Perry (2010) began the process of relating routing and survival probabilities to environmental covariates. These analyses focused on factors affecting 1) entrainment into the interior of the Delta via the Delta Cross Channel and Georgiana Slough and 2) survival in the specific reaches of the lower Delta. For example, analysis of route entrainment probabilities indicated that river inflows, tidal fluctuations, and gate operations affected an individual's probability of entering each channel. By integrating individual probabilities over each day, Perry (2010) quantified daily probabilities of entering the interior Delta and found that closing the Delta Cross Channel was expected to reduce entrainment by only about half that expected given the reduction in the proportion of water entering the interior Delta. In addition, he found that the probability of entering the interior Delta was highest during flood tides. In turn, since river inflow dampens tidal fluctuations at this river junction, a flow threshold was identified below which entrainment increases with decreasing river flow. In contrast, above this threshold the Sacramento River ceases to reverse direction and entrainment remains relatively constant with further increases in discharge. These are critical relationships that need to be incorporated into management models, but these particular relationships consider only that fraction of population that encounters the Delta Cross Channel. Twenty to forty percent of the population also migrates through the Delta via Sutter and Steamboat sloughs, which diverges from the Sacramento River upstream of the Delta Cross Channel (Figures 1 and 2). Similar analyses have yet to be conducted at this river junction. Thus, one goal is to develop routing models for both river junctions to fully relate movement among migration routes at the population level to river flow, tides, and gate operations.

3. Approach and Scope of Work

The project objectives, tasks, and budget are structured such that Objectives 1 is tackled in year 1, Objective 2 in year 2, etc. Objectives 1 and 2 are independent analyses, but Objective 3 is dependent on the results of analyses from Objectives 1 and 2.

Objective 1: Quantify factors affecting migration routing of juvenile salmon emigrating from the Sacramento River.

Task 1.1. Data processing

- Collate telemetry data from multiple sources into a single dataset relevant to analysis of migration routing at river junctions.
- Apply quality assurance and control processes (data proofing) for false-positive detections and data integrity.
- Identify and secure environmental data to relate to route entrainment probabilities.
- Construct a single data set comprised of telemetry and environmental data to be used in quantitative analysis of migration routing.

Task 1.2. Analysis of Migration Routing

Analysis of migration routing will focus on the two river junctions shown Figures 1 and 2. Analyses will be conducted separately for each river junction, but using the same methodology. Perry (2010) developed methods to quantify route entrainment probabilities of individual tagged fish at the junction of the Sacramento River with the Delta Cross Channel and Georgiana Slough. Below, we briefly describe the statistical methodology that was developed for this river junction. This project builds on previous work by proposing to 1) incorporate additional data not previously available, 2) extend the analysis to the junction of Sacramento River with Sutter and Steamboat Sloughs, and 3) use the relationships for both river junctions to understand how environmental variability and management actions affect population distribution through all primary migration routes.

At the junction of the Sacramento River (S) with the Delta Cross Channel (D) and Georgiana Slough (G), routes used by each fish form a categorical response variable that is distributed as trinomial when the Delta Cross Channel gate is open and binomial when the gate is closed. The probability distribution for each individual can be expressed as

$$P\left(Y_{ij} = y_{ij}\right) = \pi_{i,\mathrm{D}}^{y_{i,\mathrm{D}}} \pi_{i,\mathrm{G}}^{y_{i,\mathrm{G}}} \pi_{i,\mathrm{S}}^{y_{i,\mathrm{S}}} \qquad \text{when the Delta Cross Channel is open}$$

and $$P\left(Y_{ij} = y_{ij}\right) = \pi_{i,\mathrm{G}}^{y_{i,\mathrm{G}}} \pi_{i,\mathrm{S}}^{y_{i,\mathrm{S}}} \qquad \text{when the Delta Cross Channel is closed,}$$

where $y_{ij} = 1$ when the ith fish enters the jth river channel and zero otherwise, and π_{ij} is the probability of the ith individual entering the jth river channel. The probability of entering the interior Delta through either the Delta Cross Channel or Georgiana Slough, π_{ID}, is $\pi_{\mathrm{D}} + \pi_{\mathrm{G}} = 1 - \pi_{\mathrm{S}}$. More generally, the distribution for each individual can be represented as

$$P\left(Y_{ij} = y_{ij}\right) = \pi_{i,\mathrm{D}}^{y_{i,\mathrm{D}} I_{i,\mathrm{D}}} \pi_{i,\mathrm{G}}^{y_{i,\mathrm{G}}} \pi_{i,\mathrm{S}}^{y_{i,\mathrm{S}}}$$

where $I_{i,\mathrm{D}}$ is an indicator variable resolving to one if the ith fish passes the river junction when the Delta Cross Channel gate is open and zero if it passes the junction when the gate is closed.

Our goal is to model entrainment probabilities (π_{ij}) as a function the hydraulic conditions of the river junction at the time the ith fish entered the jth migration route. We will use a generalized linear model framework with a baseline-category logit function to link $g(\pi_{ij})$ to a linear combination of the explanatory variables

$$g\left(\pi_{ij}\right) = \ln\left(\frac{\pi_{ij}}{\pi_{iJ}}\right) = \beta_{j0} + \beta_{j1} x_{ij1} + \ldots + \beta_{jp} x_{ijp} = \boldsymbol{\beta}'_j \mathbf{x}_{ij}$$

where π_{ij} is measured relative to the baseline category π_{iJ}, β_{j0} is the intercept for the jth migration route, and β_{jk} are slope parameters for $k = 1, \ldots, p$ explanatory variables (x_{ijk}) for the ith individual and jth route. Perry (2010) used the Sacramento River route (J = S) as the baseline category against which to measure the probabilities of entering the Delta Cross Channel and Georgiana Slough. Each baseline logit function is modeled with its own set of explanatory variables, allowing a different set of variables to affect the probability of entrainment into each river channel. Entrainment probabilities are expressed directly as a function of the explanatory variables by taking the inverse of the baseline-category logits:

$$\pi_{ij} = \frac{\exp\left(\boldsymbol{\beta}'_j \mathbf{x}_{ij}\right)}{\sum_{h=1}^{J} \exp\left(\boldsymbol{\beta}'_h \mathbf{x}_{ih}\right)}$$

where $\boldsymbol{\beta}_J$ for the baseline category (J = S) is set to zero.

River discharge, water velocity, and the proportion of total outflow entering each river channel will be the primary variables used to explain variation in entrainment probabilities. USGS gauging stations record discharge and water velocity every 15 min, providing detailed information about the hydraulic conditions that tagged fish experienced when they migrated through the river junction. The effect of tidal fluctuations on hydraulic conditions of the river junction will be captured by two variables. First, we will use the rate of change in discharge (Q) of the Sacramento River as $\Delta Q_{\mathrm{S}}(t) = Q_{\mathrm{S}}(t+1) - Q_{\mathrm{S}}(t)$ where t is measured in units of 15 minutes. This variable accounts for hydraulic conditions that may be quite different on a flood-to-ebb transition compared to an ebb-to-flood transition, even though total discharge may be similar

during each transition. Second, U is a dummy variable set to one when water is flowing upstream in the Sacramento River (i.e., $U = 1$ when $Q_S < 0$), and zero otherwise. We will include a number of other variables in the analysis unrelated to hydraulic conditions but that may also affect the probability of fish entering a given migration route. These variables included fork length, time of day (day or night), and daily water temperature when fish passed through the river junction.

The regression parameters are estimated by maximizing the log likelihood function of the joint probability distribution over all individuals (Agresti, 2002). A set of models with different explanatory variables will be constructed and standard model selection techniques will be used to assess which variables best explain variation in entrainment probabilities.

We will use the best-fit model to understand how entrainment probabilities vary over a range of time scales. Time-specific entrainment probabilities reveal the individual consequences of arriving at a junction at a particular time of day and tidal cycle. At the population level, however, the fraction of fish entering each route depends on 1) fluctuation in time-specific entrainment probabilities over each day and 2) the distribution of fish arrival times at the junction over the diel cycle.

For time-specific entrainment probabilities that vary among individuals, the expected number of fish entering migration route j on day d, n_{jd}, is

$$\mathrm{E}\left(n_{jd}\right) = \sum_{i=1}^{N_d} \pi_{ijd}$$

where N_d is the total number of fish migrating past the junction on day d. The expected fraction of fish entering route j is then:

$$\frac{\mathrm{E}\left(n_{jd}\right)}{N_d} = \frac{1}{N_d} \sum_{i=1}^{N_d} \pi_{ijd} = \bar{\pi}_{jd},$$

showing that the expected fraction is equivalent the mean entrainment probability on a given day. We will use this approach as the basis for extending individual probabilities to population-level entrainment on a daily scale.

Task 1.3. Report and publication preparation

We propose to publish our findings as agency reports and in the peer-reviewed literature. We also propose to communicate our findings through regional and national conferences, as well as upon the request of interested parties the Bay-Delta Region.

Objective 2: Quantify factors affecting survival of juvenile salmon within specific migration routes.

Task 2.1. Data processing

- Collate telemetry data from multiple sources into a single dataset relevant to analysis of survival through individual reaches.
- Apply quality assurance and control processes (data proofing) for false-positive detections and data integrity.
- Identify and secure environmental data to relate to reach-specific survival probabilities.
- Construct a single data set comprised of telemetry and environmental data to be used in quantitative analysis of survival.

Task 2.1. Data analysis

To quantify factors affecting survival, we will incorporate covariates into a Cormack-Jolly-Seber (CJS) model that focuses on a subset of reaches in the Delta (Cormack, 1964; Jolly, 1965; Seber, 1965). For example, Perry (2010) constructed a CJS model to estimate survival to the exit of the Delta at Chipps Island from entry points into three major migration routes: 1) Sutter and Steamboat sloughs, 2) the Sacramento River, and 3) the interior Delta. Below, we briefly describe these statistical methods. This project proposes to extend the initial analyses by 1) incorporating additional data not previously available and 2) apply similar statistical methods to reaches that have yet to be analyzed.

The CJS model used by Perry (2010) had two sampling occasions with four possible captures histories (111, 110, 101, and 100). The two occasions were formed from detections at Chipps Island and telemetry stations seaward of Chipps Island (See Figure 1). These capture histories form a multinomial distribution and maximum likelihood techniques can be used to estimate the parameters of this distribution. The maximum likelihood function of the CJS model

was constructed following the approach of Skalski et al. (1993) where each individual fish's contribution to the likelihood is explicit:

$$\ln L\left(S_i, p_i, \lambda_i \mid \mathbf{Y}\right) = -\sum_{i=1}^{n} y_{i,111} \ln\left(S_i p_i \lambda_i\right) + y_{i,110} \ln\left(S_i p_i (1-\lambda_i)\right)$$
$$+ y_{i,101} \ln\left(S_i (1-p_i)\lambda_i\right) + y_{i,100} \ln\left(1 - S_i + S_i (1-p_i)(1-\lambda_i)\right).$$

Here, y_{ij} is an indicator variable resolving to 1 if the *i*th fish has the *j*th capture history, and zero otherwise, S_i is the probability of the *i*th fish surviving to Chipps Island from one of three starting points in the Delta, p_i is the detection probability of the *i*th fish at Chipps Island, and λ_i is the joint probability of the *i*th fish surviving and being detected at telemetry stations in San Francisco Bay.

We will use the framework of generalized linear models (McCullough and Nelder, 1989) to link a linear function of the CJS parameters, $g(\theta)$, to the covariates. We will use a logit link function for all parameters:

$$g\left(\theta_i\right) = \ln\left(\frac{\theta_i}{1+\theta_i}\right) = \beta_0 + \beta_1 x_{i1} + \ldots + \beta_p x_{ip} = \boldsymbol{\beta}' \mathbf{x}_i$$

where $\theta_i = S_i$, p_i, or λ_i; β_0 is the intercept; and β_j is the slope parameter for $j = 1, \ldots, p$ covariates, x_{ij}. The covariates will be introduced into the negative log-likelihood using the inverse logit function:

$$\theta_i = \frac{\exp\left(\boldsymbol{\beta}' \mathbf{x}_i\right)}{1 + \exp\left(\boldsymbol{\beta}' \mathbf{x}_i\right)}$$

and the likelihood is then iteratively minimized using optimization routines in the R statistical computing platform to estimate the vector of β parameters.

We will model reach specific survival through the Delta as function of both group-level and individual covariates. Individual covariates consist of fork length and route-specific river discharge when individuals entered each route. Group-level covariates will consist of release group, migration route, migration year, and mean river discharge for each release group, and migration route, water temperature, and turbidity. A set of models with different explanatory variables will be compared using standard model selection techniques to determine the set of variables that best explain variation in reach specific survival (Burnham and Anderson, 2002).

Objective 3: Use relationships from objectives 1 and 2 to simulate population-level survival through the Delta under a limited number of historical and operational scenarios.

Given quantitative relationships for driving migration routing and reach specific survival, the intent of this objective is to understand how these processes interact to influence survival of the population through the Delta. We will use the Delta Simulation Model II (DSM2) to simulate 15-min river flows at key locations in the Delta (CADWR, 2010). DSM2 is a model for simulating one-dimensional, unsteady, open-channel flow in the Delta in response to river inflows, tidal forcing, and water management actions. We will use the most recent calibration of the model and the latest historical simulation. DSM2 was recently recalibrated for use in the Bay Delta Conservation Plan, and historical simulations of Delta hydrodynamics under this recalibration extend through the winter of 2007 (CH2MHILL, 2009).

Task 3.1 – Data processing

Parameterize DSM2 to reconstruct historical conditions as well as a number of hypothetical management scenarios.

Task 3.2 – Data Analysis

We will conduct a number of DSM2 simulations and use the output of these simulations to drive predictions of migration routing and reach specific survival based on the relationships quantified in Objectives 2 and 3. Survival of the population through the Delta can then be reconstructed from reach-specific survival probabilities and entrainment probabilities at each river junction. The intent here is not necessarily to reproduce reality, but rather to understand how the individual components of migration routing and survival interact in response to environmental conditions to affect Delta-wide survival. Although each component of population survival (e.g., migration routing at a particular river junction) may follow relatively simple relationships, the interaction among these components may produce complex outcomes. It is these interactions that the simulation analysis seeks to understand. For this reason, we plan on limiting the number of alternative scenarios to 1) historical flow conditions in the Delta, 2) historical conditions with reductions in mean discharge of the Sacramento River entering the

Delta, and 3) historical conditions with alternative operations of the Delta Cross Channel. Specific details of these scenarios will be formulated during the first two years of this project. Furthermore, additional scenarios may be considered since we expect that new insights from Objective 1 and 2 may suggest operational criteria not previously considered.

Task 3.3 - Report and publication preparation

We propose to publish our findings as agency reports and in the peer-reviewed literature. We also propose to communicate our findings through regional and national conferences, as well as upon the request of interested parties the Bay-Delta Region.

4. Feasibility

This project has a high probability of success because 1) the data has been collected and awaits synthesis, 2) analytical methods have been developed by the principal investigators, and 3) initial analyses have yielded new insights (Perry 2010). Furthermore, by compiling telemetry data from multiple sources over numerous years, contrast in environmental variation within and among years will be maximized. In turn, utilizing all possible data across a range of environmental conditions maximizes the likelihood of detecting underlying relationships of survival and migration routing with environmental variables.

5. Relevance to the Delta Science Program

This project "Quantifying Factors Affecting Migration Routing and Survival of Juvenile Late-Fall Chinook Salmon in the Sacramento-San Joaquin River Delta" will address three of the four Priority Research Topics: Native Fish Biology and Ecology, Coupled Hydrologic and Ecosystem models, and Water and Ecosystem Management Decision Support System Development. The proposal will further analyze data to define factors that affect the survival of late-fall juvenile Chinook salmon – a native fish species- as they migrate through the Delta. Furthermore, the data will be used to develop and parameterize models (Delta Passage Model) that couple hydrologic factors to juvenile salmon survival and in turn could be applied to estimate juvenile salmon survival under modeled hydrologic conditions. Lastly, the survival models developed from this data will be a tool for managers to use in determining the impacts

and benefits to salmon survival from some water management actions in the Delta (Delta Cross Channel Closures, flows in the Sacramento River, influence of Georgiana Slough on diversion into the interior Delta at various flows and tides, and diversion into and survival in Steamboat and Sutter Sloughs). In addition, estimating survival at various flows will help identify some of the impacts associated with reductions in Sacramento River flow from an isolated facility in the north Delta as proposed in the Bay-Delta Conservation Plan. While the data has been gathered on late-fall Chinook salmon, inferences, in a relative sense, can be made to other races of juvenile salmon actively out-migrating through the Delta.

This project will also meet other Delta Science Priorities of further synthesis, integration and collaboration. The proposal will use data from multiple studies to identify mechanisms driving movement and survival in the Delta under single framework. Thus this proposal will support both further synthesis and integration across studies. Quantifying these mechanisms is important because simulation models based on assumed functional relationships are currently being used to understand how alternative water management actions affect survival of juvenile salmon migrating through the Delta. These assumed relationships needed to be replaced with empirical relationships.

The goal of this PSP is to "establish unbiased and authoritative knowledge directly relevant to Bay-Delta actions" (page 2 of 2010 Focused Proposal Solicitation Package). How survival of juvenile salmon in the Delta is impacted by water project activities is a key unknown. Understanding how these present and future water development activities influence salmon survival through the Delta is critical to assessing impacts and recommending actions to achieve recovery and restoration. This project will support further development of initial work funded by the CALFED Bay-Delta Program Science Fellows Program. RWP was a CALFED Science Predoctoral Fellow between 2006 and 2009 and the modeling work to date has been primarily funded through CALFED Science. In addition, CALFED Bay-Delta Science has previously funded two proposals (2004 and 2007) to estimate salmon and steelhead survival from the upper Sacramento River to San Francisco Bay using acoustic tags. This proposal will use that data as well as data from other acoustic studies to identify the mechanisms driving movement and survival in the Delta.

6. Qualifications

The principal investigators are uniquely qualified to undertake this project. Russell W. Perry served as a CALFED Science Fellow developing mark-recapture models for application to the telemetry studies being conducted in the Delta. He has collaborated with investigators from multiple studies during the design and implementation phases of these studies. Such collaborative relationships are essential in order to have support from all investigators to use their data as proposed for this project. Patricia L. Brandes has been a driving force for over 20 years in research related to the effects of management actions on survival of endangered juvenile salmon migrating through the Delta. Her past research collaborating with Dr. Ken Newman to understand factors affecting survival of juvenile salmon sets the stage for the work proposed herein. Both principal investigators have published their research related to survival of juvenile salmon as both agency reports and in the peer-reviewed literature (see Literature Cited).

7. Literature Cited

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Task and Budget Summary

Task #	Task Title	Start Month	End Month	Personnel Involved	Description	Task Budget
1	Migration Routing: Data Processing and proofing	1	4	Russell Perry	Compile and proof fish release data, telemetry data, and environmental data using standard database and statistical analysis software. Conduct standardized data quality control/assurance procedures necessary for migration routing analysis.	$12,643
2	Migration Routing: Data Analysis	5	8	Mrs. Patricia Brandes	Analyze factors (i.e., river discharge, turbidity, time of day, and measures of tidal fluctuation) affecting migration routing of juvenile salmon in the Sacramento-San Joaquin River Delta	$31,300
3	Migration Routing: Report and Journal Publication	9	12	Russell Perry	Publish findings of migration routing in annual reports of research and journal publications.	$24,686
4	Survival Analysis: Data Processing and proofing	13	16	Russell Perry	Compile and proof fish release data, acoustic telemetry data, and environmental data using standard database and statistical analysis software. Conduct standardized data quality control/assurance procedures necessary for survival analysis.	$13,162
5	Survival Analysis: Data Analysis	17	20	Russell Perry	Analyze factors (i.e., river discharge, turbidity, time of day, and measures of tidal fluctuation) affecting survival of juvenile salmon in the Sacramento-San Joaquin River Delta	$32,664
6	Survival Analysis: Report and Journal Publication	21	24	Mrs. Patricia Brandes	Publish findings of juvenile salmon survival in annual reports of research and journal publications.	$25,844
7	Simulation Modeling: Data Processing and proofing	25	28	Mrs. Patricia Brandes	Parameterize Delta Simulation Model 2 (DSM2) to produce input data that drives migration routing and survival. Contrast DSM2 output against measured stream gauge data at critical locations prior to simulation of routing and survival.	$13,698
8	Simulation Modeling: Data Analysis	29	32	Mrs. Patricia Brandes	Conduct model simulations to analyze factors (i.e., river discharge, turbidity,and measures of tidal fluctuation) affecting migration routing and survival of juvenile salmon in the Sacramento-San Joaquin River Delta	$34,072
9	Simulation Modeling: Report and Journal	33	35	Russell Perry	Publish findings from simulation modeling in annual reports of research and journal publications.	$27,034