site	Detection history at Rocky Reach			Number detected	$\hat{N}$	$\widehat{\text{SE}}$
	$A1_d$–$A2_d$	$A1_d$–$A2_n$	$A1_n$–$A2_d$			
Powerhouse	226	6	8	240	240.21	0.47
Spillway	8	0	0	8	8	0
Bypass system	13	3	0	16	16	0
Surface collector	200	1	2	203	203.01	0.10

eters that are based on the truncated values (e.g., dam and pool survival) will then be biased. For the 2006 study, truncating the spillway and bypass survival estimates to 1.0 resulted in estimates of 0.9771 and 0.9544 for dam and pool survival, respectively, compared with 0.9794 and 0.9527 without truncation. The truncated and nontruncated estimates of dam and pool survival were very similar because the passage routes with truncated survival estimates were rarely used in the 2006 study, resulting in low sensitivity of dam and pool survival to spillway and bypass survival. The decision of whether or not to truncate out-of-range (but unbiased) estimators to 1.0 must be based on both analysis goals and the bias introduced by truncation.

Numerous parameters are estimated using the multiple releases in this study design, and it is reasonable to expect that some estimates will be correlated, regardless of whether method-of-moments estimators or MLEs are used. For instance, $\hat{S}_{\text{Dam}}$ and $\hat{S}_{\text{Pool}}$ will be negatively correlated because their product ($\hat{S}_{\text{RR}}$) is fixed. As estimates of multinomial probabilities, the estimated passage proportions $\hat{p}_i$ will be negatively correlated, as well. However, the relative passage survival estimates, $\hat{R}_{i/\text{SC}}$, comparing route i to the surface collector, will be pairwise independent, conditional on the assumption of common postpassage survival and detection processes in the tailrace and downstream for all passage routes. Furthermore, the relative survival estimates $\hat{R}_{i/\text{SC}}$ will each be independent of the estimate of absolute survival through the surface collector ($\hat{S}_{\text{SC}}$) because they are estimated using separate release groups. However, because of their mutual dependence on $\hat{S}_{\text{SC}}$, the estimates of absolute route-specific passage survival ($\hat{S}_i$) will be positively correlated.

TABLE 4.—Estimated passage proportions ($\hat{p}$) and survival probabilities ($\hat{S}$) for the 2006 sockeye salmon study at Rocky Reach Dam, Columbia River, Washington. The pool and the dam together = project.

Parameter	Description	Estimate	$\widehat{\text{SE}}$
p_{PH}	Proportion through powerhouse	0.5141	0.0231
p_{SP}	Proportion through spillway	0.0171	0.0060
p_{BS}	Proportion through bypass system	0.0342	0.0084
p_{SC}	Proportion through surface collector	0.4345	0.0229
S_{PH}	Survival through powerhouse	0.9657	0.0220
S_{SP}	Survival through spillway	1.0301	0.0160
S_{BS}	Survival through bypass system	1.0301	0.0160
S_{SC}	Survival through surface collector	0.9895	0.0062
S_{Dam}	Survival past Rocky Reach Dam	0.9794	0.0264
S_{Pool}	Survival through Rocky Reach pool	0.9527	0.0285
S_{RR}	Survival through Rocky Reach project	0.9331	0.0121

Using the generalized quadruple-release study design, the estimate of project survival ($\hat{S}_{\text{RR}}$) and the estimate of absolute passage survival through the surface collector ($\hat{S}_{\text{SC}}$) will be independent because they are estimated using separate release groups. Moreover, the quadruple-release design produces independent estimates of dam and project survival ($\hat{S}_{\text{Dam}}$ and $\hat{S}_{\text{RR}}$), conditional on the assumption of common postpassage downstream survival and detection processes for all passage routes.

Design Considerations

In some cases, it may be possible to simplify the study design by using three releases instead of four, as in the 2006 study at Rocky Reach Dam. The decision to use three releases instead of four should be based primarily on logistical considerations dictated by the layout of the dam in question. In the quadruple-release design, release R_4 in the tailrace is paired with the upstream release R_1 to estimate project survival. Thus, R_4 must be placed at a tailrace location where there is complete mixing of the fish from R_1 that survived dam passage, regardless of passage route. If this location corresponds with the exit from the passage route chosen for absolute survival estimation (e.g., the surface collector in the 2006 study), then it is reasonable to replace the two tailrace releases R_3 and R_4 with a single tailrace release group (R_3') in order to reduce costs. In general, the primary statistical effect of using a triple-release design instead of a quadruple-release design is that estimates of dam and project survival will no longer be independent and the variance estimator of $\hat{S}_{\text{Pool}}$ (equation 14) becomes an approximation. Point estimates of the various survival components and of overall project survival will remain unbiased if a triple-release design is used, provided that the geometry of the dam makes a triple-release design possible.

The choice of passage route for estimating absolute passage survival using the paired releases R_2 and R_3 depends both on the goals of the analysis (e.g., is one particular route of primary interest?) and on the layout of the dam. Most importantly, the entrance to the chosen passage route should be spatially well defined, which then dictates the location of the forebay release (R_2). The surface collector was chosen for absolute survival estimation at Rocky Reach because its entrance is relatively small compared with other routes, such as the spillway.

Allocation of tagged fish across the four releases also depends on the goals of the analysis. In general, a balanced design is recommended, but there may be reasons to put more effort into the upstream release (R_1). One consideration is that all relative passage survival estimates are based on R_1, so low pool survival or the presence of one or more rarely used passage routes will require more fish to be released upstream. Estimates of both relative and absolute passage survival through a rarely used route will typically have lower precision than more commonly used routes, and the size of R_1 will partly dictate the level of precision attainable. On the other hand, if the focus is on estimating dam and pool survival separately, then R_1 need be no larger than the other releases. The sizes of R_2 and R_3, as used to estimate absolute survival through one passage route, should be determined based on the necessary precision of the resulting survival estimate (Burnham et al. 1987). For the 2006 sockeye salmon study at Rocky Reach, we attained reasonable levels of precision on survival estimates via an approximately balanced design of around 480 fish in each of three release groups.

It is important to note that estimation of the absolute passage abundance at a given route is not robust to violations of the assumption of independent detections at the two entrance arrays for the route. Even with a likelihood approach, it is impossible to test the assumption of independence of the two arrays. Thus, the double arrays must be purposely constructed so that the detection fields are independent.

The locations of the detection arrays required to estimate both route-specific survival and dam survival (e.g., at entrances to all passage routes) make it necessary to use active tags, such as acoustic tags. Tags such as passive integrated transponder (PIT) tags are inappropriate because of their limited detection systems. Active tags tend to be larger than PIT tags, requiring larger study fish and resulting in possibly larger tag : body weight ratios. The sockeye salmon used in this study were at least 95 mm fork length and had tag : body weight ratios of 2.7–8.4%. Current tagging guidelines recommend a tag : body weight ratio between 5% and 6.5% (Brown et al. 1999, 2006; Anglea et al. 2004). Ideally, the size distribution among the experimental fish should match that of the run-of-river population to which inference is to be made. In 2006, approximately 1% of the run-of-river sockeye salmon population passing Rocky Reach Dam was smaller than the minimum 95-mm length used in this study, so inference may be made to the majority of the run. Concerns about tag size may be less relevant in the future, as smaller active tags are developed.

Conclusions

Route-specific survival and dam passage survival are examples of performance measures that were selected by fisheries managers before the statistical community had determined how to estimate them. This is often the natural order in which statistics and management decisions are made, whereby management needs drive creative statistical solutions. In meeting new management requirements, statisticians may sometimes be able to use preexisting methods to answer part or all of the new problem. In many cases, however, completely new design and analysis approaches may be required. It is important to realize that as management needs become more demanding, sampling schemes and analysis usually become more complex. In this case, estimating route-specific survival and dam passage survival requires considerably more effort than the simpler problem of estimating project passage survival. Complex managerial needs in resource management and other areas will continue to place creative demands on statisticians. It is important to consider both available statistical tools and their limitations when meeting those needs.

Acknowledgments

We thank Public Utility District No. 1 of Chelan County for access to the sockeye salmon data from the Rocky Reach study. Lyman McDonald and two anonymous reviewers provided helpful comments and suggestions for improving this paper. Funding was provided by the Bonneville Power Administration through Statistical Support for Salmonid Survival Studies, project 1989-107-00, contract 29651.

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Appendix: Derivation of the Likelihood Model

Estimation of project, pool, dam, and route-specific survival may be performed using likelihood-based methods. The likelihood model for the generalized quadruple-release study design is presented here. Dam passage routes are indexed by i, for i in the set A of possible passage routes. For the 2006 Rocky Reach study, $A = \{\mathrm{SC}, \mathrm{BS}, \mathrm{PH}, \mathrm{SP}\}$. The likelihood function for the study is the product of the likelihood functions for each release group, that is,

$$L = L_1 \cdot L_2 \cdot L_3 \cdot L_4, \tag{A.1}$$

where L_j is the likelihood function for release R_j (j = 1, 2, 3, 4), defined below. Except as otherwise noted, parameters and statistics are as defined in the body of the paper. Relationships among the parameters (e.g., the definition of dam survival [equation 11]) remain the same as in the body of the paper, and the same assumptions are used.

The likelihood function L_1 for release R_1 can be expressed as the product of auxiliary likelihoods $L_{1(\mathrm{surv})}$ and $L_{1(\mathrm{det})}$. Likelihood $L_{1(\mathrm{surv})}$ provides information on passage proportions and survival and makes use of the nuisance parameters S_H (survival from handling effects, which is assumed to be the same for releases R_1 and R_4), d_i (the conditional probability of being detected at the double array at the entrance of dam passage route i), and y (the joint probability of surviving from the tailrace of the dam to the downstream detection arrays and being detected at one or both of those arrays, conditional on surviving past the dam). In addition to the statistics defined in the body of the paper, for fish from release R_1 we define r_1 as the total number of fish that were detected at the dam or on the downstream arrays and m_0 as the number of fish that were not detected at the dam but that were detected on the arrays downstream of the dam. Then likelihood $L_{1(\mathrm{surv})}$ is defined as

$$\begin{aligned} L_{1(\mathrm{surv})} \propto & \left[\prod_{i \in A} (S_H S_{\mathrm{Pool}} p_i d_i)^{M_i} (S_i y)^{m_i} (1 - S_i y)^{M_i - m_i} \right] \\ & \times \left[S_H S_{\mathrm{Pool}} y \sum_{i \in A} p_i (1 - d_i) S_i \right]^{m_0} \\ & \times \left[1 - S_H S_{\mathrm{Pool}} + S_H S_{\mathrm{Pool}} \sum_{i \in A} p_i (1 - d_i)(1 - S_i y) \right]^{R_1 - r_1}, \end{aligned} \tag{A.2}$$

with the constraint that $\Sigma_{i \in A}\, p_i = 1$. The multinomial coefficient has been dropped because it does not contribute to parameter estimation.

The auxiliary likelihood $L_{1(\text{det})}$ provides information on detection probabilities at the dam (nuisance parameters). For dam passage route i, let d_{i1} and d_{i2} denote the probabilities of being detected at the first and second detection arrays located at the entrance to route i, conditional on entering that route. The overall conditional probability of being detected at the double array at the entrance to route i is then $d_i = 1 - (1 - d_{i1})(1 - d_{i2})$. Additionally, for route i, let n_{i11} be the number of fish detected at both entrance arrays, n_{i10} be the number of fish detected at the first array but not the second, and n_{i01} be the number of fish detected at the second array but not the first. Then, with $n_{i1} = n_{i11} + n_{i10}$ and $n_{i2} = n_{i11} + n_{i01}$, $L_{1(\text{det})}$ is defined as follows:

$$L_{1(\text{det})} = \prod_{i \in A} \left[\binom{M_i}{n_{i11} \quad n_{i10} \quad n_{i01}} \times d_{i1}^{n_{i1}} d_{i2}^{n_{i2}} (1 - d_{i1})^{n_{i01}} (1 - d_{i2})^{n_{i10}} d_i^{-M_i} \right]. \quad \text{(A.3)}$$

The likelihood function for release R_2 is

$$L_2 = \binom{R_2}{t \quad R_2 - t} (S'_H S_{\text{SC}} y')^t (1 - S'_H S_{\text{SC}} y')^{R_2 - t}, \quad \text{(A.4)}$$

where S'_H is survival from handling effects and y' is the conditional joint probability of surviving from the dam to the downstream detection arrays and being detected at one or both of those arrays, for fish released into the surface collector. The likelihood function for release R_3 is

$$L_3 = \binom{R_3}{c \quad R_3 - c} (S'_H y')^c (1 - S'_H y')^{R_3 - c}. \quad \text{(A.5)}$$

The likelihood function for release R_4 is

$$L_4 = \binom{R_4}{r_4 \quad R_4 - r_4} (S_H y)^{r_4} (1 - S_H y)^{R_4 - r_4}, \quad \text{(A.6)}$$

where r_4 is the number of fish from release R_4 that were subsequently detected at either or both of the detection arrays downstream of the dam.

For the simplified study design that uses the single release R'_3 in place of the two releases R_3 and R_4, the likelihood function for the study is $L = L_1 \cdot L'_2 \cdot L'_3$, where $L_1 = L_{1(\text{surv})} \cdot L_{1(\text{det})}$ as defined in equations (A.2) and (A.3). The likelihood function for release R_2 is as given in equation (A.4), with the exception that S'_H and y' are replaced with S_{H} and y, respectively. The likelihood function for release R'_3 is

$$L'_3 = \binom{R'_3}{r'_3 \quad R'_3 - r'_3} (S_H y)^{r'_3} (1 - S_H y)^{R'_3 - r'_3}, \quad \text{(A.7)}$$

where r'_3 is the number of fish from release R'_3 that were subsequently detected at either or both of the detection arrays downstream of the dam. An additional assumption introduced by the simplified study design is that fish from all three release groups have the same survival from handling effects (S_{H}) and the same conditional joint probability of surviving from the tailrace to the downstream detection arrays and being detected at one or both of those arrays (y).