CRAMER FISH SCIENCES®
Oregon • California • Washington • Idaho • Alaska

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

Memorandum
August, 05 2022
To: Steve Micko, Jacobs Engineering
From: Steven Zeug, Cramer Fish Sciences
Re: IOS model results

Proposed operational alternatives for the Sites Reservoir project were evaluated using the IOS winter run Chinook Salmon life cycle model. This model combines data from field studies, long-term monitoring programs and laboratory studies in a simulation framework. IOS is composed of six primary life cycle components that can be affected by water temperature, river flow, or ocean productivity including 1) spawning (water temperature), 2) egg incubation (water temperature), 3) fry rearing (water temperature), 4) river migration (flow), 5) Delta passage (flow) and 6) ocean survival (ocean productivity). The model has been published in a peer reviewed journal (Zeug et al. 2012) and a description of the most recent version can be found in the appendix at the end of this document.

Here we provide five model outputs to evaluate four operational alternatives and a no-action alternative on winter run Chinook Salmon. One hundred iterations of the model were run for each alternative with parameters resampled for each iteration. The five outputs reported are 1) egg survival, 2) fry survival, 3) river survival, 4) Delta survival, and 5) female escapement. Below we describe differences among alternatives over the 82-year simulation period and among water year-types.

A modification was made to the Bend Bridge flow input to reflect the length of the Red Bluff to Verona reach of the river that would be affected by the Sites diversion.

Egg survival

In most years of the 82-year simulation period, median egg survival was high and similar among the four scenarios (Figure 1). The only substantial reductions in survival occurred during the critical water year 1977. In this year, the highest survival was observed for the ALT3 and the lowest survival was observed for the No Action Alternative (NAA; Figure 2). Survival for ALT1A, 1B, and 2 fell between the other scenarios.

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

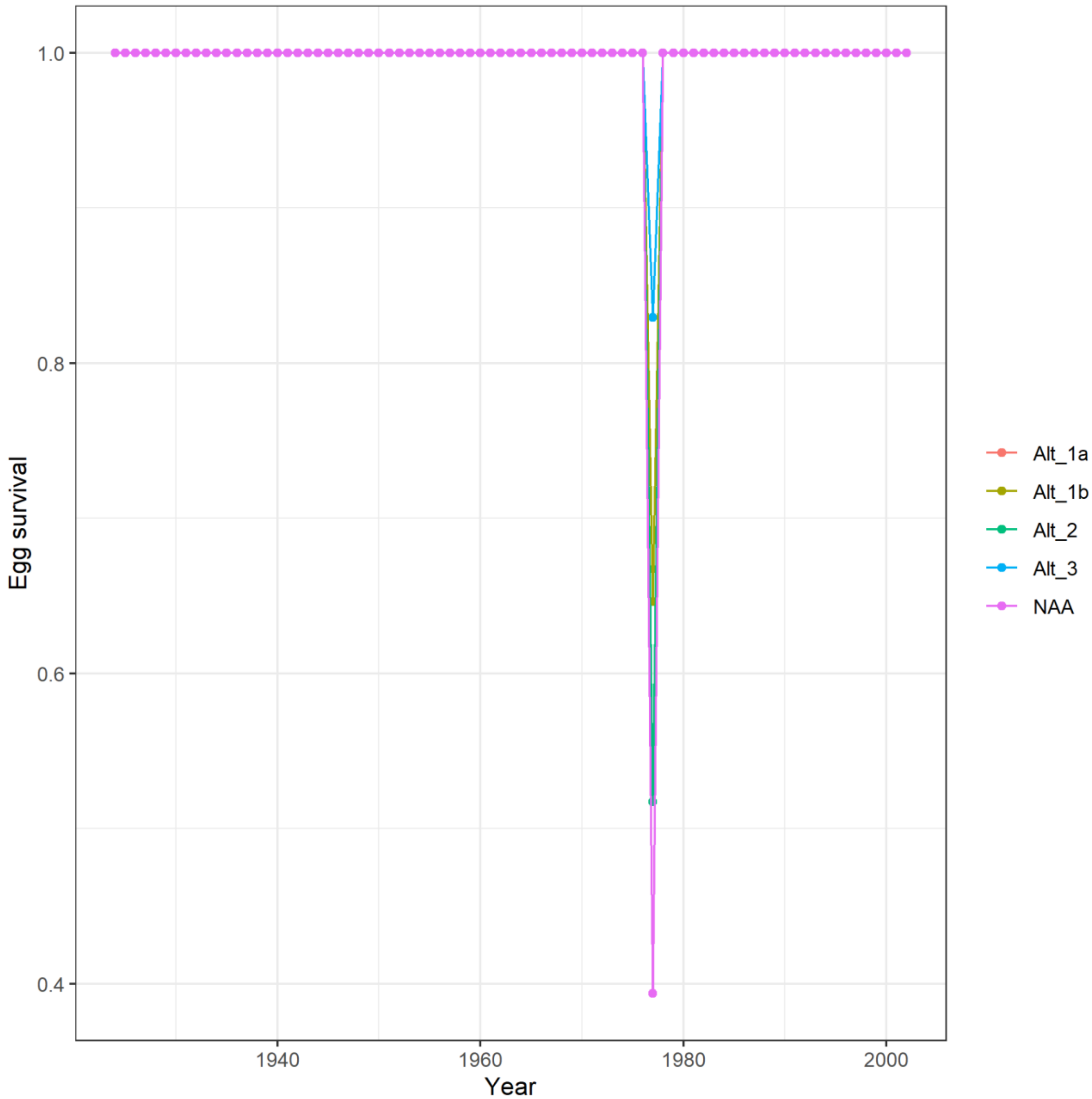


Figure 1. Median winter run Chinook Salmon egg survival over the 82-year simulation period.

CRAMER FISH SCIENCES®
Oregon • California • Washington • Idaho • Alaska
13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

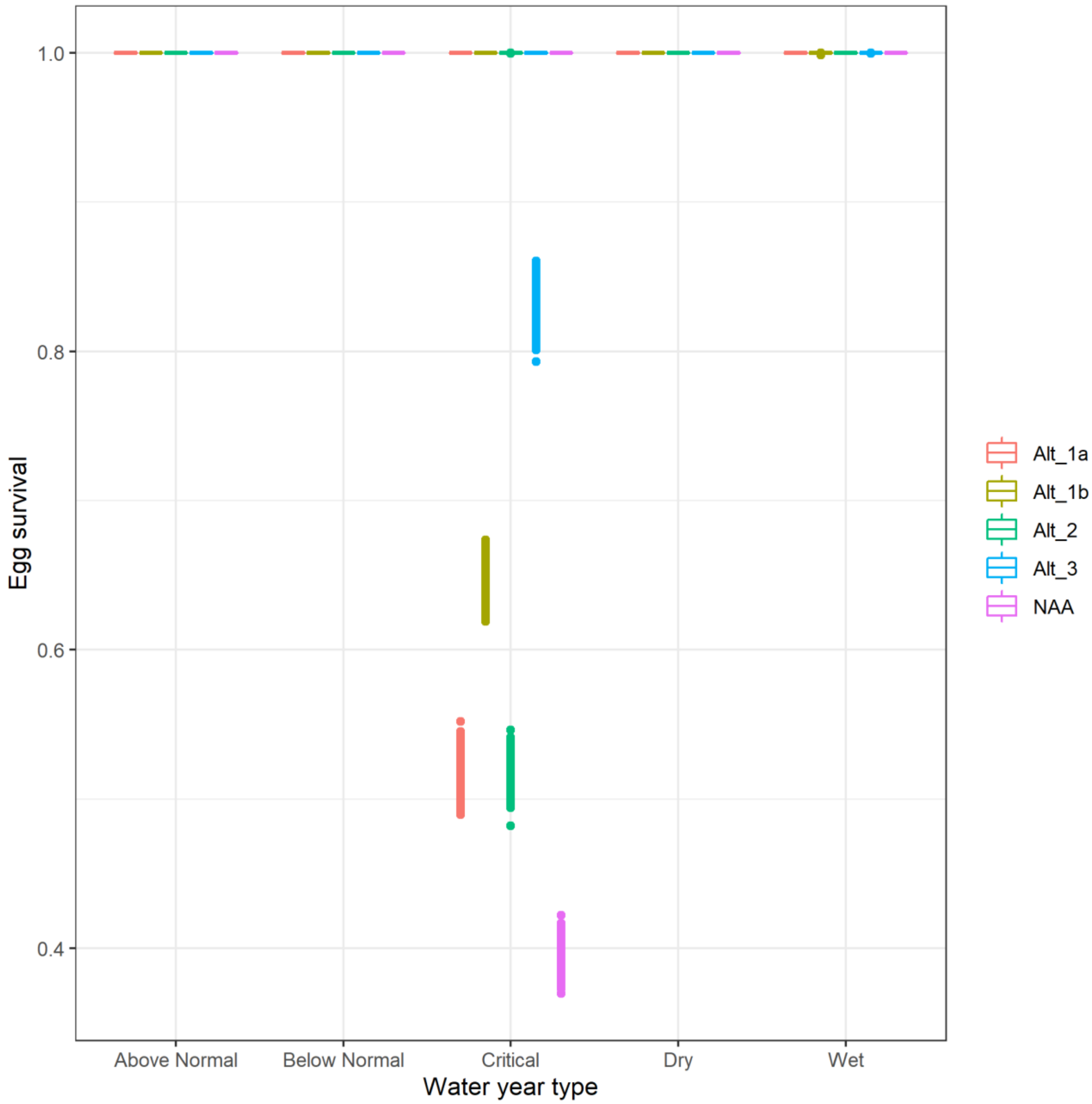


Figure 2. Box plots of egg survival by water year type for each of the alternatives evaluated. The results from all 100 iterations of each alternative are included in these plots. The box defines the interquartile range, the horizontal line is the median and the vertical lines define the largest value within 1.5 times the interquartile range. Individual points are those outside of that range.

Fry survival

During most of the 82-year period, median fry survival was > 90% and similar among the four alternatives and the NAA (Figure 3). Similar to egg survival, the only major reduction in fry survival occurred in 1977 (Figure 3). Fry survival was most variable in Critical water

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

year types and interquartile ranges did not overlap between Critical years and other water year types for any alternative (Figure 4). Among alternatives in these Critical water years, median survival was similar among scenarios and interquartile ranges overlapped substantially (Figure 4). However, in extreme years the NAA had the lowest survival values and Alt 3 the highest.

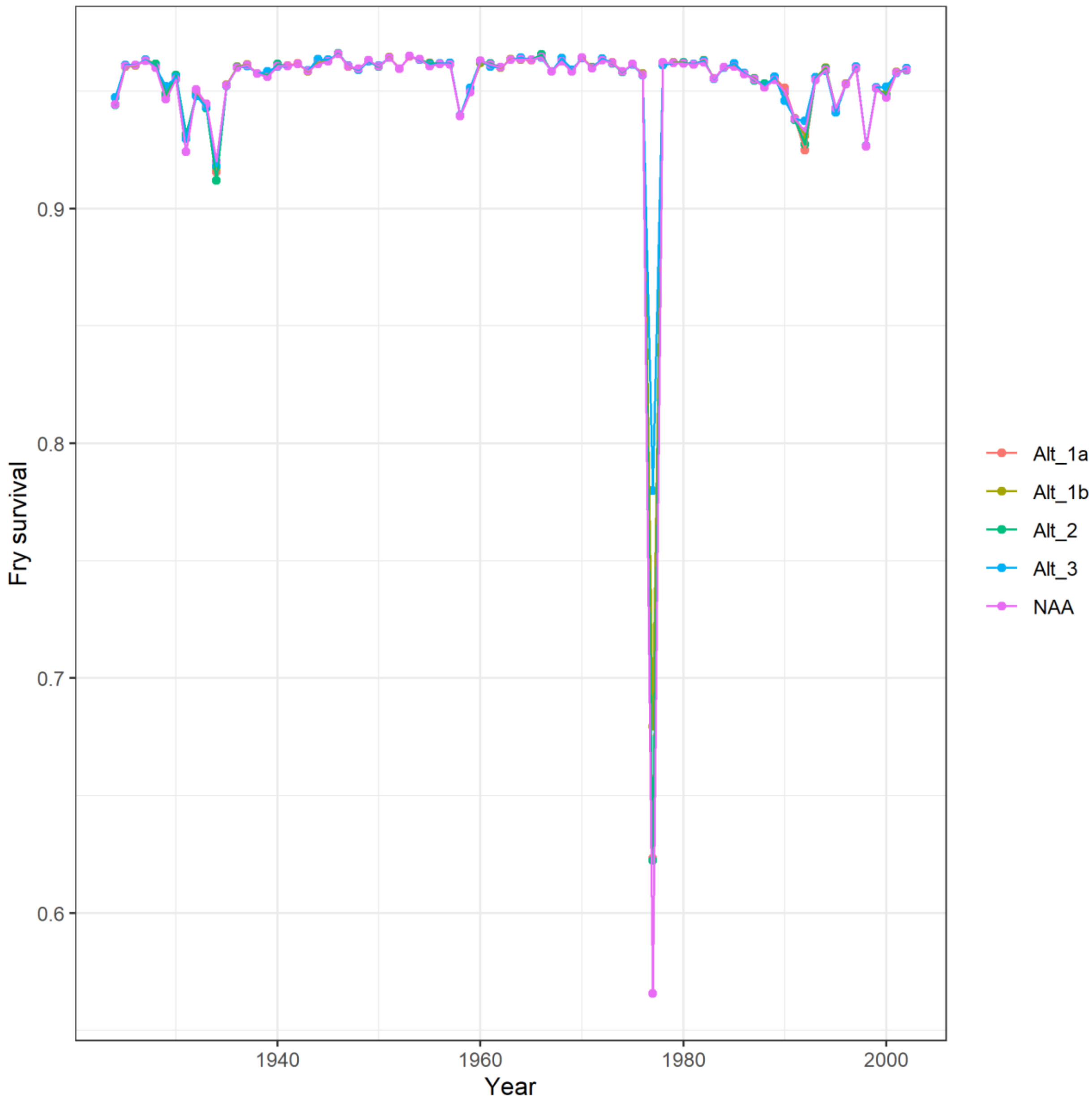


Figure 3. *Median winter run Chinook Salmon fry survival over the 82-year simulation period.*

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

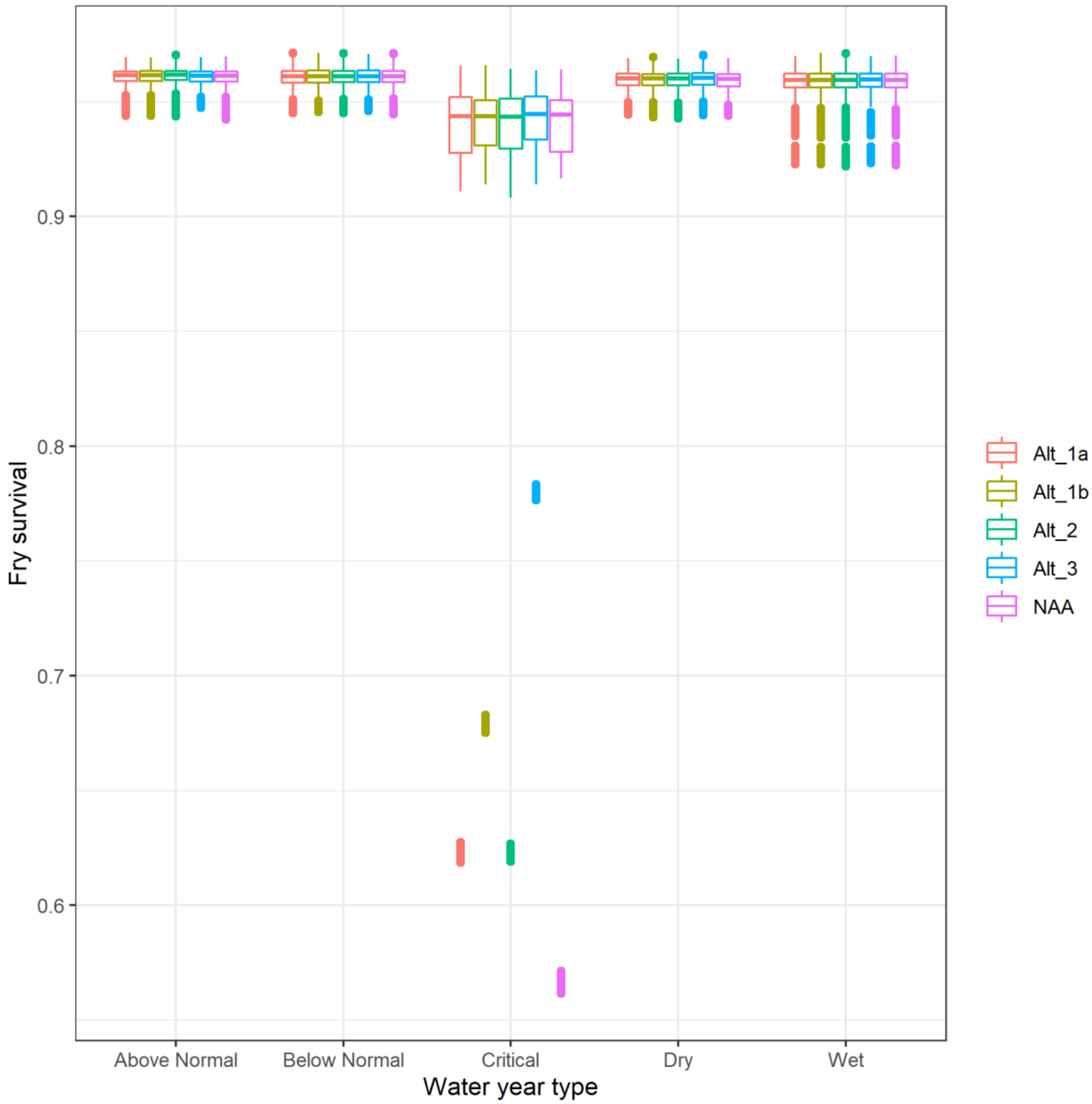


Figure 4. *Box plots of fry survival by water year type for each of the alternatives evaluated. The results from all 100 iterations of each alternative are included in these plots. The box defines the interquartile range, the horizontal line is the median and the vertical lines define the largest value within 1.5 times the interquartile range. Individual points are those outside of that range.*

River migration survival

Survival of juvenile winter run Chinook Salmon during river migration ranged between ~24.5% and 37.5% across all simulation years (Figure 5). There were only minor differences among scenarios in each year (< 2%). There was an expected pattern of

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

increasing survival between Critical and Wet water year-types. Median survival for the NAA was greater than any of alternatives in Wet, Above Normal, and Below Normal Years (Figure 6). The four alternatives and the NAA had similar median survival in Dry and Critical Water Years with extensive overlap in interquartile ranges (Figure 6).

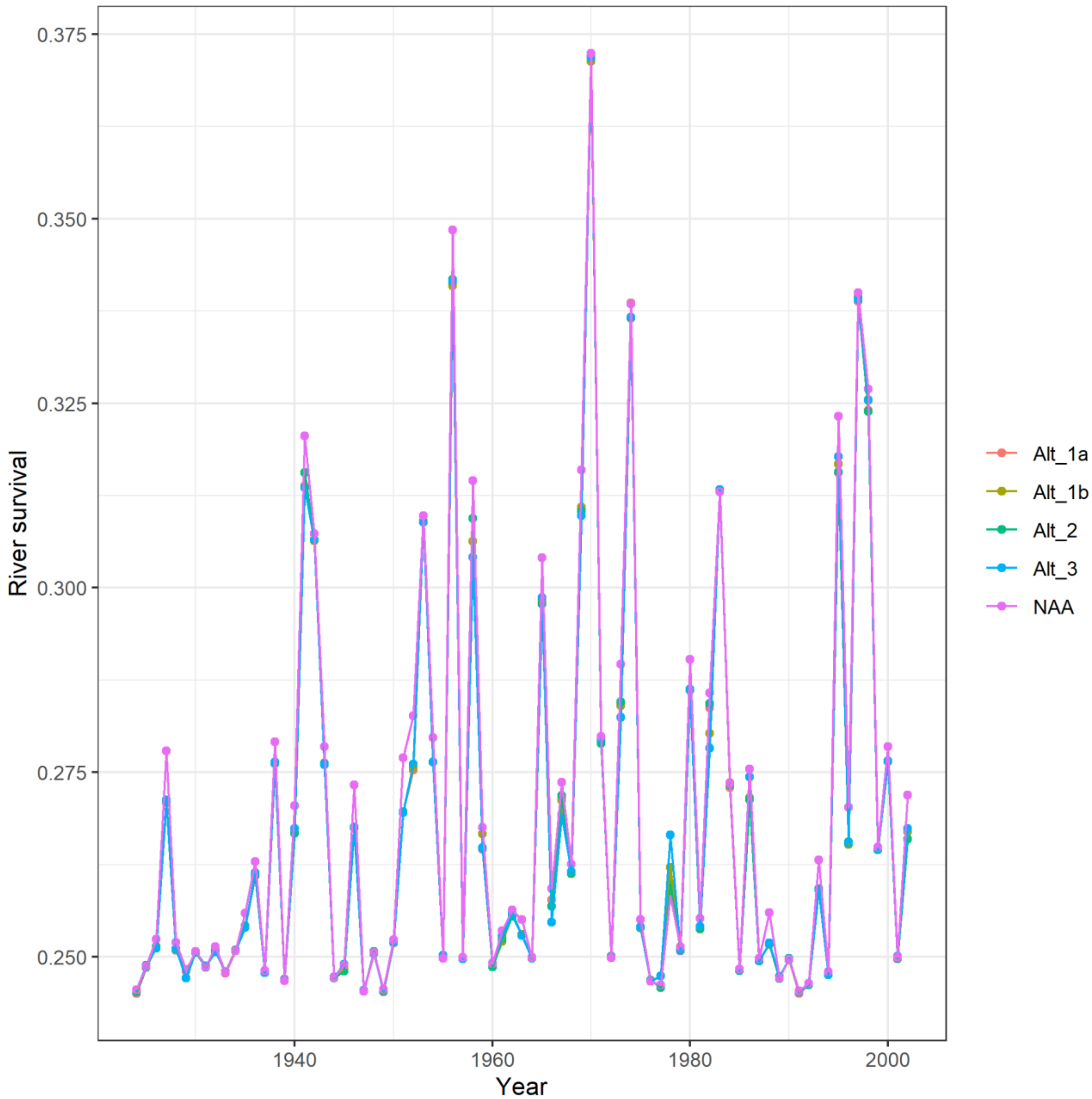


Figure 5. Median winter run Chinook Salmon river migration survival (Red Bluff to Fremont Weir) over the 82-year simulation period. Flow at Bend Bridge was adjusted to account for the location of the proposed diversion within the reach.

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

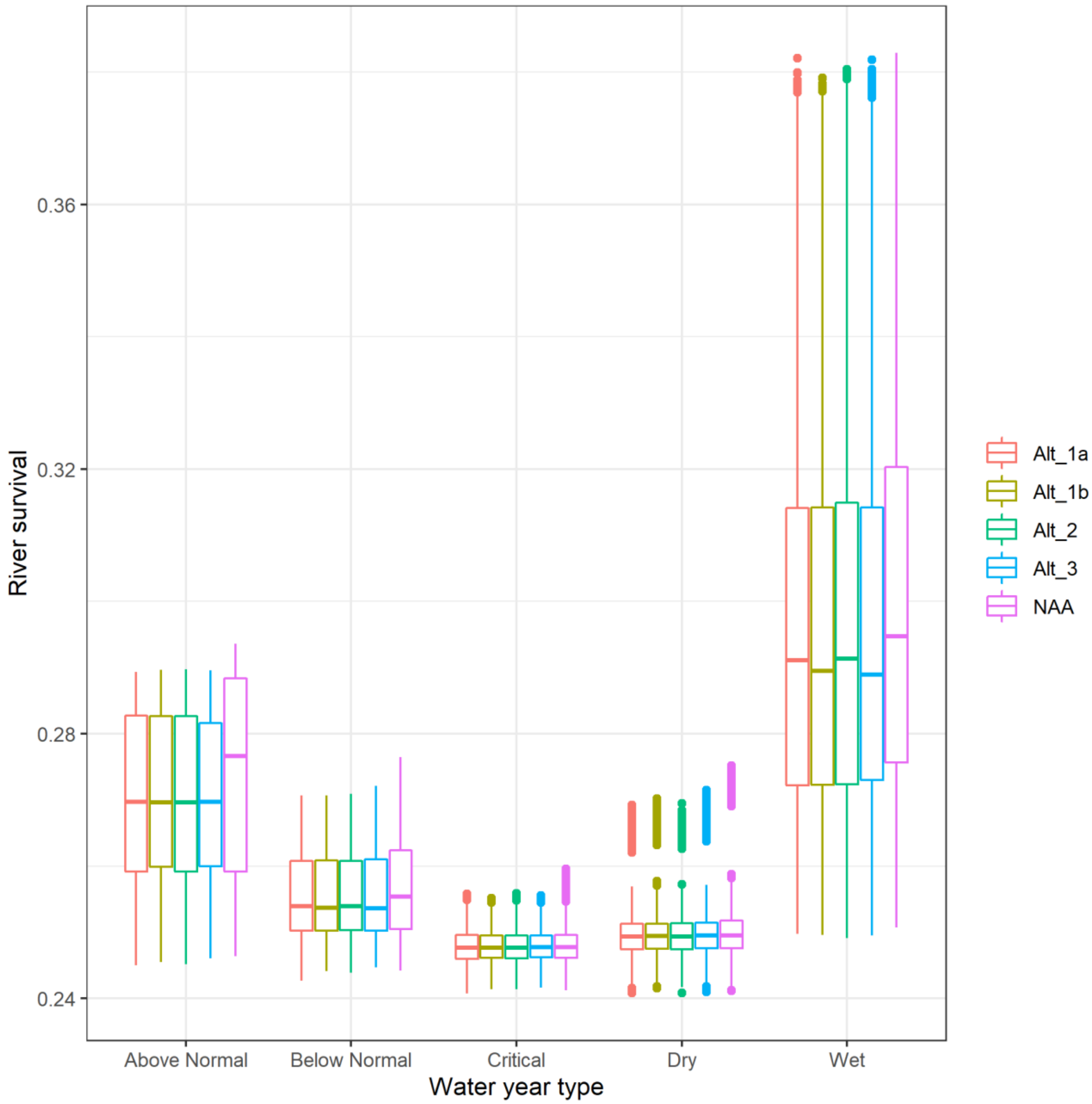


Figure 6. *Box plots of river migration survival by water year type for each of the alternatives evaluated. The results from all 100 iterations of each alternative are included in these plots. The box defines the interquartile range, the horizontal line is the median and the vertical lines define the largest value within 1.5 times the interquartile range. Individual points are those outside of that range.*

Delta passage survival

Delta passage survival ranged between ~ 12% and 41% among all years. Median Delta passage survival values over the simulation period were similar among all scenarios with less than a 2% difference in any year (Figure 7). Within water year-types, the largest

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

differences occurred in Below Normal water year-types where distributions were shifted lower for ALTs 1B and 3 relative to Alt 1A, Alt 2 and NAA. The interquartile ranges of each scenario overlapped substantially for other water year-types with a small shift toward higher survival distributions for the NAA in Wet and Dry year-types (Figure 8).

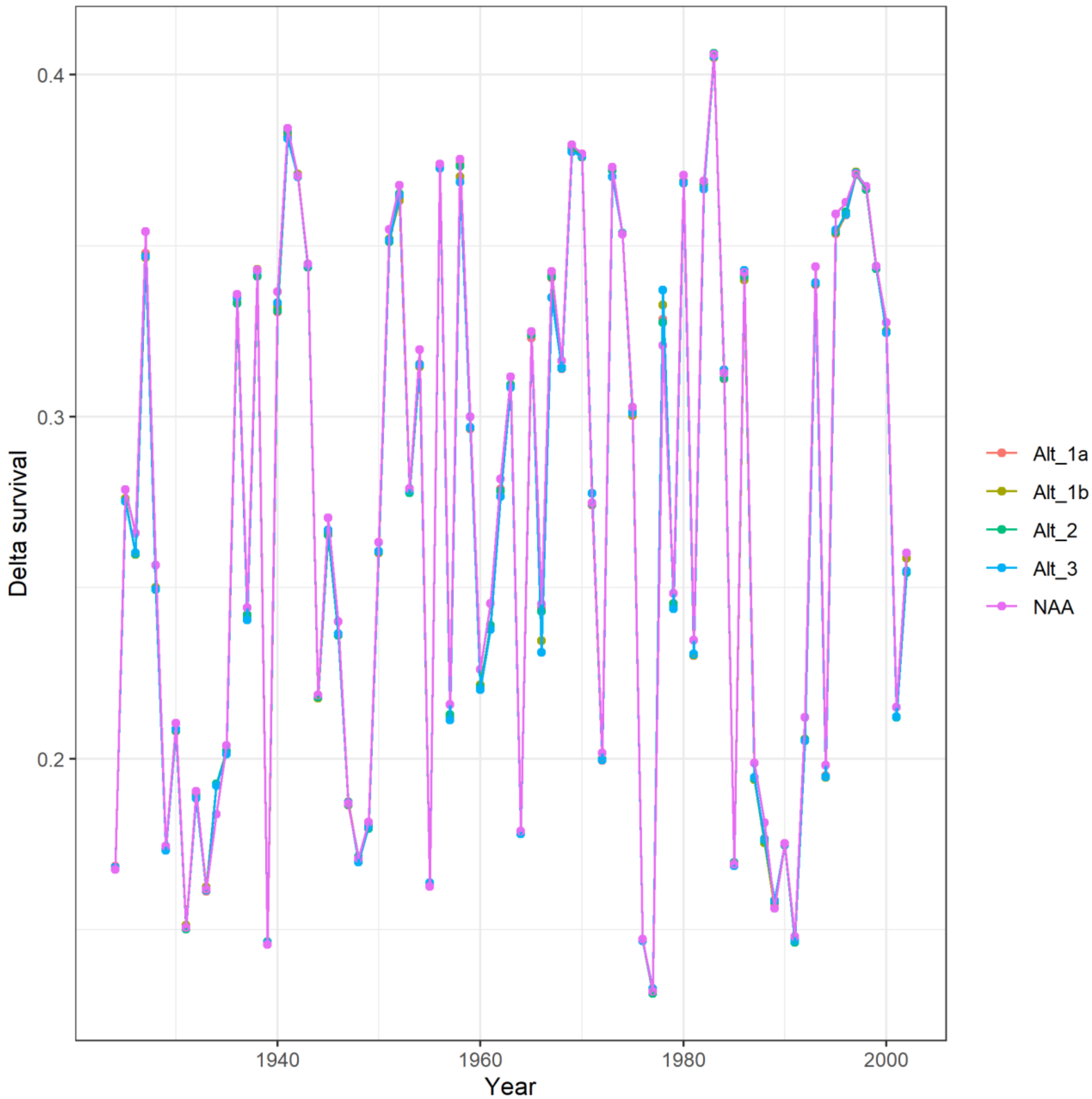


Figure 7. *Median winter run Chinook Salmon Delta passage survival (Fremont Weir to Chipps Island) over the 82-year simulation period.*

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

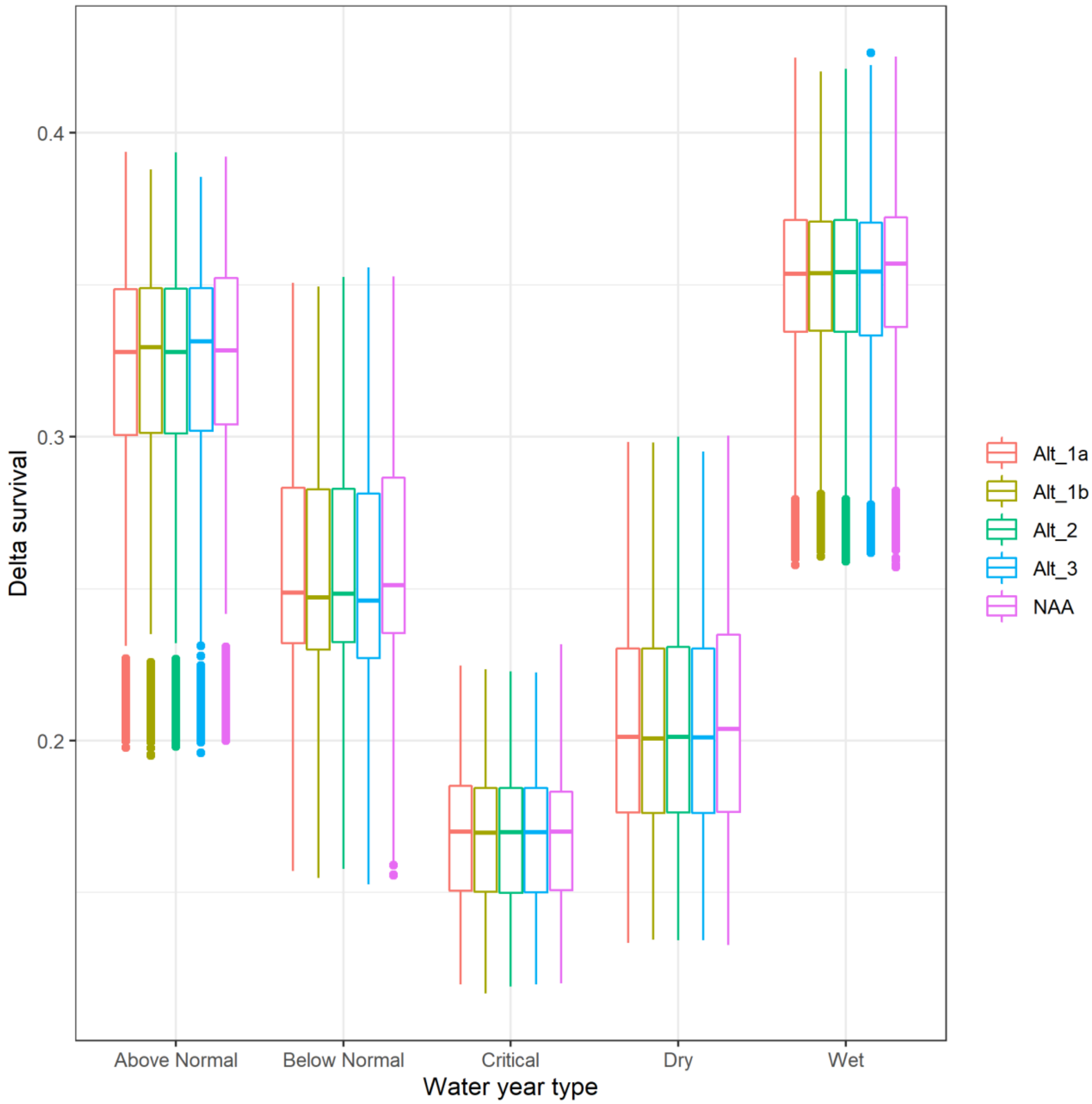


Figure 8. *Box plots of Delta passage survival by water year type for each of the alternatives evaluated. The results from all 100 iterations of each alternative are included in these plots. The box defines the interquartile range, the horizontal line is the median and the vertical lines define the largest value within 1.5 times the interquartile range. Individual points are those outside of that range.*

Female escapement

Female escapement integrates all effects from the operational alternatives into a population-level effect. Median values of female escapement were more variable than other outputs among the alternatives in individual years throughout the 82-year simulation period (Figure 9) In general, there were only small differences in individual

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

years although the NAA tended to have the most extreme values. The alternative with higher median escapement in each year was also variable. (Figure 9). Among the different water year-types, there was substantial overlap in the interquartile range of female escapement values and only small differences in median values were apparent (Figure 10).

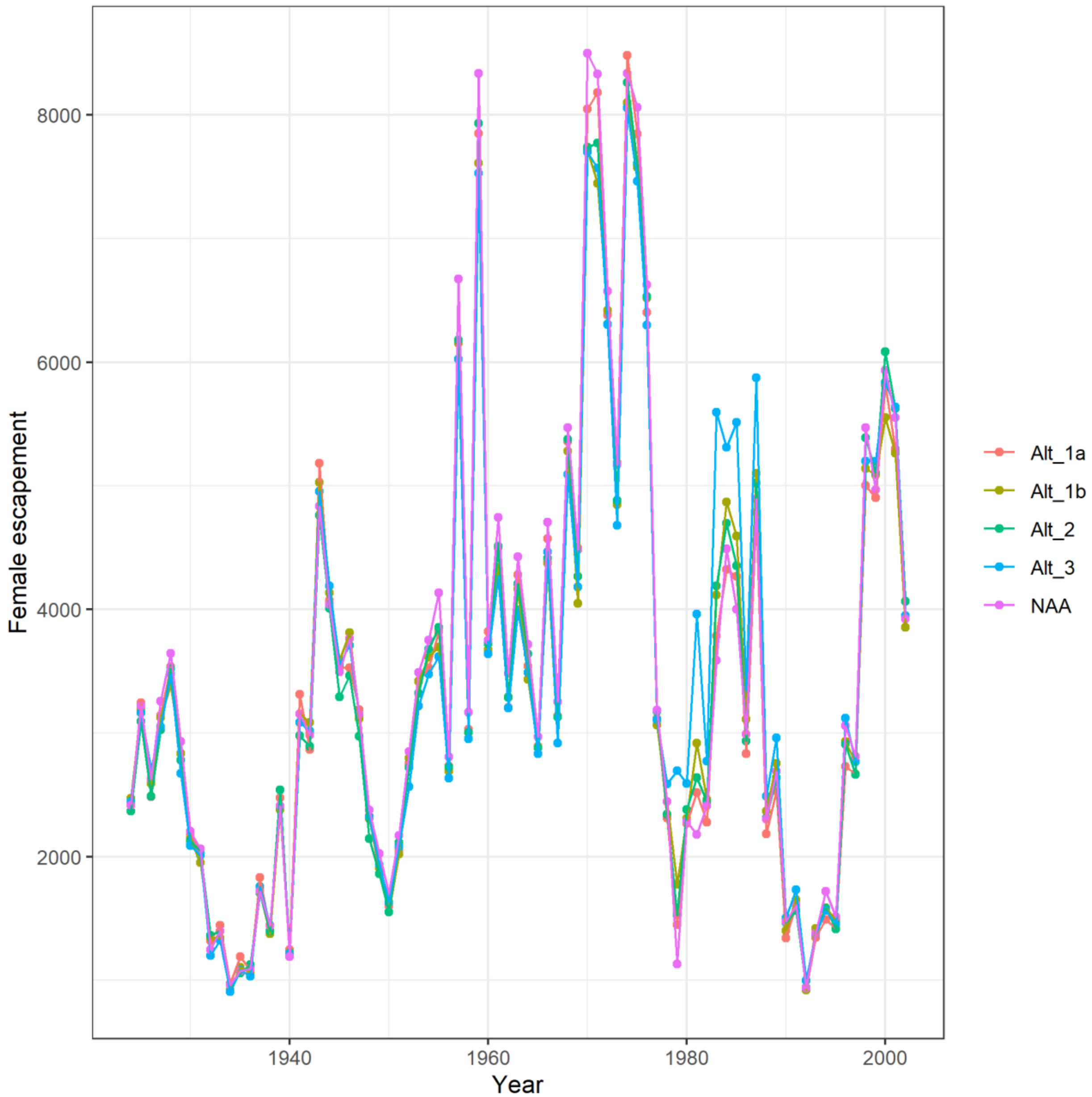


Figure 9. Median female escapement over the 82-year simulation period.

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

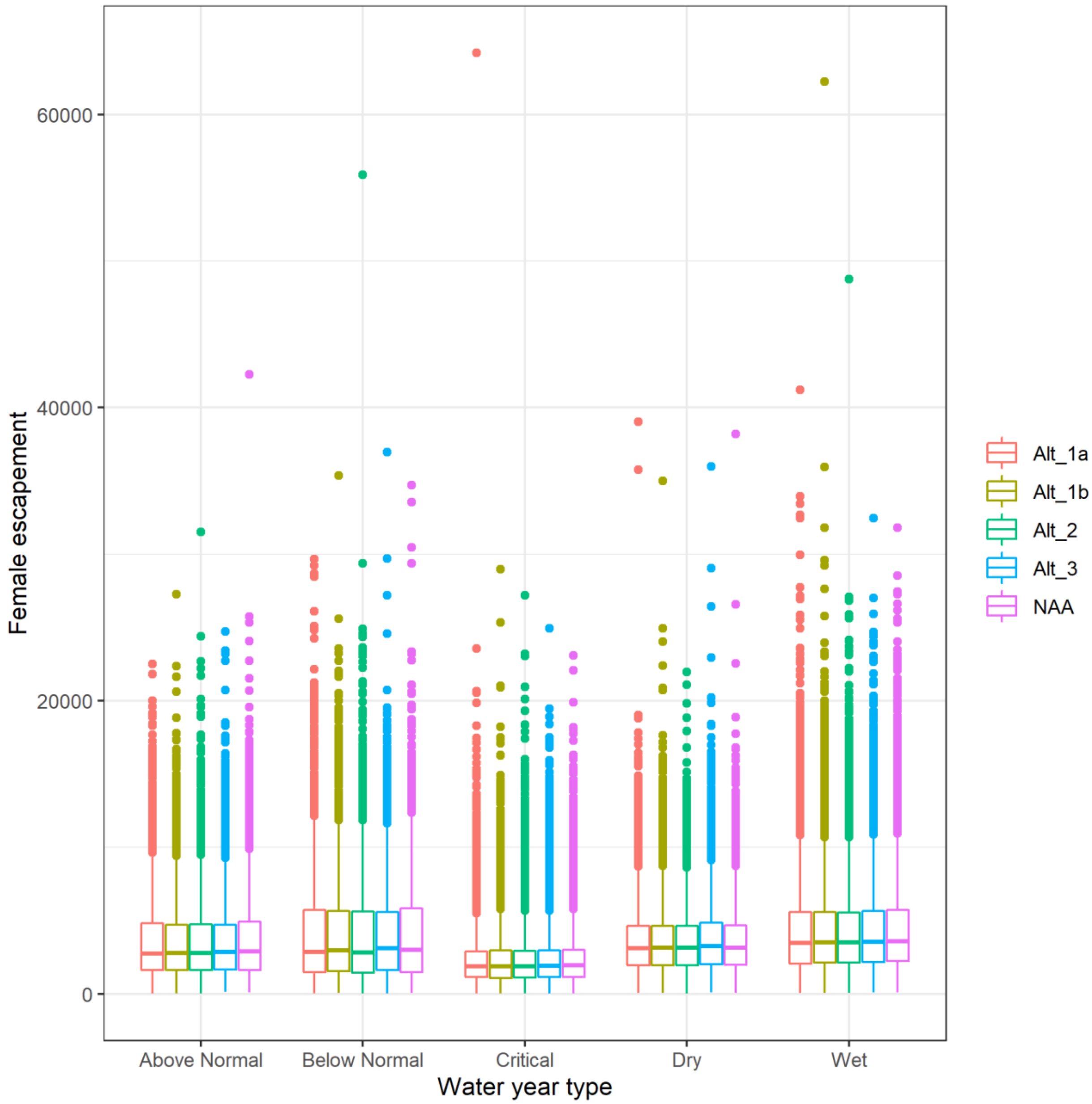


Figure 10. *Box plots of female escapement by water year type for each of the alternatives evaluated. The results from all 100 iterations of each alternative are included in these plots. The box defines the interquartile range, the horizontal line is the median and the vertical lines define the largest value within 1.5 times the interquartile range. Individual points are those outside of that range.*

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

Appendix

Interactive Object-Oriented Simulation (IOS) Model (Winter-Run Chinook Salmon)

June 22nd, 2022

Model Structure

The IOS Model is composed of six model stages defined by a specific spatiotemporal context and are arranged sequentially to account for the entire life cycle of winter-run Chinook salmon, from eggs to returning spawners (Figure 1). In sequential order, the IOS Model stages are listed below.

1. *Spawning*, which models the number and temporal distribution of eggs deposited in the gravel at the spawning grounds in the upper Sacramento River between Red Bluff Diversion Dam and Keswick Dam as a function of water Temperatures in April and May.
2. *Early Development*, which models the effect of temperature on maturation timing and mortality of eggs incubating in the gravel.
3. *Fry Rearing*, which models the relationship between temperature and mortality of fry during the river rearing period in the upper Sacramento River between Red Bluff Diversion Dam and Keswick Dam.
4. *River Migration*, which estimates mortality of migrating smolts in the Sacramento River between Red Bluff and the Delta as a function of river flow.
5. *Delta Passage*, which models the effect of flow, routing, and exports on the survival of smolts migrating through the Delta to San Francisco Bay.
6. *Ocean Survival*, which estimates the effect of natural mortality, ocean harvest, and ocean conditions to predict survival and spawning returns by age.

A detailed description of each model stage follows.

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

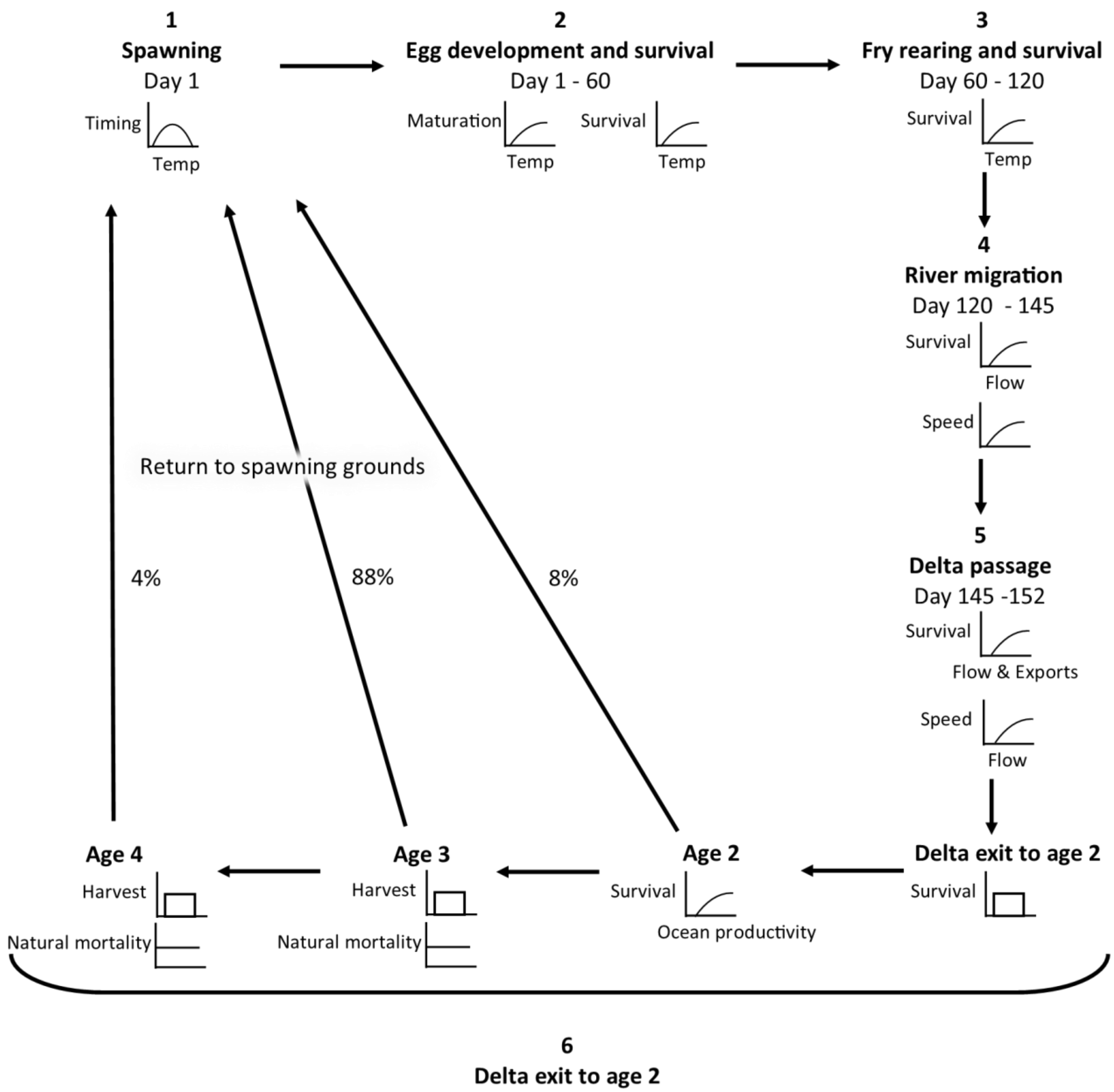


Figure 1. Conceptual Diagram of the IOS Model Stages and Environmental Influences on Survival and Development of Winter-Run Chinook Salmon at Each Stage.

Spawning

For the first four simulation years of the 82-year CALSIM simulation period, the model is seeded with 5,000 spawners, of which 3,087.5 are female based on the wild male to female ratio of spawners. In each subsequent simulation year, the number of female spawners is determined by the model's probabilistic simulation of survival to this life stage. To ensure that developing fish experience the correct environmental conditions during each year, spawn timing is a function of water tempertures in April and May as described by the function of Jennigs and

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

Hendrix (2020). Eggs deposited on a particular date are treated as cohorts that experience temperature on a daily time step during the early development stage. The daily number of female spawners is calculated by multiplying the predicted daily proportion of spawners by the total Jolly-Seber estimate of female spawners (Poytress and Carillo 2010).

(Equation 1) $$S_d = P_d S_{JS}$$

where, S_d is the daily number of female spawners, P_d is the daily proportion of total spawners and S_{JS} is the total Jolly-Seber estimate of female spawners.

To account for the time difference between egg deposition and carcass observations, the date of egg deposition is assumed to be 14 days prior to carcass observations (Niemela pers. comm.).

To obtain estimates of juvenile production, a Ricker stock-recruitment curve (Ricker 1975) was fit between the winter run Juvenile Production Index (JPI) each year (estimated by rotary screw–trap sampling at Red Bluff Diversion Dam) and the number of female spawners (from USFWS carcass surveys) for years 1996–1999 and 2002–2017:

(Equation 2) $$R = \alpha S e^{-\beta S} + \varepsilon$$

where α is a parameter that describes recruitment rate, and β is a parameter that measures the level of density dependence.

The density-dependent parameter (β) did not differ significantly from 0 (t = 1.662, p = 0.114)), indicating that the relationships between emergent fry and female spawners was linear (density-independent). Therefore, β was removed from the equation and a linear version of the stock-recruitment relationship was estimated. The number of female spawners explained 90% of the variation in fry production ($F_{1,19} = 173$, $p<0.001$) in the data, so the value of α was taken from the regression:

(Equation 3) $$R = 1027 * S$$

In the IOS Model, this linear relationship is used to predict values for mean fry production along with the confidence intervals for the predicted values. These values are then used to define a normal probability distribution, which is randomly sampled to determine the annual fry production. Although the Ricker model accounts for mortality during egg incubation, additional mortality was imposed at temperatures higher than those experinced during the years used to construct the Ricker model.

Early Development

Data from three laboratory studies were used to estimate the relationship between temperature, egg mortality, and development time (Murray and McPhail 1988; Beacham and Murray 1989; U.S. Fish and Wildlife Service 1999). Using data from these experiments, a relationship was constructed between maturation time and water temperature. First *maturation time* (days) was converted to a *daily maturation rate* (1/day):

(Equation 4) $$\textit{daily maturation rate} = \textit{maturation time}^{-1}$$

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

A significant linear relationship between maturation rate and water temperature was detected using linear regression. Daily water temperature explained 99% of the variation in *daily maturation rate* (F =2188; df =1,15; p<0.001):

(Equation 5) $$\textit{daily maturation rate} = 0.00058 \times Temp - 0.018$$

In the IOS Model, the daily mean maturation rate of the incubating eggs is predicted from daily water temperatures using a linear function; the predicted mean maturation rate, along with the confidence intervals of the predicted values, is used to define a normal probability distribution, which then is randomly sampled to determine the daily maturation rate. A cohort of eggs accumulates a percentage of total maturation each day from the above equation until 100% maturation is reached.

Data from experimental work (U.S. Fish and Wildlife Service 1999) was used to parameterize the relationship between temperature and mortality of developing winter-run Chinook salmon eggs. Predicted proportional mortality over the entire incubation period was converted to a daily mortality rate to apply these temperature effects in the IOS Model. This conversion was used to calculate daily mortality using the methods described by Bartholow and Heasley (2006):

(Equation 6) $$\textit{mortality} = 1-(1-\textit{total mortality})^{(1/\textit{development time})}$$

where *total mortality* is the predicted mortality over the entire incubation period observed for a particular water temperature and *development time* was the time to develop from fertilization to emergence.

Limited sample size in the USFWS study (1999) did not allow a statistically valid test for effects of temperature on mortality (e.g., a general additive model) to be performed. However, the following exponential relationship was fitted between observed *daily mortality* and observed water temperatures (U.S. Fish and Wildlife Service 1999) to provide the required values for the IOS Model:

(Equation 7) $$\textit{daily mortality} = 1.38 \times 10^{-15} e^{(0.503 \times Temp)}$$

Equation 7 yields the following graphic (2), which indicates that proportional daily egg mortality increases rapidly with only small changes in water temperature. For example, within the predominant water temperature range found in model scenarios (55°F to 60°F), proportional daily mortality increases over ten-fold (~0.001 at 55°F to ~0.018 at 60°F).

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

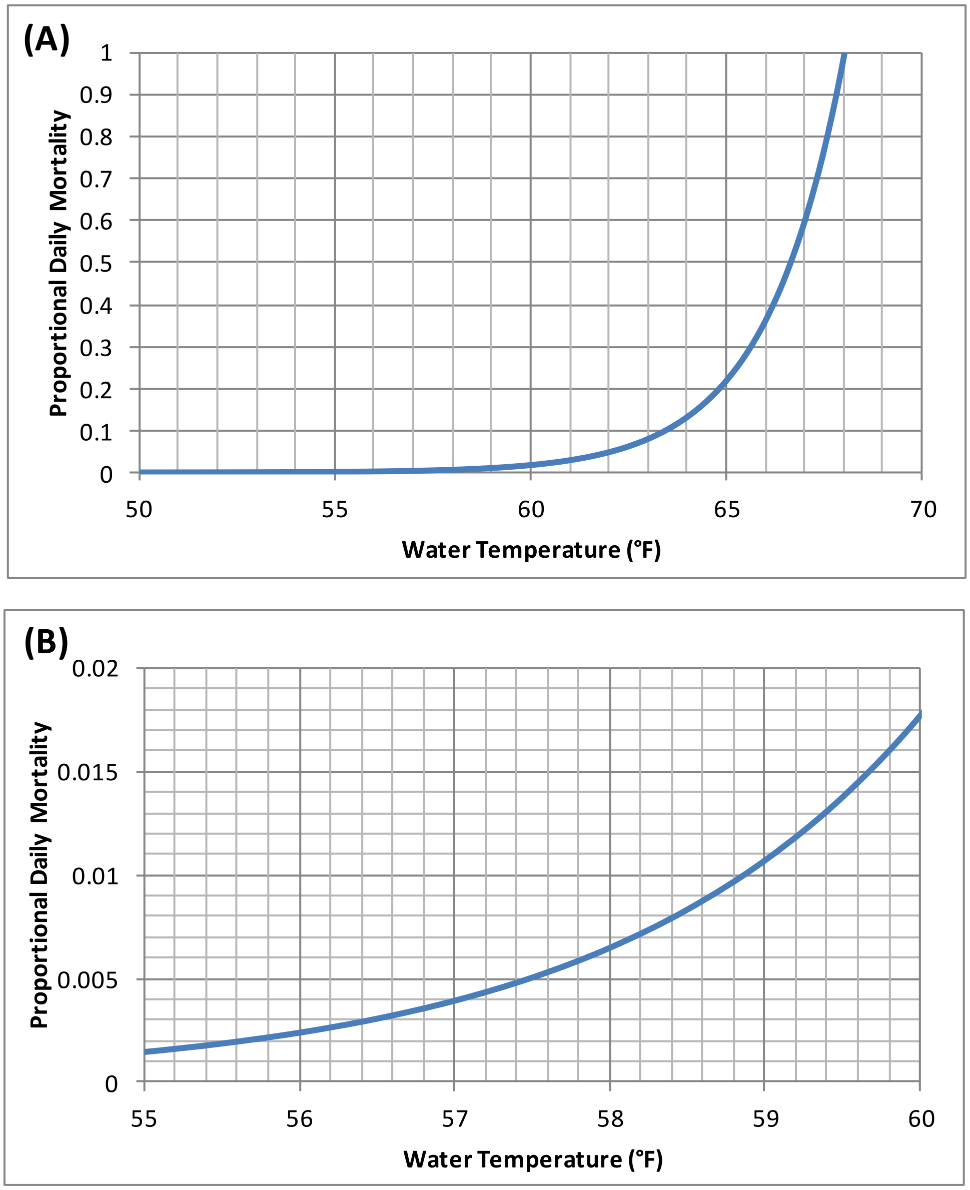


Figure 2. Relationship between Proportional Daily Mortality of Winter-Run Chinook Salmon Eggs and Water Temperature (Equation 7) for (A) the Entire Temperature Range, and (B) the Predominant Range Found in Model Scenarios

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

In the IOS Model, mean daily mortality rates of the incubating eggs are predicted from weighted mean daily water temperature at Keswick Dam and Balls Ferry where temperatures are weighted by a 10 year average distribution of winter run redds between these two locations. The predicted mean mortality rate, along with the confidence intervals of the predicted values, is used to define a normal probability distribution, which then is randomly sampled to determine the daily egg mortality rate.

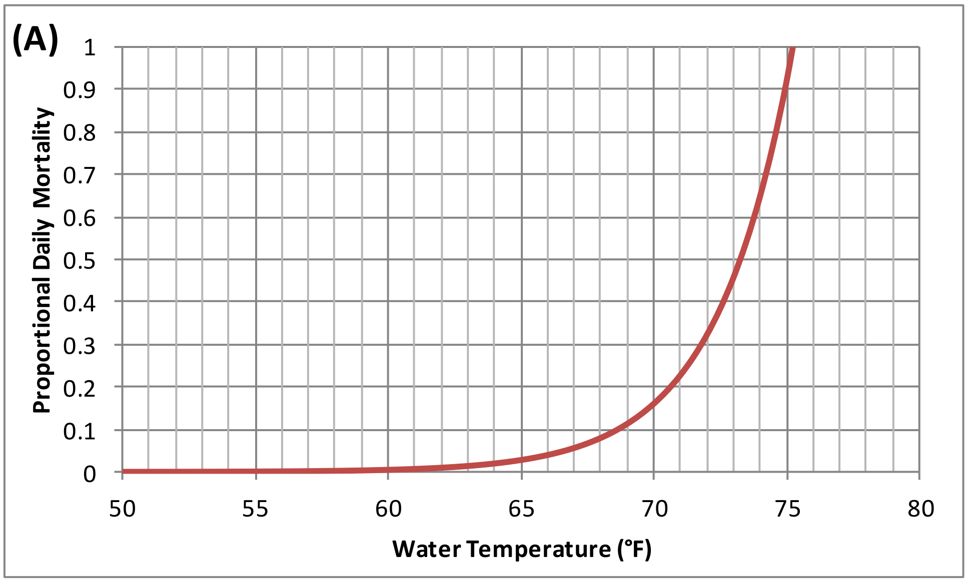
Fry Rearing

Data from USFWS (1999) was used to model fry mortality during rearing as a function of water temperature. Again, because of a limited sample size from the study by USFWS, statistical analyses to test for the effects of water temperature on rearing mortality could not be run. However, to acquire predicted values for the model, the following exponential relationship was fitted between observed daily mortality and observed water temperatures (U.S. Fish and Wildlife Service 1999):

(Equation 8) *daily mortality = 3.92*10-12e (0.349*Temp)*

Equation 8 yields the following graphic (Figure 3), which indicates that proportional daily fry mortality increases rapidly with only small changes in water temperature. For example, within the predominant water temperature range found in model scenarios (55°F to 60°F), proportional daily mortality increases over five-fold (~0.001 at 55°F to ~0.005 at 60°F). This indicates that, although fry mortality is highly sensitive to changes in water temperature, this sensitivity is not as great as that of egg mortality within the predominant range observed in the model scenarios in focus.

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net



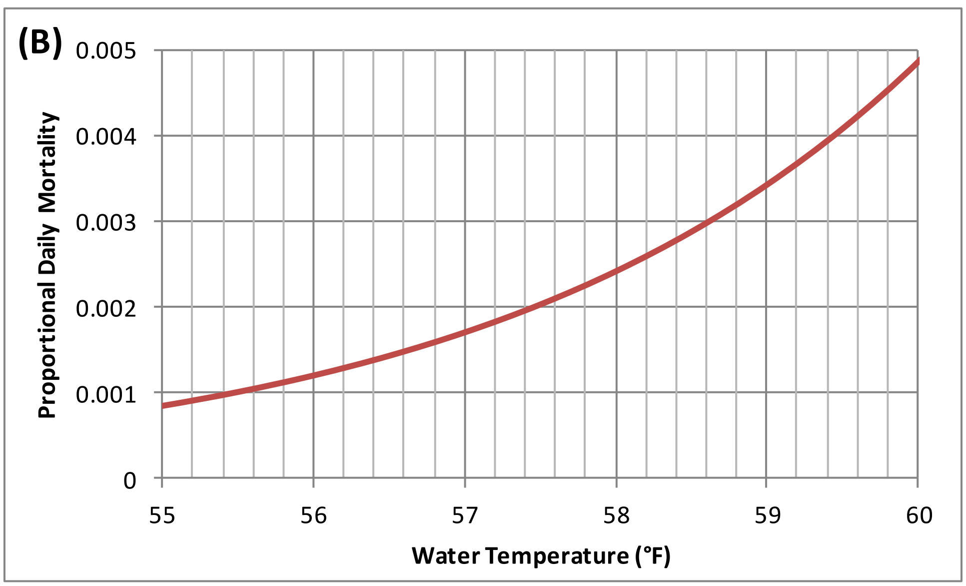


Figure 3. Relationship between Proportional Daily Mortality of Winter-Run Chinook Salmon Fry and Water Temperature (Equation 8) for (A) the Entire Temperature Range, and (B) the Predominant Range Found in Model Scenarios

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

Each day the mean proportional mortality of the rearing fish is predicted from the daily water temperature using the above exponential relationship; the predicted mean mortality, along with the confidence intervals of the predicted values, is used to define a normal probability distribution, which then is randomly sampled to determine the daily mortality of the rearing fish. Temperature mortality is applied to rearing fry for 60 days, which is the approximate time required for fry to transition into smolts (U.S. Fish and Wildlife Service 1999) and enter the *River Migration* stage. All fish migrating through the Delta are assumed to be smolts.

River Migration

To estimate survival from RedBluff to Verona, we collected JSATs detection data from 2012-2017 and flow data from the CDEC flow station. We restricted the JSATs data to receivers north of Verona (approximately 38.76 latitude), and only JSATs data for fish that were detected at either the "Cadwell Park" or "Bonnyview" release locations. There were a total of 2912 fish that met these criteria.

Each of these fish were considered to have been observed downstream if they were detected at any one of the following JSATs stations:

- Blw_FRConf
- Blw_FRConf
- Abv_FremontWeir
- Blw_FremontWeir
- Butte6
- Blw_FR_GS2

Of the original fish, only 846 were later observed at one of these locations.

CDEC flow data was summarized as the daily mean flow in cfs. Each fish was assumed to experience the flow value at the date of its release.

To estimate the effect of flow on survival while accounting for imperfect detection probability, a binomial regression was used where the measured outcome (the fish was observed downstream) was a binomial response with probability of success equal to the joint probability of a fish successfully surviving and the probability of that fish being detected by the JSATs receivers:

$$p(observed) = p(survived) * p(detected)$$

For the purposes of this analysis, the probability of detection at the receivers was assumed to be 95% (in line with other estimates of detection through multiple receivers in this region).

The quantity of interest, p(survived) was estimated as a function of a base survival probability and the effect of flow on survival. A logistic link function was used to map to the probability scale:

$$logit(p(survived)) = \alpha + \beta_{flow} * flow$$

The flow in cfs was centered so that α represented the base survival at 23,000 cfs flow, and scaled so the effect of flow was in log-odds change in survival per 1000 increase in cfs.

CRAMER FISH SCIENCES®
Oregon • California • Washington • Idaho • Alaska

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

The model code was written in the Stan probabilistic programming language, and the parameters estimated via HMC using the rstan package for R. All MCMC diagnostics were checked prior to reporting.

The estimated coefficients for log-odds base survival were -0.83 (95% CI -0.91 to -0.75), with the effect of flow estimated to be 0.0012 log-odds increase per 1000 cfs increase (95% CI 0.0011 to 0.0016; Figure 4).

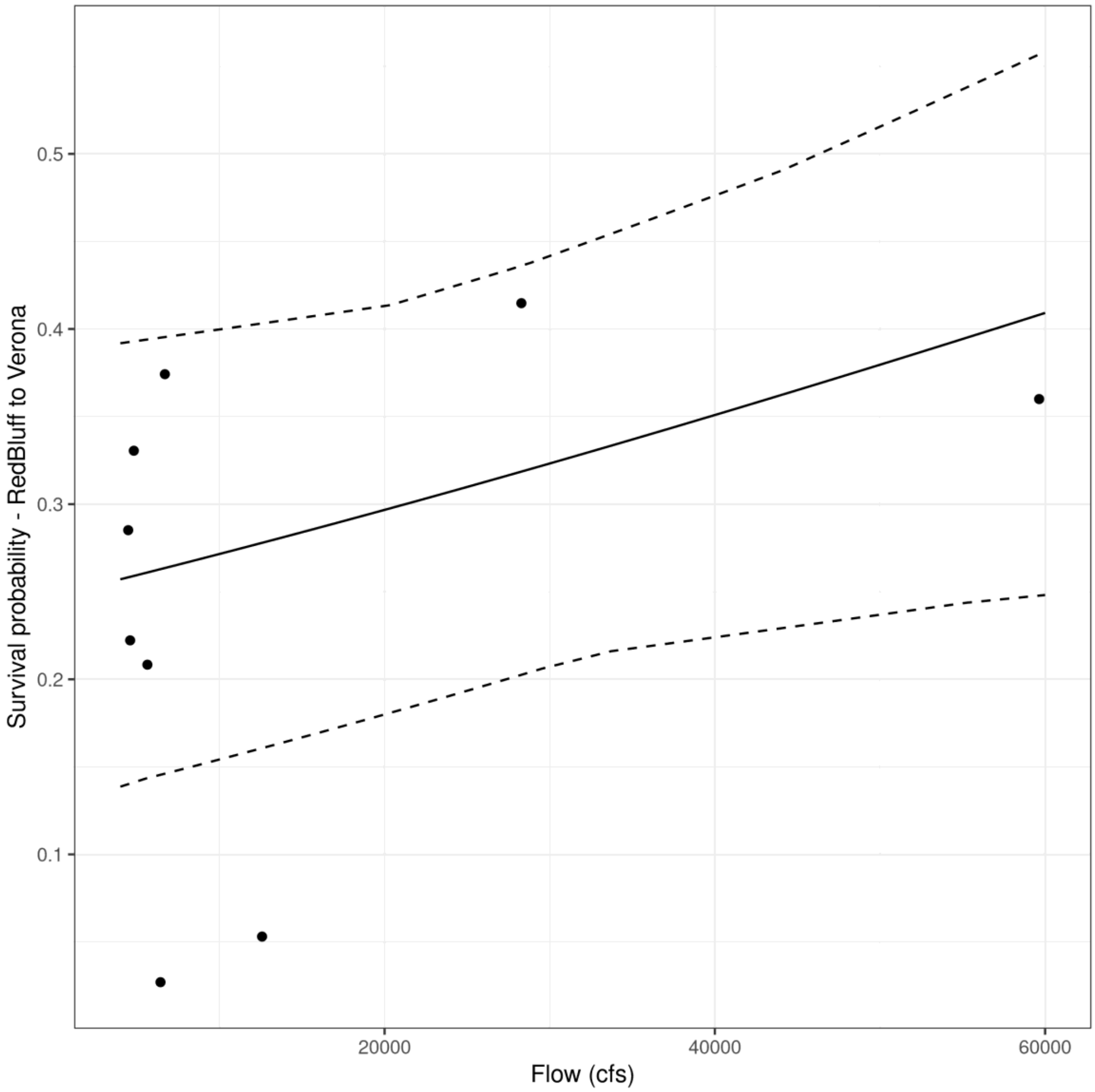


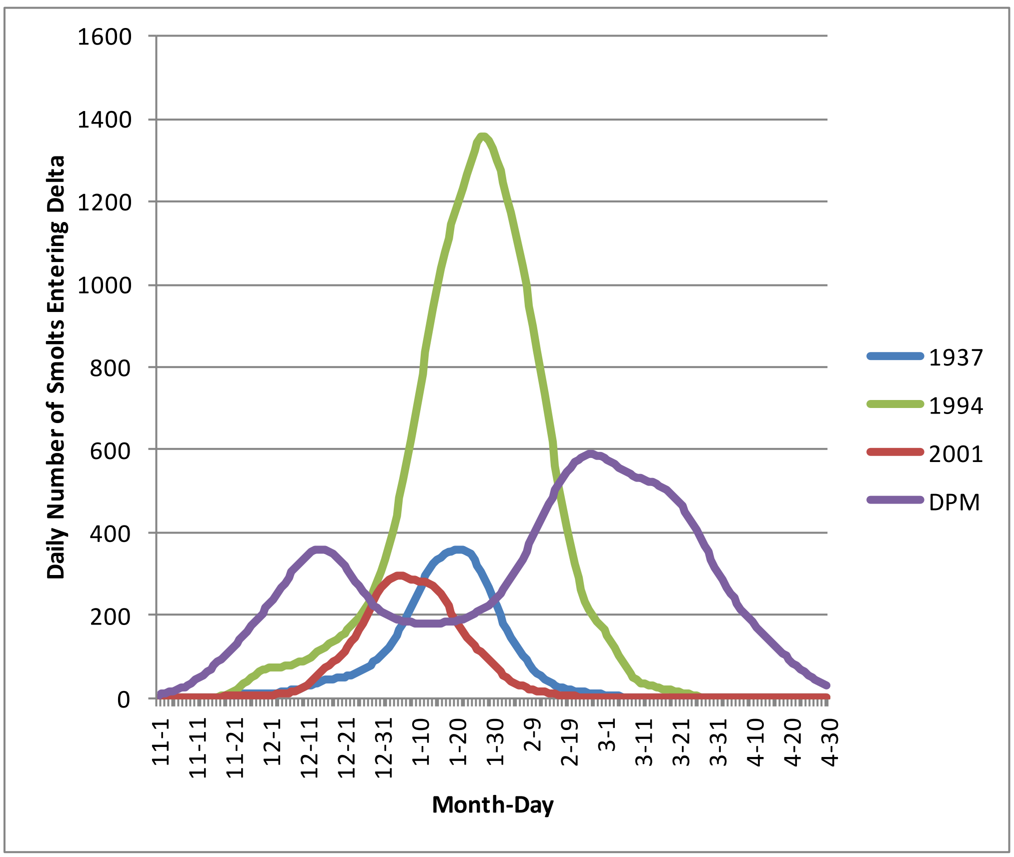
Figure 4. Comparison of estimated effects of increased flow on fish survival from Bend Bridge to Verona. The relationship was estimated with releases of juvenile winter run from Livingstone Stone National Fish hatchery implanted with JSATS transmitters. Circles are survival estimates for each release and the dashed line is the 95% confidence interval.

CRAMER
FISH SCIENCES®
Oregon • California • Washington • Idaho • Alaska

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

Delta Passage

Winter-run Chinook salmon passage through the Delta within IOS is modeled with the DPM, which is described fully in *The Delta Passage Model: A simulation model of Chinook Salmon survival, routing, and travel time in the Sacramento-San Joaquin Delta* (provided as an attachment to this document). Note that there is one difference between the implementation of the DPM in IOS and the standalone DPM. The timing of winter-run entry into the Delta is a function of upstream fry/egg rearing and river migration so timing changes annually, in contrast to the fixed nature of Delta entry for the standalone DPM. Also, the IOS entry distribution is a unimodal term that tends to peak between the bimodal peaks of the standalone DPM entry distribution (Figure 5). As each cohort of smolts exits the final reaches of the Delta (Sac4 and the interior Delta), the cohorts accumulate until all cohorts from that year have exited the Delta. After all cohorts have arrived, they all enter the *Ocean Survival* model as a single cohort and the model begins applying mortality on an annual time step.



DPM: purple line, fixed bimodal distribution.
IOS in 1937: blue line, an average peak of January 21.
IOS in 1994: green line, a late peak of January 28.
IOS in 2001: red line, an early peak of January 4.
IOS data are from scenario ALT9_LLT of the BDCP EIR/EIS.

Figure 5. Winter-Run Chinook Salmon Smolt Delta Entry Distributions Assumed under the Delta Passage Model Compared with Entry Distributions for IOS in 1937, 1994, and 2001

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

Ocean Survival

As described by Zeug et al. (2012), this model stage uses a set of equations for smolt-to-age-2 mortality, winter mortality, ocean harvest, and spawning returns to predict yearly survival and escapement numbers (i.e., individuals exiting the ocean to spawn). Certain values during the ocean survival life stage were fixed constant among model scenarios. Ocean survival model-stage elements are listed in Table 1 and discussed below.

Table 1. Functions and Environmental Variables Used in the Ocean Survival Stage of the IOS Model

Model Element	Environmental Variable	Value
Smolt-age 2 mortality	None	Uniform random variable between 94% and 98%
Age 2 ocean survival	Wells' Index of Ocean productivity	Equation 13
Age 3 ocean survival	None	Equation 14
Age 4 ocean survival	None	Equation 15
Age 3 harvest	None	Fixed at 17.5%
Age 4 harvest	None	Fixed at 45%

Relying on ocean harvest, mortality, and returning spawner data from Grover et al. (2004), a uniformly distributed random variable between 94% and 98% mortality was applied for winter-run Chinook salmon from ocean entry to age 2 and functional relationships were developed to predict ocean survival and returning spawners for age 2 (8%), age 3 (88%), and age 4 (4%), assuming that 100% of individuals that survive to age 4 return for spawning. In the IOS Model, ocean survival to age 2 is given by:

(Equation 13) $$A_2 = A_i(1\text{-}M_2)(1\text{-}M_w)(1\text{-}H_2)(1\text{-}S_{r2})*W$$

Survival to age 3 is given by:

(Equation 14) $$A_3 = A_2(1\text{-}M_w)(1\text{-}H3)(1\text{-}S_{r3})$$

And survival to age 4 is given by:

(Equation 15) $$A_4 = A_3(1\text{-}M_w)(1\text{-}H_4)$$

where A_i is initial abundance at ocean entry (from the DPM stage), $A_{2,3,4}$ are abundances at ages 2–4, $H_{2,3,4}$ are harvest percentages at ages 3–4 represented by uniform distributions bounded by historical harvest levels, M_2 is smolt-to-age-2 mortality, M_w is winter mortality for ages 2–4, and $S_{r2,r3}$ are returning spawner percentages at age 2 and age 3.

Harvest mortality is represented by a uniform distribution that is bounded by historical levels of harvest. Age 2 survival is multiplied by a scalar W that corresponds to the value of Wells Index of ocean productivity. This metric was shown to significantly influence over-winter survival of age 2 fish (Wells et al. 2007). The value of Wells Index is a normally distributed random variable that is resampled each year of the simulation. In the analysis, the following values from Grover et al. (2004) were used: H_2 = 0%, H_3 = 0-39%, H_4 = 0-74%, M_2 = 94-98%, M_w = 20%, S_{r2} = 8%, and S_{r3} = 96%.

Adult fish designated for return to the spawning grounds are assumed to be 65% female and are assigned a pre-spawn mortality of 5% to determine the final number of female returning spawners (Snider et al. 2001).

Time Step

The IOS Model operates on a daily time step, advancing the age of each cohort/life stage and thus tracking their numerical fate throughout the different stages of the life cycle. Some variables (e.g., annual mortality estimates) are randomly sampled from a distribution of values and are applied once per year. Although a daily time step is implemented for the Delta Passage component of IOS, flow inputs that rely on CALSIM outputs (i.e., all flows except flows at Fremont Weir) are based on monthly modeling and are assumed to be constant within a particular month. In addition, for the ocean phase of the life cycle, the model operates on an annual time step by applying annual survival estimates to each ocean cohort.

Model Inputs

Delta flows and export flow into SWP and CVP pumping plants were modeled using monthly flow output from CALSIM II, with the monthly average flow in a particular month being applied to all days within that month, as described above. A separate set of flow inputs was developed for each of the BDCP scenarios, based on the CALSIM II flow predictions for each scenario across the entire 1922 to 2002 prediction record. Flows into the Yolo Bypass over Fremont Weir were based on disaggregated monthly CALSIM II data based on historical patterns of variability. Temperature data for the Sacramento River was obtained from the SRWQM developed by the Bureau of Reclamation (Reclamation). The nodes in the CALSIM II and SRWQM models that were used to provide flow and temperature data for specific reaches in the Sacramento River and Delta are shown in Table 2.

Table 2. IOS Reaches and Associated Channels from CALSIM II and SRWQM Models

IOS Reach	CALSIM Channel	SRWQM
Spawning-Rearing Reach	–	Weighted average of Keswick and Balls Ferry temperatures based on spawning distribution
River Migration	Bend Bridge	
Sac1	Rsac155	–
Sac2	Sac_ds_stmbsl	–
Sac3	Rsac123	–
Sac4	Rsac101	–
SS	Sutr_sl+stmbt_sl	–
Geo/DCC	Dcc+georg_sl	–
Interior Delta	Total_exports	–

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

Model Outputs

Four model outputs are used to determine differences among model scenarios.

1. Egg survival: The Sacramento River between Keswick Dam and the Red Bluff Diversion Dam provides egg incubation habitat for winter-run Chinook salmon. Water temperature has a large effect on the survival of Chinook salmon during the egg incubation period by controlling mortality as well as development rate. Temperatures in this reach are partially controlled by releases of cold water from Shasta Reservoir and ambient weather conditions.

2. Fry survival: The Sacramento River between Keswick Dam and Red Bluff Diversion Dam provides rearing habitat for juvenile winter-run Chinook salmon. Water temperature can have a large effect on the survival of Chinook salmon during the fry rearing stage by controlling mortality and development rate. Temperatures in this reach are partially controlled by releases of cold water from Shasta Reservoir and ambient weather conditions.

3. River migration survival: The Sacramento River between Red Bluff Diversion Dam and Fremont Weir is a migration route for juvenile winter-run Chinook salmon. Flow magnitude at the Bend Bridge station influences survival and travel time in this reach. Flows at Bend Bridge are partially controlled by releases from Shasta and Keswick Reservoirs.

4. Through-Delta survival: The Delta between the Fremont Weir on the Sacramento River and Chipps Island is a migration route for juvenile winter-run Chinook salmon. Flow magnitude in different reaches of the Delta influences survival and travel time and entrainment into alternative migration routes with different survival probabilities.

5. Escapement: Each year of the IOS Model simulation, escapement is calculated as the combined number of 2-, 3-, and 4-year-old fish that leave the ocean and migrate back into the Sacramento River to spawn between Keswick Dam and the Red Bluff Diversion Dam. These numbers are influenced by the combination of all previous life stages and the functional relationships between environmental variables and survival rates.

Model Limitations and Assumptions

The following model limitations and assumptions should be recognized when interpreting results.

1. Other important ecological relationships likely exist but quantitative relationships are not available for integration into IOS (e.g., the interaction among flow, turbidity, and predation). To the extent that these unrepresented relationships are important and alter IOS outcomes, each alternative considered is assumed to be affected in the same way.

6. For relationships that are represented in IOS, operational alternatives considered are not assumed to alter those underlying functional relationships.

7. There is a specific range of environmental conditions (temperature, flow, exports, and ocean productivity) under which functional relationships were derived. These functional relationships are assumed to hold true for the environmental conditions in the scenarios considered.

13300 New Airport Rd. Suite 103
V: 530.240.6237
stevez@fishsciences.net

8. Differential growth because of different environmental conditions (e.g., river temperature) and subsequent potential differences in survival and other factors are not directly included in the model. Differences in survival related to growth are indirectly included to an unknown extent in flow-survival, temperature-survival, and ocean productivity-survival relationships.
9. Juvenile winter-run Chinook salmon migrating through the Delta all are assumed to be smolts that are not rearing in the Delta.

Model Sensitivity and Influence of Environmental Variables

Zeug et al. (2012) examined the sensitivity of the previous IOS model estimates of escapement to its input parameter values, input parameters being the functional relationships between environmental inputs and biological outputs. Although revisions have been undertaken to IOS since that time, particularly the river survival function, the main points from their analysis are still likely to be valid.

Zeug et al. (2012) found that escapement of different age classes was sensitive to different input parameters(Table 5). Escapement of age-2 fish (which compose 8% of the total returning fish in a given cohort) was most sensitive to smolt-to-age-2-survival and water year when considering either independent or interactive effects of these parameters, and there was also sensitivity to river migration survival when considering interactive effects of this parameter with other parameters. Escapement of age-3 fish (which compose 88% of the total returning fish in a given cohort) was sensitive to several input parameters when considering the independent effects of these parameters but was sensitive to through-Delta survival alone when considering first-order interactions between parameters. Escapement of age-4 fish (which compose 4% of the total returning fish in a given cohort) was sensitive to nearly all input parameters when considering the independent effects of these parameters, but was not sensitive to any of the parameters when considering first-order interactions between parameters (Zeug et al. 2012).

Zeug et al. (2012) also explored how uncertainty in model parameter estimates influences model output by increasing by 10–50% the variation around the mean of selected parameters that could be addressed by management actions (egg survival, fry-to-smolt survival, river migration survival, Delta survival, age-3 harvest, and age-4 harvest). They found that model output was robust to parameter uncertainty and that age-3 and age-4 harvest had the greatest coefficients of variation as a result of the uniform distribution of these parameters. Zeug et al. (2012) noted that there are limitations in the data used to inform certain parameters in the model that may be ecologically relevant but that are not sensitive in the current IOS configuration: river survival is a good example because it is based on a three-year field study of relatively low-flow conditions that does not cover the range of potential conditions that may be experienced by downstream-migrating juvenile Chinook salmon.

To understand the influence of environmental parameter inputs on escapement estimates from IOS, Zeug et al. (2012) performed three sets of simulations of a baseline condition and either a 10% increase or a 10% decrease in river flow, exports, water temperature (on the Sacramento

River at Bend Bridge; see above), and ocean productivity (i.e., Wells Index; see above). They found that only 10% changes in temperature produced a statistically significant change in escapement; a 10% increase in temperature produced a far greater reduction in escapement (>95%) than a 10% decrease in temperature gave an increase in escapement (>10%). Zeug et al. (2012) suggested that the lack of significant changes in escapement with 10% changes of flow, exports, and ocean productivity may reflect the fact that these variables' relationships within the model were based on observational studies with large error estimates associated with the responses. In contrast, temperature functions were parameterized with data from controlled experiments with small error estimates. Also, Zeug et al. (2012) noted that water temperatures within the winter-run Chinook salmon spawning and rearing area are close to the upper tolerance limit for the species; therefore, even small changes have the potential to significantly affect the population.

Table 5. Sobol' Sensitivity Indices (Standard Deviation in Parentheses) for Each Age Class of Returning Spawners Based on 1,000 Monte Carlo Iterations, Conducted to Test Sensitivity of IOS Input Parameters by Zeug et al. (2012)

Input Parameter	Age 2		Age 3		Age 4	
	Main Index (Effect Independent of Other Input Parameters)	Total Index (Effect Accounting for First-Order Interactions with Other Input Parameters)	Main Index (Effect Independent of Other Input Parameters)	Total Index (Effect Accounting for First-Order Interactions with Other Input Parameters)	Main Index (Effect Independent of Other Input Parameters)	Total Index (Effect Accounting for First-Order Interactions with Other Input Parameters)
Water year	0.300[a] (0.083)	0.306[a] (0.079)	0.181[a] (0.091)	0.150 (0.091)	0.073 (0.067)	0.012 (0.065)
Egg survival	0.030 (0.016)	-0.006 (0.016)	0.222[a] (0.081)	-0.021 (0.081)	0.102[a] (0.044)	-0.072 (0.044)
Fry-to-smolt survival	0.039 (0.020)	-0.009 (0.020)	0.166 (0.090)	0.091 (0.092)	0.079a (0.017)	-0.071 (0.017)
River migration survival	0.007 (0.034)	0.135a (0.034)	0.164 (0.084)	0.062 (0.085)	0.079 (0.018)	-0.07 (0.018)
Delta survival	0.010[a] (0.002)	-0.009 (0.002)	0.404[a] (0.180)	0.643[a] (0.177)	0.313[a] (0.134)	-0.009 (0.132)
Smolt to age 2 survival	0.734[a] (0.118)	0.454[a] (0.113)	0.015 (0.016)	-0.006 (0.016)	0.057a (0.017)	-0.052 (0.017)
Ocean productivity	0.003 (0.009)	0.009 (0.009)	0.034[a] (0.015)	-0.034 (0.015)	0.061[a] (0.030)	-0.048 (0.029)
Age 3 harvest	N/A	N/A	0.029[a] (0.001)	-0.028 (0.001)	1.48[a] (0.306)	0.188 (0.293)
Age 4 harvest	N/A	N/A	N/A	N/A	0.055a (0.003)	-0.054 (0.003)

Source: Zeug et al. 2012.

[a] Index value was statistically significant at α=0.05.

13300 New Airport Road, Suite 103
Auburn, CA 95602
V 530.240.6237
www.fishsciences.net

Literature Cited

Bartholow, J. M., and J. Heasley. 2006. *Evaluation of Shasta Dam Scenarios Using a Salmon Population Model*. Administrative Report. August. Fort Collins, CO. Prepared for U.S. Geological Survey, Reston, VA.

Beacham, T. D., and C. B. Murray. 1989. Variation in Developmental Biology of Sockeye Salmon (*Oncorhynchus nerka*) and Chinook Salmon (*Oncorhynchus tshawytscha*) in British Columbia. *Canadian Journal of Zoology* 67:2081–2089.

Grover, A., A. Low, P. Ward, J. Smith, M. Mohr, D. Viele, and C. Tracy. 2004. *Recommendations for Developing Fishery Management Plan Conservation Objectives for Sacramento River Spring Chinook*. Sacramento, CA. Available: <http://www.pcouncil.org/bb/2004/0304/exc7.pdf>. Accessed: November 16, 2011.

Murray, C. B., and J. D. McPhail. 1988. Effect of Incubation Temperature on the Development of Five Species of Pacific Salmon (*Oncorhynchus*) Embryos and Alevins. *Canadian Journal of Zoology* 66(1):266–273.

Poytress, W. R., and F. D. Carillo. 2010. *Brood-Year 2007 Winter Chinook Juvenile Production Indices with Comparisons to Juvenile Production Estimates Derived from Adult Escapement.* Final Annual Report 2007. Grant Number P0685507. May. Red Bluff, CA. Prepared for California Department of Fish and Game, Sacramento, CA, and California Bay Delta Authority, Sacramento, CA. Prepared by U.S. Fish and Wildlife Service, Red Bluff, CA.

Ricker, W. E. 1975. Computation and Interpretation of Biological Statistics of Fish Populations. *Fisheries Research Board of Canada, Bulletin* 191:265–296.

Snider, B., B. Reavis, and S. Hill. 2001. *Upper Sacramento River Winter-Run Chinook Salmon Escapement Survey, May-August 2000*. Stream Evaluation Program Technical Report No. 01-1. April. Sacramento, CA. Prepared by California Department of Fish and Game, Habitat Conservation Division, Sacramento, CA.

U.S. Fish and Wildlife Service. 1999. *Effects of Temperature on Early-Life Survival of Sacramento River Fall-Run and Winter-Run Chinook Salmon*. Final Report. Shepherdstown, WV.

Wells, B. K., C. B. Grimes, and J. B. Waldvogel. 2007. Quantifying the Effects of Wind, Upwelling, Curl, Sea Surface Temperature and Sea Level Height on Growth and Maturation of a California Chinook Salmon (*Oncorhynchus tshawytscha*). *Fisheries Oceanography* 16:363–382.

Zeug, S., P. Bergman, B. Cavallo, and K. Jones. 2012. *Application of a Life Cycle Simulation Model to Evaluate Impacts of Water Management and Conservation Actions on an Endangered Population of Chinook Salmon*. Environmental Modeling and Assessment. DOI 10.1007/s10666-012-9306-6.

13300 New Airport Road, Suite 103
Auburn, CA 95602
V 530.240.6237
www.fishsciences.net

Personal Communications

Niemela, Kevin pers. comm.

CRAMER FISH SCIENCES®
Oregon • California • Washington • Idaho • Alaska

13300 New Airport Rd. Suite 102
V: 530.888.7773 F: 530.888.7774
stevez@fishsciences.net

The Delta Passage Model: A simulation model of Chinook Salmon survival, routing, and travel time in the Sacramento-San Joaquin Delta.

June 9, 2021

The Delta Passage Model (DPM) simulates migration of Chinook Salmon smolts entering the Delta from the Sacramento River at Fremont Weir, and estimates survival to Chipps Island. The DPM uses available time-series data and values taken from empirical studies or other sources to parameterize model relationships and inform uncertainty, thereby using the greatest amount of data available to dynamically simulate responses of smolt survival to changes in water management. The DPM contains relationships derived from studies of all four runs of Chinook salmon. Relationships for individual runs were not developed due to sample size limitations for some runs and the model assumes all migrating Chinook salmon smolts will respond similarly to Delta conditions. Delta entry timing for each run is unique for each run based on collections in the Sacramento trawl. The DPM results presented here reflect the most current version of the model, which continues to be reviewed and refined, and for which a sensitivity analysis has been completed to examine various aspects of uncertainty related to the model's inputs and parameters.

Although studies have shown considerable variation in emigrant size, with Central Valley Chinook Salmon migrating as fry, parr, and smolts (Brandes and McLain 2001; Williams 2001), the DPM relies predominantly on data from acoustic-tagging studies of smolt-sized (≥ 80 mm) fish, and therefore should be applied cautiously to pre-smolt migrants. Salmon juveniles less than 70 mm are more likely to exhibit rearing behavior in the Delta (Moyle 2002) and thus likely will be represented poorly by the DPM. It has been assumed that the downstream emigration of fry, when spawning grounds are well upstream, is probably a dispersal mechanism that helps distribute fry among suitable rearing habitats. However, even when rearing habitat does not appear to be a limiting factor, downstream movement of fry still may be observed, suggesting that fry emigration is a viable alternative life-history strategy (Healy 1980; Healey and Jordan 1982; Miller et al. 2010). Unfortunately, survival data are lacking for small (fry-sized) juvenile emigrants because of the difficulty of tagging such small individuals. Therefore, the DPM should be viewed as a smolt survival model only, with its survival relationships generally having been derived from larger juveniles (≥ 80 mm), with the fate of pre-smolt emigrants not incorporated into model results.

The version of the DPM described here has undergone substantial revisions based on a large amount of telemetry data that has become available since the original version of the model was constructed. Initial model structure was modified based on comments received through the Bay -Delta Conservation Plan preliminary proposal anadromous team meetings and in particular through feedback received during a workshop held on August 24, 2010, a 2-day workshop held June 23–24, 2011, and since then from various meetings of a workgroup consisting of agency biologists and consultants. The current version builds on this breadth of input and resolves many of the uncertainties identified in previous reviews. This documentation reflects the most recent version of the DPM as of December 2020.

Survival and routing estimates generated by the DPM are not intended to predict future outcomes. Instead, the DPM is a decision support tool that compares the effects of different water management options on smolt migration survival, with accompanying estimates of uncertainty. The DPM is a tool to compare different scenarios and is not intended to predict actual through-Delta survival under current or future conditions. It is possible that underlying relationships (e.g., flow-survival, export-survival) that are used to inform the DPM will change in the future. Just as this latest update was completed to incorporate newly-available data, it may be necessary to re-examine the relationships as new information becomes available.

Model Overview

The DPM is based on migratory pathways and reach-specific mortality as Chinook Salmon smolts travel through a simplified network of reaches and junctions (Figure 1). The biological functionality of the DPM is based on releases of acoustically tagged Chinook salmon performed between 2007 and 2017. The previous version of the DPM primarily relied on releases of large (> 140 mm) acoustically tagged late-fall run Chinook salmon performed by Perry (2010) and coded wire tag releases of late-fall run reported by Newman and Brandes (2010). There was considerable uncertainty about the transferability of those relationships to other runs that migrate at different times of year and at smaller sizes. The revised model is based on acoustically tagged winter run, spring run, fall run and late fall run individuals (≥ 80 mm) released in the upper reaches of the Sacramento River and within the Delta. These releases are primarily comprised of hatchery fish. However, wild spring and fall run are included in the data set. These releases cover a wide range of environmental conditions including extreme drought in 2014 and 2015 and high flow years. Uncertainty is explicitly modeled in the DPM by incorporating environmental stochasticity and estimation error whenever available.

The major model functions in the DPM are as follows.

1. Delta Entry Timing, which models the temporal distribution of smolts entering the Delta for each race of Chinook salmon.
2. Fish Behavior at Junctions, which models fish movement as they approach river junctions.
3. Migration Speed, which models reach-specific smolt migration speed and travel time.
4. Route-Specific Survival, which models route-specific survival response to non-flow factors.
5. Flow-Dependent Survival, which models reach-specific survival response to flow.
6. Export-Dependent Survival, which models survival response to water export levels in the Interior Delta reach (see Table 1 for reach description).

Functional relationships are described in detail in the Section *Model Functions*.

Model Time Step

The DPM operates on a daily time step using simulated daily average flows and south Delta exports as model inputs. The DPM does not attempt to represent sub-daily flows or diel salmon smolt behavior in response to the interaction of tides, flows, and specific channel features. The DPM is intended to represent the net outcome of migration and mortality occurring over one day, not three-dimensional movements occurring over minutes or hours (e.g., Blake and Horn 2003). It is acknowledged that finer scale modeling with a shorter time step may match the biological processes governing fish movement better than a daily time step (e.g., because of diel activity patterns; Plumb et al. 2015) and that sub-daily differences in flow proportions into junctions make daily estimates somewhat coarse (Cavallo et al. 2015).

Spatial Framework

The DPM is composed of ten reaches and three junctions (Figure 1; Table 1) selected to represent primary salmonid migration corridors for fish originating from the Sacramento River basin where high-quality data were available for fish and hydrodynamics. For simplification, Sutter Slough and Steamboat Slough are combined as the reach SS; and Georgiana Slough and the Delta Cross Channel (DCC) are a combined junction. Sacramento Chinook Salmon that enter the DCC migrate through the Forks of the Mokelumne and Fish entering Georgiana Slough migrate only through that route. The Interior Delta reach can be entered from the Mokelumne River or Georgiana Slough route. The entire Interior Delta region is treated as a single model reach. The three distributary junctions (channel splits) depicted in the DPM are (A) Sacramento River at Fremont Weir (head of Yolo Bypass), (B) Sacramento River at head of Sutter and Steamboat Sloughs, and (C) Sacramento River at the combined junction with Georgiana Slough and DCC (Figure 1, Table 1).

Table 1. *Description of Modeled Reaches and Junctions in the Delta Passage Model. Yolo and interior Delta reach lengths are not defined because multiple migration pathways are possible.*

Reach/Junction	Description	Approximate Reach Length (km)	Final Receiver name/location
Verona	Sacramento River Between Fremont Weir and Freeport	57	Freeport
Sac_1	Sacramento River Between Freeport and the combined junction of Steamboat and Sutter Slough	19	Sacramento River Below Steamboat Slough
Sac_2	Sacramento River from Sutter/Steamboat Sloughs junction to junction with Delta Cross Channel/Georgiana Slough	11	Sacramento River Below Georgiana Slough
Sac_3	Sacramento River from Below Georgiana Slough to Rio Vista	16	Chipps Island
SS	Steamboat and Sutter Sloughs from their junction with the Sacramento River to Chipps Island	21	Chipps Island
Yolo Bypass	Fremont weir to Highway 84 Ferry	NA	Highway 84 Ferry
Sac_4	Rio Vista to Chipps Island	30	Chipps Island
Geo/DCC	Georgiana Slough from the junction with the Sacramento River to the base of the Mokelumne River. Includes fish that	25	Mokelumne Base

	migrate through the Mokelumne River via the Delta Cross Channel		
Interior Delta	Confluence of Mokelumne and San Joaquin Rivers to Chipps Island	NA	Chipps Island
A	Junction of Yolo Bypass and Sacramento River	NA	NA
B	Combined junction of Sutter Slough and Steamboat Slough with the Sacramento River	NA	NA
C	Combined junction of the Delta Cross Channel and Georgiana Slough with the Sacramento River	NA	NA

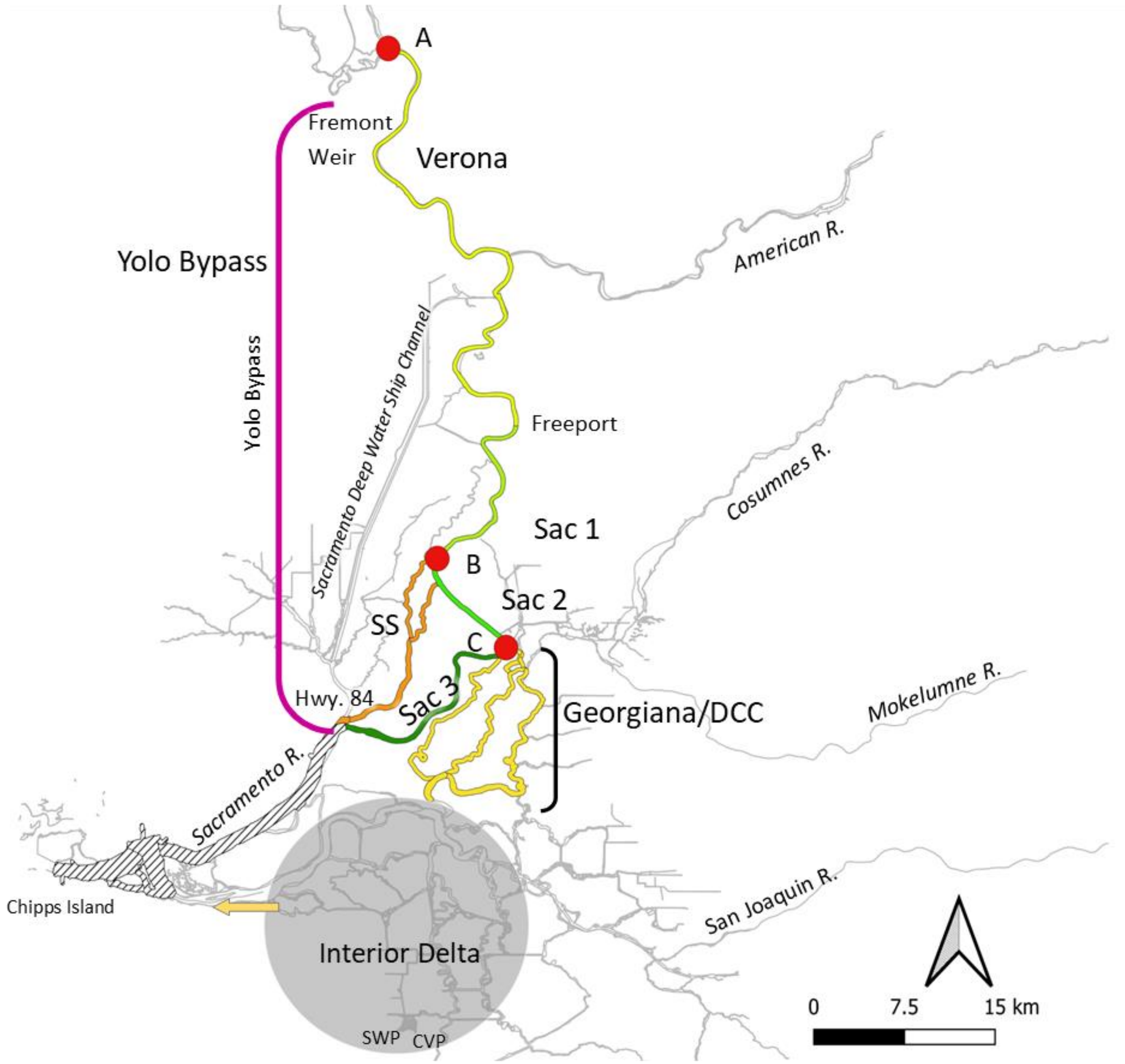


Figure 1. *Map of the Sacramento–San Joaquin River Delta Showing the Modeled Reaches and Junctions of the Delta Applied in the Delta Passage Model.*

Flow Input Data

Water movement through the Delta as input to the DPM is derived from daily (tidally averaged) flow output produced by the hydrology module of the Delta Simulation Model II (DSM2- HYDRO; <http://baydeltaoffice.water.ca.gov/modeling/deltamodeling/>) or from CALSIM-II. The nodes in the DSM2-HYDRO and CALSIM II models that were used to provide flow for specific reaches in the DPM are shown in Table 2.

Table 2. *Delta Passage Model Reaches and Associated Output Locations from DSM2-HYDRO and CALSIM II Models.*

DPM Reach or Model Component	DSM2 Output Locations	CALSIM Node
Sac1	rsac155	
Sac2	rsac128	
Sac3	rsac123	
Sac4	rsac101	
Yolo		d160a+d166aa
Verona		C160a
SS	slsbt011	
Geo/DCC	dcc+georg_sl	
South Delta Export Flow	Clifton Court Forebay + Delta Mendota Canal	
Sacramento River flow at Fremont Weir		C129a

Model Functions

Delta Entry Timing

Catch data for emigrating juvenile smolts for five Central Valley Chinook salmon runs were used to inform the daily proportion of juveniles entering the Delta for each run (Table 3). Because the DPM models the survival of smolt-sized juvenile salmon, pre-smolts were removed from catch data before creating entry timing distributions. The lower 95th percentile of the range of salmon fork lengths visually identified as smolts by the USFWS in Sacramento trawls was used to determine the lower length cutoff for smolts. A lower fork length cutoff of 70 mm for smolts was applied, and all catch data of fish smaller than 70 mm were eliminated. To isolate wild production, all fish identified as having an adipose-fin clip (hatchery production) were eliminated, recognizing that most (75%) of the fall-run hatchery fish released upstream of Sacramento are not marked. Daily catch data for each brood year were divided by total annual catch to determine the daily proportion of smolts entering the DPM for each run (Figure 2). Sampling was not conducted daily at most stations and catch was not expanded for fish caught but not measured. Finally, a generic probability density function was fit to the data using the package “sm” in R software (R Core Team 2012). The R fitting procedure estimated the best-fit probability distribution of the daily proportion of fish entering the DPM.

For the current analysis, the most recent data from the Sacramento Trawl survey was added to the previous data to determine if entry distributions had shifted since the original fitting. Only late fall Chinook Salmon exhibited substantial change from the original fit and the entry distribution for that race was updated

Table 3. *Sampling Gear Used to Create Juvenile Delta Entry Timing Distributions for Each Central Valley Run of Chinook Salmon.*

Chinook Salmon Run	Gear	Agency	Brood Years
Sacramento River Winter Run	Trawls at Sacramento	USFWS	1995–2009
Sacramento River Spring Run	Trawls at Sacramento	USFWS	1995–2005
Sacramento River Fall Run	Trawls at Sacramento	USFWS	1995–2005
Sacramento River Late Fall Run	Trawls at Sacramento	USFWS	1995–2018
Agencies that conducted sampling are listed: USFWS = U.S. Fish and Wildlife Service, EBMUD = East Bay Municipal District, and CDFW = California Department of Fish and Wildlife.			

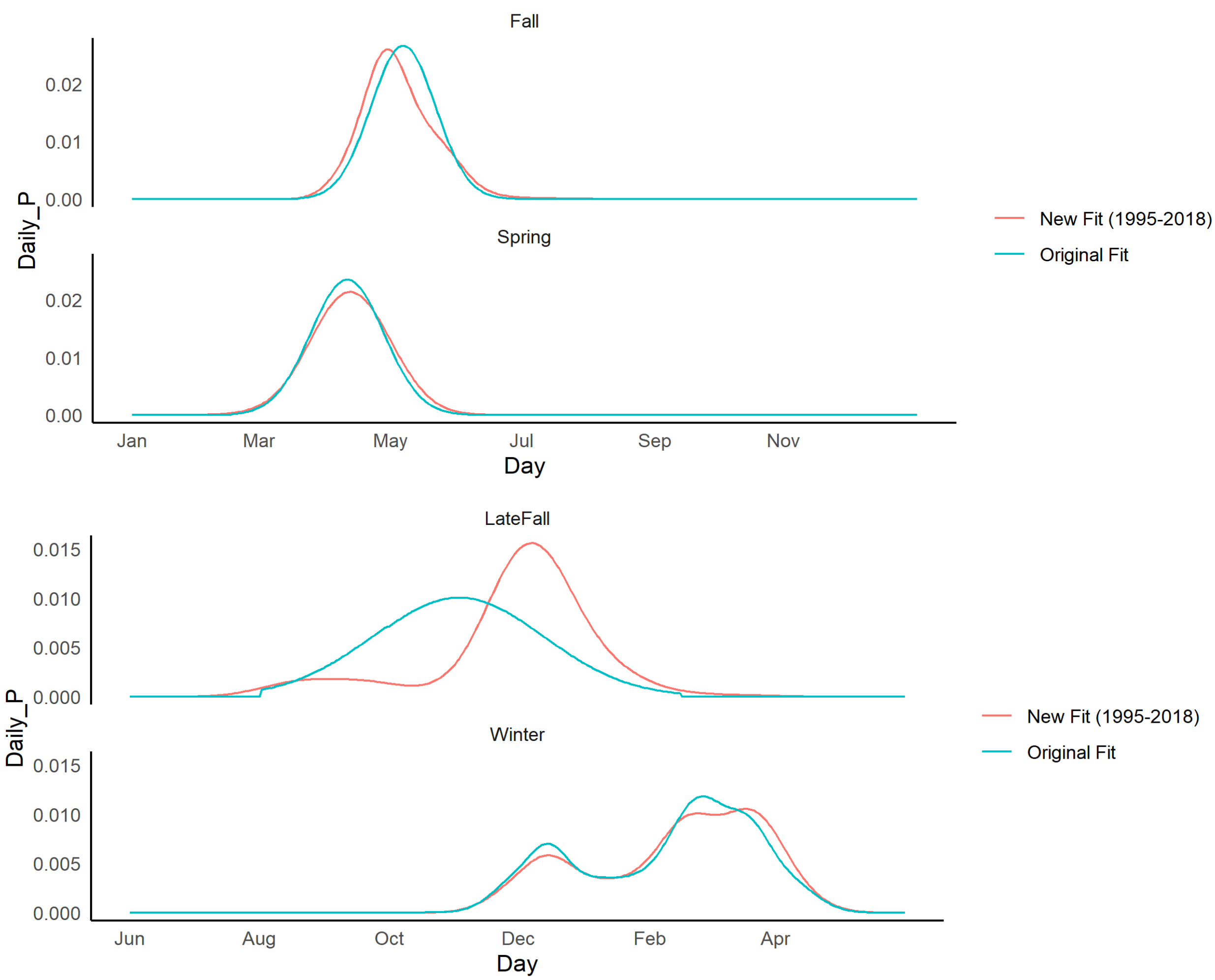


Figure 2. *Delta Entry Distributions for Chinook Salmon Smolts Applied in the Delta Passage Model for Sacramento River Winter-Run, Central Valley Spring-Run (Sacramento River), Central Valley Fall-Run (Sacramento River), and Central Valley Late Fall–Run. Note the change in x axes between the upper and lower panel.*

Migration Speed

The DPM assumes a net daily movement of smolts in the downstream direction. The rate of smolt movement in the DPM affects the timing of arrival at Delta junctions and reaches, which can affect route selection and survival as flow conditions or water project operations change.

Smolt movement in all reaches except Yolo Bypass and the Interior Delta is a function of reach-specific length and migration speed as observed from acoustic-tagging results. Reach-specific length (kilometers [km]) is divided by reach migration speed (km/day) the day smolts enter the reach to calculate the number of days smolts will take to travel through the reach.

For north Delta reaches Verona, Sac1, Sac2, SS, and Geo/DCC, mean migration speed through the reach is predicted as a function of flow. Many studies have found a positive relationship between juvenile Chinook salmon migration rate and flow in the Columbia River Basin (Raymond 1968; Berggren and Filardo 1993; Schreck et al. 1994), with Berggren and Filardo (1993) finding a logarithmic relationship for Snake River yearling Chinook salmon. Ordinary least squares regression was used to test for a logarithmic relationship between reach-specific migration speed (km/day) and average daily reach-specific flow (cubic meters per second [m^3/sec]) for the first day smolts entered a particular reach for reaches where acoustic-tagging data was available (Sac1, Sac2, Sac3, Sac4, Geo/DCC, and SS):

$$Speed = \beta_0 \ln(flow) + \beta_1;$$

Where β_0 is the slope parameter and β_1 is the intercept.

Individual smolt reach-specific travel times were calculated from detection histories of releases of acoustically-tagged smolts conducted in December and January for three consecutive winters (2006/2007, 2007/2008, and 2008/2009) (Perry 2010). Reach-specific migration speed (km/day) for each smolt was calculated by dividing reach length by travel days. Flow data was queried from the DWR's California Data Exchange website (<http://cdec.water.ca.gov/>).

Migration speed was significantly related to flow for reaches Sac1 (df = 450, F = 164.36, P < 0.001), Sac2 (df = 292, F = 4.17, P = 0.042), and Geo/DCC (df = 84, F = 13.74, P <0.001). Migration speed increased as flow increased for all three reaches (Table 4, Figure 3). Therefore, for reaches Sac1, Sac2, and Geo/DCC, the regression coefficients shown in Table 4 are used to calculate the expected average migration rate given the input flow for the reach and the associated standard error of the regressions is used to inform a normal probability distribution that is sampled from the day smolts enter the reach to determine their migration speed throughout the reach. The minimum migration speed for each reach is set at the minimum reach-specific migration speed observed from the acoustic-tagging data. The flow-migration rate relationship that was used for Sac1 also was applied for the Verona reach.

__Table 4.__ Sample Size and Slope (β_0) and Intercept (β_1) Parameter Estimates with Associated Standard Error (in Parenthesis) for the Relationship between Migration Speed and Flow for Reaches Sac1, Sac2, and Geo/DCC.

Reach	N	β_0	β_1
Sac1	452	21.34 (1.66)	-105.98 (9.31)
Sac2	294	3.25 (1.59)	-8.00 (8.46)
Geo/DCC	86	11.08 (2.99)	-33.52 (12.90)

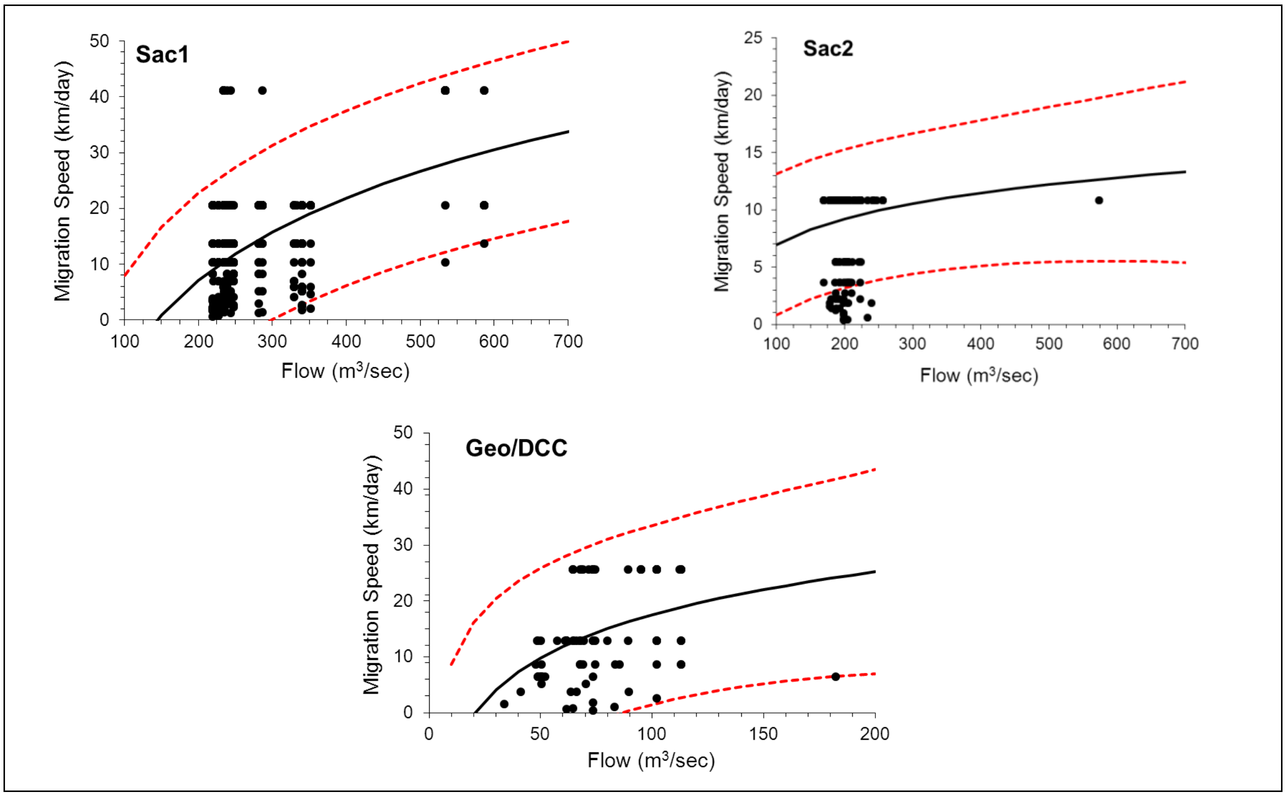


***Figure 3.** Reach-Specific Migration Speed (km/day) as a Function of Flow (m^3/sec) Applied in Reaches Sac1, Sac2, and Geo/DCC.*

No significant relationship between migration speed and flow was found for reaches Sac3 (df = 100, F = 1.13, P =0.29), Sac4 (df = 60, F = 0.33, P = 0.57), and SS (df = 28, F = 0.86, P = 0.36). Therefore, for these reaches the observed mean migration speed and associated standard deviation is used to inform a normal probability distribution that is sampled from the day smolts enter the reach to determine their migration speed throughout the reach. As applied for reaches Sac1, Sac2, and Geo/DCC, the minimum migration speed for reaches Sac3, Sac4, and SS is set at the minimum reach-specific migration speed observed from the acoustic-tagging data.

Yolo Bypass travel time data from Sommer et al. (2005) for coded wire-tagged, fry-sized (mean size = 57 mm fork length [FL]) Chinook Salmon were used to inform travel time through the Yolo Bypass in the

DPM. Because the DPM models the migration and survival of smolt-sized juveniles, the range of the shortest travel times observed across all three years (1998–2000) by Sommer et al. (2005) was used to inform the bounds of a uniform distribution of travel times (range = 4–28 days), on the assumption that smolts would spend less time rearing, and would travel faster than fry. On the day smolts enter the Yolo Bypass, their travel time through the reach is calculated by sampling from this uniform distribution of travel times.

The travel time of smolts migrating through the Interior Delta in the DPM is informed by observed mean travel time (7.95 days) and associated standard deviation (6.74) from North Delta acoustic-tagging studies (Perry 2010). However, the timing of smolt passage through the Interior Delta does not affect Delta survival because there are no Delta reaches located downstream of the Interior Delta.

Fish Behavior at Junctions (Channel Splits)

Perry et al. (2010) and Cavallo et al. (2015) found that acoustically-tagged smolts arriving at Delta junctions exhibited inconsistent movement patterns in relation to the flow being diverted. For Junction A (entry into the Yolo Bypass at Fremont Weir), the following relationships were used.

- Proportion of smolts entering Yolo Bypass = Fremont Weir spill/ (Fremont Weir spill + Sacramento River at Verona flows).

As noted above in *Flow Input Data*, the flow data informing Yolo Bypass entry were obtained by disaggregating CALSIM estimates using historical daily patterns of variability because DSM2 does not provide daily flow data for these locations.

For Junction B (Sacramento River-Sutter/Steamboat Sloughs), Both Perry et al. (2010) and Cavallo et al. (2015) found that smolts consistently entered downstream distributaries in proportion to the flow being diverted. Therefore, smolts arriving at Junction B in the model move proportionally with flow according to the linear relationship found in Cavallo et al. (2015):

$$P_{SS} = -0.00203 + P_{flowSS} * 0.775344$$

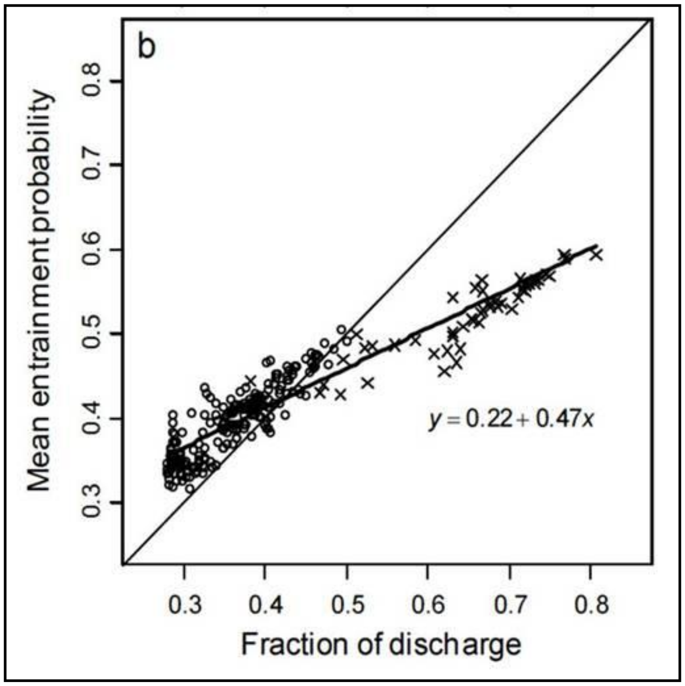
Where P_{SS} is the proportion of fish entering the SS reach, and P_{flowSS} is the proportion of flow entering Sutter/Steamboat Slough distributaries from the total flow in the mainstem Sacramento River.

For Junction C (Sacramento River–Georgiana Slough/DCC), Perry (2010) found a linear, nonproportional relationship between flow and fish movement. His relationship for Junction C was applied in the DPM:

$$y = 0.22 + 0.47x;$$

where *y* is the proportion of fish diverted into Geo/DCC and *x* is the proportion of flow diverted into Geo/DCC (Figure 4).

In the DPM, this linear function is applied to predict the daily proportion of fish movement into Geo/DCC as a function of the proportion of flow into Geo/DCC.



Circles Depict DCC Gates Closed, Crosses Depict DCC Gates Open.

Figure 4. *Figure from Perry (2010) Depicting the Mean Entrainment Probability (Proportion of Fish Being Diverted into Reach Geo/DCC) as a Function of Fraction of Discharge (Proportion of Flow Entering Reach Geo/DCC).*

Reach-Specific Survival

To update survival estimates in the DPM, we analyzed a dataset of detections from >2000 acoustically-tagged (JSATS) fish recorded in the DPM region of the Sacramento-San Joaquin Delta from 2013-2019. To estimate survival from such a large and heterogeneous dataset (receiver combinations, monitored reaches, and release locations differed from year to year), we used only detections from receivers at the endpoint of reaches in the DPM, and constructed binary detection histories along DPM routes. Moving downstream from receiver to receiver along a route, we assumed that if a fish was not seen again in the route after a given receiver, the fish did not survive. The probability of being detected again downstream (assumed to be a direct proxy for survival) was then modeled as a function of an individual's detection history and time-specific covariates associated with reach entry. From this analysis, four reaches were associated with a consistent relationship between flow and survival: Sac1, Sac2, Sac3, and Sac4; all other reaches had no consistent flow-survival relationship, and survival in those reaches of the DPM is drawn from a normal distribution derived from a reach-specific, intercept-only model of survival and standard deviation from the JSATS data.

Flow-Dependent Survival

Survival through a given reach is estimated and applied the first day smolts enter that reach. For reaches where analysis of the JSATS detections supported a consistent flow-survival relationship, flow on the day fish enter the reach is used to predict survival through the entire reach even if migration through the reach takes place over more than one day.

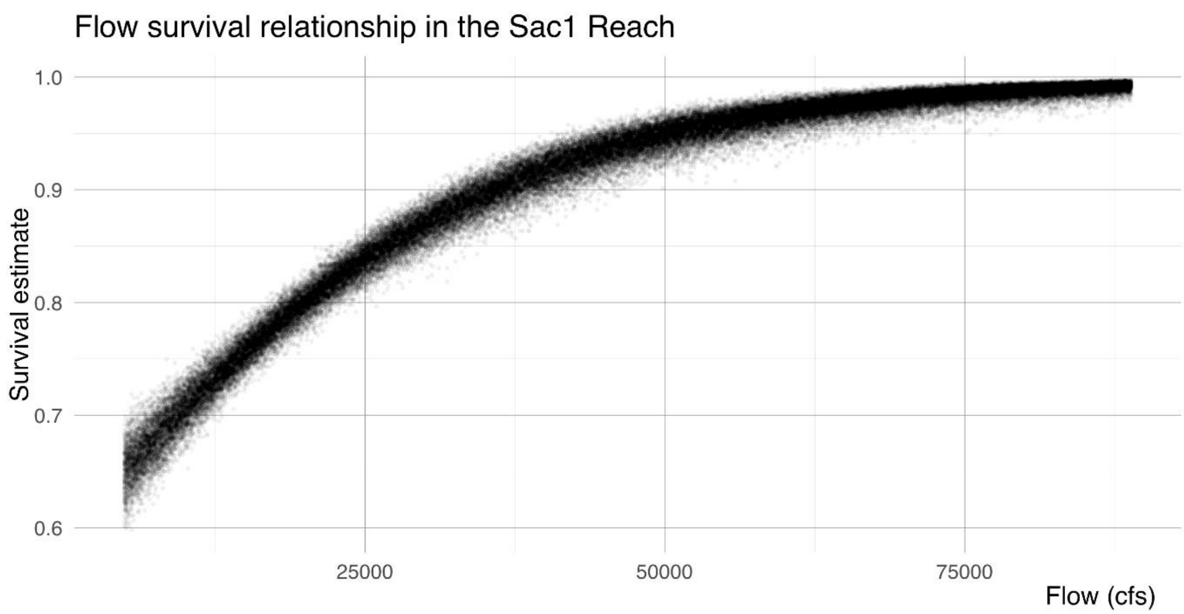


Figure X. Relationship between Sacramento River discharge and survival through the Sac 1 reach modeled with JSATS releases of multiple runs of Chinook Salmon.

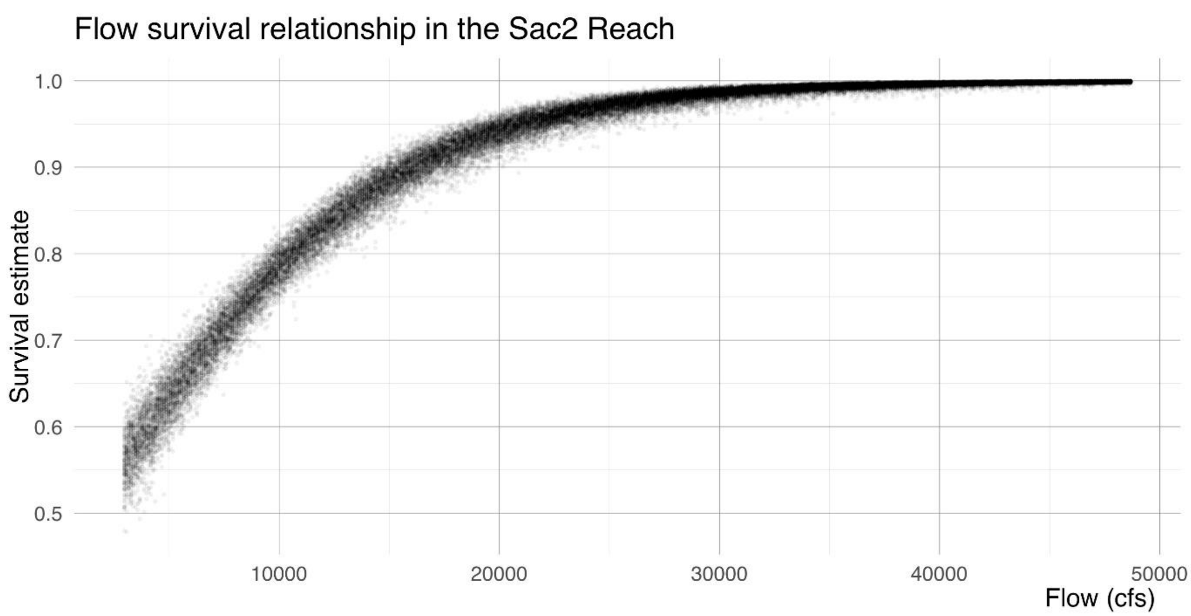


Figure X. Relationship between Sacramento River discharge and survival through the Sac 2 reach modeled with JSATS releases of multiple runs of Chinook Salmon.

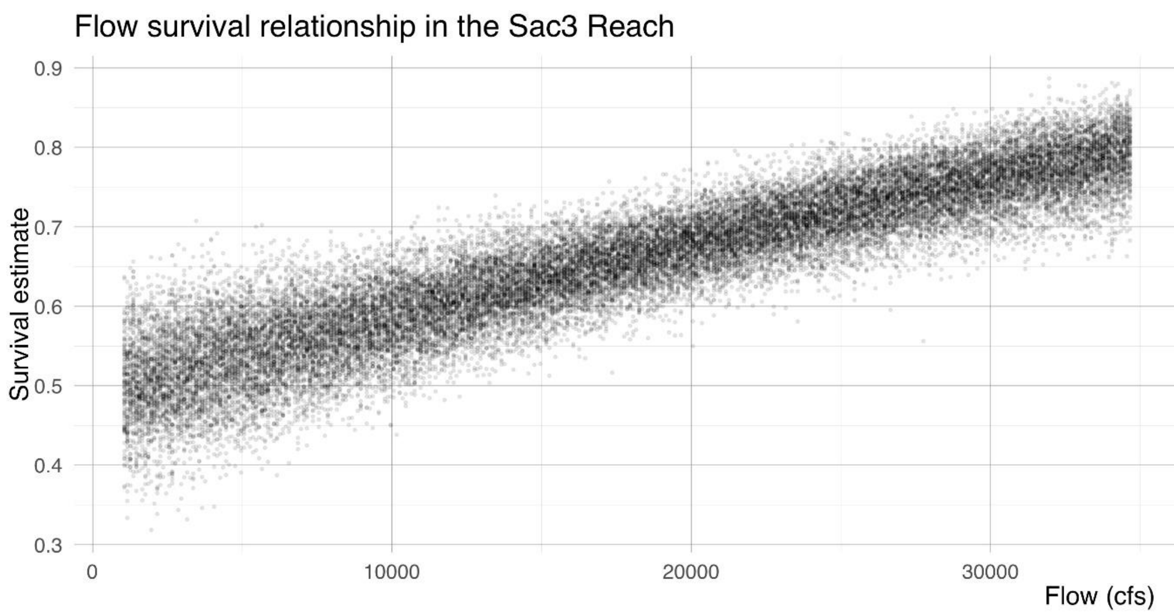


Figure X. Relationship between Sacramento River discharge and survival through the Sac 3 reach modeled with JSATS releases of multiple runs of Chinook Salmon.

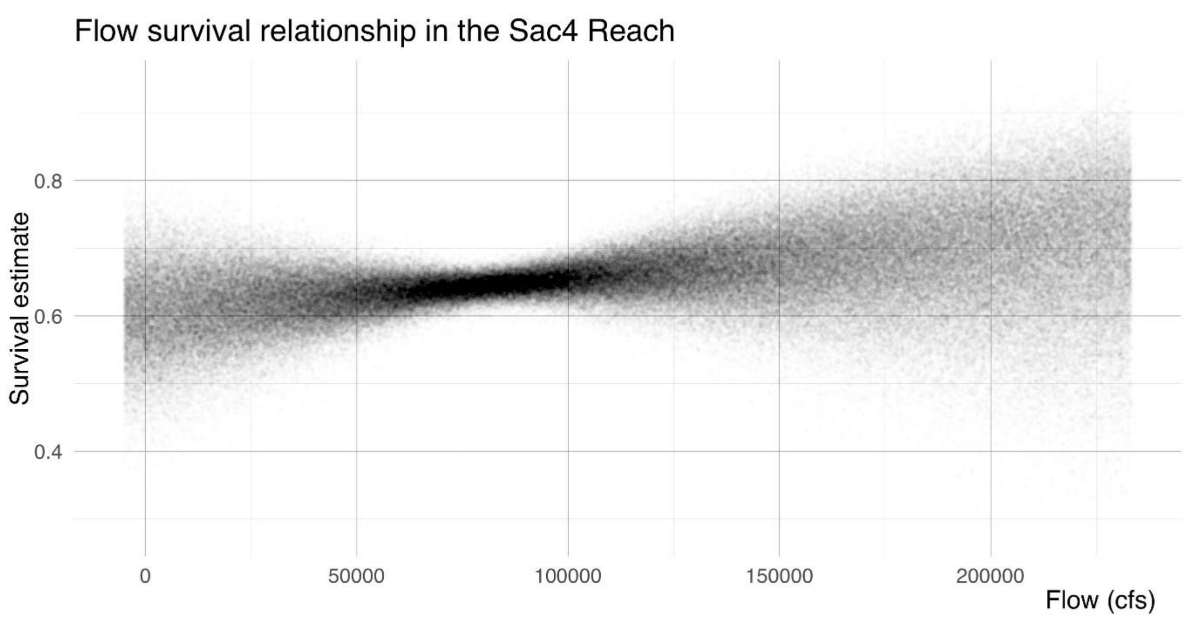


Figure X. Relationship between Sacramento River discharge and survival through the Sac 4 reach modeled with JSATS releases of multiple runs of Chinook Salmon.

Export-Dependent Survival

An export-survival relationship was tested for fish entering the interior Delta from the Mokelumne River and Georgiana Slough. Hydrodynamic data for exports covering the period of JSATS detection data

(2013 – 2019) was queried from Dayflow (https://data.cnra.ca.gov/dataset/dayflow/resource/21c377fe-53b8-4bd6-9e1f-2025221be095). A model that included exports and Freeport flow was also tested. Exports observed over the data period ranged from 1038 – 14650 cfs. For the Interior Delta route, the export value (in cfs) on the day the fish enters the reach and the effect of exports from the JSATs model is used to predict survival through the entire reach, even if migration through the reach takes place over more than one day.

For the model that included exports only, the coefficient for the export effect was positive and well-supported indicating higher survival probabilities with greater exports. In the model including both exports and flow, the export coefficient remained positive but was not well supported with a mean effect that included zero in the distribution. This positive effect of exports may seem contradictory based on coded wire tag studies used in the previous model version that includes a weak, yet negative effect (Newman and Brandes 2010). The effect of exports on Sacramento River-origin Chinook Salmon was a source of uncertainty identified in the previous version. Hydrodynamic analysis indicates that there is little effect of exports on hydrodynamics in the Sacramento River (Cavallo et al. 2015) and only fish entering the interior Delta, and the Old-Middle River corridor specifically, are likely to be exposed to the hydrodynamic effects of exports (BOR 2019). Previous studies of export effects relied on the relative survival of coded wire tagged salmon released into Georgiana Slough relative to the Sacramento River (Newman and Brandes 2010). Thus, export effects in the coded wire tag studies are not directly estimated for fish in the area of interest. In previous workshops and comments, it was suggested that modeling potential effects of exports on individually tagged fish would be a superior approach. The JSATS data analyzed here represents the best data set available and covers a wide range of export conditions. Thus, the data strongly suggest the absence of a negative effect of exports on survival of Sacramento River-origin Chinook Salmon that enter the interior Delta.

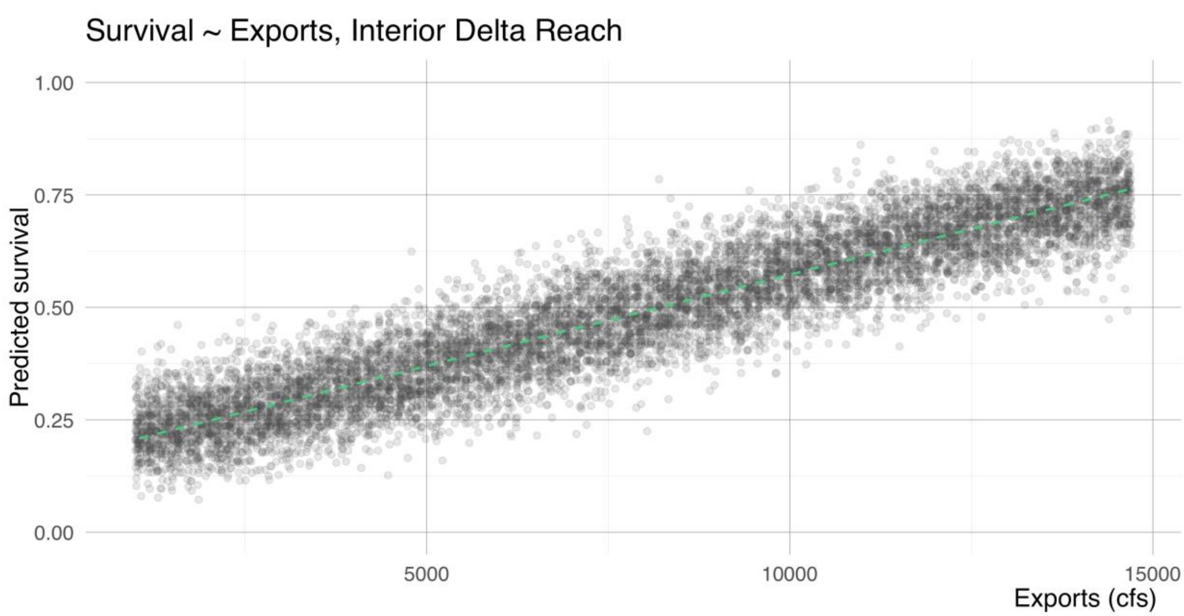


Figure X. Relationship between exports and survival of JSATS tagged juvenile Chinook salmon. The coefficient for the effect of exports was well-supported with a credible interval that did not include zero.

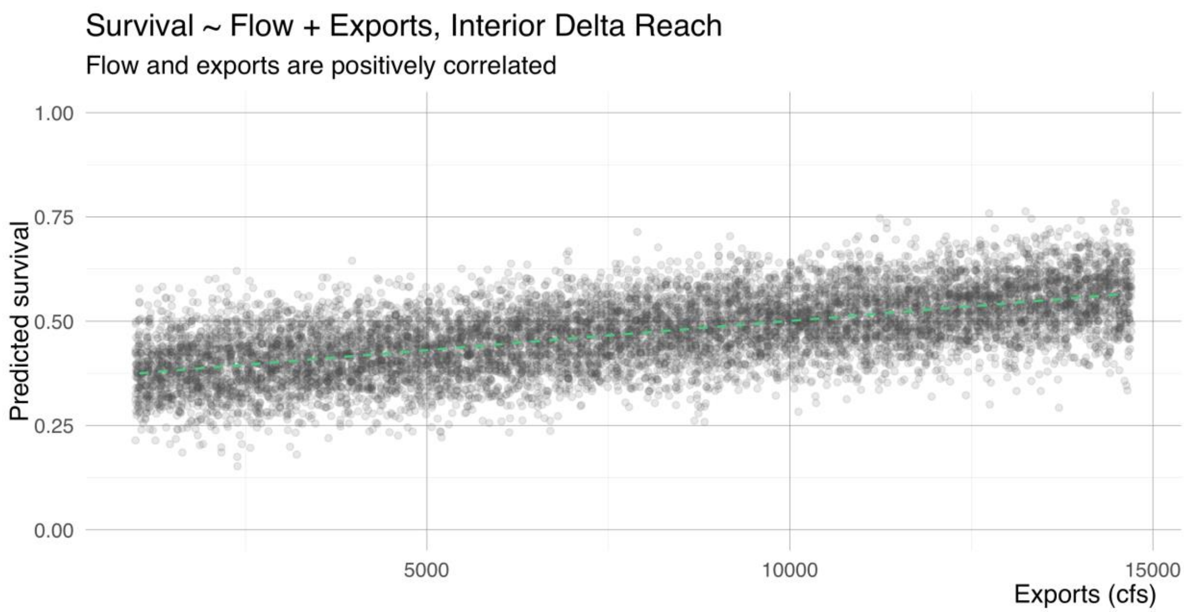


Figure X. Relationship between exports and survival of JSATS tagged juvenile Chinook salmon with Freeport flow was held at the mean value. When flow is included in the model, the effect of exports on survival remains positive but is no longer well-supported.

Acknowledgements

This update would not have been possible without the generous cooperation of multiple researchers that allowed us to analyze their JSAT tag detections. Specifically, Arnold Ammann, Cyril Michel, Jeremy Notch, and Flora Cordoleani provided access to their transmitter and receiver data.

Literature cited

Berggren, T. J., and M. J. Filardo. 1993. An Analysis of Variables Influencing the Migration of Juvenile Salmonids in the Columbia River Basin. North American Journal of Fisheries Management 13(1):48–63.

Blake, A. and M. J. Horn. 2003. Acoustic Tracking of Juvenile Chinook Salmon Movement in the Vicinity of the Delta Cross Channel, Sacramento River, California – 2001 Study Results. Prepared for U.S. Geological Survey and SRI International.

Brandes, P. L., and J. S. McLain. 2001. Juvenile Chinook Salmon Abundance, Distribution, and Survival in the Sacramento-San Joaquin Estuary. Pages 39–95 in Contributions to the Biology of Central Valley Salmonids. Fish Bulletin 179:2. Available: <http://escholarship.org/uc/item/6sd4z5b2>.

Cavallo, B., P. Gaskill, J. Melgo, and S. C. Zeug. 2015. Predicting juvenile Chinook Salmon routing in riverine and tidal channels of a freshwater estuary. Environmental Biology of Fishes 98(6):1571-1582.

Healey, M. C. 1980. Utilization of the Nanaimo River Estuary by Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*). U.S. National Marine Fisheries Service Fishery Bulletin 77:653–668.

Healey, M. C. and F. P. Jordan. 1982. Observations on Juvenile Chum and Chinook and Spawning Chinook in the Nanaimo River, British Columbia, during 1975-1981. Canada Manuscript Report of Fisheries and Aquatic Sciences 1659:4.

Miller, J. A., A. Gray, and J. Merz. 2010. Quantifying the Contribution of Juvenile Migratory Phenotypes in a Population of Chinook Salmon *Oncorhynchus tshawytscha*. Marine Ecology Progress Series 408:227–240.

Moyle, P. B. 2002. Inland Fishes of California, Revised and Expanded. Berkeley: University of California Press.

Newman, K. B., and P. L. Brandes. 2010. Hierarchical modeling of juvenile Chinook salmon survival as a function of Sacramento-San Joaquin Delta water exports. North American Journal of Fisheries Management 30:157–169.

Perry, R. W. 2010. Survival and Migration Dynamics of Juvenile Chinook Salmon (*Oncorhynchus tshawytscha*) in the Sacramento-San Joaquin River Delta. Ph.D. Dissertation. University of Washington, Seattle, WA.

Plumb, J. M., N. S. Adams, R. W. Perry, C. M. Holbrook, J. G. Romine, A. R. Blake, and J. R. Burau. 2015. Diel Activity Patterns of Juvenile Late Fall-run Chinook Salmon with Implications for Operation of a Gated Water Diversion in the Sacramento–San Joaquin River Delta. River Research and Applications. DOI: 10.1002/rra.2885.

R Core Team. 2012. R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. Available: <http://www.R-project.org>.

Raymond, H. L. 1968. Migration Rates of Yearling Chinook Salmon in Relation to Flows and Impoundments in the Columbia and Snake Rivers. Transactions of the American Fisheries Society 97:356–359.

Schreck, C. B., J. C. Snelling, R. E. Ewing, C. S. Bradford, L. E. Davis, and C. H. Slater. 1994. Migratory Characteristics of Juvenile Spring Chinook Salmon in the Willamette River. Completion Report. Bonneville Power Administration.

Sommer, T. R., W. C. Harrell, and M. L. Nobriga. 2005. Habitat Use and Stranding Risk of Juvenile Chinook Salmon on a Seasonal Floodplain. North American Journal of Fisheries Management 25:1493–1504.

Williams, J. G. 2001. Chinook Salmon in the Lower American River, California's Largest Urban Stream. Pages 1–37 in R. Brown (ed.). Contributions to the Biology of Anadromous Salmonids of the Central Valley, California. Fish Bulletin 179:2. Sacramento: California Department of Fish and Game.