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THE DESIGN AND ANALYSIS OF SALMONID TAGGING STUDIES IN THE COLUMBIA BASIN

Volume XI: Recommendations on the Design and Analysis of Radiotelemetry Studies of Salmonid Smolts to Estimate Survival and Passage Efficiencies

Technical Report

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VOLUME XI

Recommendations on the Design and Analysis of Radiotelemetry Studies of Salmonid Smolts to Estimate Survival and Passage Efficiencies

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Preface

The Bonneville Power Administration sponsored project No. 89-107 was initiated to develop statistical methods for salmonid survival studies. The project began with the development of statistical models for the analysis of smolt PIT-tag survival studies. Subsequently, the statistical methods have been extended to the analysis of adult PIT-tag returns. This report continues this evolution of tagging studies by examining the feasibility of using radiotagging and telemetry data to extract smolt survival estimates.

The purpose of this investigation was to determine the feasibility of extracting detailed survival and passage efficiency estimates from a properly designed smolt radiotelemetry study. We obtained radiotagging data from the Chelan Public Utility District (PUD) to use as an exploratory dataset to formulate and evaluate the analytical models we developed. The double-antenna array at Rocky Reach Dam composed of primary and secondary detection transects in parallel was a key design feature that permitted the model development and analysis. However, this initial PUD radiotelemetry study was not initially designed to estimate smolt survival, nor, more importantly, to test key assumptions. And as such, desired sample sizes and ancillary data to test assumptions were not necessarily available, as would be the case in a planned survival investigation. Thus, the parameter estimates reported in this report are for purposes of illustration only, and may not necessarily represent the true smolt populations nor the performance of a consummate investigation.

Abstract

Two approaches for estimating smolt survival from the radiotelemetry dataset are examined: (1) the single-recapture model (SRM) of Cormack (1964), currently used in PIT-tag studies and (2) a new model we formulated, the Route Specific Survival Model (RSSM). The RSSM permits a variety of survival estimates (pool, dam, and passage-route-specific) to be extracted from a properly designed radiotelemetry monitoring system. These include survival estimates through reservoirs and dams separately, offering the capability for direct estimate of reservoir mortality in the Columbia hydroelectric system. Also, passage-route-specific survival and passage efficiency estimates can be obtained for each powerhouse, spillway, and any bypass system. This capability to generate so many types of passage-related estimates with a single tool is unique to radio-tag analyses.

This evaluation determined that smolt survival probabilities can be extracted from radiotelemetry data. Furthermore, precision and more detailed information can be extracted from radio-tagging studies than current PIT-tag investigations. Comparable precision can be obtained with a fraction of the number of smolts currently used in PIT-tag studies. Equally important, route-specific survival and passage rates can be obtained to better understand critical uncertainties in smolt passage at hydroelectric projects. These advances in the study of smolt migration dynamics come at a time when information needs are expanding and the ability to mark and handle large numbers of smolt is declining because of the listing of salmonid stocks under the Endangered Species Act of 1973.

Executive Summary

Objectives

1. Determine the feasibility of extracting detailed survival and passage efficiency estimates from a properly designed smolt radiotelemetry study.

3. Innovate new statistical methods to utilize radiotelemetry data.

2. Consider guidelines, key points, and assumptions necessary in the preparation of future radiotelemetry survival studies.

Results

This evaluation determined that smolt survival probabilities can be extracted from radiotelemetry data. Furthermore, precision and more detailed information can be extracted from radio-tagging studies than current PIT-tag investigations. Comparable precision can be obtained with a fraction of the number of smolts currently used in PIT-tag studies. Equally important, route-specific survival and passage rates can be obtained to better understand critical uncertainties in smolt passage at hydroelectric projects. These advances in the study of smolt migration dynamics come at a time when information needs are expanding and the ability to mark and handle large numbers of smolt is declining because of the listing of salmonid stocks under the Endangered Species Act of 1973.

Recommendations

Two key assumptions should be critically examined when considering the use of radio-tags in survival studies. The first is that tag regurgitation (in the case of gastric implants) is negligible or can be estimated and the survival estimates be adjusted accordingly. The low survival estimate for steelhead traversing the forebay suggest that tag regurgitation may have been problematic in the 1997 dataset. Surgical implantation of tags could rectify this tag loss problem. Another important assumption is that dead fish bearing active radio-tags are not detected at the recovery sites. This assumption could be readily evaluated empirically as part of an actual survival study. We recommend that these assumptions be formally treated in the conduct of any radiotelemetry-based survival study.

Acknowledgements

We wish to thank Chuck Peven at Chelan County Public Utility District #1 for permitting the use of the 1997 radiotelemetry data used in the examples. Appreciation is also extended to Bill Koski at LGL for supplying the detection files used in the radiotelemetry analyses.

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Introduction

Smolt survival studies have been a cornerstone in Snake-Columbia River research for more than three decades (Bickford 1996). Initial studies used freeze-branding to mark groups of control and treatment fish in order to estimate survival over a river reach or hydroproject (Ricker 1958). These studies required tens of thousands of marked fish and had the restrictive assumption of downstream mixing of control and treatment groups that was rarely achieved (Bickford 1996). With the advent of PIT-tags (passive integrated transponder tags), more advanced release-recapture models (Cormack 1964, Jolly 1985, Seber 1965) could be used to estimate reach survival based on the downstream capture histories of individually marked fish. Reach survival could now be estimated from a single release of 1-2 thousand tagged fish (Iwamoto et al. 1994; Muir et al. 1995, 1996; Smith et al. 1998). This advance in tagging methodology provided a more precise and logically feasible means of estimating downstream smolt survival and the ability to begin to investigate the processes influencing smolt survival.

Mitigation projects such as surface bypass collectors, extended-length bar screens, and biological guidance systems in the Columbia-Snake River Basin have, however, increased the demands for precise information on route-specific passage rates and subsequent survival. However, the PIT-tag technology is unable to obtain this level of fine-scale information on hydroproject passage and survival increasingly needed for monitoring and evaluation activities.

With the advent of small, relatively long-life radiotelemetry tags, researchers have been able to use this technology to study outmigration dynamics of salmonid smolts over one to few hydroprojects. Initially, these studies focused on estimating travel times, residence times in pools and forebays, and route-specific passage rates (Adams et al. 1997, 1998a, b; Stevenson et al. 1997). The very high detection rates of radiotags and the ability to monitor detection through spillbays, turbines, and surface collectors provide the opportunity to obtain precise route-specific survival rates currently needed to evaluate mitigation projects in the Columbia Basin. At Rocky Reach Dam in 1997, for example, radio-tagged chinook salmon and steelhead smolt had detection rates of 86-94% and 90-95%, respectively, that are far greater than PIT-tag detection rates. Furthermore, the high detection rates of radio-tags hold the promise of precise survival estimates with hundreds rather than thousands of tagged smolt. In so doing, survival studies can be performed more economically, while providing detailed information on outmigration dynamics, and with less impact to the salmonid population being studied.

Objectives

The purpose of this technical report is to evaluate the feasibility of extracting statistically valid estimates of smolt survival from radiotelemetry tagging studies. To this end, new statistical estimation procedures are developed to extract maximum information on project-wide as well as route-specific survival probabilities for outmigrating chinook salmon and steelhead smolt. A route-specific survival model (RSSM) is developed and compared to the existing single release-recapture model (Cormack 1964, Jolly 1965, Seber 1965) that can also be used to estimate smolt survival rates.

To develop and test our analytical methods, we obtained a set of radiotelemetry data that had characteristics particularly suitable for our needs. Chelan County PUD provided us with data from the 1997 telemetry-based smolt passage investigations at Rocky Reach and Rock Island Dams. That study was not designed to generate survival estimates, and key assumptions were not examined or verified. Thus, the resultant survival estimates in this feasibility study should not be considered representative of the general smolt populations. But these data clearly illustrate what the capabilities of these survival models can be when using telemetry data.

We used two models to estimate smolt survival and compared those results. One model is the single-recapture model of Cormack, which is commonly applied in PIT-tag studies, and the other is the Route Specific Survival Model (RSSM) that we developed in this investigation. The RSSM has additional capabilities that permit separate reservoir and dam survival estimates, as well as powerhouse, spillway, and bypass system survival and passage efficiency estimates.

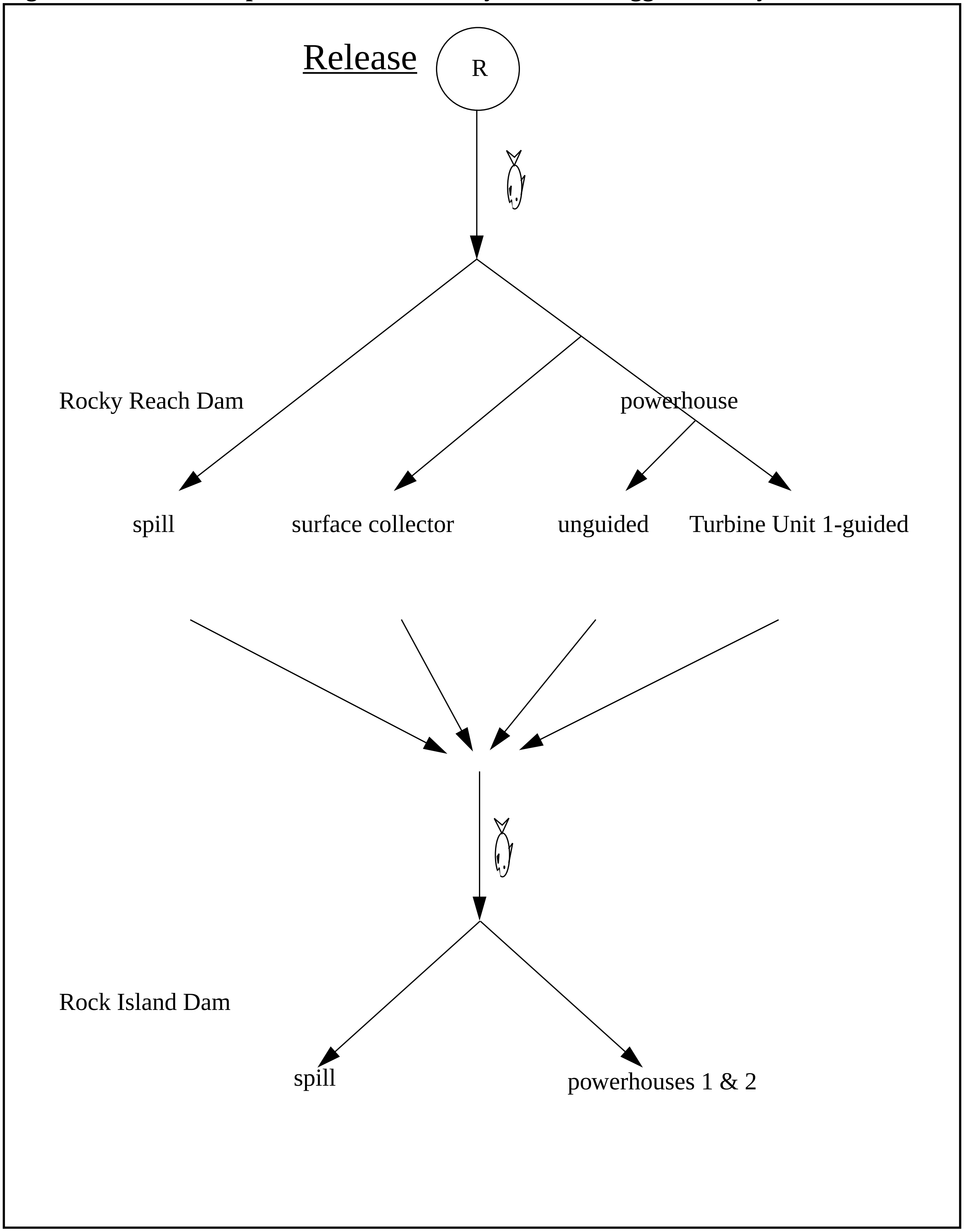
The intent of this feasibility study is to illustrate the precision and detail of information that can be potentially extracted from a scientific radio-tagging study and state-of-the-art statistical analyses. Recommendations on study design and data analysis following from this statistical investigation should be helpful in improving future smolt radio-tagging studies and should lead to better data interpretation. By maximizing information extraction, future radio-tagging investigations should have the potential to improve our understanding of smolt migration dynamics and the effects of hydroproject mitigation while better preserving dwindling fish resources.

Description of the Study Site

Reach Description

Rocky Reach Dam is located on the Columbia River at River Kilometer 762.3. The dam consists of a single powerhouse with 11 turbine units and a spillway with 12 spillbays. A surface collector and a screen system for guiding fish through a bypass facility were constructed near Turbine Unit 1. At Rocky Island Dam, located 32.6 km. downstream from Rocky Reach Dam, there are two powerhouses connected by a single spillway. The spillway is separated by an adult fish passage facility with 14 spillbays on one side and 17 spillbays on the other. The powerhouses have 10 and 8 turbine units. For the purpose of this analysis, the possible migration routes were generalized into spillway, surface collector, guided and unguided fish through the powerhouse at Rocky Reach Dam; spillway and powerhouse for Rock Island Dam. This partitioning resulted in 15 possible migration pathways (Figure 1). For more detailed information about the two study sites, see the report to Chelan County Public Utility District #1 from which these results originated (Stevenson et. al. 1997).

Figure 1: Schematic of possible routes taken by fish radio-tagged in study.



Antenna Deployment

Along the spillway and powerhouse at Rocky Reach Dam, a series of aerial antennas were placed to detect downstream migrating radio-tagged smolt (Figure 2). At the spillway, a series of aerial antennas were deployed upstream as well as downstream of the spillbays. At the powerhouse, an array of aerial antennas were deployed upstream the forebay. A second underwater antenna array was deployed upstream of the turbines but positioned within the intake where smolt would be committed to turbine passage. Turbine Unit 1 had a different setup from the rest of the powerhouse, as guidance screens were deployed within the intake. Within Turbine Unit 1, the primary detection antenna array consisted of two underwater dipole antennas attached to the top and bottom of each diversion screen located in slots A, B, and C. The secondary system consisted of two underwater dipole antennas deployed downstream of the collection gallery in the gatewell collector dewatering structure. The surface collector had a total of 20 underwater dipole antennas within the surface collector and the associated transport channel. Results from the original study suggested that detection rates for both the surface collector and the guided portion of Turbine Unit 1 were 100% of the tagged fish passing through those routes (Stevenson et al. 1997).

Rock Island Dam's primary detection system were aerial antennas deployed along the upstream side of the dam face. The secondary systems were also aerial antennas set in the tailraces of both the spillway and powerhouses.

Description of Data

Release Sizes and Timing

We analyzed data from 186 radio-tagged chinook salmon smolt (*Oncorhynchus tshawytscha*) and 210 steelhead smolt (*Oncorhynchus mykiss*). Smolt were released approximately 4 km upstream of Rocky Reach Dam. Releases occurred from 24 April through 21 May 1997 (Stevenson et al. 1997).

Cormack-Jolly-Seber Model Data

The general model used in release-recapture survival analyses was suggested by Cormack-Jolly-Seber (Cormack 1964, Jolly 1965, Seber, 1965). A study is set up so that detections are made at the end of each river section of interest, usually at a dam or trap placed with a detection device. Capture and survival probabilities are then estimated for each section, up to and including the capture site. The results of the single release-recapture surveys can be summarized by the number of tagged fish that had one of four mutually exclusive and exhaustive capture histories (Table 1). Letting a 1 denote the detection of a fish, and 0 denote its nondetection at a site, the capture histories can be defined by an array denoting detection or not at Rocky Reach and Rock Island Dams. Table 1 summarizes the capture histories for the chinook and steelhead releases.

Figure 2: Schematic of antenna arrays deployed at Rocky Reach Dam in 1997.

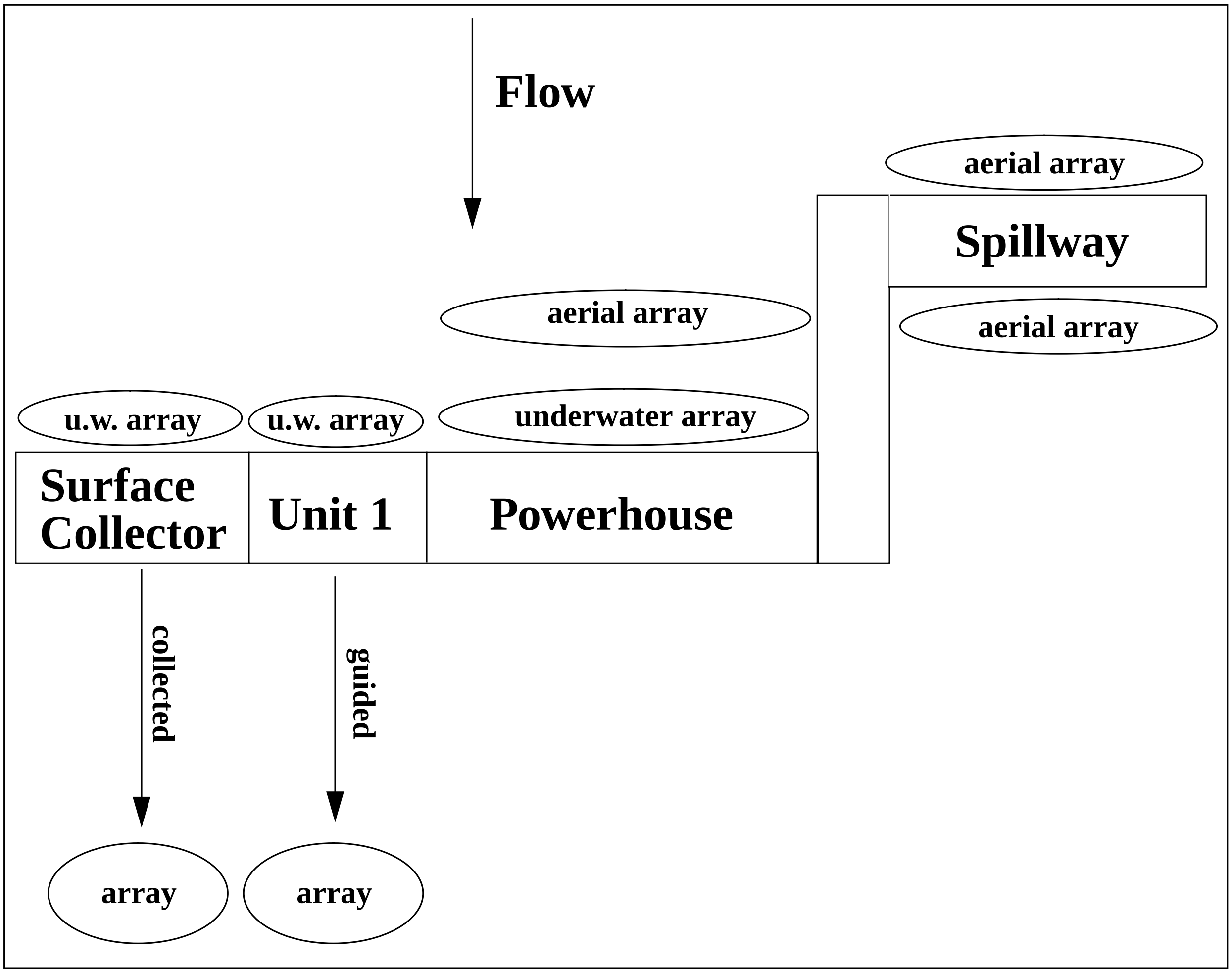


Table 1: Summary of individual capture histories used in the Cormack-Jolly-Seber model. Summaries are based on upstream detections at Rocky Reach Dam and all detections at Rock Island Dam.

Capture History			
Rocky Reach	Rock Island	Chinook	Steelhead
1	1	41	49
1	0	14	15
0	1	97	115
0	0	34	31

The double-set of antennas at Rocky Reach Dam made a variation on the usual mark-recapture study possible. Rather than solely noting whether a tag was detected or not at Rocky Reach Dam, the analysis used upstream-only detections to give a survival estimate through the Rocky Reach pool to arrival at the dam.

Route-Specific Data

Differences in passage behavior between chinook salmon and steelhead can be readily seen by the numbers of smolt detected in each passage route at Rocky Reach and Rock Island Dams (Table 2). The category "not detected" contains those fish which were not detected either because of upstream mortality or not being detected while passing through the dam. At Rocky Reach Dam, steelhead used the surface collector at a much higher percentage than chinook salmon smolt, 24.0% versus 4.3%, respectively. At Rock Island Dam, steelhead were detected at the spillway at a much higher percentage than the chinook salmon smolt, 31.0% versus 14.5%, respectively (Table 2).

The route-specific detections of smolt through both dams are summarized in Table 3. A detection was defined as the last detected position of a fish on either side of the dam. Where two sets of antennas were situated, a fish was assumed to have passed through that particular passage route when detected by either the upstream and/or the downstream set of antenna. Where a fish was detected both upstream and downstream at a dam, the downstream location was used as its designated passage route. For example, a fish detected upstream of the spillway and then upstream of the powerhouse but nowhere else, was designated as a powerhouse-route detection. No fish was ever detected at more than one downstream antenna at a dam.

Auxiliary Likelihood Data

In addition to increasing the detection rate for the routes through the spill and powerhouses of the two dams, the use of two sets of antennas made it possible to estimate detection rates for each set of antennas. Without this information, it is difficult to differentiate between nondetections of alive fish and mortality. Furthermore, estimation of detection rates enabled the estimation of absolute passage probabilities instead of relative passage rates (e.g., Table 2) at a dam. Upstream, downstream, and double detections of smolts at spillways and powerhouse for Rocky Reach and Rock Island Dams are summarized in Table 4. The Route Specific Survival model incorporates this data to calculate the probability that a fish was detected by at least one antenna, and adjusts survival through each passage according to the detection probability.

Table 2: Counts of observed chinook and steelhead passing through each passageway at each dam.

Site	Passageway	Chinook		Steelhead	
		Counts	%	Counts	%
Rocky Reach	Spillway	56	30.1	43	20.5
	Powerhouse	90	48.4	68	32.4
	Surface collector	8	4.3	61	24.0
	Powerhouse-guided	6	3.2	16	7.6
	Not detected	26	14.0	22	10.5
	Total	186	100.0	210	100.0
Rock Island	Spillway	27	14.5	65	31.0
	Powerhouse	111	59.7	99	47.1
	Not detected	48	25.8	46	21.9
	Total	186	100.0	210	100.0

Table 3: Specific routes detected for chinook salmon and steelhead smolt passage. A detection was defined as the last detected position by upstream and/or downstream antenna.

Rocky Reach Passage	Rock Island Passage	Chinook	Steelhead
Spillway	Spillway	10	9
	Powerhouse	35	25
	Not detected	11	9
Powerhouse[a]	Spillway	15	25
	Powerhouse	56	30
	Not detected	19	13
Surface collector	Spillway	1	25
	Powerhouse	5	29
	Not detected	2	7
Powerhouse-guided	Spillway	0	2
	Powerhouse	5	9
	Not detected	1	5
Not detected	Spillway	1	4
	Powerhouse	10	6
	Not detected	15	12
	Total fish released	186	210

a. Includes Rocky Reach Powerhouse Turbine Unit 1 unguided fish. See Figure 1.

Table 4: Number of radio-tags detected by upstream and/or downstream antenna for Rocky Reach (RR) and Rock Island (RI) Dam spill and turbine passage routes.

Dam	Route Location	Chinook			Steelhead		
		upstream only	downstream only	up and downstream	upstream only	downstream only	up and downstream
RR	Spillway	11	22	23	7	12	24
	Turbines[a]	10	57	11	11	21	22
RI	Spillway	13	2	12	26	6	33
	Turbines	25	32	54	26	26	47

a. Counts from unguided fish through Rocky Reach Turbine Unit 1 were not included in the auxiliary likelihood.

Description of the Statistical Methods

Single Release-Recapture Model

The single release-recapture model (SRM) can be used to estimate pool survival through the Rocky Reach project using the upstream antenna detections at that site (Table 1). The analysis is based on the counts of fish in each of the four possible (n_{ij}; i=0,1; j=0,1) capture histories (Table 1). The multinomial likelihood can be written as

$$L(\underset{\sim}{x}|R, S_1,\lambda) = \binom{R}{\underset{\sim}{n}}(S_1 p_1 \lambda)^{n_{11}}(S_1 p_1(1-\lambda))^{n_{10}} \cdot (S_1(1-p_1)\lambda)^{n_{01}}((1-S_1)+S_1(1-p_1)(1-\lambda))^{n_{00}} \quad (1)$$

where

R = number of radio-tagged fish released,

S_1 = survival in initial pool,

p_1 = detection probability at Rocky Reach in the upstream antenna array,

λ = probability of surviving downstream of Rocky Reach Dam and being detected at Rock Island Dam,

n_{ij} = number of smolt with capture history ij.

Parameters of the survival model are illustrated in Figure 3.

The maximum likelihood estimators are then

$$\hat{S}_1 = \frac{(n_{01}+n_{11})(n_{10}+n_{11})}{Rn_{11}} \quad (2)$$

$$\hat{p}_1 = \frac{n_{11}}{(n_{01}+n_{11})},$$

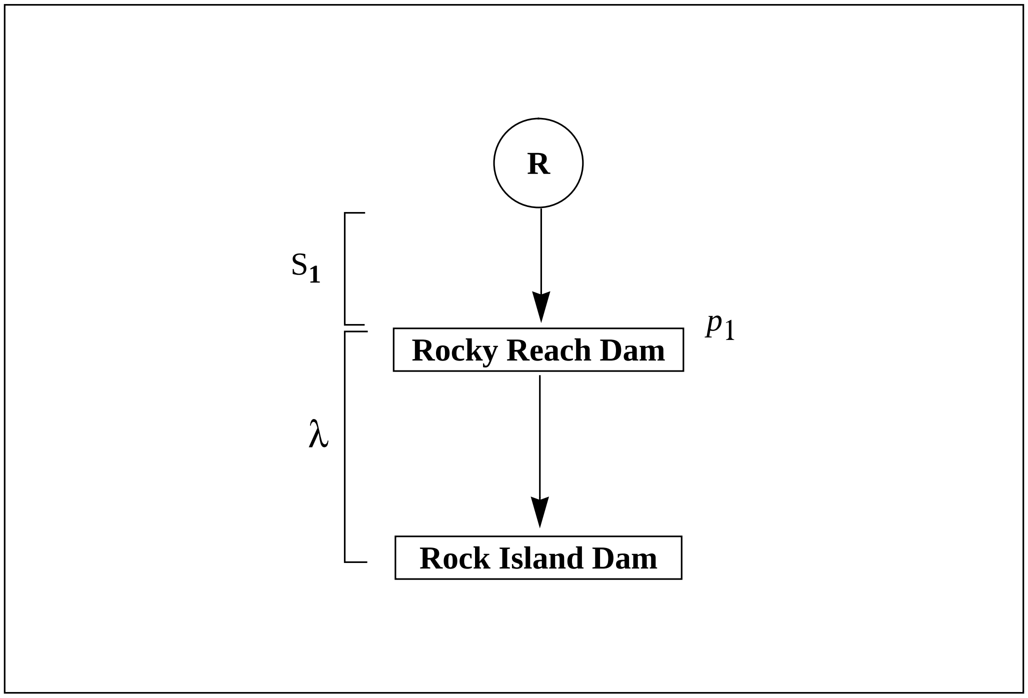
$$\hat{\lambda} = \frac{n_{11}}{(n_{10}+n_{11})}.$$

Assumptions of the SRM model include:

A1. Individuals marked for the study are a representative sample from the population of interest.

A2. Survival and capture probabilities are not affected by tagging or sampling. That is, tagged animals have the same probabilities as untagged animals.

Figure 3: Schematic of parameters used in the analysis of the single release-recapture model.



A3. All sampling events are “instantaneous.” That is, sampling occurs over a negligible distance relative to the length of the intervals between sampling events.
A4. The fate of each tagged individual is independent of the fate of all others.
A5. All tagged individuals alive at the beginning of a sampling interval have the same probability of surviving until the end of that interval.
A6. All tagged individuals alive at a sampling location have the same probability of being detected on that event.
A7. All tags are correctly identified and the status of smolt (i.e., alive or dead), correctly assessed.

The first assumption (A1) concerns making inferences from the sample to the target population. For example, if inferences are sought to wild chinook salmon smolt, then the sample of tagged fish should be drawn from that class of fish. Otherwise, nonstatistical inferences are necessary, justifying the similarity between the target population and the representatives of radio-tagged fish. Assumption (A2) again relates to making inferences to the population of interest (i.e., untagged fish). If tagging has a detrimental effect on survival, then estimates will underestimate the true survival rate of smolt.

The third assumption (A3) specifies that mortality is negligible immediately in the vicinity of the sampling stations, so that the estimated mortality is related to the river reaches in question and not during the sampling event. In the case of outmigrating smolt, the time they spend in the vicinity of the antenna arrays is brief and small, relative to the size of the river reaches in question. The assumption of independence (A4) implies that the survival or death of one smolt has no effects on the fates of others. In the larger river system with tens of thousands of smolts, this is likely true. Nevertheless, violations of assumption (A4) have little effect on the point estimate but might bias the variance estimate with precision being less than calculated.

Assumption (A5) specifies that a smolt’s prior detection history has no effect on subsequent survival. This could be violated if some smolt were self-trained to repeatedly go through turbine or spill routes or alternatively avoid routes because of prior experience. This occurrence is unlikely and can be assessed from the detection histories of the individual smolts. The lack of subsequent handling after the release of radio-tagged smolt further minimizes the risk that subsequent detections influence survival. Similarly, assumption (A6) could be violated if downstream detections were influenced by upstream passage routes taken by the smolt. Violation of this assumption is minimized by placing antenna arrays across the breadth of the river or below remixing zones for smolt following different passages at the dam.

The final assumption (A7) implies that the smolt do not lose their tags and are subsequently misidentified as dead or not recaptured, nor are dead fish falsely recorded as alive at detection locations. The high retention rates of their radios minimize the case of false negatives and estimates of that survival that are biased low. Dead fish drifting downstream could result in false-positive detections and upwardly bias survival estimates. While the false detection of dead smolt is unlikely to be a major concern in the pool, it is a serious possibility at the dam itself. The detection of mortalities would include fish that died acutely in either the spillway, turbines, or surface bypass system yet detected by the antenna array. For this reason, pool survival at Rocky

Reach Dam can be detected but not project-wide (i.e., pool and dam) survival. This assumption also excludes the possibility of radio failures. Radio failures would be interpreted by the model as mortalities, resulting in underestimation of survival probabilities. Tag regurgitation rate and tag failure rate can be empirically established, and we recommend such in an actual study designed to generate representative survival estimation. The incidence of dead fish bearing active tags should be established experimentally.

Route Specific Survival Model

The previous SRM, while providing the ability to estimate pool survival, does not utilize all of the available information on smolt passage and survival collected by radiotelemetry studies. Capture histories that indicate the exact routes smolt took through the projects (Table 3) contain more information than the basic detected or nondetected data (Table 1). This greater information can be potentially used to obtain more detailed information on route-specific passage rates and survival.

The ability to extract route-specific passage rates and survival is possible because of the double-antenna array systems at Rocky Reach and Rock Island Dams. Furthermore, for both chinook salmon and steelhead smolt at both dams, fish passage through the double-array antenna systems was direct and contained within the respective systems. Fish last detected in an upstream antenna array were also either detected at the downstream antenna array of the same route or not at all, but never at the downstream antenna array of another passage route. The assumption was then made that fish detected upstream only or downstream only within a passage route had a high probability of having passed through that route, and that any detection combination (upstream/ downstream, upstream only, downstream only) could be attributed to that particular passage route. Passage through the surface collector and the guided portion of Turbine Unit 1 at Rocky Reach Dam were assumed to have a 100% detection rate. Passage through the unguided portion of Turbine Unit 1 was assumed to have the same detection probability as the other turbine units at the powerhouse.

In constructing the route-specific survival likelihood model (RSSM), the following parameters are defined:

S_1 = probability of survival in the Rocky Reach pool,
S_2 = probability of survival in the Rock Island pool,
E_1 = spill efficiency at Rocky Reach,
E_2 = spill efficiency at Rock Island,
C = surface collector efficiency at Rocky Reach, given smolt arrives at powerhouse,
F = probability a smolt is guided by the screens at Unit 1, given smolt will go through the powerhouse at Rocky Reach,
W_1 = spillway survival at Rocky Reach,
B_1 = surface collector survival at Rocky Reach,
T_1 = turbine survival at Rocky Reach,

G_1 = bypass survival at Rocky Reach,
p'_{W1} = probability of upstream detection in spillway at Rocky Reach,
p_{W1} = probability of downstream detection in spillway at Rocky Reach,
p'_{T1} = probability of upstream detection in turbine units at Rocky Reach,
p_{T1} = probability of downstream detection in turbine units at Rocky Reach,
p'_{W2} = probability of upstream detection in spillway at Rock Island,
p_{W2} = probability of downstream detection in spillway at Rock Island,
p'_{T2} = probability of upstream detection in turbine units at Rock Island, and
p_{T2} = probability of downstream detection in turbine units at Rock Island.

The passage of smolt through the Rocky Reach-Rock Island projects is depicted as a branching process in Figure 4. It should be noted that *F* is not estimating the traditional fish guidance efficiency (FGE) at a particular turbine unit, but rather, the probability of being guided by the screens in Turbine Unit 1, given the smolt will go through the powerhouse. Hence, *F* is an estimate of the powerhouse-wide fish guidance efficiency.

The route-specific likelihood will be a multinomial model with 15 possible route-specific detection histories (Table 5). The cell counts and their respective cell probabilities are presented in Table 5. The multinomial model can then be written as follows:

$$L(\underset{\sim}{n}|S_1, S_2, E_1, E_2, C, F, W_1, B_1, T_1, G_1, p'_{W1}, p_{W1}, p'_{T1}, p_{T1}, p'_{W2}, p_{W2}, p'_{T2}, p_{T2}) = \binom{R}{\underset{\sim}{n}} \prod_{i=1}^{15} P_i^{n_i} \tag{3}$$

where

R = the release size ($R = \sum_{i=1}^{15} n_i$), and

P_i = the likelihood probability of the i^{th} passage route from Table 5.

As written, likelihood equation (3) has more parameters than sufficient statistics, making estimation impossible. However, additional information from the detections at the upstream and downstream antenna arrays can be used to support the likelihood (3), making estimation feasible. Define the following variables:

w_1 = number of detections by upstream antenna only at Rocky Reach spillway,
w_2 = number of detections by downstream antenna only at Rocky Reach spillway,

Figure 4: Graph of possible routes taken by fish radio-tagged in study. Variables are defined above.

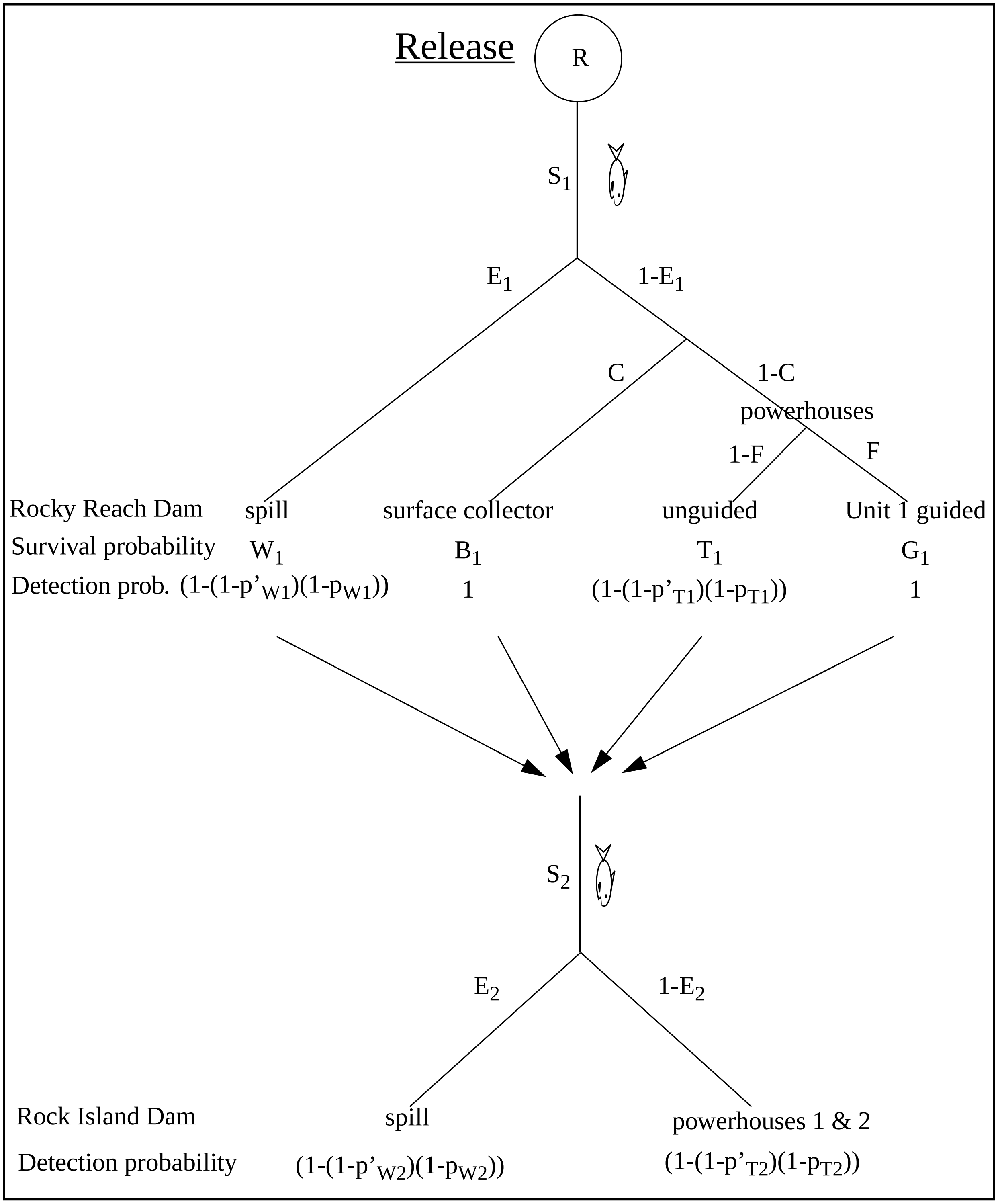


Table 5: Cell probabilities for each route-specific detection history through Rocky Reach and Rock Island Dams. The cell probabilities were combined to create the Route Specific Survival likelihood Model (8).

Number of tags observed	Passage point through		Probability
	Rocky Reach	Rock Island	
n_1	Spillway	spillway	$S_1E_1(1-(1-p'_{W1})(1-p_{W1}))W_1S_2E_2(1-(1-p'_{W2})(1-p_{W2}))$
n_2		powerhouse	$S_1E_1(1-(1-p'_{W1})(1-p_{W1}))W_1S_2(1-E_2)(1-(1-p'_{T2})(1-p_{T2}))$
n_3		not detected	$S_1E_1(1-(1-p'_{W1})(1-p_{W1}))[(1-W_1) + W_1(1-S_2) + W_1S_2(E_2(1-p'_{W2})(1-p_{W2}) + (1-E_2)(1-p'_{T2})(1-p_{T2}))]$
n_4	Powerhouse	spillway	$S_1(1-E_1)(1-C)(1-F)(1-(1-p'_{T1})(1-p_{T1}))T_1S_2E_2(1-(1-p'_{W2})(1-p_{W2}))$
n_5		powerhouse	$S_1(1-E_1)(1-C)(1-F)(1-(1-p'_{T1})(1-p_{T1}))T_1S_2(1-E_2)(1-(1-p'_{T2})(1-p_{T2}))$
n_6		not detected	$S_1(1-E_1)(1-C)(1-F)(1-(1-p'_{T1})(1-p_{T1}))[(1-T_1) + T_1(1-S_2) + T_1S_2(E_2(1-p'_{W2})(1-p_{W2}) + (1-E_2)(1-p'_{T2})(1-p_{T2}))]$
n_7	Surface collector	spillway	$S_1(1-E_1)CB_1S_2E_2(1-(1-p'_{W2})(1-p_{W2}))$
n_8		powerhouse	$S_1(1-E_1)CB_1S_2(1-E_2)(1-(1-p'_{T2})(1-p_{T2}))$
n_9		not detected	$S_1(1-E_1)C[(1-B_1) + B_1(1-S_2) + B_1S_2(E_2(1-p'_{W2})(1-p_{W2}) + (1-E_2)(1-p'_{T2})(1-p_{T2}))]$
n_{10}	Powerhouse - guided	spillway	$S_1(1-E_1)(1-C)FG_1S_2E_2(1-(1-p'_{W2})(1-p_{W2}))$
n_{11}		powerhouse	$S_1(1-E_1)(1-C)FG_1S_2(1-E_2)(1-(1-p'_{T2})(1-p_{T2}))$
n_{12}		not detected	$S_1(1-E_1)(1-C)F[(1-G_1) + G_1(1-S_2) + G_1S_2(E_2(1-p'_{W2})(1-p_{W2}) + (1-E_2)(1-p'_{T2})(1-p_{T2}))]$
n_{13}	Not detected	spillway	$S_1[E_1(1-p'_{W1})(1-p_{W1})W_1 + (1-E_1)(1-C)(1-F)(1-p'_{T1})(1-p_{T1})T_1]S_2E_2(1-(1-p'_{W2})(1-p_{W2}))$
n_{14}		powerhouse	$S_1[E_1(1-p'_{W1})(1-p_{W1})W_1 + (1-E_1)(1-C)(1-F)(1-p'_{T1})(1-p_{T1})T_1]S_2(1-E_2)(1-(1-p'_{T2})(1-p_{T2}))$
n_{15}		not detected	$(1-S_1) + S_1[E_1(1-p'_{W1})(1-p_{W1})(1-W_1)] + S_1[E_1(1-p'_{W1})(1-p_{W1})W_1((1-S_2) + S_2(E_2(1-p'_{W2})(1-p_{W2}) + (1-E_2)(1-p'_{T2})(1-p_{T2})))] + S_1[(1-E_1)(1-C)(1-F)(1-p'_{T1})(1-p_{T1})(1-T_1)] + S_1[(1-E_1)(1-C)(1-F)(1-p'_{T1})(1-p_{T1})T_1((1-S_2) + S_2(E_2(1-p'_{W2})(1-p_{W2}) + (1-E_2)(1-p'_{T2})(1-p_{T2})))]$

w_{12}= number of detections by both up- and downstream antennas only at Rocky Reach spillway,

x_1 = number of detections by upstream antenna only at the Rocky Reach turbines,

x_2 = number of detections by downstream antenna only at the Rocky Reach turbines,

x_{12} = number of detections by both up- and downstream antennas only at the Rocky Reach turbines,

y_1 = number of detections by upstream antenna only at Rock Island spillway,

y_2 = number of detections by downstream antenna only at Rock Island spillway,

y_{12} = number of detections by both up- and downstream antennas only at Rock Island spillway,

z_1 = number of detections by upstream antenna only at the Rock Island turbines,

z_2 = number of detections by downstream antenna only at the Rock Island turbines,

z_{12} = number of detections by both up- and downstream antennas only at the Rock Island turbines,

$$r_w = w_1 + w_2 + w_{12},$$

$$r_x = x_1 + x_2 + x_{12},$$

$$r_y = y_1 + y_2 + y_{12},$$

$$r_z = z_1 + z_2 + z_{12}.$$

Using the counts from each upstream and downstream antenna array, auxiliary likelihoods can be derived for the probability that a fish was detected by only the upstream antenna, by only the downstream antenna, or by both, given that it was detected at least once.

For the Rocky Reach data, the auxiliary likelihoods can be written as:

$$L(\underset{\sim}{w}|r_W, p_{W1}, p'_{W1}) = \binom{r_w}{w_1, w_2, w_{12}}\left(\frac{p'_{W1}(1-p_{W1})}{1-q'_{W1}q_{W1}}\right)^{w_1}\left(\frac{p_{W1}(1-p'_{W1})}{1-q'_{W1}q_{W1}}\right)^{w_2}\left(\frac{p_{W1}p'_{W1}}{1-q'_{W1}q_{W1}}\right)^{w_{12}} \quad (4)$$

where

$$q_{W1} = 1 - p_{W1},$$

$q'_{W1} = 1 - p'_{W1}$ for the spillways, and

$$L(\underset{\sim}{x} | r_x, p_{T1}, p'_{T1}) = \binom{r_x}{x_1, x_2, x_{12}} \left(\frac{p'_{T1}(1 - p_{T1})}{1 - q'_{T1} q_{T1}} \right)^{x_1} \left(\frac{p_{T1}(1 - p'_{T1})}{1 - q'_{T1} q_{T1}} \right)^{x_2} \left(\frac{p'_{T1} p_{T1}}{1 - q'_{T1} q_{T1}} \right)^{x_{12}} \tag{5}$$

where

$q_{T1} = 1 - p_{T1}$,

$q'_{T1} = 1 - p'_{T1}$ for the powerhouse detections.

Similarly, for Rock Island Dam, the auxiliary likelihoods can be written as follows:

$$L(\underset{\sim}{y} | r_y, p_{W2}, p'_{W2}) = \binom{r_y}{y_1, y_2, y_{12}} \left(\frac{p'_{W2}(1 - p_{W2})}{1 - q'_{W2} q_{W2}} \right)^{y_1} \left(\frac{p_{W1}(1 - p'_{W2})}{1 - q'_{W2} q_{W2}} \right)^{y_2} \left(\frac{p'_{W2} p_{W2}}{1 - q'_{W2} q_{W2}} \right)^{y_{12}} \tag{6}$$

where

$q_{W2} = 1 - p_{W2}$,

$q'_{W2} = 1 - p'_{W2}$ for the spillway, and

$$L(\underset{\sim}{z} | r_z, p_{T2}, p'_{T2}) = \binom{r_z}{z_1, z_2, z_{12}} \left(\frac{p'_{T2}(1 - p_{T2})}{1 - q'_{T2} q_{T2}} \right)^{z_1} \left(\frac{p_{T2}(1 - p'_{T2})}{1 - q'_{T2} q_{T2}} \right)^{z_2} \left(\frac{p'_{T2} p_{T2}}{1 - q'_{T2} q_{T2}} \right)^{z_{12}} \tag{7}$$

where

$q_{T2} = 1 - p_{T2}$,

$q'_{T2} = 1 - p'_{T2}$ for the powerhouse detections.

The complete likelihood for the RSSM is then the joint likelihood of Equations (3-7) such that

$$L(\underset{\sim}{n}|S_1, \ldots, p_{T2}) = \binom{R}{\underset{\sim}{n}} \prod_{i=1} P_i^{n_i} \cdot L(\underset{\sim}{w}|r_W, p'_{W1}, p_{W1}) \cdot L(\underset{\sim}{x}|r_X, p'_{T1}, p_{T1})$$
$$L(\underset{\sim}{y}|r_Y, p'_{W2}, p_{W2}) \cdot L(\underset{\sim}{z}|r_Z, p'_{T2}, p_{T2}) \quad (8)$$

Iterative numerical methods were used with likelihood (8) to obtain maximum likelihood estimates of the parameters and their associated variance estimates.

Assumptions of the RSSM are essentially the same as those for the SRM. The RSSM has the additional assumption:

A8. Routes taken by the radio-tagged smolt through the hydroprojects are known without error.

Detection histories at the double-antenna arrays fully support this assumption for the Rocky Reach-Rock Island study in 1997. In all cases, fish detected in the upstream arrays located at the spillway or powerhouse were also detected at the corresponding downstream array or not at all. In no case was a fish detected at both spillway and powerhouse while exiting the dam.

Results

Test of Assumptions

The SRM model has an assumption of independence inherent in the analysis. That is, fish that have passed through various routes of one dam will remix afterwards and all fish will have equal probabilities of subsequent passage fates at downstream dams (i.e., Assumptions A5 and A6). The assumption of independence of migration route selected at upstream and subsequently downstream dams is necessary for the model to provide unbiased estimates.

Chi-square R x C contingency table tests of independence were applied to the counts of smolts detected at both dams to see if passage route selection at one dam influenced passage route selection at the second dam. Chinook salmon and steelhead counts were grouped by specific routes (i.e., spillway vs. powerhouse passage) (Table 6). There was no indication of passage preference in the chinook release (p-value = 0.6953), but there was in steelhead (p-value = 0.0953). This possible preference may not actually exist, in that steelhead are thought to select a passage based on depth. The depths of the spillway and powerhouse passages were not the same for both dams, so that if steelhead were preferring one passage depth over another, it would not show in this homogeneity test. Steelhead detections regrouped to determine if a vertical preference existed (shallow vs. deep passage) had a nonsignificant p-value of 0.8016 (Table 7). The other assumptions (i.e., A1-A4 and A7-A8) cannot be explicitly evaluated with the data available for 1997.

Table 6: Chi-square tests of independence for (a) chinook and (b) steelhead passage route selection at Rocky Reach and Rock Island Dams. The null hypothesis is that passage through a particular route at Rocky Reach Dam is independent of passage through Rock Island Dam.

a)

Rock Island	Rocky Reach			
	spillway	powerhouse	surface collector	guided
Spillway	10	15	1	0
Powerhouse	35	56	5	5

$P(\chi^2_3 > 1.4438) = 0.6953$

b)

Rock Island	Rocky Reach			
	spillway	powerhouse	surface collector	guided
Spillway	9	25	25	2
Powerhouse	25	30	29	9

$P(\chi^2_3 > 6.3601) = 0.0953$

Table 7: Chi-square test of independence for steelhead in dam passageway routes between Rocky Reach and Rock Island Dams. The null hypothesis is that passage through a particular depth at Rocky Reach Dam will not influence choice of passage depth through Rock Island Dam.

	Rocky Reach	
Rock Island	spillway & powerhouse (deep)	surface collector & guided (shallow)
Spillway (shallow)	34	27
Powerhouse (deep)	55	38

$P(\chi_1^2 > 0.0631) = 0.8016$

Pool Survival Estimates From Single Release-Recapture Model

The Cormack-Jolly-Seber model, using only the upstream detections at Rocky Reach Dam, estimates a 0.934 survival probability (SE = 0.025) for the Rocky Reach pool for the chinook (Table 8). Steelhead smolt had similar pool survival through Rocky Reach reservoir of 0.959 (SE = 0.018). The complete list of parameter estimates for the SRM are given in Table 8.

Route Specific Survival Model Estimates and Variances

The survival and capture probabilities in the RSSM likelihood equation were maximized for each of the two releases. Point estimates of the parameters are shown in Figure 5 (chinook) and Figure 6 (steelhead), and the standard errors and the profile likelihood 90% confidence intervals are presented in Table 9.

For chinook salmon smolt, Rocky Reach pool survival was estimated comparably using the SRM and RSSM with values of 0.934 (0.025) and 0.9474 (0.0219), respectively. Similarly, for steelhead smolt, Rocky Reach pool survival was estimated comparably with values of 0.959 (0.018) and 0.9562 (0.0168), respectively, for the SRM and RSSM. Spill efficiency during the release trials was estimated at 0.3441 (0.0385) and 0.2286 (0.0314) for chinook and steelhead, respectively.

Survival of chinook salmon smolt through the spillway was estimated to be 0.9408 (SE = 0.3060) and for turbine passage, 0.9175 (SE = 0.2974). Route-specific survival estimates for chinook were generally estimated with low precision because of the relative small sample size (n = 186) and low rate of passage through some routes. For steelhead smolt, highest survival was estimated for passage through the surface collector (0.9932, SE = 0.0505), followed by the unguided turbine route (0.9078, SE = 0.0741), spillway (0.8893, SE = 0.0860), and Unit #1 bypass (0.7756, SE =0.1376). Precision of survival estimates through these routes would be further improved with sample sizes greater than the approximately 200 fish used in the 1997 study.

Powerhouse-wide fish guidance efficiency for chinook was estimated to be 0.0557 (SE = 0.0222) and 0.1753 (SE = 0.0391) for steelhead. Powerhouse-wide FGE is the proportion of all the fish that enter turbines across the powerhouse that are subsequently diverted by screens. At Rocky Reach Dam in 1997, only one of 11 turbine units had a screen system for guiding fish through a bypass facility. These values of powerhouse-wide FGE therefore represent the probability of a smolt being guided by Unit 1 screens, given they entered the turbine units anywhere at the Rocky Reach powerhouse. Precision of the powerhouse-wide FGE was very good, considering the relatively small release size.

Estimating Dam and Project-Wide Survival From RSSM

Survival through the dam can be estimated from the results of the route-specific passage and survival rates. Survival through the dam (S_D) would be estimated by the relationship

Table 8: SURPH[a] estimates for the chinook and steelhead releases, using upstream detections[b] at Rocky Reach Dam and both upstream and downstream detections at Rock Island Dam. (Standard errors are in parentheses.)

Species	Pool Survival ($\hat{S}_1$)	Capture Probability ($\hat{p}_1$)	($\hat{\lambda}$)
Chinook	0.934 (0.025)	0.794 (0.034)	0.811 (0.035)
Steelhead	0.959 (0.018)	0.874 (0.026)	0.825 (0.031)

a. SURPH, "SURvival under Proportional Hazards", is statistical software for analyzing data from tagging studies, and is available through the School of Fisheries, University of Washington, at *http://www.cqs.washington.edu/surph/*.

b. The surface collector & turbine unit 1 detections are considered to be on the both sides of Rocky Reach Dam for this analysis approach.

Table 9: Point estimates, standard errors, and profile likelihood 90% confidence intervals for the Route Specific Survival Model.

parameter	Chinook			Steelhead		
	point estimate	SE	90% profile confidence interval	point estimate	SE	90% profile confidence interval
S_1	**0.9474**	0.0219	0.8786, 0.9818	**0.9562**	0.0168	0.8563, 0.9717
S_2	**0.9493**	0.3025	0.8328, 1.0000	**0.9897**	0.0550	0.8522, 1.0000
E_1	**0.3441**	0.0385	0.2466, 0.4195	**0.2286**	0.0314	0.1991, 0.2481
E_2	**0.1881**	0.0343	0.1093, 0.2577	**0.3812**	0.0393	0.3463, 0.3969
C	**0.0692**	0.0237	0.0220, 0.1252	**0.3938**	0.0398	0.3686, 0.4059
F	**0.0557**	0.0222	0.0142, 0.1100	**0.1703**	0.0391	0.1203, 0.1916
W_1	**0.9408**	0.3060	0.7372, 1.0000	**0.8893**	0.0860	0.7094, 1.0000
B_1	**0.8885**	0.3389	0.3283, 1.0000	**0.9932**	0.0505	0.2831, 1.0000
T_1	**0.9175**	0.2974	0.7599, 1.0000	**0.9078**	0.0741	0.7326, 0.9712
G_1	**0.9772**	0.2741	0.3420, 1.0000	**0.7756**	0.1376	0.3033, 1.0000
p'_{W1}	**0.5606**	0.0678	0.3796, 0.6867	**0.6747**	0.0757	0.4744, 0.8129
p_{W1}	**0.7420**	0.0640	0.5579, 0.8506	**0.7833**	0.0705	0.5915, 0.9032
p'_{T1}	**0.2409**	0.0463	0.1308, 0.3380	**0.5358**	0.0651	0.3808, 0.6764
p_{T1}	**0.7802**	0.0495	0.6399, 0.8633	**0.6981**	0.0614	0.5550, 0.8249
p'_{W2}	**0.8579**	0.0932	0.5708, 0.9725	**0.8475**	0.0570	0.5903, 0.9108
p_{W2}	**0.4802**	0.0999	0.2386, 0.6648	**0.5604**	0.0644	0.3693, 0.6605
p'_{T2}	**0.6280**	0.0521	0.4983, 0.7157	**0.6461**	0.0549	0.5255, 0.7547
p_{T2}	**0.6837**	0.0523	0.5539, 0.7686	**0.6460**	0.0549	0.5255, 0.7547

Figure 5: Route Specific Survival Model point estimates for the radio-tagged chinook release.

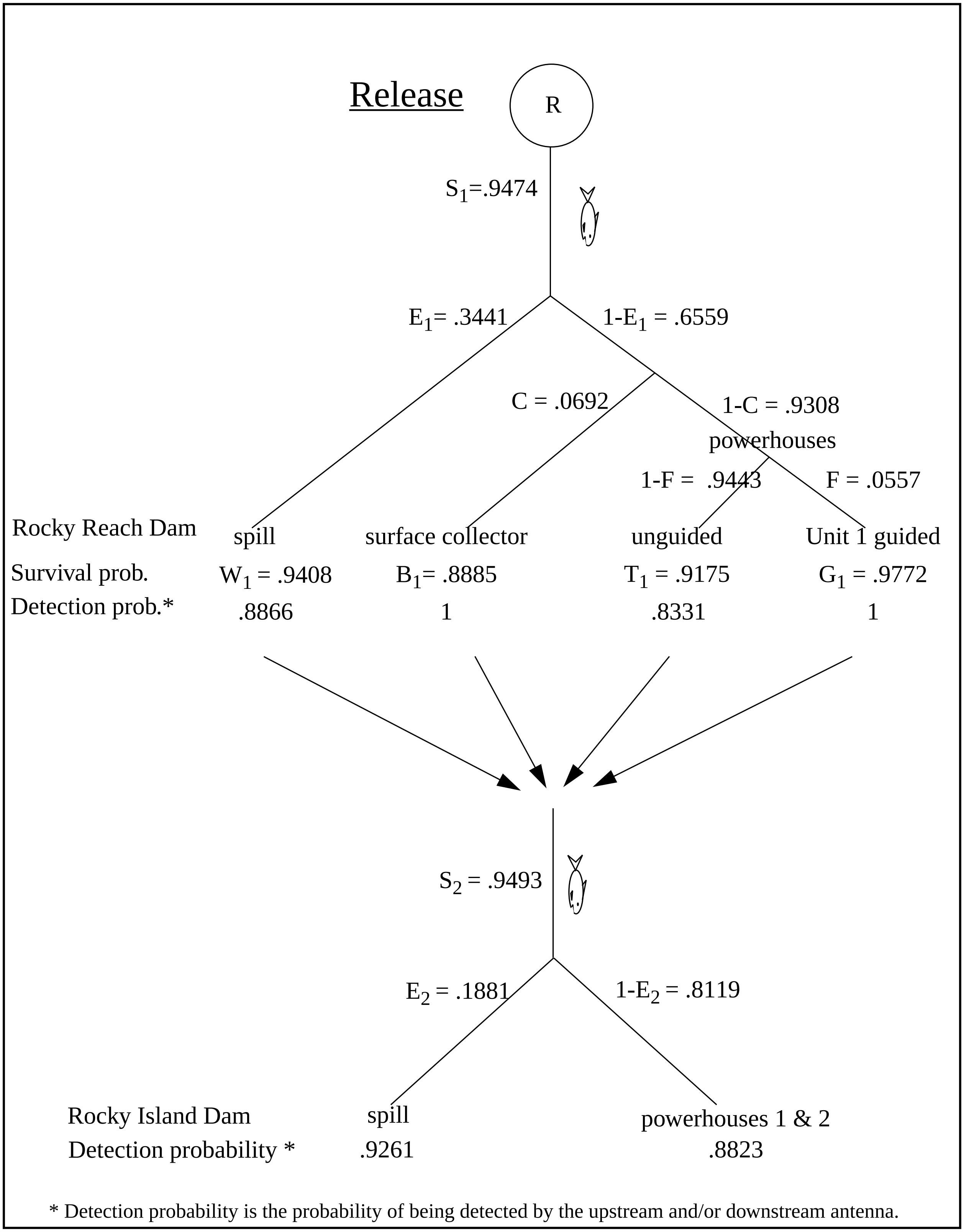
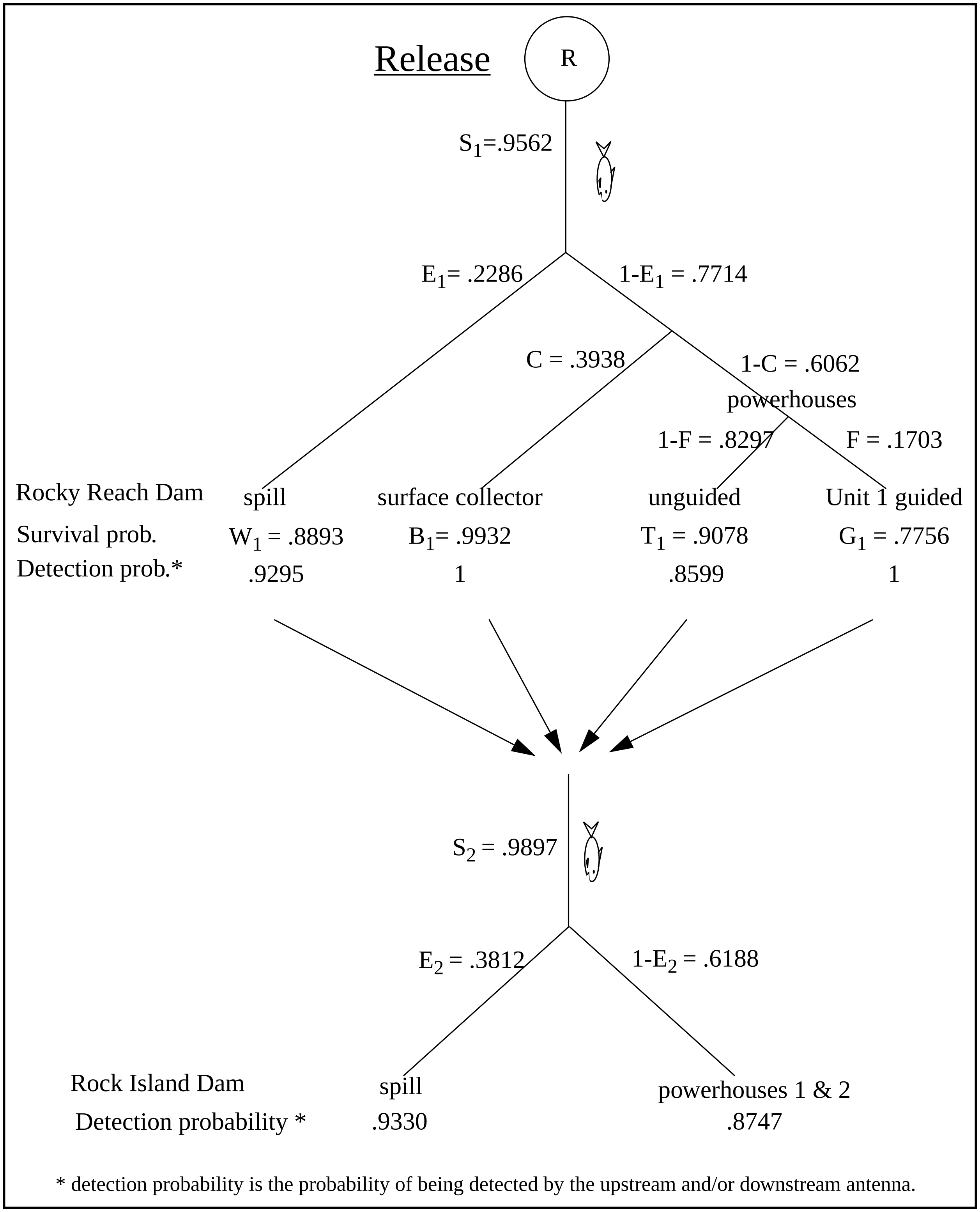


Figure 6: Route Specific Survival Model point estimates for the radio-tagged steelhead release.



$$\hat{S}_D = \hat{E}_1\hat{W}_1 + (1-\hat{E}_1)[\hat{C}\hat{B}_1 + (1-\hat{C})(\hat{F}\hat{G}_1 + (1-\hat{F})\hat{T}_1)] \quad (9)$$

The route-specific survival estimates were estimated less precisely than pool survival because fewer smolt passed any specific route. For chinook, highest survival was observed through the Unit #1 bypass (0.9772, SE = 0.2741), followed by spillway (0.9408, SE = 0.3060), unguided Total project survival (S_P) would then be estimated as a product of pool survival $(\hat{S}_1)$ and dam survival $(\hat{S}_D)$ as

$$\hat{S_P} = \hat{S}_1 \cdot \hat{S}_D \quad (10)$$

Estimating Surface-Collector Efficiency From RSSM

The estimate of $\hat{C}$ from the RSSM is the conditional probability of a smolt entering the surface collector, given it is not going over the spillway and is heading to the powerhouse. The unconditional surface collector passage efficiency (SCE) would be calculated as

$$S\hat{C}E = (1-\hat{E}) \cdot \hat{C} \quad (11)$$

Discussion

This statistical evaluation has demonstrated the ability to extract survival estimates from well-designed smolt radio-tagging studies. Because of the high detection rates of radio-tagged smolt, survival probabilities can be estimated with relatively high precision using a relatively small number of smolt. Release sizes can be reduced by 50-80% over current tagging numbers used for PIT-tagged fish. Furthermore, the RSSM demonstrates that project-wide survival can be partitioned into components of pool, dam, and route-specific estimates of survival. These elements of project survival can be subsequently used to evaluate the sources of mortality and the benefits of focused mitigation programs. Estimates of passage rates from the RSSM also provide the means to monitor and evaluate the effectiveness and efficiency of surface bypass and diversion screens.

Many of the point estimates for passage-route-specific estimates have broad variances, particularly those describing the surface collector and screen bypass systems at Rocky Reach Dam. In a large part, this is due to the low percentage of the overall population that uses those routes, especially for yearling chinook. Such broad variances diminish the reliability of the point estimates. For future studies, this problem can be rectified by increasing release numbers.

Recommendations for SRM Studies

The single release-recapture model can be used to estimate survival over a stretch of river. The statistical model necessitates that detections following release be of alive smolt only. The radio-tags, however, can be detected after a smolt dies and possibly at downstream sites as carcasses move downstream. Hence, placement of antenna array need to be strategically planned to minimize these false positive detections of radio-tagged dead smolt. For example, this is why the downstream spillway antenna array could not be used at Rocky Reach Dam in the SRM analysis, and survival estimation was restricted to estimating pool survival at the Rocky Reach project in 1997.

The general design of a radio-tagged SRM study is depicted in Figure 7. The design is based on a series of downstream detection sites, each site in the forebay of a hydroproject. Unlike PIT-tag single release-recapture studies, the model would estimate survival in the first pool (i.e., S_1, Figure 7), then in each subsequent reach, joint survival through the dam and downstream pool (i.e., S_2, Figure 7).

The radio-tag methodology could be used in a paired-release design, that would provide the ability to partition dam from pool survival at these subsequent reaches (Figure 8). Using a tailrace release below the first detector dam, survival through the first dam can be partitioned from survival in the second pool. This partitioning of reach survival into pool and dam survival components may be much more successful with the radio-tag methodology than with PIT-tags. With radio-tags, the tailrace release has an entire reservoir to distribute and properly mix prior to arriving at the next detector dam. However, with PIT-tags, the second release must occur in the forebay of the first dam, and experience suggests little success in proper redistribution of smolt in the pool before detection in this case.

Hence, if the study goals are to simply estimate pool, reach, or dam survival rates of smolt, the SRM, in conjunction with radio-tags, provides an effective alternative to PIT-tag survival studies. Indeed, precision can be equal or greater with radio-tags than PIT-tags with even fewer marked fish. An additional advantage of radio-tags is that detection arrays can be established in reaches where PIT-tag detection facilities do not or cannot be located, making the technology more flexible to existing study requirements.

Recommendations for RSSM Studies

The key factor permitting the detailed estimation of route-specific passage and survival rates is the double-array system of antennas at detector dams. Ideally, there would be a separate forebay and a separate tailrace array at each passage route at the dam under investigation. The minimum design configuration for an RSSM is depicted in Figure 9. With this design, similar to the Rocky Reach-Rock Island 1997 study, pool as well as route-specific estimates could be generated at the first dam. Double-array systems at additional intermediate dam sites would permit similar estimation. At the last dam, no useful parameters can be estimated unless it, too, is equipped with a double-detection array. In which case, pool survival and passage rate efficiencies can be established, but not route-specific survival rates.

Figure 7: **Schematic of a single release [denoted (R)] of radio-tagged smolt and downstream parameter estimation based on arrays in the forebays of downstream dams.**

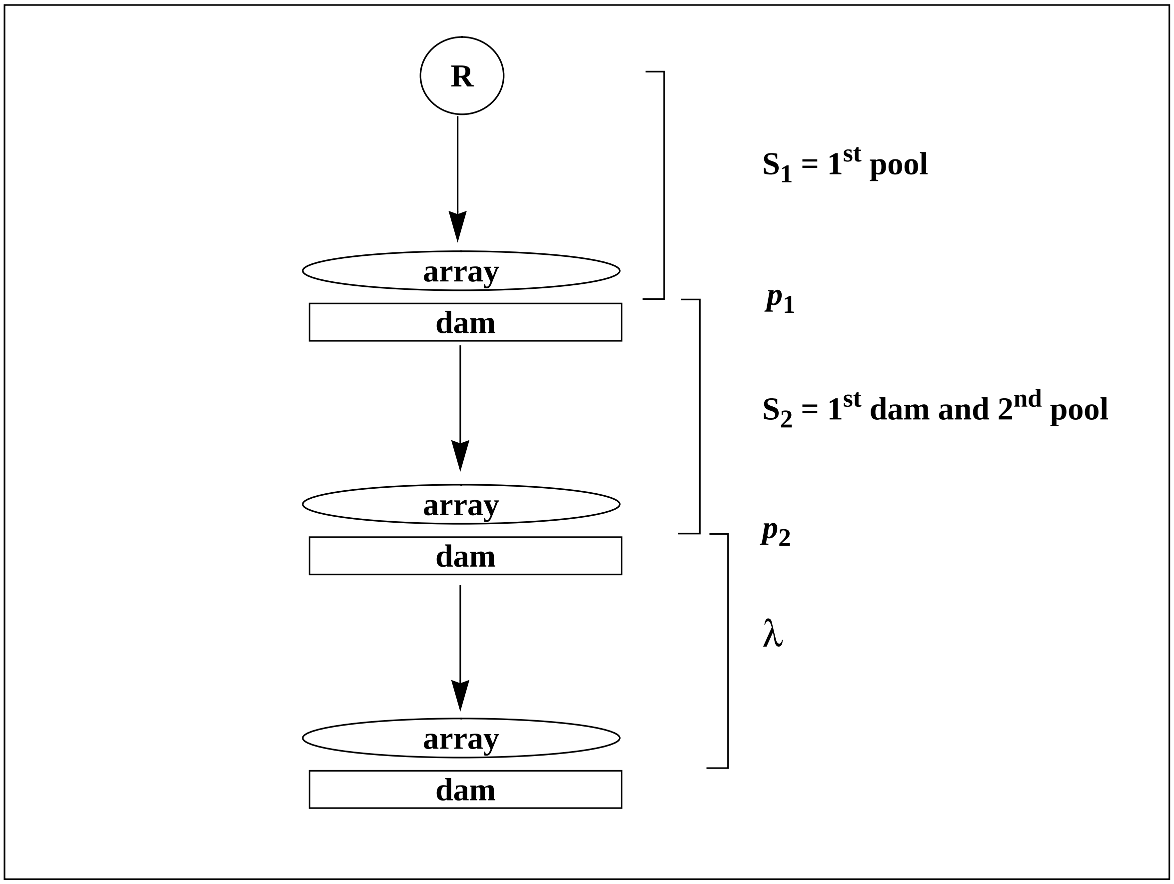


Figure 8: Schematic of a paired release [denoted (R)] of radio-tagged smolt and subsequent downstream parameter estimation based on arrays in the forebays of downstream dams.

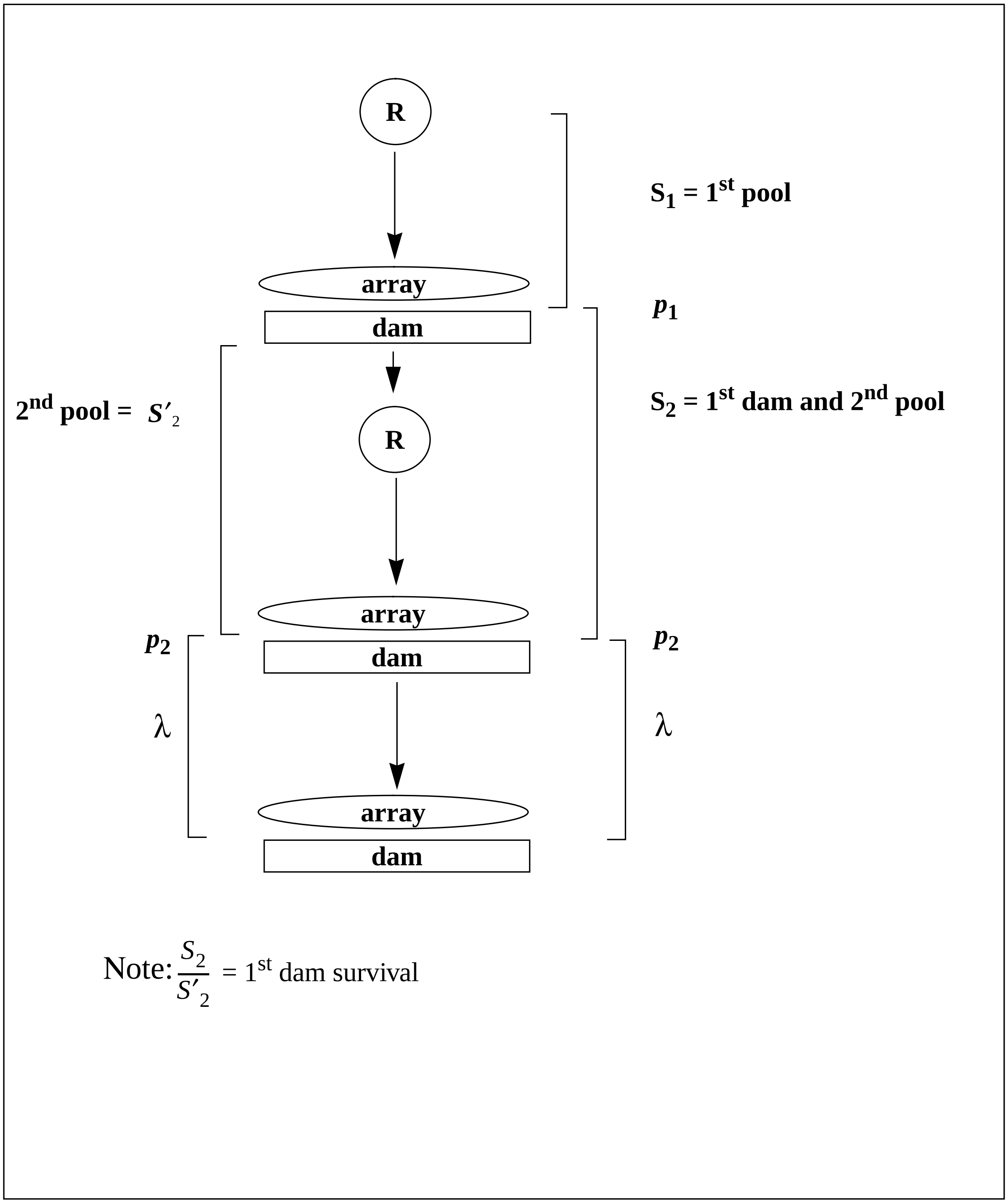
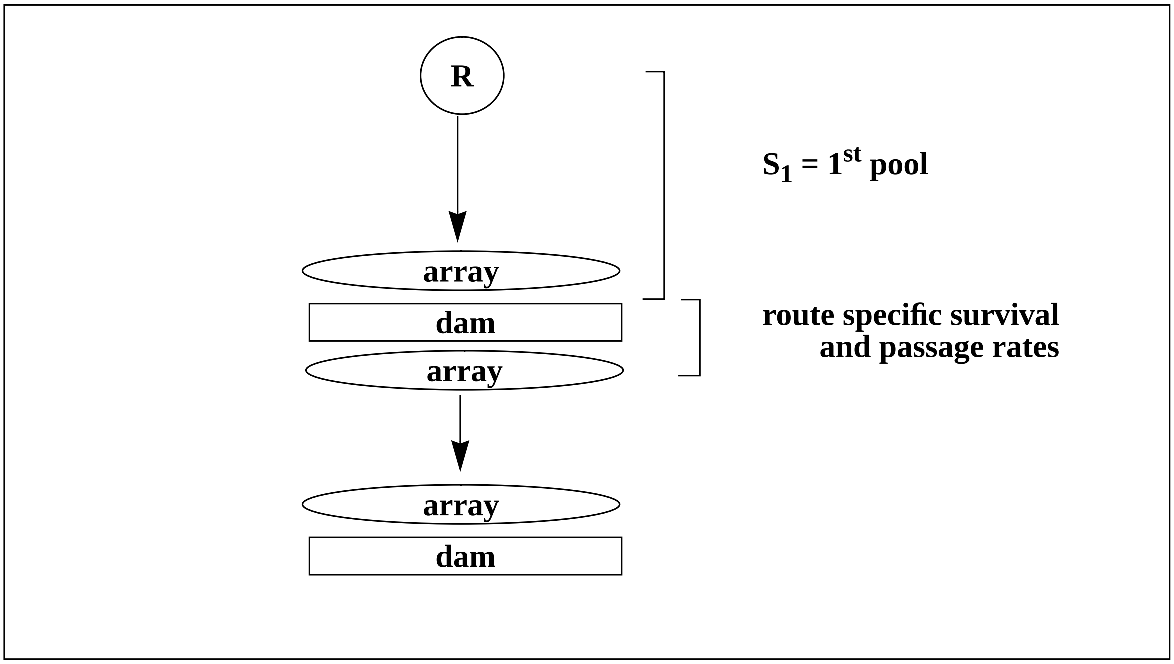


Figure 9: Schematic of the minimal design configurations needed to estimate route-specific passage and survival rates at the first radio-tag detector dam.



Should a study have only one dam set up for radio-tag detections, the passage rate information and survival for the pool is still available. However, survival estimates for the individual pathways are not possible with this simple study design.

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