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

VOLUME XXII

Evaluating Wetland Restoration Projects in the Columbia River Estuary using Hydroacoustic Telemetry Arrays to Estimate Movement, Survival, and Residence Times of Juvenile Salmonids

Prepared by:
Russell W. Perry and John R. Skalski
School of Aquatic and Fishery Sciences
University of Washington
1325 Fourth Avenue, Suite 1820
Seattle, WA 98101-2509

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U.S. Department of Energy
Bonneville Power Administration
Division of Fish and Wildlife
P.O. Box 3621
Portland, OR 97208-3621

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Other Publications in this Series

Volume I: Skalski, J. R., J. A. Perez-Comas, R. L. Townsend, and J. Lady. 1998. Assessment of temporal trends in daily survival estimates of spring chinook, 1994-1996. Technical report submitted to BPA, Project 89-107-00, Contract DE-BI79-90BP02341. 24 pp. plus appendix.

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Preface

Project 1989-107-00 was initiated to develop the statistical theory, methods, and statistical software to design and analyze PIT-tag survival studies. This project developed the initial study designs for the NOAA Fisheries/University of Washington (UW) Snake River survival studies of 1993−present. This project continues to respond to the changing needs of the scientific community in the Pacific Northwest as we face new challenges to extract life-history data from an increasing variety of fish tagging studies. The project's mission is to help assure tagging studies are designed and analyzed from the onset to extract the best available information using state-of-the-art statistical methods. In so doing, investigators can focus on the management implications of their findings without being distracted by concerns of whether the study's design and analyses are correct.

All studies in the current series, the Design and Analysis of Tagging Studies in the Columbia Basin, were conducted to help maximize the amount of information that can be obtained from fish tagging studies for the purposes of monitoring fish survival and related demographic parameters throughout its life cycle. Volume XXII of this series investigates the statistical design and hydroacoustic-array deployments to estimate movements, survival, and residence times of juvenile salmonids within restored wetlands of the Columbia River Estuary. Design of statistical models *prior to* implementation of such field studies is imperative to assure study objectives can be fulfilled and parameters of interest are estimable.

Abstract

Wetlands in the Columbia River estuary are actively being restored by reconnecting these habitats to the estuary, making more wetland habitats available to rearing and migrating juvenile salmon. Concurrently, thousands of acoustically tagged juvenile salmonids are released into the Columbia River to estimate their survival as they migrate through the estuary. Here, we develop a release-recapture model that makes use of these tagged fish to measure the success of wetland restoration projects in terms of their contribution to populations of juvenile salmon. Specifically, our model estimates the fraction of the population that enter the wetland, survival within the wetland, and the mean residence time of fish within the wetland. Furthermore, survival in mainstem Columbia River downstream of the wetland can be compared between fish that remained the mainstem and entered the wetland. These conditional survival estimates provide a means of testing whether the wetland improves the subsequent survival of juvenile salmon by fostering growth or improving their condition. Implementing such a study requires little additional cost because it takes advantage of fish already released to estimate survival through the estuary. Thus, such a study extracts the maximum information at minimum cost from research projects that typically cost millions of dollars annually.

Executive Summary

We developed a release-recapture model to evaluate the use of restored wetlands by juvenile salmonids in the Columbia River estuary. The model estimates the fraction of the population that enter the wetland, survival within the wetland, and the mean residence time of fish within the wetland. In addition, survival in mainstem Columbia River downstream of the wetland can be estimated compared between fish that remained the mainstem or entered the wetland. Evaluation of wetland restoration projects as described here takes advantage of thousands of acoustically tagged fish migrating through the estuary as part of other survival studies. Thus, for relatively low cost such a research project could evaluate the success in terms of the wetland's contribution to the population of juvenile salmonids.

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1.0 Introduction

The recent development of miniaturized acoustic tags permits the investigation of salmonid smolt survival and movements in the Columbia River estuary between Bonneville Dam and the mouth of the Columbia River. Concurrently, wetland restoration projects are reconnecting wetland habitats to the estuary in an effort to improve ecological function of the estuary and to increase available habitat for migrating and rearing juvenile salmonids. Millions of dollars are spent annually to tag and track movements of juvenile salmonids through the estuary. Yet to date, monitoring and evaluation of wetland restoration projects has not capitalized on the thousands of tagged juvenile salmonids migrating through the estuary. Information gathered from these tagged salmonids could be used to evaluate the success of restoration projects in terms of movement rates into, and residence times and survival within, restored wetlands. Such information would measure success of restoration projects in terms of their contribution to the population of juvenile salmon, and these studies stand to improve our understanding of the role of wetlands in the early life history of salmon. Given the thousands of acoustic-tagged fish migrating in-river each year, the cost of monitoring restored wetlands with hydroacoustic arrays is low relative to the potential information gained from such a study.

The purpose of this report is to illustrate the design of a hydrophone configuration and an associated statistical model that estimates movement into, and residence times and survival within, restored wetlands. The success of such studies will be highly dependent on the release-recapture design used and the deployment scheme for the hydroacoustic arrays. This concern is particularly pertinent when release-recapture models are used to estimate not only survival but, in addition, movement parameters. Thus, a release-recapture model will be designed and estimable parameters identified, along with associated model assumptions.

2.0 Hydrophone Configuration to Monitor Restored Wetlands

Wetland restoration in the Columbia River estuary typically involves reconnecting wetlands with the estuary by removing barriers in channels that block water flow and fish passage into and out of wetlands. By providing fish passage, tagged fish may freely move into wetlands through a restored channel. These movements may be monitored by use of replicate hydrophone arrays within the restored channel leading to a wetland (Fig. 2.1). The replicate hydrophone array consists of two closely spaced arrays that can be used to determine the direction of movement of fish passing through the restored channel connecting the wetland to the estuary. The key feature of the replicate hydrophone array is the ability to obtain information about (1) the time of entry into the wetland, (2) the time of exit out of the wetland, and

(3) survival within the wetland. With just a single hydrophone array at the entrance to the wetland, it is impossible to distinguish whether fish are entering or exiting the wetland, and thus impossible to estimate residence time and survival within the wetland. By combining this information with hydroacoustic arrays already in the mainstem Columbia River, a release-recapture model can be developed to estimate important demographic parameters that measure the success of wetland restoration projects.

2.1 Parameters and Performance Measures

As smolts migrate downstream, some will remain in the mainstem Columbia River, while others will enter the wetlands where they will reside for some amount of time before resuming their journey to the ocean (Fig. 2.1). The following parameters estimated through a release-recapture model will quantify movement and survival in the mainstem river and the restored and monitored wetland:

ψ – Probability of entering the wetland conditional on fish surviving to this point in the river. In other words, this parameter estimates the proportion of the population that visited the wetland of those that passed the entrance to the wetland. Its complement, $1-\psi$, estimates the fraction of fish remaining in the mainstem Columbia River.

S_0 – Probability of surviving from release to the arrays at the wetland or to the channel cross-section in the mainstem river just downstream of the entrance to the wetland.

S_{MSi} – Probability of surviving in each of k reaches ($i = 1, \ldots, k$) downstream of the wetland, conditional on fish having remained in the mainstem (MS) Columbia River.

S_{WL0} – Probability of surviving from the time of entering the wetland to the time of exiting the wetland (WL).

S_{WLi} – Probability of surviving in each of k reaches ($i = 1, \ldots, k$) downstream of the wetland, conditional of fish having used the wetland.

These parameters directly measure the success of the restoration project in terms of the entire population of tagged fish migrating through the estuary. The parameter ψ directly measures the fraction of the population that visits the wetland, while S_{WL0} estimates the proportion of fish that survive their visit to the wetland. Further, if use of the wetland by smolts improves their survival by facilitating growth or improving their condition, then this benefit of the wetland may be reflected in the subsequent survival of smolts in the mainstem river after they leave wetland (i.e., S_{WLi} compared to S_{MSi}). Thus, within a given reach, the survival probabilities downstream of the wetland can be compared between fish that remain in the mainstem river (S_{MSi}) and those that visit the wetland and subsequently continue their migration in the mainstem river (S_{WLi}). However, whether use of the wetland by smolts improves population-level survival depends on the mortality incurred in the wetland relative to the subsequent improvement in survival downstream of the wetland. This hypothesis can be expressed by comparing total passage survival through the estuary for fish remaining in the mainstem river and visiting the wetland:

$$H_0: S_{MS} = S_{WL} \qquad (1)$$

where $$S_{MS} = S_{MS1}S_{MS2}$$

and where $$S_{WL} = S_{WL0}S_{WL1}S_{WL2}S_{WL3}$$

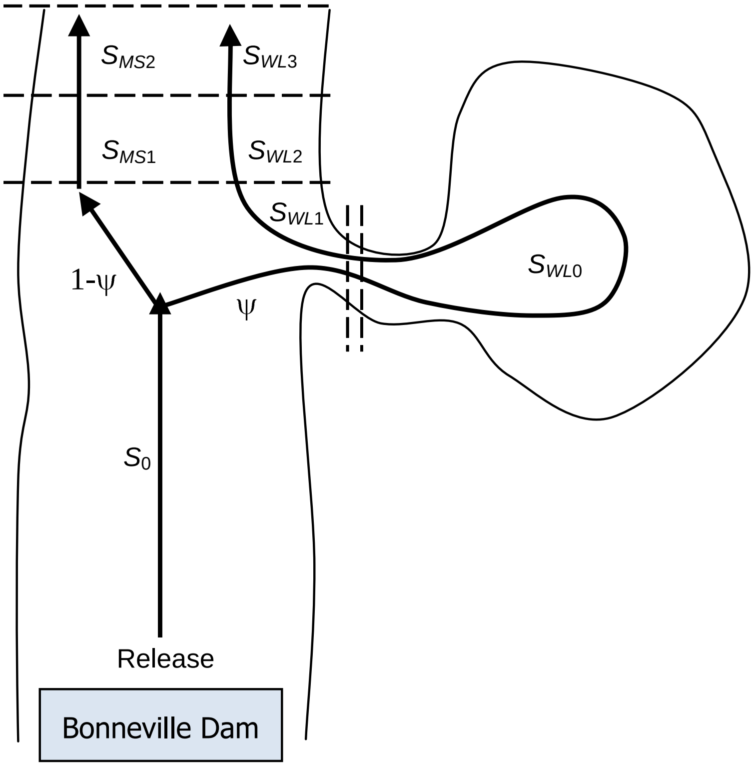

Figure 2.1. Schematic of the study area showing two possible migration pathways: (1) a juvenile salmon that visits the restored wetland with probability ψ and (2) a juvenile salmon that remains in the mainstem river with probability 1-ψ. Dashed lines show possible locations of telemetry stations. Survival parameters include probability of surviving the wetland (S_{WL0}), probabilities of surviving downstream of the wetland for fish that visited the wetland (S_{WL1}, S_{WL2}, S_{WL3}) and for fish that remained in the mainstem (S_{MS1}, S_{MS2}).

These functions of model parameters quantify survival through the estuary to the last array where survival is estimated, but the term on the left-hand side of Eq. (1) is estuary survival for fish that remain in the mainstem river, and the term on the right-hand side is estuary survival for fish that visit the wetland. The parameter ψ also indicates the relative contribution of each of these terms to the population, and thus, survival through the estuary for all tagged fish is:

$$S_{\text{Estuary}} = (1-\psi)\, S_{MS} + \psi\, S_{WL}$$

In addition to the demographic parameters described above, the replicate hydroacoustic arrays provide information about the amount of time fish spend in the wetland:

$$\bar{T}_{WL} = \frac{1}{n}\sum_{j=1}^{n} T_{WL,j} \qquad (2)$$

where $\bar{T}_{WL}$ is the mean time spent in the wetland, $T_{WL,j}$ is the elapsed time between entry and exit from the wetland for individual j, and n is the number of fish with entry and exit times.

Using the parameters described above, another integrated performance measure combines information about (1) the fraction of the population using the wetland, (2) survival within the wetland, and (3) time spent within the wetland:

$$\bar{T}_{WL}\, \psi S_{WL0} + \bar{T}_{WL}\, (1-\psi)\, S_{MS} + \psi\, \bar{T}_{WL}\, (1-S_{WL0}) + \bar{T}_{WL}\, (1-\psi)(1-S_{MS})$$

Because time spent in the wetland is zero for fish remaining in the mainstem and non-surviving fish do not contribute to the population, the above equation reduces to:

$$\bar{T}_{WL}\, \psi\, S_{\text{WL0}} \qquad (3)$$

This population-level performance measure integrates the three key parameters of residence time, survival, and fractional use of the wetland and can be used to compare the success of multiple restoration projects in the estuary.

2.2 Release-Recapture Model

The release-recapture model consists of two independent likelihoods, each based on a multinomial probability distribution. The first likelihood uses information from only the replicate hydrophone array monitoring movement into the wetland to estimate detection probabilities and survival within the wetland (Fig. 2.2). The second likelihood estimates the movement parameter ψ, detection probabilities in the mainstem Columbia River (P_i), and survival probabilities in the mainstem river (Fig. 2.2). It is important to note that information contained in the replicate arrays at the mouth of the wetland is sufficient to estimate all detection probabilities, as well as survival within the wetland. Thus, Likelihood 1 can be fit to the data independent of any information provided by hydroacoustic arrays in the mainstem Columbia River. The second likelihood, describing migration in the mainstem, is overparameterized and does not contain enough information to estimate P_{WL}, the probability of being detected at least once by the replicate hydrophone array. Thus, a joint likelihood is used to estimate all parameters where information from Likelihood 1 is used to estimate P_{WL}. Given P_{WL}, all parameters in Likelihood 2 then become estimable.

2.1.1. Likelihood 1: Survival within the Wetland

The replicate hydrophone array contains all the information necessary to estimate detection probabilities and survival in the wetland. Consider a fish that enters and subsequently exits the wetland (see Fig. 2.1). Further, suppose this fish is detected on the first and second detection stations as it enters the wetland, and the second then first station as it exits (say, detection history “1221”). The probability of this event is $P_{11}\, P_{21}\, S_{WL0}\, P_{12}\, P_{22}$. That is, the fish was detected with probability P_{11} at the first station and with probability P_{21} at the second station as it entered the wetland, survived with probability S_{WL0}, and was then detected at both stations as it exited with probability P_{12} and P_{22}. The likelihood is formed by identifying all unique detection histories and their probability of occurrence in terms of the parameters (Table 2.1). However, some detection histories, such as 1000 and 0001 (where “0” indicates nondetection) are impossible to distinguish because with only a single detection, we cannot differentiate whether a fish was entering or exiting the wetland. By modeling the series of events as a single likelihood, both possibilities are accounted for in the probability structure of this detection history (Table 2.1). Finally, the detection history “0000” is not observable, so the likelihood is constructed conditional on being detected at least once on any detection station during either entrance or exit events. Since Pr(“0000”) is the probability of not being detected, 1–Pr(“0000”) is the probability of being detected one or more times. Thus, the conditional likelihood is formed simply by dividing each multinomial cell probability by 1–Pr(“0000”). There are 13 unique detection histories, with counts of each detection history and associated probabilities of occurrence forming the 13 cell probabilities of a multinomial likelihood model (Table 2.1):

$$L_1 = \binom{R_1}{\underset{\sim}{n}} \prod_{i=1}^{13} \pi_i^{n_i} \qquad (4)$$

where L_1 is the likelihood, R_1 is the total number of fish detected at the replicate arrays, $\underset{\sim}{n}$ is the vector of observed frequencies for each detection history, π_i is the probability of occurrence of the ith detection history, and n_i is the number of fish with the ith detection history.

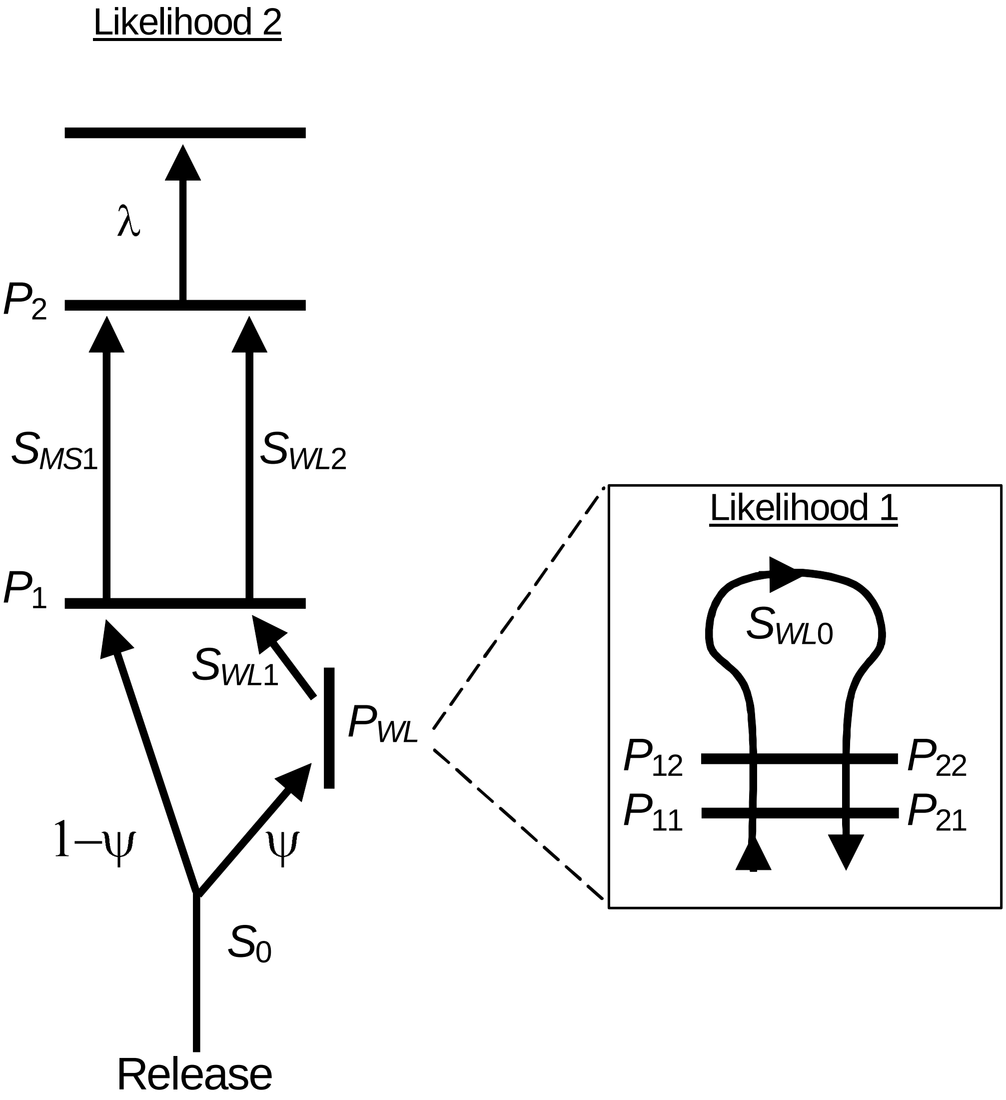

Figure 2.2. Schematic of the release-recapture model showing parameters estimated by Likelihoods 1 and 2. Solid horizontal lines show where detection probabilities (P_i) are estimated at detection stations, the forked arrows show where fish move from the mainstem river to the wetland (ψ) or remain in the mainstem river (1-ψ), and the remaining arrows show reaches where survival (S_i) is estimated. Likelihood 1 is shown as the inset schematic at the location in the Likelihood 2 where information is used from Likelihood 1 to estimate P_{WL}. In the last reach, λ is the joint probability of surviving and being detected at the last hydroacoustic array.

Table 2.1. Multinomial cell probabilities for the Likelihood 1, which estimates detection probabilities and survival within the wetlands (see Fig. 2.2). The probability of being detected at least once at the wetlands telemetry stations (P_{WL}) is $(1-(1-P_{11})(1-P_{21})(1-S_{WL0}+S_{WL0}(1-P_{22})(1-P_{12})))$.

Detection history	Probability of occurrence (π_i)
1221	$P_{11} P_{21} S_{WL0} P_{22} P_{12}/P_{WL}$
0221	$(1-P_{11}) P_{21} S_{WL0} P_{22} P_{12}/P_{WL}$
1021	$P_{11} (1-P_{21}) S_{WL0} P_{22} P_{12}/P_{WL}$
0021	$(1-P_{11}) (1-P_{21}) S_{WL0} P_{22} P_{12}/P_{WL}$
1201	$P_{11} P_{21} S_{WL0} (1-P_{22}) P_{12}/P_{WL}$
0201	$(1-P_{11}) P_{21} S_{WL0} (1-P_{22}) P_{12}/P_{WL}$
1001	$P_{11} (1-P_{21}) S_{WL0} (1-P_{22}) P_{12}/P_{WL}$
1	$(1-P_{11}) (1-P_{21}) S_{WL0} (1-P_{22}) P_{12}/P_{WL}+P_{11} (1-P_{21}) (1-S_{WL0}+S_{WL0} (1-P_{22}) (1-P_{12}))/P_{WL}$
1220	$P_{11} P_{21} S_{WL0} P_{22} (1-P_{12})/P_{WL}$
0220	$(1-P_{11}) P_{21} S_{WL0} P_{22} (1-P_{12})/P_{WL}$
1020	$P_{11} (1-P_{21}) S_{WL0} P_{22} (1-P_{12})/P_{WL}$
2	$(1-P_{11}) (1-P_{21}) S_{WL0} P_{22} (1-P_{12})/P_{WL}+(1-P_{11}) P_{21} (1-S_{WL0}+S_{WL0} (1-P_{22}) (1-P_{12}))/P_{WL}$
1200	$P_{11} P_{21} (1-S_{WL0}+S_{WL0} (1-P_{22}) (1-P_{12}))/P_{WL}$

Model Assumptions

1. Each fish has an independent fate.
2. The probability of detection at one array is independent of the probability of detection at the second array.
3. The direction of movement of fish (i.e., entering or exiting) can be determined based on the time series of detections at each array.
4. Fish move through both arrays and enter the wetland.

The second assumption can be fulfilled by ensuring that the detection zone of each array completely encompasses the channel cross-section. This assumption is likely to be fulfilled given the small size of these channels relative to the typical detection range of telemetry receivers. Assumption 3 is necessary because probabilities of occurrence for each detection history are based on the order of detection at the replicate arrays. This assumption can be fulfilled by separating each hydrophone array by a distance sufficient to yield spatial and temporal resolution among detection times at each array. However, the arrays should be in close enough proximity to ensure that little mortality occurs between the replicate arrays. The last assumption may be violated if fish do not completely pass through both arrays and enter the wetland. For example, if the replicate arrays are situated too close to the mainstem Columbia River, then fish in the mainstem river passing by the entrance of the wetland may be detected at the replicate arrays. As another example, if a fish enters the channel, passes the first array, but then turns around and exits into the mainstem river, then the fourth assumption will be violated. The consequence of violating this assumption is positive bias in ψ and negative bias in S_{WL0}.

2.1.2. Likelihood 2: Movement and Survival within the Mainstem

The primary likelihood proceeds in similar fashion to a standard Cormack-Jolly-Seber model with the additional complexity of incorporating a movement probability (ψ) and estimating survival probabilities conditional on previous migration history (i.e., fish that remain in the mainstem versus those that use the wetland). The primary likelihood ignores the replicate array structure and treats each telemetry station as if it were a single detection station, considering only the presence or absence of detections at each station. For illustration, we constructed a model with three telemetry stations (i.e., two reaches) downstream of the wetland and a single reach upstream of the wetland. However, a minimum configuration consists of two telemetry stations (i.e., one reach) downstream of the wetland. Under this minimum configuration, only the ratio S_{WL2}/S_{MS1} can be estimated with the assumption that detection probabilities at the last telemetry station are the same for these two groups of fish. All other parameters can be estimated with this minimum configuration. Beyond the minimum configuration, this model can accommodate any number of reaches upstream and downstream of the wetland. The likelihood is constructed by listing all possible detection histories and writing the probability of each detection history as a function of the model parameters (Fig. 2.2, Table 2.2). To distinguish detections in the wetland from those in the mainstem, detection histories for the mainstem are coded with an “A” while those at the entrance to the wetland are denoted by “B”. Downstream of the wetland, detections or absence thereof are denoted by a “1” or “0” respectively. Thus the detection history “BA11” indicates a fish was detected either entering or exiting the wetland (B), was then detected in the mainstem river just downstream of the wetland (A), and was detected at the two downriver telemetry stations (Fig. 2.1 and 2.2). The probability of this detection history is simply the joint probability of parameters that describe this pathway through the system (Fig. 2.2): $S_0 \psi P_{WL} P_1 S_{WL1} P_2 \lambda$.

Another important feature of the primary likelihood is the inability to distinguish among some of the possible detection histories. For example, the detection history “A11” cannot be distinguished from “0A11”. In other words, from the detection data there is no way to distinguish whether a fish migrated only in the mainstem, or entered the wetland, survived, and exited the wetland without being detected. The probability structure of this detection history must incorporate the possibility that either event could have occurred (see Table 2.1). For this likelihood, there are 16 unique detection histories, each forming the 16 cell probabilities of a multinomial distribution:

$$L_2 = \binom{R_2}{\underset{\sim}{n}} \prod_{j=1}^{16} \pi_j^{n_j} \tag{5}$$

and R_2 is the total number of fish released, $\underset{\sim}{n}$ is the vector of observed frequencies for each detection history, π_j is the probability of occurrence of the jth detection history, and n_j is the number of fish with the jth detection history.

Table 2.2. Multinomial cell probabilities for the Likelihood 2, which estimates detection, movement, and survival probabilities within the mainstem Columbia River (see Fig. 2.2). The probability of being detected at least once at the wetland telemetry stations (P_{WL}) is $(1-(1-P_{11})(1-P_{21})(1-S_{WL0}+S_{WL0}(1-P_{22})(1-P_{12})))$.

Detection history	Probability of occurrence (π_j)
BA11	$S_0\,\psi\,P_{WL}\,S_{WL1}\,P_1\,S_{WL2}\,P_2\,\lambda$
A11	$S_0\,\psi\,(1-P_{WL})\,S_{WL1}\,P_1\,S_{WL2}\,P_2\,\lambda+S_0\,(1-\psi)\,P_1\,S_{MS1}\,P_2\,\lambda$
B011	$S_0\,\psi\,P_{WL}\,S_{WL1}\,(1-P_1)\,S_{WL2}\,P_2\,\lambda$
011	$S_0\,\psi\,(1-P_{WL})\,S_{WL1}\,(1-P_1)\,S_{WL2}\,P_2\,\lambda+S_0\,(1-\psi)\,(1-P_1)\,S_{MS1}\,P_2\,\lambda$
BA01	$S_0\,\psi\,P_{WL}\,S_{WL1}\,P_1\,S_{WL2}\,(1-P_2)\,\lambda$
A01	$S_0\,\psi\,(1-P_{WL})\,S_{WL1}\,P_1\,S_{WL2}\,(1-P_2)\,\lambda+S_0\,(1-\psi)\,P_1\,S_{MS1}\,(1-P_2)\,\lambda$
B001	$S_0\,\psi\,P_{WL}\,S_{WL1}\,(1-P_1)\,S_{WL2}\,(1-P_2)\,\lambda$
001	$S_0\,\psi\,(1-P_{WL})\,S_{WL1}\,(1-P_1)\,S_{WL2}\,(1-P_2)\,\lambda+S_0\,(1-\psi)\,(1-P_1)\,S_{MS1}\,(1-P_2)\,\lambda$
BA10	$S_0\,\psi\,P_{WL}\,S_{WL1}\,P_1\,S_{WL2}\,P_2\,(1-\lambda)$
A10	$S_0\,\psi\,(1-P_{WL})\,S_{WL1}\,P_1\,S_{WL2}\,P_2\,(1-\lambda)+S_0\,(1-\psi)\,P_1\,S_{MS1}\,P_2\,(1-\lambda)$
B010	$S_0\,\psi\,P_{WL}\,S_{WL1}\,(1-P_1)\,S_{WL2}\,P_2\,(1-\lambda)$
010	$S_0\,\psi\,(1-P_{WL})\,S_{WL1}\,(1-P_1)\,S_{WL2}\,P_2\,(1-\lambda)+S_0\,(1-\psi)\,(1-P_1)\,S_{MS1}\,P_2\,(1-\lambda)$
BA00	$S_0\,\psi\,P_{WL}\,S_{WL1}\,P_1\,(1-S_{WL2}+S_{WL2}\,(1-P_2)\,(1-\lambda))$
A00	$S_0\,\psi\,(1-P_{WL})\,S_{WL1}\,P_1\,(1-S_{WL2}+S_{WL2}\,(1-P_2)\,(1-\lambda))+S_0\,(1-\psi)\,P_1\,(1-S_{MS1}+S_{MS1}\,(1-P_2)\,(1-\lambda))$
B000	$S_0\,\psi\,P_{WL}\,(1-S_{WL1}+S_{WL1}\,(1-P_1)\,(1-S_{WL2}+S_{WL2}\,(1-P_2)\,(1-\lambda)))$
000	$1-S_0+S_0\,\psi\,(1-P_{WL})\,(1-S_{WL1}+S_{WL1}\,(1-P_1)\,(1-S_{WL2}+S_{WL2}\,(1-P_2)\,(1-\lambda)))+S_0\,(1-\psi)\,(1-P_1)\,(1-S_{MS1}+S_{MS1}\,(1-P_2)\,(1-\lambda))$

Model Assumptions

1. Each fish has an independent fate.
2. Capture, survival, and movement are not affected by previous capture history.
3. Movements defining fish that remain in the mainstem or move into the wetland occur over short distances such that mortality is zero.

The last assumption can be fulfilled by placing a hydroacoustic array in the mainstem river as close as possible to the entrance to the wetland. This assumption is particularly important, as the consequence of failing this assumption is biased movement probabilities. For example, consider a hydroacoustic array that is placed considerable distance downstream of the wetland entrance. Now, a fish passes by the entrance to the wetland but remains in the mainstem river with probability $(1-\psi)$, and from that point, it survives with probability <1 to the next array downriver. Since there is no array at the point of transition between the mainstem and wetland, the movement and survival process cannot be separated, resulting in biased estimates of ψ. However, for fish that enter the wetland, we can estimate survival between the exit of the wetland and the first downriver array (S_{WL1} in Figs. 2.1 and 2.2). This survival probability can act as a check on assumption 3, since if assumption 3 is fulfilled, we would expect the estimate of S_{WL1} to be close to 1.

2.1.3. Joint Likelihood: Movement and Survival within the Mainstem and Wetland

As discussed above, the primary likelihood does not contain enough information to estimate P_{WL}, the probability of being detected at least once during a visit to the wetland. Thus, P_{WL} is estimated as a function of parameters in the Likelihood 1:

$$P_{WL} = 1-(1-P_{11})\,(1-P_{21})\,(1-S_{WL0}+S_{WL0}\,(1-P_{22})\,(1-P_{12}))$$

Given P_{WL} is estimated from Likelihood 1, all remaining parameters in Likelihood 2 become estimable and the joint likelihood for estimating all parameters is simply the product, L_1L_2.

2.1.4. Parameter Estimation and Precision

Maximum likelihood estimates of the parameters are found by numerically maximizing the likelihood with respect to the parameters with appropriate software such as Program USER (http://www.cbr.washington.edu/paramest/user/). Program USER can also be used *a priori* when planning a study to estimate the expected precision of parameters, given a release sample size and a hypothesized set of parameter values (or preliminary estimates from a pilot study). An example of using the model to estimate expected precision is shown below for a release sample size of $R_2 = 1000$ fish (Table 2.3). First, expected counts of each detection history [n_i in Eq. (2), and n_j in Eq. (3)] are calculated as the expected values of a multinomial distribution where $E(n_i) = R_1\pi_i$, $E(n_j) = R_2\pi_j$, and $R_1 = R_2 S_0 \psi P_{WL}$. True parameter values were selected in an *ad hoc* fashion for this example, but were chosen such that each parameter had a unique value (Table 2.3). The expected counts of detection histories are then input into USER, along with the joint likelihood, to estimate the parameters and the associated variances. In this example, the expected standard error of survival in the wetland (S_{WL0}) is more than twice that of standard errors for survival probabilities in the mainstem, while survival of fish that remain in the mainstem (S_{MS1}) has the lowest standard error. Differences in precision occur largely due to the relatively low proportion of fish that entered the wetland ($\psi = 0.20$). This example shows how insights about the expected precision of such a study can be used to help determine appropriate sample sizes during the planning phases of the study.

Table 2.3. True parameter values, parameter estimates and standard errors for a simulated data set of $R_2 = 1000$ fish using the release-recapture model shown in Tables 2.1 and 2.2.

Parameter	True value	Estimated value	Estimated standard error
ψ	0.20	0.199	0.014
S_{WL0}	0.92	0.915	0.078
S_{WL1}	0.99	0.990	0.029
S_{WL2}	0.90	0.899	0.031
S_{MS1}	0.80	0.800	0.024
S_0	0.90	0.899	0.017
P_1	0.55	0.550	0.019
P_2	0.78	0.780	0.018
P_{11}	0.45	0.450	0.040
P_{21}	0.68	0.683	0.038
P_{22}	0.34	0.341	0.044
P_{12}	0.71	0.717	0.064
λ	0.68	0.680	0.019

3.0 Discussion and Other Considerations

This report illustrates how acoustic telemetry combined with release-recapture models can be used to examine the evaluation of wetland restoration projects for juvenile salmonids. The analytical framework described herein provides a means by which to evaluate wetland restoration projects by estimating (1) the proportional use of these habitats by juvenile salmonids, (2) survival while residing in these habitats, and (3) possible future benefits of using such habitats in terms of improving subsequent survival. The cumulative effect of restoration projects in general may provide numerous habitats to the benefit of the juvenile salmonid population as they transition from the riverine to ocean environment. Toward this end, the models and telemetry network described here could be extended to numerous off-channel habitats to better understand the universal importance of these habitats to juvenile salmonid populations.

Monitoring and evaluation of restored wetlands to measure benefits to juvenile salmonids is expensive. Yet, we are unaware of collaboration among research projects that takes advantage of tagged fish already in the mainstem to estimate survival in the Columbia River estuary. Given the expense of these survival studies, it seems prudent to extract as much information as possible from existing tagged fish. The model presented here represents a small additional cost (a replicate hydroacoustic array at the mouth of the wetland), relative to the information gained about the use of restored wetlands by juvenile salmonids. Furthermore, the model presented here measures success of restoration projects in terms of their contribution to the population of juvenile salmonids migrating through the estuary.

In conducting such a study, it is *essential* that model development occur before implementation to assure study objectives can be fulfilled. Joint movement – survival studies are among the most complex and difficult release-recapture studies to design and implement. It is reckless to implement a study without first formally evaluating what can and cannot be statistically estimated. Beyond determining estimability is the need to perform sample size calculations to help assure studies can yield precise and useful information. Hopefully, this report will spur interest in the implementation of quantitatively defensible tag investigations that take advantage of tagged smolts in the estuary to measure movement into, and survival and residence times within, restored wetlands.