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FELLOWSHIP APPLICATION COVER PAGE

APPLICANT TYPE ☐ Postdoctoral Researcher ☒ Ph.D. Graduate Student

PROJECT NUMBER ____________

PROJECT TITLE Estimating route-specific survival and distribution of juvenile salmonids migrating through the Sacramento - San Joaquin River Delta

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Will animal subjects be used? ☐ Yes ☒ No

APPROVAL DATE: ____________ PROTOCOL #: ____________ PENDING: ____________

Does this application involve any recombinant DNA technology or research? ☐ Yes ☒ No

Proposed Research – CALFED Science Fellowship Application

Title

Estimating route-specific survival and distribution of juvenile salmonids migrating through the Sacramento – San Joaquin River Delta

Question/Problem Statement

How does variation in the distribution of water in the Sacramento – San Joaquin River Delta (hereafter “the Delta”) affect 1) distribution of juvenile salmon migrating through the Delta, 2) survival rates of juvenile salmonids negotiating different migratory pathways, and consequently 3) survival of the population migrating through the Delta?

Objective

Our objective is to develop a mark-recapture model that will estimate parameters of population distribution through the Delta, survival probabilities of juvenile salmonids traversing different migratory pathways, and overall survival probabilities of the population migrating through the Delta.

Rationale

The interaction between seasonal timescale variations in upstream hydrology and strong tidal forcing within the complex network of channels that make up the Delta has made it difficult to clearly identify the effects of water management actions on survival and recovery endangered juvenile salmon populations. Long-term studies (e.g., Anadromous Fish Restoration Program’s (AFRP) Delta Action 8) have generated working hypotheses that water exports reduce survival of juvenile salmon migrating through the central and southern Delta. Although these studies provide critical information, what remains unclear is the proportion of the population subject to these lower survival rates. As juvenile salmon populations migrate downstream, they distribute among the complex channel network of the Delta. How juvenile salmon distribute among the available migration routes combined with survival rates through each route will determine the overall survival of the population. For instance, if only 10% of the population migrating through the Delta is subject to lower survival rates (e.g., 50% survival) caused by water exports, while 90% of the population choose other pathways with higher survival (e.g., 85%), then the impact of exports on survival of the population may be minimal (overall survival = 81.5%). Although a simple example, it shows how implementation of costly management actions (e.g., AFRP Delta Action 9) may have relatively little effect on improving survival of the population.

To fully understand population-level responses to both natural variation and human-imposed management actions, we propose a Delta-wide approach that will explicitly estimate how juvenile salmonid populations distribute through the Delta and survive within each migratory pathway. Ultimately, this approach will combine information about population distribution and route-specific survival rates to estimate the overall survival rate of the population migrating through the Delta. Under this framework, researchers will gain better understanding of population-level responses to changes in water distribution, and resource managers will gain better information on which to base important decisions affecting water resources. Specifically, this proposal addresses the CALFED Agency Science need to "Analyze ultrasonic tagging and tracking data on juvenile salmon survival through the Delta" (http://www.csgc.ucsd.edu/EDUCATION/CALFED/CALFEDAppendixF.html).

Introduction

The Sacramento – San Joaquin River Delta provides important rearing habitat and a migration corridor to threatened and endangered stocks of juvenile salmon and steelhead. The Delta is a complex network of armored channels. Juvenile salmon and steelhead smolts traversing this complex network may take any number of migration routes on their journey to the ocean. For example, Steamboat and Sutter Slough, entering the Sacramento River upstream of the Delta Cross Channel (DCC), is one major route through which juvenile salmon may migrate. In addition to the mainstem Sacramento River and numerous secondary routes, other major routes through the Delta include the Delta Cross Channel and Georgiana Slough, both of which may divert fish into the central and southern Delta.

Added to the physical complexity, in the form of a channel network system, is hydrodynamic complexity that varies significantly at daily to seasonal timescales due to natural processes, such as the tides and hydrologic cycle, and human influences, such as reservoir releases, DCC gate operations, an export rates. Discharge and water velocities within the Delta channels are influenced strongly by the tides which can vary both at daily and fortnightly (14-day) time scales. The tides not only affect water velocities at a given point in a channel, but can also affect how total river discharge splits among the channels at junctions. For instance, Blake and Horn (in press) found that during flood tides, water enters the Delta Cross Channel from both an upstream and downstream direction, but on ebb tides, the flow in the mainstem Sacramento River can bypass the DCC altogether. Other natural processes affecting river discharge through the Delta network include rainfall and snowmelt events in the winter and spring, respectively.

The Delta is also affected by numerous human demands on its water resources. Of primary importance here is the State Water Project (SWP) and Central Valley Project (CVP), both of which export water out of the southern Delta for agriculture and human consumption. Water project operations affect the net (tidally-averaged) discharge throughout the Delta, and at some locales, water can flow in a net upstream direction (depending on the difference between exports and inflows). The Delta Cross Channel, a man-made channel used to divert flow from the Sacramento River into the central and southern Delta is a critical component of the CVP. The DCC improves the quality of water exported for agricultural and human uses by reducing salinities in the central and southern Delta. Flow into the DCC is controlled by radial gates and the magnitude of flow into the DCC affects not only the discharge in the mainstem Sacramento River, but also flow into channels upstream and downstream of the DCC (e.g., Steamboat and Sutter Slough and Georgiana Slough, Jon Burau, personal communication). Additional human influences on the routing of water, and juvenile salmon, through the Delta include extensive dikes, dredged channels, and rip-rap revetments.

As migrating fish enter the Delta region from the mainstem Sacramento River the population distributes through the complex network of channels. Each channel chosen as a migratory pathway will have a unique set of biotic and abiotic processes that affect migration rates, predation rates, feeding and growth rates, and ultimately, survival. For example, Sommer et al. (2001) showed that apparent growth of juvenile salmon in the Yolo Bypass, a seasonally-inundated flood plain, was significantly greater than in the adjacent channels. In contrast, fish entering the central and southern Delta must traverse longer routes and are subject to entrainment at the CVP and SWP, both of which may decrease survival of juvenile salmon using this migratory pathway (Brandes and McLain 2001). These examples show that population-level survival rates of juvenile salmon migrating through the Delta will be driven by 1) the proportion of the population using each migratory pathway, and 2) the survival rates arising from the set of unique biotic and abiotic processes of each migratory pathway. In turn, natural and human-imposed variation in discharge, water velocities, and water routing will drive the population distribution and survival rates within each channel, affecting survival of the population migrating through the Delta.

Currently, there is poor understanding of how human-imposed and natural changes in water distribution affect population distribution and route-specific survival probabilities. However, recent work has shed light on some of the physical and biological processes likely to influence population distribution and survival. For example, recent work by the USGS (Jon Burau, personal communication) has shown that operation the Delta Cross Channel affects not only discharge of the Sacramento River, but the discharge of Steamboat and Sutter sloughs and Georgiana slough. Thus we can expect that changes in operation of the DCC will directly effect changes in the distribution of salmon populations entering these various channels. Recent research by Blake and Horn (in press, in prep) has shown that juvenile salmon approaching channel junctions are entrained disproportionately into specific channels relative to the discharge entering those channels. These authors hypothesize that secondary circulation (Dinehart and Burau, 2005) at river bends where channel junctions are located interact with fish behavior to concentrate juvenile salmon on the outside of river bends where they are more likely to become entrained in channels located on the outside of the river bend. Furthermore, other researchers have shown that reversing flows due to the tides can advect juvenile salmon past a junction, only to be entrained into other channels such as Cache or Georgiana Slough (Vogel 2004). These complex interactions between fish behavior, water management actions, and natural phenomena occur at fine temporal and spatial scales, but integrate over space and time to determine population distribution and survival rates over the duration of the juvenile salmonid migration season.

We propose to develop a mark-recapture model that will estimate both population distribution and survival rates through the Delta. Traditional mark-recapture techniques that depend on the physical recapture of fish are incapable of providing the level of detailed information needed to understand the complex physical and biological processes acting on survival of juvenile salmonid populations migrating through the Delta. In contrast, telemetry is a passive recapture technique that can provide detailed information on the movement of individual fish. In addition, recent advances in telemetry technology have progressively reduced the size of transmitters, making it possible to study movements of juvenile salmonids without significantly altering their behavior or survival (Hockersmith et al. 2003). Strategic placement of telemetry arrays in the Delta will allow for individual-specific information on routes used by juvenile salmon and migration timing through those routes. Furthermore, telemetry arrays can be implemented under a mark-recapture framework to estimate survival probabilities through various routes of the Delta.

This proposal describes research that will use data from three independent telemetry studies and will be implemented collaboratively through community mentors involved in each study (Pat Brandes, U.S. Fish and Wildlife Service; Jon Burau, U.S. Geological Survey; and Steve Lindley, NOAA Fisheries). First we describe recent advances in mark-recapture models to show how models similar to that proposed for the Delta have been used elsewhere. Second, using these recent models as an example, we describe the statistical and modeling framework that will be used to implement the mark-recapture model. Third, all mark-recapture models are subject to important assumptions necessary for interpretation of parameter estimates; these assumptions will be discussed and a plan for testing assumptions set forth. Last, a three-year plan will be laid out to gradually develop a full-scale study capable of estimating population-level distribution and survival probabilities. A full-scale study to estimate survival and distribution among migration routes over the migration season of juvenile salmon may require large sample sizes to obtain the necessary precision on which to base management decisions. Thus, we also focus on analyses that will allow managers and researchers to weigh the cost of research against the benefit of the information gained in terms of reducing uncertainty about the effects of implementing expensive water management actions.

Approach/Methods

Description of survival models

Historically, simple recapture rates of marked animals have been used as a survival “index”, but this approach does not account for imperfect recovery of all marked animals alive at subsequent sampling occasions (Nichols 1992). As a consequence, recapture rates will almost always underestimate the probability of survival since the recapture rate is the product of both the capture probability (p) and survival probability (S). Furthermore, if the capture probability is not constant over sampling occasions then inferences about changes in survival will be invalid. The classical works of Cormack (1964), Jolly (1965), and Seber (1965) developed the “CJS” model, which estimates both capture and survival probabilities allowing for an unbiased estimate of survival probability. Since the ground-breaking work of Cormack, Jolly, and Seber, much advancement has taken place in both the structure of survival models and the framework within which they are implemented (Lebreton et al. 1992, Williams et al. 2002).

Although numerous mark-recapture models have been tailored to meet the specific needs of fisheries research (see Burnham et al. 1987, Pevan et al. 2006), the route-specific survival model (Skalski et al. 2002) comes closest to emulating the model structure that is needed for the Delta. This mark-recapture model was developed to estimate survival probabilities of juvenile salmon as they migrate through the Columbia River and pass through a hydroelectric project (for examples, see Counihan et al. 2003 and Perry et al. 2006). This model estimates survival probabilities of fish migrating through the reservoir (S_{pool}) between an upstream release point (R_t) and the dam (Figure 1). Once fish arrive at the dam, they may pass the dam through a number of available routes such as the turbines or the spillway. By monitoring passage routes with telemetry equipment and recording detections of tagged fish in each passage route, the model estimates the probability of survival through each passage route (S_{By}, S_{Tu}, and S_{Sp}; Figure 1) as well as conditional probabilities of passing through each route (Sp, Tu, and By; Figure 1). Both the passage distribution through all routes and the overall probability of surviving dam passage can be estimated as functions of conditional survival and passage probabilities. Specifically, the overall probability of surviving passage through the dam is estimated as the average probability of survival through all routes weighted by the probability of passing each route.

Clearly, the physical settings of the Columbia River and the Sacramento – San Joaquin Delta could not differ more, but conceptually, the problem is the same. What is the survival of fish passing each route (i.e., passage route at a dam or migratory route through a specific channel in the Delta)? What is the proportion of the population that is subject to each route-specific survival probability? And, what is the overall survival probability through all routes? Most importantly, in both cases this approach allows managers and researchers to explicitly answer the important question, “How do management actions in the Delta (e.g., reservoir releases, DCC gate operations, export rates) affect the distribution of fish passing available routes and in turn, how are survival probabilities affected”. Moreover, the spatial distribution of survival probabilities could suggest optimal locations for restoration efforts aimed at increasing overall salmon survival.

Statistical approach and modeling framework

The foundation of the proposed mark-recapture model is based on the classical single release-recapture models of Cormack (1964), Jolly (1965), and Seber (1965). Detection (or “capture”) histories of each fish form the basis of these models and allow for the estimation of route-specific survival, detection, and passage probabilities. In general, survival and detection probabilities are estimated by:

1) Creating detection histories for each fish.

2) Estimating the probability of each possible detection history from the number of fish with that detection history (i.e., from the observed frequencies of each detection history).

3) Using maximum likelihood methods to find parameter estimates of survival, passage, and detection probabilities that were most likely, given the observed data set of detection histories.

We will the USER software program (User Specified Estimation Routine) to implement the mark-recapture survival model and estimate survival, detection, route-specific passage parameters (Lady et al. 2003). To prepare the data for input into USER, telemetry records for each fish will be summarized into detection histories to indicate the migratory-route of each fish and whether fish were detected or not detected at antenna arrays located throughout the Delta. For example, the route-specific model uses a primary likelihood to estimate survival and passage probabilities and a secondary likelihood to estimate route-specific detection probabilities. At Columbia River dams, the detection history for the primary likelihood is typically composed of 3 digits indicating 1) the release site (1 = upstream of the dam, 0 = tailrace), 2) the route of passage for each fish coded by numbers ranging from 0 to 4 (see Figure 1), and 3) whether fish were detected (1) or not detected (0) at telemetry arrays downriver of the dam. For example, the detection history 140 indicates a fish that was released upstream of the dam and passed the dam via the spillway, but was not subsequently detected by downriver telemetry arrays.

Each unique detection history has a probability of occurrence that can be completely specified in terms of the survival, route-specific passage, and detection probabilities. For example, if a fish was detected passing the spillway, then it survived through the preceding reach. Thus, the probability of this event is the joint probability that it survived through the reservoir (S_{Pool}), passed the spillway (Sp), and was detected in the spillway (P_{Sp}). However, if this fish was not subsequently detected at an array downriver of the dam, then two possibilities arise, 1) the fish died ($1-S_{\mathrm{Sp}}$, the probability of not surviving through the spillway), or 2) the fish survived the spillway but was not detected by downriver telemetry arrays, $S_{\mathrm{Sp}}(1-\lambda)$, the joint probability of surviving and not being detected. Therefore, the probability of detection history 130 can be specified as $S_{\mathrm{Pool}*}\mathrm{Sp}*P_{\mathrm{Sp}}*(1-S_{\mathrm{Sp}}+S_{\mathrm{Sp}*}(1-\lambda))$.

The expected probability of each detection history is then estimated from the observed frequencies of fish with that detection history. Given the expected probability of each detection history and its probability function in terms of survival, route-specific passage, and detection probabilities, maximum likelihood methods are used to find the combination of survival, passage, and detection probabilities most likely to occur, given the observed frequencies of each detection history. The maximum likelihood function to be maximized is simply the joint probability of all possible detection histories.

Sampling variances for parameters estimated by maximum likelihood are calculated using the inverse Hessian matrix provided by the USER software. Further details on the maximum likelihood methods for estimating survival and detection probabilities, including estimation of theoretical variances, can be found in Burnham et al. (1987), Lebreton et al. (1992), and Skalski et al. (2001). Additional parameters, such as overall survival through multiple routes, can be estimated as functions of model parameters. Variances for these parameters are calculated using the Delta method (Seber 1982). Confidence intervals for all model parameters will be calculated using likelihood profile methods as supplied in USER software. Likelihood profile confidence intervals are presented as ranges because profile likelihood intervals may not be symmetrical about the point estimate due to asymmetrical likelihood distributions.

Dual detection arrays are another important aspect of the route-specific survival model that would likely need to be implemented in this study. To estimate the proportion of fish choosing various routes through the Delta, two independent telemetry arrays would be deployed closely-spaced together at the entrance to each channel just downstream of a channel junction. These dual arrays serve two important functions. First, the dual arrays allow for the estimation of detection probabilities at the entrance to each channel by using the Lincoln/Petersen mark-recapture model (Seber 1982). Without estimating the detection probability of arrays located at the entrance to each channel, estimates of the proportion of fish using each channel may become biased if detection probabilities differ between arrays at each channel entrance (e.g., arrays with lower detection probabilities at one channel entrance will underestimate the proportion of fish passing into that channel). Second, dual arrays will provide information on the direction of movement (upstream or downstream) when fish are detected at both arrays. This information may be critical to minimize errors in assigning fish to a migratory pathway in cases when fish are advected upstream during a flood tide and enter and different migratory pathway.

The dual array is implemented as a secondary likelihood in the mark-recapture model and within-route detection histories are used to calculate the detection probability of each dual array. Within-route histories are composed of two digits and indicate whether fish passing through a dual array were detected by the first array (10), the second array (01), or both arrays (11) within each route.

Assumptions of survival models

All survival models are subject to assumptions for valid interpretation of parameter estimates. These assumptions relate to inferences to the population of interest, error in interpreting telemetry signals, and statistical fit of the data to the model's structure. Some of these assumptions can be explicitly tested, while others can be fulfilled through careful study design. Where possible, we propose to assess model assumptions to validate estimates obtained from mark-recapture survival models. Assumptions are as follows:

1) Tagged individuals are representative of the population of interest. For example, if tagged fish are larger on average than the population of interest, then inferences may not apply to the unsampled fraction of the population.

2) Survival probabilities of tagged fish are the same as that of untagged fish. For example, the tagging procedures should not influence survival or detection probabilities. If the transmitter negatively affects survival, then estimates of survival rates will be biased accordingly.

3) All sampling events are instantaneous. That is, sampling should take place over a short distance relative to the distance between telemetry arrays so that the chance of mortality at a telemetry array is minimized. This assumption is necessary to correctly attribute mortality to a specific river reach. This assumption is usually satisfied by the location of telemetry arrays and the downstream migration rates of juvenile salmonids.

4) The fate of each tagged fish is independent of the fate of other tagged fish. In other words, survival or mortality of one fish has no effect on that of others.

5) The prior detection history of a tagged fish has no effect on its subsequent survival. This assumption could be violated if there are portions of the river that are not

monitored for tagged fish. For telemetry, this assumption is usually satisfied by the passive nature of detecting tags and by monitoring the entire channel cross-section of the river.

6) All tagged fish alive at a sampling location have the same detection probability. This assumption could also be violated as described in assumption 5, but is usually satisfied with telemetry by monitoring the entire channel cross-section.

7) All tags are correctly identified and the status of tagged fish (i.e., alive or dead) is known without error. This assumes fish do not lose their tags and that the tag is functioning while the fish is in the study area. Additionally, this assumes that all detections are of live fish and that dead fish are not detected and interpreted as live (i.e., false positive detections).

8) The dual detection arrays within each route are independent. This assumption is necessary to obtain valid estimates of route-specific detection probabilities. To fulfill this assumption, fish detected in one array should have the same probability of detection in the second array compared to fish not detected in the first array.

9) Routes of tagged fish are known without error. This assumption is important to avoid bias in route-specific passage and survival probabilities.

Assumptions 5 and 6 can be formally tested using χ^2 Goodness of Fit tests known as Test 2 and Test 3 (Burnham et al. 1987). Both Test 2 and 3 are implemented as a series of contingency tables. Test 2 is informally known as the “recapture test” because it assesses whether detection at an upstream array affects detections at subsequent downstream arrays (assumption 6). Test 3 is known as the “survival test” because it assesses assumption 5 that fish alive at array i have the same probability of surviving to array i+1 as fish not detected at array i. The pooled χ^2 value from Test 2 and 3 provides an overall test of overdispersion in the parameter estimates.

Assumption 7 can be tested empirically. To test for false positive detections, a subsample of euthanized tagged fish can be released and subsequent detection monitored. To test whether fish exited the study area within the battery life of the transmitter, a controlled tag life study can be conducted to estimate the probability of tag failure at any point in time after tags were turned on. The methods of Townsend et al. (In Press) can be used to estimate the average probability that a tag was alive while fish were in the study area. If tags fail prior to exiting the study area, then information from the tag life study can be used to correct survival estimates for the probability of tag failure.

Plan of Work and Timeline

During year 1 we will develop the mark-recapture model and use pilot data from first-year studies to help design the telemetry system necessary to implement the mark-recapture model. Current telemetry studies planned by the USFWS, USGS, and NOAA Fisheries are not designed to explicitly estimate within-channel survival probabilities or the proportion of the population using each migratory pathway. Thus, development of the model and implementation of the telemetry system will require working closely with community mentors to identify primary reaches of interest, important channel junctions where dual arrays should be deployed, and lessons learned from the first year of study.

During year 2, we propose to implement the mark-recapture model to estimate the migration distribution of tagged fish migrating through the Delta, survival probabilities through different migratory pathways of the Delta, and detection probabilities of telemetry arrays within the Delta. Assumptions of the mark-recapture model will be explicitly assessed to determine the validity of the parameter estimates.

During year 2, we will also conduct a sample size and power analysis. Precision of survival estimates are a function of 1) sample size, 2) detection probabilities, and 3) survival probabilities. As fish distribute through the Delta, sample sizes for individual routes will be reduced, lowering precision of survival estimates for these routes. Therefore, prior estimates of detection probabilities, survival probabilities, and migration distribution through the Delta obtained during year 2 will be used to estimate precision of survival estimates over a range of sample sizes. We will also conduct a power analysis which will quantify the minimum detectable difference (for a given significance level [α] and power [$1-\beta$]) in survival estimates between two “treatments”. Although as of yet unidentified, these “treatments” imply statistical comparison between two survival estimates during either a planned experiment or unplanned environmental conditions. Research studies can be expensive and water management actions may have costly consequences. Thus, sample size and power analysis allows for explicit *a priori* tradeoffs between the cost of conducting a study (in terms of sample size) and the return on the research investment (in terms of precision and power) prior to the commitment of scarce research dollars. Furthermore, this analysis is intended to provide both managers and researchers necessary information to implement a future study that will obtain the necessary precision and statistical power on which to base management decisions.

During year 3, focus will center on analyzing the relation between water distribution and fish distribution through the Delta, and how this relation affects survival of the population of juvenile salmonids passing through the Delta. Two approaches will provide insights into these relationships. First, data on water distribution through the Delta during the 3-year study will be analyzed to examine variations that occurred during the telemetry study period. For example, distribution of tagged fish passing through the Delta and the resulting survival probabilities could be compared between periods when the Delta Cross Channel was open and closed. Insights about the effects of tides on migration and survival may also be gained by comparing spring versus neap tides. However, outcomes of this investigation are unknown due to uncertainty in level of variation in environmental conditions that will occur during the future studies. We are also unsure of whether sample sizes of tagged fish will be adequate to examine relationships at this level of detail.

The second approach during year 3 will be to undertake a simulation experiment that will combine aspects of the mark-recapture study, individual-based modeling, and power analysis to provide a predictive framework to aid in designing future studies. The simulation experiment will also help to understand the complex physical and biological processes that govern the proportion of fish using different migration routes and the consequent survival through all routes in response to water management actions. Conceptually, the approach will be as follows: 1) Use an individual based model to predict the fine-scale movement at important channel junctions in the Delta, 2) determine the proportion of fish migrating through different channels in response to modeled water management actions, 3) simulate the survival and detection process of tagged juvenile salmon taking specific migration pathways, and 4) generate precision and power estimates of survival for a given sample size of tagged fish. An individual based model will be developed by USGS based on measurements of fine-scale three-dimensional behavior of acoustically-tagged juvenile salmon as they migrate through a sharp bend in the Sacramento River. This data will be used to develop the individual based model that will simulate movement paths of juvenile salmonids in response to water velocity dynamics at channel junctions in the Delta.

Modeling fine-scale movements of fish at channel junctions will provide a means to gain insights on how fish might distribute throughout the Delta under various conditions that would otherwise be costly to implement. Fine-scale movements of fish at channel junctions will affect the proportion of fish using different routes and thereby, the overall survival of the population. These factors, in turn, will affect the precision of survival estimates. This process will help to design experiments with a high probability of yielding critical information to guide recovery of juvenile salmonid populations.

Expected Benefits

This research is intended to help fulfill the objective of the Environmental Water Account to recover declining fish populations while meeting the needs of water users. Thus, the primary beneficiaries of this research will be endangered salmon and steelhead and the water users of California. The research proposed here will help fulfill the mission of the CALFED Science Program by addressing a significant knowledge gap about the effects of water management actions on juvenile salmonid populations (http://science.calwater.ca.gov/workshop/ewa.shtml). This gap will be filled by building a framework for 1) developing a model to estimate important population parameters in the Delta, 2) designing field studies to collect data for parameterizing the model, 3) implementing power and sample size analysis to design future studies, and 4) conducting simulation experiments to help understand effects of complex physical and biological processes.

Filling this knowledge gap can only be achieved through collaboration among many individuals that bring different strengths to tackle the problem. The community mentors of this research are experts in their field and in the Delta; collectively, they bring decades of experience and knowledge about the biological, physical, and institutional dynamics of the Delta. Each community mentor is involved with telemetry studies with unique objectives, but this research proposal aims to contribute to each. This research will provide detailed survival and population distribution data, which will provide context to the Delta Action 8 study (Pat Brandes, USFWS) and help to interpret survival indices obtained from coded-wire tags. Jon Burau, USGS, is currently planning an acoustic telemetry study to gain further understanding of the physical and behavioral factors influencing entrainment of juvenile salmonids at channel junctions. The research proposed here will contribute to the work of USGS by linking the consequences of movement at fine-scales to the population-level effects at the broader scale of the Delta. Steve Lindley and his colleagues (NOAA Fisheries) are planning a large-scale telemetry study to examine movement, behavior, and survival of juvenile salmonids from Battle

Creek to the ocean. Their objective is to relate survival through reaches at the watershed scale to migration behavior and environmental covariates. This proposed research will benefit Steve Lindley’s research by focusing at a finer scale within the Delta, aiding in design of the telemetry system needed within the Delta, and conducting sample size and power analysis to guide future studies.

Dr. John Skalski will contribute his expertise in developing novel applications of mark-recapture models for complex physical and biological settings. I have extensive experience designing and conducting large-scale telemetry studies in the Columbia River Basin and analyzing data from these studies to estimate survival of juvenile salmonids. Dr. Skalski and I will both benefit from this research by addressing a challenging resource issue in a new environment; by learning, developing, and applying new analytical techniques; and by fostering long-term collaborative relationships with individuals and institutions in the Delta.

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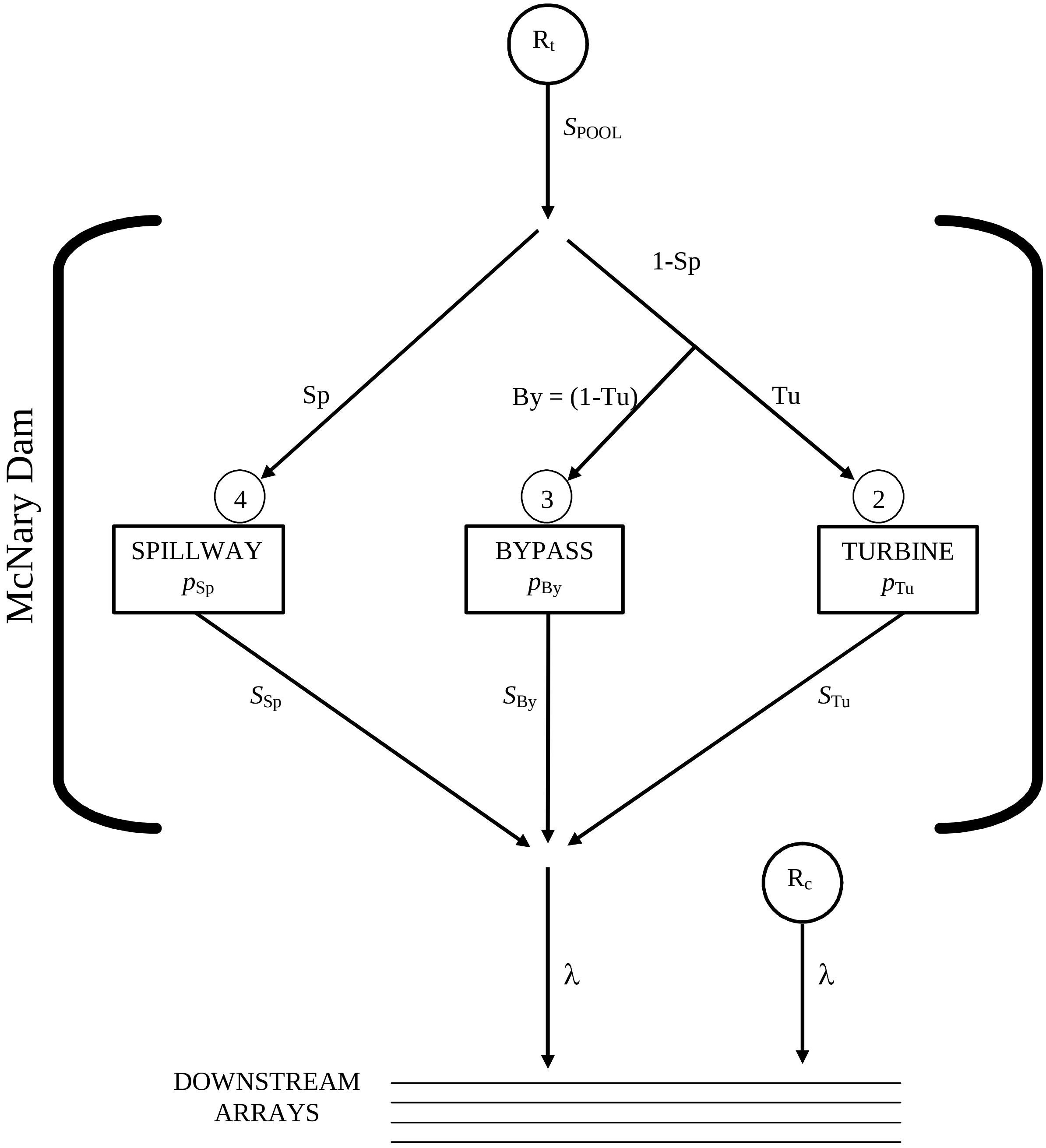

Figure 1. — Schematic of the route-specific survival model developed by Skalski et al. (2002) and used by Perry et al. (2006). Shown are fish release locations (R_t and R_c) and passage (Sp, By, and Tu), detection (P_{Sp}, P_{By}, and P_{Tu}) and survival probabilities (S_{POOL}, S_{Sp}, S_{By}, and S_{Tu}). Circled numbers show coding used in detection histories to indicate the route of passage of each fish. Lambda (λ) is the joint probability of surviving and being detected by telemetry arrays downriver of the dam.