SacPAS Fish Model

Version 3.1

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Models, User's Guide, and Example Results & Interpretations

SacPAS Fish Model
A set of models for Sacramento River Winter-Run Chinook Salmon and other salmon runs: spawned egg to emerged fry, and juvenile migration and survival to the Delta

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1 Background

Decision support modeling (DSM) tools can be powerful tools to help with river and fish management decisions pre-season and in-season. The SacPAS Fish Model is a DSM tool, available online (https://www.cbr.washington.edu/sacramento/fishmodel/), that provides access to the data and models on juvenile salmon survival and migration in the Sacramento River and Sacramento-San Joaquin River Delta.

Management of river conditions and endangered salmon species is particularly important in the upper Sacramento River. Temperature-dependent mortality (TDM) is particularly important to prevent for Winter-Run Chinook salmon (*Oncorhynchus tshawytscha*), which evolved to have egg and fry-rearing life history stages in late spring and early summer (May through August) when snowmelt from Mt. Shasta had cooler temperatures than present day because of Shasta Dam (construction 1938-1945) and Keswick Dam (construction 1941-1950). Water management in the upper Sacramento River during the summer are primarily temperature control, instream demands, Delta outflows, and exports (NMFS 2019a). In the fall, providing sufficient cool river temperature and water for spawning habitat is important. To help target sufficiently cool water during the incubation period of Chinook salmon eggs and pre-emergent fry and water for other current and future uses, a tiered approach is part of the proposed action (NMFS 2019a). Tier 1 targets 53.5°F or lower starting May 15; Tier 2 targets 53.5°F during the critical eff incubation period; Tier 3 targets 53.5–56°F during the critical egg incubation period; and Tier 4 targets 56°F or higher. With forecasted river temperature data, scenario-based data, and real-time data inputted into various models accessible online, users can explore and compare predicted TDM. Other phenomena that occur that impact the successful survival of fish in the river include redd dewatering, river migration rate to and through the Sacramento-San Joaquin River Delta, as well as routing through the Delta. River flow, floods, and temperature can affect migration rate and routing, travel time and ultimately survival. With data on river conditions, operations, and parameters input into various models accessible online, users can explore and compare predicted passage timing, routing, and survival.

The goals of the manual for SacPAS Fish Model version 3.0 were to document what currently existed in the online DSM tool in version 2.8.1 and provide a new graphical user interface (GUI) that is more accessible than what was in that version (Appendix 1 and Appendix 2). The updates for version 3.1 are mainly to reintroduce some customized options for users in the input consoles that were not available in version 3.0. Model calibration and refinement of the models and the GUI are ongoing, and will be updated in future versions of SacPAS Fish Model.

2 Overview of SacPAS Fish Model

The **SacPAS Fish Model** (https://www.cbr.washington.edu/sacramento/fishmodel/) offers a web interface to multiple, interconnected models for Sacramento River Chinook salmon (Figure 1). Predictions of salmon responses (hindcasts and hypothetical scenarios) are possible with the use of historical data, real-time data, and user-specified data (e.g., alternative scenarios).

Egg-to-Fry Modeling is the first modeling tool under the SacPAS Fish Model. The online tool includes various temperature-dependent mortality models, egg-to-emergence timing models, density-dependent models, and a redd dewatering model. It can include historical data, current/forecasted data, and user-specified data. The interface can be used in three different settings (Basic, Intermediate, and Full).

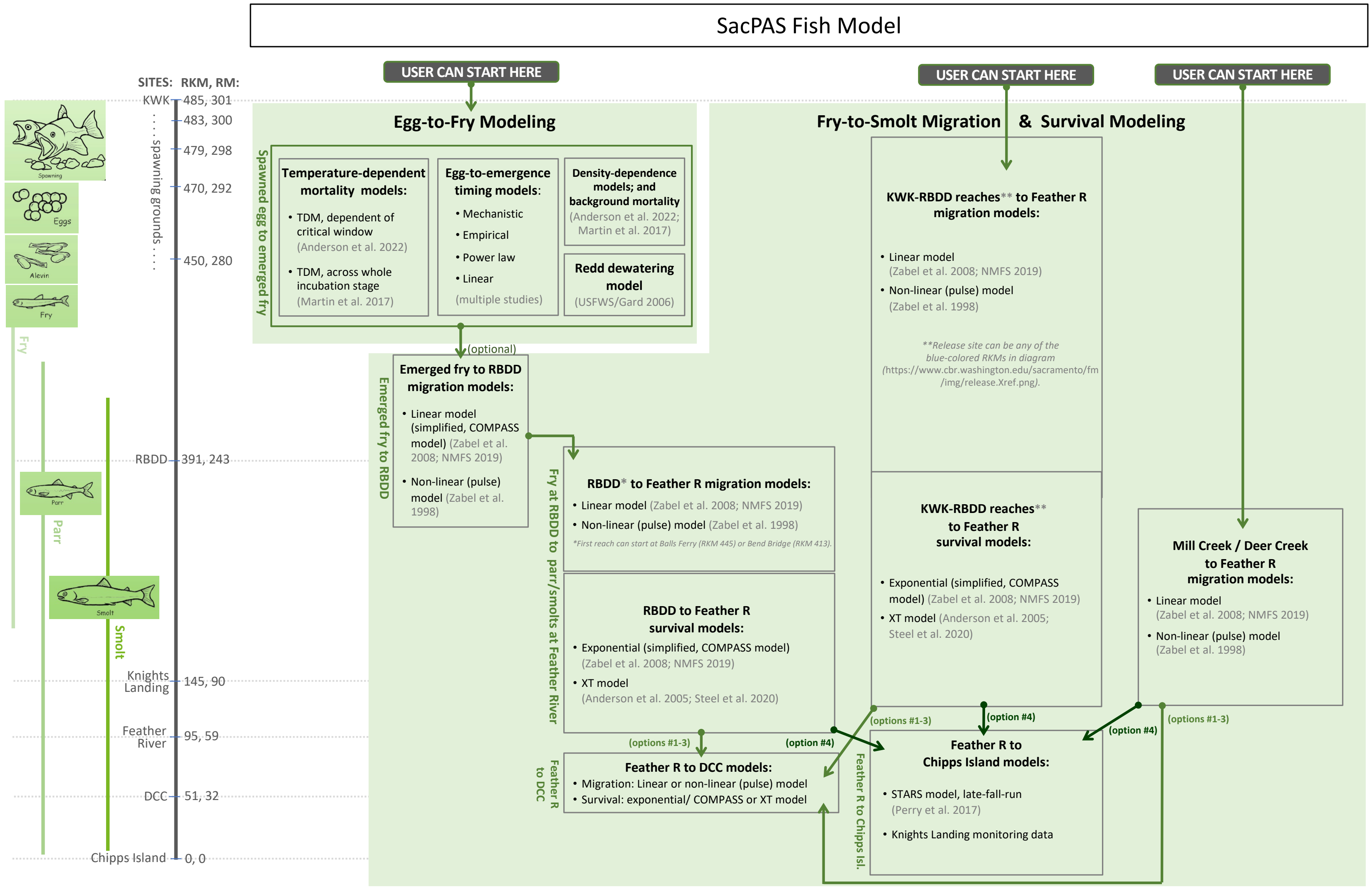
Migration and Survival Modeling is the second modeling tool under the SacPAS Fish Model. This online tool includes several models that can include input data from the Egg-to-Fry Modeling tool, historical data, and user-specified data.

This manual is organized into three main sections:

- **Section 3. Models:** summarizes background on the models for survival and migration that are included in SacPAS Fish Model, divided by three main groupings of life stages and reaches: Egg-to-Fry modeling from redds to Red Bluff Diversion Dam (RBDD); River Migration and Survival modeling from RBDD to Feather River; and River Migration and Survival from Feather River to the Sacramento and San Joaquin River Delta. This section includes model equations, study references, and how the models are adapted for and interconnected in SacPAS Fish Model.

- **Section 4. User's Guide**: provides user guidelines and tips for using the online tools, including screenshots of the SacPAS Fish Model online tools. Screenshots of some results are included so that users know what to expect as outputs.

- **Section 5. Example Results and Interpretations:** shares some results to demonstrate possible outputs, ways to interpretate the results, and sensitivity analyses. It includes comparisons of output results from different year types based on the Hydrological Classification Indices, from Anderson et al. (2022) vs. Martin et al. (2017) model, conditions when flow does not affect survival in the XT model (Anderson et al. 2005), and comparisons of survival and travel time of migration down the Sacramento River between the COMPASS model (Zabel et al. 2008) and the XT model.



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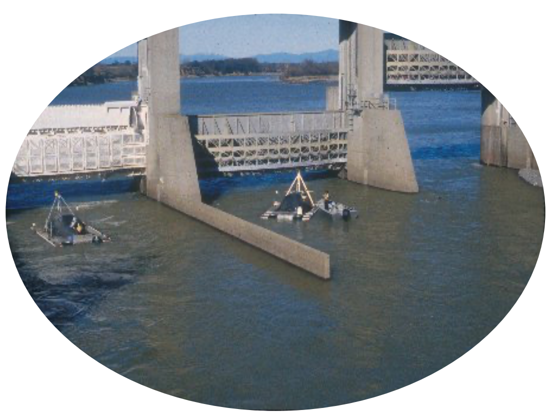
3 MODELS Section

3.1 Egg-to-Fry Model (Redds to RBDD)

Life history stages from spawned egg to fry/smolt passage at Red Bluff Diversion Dam



3.1.1 Survival Models

Temperature-dependent, density-dependent, background mortality

3.1.1.1 Anderson et al. 2022 model:

Population egg incubation survival (*S_j*) is: $S_j = \frac{B}{A_j}\sum_{i=1}^{A_j} U_{i,j}\, V_{i,j}$

where *B* is the background survival, A_j is the total number of redds (Box 1) in year *j*, $U_{i,j}$ is the density-dependent survival for redd *i* in year *j*, and $V_{i,j}$ is the temperature-dependent survival within a critical thermal window for redd *i* and year *j*.

Background mortality (BGM; or the complement of background survival) is from when fry emerge from redds to when fry/smolts pass RBDD, and is mainly characterizing predation on fry after emergence and prior to detection downstream. It is assumed constant for all years and all redds, as that is how the parameter was estimated in the model calibration (Anderson et al. 2022).

Density-dependent survival (U_i) is adapted from the Beverton-Holt model and is: $U_i = \frac{1}{1+\frac{\rho_i}{D}}$

where ρ_i designates the density of redds surrounding redd *i* and is calculated for each river reach segment by dividing the number of redds in a reach by its river length (km), and *D* represents the carrying capacity.

Temperature-dependent survival (V_i) within critical window is: $V_i = \exp\left(-b_\delta \sum_{Y_i-\delta}^{Y_i} \Delta_{y_i}\right)$

where b_δ is the thermal mortality rate per degree day (1/°C·d) for redd *i* in the critical thermal window δ (days), and Δ_{y_i} is the temperature differential at the embryo age *y* (days) in redd *i*, from the day when the critical window starts ($Y_i - \delta$) to the age of the embryo when the critical window ends (Y_i) for redd *i*.

Additional model details:
The b_δ temperature-dependent survival rate per degree day is assumed to be $\boldsymbol{\alpha}$ **intrinsic mortality rate** (1/°C) in the days of δ critical thermal window as follows: $b_\delta = \alpha/\delta$.

The **embryo age** at end of critical window is $ATU_Y = \sum_0^{Y_i} T_{y,i}$, while the ATU at the beginning of the critical thermal window is $ATU_0 = ATU_Y - \bar{T}_\delta \delta$, and at the middle of the critical thermal window is $ATU_Y = \sum_0^{Y_i} T_{y,i}$, where $\bar{T}_\delta$ is the mean temperature over and the δ critical thermal window.

The **core concept within temperature-dependent mortality is hypoxia** that occurs during the critical thermal window: $\gamma = y_H - y_F = \frac{ATU_H}{T-c_H} - \exp\,(\log F - a_R - c_R \log T)/b_R$, where y_H is the age at hatching, y_F is the age when the egg membrane oxygen flux (µg O_2/h) occurs, ATU_H is the ATU at hatching in degree days, *T* is the temperature, c_H is the hatch adjustment factor, and a_R, b_R, c_R are respiration coefficients (Anderson et al. 2022).

SacPAS Egg-to-Fry input data handling: For additional details on how SacPAS Egg-to-Fry Model incorporates and handles input data: to compute the spatiotemporal distribution of redds from carcass survey data, see Box 2; for prospective modeling of the seasonal and spatial distributions of redds with river temperatures, see Box 3; and for redd dewatering, see Box 4.

3.1.1.2 Martin et al. 2017 model:

The model from Anderson et al. (2022) was fashioned after that from Martin et al. (2017), and thus these two models are similar in many ways. One major difference is that $V_{i,j}$ temperature-dependent survival in Martin et al. (2017) is the temperature-dependent survival during incubation for redd *i* and year *j* across the whole incubation period and not only during a critical thermal window before egg hatching, as it is in Anderson et al. (2022). Another difference is in how density-dependent survival is handled in the model.

Temperature-dependent survival (V_i) during the incubation period is:

$$V_i = \exp\left(-b \sum_{y=0}^{y=Y} \max\left(T_{y,i} - T_{crit}, 0\right)\right)$$

where b is the thermal mortality rate per degree per day (°C^{-1}·d^{-1}) for redd *i* during the incubation period $T_{y,i}$ is the temperature on the day when the embryo is age *y* (days) in redd *i*, T_{crit} is the temperature above which temperature-dependent mortality occurs.

Density-dependent survival (U_i) is adapted from the Beverton-Holt model and is: $U_i = \frac{U_0}{1+\frac{A_j}{D}}$

where U_0 designates the density-dependent survival, A_j is the total number of redds in year *j*, and *D* represents the carrying capacity as the total female spawner abundance (assumed as redds in SacPAS Fish Model).

3.1.2 Migration models

The migration model is applied from when fry emerge from redds (RKM 486, 479, 470, and 450 for winter-run Chinook salmon) to when they passage Red Bluff Diversion Dam (RKM 395).

Egg-to-Fry model outputs can be used to initiate migration modeling. The distribution of emergence timing at each location computed by the Egg-to-Fry model becomes a release of fish for downstream movement. The initial release points are at the locations of the redds. Fish movement is modeled as a function of river velocity computed from flow which can vary along the length of the river on a reach-by-reach basis.

There are two migration models that can be applied: the linear migration rate model and the non-linear (pulse-flow) migration rate model.

3.1.2.1 Linear migration model

The model is a modified, simplified, linear version of the Comprehensive Passage (COMPASS) migration model (Zabel and Anderson 1997, Zabel et al. 2008, NMFS 2019b).

The model to estimate the mean migration rate (r) for the distribution of migrants in the cohort, defined by their occurrence in reach j and timestep t, is:

$$r_{j,t} = \beta_0 + \beta_1 \bar{V}_j \qquad \text{Eq. 1}$$

where β_0 is the intercept, and β_1 is the slope parameter (default = 0.05) associated with the average river velocity $\bar{V}_j$ over timestep t.

3.1.2.2 Non-linear (pulse-flow) migration model

The non-linear (or pulse-flow) migration rate (or fish velocity) model, adapted from Zabel et al. (1998), is:

$$r_{j,t} = \beta_0 + \beta_1 \bar{V} \left[\frac{1}{1+\exp\left(-\alpha_1(Q-Q_{crit})-\alpha_2(D-D_{crit}\right)}\right] + \varepsilon \qquad \text{Eq. 2}$$

where β_0 is the intercept and β_1 determines the proportion of the river velocity $\bar{V}$ used for downstream migration. The non-linear portion of the model involves α_1 slope parameter that determines response of velocity with flow Q relative to critical flow Q_{crit}, below which fish migration velocity is less influenced by flow, and above which it is more influenced by flow (i.e., the pulse-flow migration). Similarly, α_2 slope parameter determines the response of fish velocity to migration day D where the effects on velocity are stronger after the critical day D_{crit}. The population's migration rate is a distribution with $r_{j,t}$ mean and $s_{j,t}$ variance for spread in the migration rate. The default values in the online tool are: β_0=1.0, β_1=0.5, α_1=0.8, Q_{crit}=11 kcfs, α_2=0.04, D_{crit}=350, and s (or Fish_velocity variance) = 50 (see Box 5 in the section 3.2 for information on calibration of juvenile fish migration and these default values).

Box 1. Computing time to hatching

Time to hatching is based on the exposure of the eggs to daily temperatures. There are two available methods for this: 1) accumulated temperature units (ATUs), and 2) cumulative percentage of development.

ATU Method: Temperature units are accumulated on a daily basis. After reaching the specified value, the egg hatches. The default value for the Egg-to-Fry Model is 400 ATUs from fertilization to hatching. This can be changed by the user. Hatching is approximately halfway through the egg development period.

Cumulative Percentage of Development Method: A given temperature results in a small percentage increase in development. When the accumulated percentage is 100%, that day is the hatching day. The daily accumulated percentage formula is based on an equation from Běhrádek (1930) in log-inverse form: $\ln(p) = \ln(k) + b(\ln(t-c))$, where *P* is the daily development rate and *t* is the daily temperature. The model parameters used are from a study (Alderdice and Velsen 1978) drawing from several other studies (Wallich 1901, Donaldson 1955, Seymour 1956, Burrows 1963, Silver et al. 1963) and unpublished data and personal communications from Griffioen, Harvey, Velsen and Alderice, as cited in Alderdice and Velsen (1978) that determined the parameter values as follows: *k* = 0.08646, *b* = 1.23473, and *c* = –2.26721.

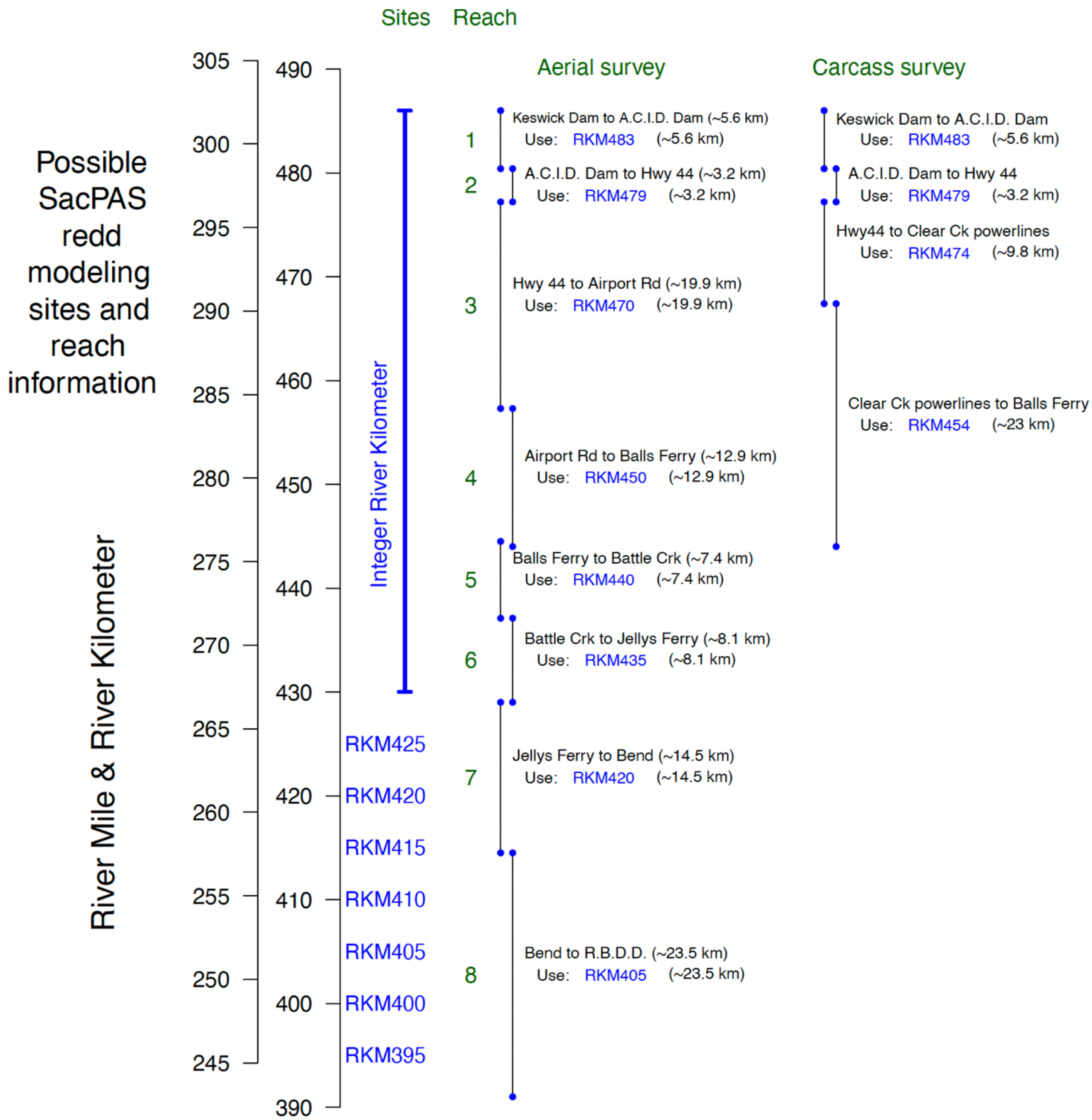


Figure 2. Sites (blue dots) and reaches (lines between blue dots) associated with aerial and carcass surveys (Killam 2023) for Winter-Run Chinook Salmon redds modeling in the Egg-to-Fry Model. Diagram is also available at: https://www.cbr.washington.edu/sacramento/fm/img/spawning.Xref.png.

Box 2. Computing the spatiotemporal distribution of redds from carcass survey data for input to the Egg-to-Fry model

Knowing where and when WRCS redds occur is important for evaluating the susceptibility of the eggs to temperature-dependent mortality. The redds are distributed from below Keswick Dam to as far downstream as Red Bluff Diversion Dam and are referenced by river reaches (Figure 2) in the Egg-to-Fry model. The WRCS spawning season is generally May through July.

The spatiotemporal distribution of WRCS redds are referenced with two methods: 1) direct observations from aerial surveys (Killam 2023), and 2) expanded estimates from carcass surveys and Cormack-Jolly-Seber mark-recapture modeling (Killam 2023). Since 1981, annual aerial surveys of the spawning grounds have been conducted across eight reaches extending from around Red Bluff Diversion Dam to upstream to Keswick Dam (Figure 2). While aerial surveys are a rapid method of surveying an extended area, accurate counts can be hampered by high flows, turbidity, and bad weather. Carcass surveys began almost a decade later, in 2000, and with a change in methods in 2004. The carcass surveys cover four upper reaches of the Sacramento River and the expanded estimates from the carcass surveys are used for computing the spatiotemporal distribution of redds as inputs to the SacPAS Egg-to-Fry model.

Estimating redd distributions from carcass data involves six steps. The first two steps are based on CDFW methods for enumerating spatial distribution (Doug Killam, CDFW, *pers. comm.* 1 October 2021). The next three steps are used to obtain the temporal distribution. The final step associates the redds with a specific location.

Step 1: Start with preliminary counts by reach. The fresh female spawners (FFS) in each of the four carcass survey reaches (R = 1, 2, 3, or 4; Figure 2) on each day (D) are counted. Each single redd from the aerial survey is attributed to each spawner by reach and day ($FFS_{R,D}$).

Step 2: Adjust counts to account for drift across reaches. Because carcasses drift downstream with the river flow from their initial redd locations, the actual redd location associated with each carcass is estimated by adjusting the number of S_R, by a set of downstream drift fractions, $f_{m,n}$, which are the fraction of S_R carcasses tagged in reach *m* and captured in downstream reach *n* (Table 1).

Table 1. Fraction of fresh female spawners (FFS) that drifted downstream ($f_{m,n}$) from reach m, where they were tagged, to reach n, where they were recaptured. These estimates were determined from carcass survey data in years 2012-2021 (Doug Killam, CDFW, *pers. comm.* 1 October 2021).

	Tagged in:			
Recaptured in:	**Reach 1**	**Reach 2**	**Reach 3**	**Reach 4**
Reach 1	$f_{1,1}$ = 86.8%	-	-	-
Reach 2	$f_{1,2}$ = 11.8%	$f_{2,2}$ = 77.8%	-	-
Reach 3	$f_{1,3}$ = 1.2%	$f_{2,3}$ = 21.3%	$f_{3,3}$ = 96.5%	-
Reach 4	$f_{1,4}$ = 0.2%	$f_{2,4}$ = 0.9%	$f_{3,4}$ = 3.5%	$f_{4,4}$ = 100.0%

Box 2. (*continued*)

The adjusted number of spawners in each reach (A_R) is computed with FFS_R and the $f_{m,n}$ fractions, as follows:

$$\hat{A}_1 = \frac{FFS_1}{1-(f_{1,2}+f_{1,3}+f_{1,4})} \quad \text{(Eq. 3.1)}$$

$$\hat{A}_2 = \frac{FFS_2-\hat{A}_1 f_{1,2}}{1-(f_{2,3}+f_{2,4})} \quad \text{(Eq. 3.2)}$$

$$\hat{A}_3 = \frac{FFS_3-(\hat{A}_1 f_{1,3}+\hat{A}_1 f_{2,3})}{1-f_{3,4}} \quad \text{(Eq. 3.3)}$$

$$\hat{A}_4 = FFS_4 - (\hat{A}_1 f_{1,4} + \hat{A}_2 f_{2,4} + \hat{A}_3 f_{3,4}) \quad \text{(Eq. 3.4)}$$

If $A_R < 0$, then $A_R = 0$, which has occurred for A_3 and A_4 in some years.

Step 3: Determine preliminary temporal distribution of counts by reach. The estimated adjusted values in each reach on each day ($\hat{A}_{R,D}$) are distributed in time by the proportions $\left(\frac{FFS_{D,R}}{FFS_R}\right)$ for each survey day (*D*), as follows:

$$\hat{A}_{R,D} = \hat{A}_R \left(\frac{FFS_{D,R}}{FFS_R}\right) \quad \text{Eq. 4}$$

Thus, the proportions of A_R associated with each survey date are the same as those for FFS_R.

Step 4: Re-allocate fractional spawners. In practice Eq. 4 generates fractional spawners and they are adjusted with the following process:

Step 4.1. Where any estimate of $\hat{A}_{D,R}$ is greater than 0, designate $\hat{A}^*_{D,R}$ = $\hat{A}_{D,R}$ and then round to the nearest integer (rounded estimate symbolized by the asterisk).

Step 4.2. Calculate the remainder from $\hat{A}_{D,R} - \hat{A}^*_{D,R}$ and add the remainder to $\hat{A}_{D+1,R}$.

Step 4.3. Repeat steps 4.1 and 4.2 for each survey day *D* in consecutive order for each reach *R*. If $\hat{A}_{D,R} = 0$ on any particular day *D*, then $\hat{A}_{D,R}$ remains 0.

Step 5: Determine date of redd creation. The date of redd creation is computed by assuming that 7 days passed between the actual redd creation date and the carcass observation date. The number of redds created in reach *R* on day *D* is:

$$Redds_{R,D} = A_{R,D-7} \quad \text{Eq. 5}$$

Small discrepancies each year occur between the total estimates of $\sum_{R=1}^{R=4} A_R$ and $\sum_{R=1}^{R=4} FFS_R$ because adjusted reach counts less than zero are ignored (Step 2), and the timing adjustment (Step 4) ignores any fractional values after the survey period. The annual discrepancies in counts from 2004–2023 ranged from -1 to 23 redds, with a median of 4.5.

Step 6: Assign river location and associated river temperature. The group of redds created on the same day and in the same reach is termed a cohort. The modeling locations for cohorts are predefined within the carcass survey reaches (Figure 2), and the RKM location in the center of each reach is used to associate with temperature data.

Box 3. Prospective modeling of the seasonal and spatial distributions of redds with river temperatures

Prospective modeling of the seasonal distribution of WRCS redds is based on the study by Dusek Jennings and Hendrix (2020), which differs from retrospective modeling of the spatiotemporal distributions of redds (Box 2). Although both methods use the data from the seasonal carcass monitoring program (Killam 2023), the prospective modeling uses a proportional-odds logistic regression of April and May river temperatures to predict spawn timing at a 10-day temporal resolution. The model parameters determined in the study (Dusek Jennings and Hendrix 2020) are used in SacPAS Egg-to-Fry modeling.

In this Dusek Jennings and Hendrix (2020) study, the spatial distribution was not included because the variation in temperatures across the river locations is relatively small compared to the variation in temperatures across the season. For example, in 2022, 98% of the redds observed in the aerial survey were within 9 km of the Keswick dam (Killam 2023). Spawning is generally observed April–August, mostly occurs May–July, and peaks for over a month, mostly in July (Dusek Jennings and Hendrix 2020). During the spawning season April – August in 2020 temperatures ranged from 49 to 54 °F at the KWK gage while differences in temperatures between the KWK (RKM483) and SAC (RKM479) gages ranged from 0.1 – 1.1 °F. Nonetheless, in the SacPAS Egg-to-Fry model, a proportional-odds logistic regression is applied to the spatial data to predict RKM locations of spawning with river temperature data.

Predicting the temporal distribution of spawn timing (Dusek Jennings and Hendrix 2020). The probability of an event Y of an individual i spawning on boundary day j or earlier, on the logit scale, is:

$$\text{logit}\left(p\left(Y_{i,t} \leq j\right)\right) = \alpha_j - \beta_{Apr}Apr_t - \beta_{May}May_t \qquad \text{Eq. 6}$$

where α_j is the intercept and the slope coefficients β_{Apr} and β_{May} (Table 2) are applied to standardized, monthly mean river temperatures Apr_t and May_t in year t.

Predicting the spatial distribution of spawn timing. The probability of individual $\boldsymbol{i}$ spawning event Y at or upstream of RKM k, on the logit scale, is:

$$\text{logit}\left(p\left(Y_{i,t} \leq k\right)\right) = \varphi_k - \gamma_{Apr}Apr_t \qquad \text{Eq. 7}$$

where φ_k is the intercept and the slope coefficient γ_{Apr} (Table 3) is the effect associated with the mean Apr_t river temperatures in year t. Four reaches are modeled: upper reach (Keswick Dam to Anderson-Cottonwood Irrigation District [ACID] Dam), middle reach (ACID Dam to Hwy 44), lower reach (Hwy 44 to Airport Road), and bottom reach (Airport Road to Balls Ferry). Note the model includes only Apr_t because it was the only monthly temperature that was a significant predictor of spawning.

The predictive modeling for the spatial and temporal spawning distributions are done independently, with the seasonal distribution computed first and the spatial distribution computed second.

Table 2. Slope coefficients of the proportional-odds logistic regression model of spawn timing (logit$\left(p\left(Y_{i,t} \leq j\right)\right) = \alpha_j - \beta_{Apr}Apr_t - \beta_{May}May_t$ Eq. 6) that includes the effects from river temperatures in April and May in years 2000-2016.

Parameter	Coefficient values	Time group	Day of year (*j*)	Date*
β_{Apr}	0.08	-	-	-
β_{May}	0.34	-	-	-
α_1	-4.00	1	135	May 15
α_2	-3.19	2	145	May 25
α_3	-2.50	3	155	June 4
α_4	-1.58	4	165	June14
α_5	-0.73	5	175	June 24
α_6	0.24	6	185	July 4
α_7	1.40	7	195	July 14
α_8	2.65	8	205	July 24
α_9	4.34	9	215	Aug 3
α_{10}	10**	10	225	Aug 13

*Date in a non-leap year.
**Inferred. Captures long tail in probability distribution.

Table 3. Slope coefficients of the proportional-odds logistic regression model of spawn timing (logit$\left(p\left(Y_{i,t} \leq k\right)\right) = \varphi_k - \gamma_{Apr}Apr_t$ Eq. 7) that includes the effects from river temperatures in April and in four reaches in years 2003-2019.

Parameter	Coefficient values	SD	t-value	Reach Location
β_{Apr}	-0.3032	0.02553	11.88	-
α_1	-0.0972	0.0245	-3.9617	Upper
α_2	1.7096	0.0332	51.5323	Middle
α_3	4.9934	0.1395	35.8017	Lower
α_4	10**			Bottom

**Inferred. Captures long tail in probability distribution.

Box 4. Redd dewatering mortality

Redd dewatering is a concern when river flow during the incubation period is less than the flow at the time of spawning. Fluctuations in flow increases the risk of mortality during the incubation period of salmon eggs and pre-emergent fry. Conditions that influence the risk of mortality during the salmon incubation period in the upper Sacramento River include: 1) Maximum drop in flow between spawning and emergence; 2) Configuration of the Anderson Cottonwood Irrigation District (ACID) dam which can have "boards in" or "boards out" which indicates the positions of gates that affect water-levels upstream; and 3) Run of Chinook salmon (Fall, Late-Fall, or Winter) due to inter-specific differences in spawning behavior (e.g. variability in egg-pocket depth).

To estimate redd dewatering mortality in as part of SacPAS Egg-to-Fry modeling, the (USFWS 2006) method to predict the risk of redd dewatering is used. It involves empirical relationships with river flow and is reported in tables of percentages of redds dewatered (Appendix E in USFWS 2006). There is no closed-form expression of a function with constants and variables available to the best of our knowledge. These tables provide the percentages of redds dewatered for a specific combination of spawning flows and the minimum flow experienced during the incubation period.

The mortality from redd dewatering (i.e., $\hat{\rho}_y$ percentage of redds dewatered for cohort y) is calculated as follows:

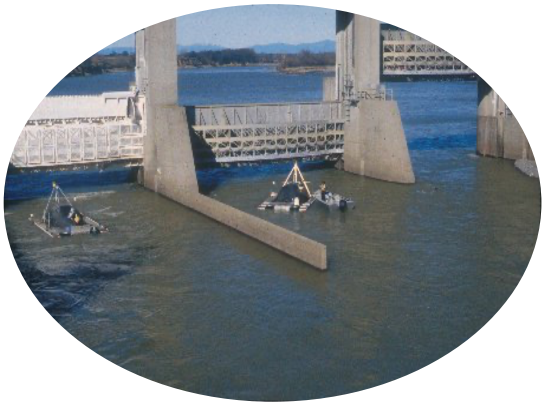
$$\hat{\rho}_y = \frac{\sum_{l=1,d=1}^{L,D}(R_{l,d} \times g_{l,d})}{\sum_{l=1,d=1}^{L,D}(R_{l,d})} \qquad \text{Eq. 8}$$

where $R_{l,d}$ is the number of redds created at location l, on day-of-year d, belonging to a particular cohort $C_{l,d}$ of redds (i.e., all redds with the same l and d values) , and $g_{l,d}$ is a pre-determined percentage of redds dewatered due to water depth and velocity from the tables in Appendix E of USFWS (2006). The value for g associated with $R_{l,d}$ is determined by looking up the relevant value based on: 1) the species (e.g., WRCS tables on p. 63-66; USFWS 2006]); 2) Anderson Cottonwood Irrigation District (ACID) Dam configuration (i.e., boards out [table on p. 63-64] or boards in [table on p. 65-66]), 3) the flow (Keswick Dam, KWK; USGS) associated with when and where the redd was created (table columns "Spawning Flow"); and 4) the minimum flow experienced by cohort $C_{l,d}$ during the incubation period from day of spawning to day of fry emergence from the redd (table rows "Dewatering Flow"). Values of initial and minimum flow were rounded downward to levels stipulated in the redd dewatering tables.

Assumptions in this method include the following: 1) A cohort of redds (i.e., redds in the same reach on the same day), experience the same environmental conditions. Thus, each redd in a cohort has identical risk of mortality from redd dewatering. 2) All cohorts of the population experience the same mortality risk from redd dewatering. 3) The mortality risk from redd dewatering is independent of the total number of redds. 4) The mortality risk from redd dewatering is identical for the entire incubation period regardless of developmental state of the eggs, alevins, and pre-emergent fry. 5) The magnitude of the minimum flow during the incubation period is necessary and sufficient for computing the risk, regardless of the duration of the Q_{MIN}. 6) Spring-run Chinook salmon mortality risk is the same as that of Winter-run Chinook salmon. 7) Any out-of-study-region redds, i.e. downstream of Battle Creek, are assumed to have the same mortality risk as their upstream counterparts for calculation of population-level dewatering mortality risk.

3.2 River Migration and Survival of Fry/Smolts (RBDD* to Feather River)

*From Redd Bluff Diversion Dam (RBDD), or
release location within Keswick Dam and RBDD, or
in Sacramento River at Deer or Mill creek confluences



Methods in this section apply to model simulations from a release location at Red Bluff Diversion Dam (RBDD; RKM 392); between Keswick Dam and RBDD at several possible locations; or downstream of RBDD on the Sacramento River at the Deer or Mill Creek confluences (Figure 3).

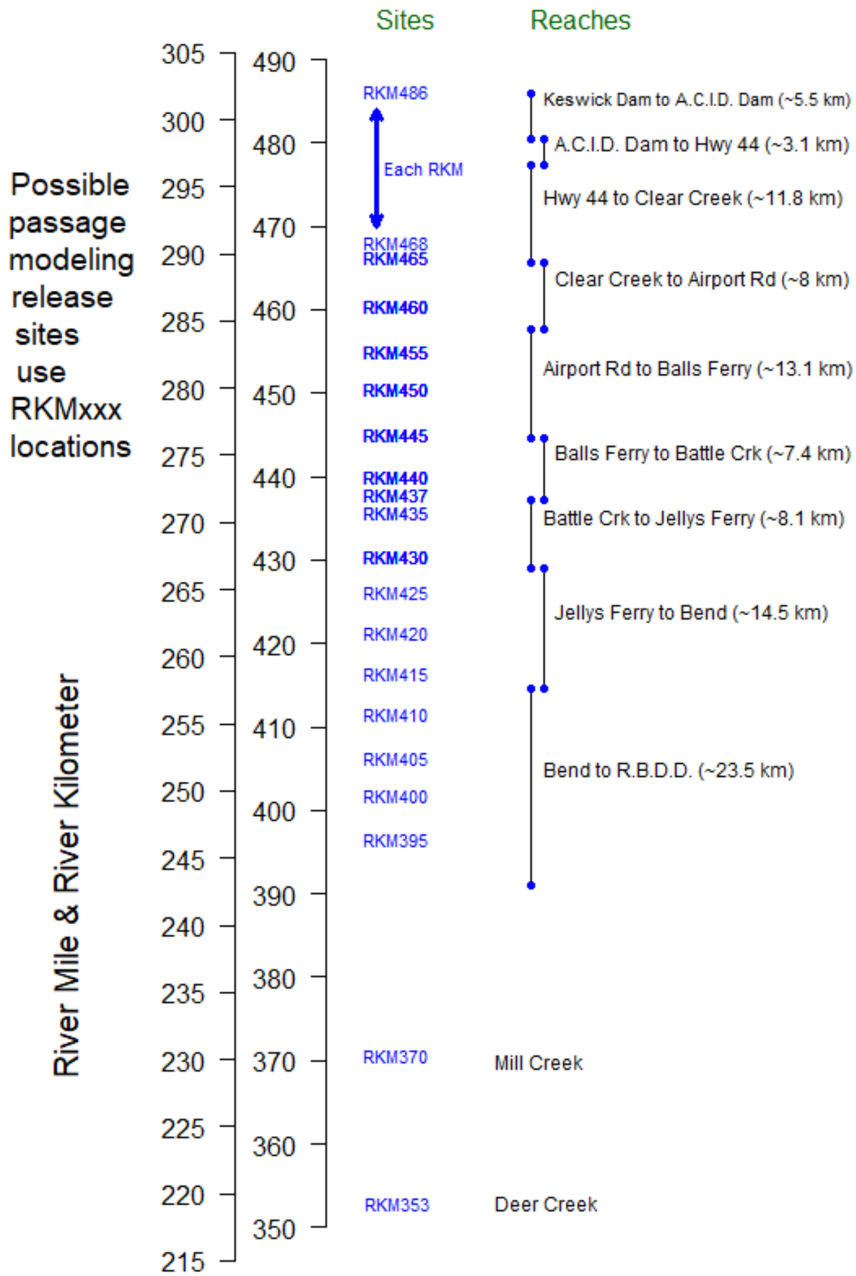


Figure 3. Release locations for modeling migration in SacPAS Fish Model. Diagram is also available at: https://www.cbr.washington.edu/sacramento/fm/img/release.Xref.png.

3.2.1 Survival Models

In SacPAS Fish Model, there are two options for survival modeling: the exponential model (Zabel et al 2008; section 3.2.1.1) and the XT model (Anderson et al. 2005; section 3.2.1.2).

3.2.1.1 Exponential (COMPASS) model

The exponential survival model is adapted from (Zabel et al. 2008, NMFS 2019b) where survival is a function of time and distance.

$$S(t,d) = \exp\left(-(r_t t + r_d d)\right) \qquad \text{Eq. 9}$$

$$\log\left(S(t,d)\right) = -(r_t t + r_d d) \qquad \text{Eq. 10}$$

with S survival rate, t time, and d distance. Survival is computed for each reach as a function of reach length and fish travel time through the reach. Behavioral and mortality parameters can be defined for each reach. The water and fish properties are computed on sub-daily time steps (currently 4 to 8 steps per day).

To gain a better understanding of the model and explore parameters, visit for the SURVDEMO Shiny app (https://www.cbr.washington.edu/shiny/SURVDEMO/) that displays the COMPASS-based survival model in black (and labeled "Base" model in the Shiny app). Default values for the parameters associated with distance and time are respectively, p_X = 0.0035 and p_T = 0.0035.

3.2.1.2 XT Model

The survival model (Anderson et al. 2005, Steel et al. 2020) as a function of distance (x) and time (t) is:

$$S = \exp\left(-\frac{1}{\lambda}\sqrt{x^2 + \omega^2 t^2}\right) \qquad \text{Eq. 11}$$

where λ is the mean length of the unconstrained path of the prey before it encounters a predator, and ω^2 is the squared mean speed (km·d^{-1}) between the predator and prey.

Survival is computed for each reach as a function of reach length and fish travel time through the reach. Behavioral and mortality parameters can be defined for each reach. The water and fish properties are computed on sub-daily time steps (currently 4 to 8 steps per day).

To gain a better understanding of the XT model and explore parameters, visit for the SURVDEMO Shiny app (https://www.cbr.washington.edu/shiny/SURVDEMO/) that displays the model and results in blue. Default values for the parameters are λ = 154km (95.7 mi) and ω = 2.3 cm s^{-1} (1.24 mi d^{-1}).

3.2.2 Migration Models

There are two migration models that can be applied: the linear migration rate model (section 3.2.2.1) and the non-linear (pulse-flow) migration rate model (section 3.2.2.2).

Either of these two migration models can be applied: as a continuation from the Egg-to-Fry model (section 3.1); at RBDD; starting at a release locations within 8 possible reaches between KWK and RBDD (Figure 3); or further downstream at a release location on the Sacramento River at the Mill Creek or the Deer Creek confluence.

3.2.2.1 Linear migration model

The linear migration model here is similar to what is described in section 3.1.2, but it is also assumed to have different migration rates above and below RBDD.

Migration rates for juvenile fish (fry, parr, and smolts) from each cohort i (i.e., cohort by reach and day) are defined as follows:

$$r_{i,up} = \beta_0 + \beta_1 \bar{V}, \qquad \text{upstream of RBDD} \qquad \text{Eq. 12.1}$$
$$r_{i,down} = \beta_0 + \beta_2 \bar{V}, \qquad \text{downstream of RBDD} \qquad \text{Eq. 12.2}$$

where β_0 is the intercept, β_1 slope parameter scales the effects of river velocity $\bar{V}$ upstream of RBDD to migration rate $r_{i,up}$, and slope parameter β_2 scales the effects of $\bar{V}$ downstream of RBDD to migration rate $r_{i,down}$. With model calibration in progress, default values of β_1 = 0.05 and β_2 = 0.07 were chosen for the online tool because they generally fit the data well.

3.2.2.2 Non-linear (pulse-flow) migration rate model

Same model as in section 3.1.2.2. For information on calibration of the Migration Model, see Box 5.

Box 5. Calibration of migration rate parameters

A more formal calibration process for the Migration Model is in progress. The default survival rate and migration rate parameters are described above in the sections: "In-river survival model" and "Migration model".

The state of the data includes indices of winter Chinook counts at various locations along the Sacramento River. Based on SacPAS data queries for: "Migration Timing and Conditions by Cohort" (see: https://www.cbr.washington.edu/sacramento/data/query_hrt.html), travel times were computed for each cohort between RBDD and the Sacramento Beach Seine trawls over the last 20 years (Table 4, Figure 4, Figure 5). Exploring the mechanisms that produce such highly variable travel time data (from 51 to 159 days) will help make the SacPAS Fish Model a better predictive tool. Note that the estimates of travel time may be based on extremely low samples, and therefore may not represent the cohort as a whole. This is an important complication when applying these data to the migration rate model. The ratio of the Sacramento Beach Seines catch index to the RBDD estimated passage varied from 0.0000019 (2020) to 0.00023 (2014) over the last 20 years.

Migration rate affects travel time from release into the Sacramento River to the Sacramento-San Joaquin River Delta and is modeled as a function of river velocity . In turn, river velocity is a function of flow, which is modeled with a power-curve relationship:

$$V = p_1 Q^{p_0} \qquad \text{Eq. 13}$$

using flow and velocity data (provided by Andrew Pike, pers. communication February 12, 2016, based on Hec-RES model, https://www.hec.usace.army.mil/software/hec-ressim/) for several locations along the length of the Sacramento River (Figure 6). Transects were grouped according to the reaches that correspond to river modeling reaches bounded by landmarks along the Sacramento River and resulted in the parameters shown in Table 5.

For a sensitivity analysis of the pulse-flow equation (Eq. 2) (in place of full calibration due to lack of data), a base set of migration parameters was chosen (β_0=1.0, β_1=0.5, α_1=0.8, Q_{crit}=11 kcfs, α_2=0.04, D_{crit}=350, and $V_{var} = 50$) and each parameter in turn was varied over a range to show one-at-a-time sensitivity of survival (Figure 7) and migration rate (Figure 8).

The scenario is a simulated release at Red Bluff Diversion Dam (RKM391) on day 300 (October 27) of 2010. The timeframe for a model run spans two calendar years because the WRCS spawn in the summer and juveniles can begin migration in the winter. Thus, a day value greater than 365 represents a day in the second year of the time series (i.e. day 425 = March 1).

Table 4. Winter-Run Chinook Salmon (unclipped) passage timing and run size at Red Bluff Diversion Dam (RBDD), and median travel time to the Sacramento Beach Seines and catch from 2004 to 2023.

Brood Year	50% Passage Date at RBDD	50% Passage Date in Sacramento Beach Seines	Travel Time (Days)	RBDD Run size	Beach Seines Catch
Average (2004 - 2023)	5-Oct	26-Dec	82	1,790,052	118.3
Median (2004 - 2023)	5-Oct	18-Dec	74	1,135,605	65
2023	10/17/2023	1/16/2024	91	1,069,769	22
2022	10/11/2022	12/30/2022	80	209,457	12
2021	9/29/2021	11/1/2021	33	557,652	23
2020	10/9/2020	1/14/2021	97	2,078,101	4
2019	10/1/2019	12/13/2019	73	3,666,516	90
2018	10/16/2018	12/12/2018	57	1,084,961	207
2017	10/20/2017	12/20/2017	61	591,066	43
2016	10/5/2016	12/2/2016	58	498,386	56
2015	10/6/2015	1/20/2016	106	324,246	31
2014	9/27/2014	12/17/2014	81	270,279	63
2013	10/28/2013	2/15/2014	110	1,392,950	67
2012	10/20/2012	12/10/2012	51	1,186,248	253
2011	10/7/2011	1/26/2012	111	742,344	24
2010	10/5/2010	12/17/2010	73	1,228,975	131
2009	9/18/2009	11/18/2009	61	3,274,893	37
2008	9/18/2008	2/24/2009	159	953,310	5
2007	10/2/2007	1/8/2008	98	1,337,160	14
2006	9/27/2006	12/26/2006	90	5,015,440	236
2005	9/30/2005	12/7/2005	68	7,458,477	362
2004	9/22/2004	12/13/2004	82	2,860,810	279

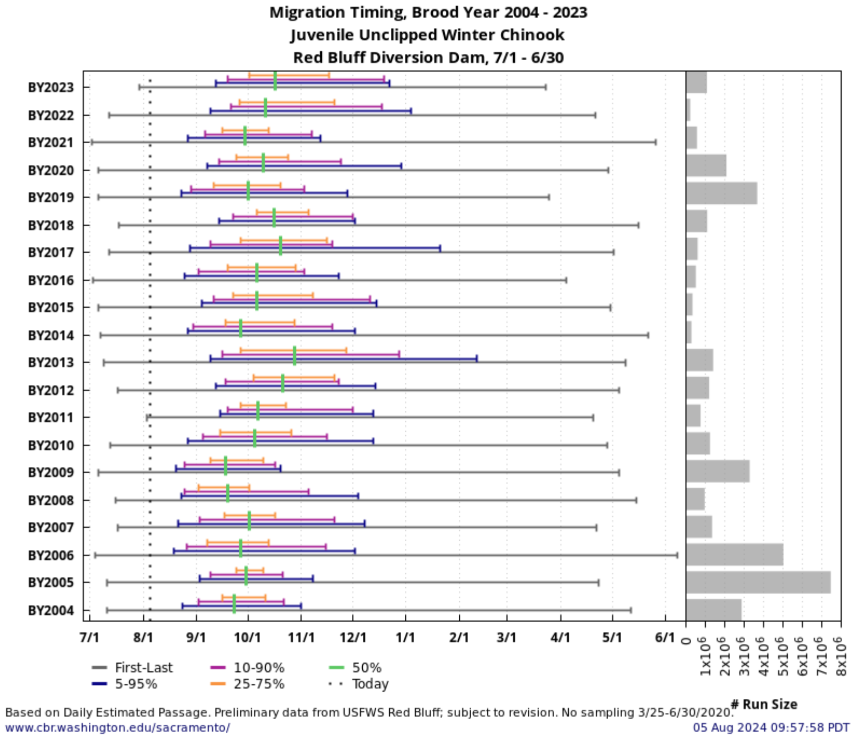


Figure 4. Migration timing of juvenile, unclipped Winter Chinook at Red Bluff Diversion Dam over years 2004-2023.

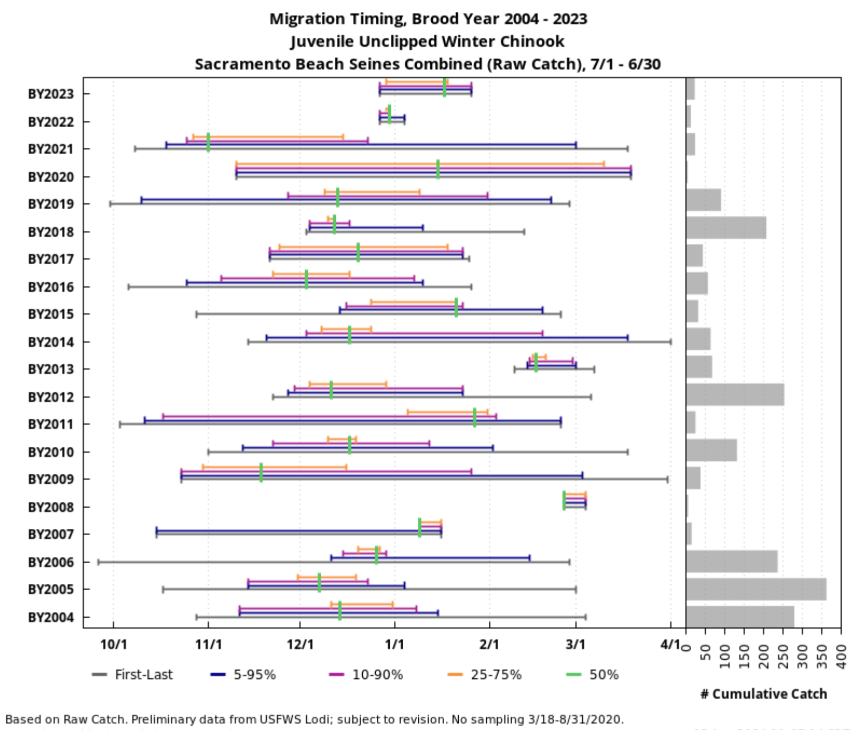


Figure 5. Migration timing and cumulative catch of juvenile, unclipped Winter Chinook at the Sacramento Beach Seines over years 2004-2023.

Table 5. Coefficients by reach for converting flow (KCFS) to water velocity (ft sec^{-1}) using a power-curve relationship ($V = p_1 Q^{p_0}$ Eq. 13).

Migration Model reach name	p_0	p_1
Spawning Grounds	0.345	1.7221
Balls Ferry	0.3262	1.5852
Abv. Cotton	0.1101	3.5248
Above Battle	0.2538	1.750
Bend	0.2963	1.6343
Woodson	0.2009	1.8236
Colusa	0.1761	1.8214
Knights Landing	0.2662	1.3952
Verona	0.3601	1.5426
Airport	0.4698	0.7187

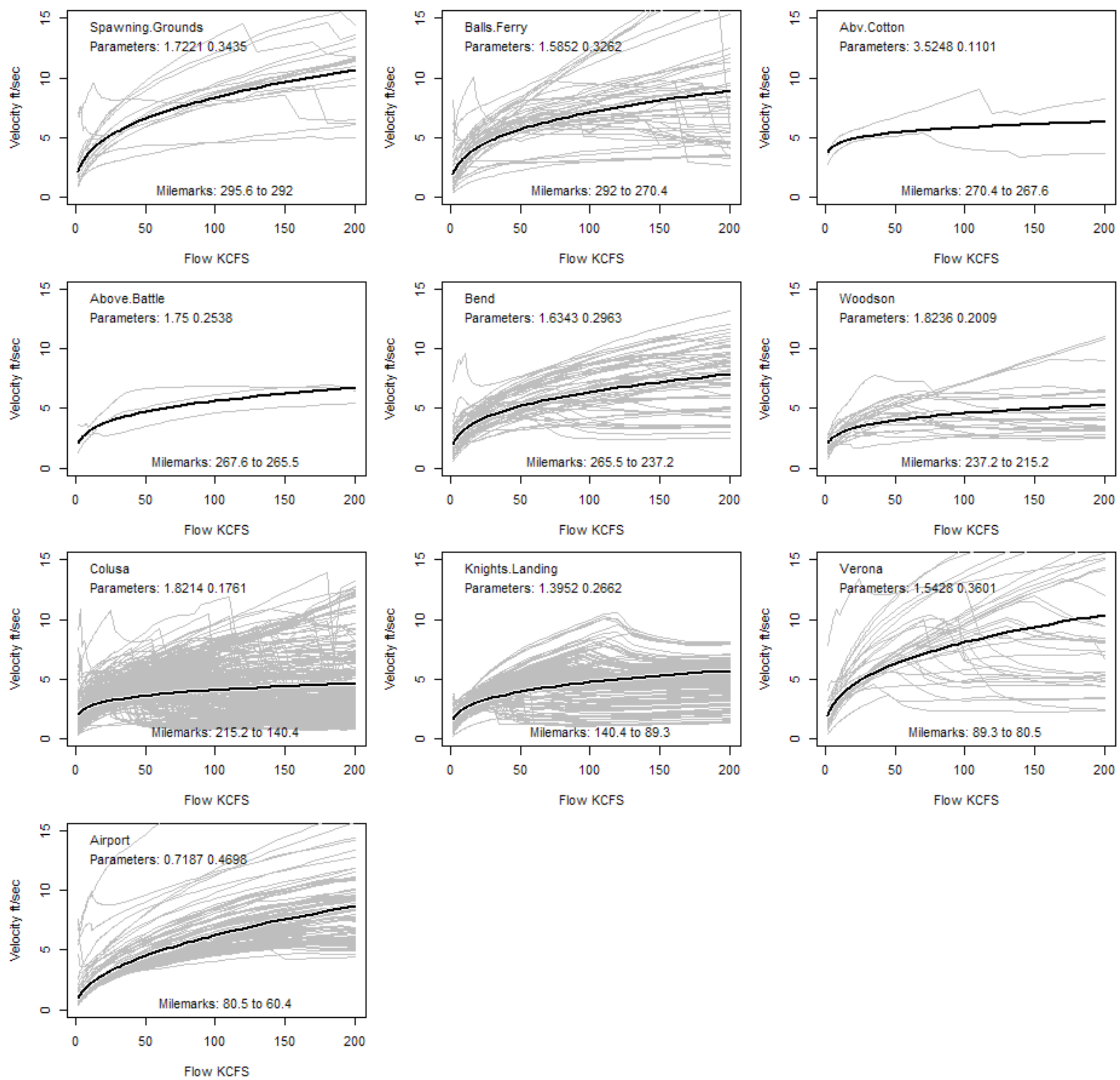


Figure 6. Flow-velocity relationships used for the migration model. Each gray line is a flow-velocity relationship transect at a cross section, and these are organized by reach. The black line is a fit ($V = p_1 Q^{p_0}$ Eq. 13) to the data in that reach and provides the parameters required for velocity modeling. The parameters for each reach are summarized in Table 5.

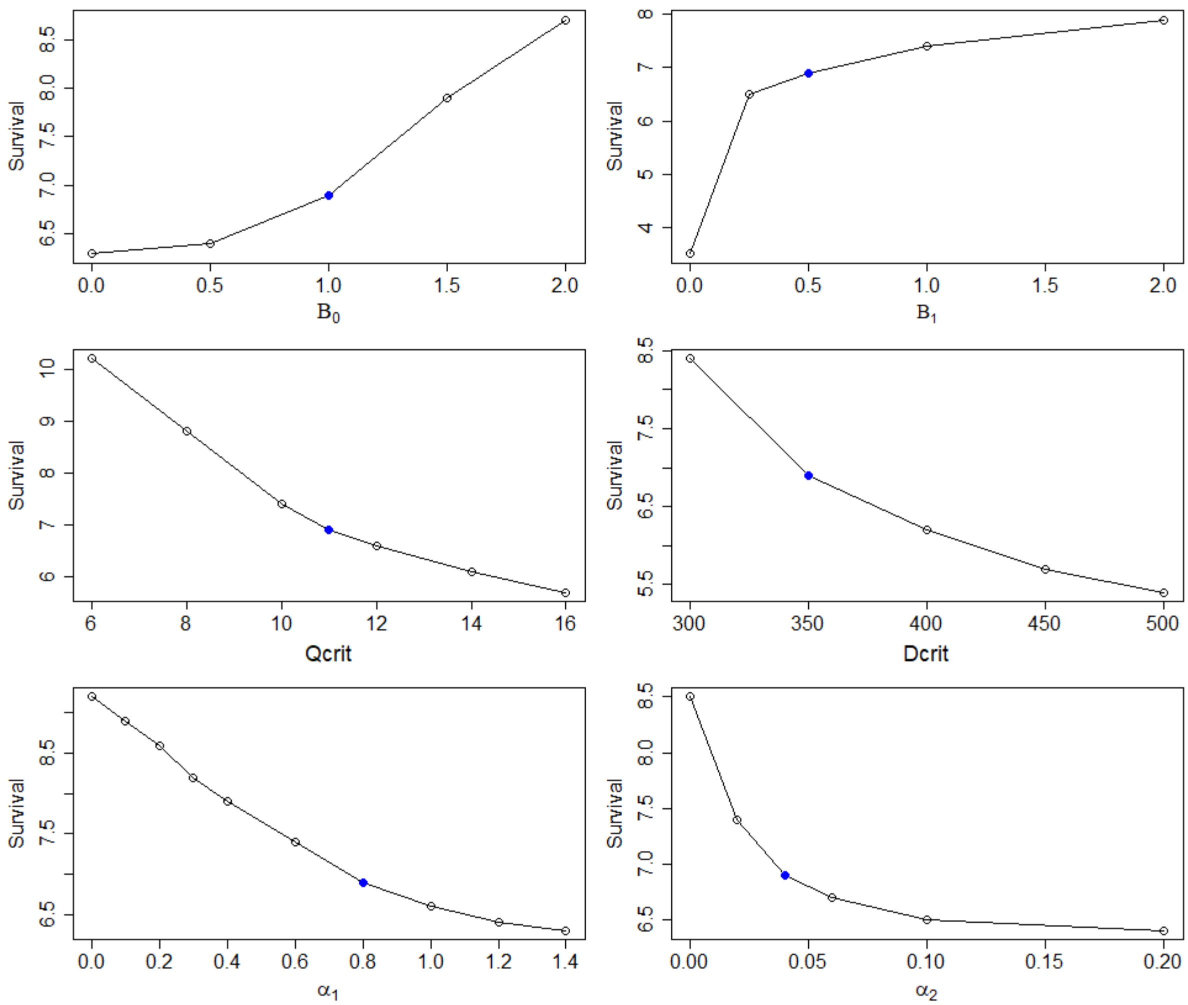


Figure 7. Sensitivity of survival to migration rate parameters in the pulse-flow model ($r_{j,t} = \beta_0 + \beta_1 \bar{V}\left[\frac{1}{1+\exp\,(-\alpha_1(Q-Q_{crit})-\alpha_2(D-D_{crit}))}\right] + \varepsilon$ Eq. 2) in place of full calibration due to lack of data. Analysis is based on a cohort of fish released in the Sacramento River on day 300 in 2010 (October 27) migrating from Red Bluff Diversion Dam to the Delta Cross Channel. The solid blue dots are associated with the mean survival response at 6.9% survival and other points in each panel show the survival if the parameter in the x-axis adjusted over a range of values.

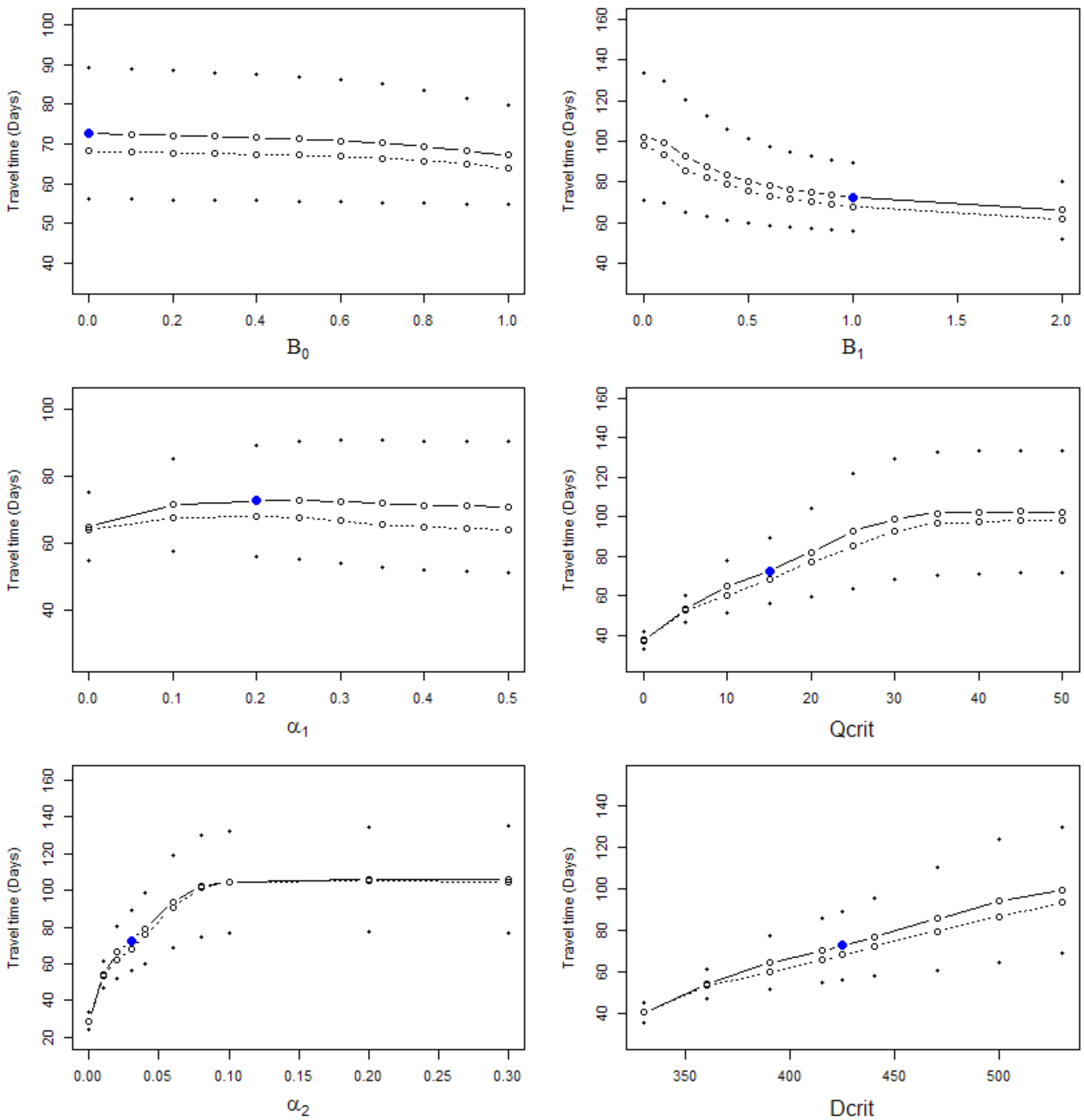


Figure 8. Sensitivity of travel time to migration rate parameters ($r_{j,t} = \beta_0 + \beta_1 \bar{V}\left[\frac{1}{1+\exp\left(-\alpha_1(Q-Q_{crit})-\alpha_2(D-D_{crit})\right)}\right] + \varepsilon$ Eq. 2) and determination of parameters (section 3.1.2.2) in place of full calibration due to lack of data. Analyses were based on a cohort of fish in the Sacramento River released on day 300 in 2010 (October 27) from Red Bluff Diversion Dam to the mouth of the Feather River. Larger solid blue dots are associated with the mean travel time response at approximately 70 days.

3.3 River Migration and Survival of Fry/Smolts (Feather River to DCC or Chipps Island)

Fry/smolts in Sacramento River at Feather River to Delta Cross Channel (DCC) or Chipps Island

Survival and migration from Feather River to DCC (i.e., lower Sacramento River and Delta) can be modeled in three different ways: 1) continue migration model to DCC; 2) DCC fish passage is proportion to flow at DCC; 3) fish passage at DCC is dependent on simple rules of DCC operations. Additionally, a fourth way to model survival and migration is from Feather River to Chipps Island by using the STARS model (Perry et al. 2018).

3.3.1 Survival Models

For the first three options in which the model terminates at DCC (sections 3.3.2.1 to 3.3.2.3), survival can be either the exponential model (section 3.2.1.1) or the XT model (section 3.2.1.2). For the Delta STARS model (Survival, Travel Time, and Routing Simulation model; Perry et al. 2018), survival is jointly modeled with travel time and migration routing in relation to individual time-varying covariates of acoustic-tagged salmon in a Bayesian framework (section 3.3.2.4).

3.3.2 Migration Models

The first three methods in which the model terminates at DCC are described in detail in sections 3.2.1. to 3.2.3, and the fourth method of migration to Chipps Island is described in section 3.2.4.

3.3.2.1 Continue migration model to DCC

In this method, either the linear model or the non-linear migration model can be continued to the DCC.

3.3.2.2 DCC fish passage proportional to DCC flow

In this method, either the linear model or the non-linear migration model can be continued to the DCC, and then fish are routed at DCC proportional to the flow at that location. The proportion of flow is calculated as DLC gage flow divided FPT flow. Fish are routed out of the Sacramento River in proportion to positive flow into the Delta (i.e. fish do not return to river). All fish on each day are subject to this potential division. User can choose:

1. Observed flows, which matches the “Fixed Site Flow” or "Historical System Flow" used for migration from the release point to the DCC.
2. Ten-year-average DLC flows, which is a default if "User Flows" was selected for migration.
3. Custom flows, entered through copy-pasted values or file upload.

3.3.2.3 DCC fish passage with simple rules of DCC operations

In this method, either the linear model or the non-linear migration model can be continued to the DCC, and the trigger to open or close the DCC gates is dependent on the number of “modeled” fish caught at Knights Landing (i.e., near Feather River). The triggers modeled are similar to those in the LTO Biological Opinion (NMFS2019a). The triggers modeled are as follows: A catch of 5 fish at Knights Landing triggers a closer of the DCC gates in 2 days, and stays closed until the fish catch is below 3 fish. If there are 3-5 fish in the Knights Landing catch, then the DCC gates stay closed for 3 days. The gate is also forced closed on a schedule. Default is Dec. 1 - June 15 (days 1-166 and days 335-365). Note that diurnal operation modeling and other operations criteria are beyond scope of this model, thus water quality impacts are not assessed here even though they may be a part of management operations.

A "Passage-To-Trigger ratio" (PTT) is applied to scale the modeled arrivals to a daily catch index. Modeled passage numbers are 100x greater than input numbers in order to reduce rounding errors when computing survival and travel time. The default value for PTT is 100, so modeled passage must be 300 to get a catch index of 3. If the catch index is equal or greater than the trigger value, then DCC gate is closed.

3.3.2.4 STARS model of Delta passage

The Delta STARS model is an individual-based simulation model that predicts survival, travel time, and routing of juvenile salmon migrating through the Sacramento-San Joaquin River Delta (Perry et al. 2018). The model's structure and parameters are based on late-fall Chinook salmon, daily Sacramento River flows at Freeport (USGS; flow gage 11447650) and Delta Cross Channel operations (USBR; https://www.usbr.gov/mp/cvo/vungvari/Ccgates.pdf).

4 USER'S GUIDE Section

From the landing page of the SacPAS Fish Model (www.cbr.washington.edu/sacramento/fishmodel/), users can access the entry points for Egg-to-Fry modeling and River Migration and Survival modeling (Figure 9).

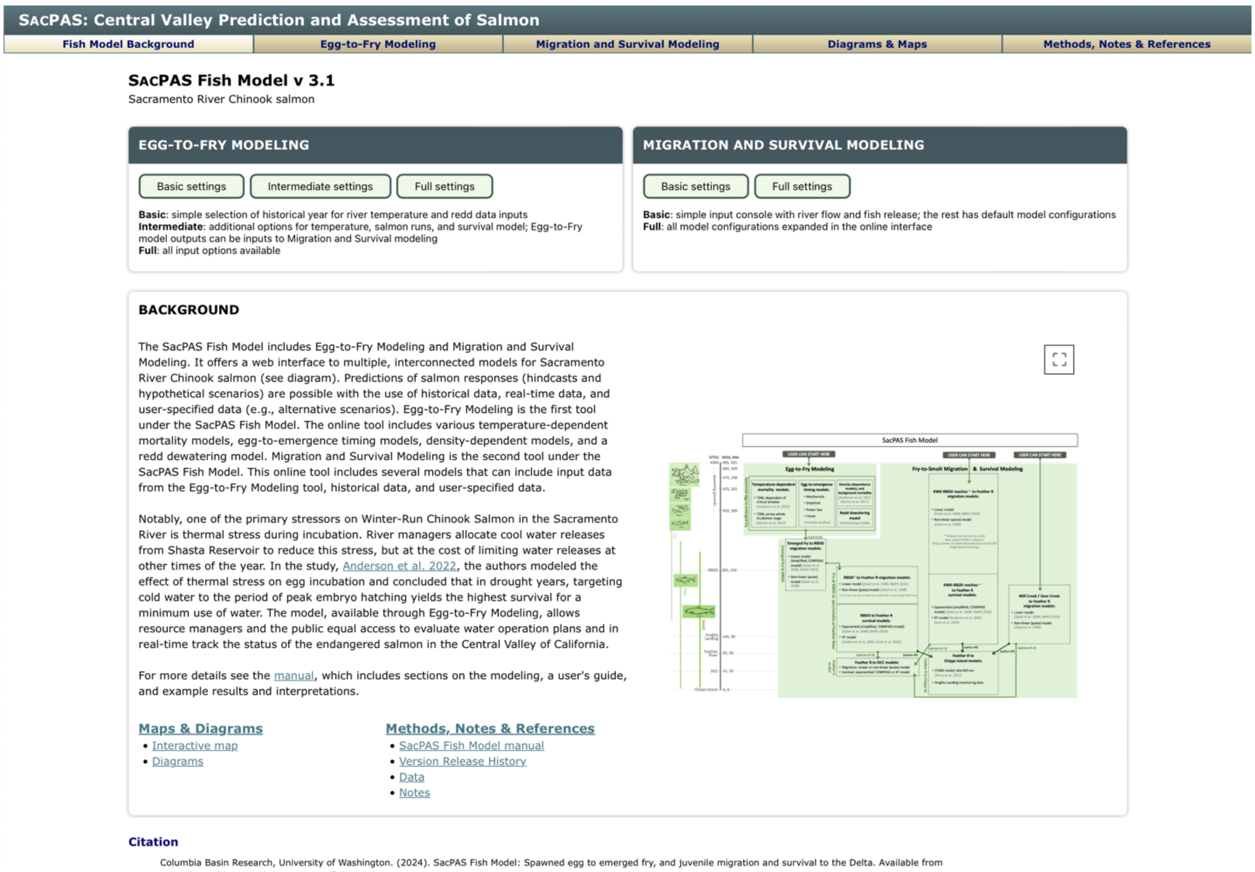
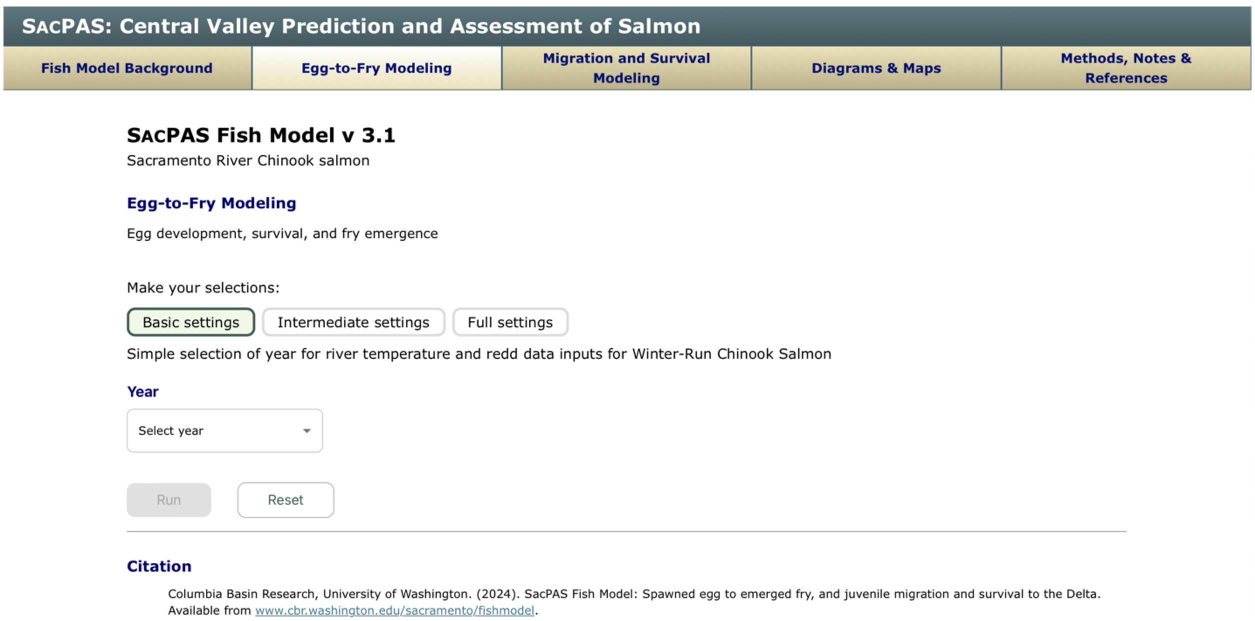


Figure 9. Landing page of the SacPAS Fish Model (https://www.cbr.washington.edu/sacramento/fishmodel/).

4.1 Egg-to-Fry Model (Redds to RBDD)

To help users at different levels of interest and experience with the SacPAS Fish Model, the entry points to Egg-to-Fry modeling can be to Basic settings (Figure 10a), Intermediate settings (Figure 10b) or Full settings (Figure 10c). We describe the options available to the users in further detail in section 4.1.1.



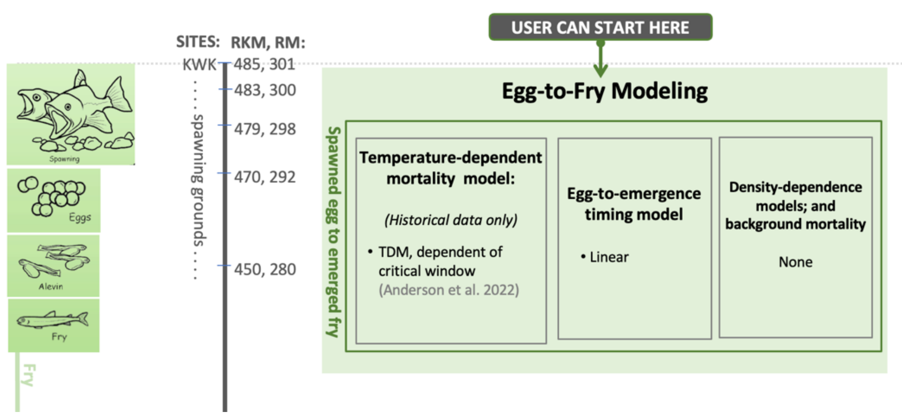
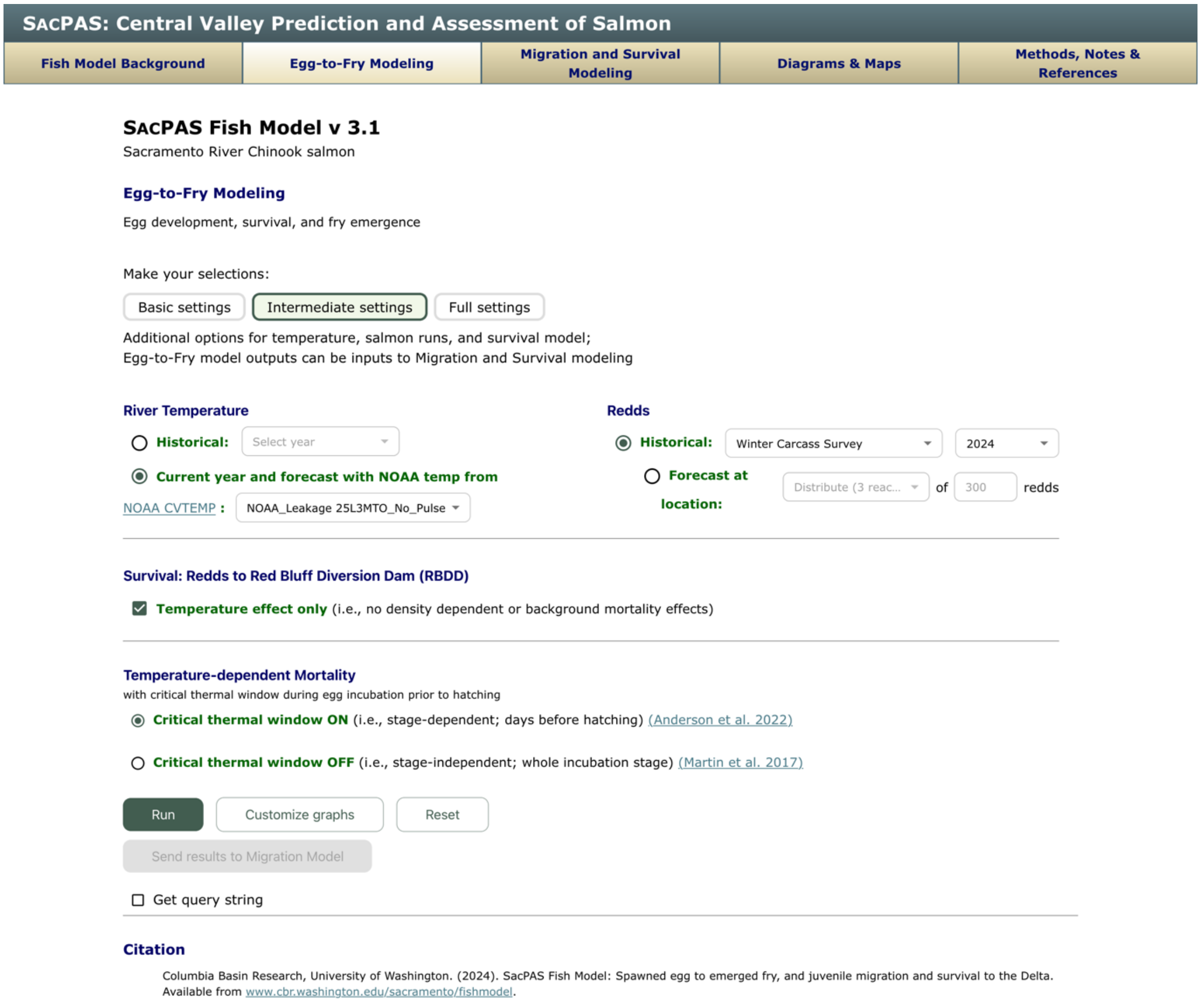


Figure 10a. Basic settings of the Egg-to-Fry modeling graphical user interface (top) and diagram of associated models (bottom).



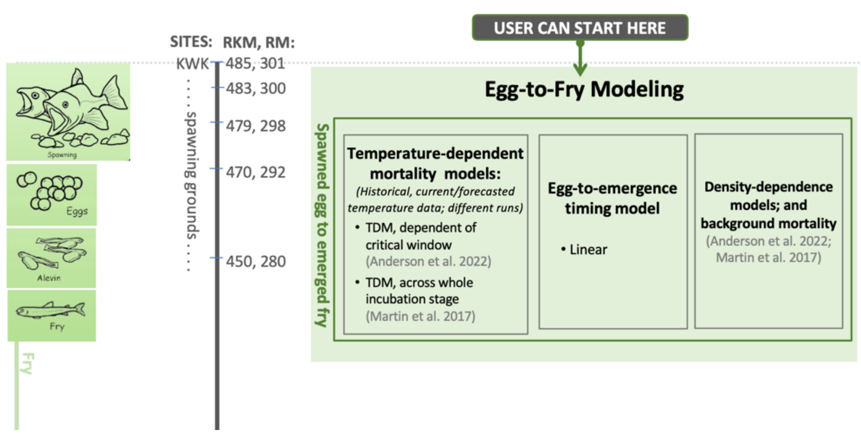


Figure 10b. Intermediate settings of the Egg-to-Fry modeling graphical user interface (top) and diagram of associated models (bottom).

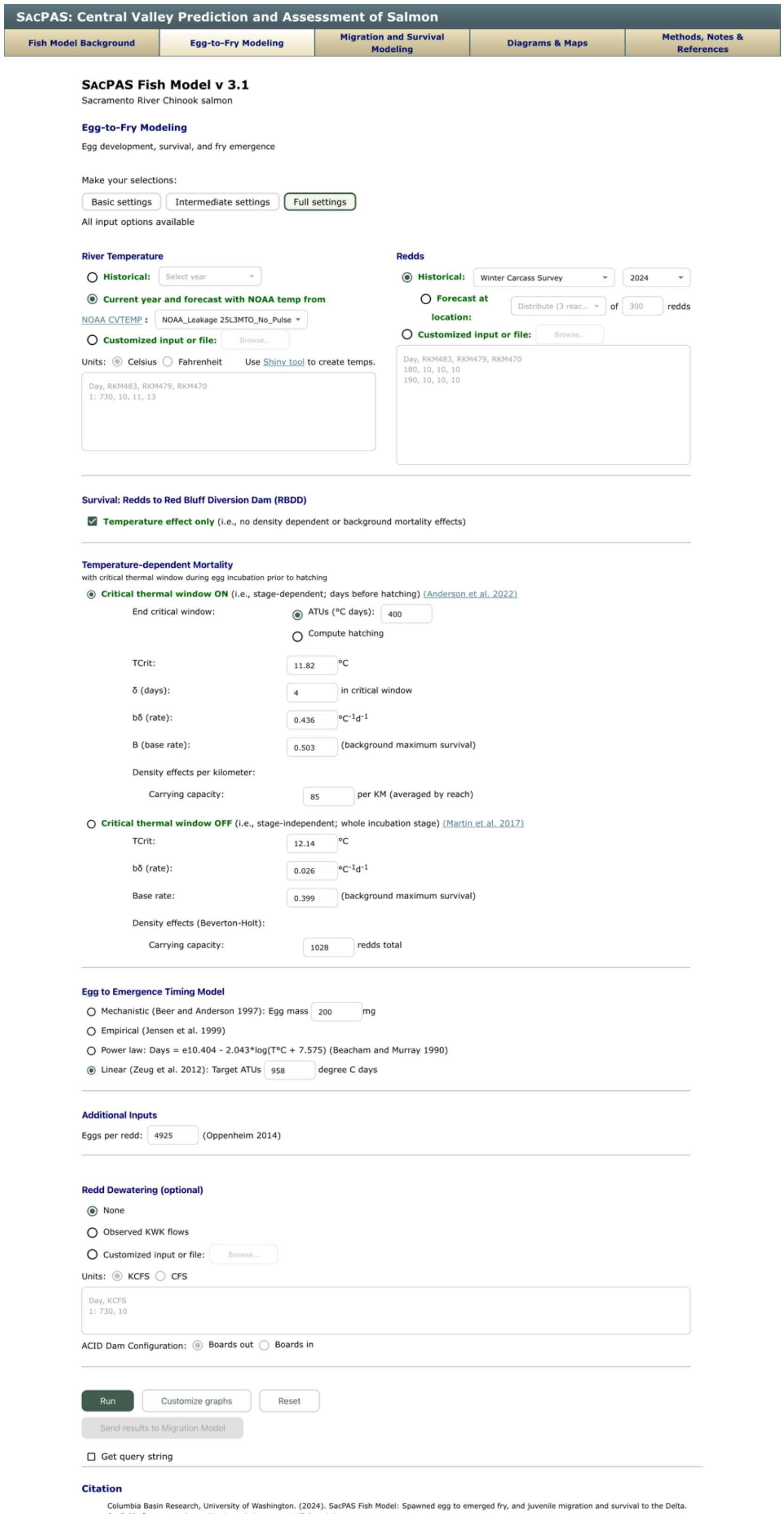


Figure 10c. Full settings of the Egg-to-Fry modeling graphical user interface.

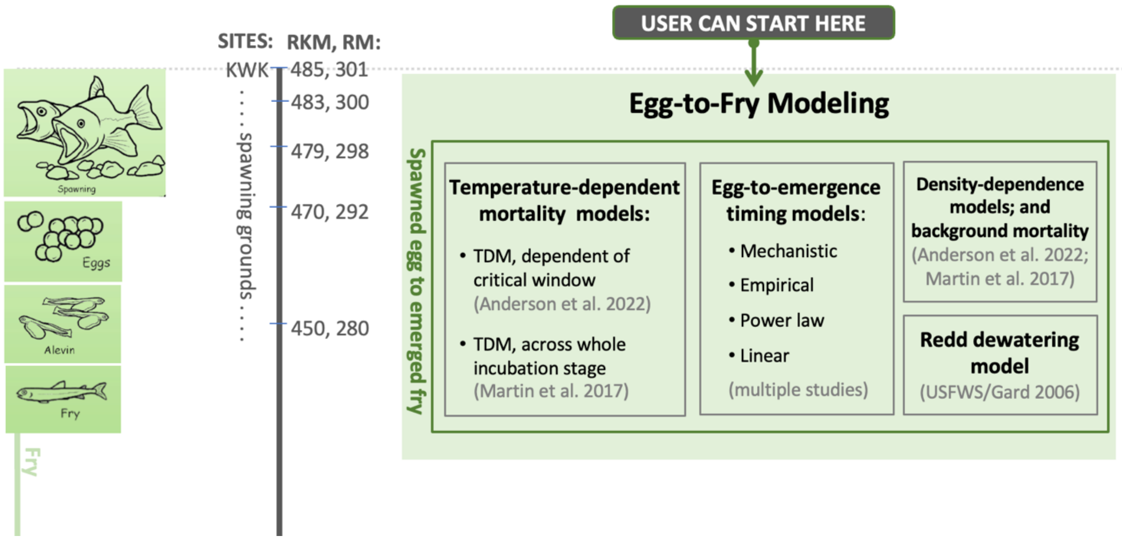


Figure 10c *(continued)*. Diagram of models with Full settings of Egg-to-Fry modeling.

4.1.1 Survival Models

4.1.1.1 GUI and Inputs

The online tool of the Egg-to-Fry model for the Chinook salmon was originally developed for winter-run Chinook salmon to estimate:

- survival from spawned eggs in redds to emerged fry emerge from redds,
- timing of fry emergence, and
- number of emerged fry.

The online tool can now also be used for fall-run, late-full-run, and spring-run Chinook salmon with some assumptions due to data limitations.

Overall, the online tool allows users to specify selections, including:

a) **Temperature profiles** (time series of historical, forecasted, or custom data: respectively, observations with data from CDEC, forecasted data from CVTEMP or USBR, and user-specified data)
b) **Spawn timing and number of new redds** (time series of historical observations or user-specified, custom data)
c) **critical thermal window, density-dependent effects, and background mortality** (Martin et al. 2017, Anderson et al. 2022);
d) **egg-to-emergence timing** (Beacham and Murray 1990, Beer and Anderson 1997, Jensen and Jensen 1999, Zeug et al. 2012);
e) **number of eggs per redd** (Oppenheim 2014);
f) **redd dewatering mortality** (USFWS 2006).

These options are described in further detail:

a) Temperature profiles

Temperature data may be specified from historical data (2000-present) or forecasted data, as well as entered as customized inputs through copy-pasted values, or file upload (Figure 11).

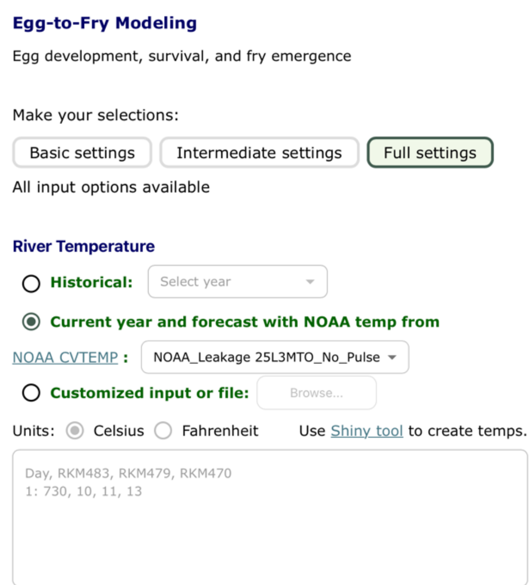


Figure 11. River temperature input console for Egg-to-Fry Modeling.

Furthermore, users can enter temperature data via the TEMPMAKER Shiny app (https://www.cbr.washington.edu/shiny/TEMPMAKER/; Figure 12).

Figure 12. General User Interface of TEMPMAKER Shiny app (https://www.cbr.washington.edu/shiny/TEMPMAKER/) that can be used for input data under Full Settings of Egg-to-Fry Modeling.

b) Number of redds and spawn timing

The observed input data for redds is from the carcass survey (CDFW 2024) and are spatiotemporally specific. User-specified inputs are also possible.

In the Intermediate and/or Full settings, users can choose from three different types of options:

- Historical data from carcass and aerial redd surveys (Killam 2023) (
- Figure **13**).
- Forecasted spatiotemporal distributions of redds based on river temperatures and reach(es) (
- Figure **14**; Box 3).
- User-customized inputs into an entry box (
- Figure **15**).

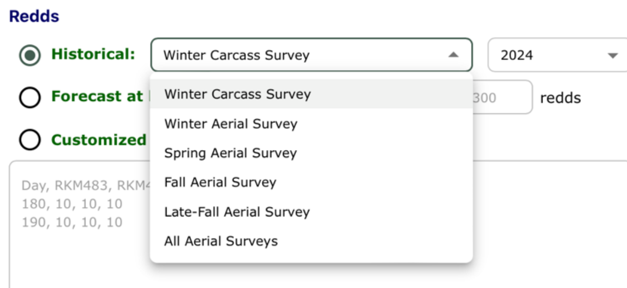


Figure 13. Part of the input console for redd data with choices of salmon run, survey, and year in Egg-to-Fry Modeling.

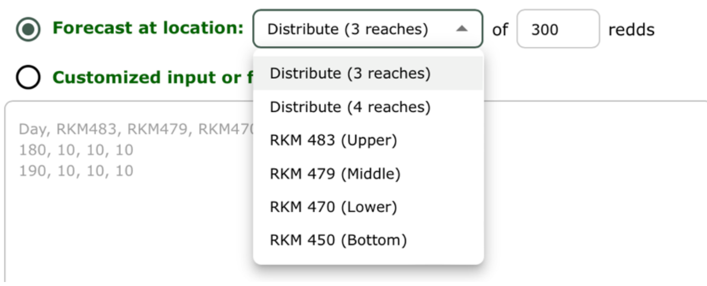


Figure 14. Part of the input console for redd data with choices of redd distribution forecasts in Egg-to-Fry Modeling.

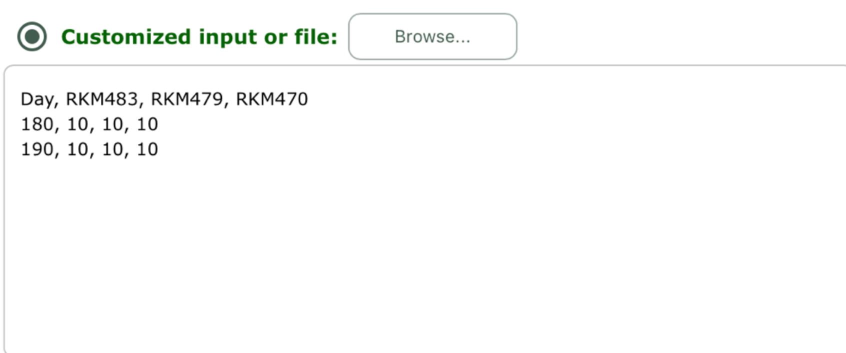


Figure 15. Part of the input console for user-customized inputs of redd data into a text box area in Egg-to-Fry Modeling

c) Critical thermal window, density-dependent effects, and background mortality

Critical thermal window for temperature-dependent mortality: ON/OFF and specifications

The user can choose to include a critical thermal window (ON) that represents when temperature-dependent mortality occurs in relatively large-sized alevin occurring later in development, but still in the egg stage, and thus suffering from hypoxia when water temperature is warm. Or, the user can choose to not designate a critical thermal window (OFF).

- **ON (Anderson et al. 2022 model)**: a critical thermal window from several days (default = 4 days) before eggs hatch to the day when eggs hatch, as well as when critical temperature threshold for when mortality occurs (default = 53.3 °F or 11.8 °C; calibrated with Anderson et al. (2022) model). When the temperature rises above the critical temperature threshold in the days prior to hatching (within the critical thermal window), mortality is computed and on a daily basis.

- **OFF (Martin et al. 2017 model)**: the thermal window is from spawned eggs until emergence, thus not representing a critical thermal window, but there is still a critical temperature threshold when mortality occurs (default = 53.9 °F or 12.1 °C; calibrated with Martin et al. (2017) model). When the temperature rises above Critical Temperature (T-crit) on *any day* for each individual redd, mortality is computed.

Customized specifications:

- **Critical thermal window ON (Anderson et al. 2022 model):**
  - End of critical window can be specified in ATUs (default = 400 °C·d) or through one of the four egg-to-emergence timing models (computation of hatching).
  - Critical temperature threshold (T_{Crit}; default = 11.8°C or 53.3°F)
  - Duration of the critical thermal window (d; default = 4 days)
  - Thermal mortality rate (b_δ; default = 0.436 $°C^{-1} \cdot d^{-1}$ or 0.242 $°F^{-1} \cdot d^{-1}$)
  - Background maximum survival (or complement of background mortality; default = 0.503)

- **Critical thermal window OFF (Martin et al. 2017 model):**
  - Critical temperature threshold (T_{Crit}; default = 12.1°C or 53.9°F)
  - Thermal mortality rate (b_δ; default = 0.026 $°C^{-1} \cdot d^{-1}$ or 0.0144 $°F^{-1} \cdot d^{-1}$)
  - Carrying capacity for density-dependent effects (default = 1023 redds total)
  - Background maximum survival (or complement of background mortality; default = 0.399)

In the Intermediate and Full settings, the user can select whether to turn ON/OFF the critical thermal window for temperature-dependent mortality (FIGURE). In the Full settings, the user can specify the values of the model parameters (Figure 10c). Default values are from the calibrated models from the studies (Martin et al. 2017, Anderson et al. 2022).

The user can also choose to only include temperature-dependent effects, thereby turning off any density-dependent effects and background mortality effects (FIGURE).

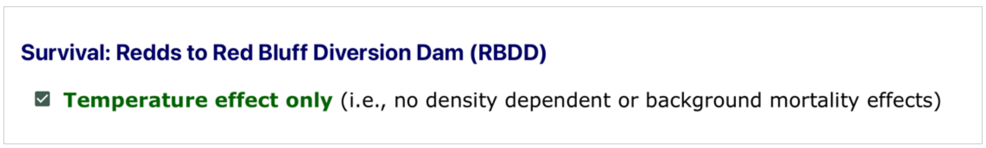


Figure 16. Part of Egg-to-Fry Modeling input console to select whether to turn ON or OFF the critical thermal window of temperature-dependent mortality based on Anderson et al. (2022).

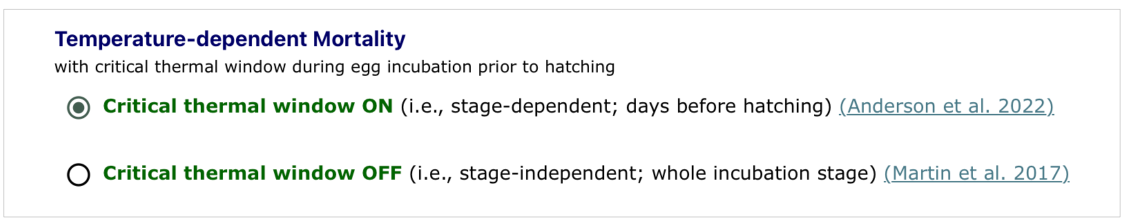


Figure 17. Part of Egg-to-Fry Modeling input console to include only the temperature-dependent mortality effect, or also include density-dependent effects and background mortality.

Density-dependent effects

The density-dependent effect that is included is based on which of the two models is selected:

- **Critical thermal window ON (Anderson et al. 2022 model):**
  - Carrying capacity for density-dependent effects (*D*; default = 85 redds·d^{-1})
- **Critical thermal window OFF (Martin et al. 2017 model):**
  - Carrying capacity for density-dependent effects (default = 1023 redds total)

To turn off any density-dependent effects and only include temperature-dependent effects, the user can checkmark this option. Note that this would also exclude background mortality in the model and results.

Background mortality

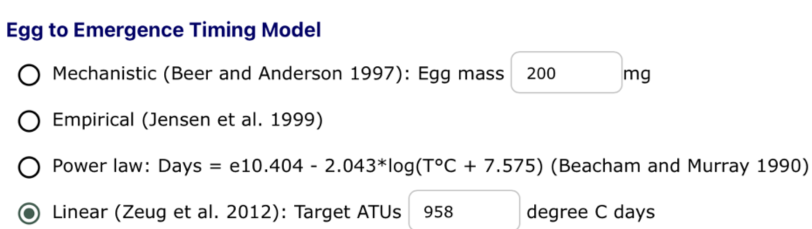
With the Anderson et al. (2022) option, the background mortality is from when fry emerge from redds to when fry/smolts pass RBDD and assumed constant for all years and all redds, as determined during model calibration for the study. The default is 0.503. In the Martin et al. (2017) study, the background mortality is also similarly defined and the default is 0.399.

d) Egg-to-emergence timing

The user can choose from one of four development models for egg-to-emergence timing:
1) Mechanistic (Beer and Anderson 1997)
2) Empirical (Jensen and Jensen 1999)
3) Power law (Beacham and Murray 1990)
4) Linear (Zeug et al. 2012)

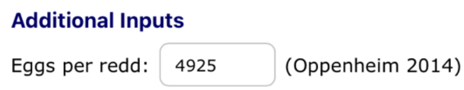
More specifically:
1) The mechanistic model (Beer and Anderson 1997) does not have a closed form. The egg mass and embryo are coupled, and temperature drives the rate and efficiency of growth. When the yolk is sufficiently depleted, the fish emerges.
2) In the empirical model (Jensen and Jensen 1999), each day, the fraction of total development is related to temperature as: $0.002755949 + (6.340096 \times 10^{-5})T + (9.564633 \times 10^{-5})T^2 - (5.250954 \times 10^{-6})T^3 + (3.046699 \times 10^{-7})T^4$, where T is temperature.
3) In the power law model (Beacham and Murray 1990), at a fixed temperature, the number of days for development is: $\exp\,(10.404 - 2.043 \times \log\,(T + 7.575)$, where T is temperature in °C. To use this in fluctuating temperatures, development rate is computed each day (day^{-1}), and these fractions are summed until they add up to one at emergence.
4) In the Zeug et al. (2012) model, the accumulated temperature units (ATUs) are accumulating across days until the total number of degree days exceeds a specified threshold. The published threshold ATU is 958 °C. The development rate per day is: $0.001044(T)$, where T is temperature in °C; or $0.0058(T) - 0.018$, where T is temperature in °F.

Under the Full settings, users can specify the egg-to-emergence timing model to include:



c) Eggs per redd

The default value of 4,925 eggs/redd is from a 5-year average spanning 2009-2013 reported by John Rueth (USFWS) using average fecundity of adults returning to Livingston Stone National Fish Hatchery (from Oppenheim 2014). The user can specify another value:



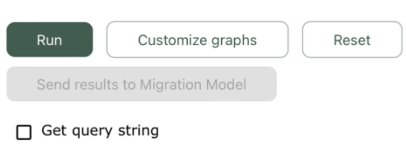
d) Redd dewatering (USFWS 2006)

Under the Full settings, users can access the option to include redd dewatering mortality, using the (USFWS 2006) method (Figure 18). The option of "Boards Out" or "Boards In" pertains to the configuration of flashboards at the Anderson Cottonwood Irrigation District (ACID) Diversion Dam at Lake Redding Park.

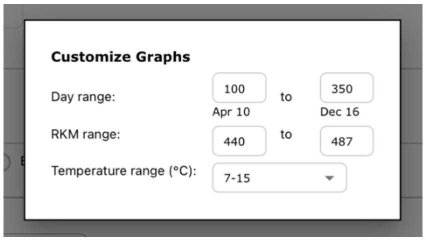
Figure 18. Part of the GUI of Egg-to-Fry Modeling to include redd dewatering mortality based on the method by (USFWS 2006).

Other Features

Users can customize the ranges of the x-axis and y-axis of the output graphs by clicking on "Customize Graph":



and specifying values or selecting ranges in the pop-up window:



The "Get query string" option can be selected to get output results in coding scripts, such as R script, accessed through urls, for example:

```
Default, GUI-provided values are used for every parameter you did not alter.

# Results Summary has several metrics:
https://www.cbr.washington.edu/sac-bin/fishmodel/getandplottemp.pl?temponly=on&dirUseId=1723221003333&redds=computeredds&tempsource=dbtemp&raw=13


# Grand Survival:
https://www.cbr.washington.edu/sac-bin/fishmodel/getandplottemp.pl?temponly=on&dirUseId=1723221003333&redds=computeredds&tempsource=dbtemp&raw=1

# Redd counts:
https://www.cbr.washington.edu/sac-bin/fishmodel/getandplottemp.pl?temponly=on&dirUseId=1723221003333&redds=computeredds&tempsource=dbtemp&raw=2

# Special Query, please consult with web.washington.edu for more information:
https://www.cbr.washington.edu/sac-bin/fishmodel/getandplottemp.pl?temponly=on&dirUseId=1723221003333&redds=computeredds&tempsource=dbtemp&raw=3

# Dewater survival:
https://www.cbr.washington.edu/sac-bin/fishmodel/getandplottemp.pl?temponly=on&dirUseId=1723221003333&redds=computeredds&tempsource=dbtemp&raw=4

# Redd distribution:
https://www.cbr.washington.edu/sac-bin/fishmodel/getandplottemp.pl?temponly=on&dirUseId=1723221003333&redds=computeredds&tempsource=dbtemp&raw=5

# Flows & Dewatering (Choose dewatering first)
# Emergence timing table:
https://www.cbr.washington.edu/sac-bin/fishmodel/getandplottemp.pl?temponly=on&dirUseId=1723221003333&redds=computeredds&tempsource=dbtemp&raw=7

# Maximum temperature exposure during incubation table:
https://www.cbr.washington.edu/sac-bin/fishmodel/getandplottemp.pl?temponly=on&dirUseId=1723221003333&redds=computeredds&tempsource=dbtemp&raw=8

# Hatching timing table:
https://www.cbr.washington.edu/sac-bin/fishmodel/getandplottemp.pl?temponly=on&dirUseId=1723221003333&redds=computeredds&tempsource=dbtemp&raw=9

# Mean temperature exposure during critical window (near hatching):
https://www.cbr.washington.edu/sac-bin/fishmodel/getandplottemp.pl?temponly=on&dirUseId=1723221003333&redds=computeredds&tempsource=dbtemp&raw=10

# Maximum temperature exposure during critical window (near hatching):
https://www.cbr.washington.edu/sac-bin/fishmodel/getandplottemp.pl?temponly=on&dirUseId=1723221003333&redds=computeredds&tempsource=dbtemp&raw=11

# Redd distribution:
https://www.cbr.washington.edu/sac-bin/fishmodel/getandplottemp.pl?temponly=on&dirUseId=1723221003333&redds=computeredds&tempsource=dbtemp&raw=12

# Results Summary:
https://www.cbr.washington.edu/sac-bin/fishmodel/getandplottemp.pl?temponly=on&dirUseId=1723221003333&redds=computeredds&tempsource=dbtemp&raw=13

# Survival table:
https://www.cbr.washington.edu/sac-bin/fishmodel/getandplottemp.pl?temponly=on&dirUseId=1723221003333&redds=computeredds&tempsource=dbtemp&raw=14

# Temperatures table:
https://www.cbr.washington.edu/sac-bin/fishmodel/getandplottemp.pl?temponly=on&dirUseId=1723221003333&redds=computeredds&tempsource=dbtemp&raw=15

# Redds per kilometer (density):
https://www.cbr.washington.edu/sac-bin/fishmodel/getandplottemp.pl?temponly=on&dirUseId=1723221003333&redds=computeredds&tempsource=dbtemp&raw=16

# Build Mode (internal):
https://www.cbr.washington.edu/sac-
bin/fishmodel/getandplottemp.pl?temponly=on&dirUseId=1723221003333&redds=computeredds&tempsource=dbtemp&raw=17&mode=build

# Build Mode (internal w/ path):
https://www.cbr.washington.edu/sac-
bin/fishmodel/getandplottemp.pl?temponly=on&dirUseId=1723221003333&redds=computeredds&tempsource=dbtemp&raw=18&mode=build
```

4.1.1.2 Result Outputs

After running the Egg-to-Fry Model, the results can be downloaded as an image of the results or a text file with one of the two buttons shown (Figure 19).

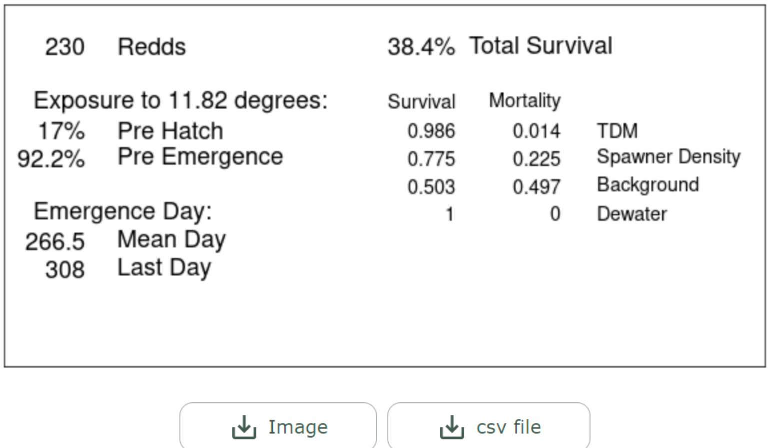


Figure 19. Example of summary results for Egg-to-Fry modeling.

Temperature-dependent mortality: TDM for each cohort varies because they have distinct exposures to the thermal profile. After the "Run" button is pressed these results are presented in two plots: a heatmap of the thermal landscape of the river with the distribution of the cohorts, and a timeseries plot showing thermal profiles at points along the river and the status of the cohorts.

Heatmap Plots: There are three heatmap plots generated after each run that correspond to: 1) spawning distribution, 2) hatching distribution, and 3) emergence distribution. Each point on a heatmap represents one of the cohorts and the size of the point is proportional to the number of redds. If the point is colored red, then it was exposed to the critical temperature above which mortality occurs during that period of development. An example for spawning, hatching and emergence of winter-run cohorts based on the carcass survey in 2022 are shown in Figure 20, Figure 21, and Figure 22.

Timeseries plot: The timeseries plot depict temperature profiles along the river and the status of the cohorts as they develop. This includes temperature profiles at KWK, BSF, and BND gages; redd status from spawning, through hatching to emergence; and flow at KWK and BND. Two seasonally varying metrics are also shown when the temperature profile gradient reverses from warming to cooling, and when the KWK gage drops below Tcrit.

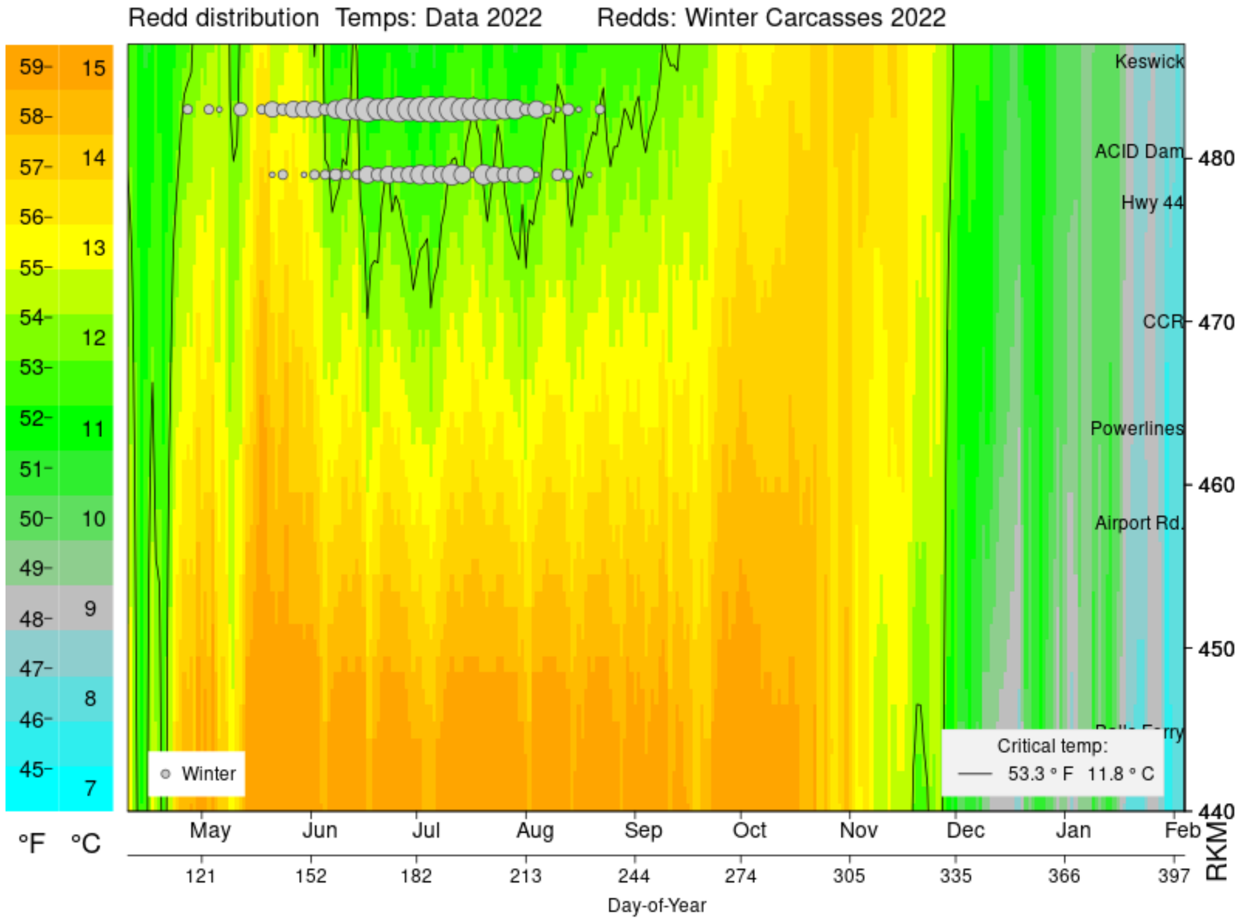


Figure 20. Heatmap of Winter-Run Chinook Salmon cohort status at spawning. Each point represents a cohort. Points are colored red if they were exposed to 11.8 °C at spawning and the size of the point is proportional to the number of redds in the cohort. The isoline of Tcrit is shown in black on the thermal landscape.

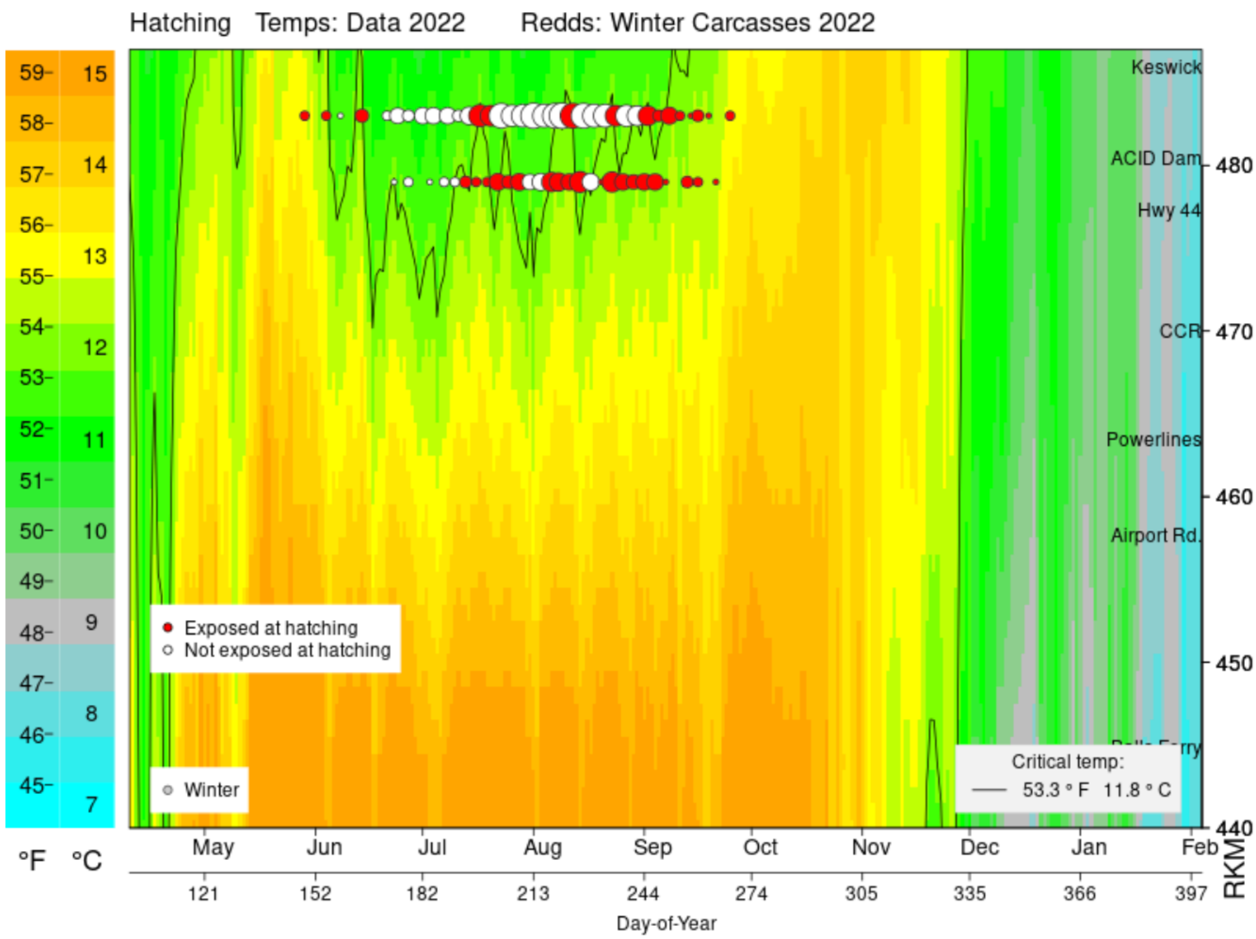


Figure 21. Heatmap of Winter-Run Chinook Salmon cohort status at hatching. Each point represents a cohort. Points are colored red if they were exposed to 11.8 °C at hatching and the size of the point is proportional to the number of redds in the cohort. The isoline of Tcrit is shown in black on the thermal landscape.

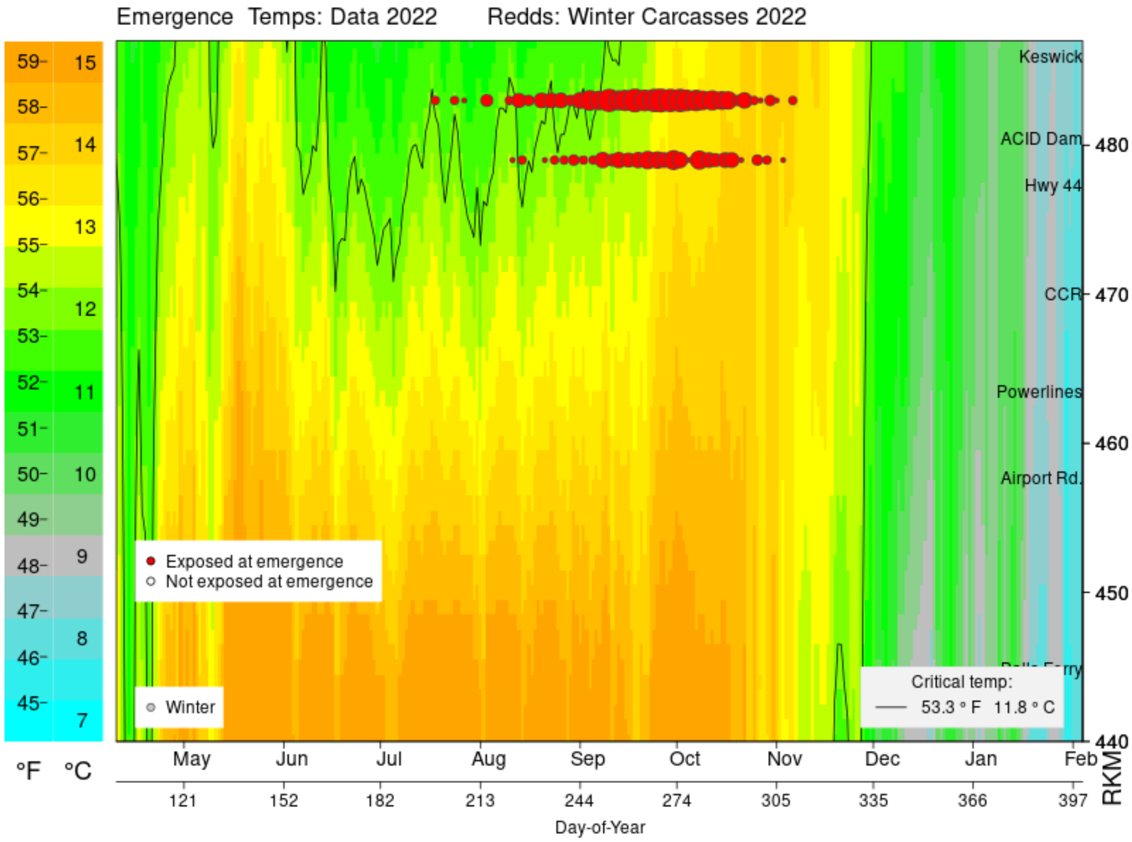


Figure 22. Heatmap of Winter-Run Chinook Salmon cohort status at emergence. Each point represents a cohort. Points are colored red if they were exposed to 11.8 °C prior to emergence and the size of the point is proportional to the number of redds in the cohort. The isoline of Tcrit is shown in black on the thermal landscape.

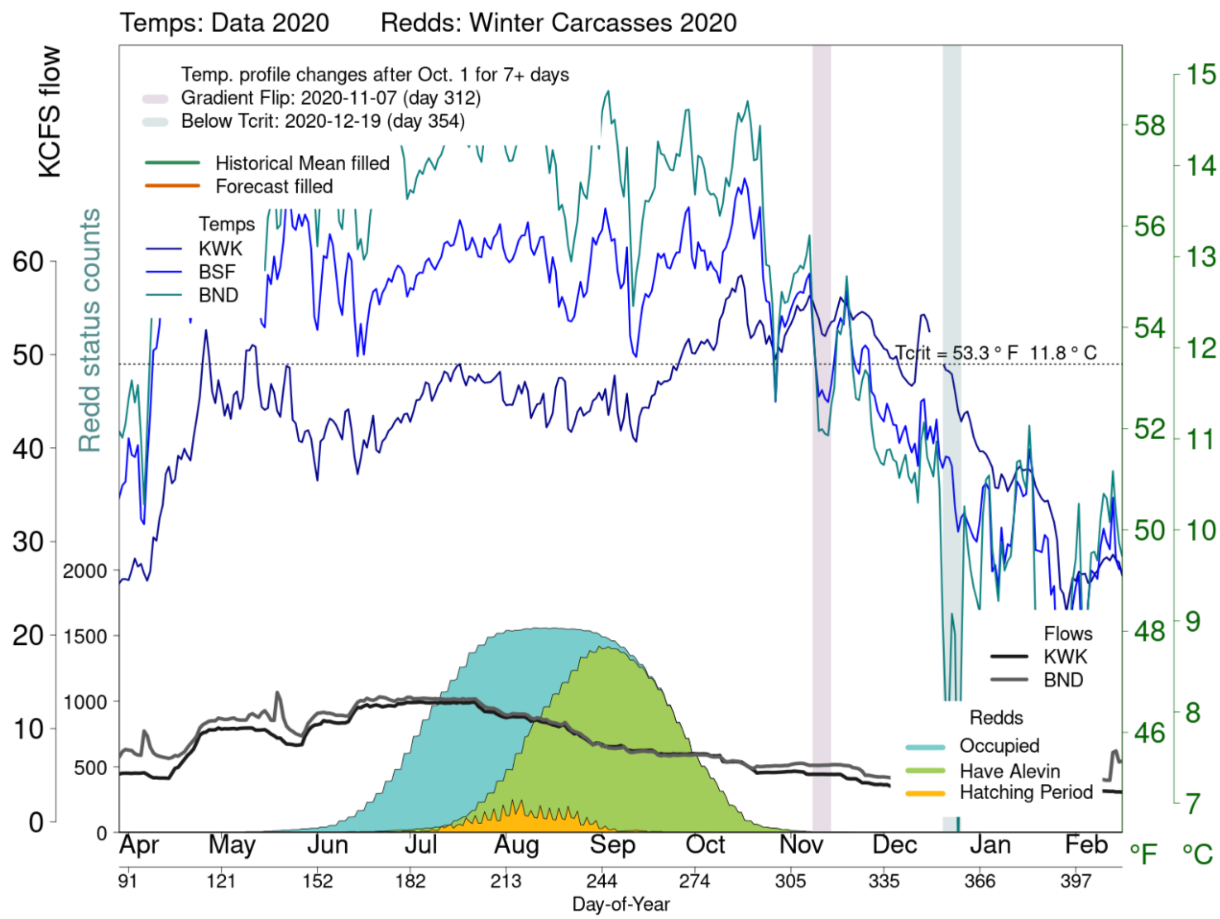


Figure 23a. Timeseries plot of environmental conditions (temperature and flow) and status of the redds. Temperature profiles are shown in cool (blue-green) colors. Flow is shown in black and grey. Status of all the redds are shown as filled areas proportional to their status: initially occupied after spawning, the hatching period transition from egg to alevin, and pre-emergence when the redds are occupied by the alevin. The plot also includes some critical transitions of the thermal landscape: the first week of the season after October 1 when either of two events occurs: 1. when the downstream gradient of temperatures changes from warming to cooling (Gradient Flip) and 2. when the KWK gage temperature drops below Tcrit.

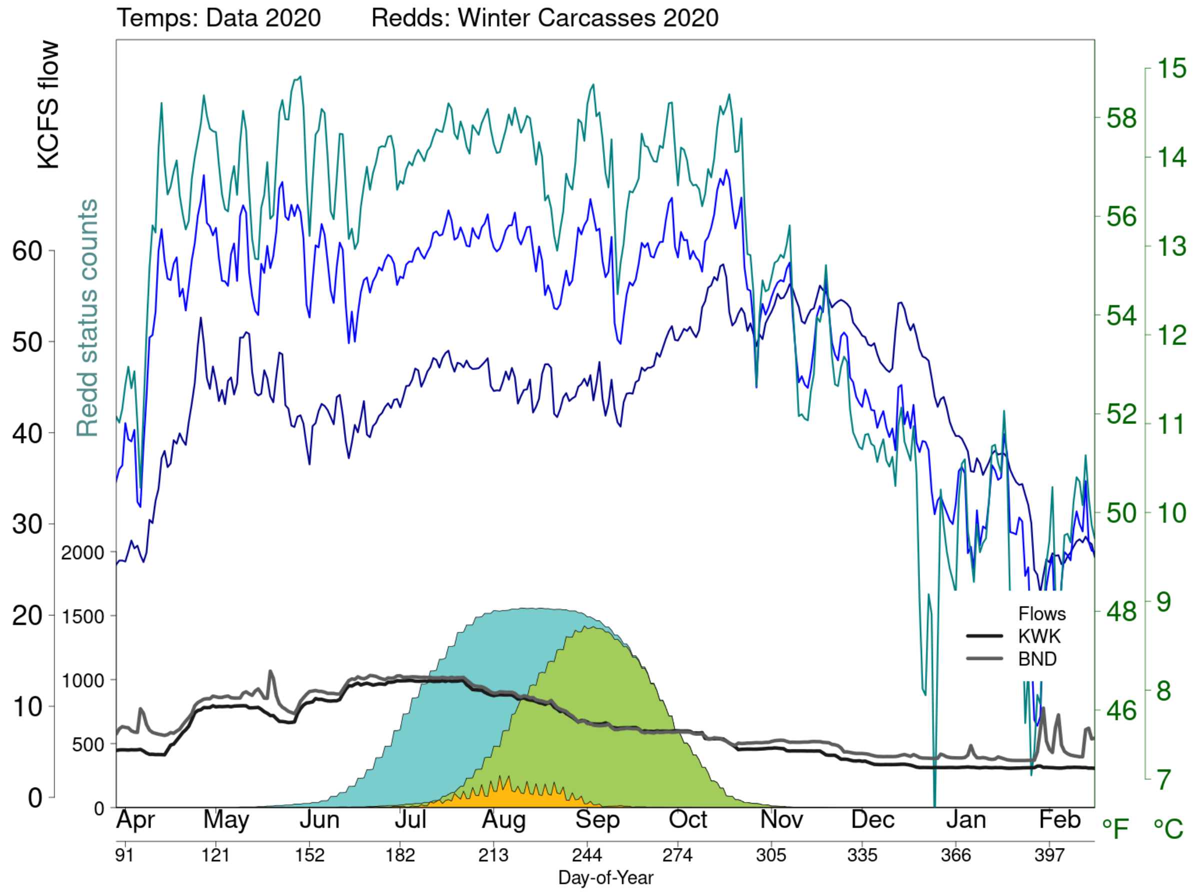


Figure 23b. Same as Figure 23a, but with fewer legends, no Tcrit line, and no "Gradient Flip" nor "Below Tcrit" markers, for better visibility of the data.

Temperature Timeseries Metrics

The historical, and/or forecast temperature profiles at various locations on the Sacramento River are shown in the timeseries plot after the Egg-to-Fry model is run.

Two particular events, in the autumn, that indicate that the river's thermal regime is changing: the day when the temperature gradient flips, and the day when the temperatures go below the T_{crit} threshold.

Gradient Flip: In the summer, water at KWK begins to warm as it moves downstream in response to air temperature. There is a gradient in temperature from upstream to downstream. As air temperatures cool in the autumn, eventually this process decays and reverses so that the water begins to cool as it flows downstream. This is the gradient flip and is identified as the first day on or after October 1, when this cooling pattern between the Keswick Dam (KWK) gage and the Balls Ferry (BSF) gage is observed for 7 days.

Threshold Day: T_{crit} is the temperature above which temperature-dependent mortality is significant. In the summer, water temperatures frequently exceed this value. As the autumn progresses, water passing KWK cools and eventually is less than T_{crit}. After October 1, when temperatures are below T_{crit} for 7 days, that day is identified as the threshold crossing day for T_{crit}.

Example: Winter Chinook development in 2022 is shown in Figure 24. The temperature gradient flipped over on Nov. 1 or 7 or more days, and the temperatures at KWK dropped below Tcrit (11.8 °C) on Dec 1 for 7 or more days. Note that there are other gradient-flip and threshold-crossing events.

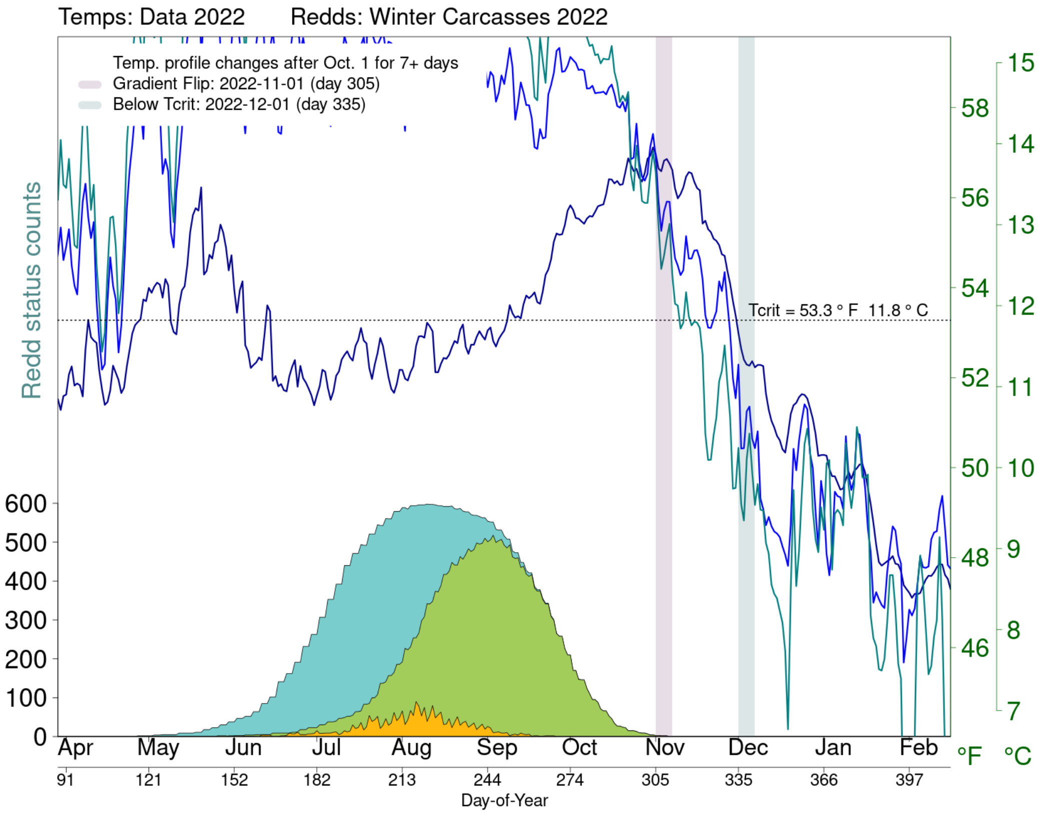


Figure 24. Example Egg-to-Fry Modeling output of the timeseries plot of environmental conditions showing the first threshold crossing and gradient flip events. The temperature gradient flipped on Nov. 1 or 7 or more days. Prior to this, temperatures warmed as the water moved downstream, and after this, temperatures cooled as the water moved downstream. The temperatures at KWK dropped below Tcrit (11.8 °C) on Dec 1 for 7 or more days. Note that there are other gradient-flip and threshold-crossing events that did not meet the criteria of being both after October 1 and for a duration of 7 days.

Linking Egg-to-Fry Model with River Migration and Survival Modeling

After the Egg-to-Fry Model is run, the outputs can be sent as inputs to the River Migration and Survival modeling GUI (**Error! Reference source not found.**).

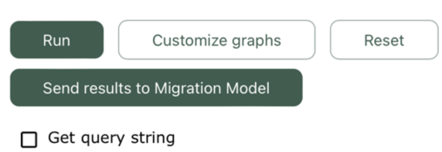


Figure 25. Controls for Egg-to-Fry Modeling allow results to be sent to the Migration and Survival modeling GUI.

4.1.2 Migration models

With the results from the Egg-to-Fry model run sent to Migration and Survival modeling, these outputs will be auto-populated as inputs on the webpage (Figure 26).

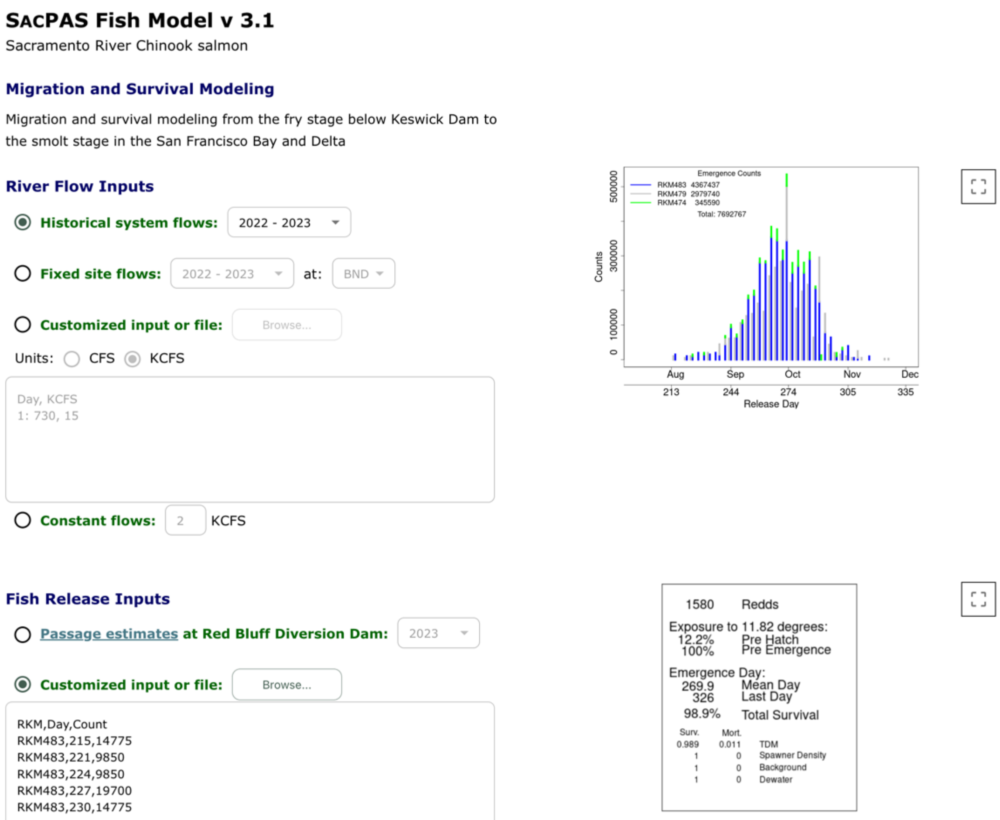


Figure 26. Example of Migration and Survival Modeling GUI with inputs coming from the Egg-to-Fry Modeling outputs.

Because the reach and life stage most relevant to river migration and survival modeling is in section 4.2, we describe the interface in more detail in that section.

Note that migration timing at RBDD, from redds (i.e., Egg-to-Fry Modeling) is an intermediate report at the end of the migration run (i.e., would need to run the whole migration model to Feather River; see the next section).

4.2 River Migration and Survival of Fry/Smolts (RBDD* to Feather River, and then to DCC or Chipps Island)

*From Redd Bluff Diversion Dam (RBDD), or
release location within Keswick Dam and RBDD, or
in Sacramento River at Deer or Mill creek confluences

4.2.1 GUI and Inputs

To help users at different levels of interest and experience with the SacPAS Fish Model, the entry points to River Migration and Survival modeling can be accessed via the Basic settings (Figure 27) or the Full settings (Figure 28). With Basic settings, the default migration model for the river reaches to Feather River is the linear model (section 3.1.2.1) and default survival is the XT model (section 3.2.1.2). With Full settings, the user can choose the survival model (sections 3.2.1 and 4.2.1.1), the migration model from release to Feather River (sections 3.2.1 and 4.2.1.2), and the migration model from Feather River to DCC or Chipps Island (sections 3.3.2 and 4.2.1.3). (See Figure 1 for an overview of how models are linked.)

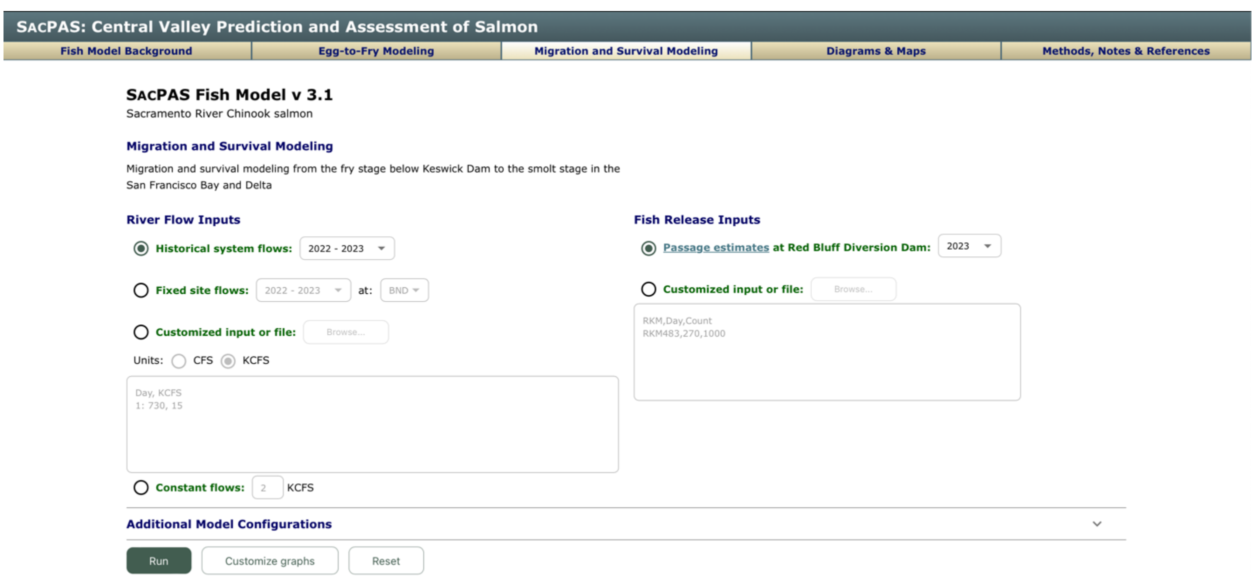


Figure 27. Screenshot of the graphical user interface of Basic settings of the River Migration and Survival modeling webpage in SacPAS Fish Model.

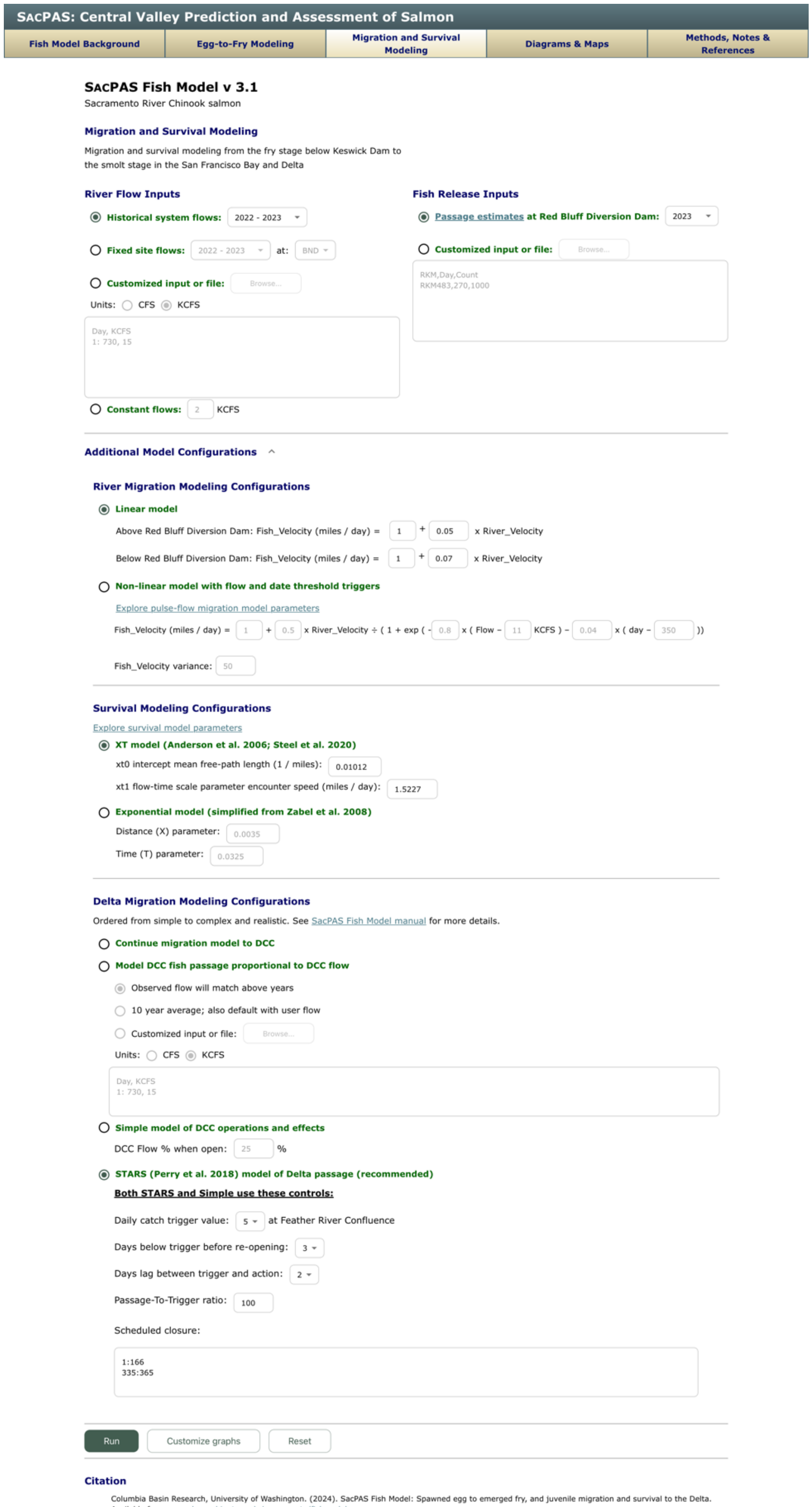


Figure 28. Expanded view of Additional Model Configurations for Full settings of River Migration and Survival modeling in SacPAS Fish Model.

At the top of the GUI is where users can input data for river flow and fish release (Figure 29).

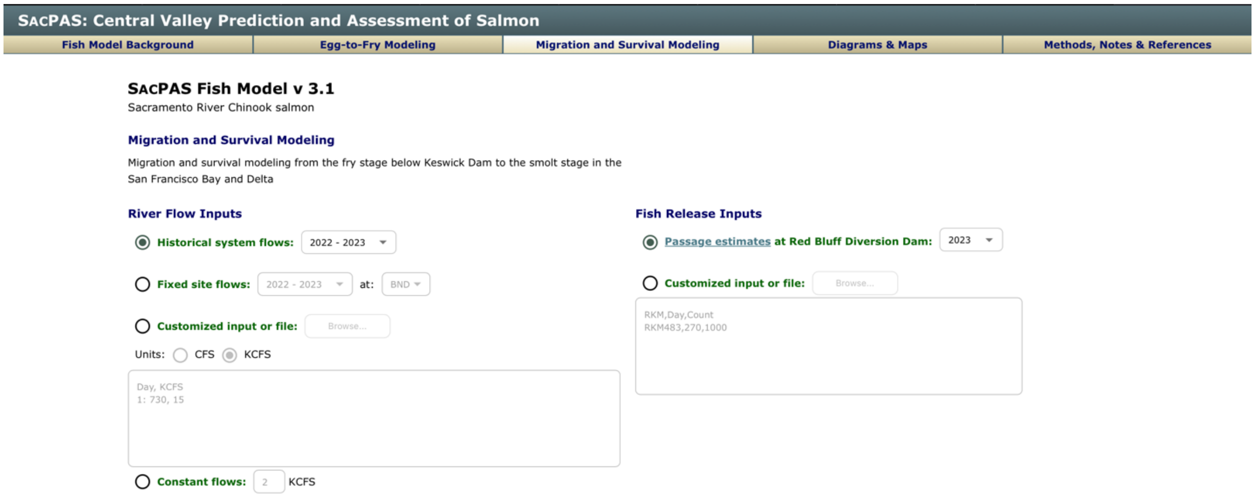
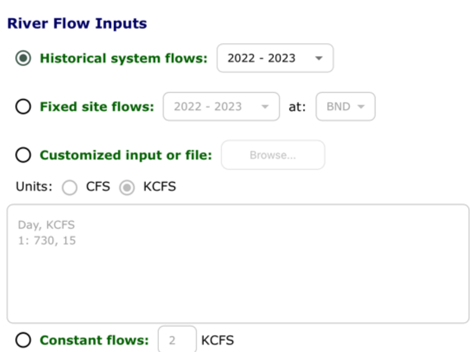


Figure 29. Input of river flow and fish release data for the Migration and Survival modeling of SacPAS Fish Model.

For river flow inputs, users can easily select from historical flows in a particular year. Or more specifically, fixed site flows from select locations (BND, FPT, KWK, VON, WLK; CDEC 2024; https://www.cbr.washington.edu:2024/sacramento/data/query_river_graph.html), by selecting from the dropdown:



Flow data may alternatively be entered as customized inputs through copy-pasted values, or file upload. Users can also specify a constant flow.

For the fish release data inputs, users can select from observed estimates at RBDD (https://www.cbr.washington.edu/sacramento/data/query_redbluff_daily.html), or enter customized inputs into the text box area (for more details on customized inputs, see Box 6). For the observed estimates, because of data gaps, the total biweekly estimates are used for an averaged daily estimate.

To visualize the spatial extent of the model and associated river temperature and flow covariates, the user can view the interactive map (Figure 30) or download the KML file named “sacramento.desc.kml” here for viewing Google Earth, Google Maps or other compatible programs.

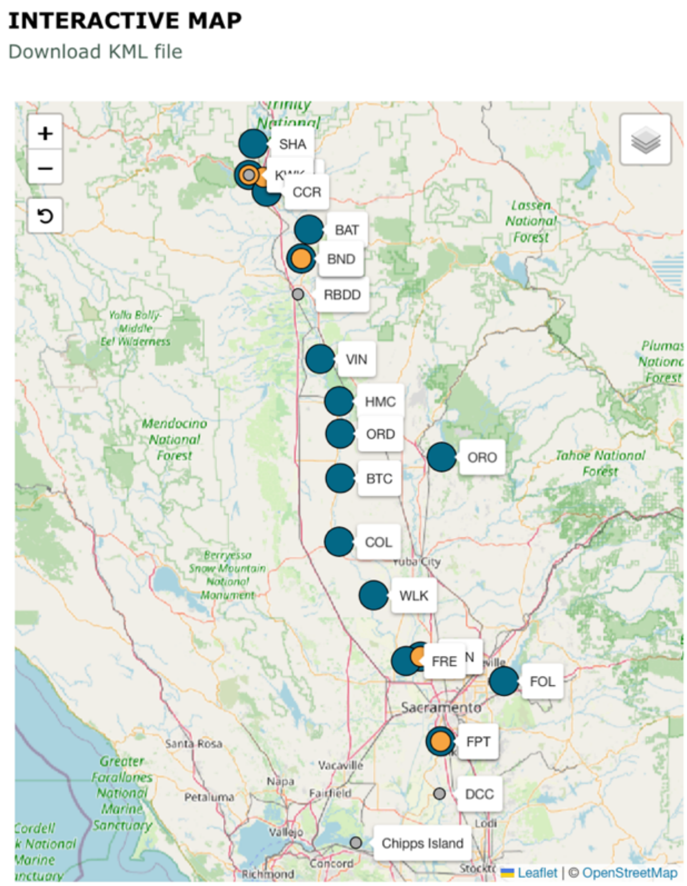


Figure 30. Interactive online map that shows the spatial extent of the SacPAS Fish Model and stations of associated river condition data.

4.2.1.1 Survival Models

In the Full settings (with additional configurations expanded), users can select either the XT model or the exponential (simplified, COMPASS) model (Figure 31).

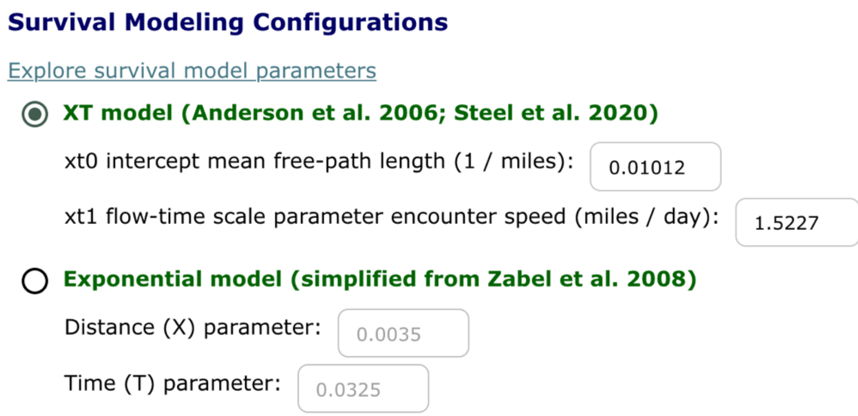


Figure 31. Survival model options on the Migration and Survival Modeling webpage, under the expanded model configurations section.

4.2.1.2 Migration Models to Feather River

In the Full settings (with additional configurations expanded), users can specify the migration model in river reaches to Feather River. Users can select either the linear model or the non-linear (pulse-flow) model (Zabel et al. 1998) (Figure 32).

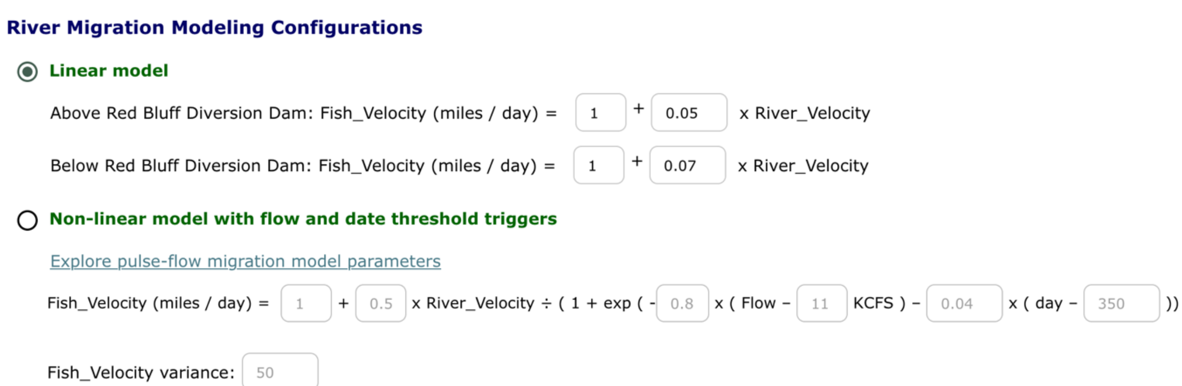


Figure 32. River migration model options on the Model and Survival Modeling webpage, under the expanded model configurations section.

4.2.1.3 Migration Models from Feather River to DCC or Chipps Island

Users can select one of four models for Delta migration modeling (Figure 33).

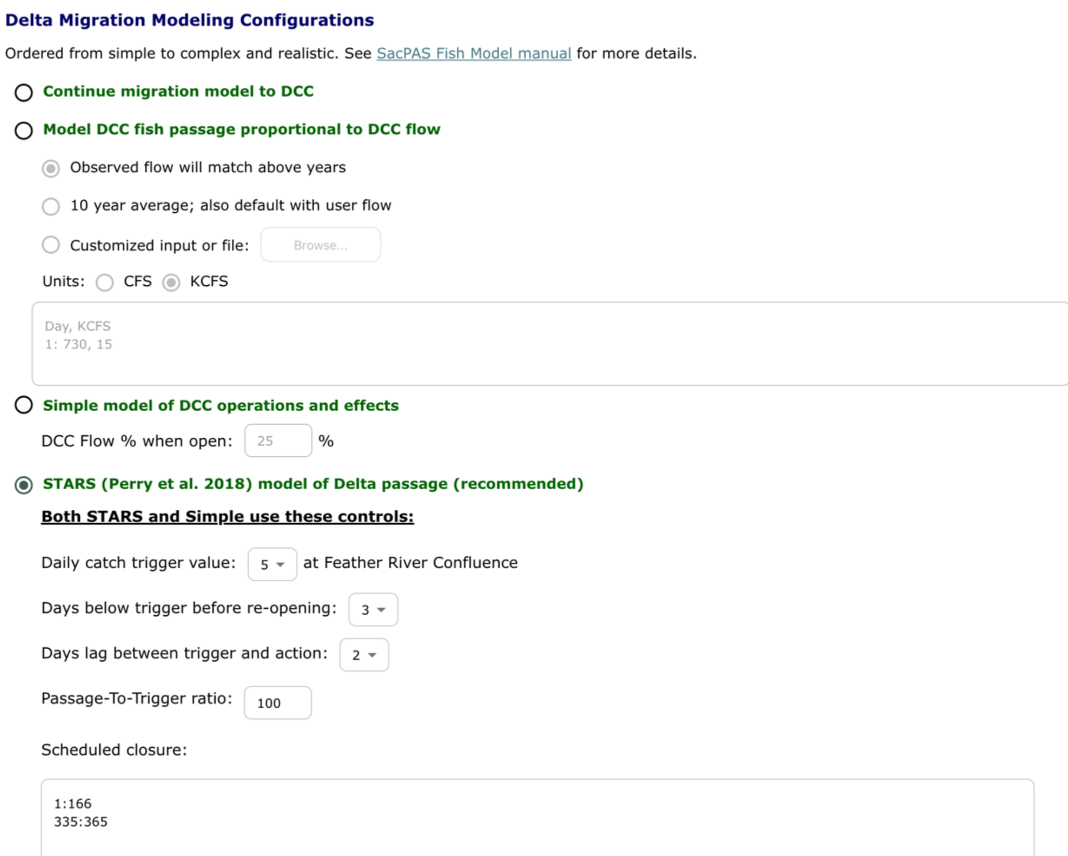


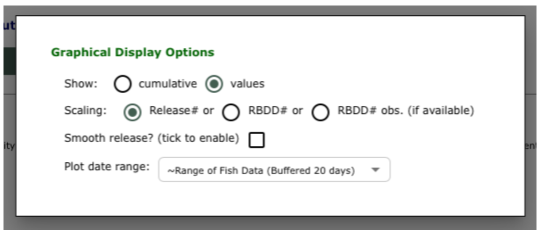
Figure 33. Delta migration models and configuration options on the Model and Survival Modeling webpage, under the expanded model configurations section.

With the third option (Simple Model of DCC operations and effects) and the fourth option (STARS Model), the user can set the daily catch trigger at Knights Landing. The default values are set to match what is in the LTO Biological Opinion (NMFS 2019a) as closely as possible (section 3.3.2.3)

Other Features

Users can click on "Customize Graph":

to select how they would like to see the outputs:



4.2.2 Results Outputs

In general, the outputs that the user gets after a run of Migration and Survival modeling are:

- summary results on the webpage,
- graphical outputs,
- links to text outputs, and
- downloadable results files.

More specifically, the River Migration and Survival modeling generates a timeseries plot with release counts, arrival distributions at three locations (Woodson Bridge State Recreational Area [RKM 425], Feather River [RKM 95], Delta Cross Channel [RKM 51]), flows used for the model run and a text summary of timing and survival at the three locations and a grand summary of modeling. If Egg-to-Fry model outputs were sent to the Migration and Survival modeling webpage as inputs, these estimates are also plotted in the graph (Figure 34). Colors in the timeseries plots match the text results to the side.

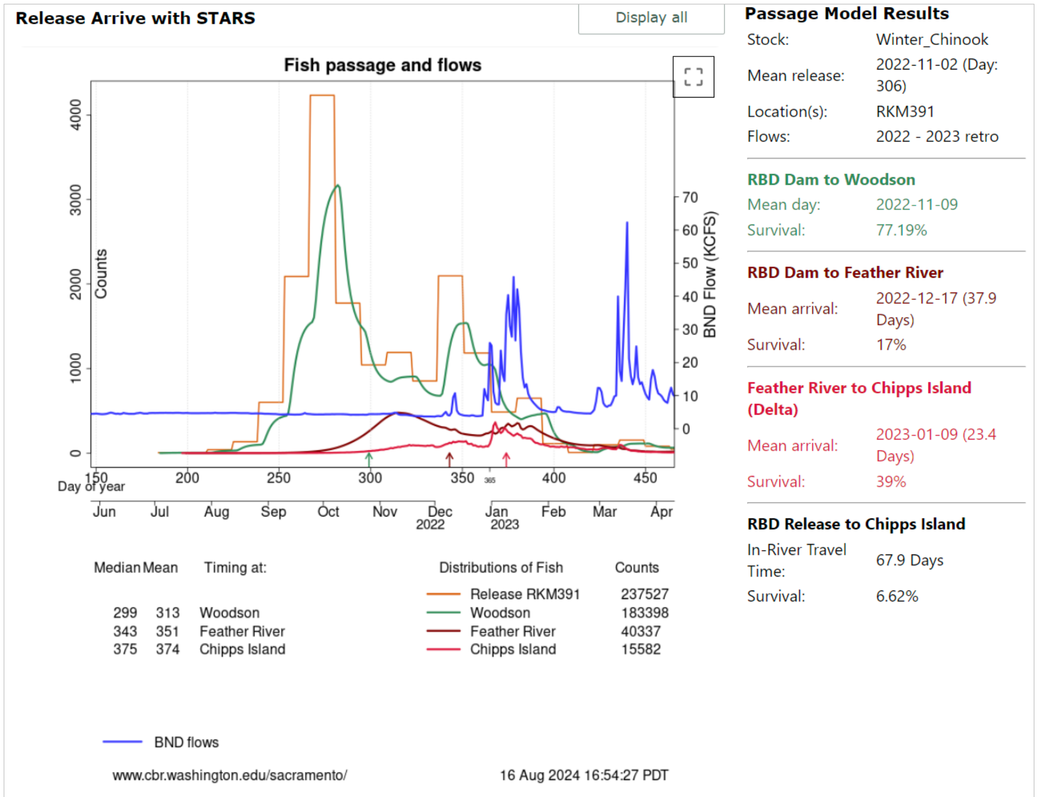


Figure 34. Example output from the Migration and Survival model which included the use of the STARS model (Perry et al. 2018) in the Delta. Text on the right side holds passage model results and the colors correspond to the passage distributions in the plots. The release is at RKM391 which is the Red Bluff Diversion Dam. Survival and travel time results at intermediate locations in the river are also depicted. Final survival and travel time to Chipps Island is summarized in black. The passage distributions show how the population moves downstream (see modes of individual timeseries), disperses, and suffers mortality (reduced counts). In this simulation, the RBD distribution is modelled to have 6.62% survival and requiring a mean travel time of 67.9 days.

At the bottom of the webpage, users can access model output text files to be viewed online or downloaded:

Model Run Related Files

summary.dat (Download file)

releaseuser.csv (Download file)

Passage.txt (Download file)

Download all files

Figure 35. Links to Migration and Survival Modeling outputs: Model Run Related Files.

The output results that the user sees depends on which of the four Delta model options chosen. The list of output values would look similar to the following:

- Continue migration model to DCC:

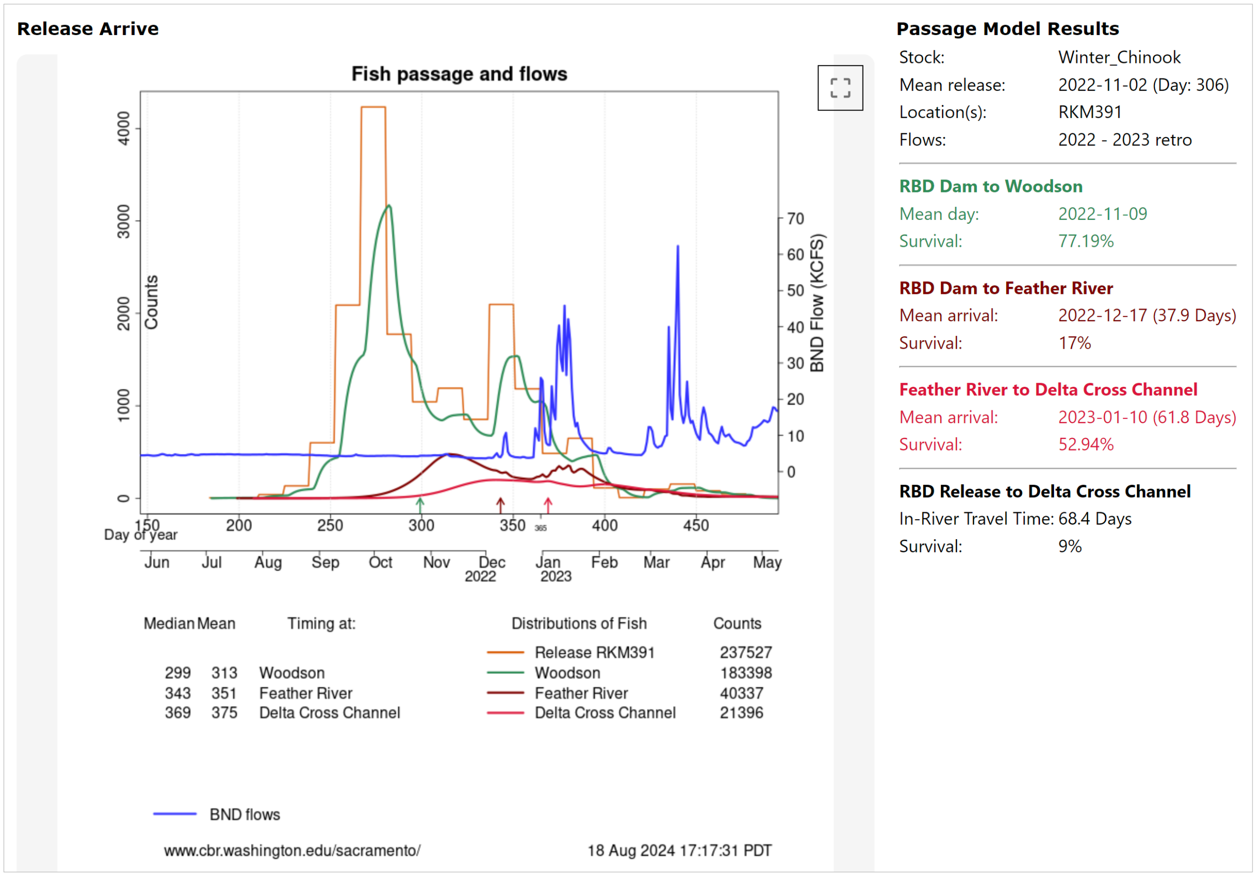


Figure 36. Example results, from SacPAS Migration and Survival Modeling, when Continue Migration Model to DCC is selected, as the Delta migration model.

Model DCC fish passage proportional to DCC flow:

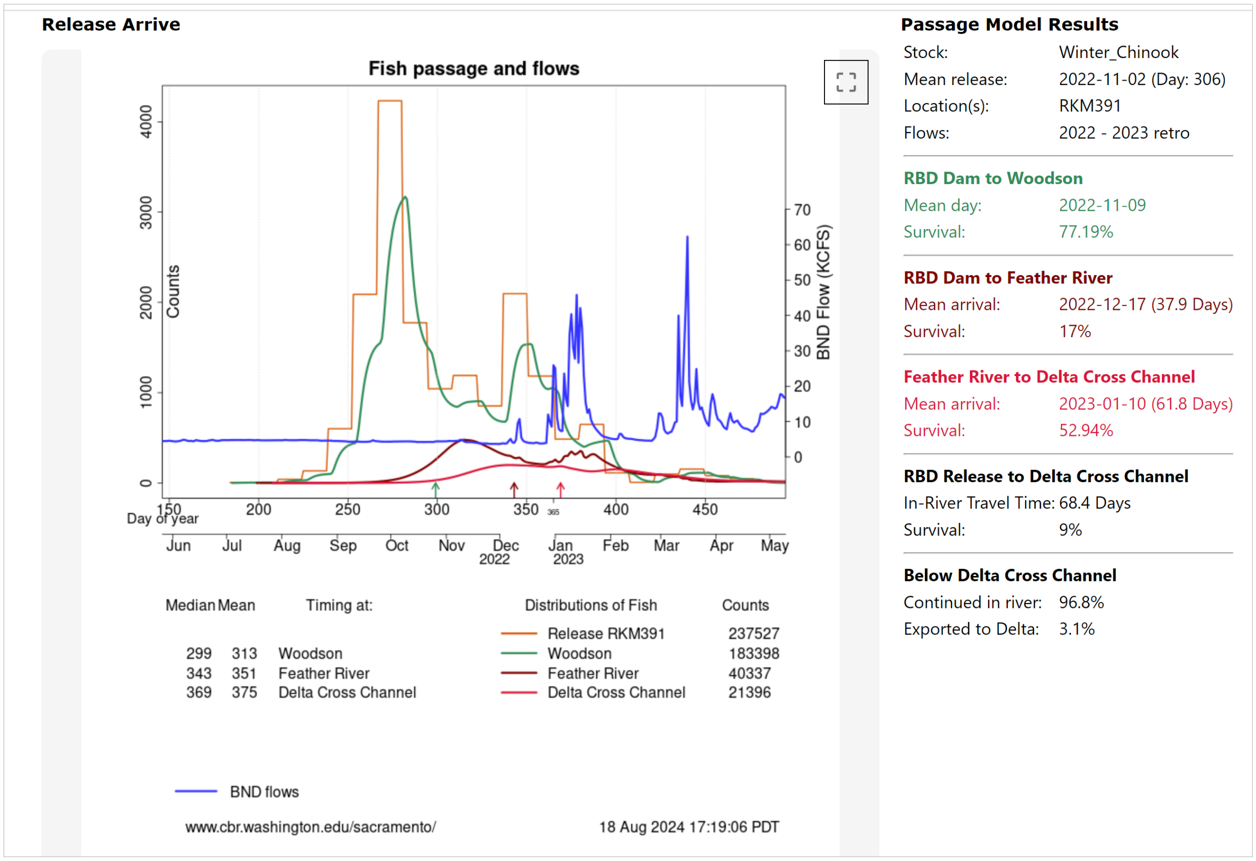
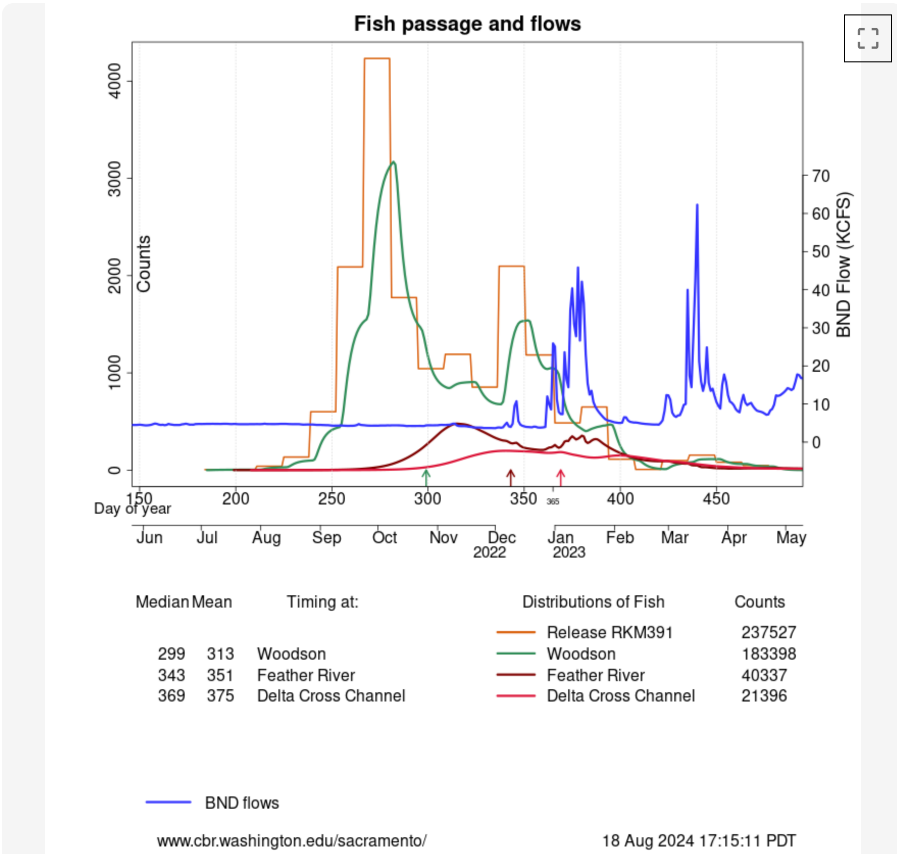


Figure 37. Example results, from SacPAS Migration and Survival Modeling, when Model DCC fish passage proportional to DCC flow is selected as the Delta migration model.

- Simple migration model of DCC operations and effects:

Release Arrive



Passage Model Results

Stock: Winter_Chinook
Mean release: 2022-11-02 (Day: 306)
Location(s): RKM391
Flows: 2022 - 2023 retro

RBD Dam to Woodson
Mean day: 2022-11-09
Survival: 77.19%

RBD Dam to Feather River
Mean arrival: 2022-12-17 (37.9 Days)
Survival: 17%

Feather River to Delta Cross Channel
Mean arrival: 2023-01-10 (61.8 Days)
Survival: 52.94%

RBD Release to Delta Cross Channel
In-River Travel Time: 68.4 Days
Survival: 9%

Below Delta Cross Channel
Continued in river: 99.4%
Exported to Delta: 0.5%

Figure 38. Example results, from SacPAS Migration and Survival Modeling, when Simple Migration Model of DCC operations and effects is selected as the Delta migration model.

- STARS model:

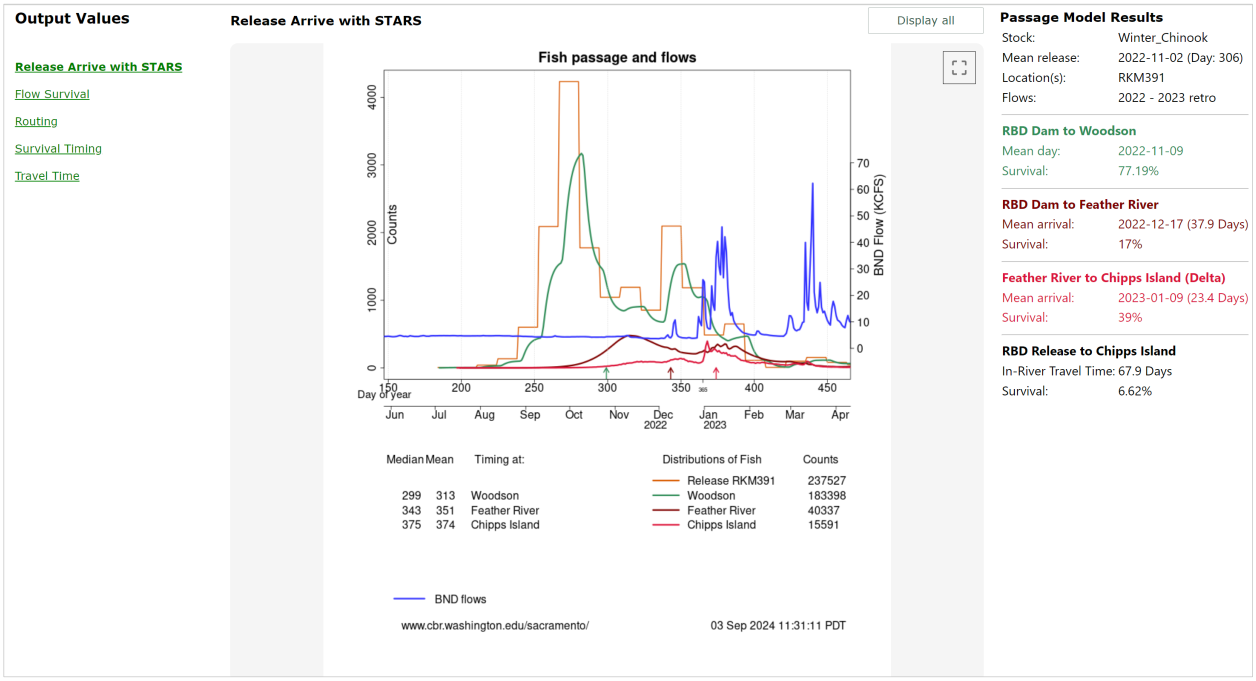


Figure 39. Example results, from SacPAS Migration and Survival Modeling, when STARS model (Perry et al. 2018) is selected as the Delta migration model.

For migration to DCC, when the results are displayed, details on the number of fish routed through the DCC are shown along with a sensitivity interpretation of the DCC routing to the selected trigger and the lag. There is a control to display either the absolute tradeoffs or relative tradeoffs. In the example below of absolute tradeoffs, the user selections: 2-day lag and 5-fish trigger (NMFS 2019a) are circled. As a result of this modeling, 1186 fish and 173 thousand-acre-feet (TAF) of water have entered the DCC before the gate closed. The other points in the grids are counts and water volumes respectively, that correspond to alternative lag and trigger values. E.g. choosing a trigger value of 3 fish would have resulted in a total of 134 fish and 56 TAF of water going through the DCC.

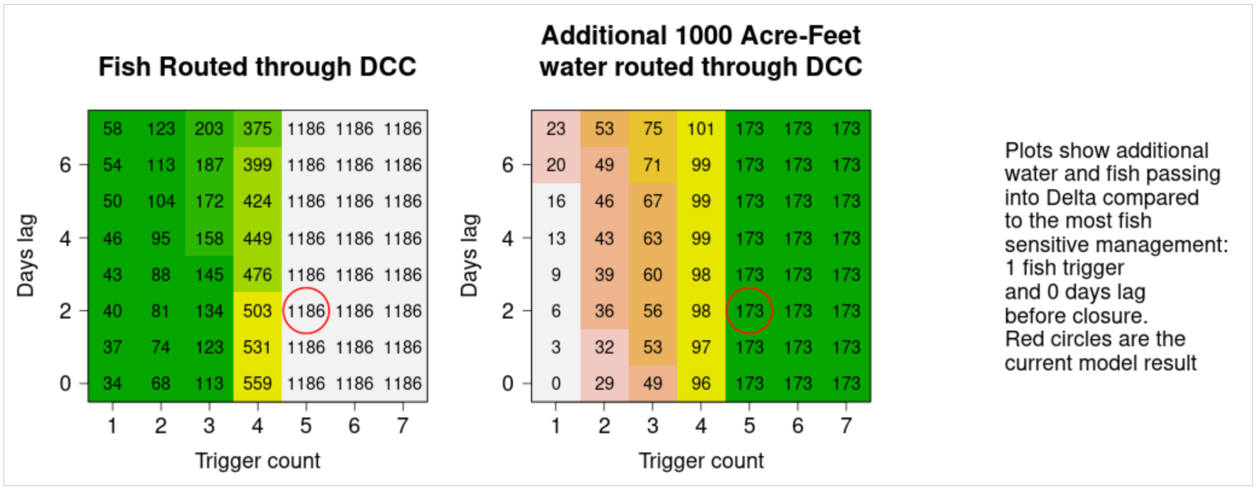


Figure 40. Example results of water routing and fish passage tradeoffs for user-selected DCC operations based on the number of fish that trigger a DCC gate closure and the number of days lag allowed before the DCC gate is closed after the trigger condition is met.

STARS model of Delta passage

With this method the migration model terminates at the Feather River confluence and the outputs are converted to inputs for the STARS model (Perry et al. 2018). STARS uses the catch trigger, passage-to-trigger ratio, time lag, and schedule described above to control operations of the DCC. It then computes the routing, travel time, and survival of fish to Chipps Island routed though the Lower River, Georgiana Slough, Steamboat Slough and the Delta.

Four plots illustrate the timeseries of environmental conditions and fish status: Survival and Freeport River flow and Survival through the four Delta routes (Figure 41); Survival Timing, Abundance entering the Delta, and Abundance and Survival rate exiting the Delta (Figure 42); Travel Time: Median travel time for fish entering each of the four Delta routes (Figure 43); and Routing, Cumulative routing through the four Delta routes (Figure 44).

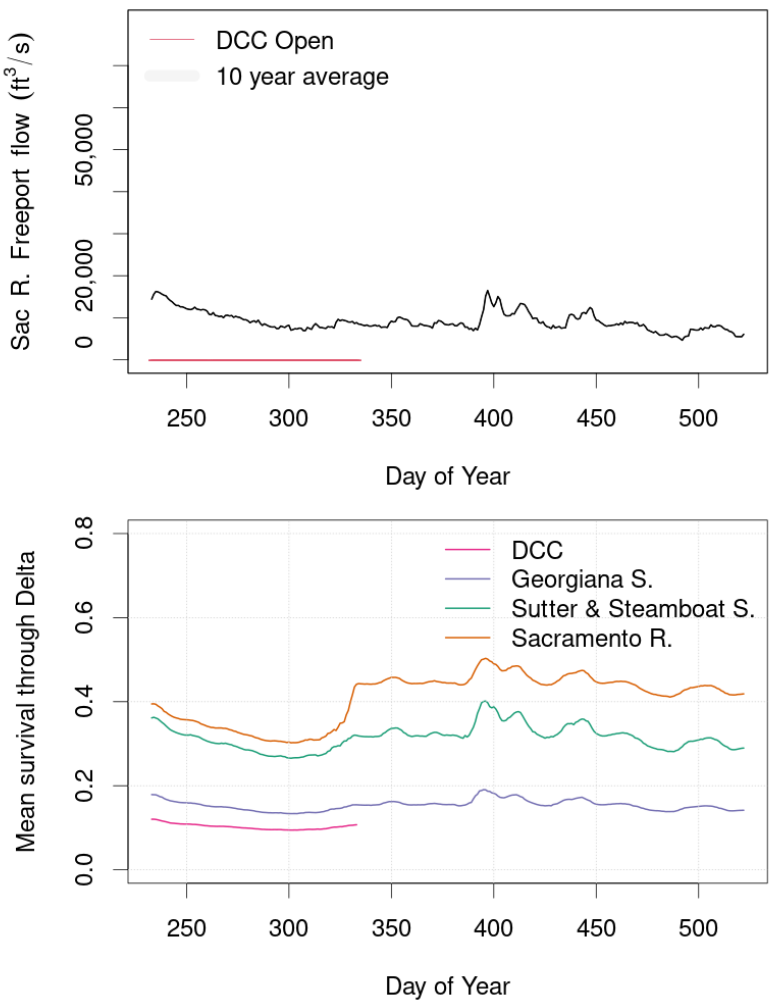


Figure 41. STARS model (Perry et al. 2018) output plots showing timeseries of flow in the Sacramento River at Freeport (above) and mean survival through the Delta via various passage routes that vary in time. On all days of the year, survival in the Sacramento River to Chipps Island (orange line) is higher than via other routes. The end of the DCC passage period occurs when the gate is closed according to the criteria specified by the user, and the DCC survival line ends. Fish entering the DCC have the lowest survival to Chipps Island than via other routes, and survival through the Georgiana Slough is also lower that the Sacramento River or Sutter and Steamboat Slough routes. Lower survival is also associated with longer travel time (see Figure 43).

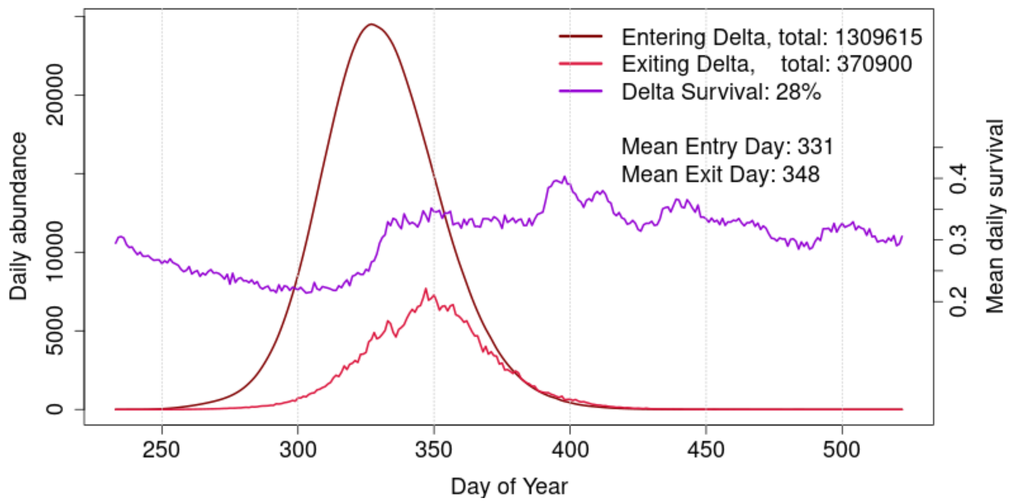


Figure 42. Example of STARS model (Perry et al. 2018) output showing survival and passage timing through the Delta. The brown line shows the modelled distribution of arrivals entering the Delta in the STARS model. The purple line depicts the day-to-day survival of fish and the red distribution line depicts the number passed as a function of the arrival timing and the day-to-day survival.

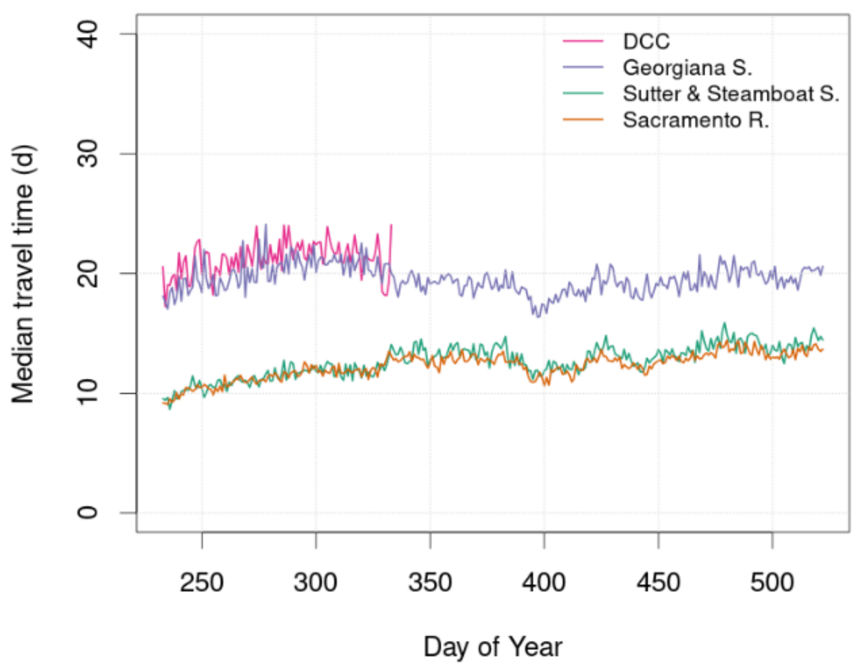


Figure 43. STARS model (Perry et al. 2018) output travel time example. On each day for which the STARS model is computing travel time and survival, the travel time through the four routes is plotted from the Delta entry point to Chipps Island. Sacramento River travel time and the Sutter and Steamboat Slough travel times are very similar (green and orange). Fish routed through the DCC or into Georgiana Slough have longer travel times (pink and purple). The DCC gate closes during the simulation with the user-provided criteria and therefore travel time is not computed for this route after this time. The longer travel times are also associated with poorer survival compared to other routes (see Figure 41).

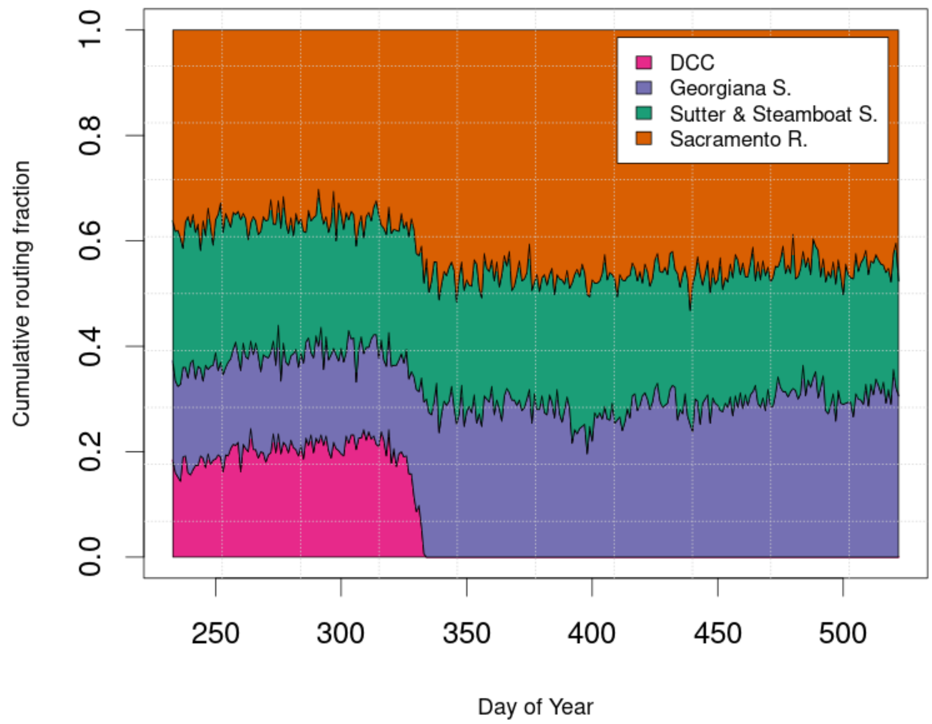


Figure 44. STARS model (Perry et al. 2018) output Delta routing example. Fish on each day are separated into one of four routes with the STARS model and the relative proportions are shown in colored bands. When the DCC gate closes, fish remain in the Sacramento River and the transition is shown as an increase in the Sacramento River proportion (orange) and the end of DCC routing (pink).

After the migration model completes, several files with additional details are generated: summary.dat, TravelStats.txt, releaseuser.csv, and Passage.txt.

summary.dat: This file has detailed results generated by the migration model which is built on the COMPASS platform (Zabel et al. 2008) and configured for use in the Sacramento River. These results summarize the population's status through each reach including survival and travel time. An example is shown in Figure 45.

The following points are some important details for interpreting these results directly:

1. This is an output file generated by the COMPASS model with details on each component of the river system for which it is configured. COMPASS includes methods for modeling and supporting various dam passage routes and outcomes and if they do not apply for any particular component, then a "0.00" indicates that are no values for this metric.
2. COMPASS model outputs are extracted by the Migration Model for Delta passage modeling. For Delta passage modeling with STARS, the results at the internally named Verona reach are used as inputs, otherwise the results for the Delta Cross Channel are reported to the user. The Verona reach represents the river between the Feather River confluence and Knights Landing.
3. COMPASS moves the fish with an advection-diffusion algorithm. A consequence of this is that the timing of fish passage at each location is described as a distribution with tails that extend beyond the timeframe of the model. In final reporting, the fish in these tails are censored and the outputs truncated. In order to reduce this effect on actual number of fish in the results, the user's release counts are scaled upward in the Migration Model according to these rules:
   A release of 1 to 9,999 fish is scaled by 1000 before modeling.
   A release of 10,000 to 99,999 is scaled by 100 before modeling.
   A release of 100,000 to 999,999 is scaled by 10 before modeling.
   A release of 1,000,000 to 9,999,999 is *not* scaled.
   A release of > 100,000,000 fish is not valid and generates an error.

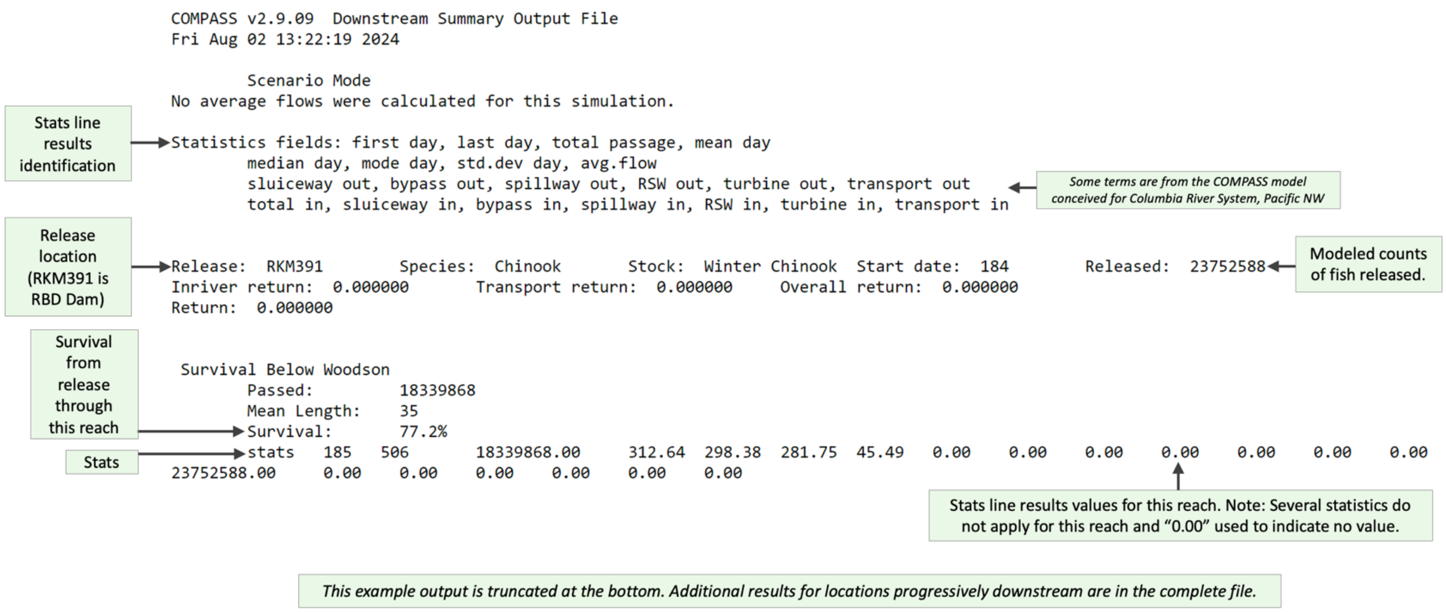


Figure 45. Sample of the top of the summary.dat file (Migration and Survival Model results) with annotations.

TravelStats.txt: This file is a compact, machine-readable, tab-formatted table of the reach statistics ("stats") found in the summary.dat file described above.

releaseuser.csv: This file has the complete details of the release of fish used to initiate the migration model run. It has the format described in Box 9.

Passage.txt: This file is a compact, machine-readable, tab-formatted table of the modeled counts at each reach. This is the "Expanded Count", i.e. scaled-up counts of fish (see above). Reaches that are not modeled have NA in the Expanded count column. In the example below, the release is at RKM391 as indicated by the first part of the stock name, and this corresponds to Red Bluff Diversion Dam (RBD.Dam). Because the Spawning Ground, Balls Ferry, and Bend reaches are all upstream of the RBD dam, there are no results for these reaches as indicated by NA. The first reach where results are reported is the reach downstream of RBDD (Woodson). The Delta Cross Channel is downstream of the reach named Sacramento and inherits the values from that reach, because no additional mortality nor delay is applied.

```
Stock                Passage              Expanded count
RKM391.Winter.Chinook Release               23752588
RKM391.Winter.Chinook Spawning.Grounds            NA
RKM391.Winter.Chinook Balls.Ferry                 NA
RKM391.Winter.Chinook Bend                        NA
RKM391.Winter.Chinook RBD.Dam                     NA
RKM391.Winter.Chinook Woodson               18339868
RKM391.Winter.Chinook Above.Big.Chico       13954146
RKM391.Winter.Chinook Colusa                 8196653
RKM391.Winter.Chinook Knights.Landing        4437415
RKM391.Winter.Chinook Verona                 4033700
RKM391.Winter.Chinook Airport                3213360
RKM391.Winter.Chinook Sacramento             2139654
RKM391.Winter.Chinook Delta.Cross.Channel    2139654
```

Box 6. Customized inputs in text box area and upload file formats for redd data

Redd distributions for user-generated scenarios are implemented by selecting "Customized input or file" for the Redds distribution. User's data can be typed directly into the text area, pasted from another text file, or uploaded from a file on the user's computer.

The redd distribution format requires two or more columns, separated with commas, which includes a header row and one or more data rows. The first column is the day-of-year, and redd counts at each location are in subsequent columns identified by the column heading for the location as a river kilometer (RKM). The column heading format is 6 characters beginning with "RKM" and followed by three digits for the river kilometer position of the redds, e.g. RKM483.

Data rows begin with the day-of-calendar-year which can range over a two-year period because spawn timing of Chinook in the Sacramento River may span the calendar year. The data for each day, in each column, are the number of redds at the corresponding location, which must be positive, whole numbers. Each data point must be an integer (zeroes are accepted). The text area has an example of the required format and Table 6 is an example of redd data in a CSV file displayed in a spreadsheet application.

Table 6. Example of redd distribution data in a spreadsheet application.

Day	RKM483	RKM479	RKM470
135	0	1	0
142	0	1	0
163	0	1	0
171	0	1	0
177	2	2	5
184	0	0	1
191	1	3	2
199	10	19	7
205	3	4	0
214	1	0	0

Box 7. Customized inputs in text box area and upload file formats for temperature data

In the Egg-to-Fry Model, the user can create scenarios of temperature conditions. These data can be pasted into text areas on the model page or uploaded from files on the user's computer. Both upload and input data require plain text, comma-separated variable formats.

Temperature data format has two or more columns, separated with commas. The format includes a header row and one or more data rows. The first column is the day-of-year, and location names are in the header of subsequent columns. The location names are identified by river kilometer (RKM) with 6 characters such as: "RKMxxx" where xxx is numeric. Only integer values for river kilometer are allowed.

Data rows begin with the day-of-calendar-year which ranges over a 2-year (or 730-day) period because spawning often spans the calendar year. The data for each day, in each column, are temperature values which must be positive. Values can be designated in units of °C or °F, controlled by a radio button selection. Missing temperature locations that correspond to a redd location are filled in by the fish model with a distance-weighted linear interpolation between the two nearest locations based on RKM, for each day, as needed.

Historical data from the SacPAS database will have a header row and 730 data rows, with values at different river positions identified by the river kilometer location in the header. This format can be used in an uploaded file or typed into the text box area (Table 7).

User-generated data can be condensed into a compact format that meets the 730-day requirement for temperature data. It can have dummy values outside the range of days of interest, and gradients of temperature through time. Blocks of days can be condensed with format: "first_day:final_day" where subsequent columns are values at different river positions identified by the river kilometer location in the header. When the condensed day format is used, temperature value gradients can also be specified with the condensed format as "value1:value2" which will interpolate the temperature values for each day over the range of days found in the first column. Values for missing days are filled-in by the fish model with linear interpolation between specified days, and missing days at the beginning or end of the provided data are filled in with the corresponding first or last value available. Each line of data may also have spaces for ease of readability. Figure 46 illustrates the compact format. In this example, days 1:82 would be filled with 10, and 12 respectively for the 2 locations and days 366:730 would be filled with 10.1 and 12.1 respectively.

A Shiny app specifically designed for generating these data and visualizing the temperature profile with a graphical interface can be accessed at: https://cbr.washington.edu/SHINY/TEMPMAKER/.

Table 7. Example of a spreadsheet format of temperature data with a single value for each day at five locations. This example is truncated to day 8.

Day	RKM485	RKM465	RKM444	RKM415	RKM391
1	9.807	9.333	8.312	7.831	7.657
2	9.701	9.127	8.118	7.615	7.342
3	9.557	9.273	8.543	7.99	7.506
4	9.537	9.511	8.898	8.969	8.703
5	9.534	9.745	9.62	9.618	9.372
6	9.56	9.564	9.659	9.784	9.731
7	9.615	9.611	9.854	9.793	9.585
8	9.601	9.516	9.562	9.611	9.662

```
Day,  RKM483,  RKM470
83:125,    10:12.5,    12:14.5
126:323,  12.5:12.7,  14.5:14.7
324:365,  12.7:10.1,  14.7:12.1
```

Figure 46. Example of compact temperature data format used in the customized input text area for temperature data.

Box 8. Customized inputs in text box area and upload file formats for flow data

The user can create scenarios of flow conditions for computing redd dewatering in the Egg to Fry Model, as well as computing fish travel time and survival in the Migration and Survival Model, both outside and inside the DCC. These data can be pasted into text areas on the model page or uploaded from files on the user's computer. Both upload and input data require plain text, comma-separated variable formats.

The flow data are formatted with two columns, separated with commas. The format includes a header row and one or more data rows. The first column is the day-of-year, and the second column can have a user-defined name. Data rows begin with the day-of-calendar-year which ranges over a two-year (730 day) period because modeling often spans the calendar year. The data for each day are flow values in units of KCFS or CFS, controlled by a radio button selection. Negative values are not allowed, with the exception of those in flow data for computing DCC fish passage, where they are treated as zero, due to tidally influenced flows in the DCC that cause true negatives.

Historical data from the CBR database will have a header row and 730 data rows, with values at different river positions identified by the river kilometer location in the header. This format can be used in an uploaded file or typed into the text box area.

User-provided data from an uploaded file or typed into the text box area can be condensed into a compact format. It can have dummy values outside the range of days of interest, and gradients of flow through time. Blocks of days can be condensed with format: "first_day:final_day" where the second column has values for flow. When the condensed day format is used, flow value gradients can also be specified with the condensed format as "value1:value2" which will interpolate the flow values for each day over the range of days found in the first column. Values for missing days are filled-in by the fish model with linear interpolation between specified days, and missing days at the beginning or end of the provided data are filled in with the corresponding first or last value available. Each line of data may also have spaces for ease of readability. **Figure 48** illustrates the compact format. In this example, days 1 to 119 would be filled with 20, and days 181 to 730 would be filled with 10.

Day	KCFS
1	3.31
2	3.3
3	3.29
4	3.4
5	3.7

Figure 47 Example (truncated) of flow data format for redd dewatering.

```
Day, KCFS
120:180, 20:10
```

Figure 48. Example of customized compact flow data format. Over days 120 to 180, the flow will drop uniformly from 20 KCFS to 10 KCFS. Days 1-119 will be at 20 KCFS and days 181-730 will be at 10 KCFS.

Box 9. Customized inputs in text box area and upload file formats for migration release data

The migration release data are formatted in three columns, separated with commas. Spaces are not allowed. The format includes a header row and one or more data rows. The header of the data must read: "RKM,Day,Count". Each data row has three attributes: First, the location identified by river kilometer (RKM) with 6 characters such as: "RKMxxx" where xxx is numeric. Only integer values for river kilometer are allowed. There are some restrictions on the release locations. The acceptable RKMxxx values are shown in Figure 3.

The second attribute is the day-of-calendar-year which can range from 1 to 730 in order to enable migration modeling that spans two calendar years.

The third attribute is the count of fish released for the corresponding day and location, which must be a positive, whole number. A given location can have multiple releases on distinct days and zero is a valid count value. In addition, any records with identical location and day are valid and summed internally before modeling.

If the Egg to Fry Model was run prior to the Migration Model, then this text box area is filled with results from Egg to Fry model.

Data that are not formatted as detailed in Box 6 through Box 9 will often trigger error messages. Given the many possible inputs, certain data formatting errors may not be accompanied by an error message and, instead, the model may make assumptions about the intended format; therefore, following the defined format is recommended.

```
RKM,Day,Count
RKM483,234,9811
RKM483,240,4905
RKM483,246,4876
RKM483,249,9752
RKM483,255,39006
```

Figure 49. Example of customized inputs for migration release data. The three columns, separated by commas show the location, day-of-year, and count of fish.

Box 10. Multi-year redd distribution groups

Historical redd distributions can be combined to create hypothetical redd distributions for scenario modeling purposes. Certain redds combinations have been predetermined and are available for the user. These can be selected from the “Redds” drop-down selection menu (Figure 50).

The combinations are: 10-year ranges (2003-2012 and 2013-2022), a five-year range (2018-2022), and groups of years that correspond to historical Water Year Hydrologic Classification Indices (HCI). The HCI is based on the historical, measured, unimpaired runoff in the Sacramento Drainage as defined by the California Department of Water Resources (https://cdec.water.ca.gov/reportapp/javareports?name=WSIHIST, see Table 8).

Redd distributions from HCI year types are combined to generate a spawning scenario that corresponds to water year types. The Water Year extends from October 1 in the previous calendar year to September 30. Depending on the beginning of the spawning season, the water year and calendar year may differ. The run-year designations correspond to the month of first spawning for the stock, regardless of its peak (Table 9). For Winter-run Chinook, the calendar-year and water-year are the same. Fall and Late-Fall runs are different. E.g. Late-Fall Chinook Salmon began spawning in December 2020 as confirmed with an aerial survey. This corresponds to water year 2021, a “Critical” year. Multi-year groupings of redds that include “Critical” years would have this one included.

Historical redd distributions can be combined according to these criteria: “Wet”, “Above Normal”, “Near Normal”, “Dry”, and “Critical”, and some combinations of these: “Critical or Dry”, ”Critical, Dry, or Below Normal”, and “Above Normal or Wet” (Table 10).

Individual years, multi-year aggregates and HCI compositions are available for the Winter Chinook carcass survey and the Winter, Spring, Fall, and Late-Fall Chinook aerial surveys. For calendar year 2021 (water year 2022), there were no surveys for Fall and Late-Fall Chinook. For 2022 there was no survey for spring Chinook.

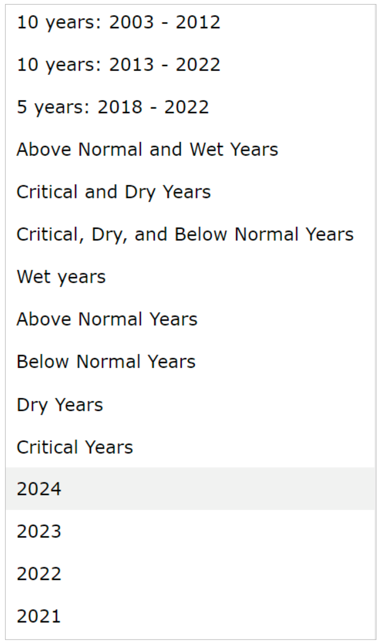


Figure 50. Top of the Redds drop-down year selection menu with redd distributions for individual years or cumulative combinations of redds for groups of years.

Table 8. Hydrologic Classification Indices (HCI) for the Sacramento Drainage (California Department of Water Resources (https://cdec.water.ca.gov/reportapp/javareports?name=WSIHIST).

Water Year	Index	Type	Water Year	Index	Type
2001	5.9	Dry	**2012**	6.9	Below Normal
2002	6.5	Dry	**2013**	5.8	Dry
2003	8.0	Above Normal	**2014**	4.0	Critical
2004	7.7	Below Normal	**2015**	4.0	Critical
2005	7.4	Below Normal	**2016**	7.1	Below Normal
2006	13.0	Wet	**2017**	14.9	Wet
2007	6.2	Dry	**2018**	7.2	Below Normal
2008	5.4	Critical	**2019**	10.2	Wet
2009	5.5	Dry	**2020**	6.0	Dry
2010	6.9	Below Normal	**2021**	4.0	Critical
2011	10.0	Wet	**2022**	4.5	Critical

Table 9. Calendar year and water year relationship for Chinook spawning seasons in the Sacramento River.

Chinook salmon run	Typical season beginning	Applicable water year
Winter-Run	May	same as calendar year
Spring-Run	October	next year
Fall-Run	November	next year
Late-Fall-Run	December	next year

Table 10. Summary of water year designations for purposes of aggregating historical spawning distributions over the years 2001- 2022.

Compositions available:	Number of years included:
Critical	5
Dry	6
Below Normal	6
Above Normal	1
Wet	4
Critical, or Dry	11
Critical, Dry, or Below Normal	17
Above Normal, or Wet	5

5 EXAMPLE RESULTS & INTERPRETATIONS Section

5.1 Egg-to-Fry Model Survival and Emergence

We provide some examples of Egg-to-Fry model outputs for comparison between years with different hydrological classification indices (HCI), and model outputs for comparison between Anderson et al. (2022) and Martin et al. (2017) methods. We then provide some results from four different models of egg emergence to gain an impression of sensitivity.

5.1.1 Egg-to-fry model output comparisons

Comparing two different types of water years (or HCI), can give a sense of the range of predicted survivals temperature-dependent mortality (Anderson et al. 2022) across years. Comparing a critical year (2015) to a wet year (2023) shows that the eggs at hatching and the emerged fry were exposed to temperatures above the critical threshold in 2015, and not in 2023 (Figure 51c,d,e,f). The temperature-dependent mortality in the egg and pre-emergent fry was very high in 2015, but non-existent in 2023 (Figure 51i,j). For further comparison, in 2014, an HCI-designated critical year, mortality was moderately high at about 60% (Figure 52i), even if all of the eggs at hatching (Figure 52c) and emerged fry (Figure 52e) were exposed to high temperatures. In 2020, a dry year, a proportion of redds had eggs exposed to high temperatures (Figure 52d), and all of the emerged fry were exposed to high temperatures (Figure 52f), but the predicted survival was nearly 100% (Figure 52j). Thus, exposure to temperatures above the critical thermal limit in pre-emergent fry does not necessarily result in temperature-dependent mortality and survival could remain quite high. Still, in critically warm and dry years, survival of eggs and pre-emergent fry can be very low to moderately high.

In comparing outputs from the Anderson et al. (2022) and Martin et al. (2017) models, we see higher survival from the former (which has a critical thermal window only occurring right before hatching) than the latter (which has a critical thermal window through the whole incubation period; Figure 53a-f). This pattern still occurs with effects from spawner density and background mortality included in the model (Figure 53g-h). Note that in these examples (Figure 53), the parameter values and default values are those from calibration of the studies, and the critical temperature threshold was changed from 12.14 °C (or 53.85 °F) to 11.82 °C (or 53.28 °F) so that the outputs were more directly comparable between models.

For further exploration of survival based on the Anderson et al. (2022) and Martin et al. (2017) methods, see the EGG_SURV Shiny app (https://www.cbr.washington.edu/shiny/EGG_SURV/; Figure 54).

2015 (HCI = critical year type):

2023 (HCI = wet year type):

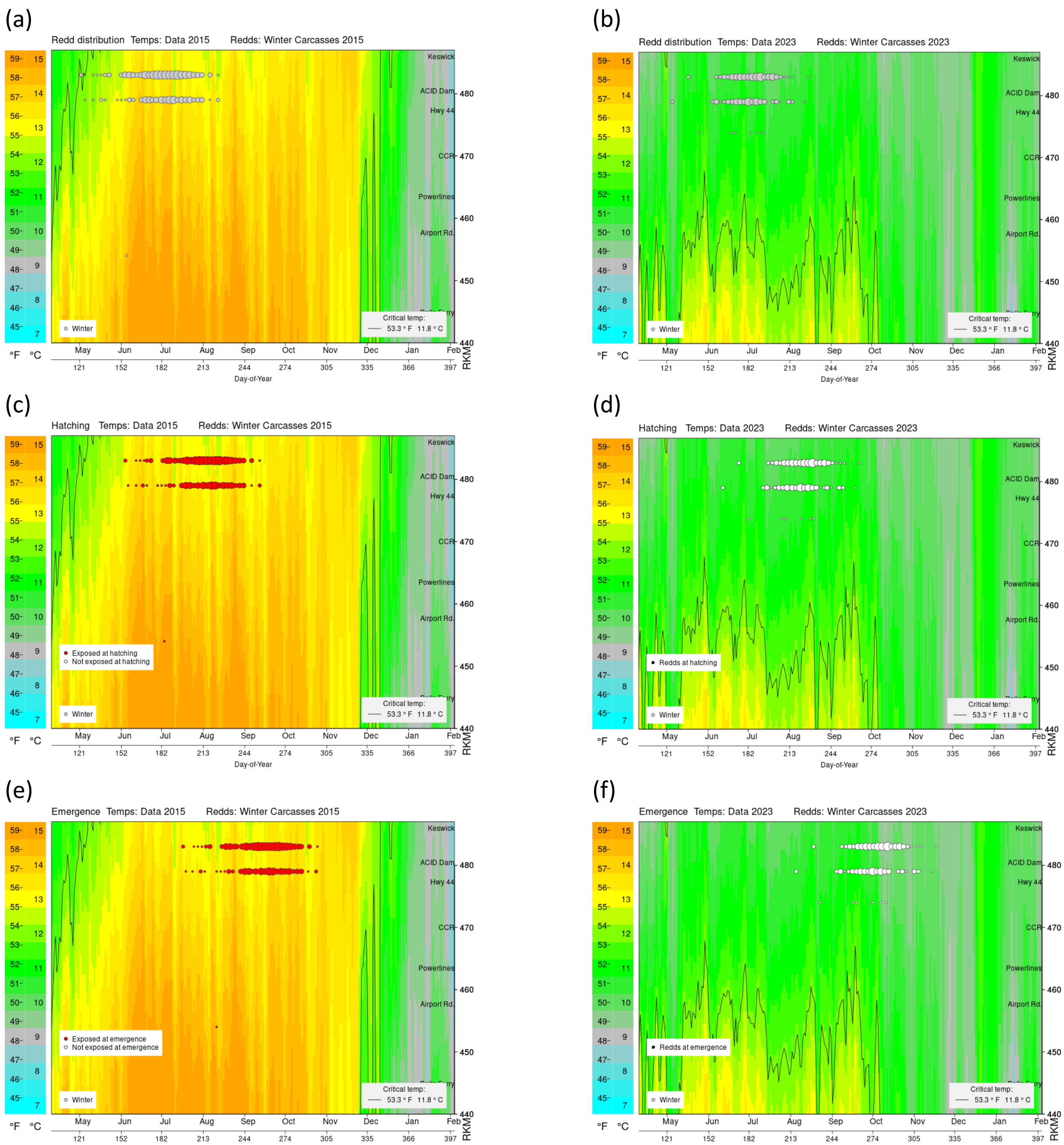
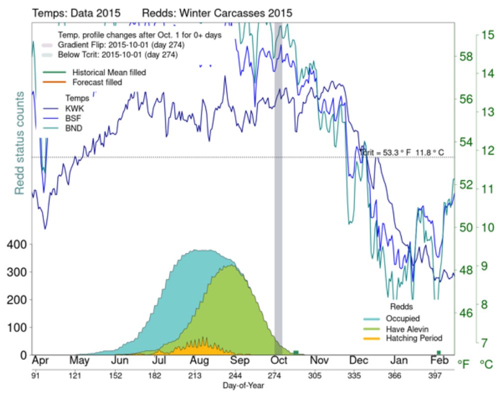


Figure 51. Egg-to-Fry model outputs from the Anderson et al. (2022) model in an HCI-based critical year (2015) and wet year (2023).

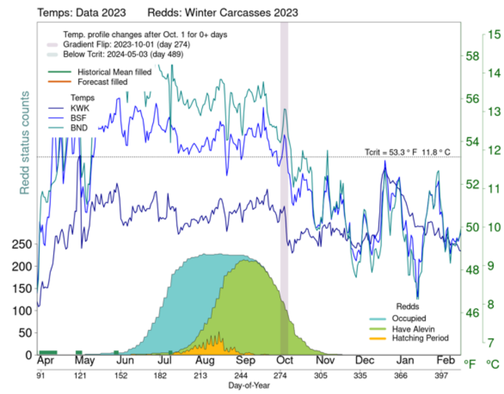
2015 (HCI = critical year type):

(g)



2023 (HCI = wet year type):

(h)



(i)

396	Redds	12.3% Total Survival		
Exposure to 11.82 degrees:		Survival	Mortality	
100%	Pre Hatch	0.123	0.877	TDM
100%	Pre Emergence	1	0	Spawner Density
		1	0	Background
Emergence Day:		1	0	Dewater
259.2	Mean Day			
298	Last Day			

(j)

230	Redds	100% Total Survival		
Exposure to 11.82 degrees:		Survival	Mortality	
0%	Pre Hatch	1	0	TDM
0%	Pre Emergence	1	0	Spawner Density
		1	0	Background
Emergence Day:		1	0	Dewater
276.2	Mean Day			
322	Last Day			

Figure 51. (continued)

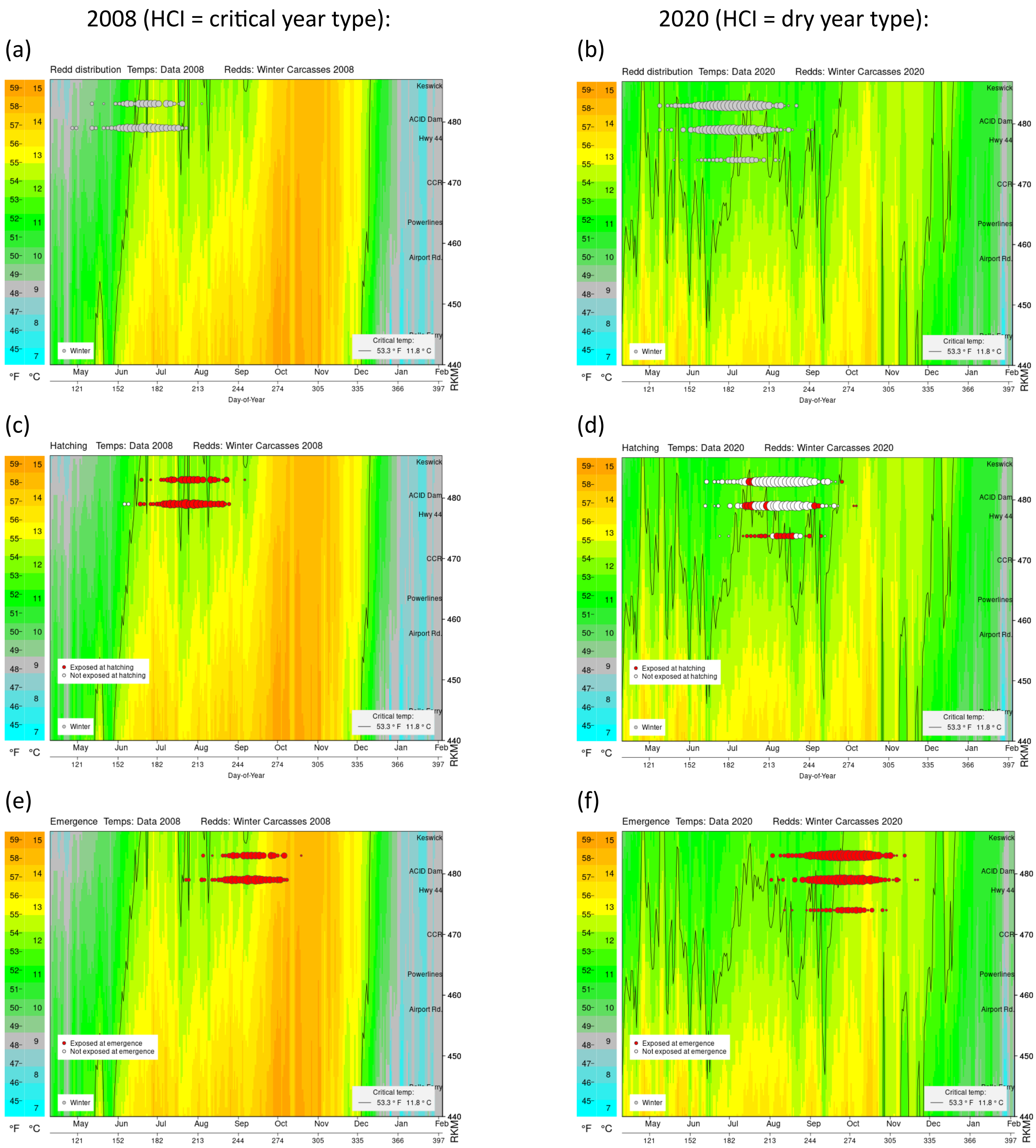
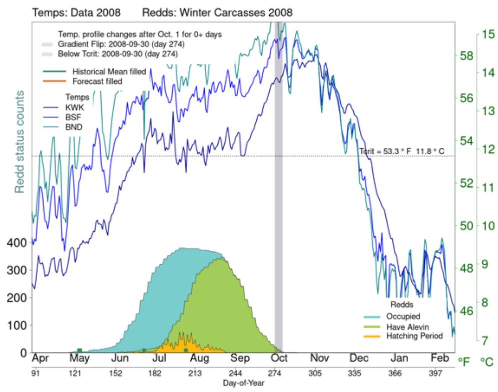


Figure 52. Egg-to-Fry model outputs from Anderson et al. (2022) model in an HCI-based critical year (2014) and dry year (2020).

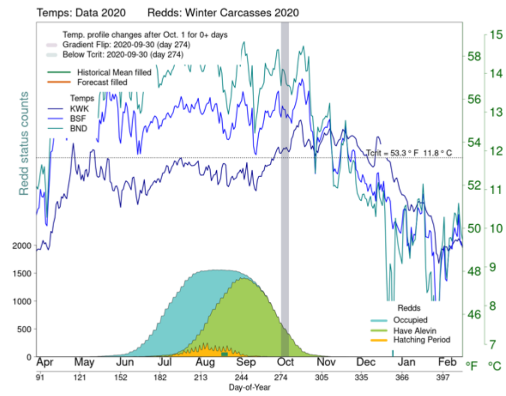
2008 (HCI = Critical year type):

(g)



2020 (HCI = Dry year type):

(h)



(i)

383 Redds

60.7% Total Survival

Exposure to 11.82 degrees:

		Survival	Mortality	
99%	Pre Hatch	0.607	0.393	TDM
100%	Pre Emergence	1	0	Spawner Density
		1	0	Background
		1	0	Dewater

Emergence Day:

252.5 Mean Day
292 Last Day

(j)

1580 Redds

98.9% Total Survival

Exposure to 11.82 degrees:

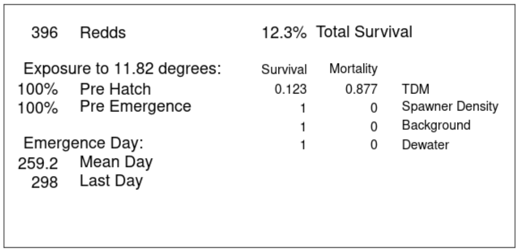
		Survival	Mortality	
12.2%	Pre Hatch	0.989	0.011	TDM
100%	Pre Emergence	1	0	Spawner Density
		1	0	Background
		1	0	Dewater

Emergence Day:

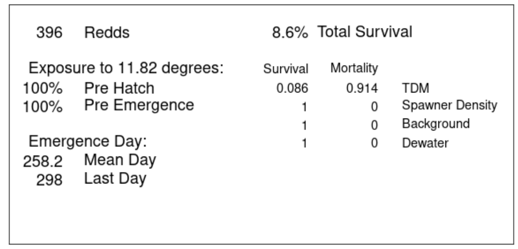
269.9 Mean Day
326 Last Day

Figure 52. (continued)

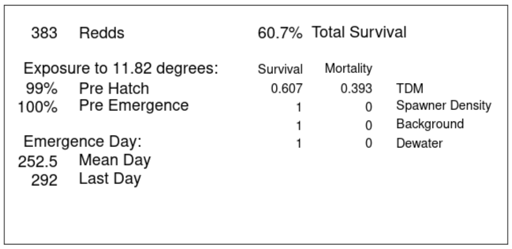
(a) Anderson et al. (2022) model; year 2015; TDM only



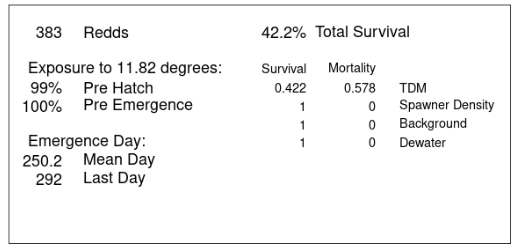
(b) Martin et al. (2017) model; year 2015; TDM only



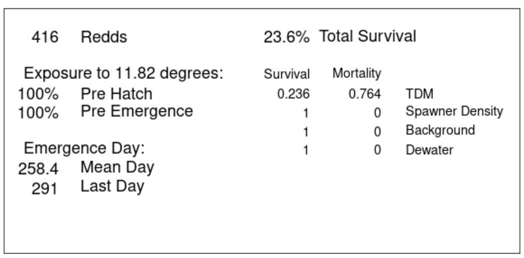
(c) Anderson et al. (2022) model; year 2008; TDM only



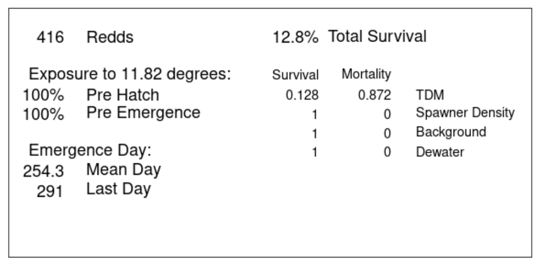
(d) Martin et al. (2017) model; year 2008; TDM only



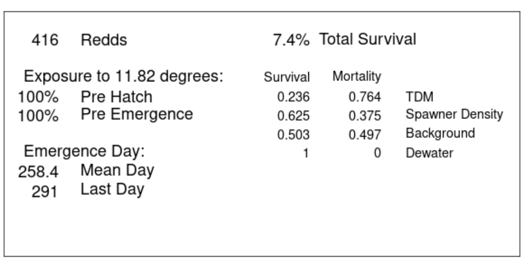
(e) Anderson et al. (2022) model; year 2014; TDM only



(f) Martin et al. (2017) model; year 2014; TDM only



(g) Anderson et al. (2022) model; year 2014



(h) Martin et al. (2017) model; year 2014

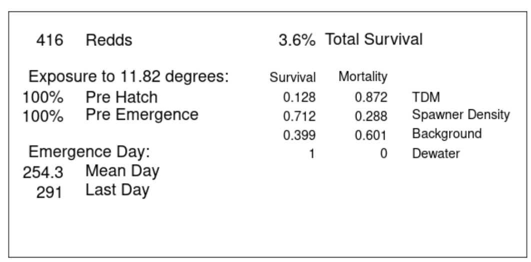


Figure 53. Examples of output results from Anderson et al. (2022) vs Martin et al. (2017) egg-to-fry models for comparison. Results include exposure to temperatures above the critical threshold, total survival, and mortality associated with temperature-dependent mortality (TDM), population density, and background mortality.

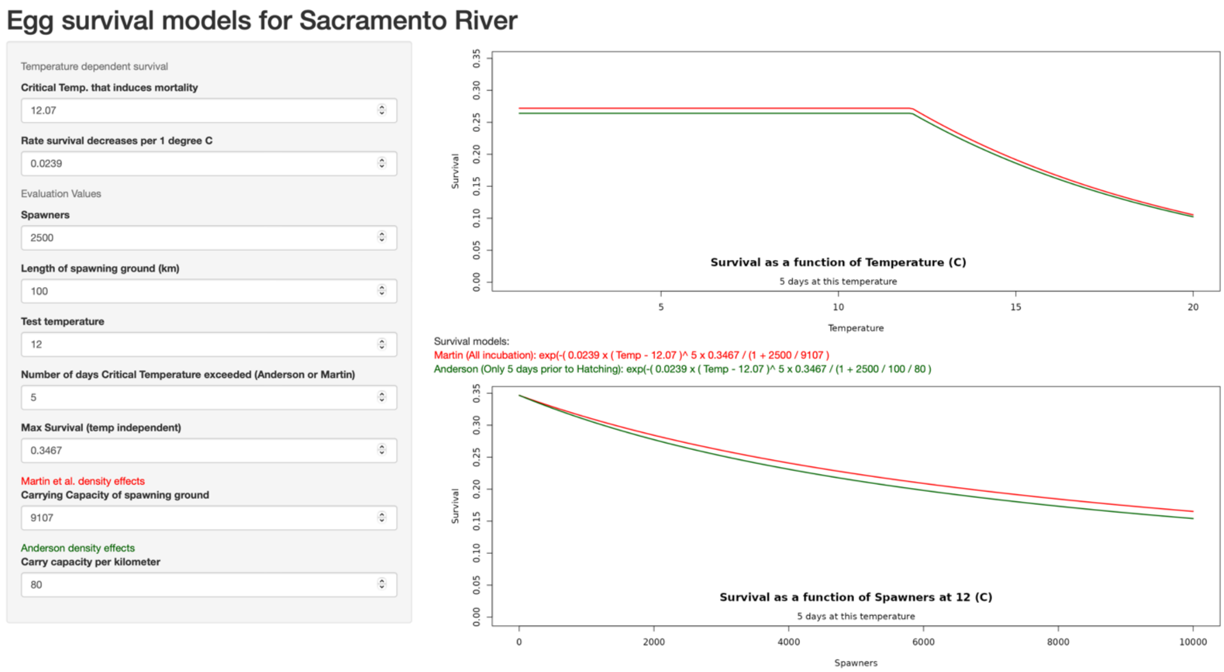


Figure 54. Screenshot of the EGG_SURV Shiny app (https://www.cbr.washington.edu/shiny/EGG_SURV/) that is based on the Anderson et al. (2022) and Martin et al. (2017) methods.

5.1.2 Egg emergence model comparisons: temperature sensitivity analysis

Several egg development models are available for inclusion into SacPAS Egg-to-Fry modeling, and comparing four of the egg development models (Beacham and Murray 1990, Beer and Anderson 1997, Jensen and Jensen 1999, Zeug et al. 2012) reveals slight differences in days to emergence (Figure 55a), even if the ATUs at emergence differs between models (Figure 55b).

To explore through an online tool the different egg growth and emergence models and their parameters, see Egg Growth Modeling: Spawned Egg to Emerged Fry (www.cbr.washington.edu/sacramento/grow/; Figure 56).

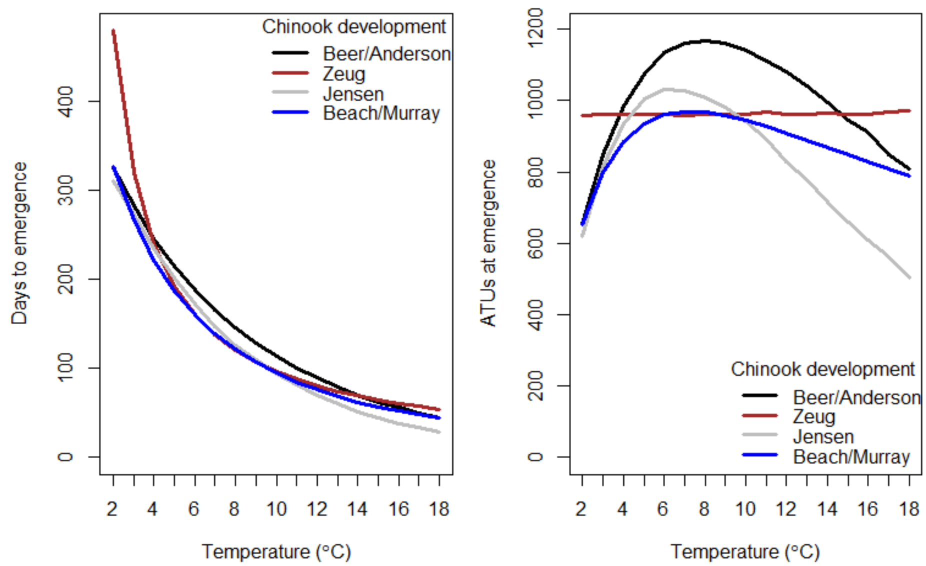


Figure 55. Sensitivity of Emergence Model to temperature. Chinook salmon egg development time (left) and accumulated thermal units [ATUs] (right) according to four models (Beacham and Murray 1990, Beer and Anderson 1997, Jensen and Jensen 1999, Zeug et al. 2012).

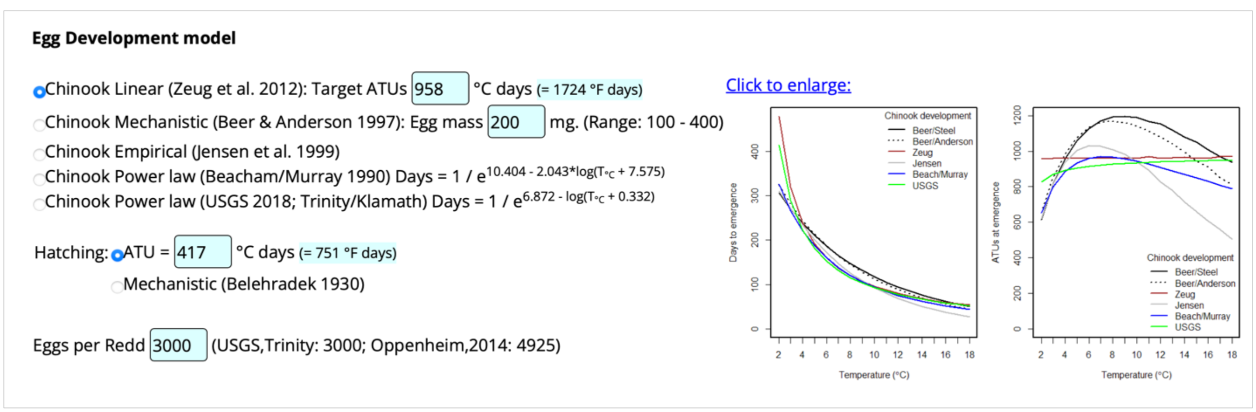


Figure 56. Screenshot of the section on Egg Development modeling as part of the online tool, Egg Growth Modeling: Spawned Egg to Emerged Fry (https://www.cbr.washington.edu/sacramento/grow/).

5.2 River Migration and Survival of Fry/Smolts (RBDD* to Feather River)

In the XT model (Anderson et al. 2005), survival depends on distance (X) traveled and time (T) elapsed. Flow varies spatially and temporally, and influences travel time directly. A slow travel rate may reduce daily predator encounters, but it also increases the time spent in the river as juvenile fish migrate downstream to the ocean. The COMPASS model also includes time and distance as explanatory variables, and thus a comparison of their predicted survival is possible (Figure 57). At a given fish velocity, the predicted survival from both models do not differ very much. Furthermore, survival is sensitive at low fish velocities, but insensitive at high flow and yield similar predictions at fish velocities above 5 miles/day (Figure 57). Thus, increasing flow may only increase survival a negligible amount.

The relationships in Figure 57 can be further broken down to view patterns by each of the explanatory variables (Figure 58). Because all the fish are released at a single location, the total distance does not vary. It is computed on a reach-by-reach basis and these vary in length. Travel time is modeled alike for all fish whether the mortality rate is low or high. A consequence of this is that changing the distance parameter affects survival, but not travel time (see Figure 58 left panels). Survival is also due to time exposure, and therefore the apparent travel time of the cohort goes down because the slower fish are more likely to die as more time passes. The result is that adjusting the time parameter affects both survival and the apparent travel time of the cohort (see Figure 58 right panels).

For a detailed exploration of the tradeoffs between time and distance and sensitivity of input parameters, see the Shiny app interactive tool (https://www.cbr.washington.edu/shiny/SURVDEMO/); Figure 59).

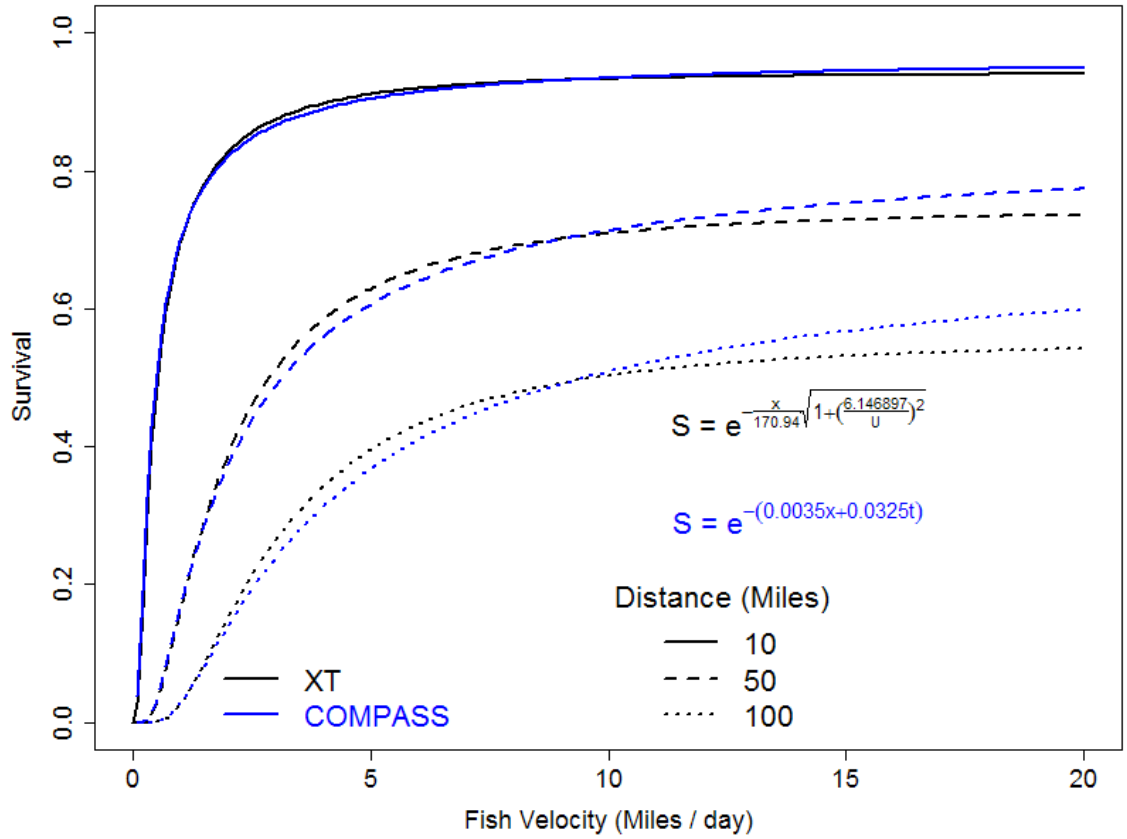


Figure 57. A comparison between survival predicted using the XT model (black text and lines; Anderson et al. 2005) and survival predicted using the COMPASS model (blue text and lines; NMFS 2019b) as a function of fish velocity.

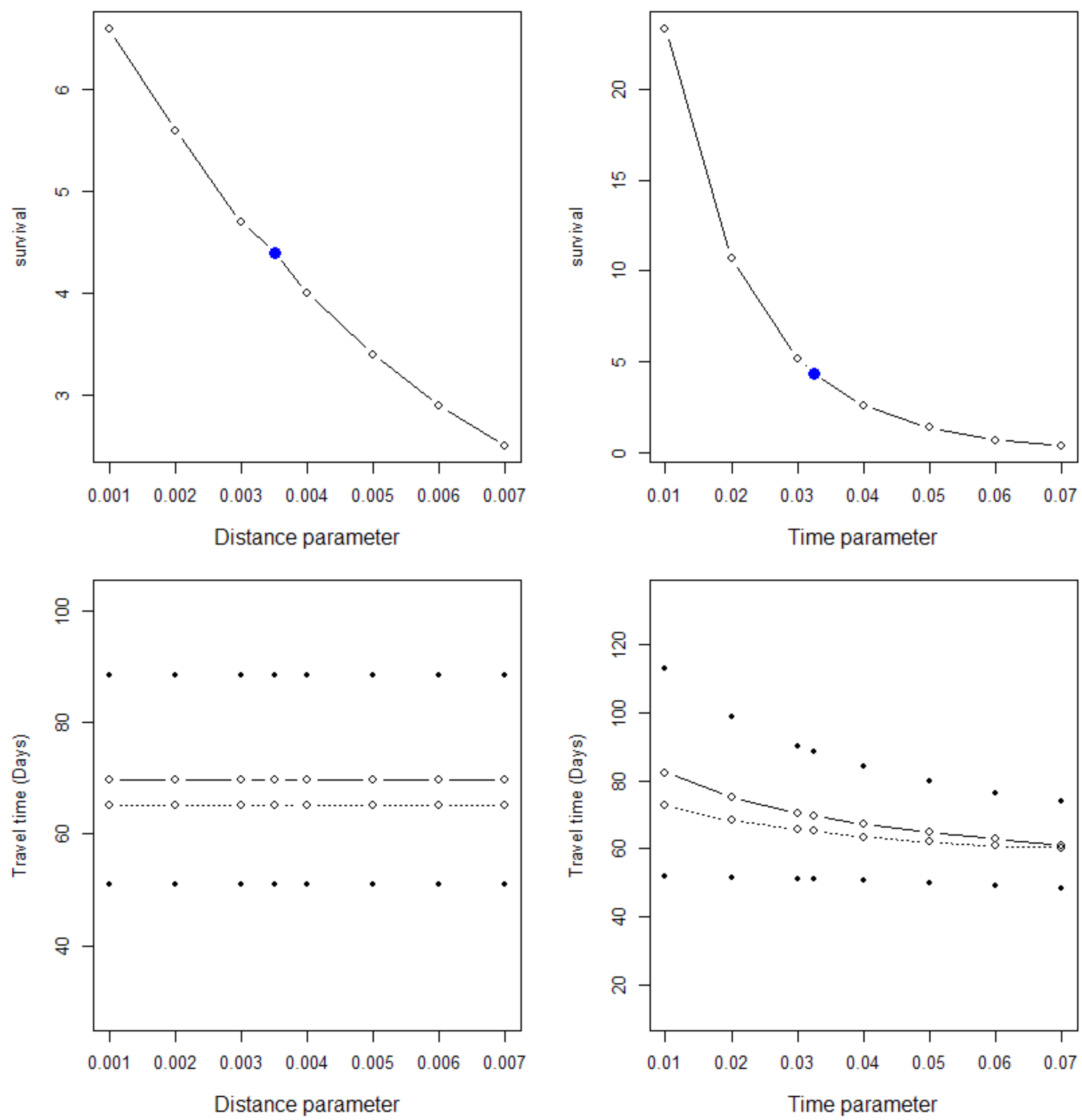


Figure 58. Sensitivity of survival (%) and travel time (days) to the COMPASS survival equation parameters. The blue dots depict the default values for the two survival parameters in the upper two plots. The mean travel time (solid line) the median travel time (dotted line) and the mean ± SD (dots) are shown for Velocity variance = 50 miles^2 day^{-2} in the bottom two plots. The distance parameter for survival does not affect the travel time. The time parameter for survival appears to influence affect travel time but this is a consequence of the fact that the surviving fish are also faster moving.

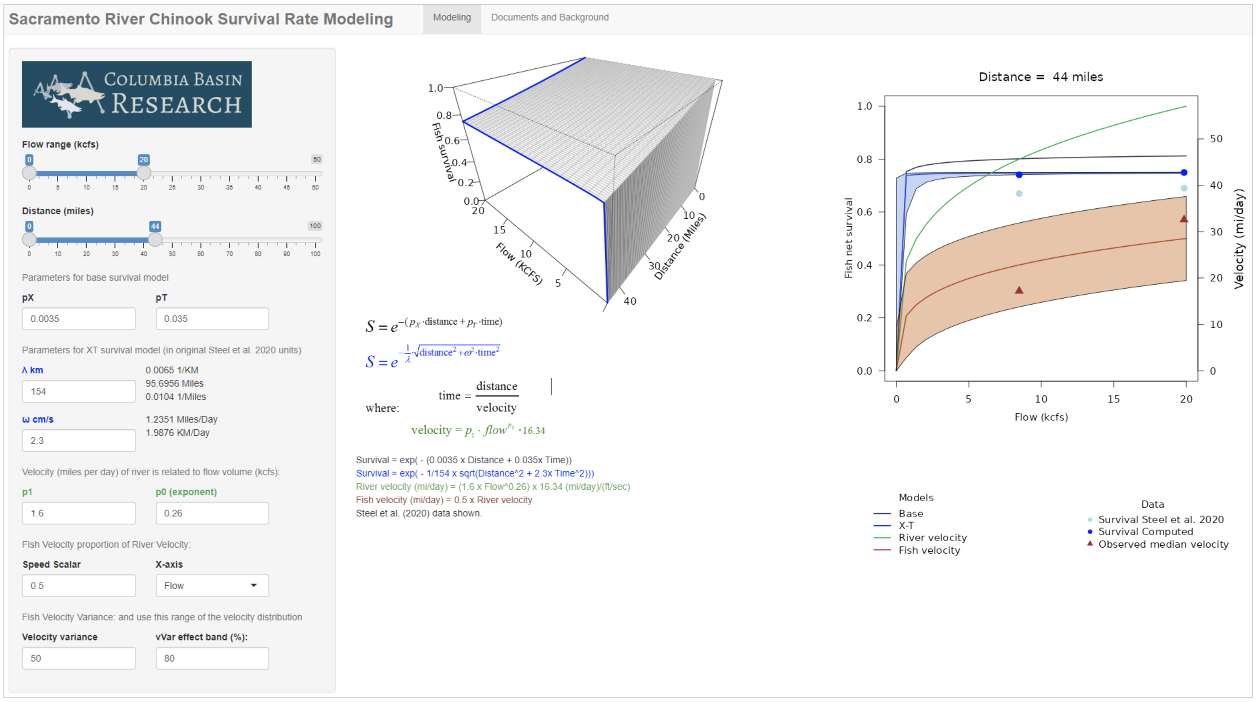


Figure 59. Interactive tool for examining sensitivity of the passage survival model to the parameters (SURVDEMO Shiny app; https://www.cbr.washington.edu/shiny/SURVDEMO/).

5.2.1 Migration Models

5.2.1.1 Fish-flow relationship

Studies on outmigration of Sacramento River juvenile Chinook Salmon migrations have shown that travel rate increases with flow (del Rosario et al. 2013, Michel et al. 2013, Steel et al. 2020, Michel et al. 2021) and that migration rates and survival have a non-linear relationship to flow (Michel et al. 2021).

This non-linearity is a property of the pulse-flow migration model ($r_{j,t} = \beta_0 + \beta_1 \bar{V}\left[\frac{1}{1+\exp\left(-\alpha_1(Q-Q_{crit})-\alpha_2(D-D_{crit})\right)}\right] + \varepsilon$ Eq. 2) and can be configured such that late season and/or high flow can trigger rapid migration. Since the two exponential terms of the pulse-flow model can have opposite signs there is the potential that they mitigate the effect of the other. Thus, in early season, flows may need to be quite a bit higher than the critical value in order to trigger fast migration. Correspondingly, late in the season, even if flows are well below the critical value, fast migration can be triggered.

To gain a better understanding of the migration model, users can explore how migration rate (or fish velocity) is affected by river velocity, and in turn how river velocity is affected by river flow in the MIGR.DISTRIB Shiny app (https://www.cbr.washington.edu/shiny/MIGR.DISTRIB/; Figure 60).

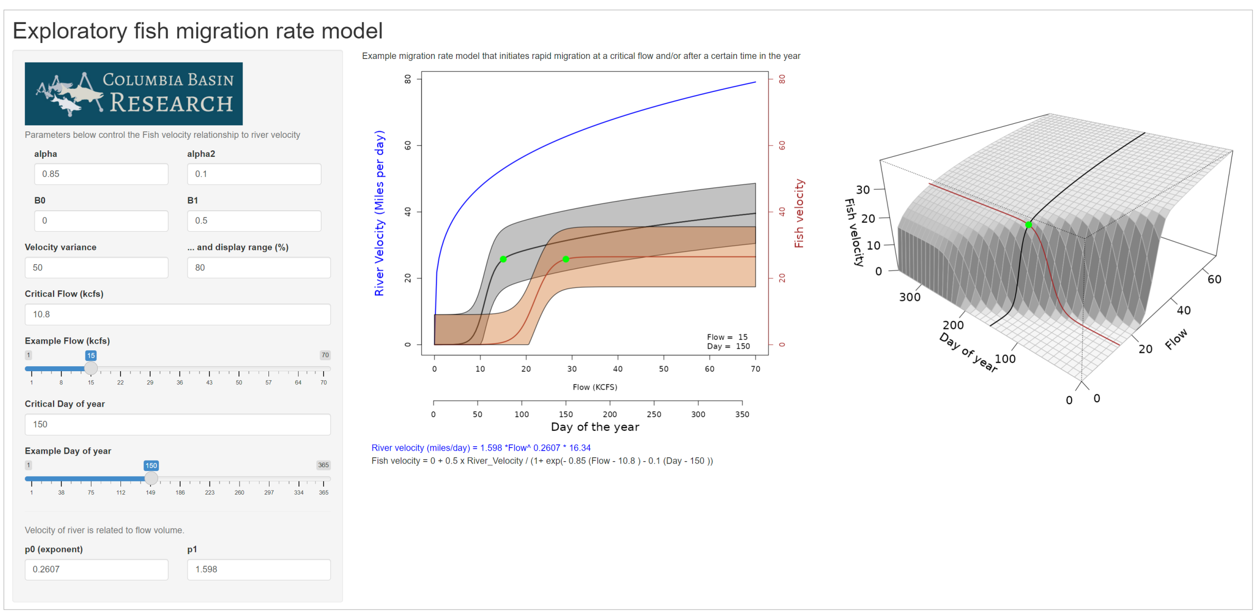


Figure 60. Exploratory fish migration rate pulse-flow model. Parameters control how fish velocity is sensitive to day-of-year and river velocity where river velocity has a power-function relationship to flow on a reach-by-reach basis as described in Box 5.

5.3 Sensitivity Analyses of Survival and Migration Models in KWK to VON reaches.

Sensitivity of the Migration Model to annual differences in flow and use of base, historical conditions vs. surrogate flow sources.

A sensitivity analysis of travel time and survival to various inputs and parameters is useful for understanding the influence of changes to a single model parameter to final results. The results of interest (survival and travel time) were assessed with a set of historical base conditions over the years 2008 through 2016, and then compared to results with alternative parameters as inputs.

The historical base conditions were established using a base set of parameters for migration and survival. Annual river conditions vary between years and along the river. Since there are multiple monitoring sites along the river it is possible to use these historical conditions that vary spatially. The alternative, for simple comparisons, or for hypothetical scenarios, is to use flow at a single site as a surrogate for the entire river. A surrogate flow represents the system in the model. In the real river, this flow may also represent the system, but there are many circumstances during the year when this relationship falls apart. Irrigation withdrawals and/or tributary contributions can alter the hydrograph significantly. Spatial variability in flow is shown in Figure 63 at four sites on the Sacramento River over a 2-year period (2012 and 2013). The historical base data set represents a hybrid of these spatially explicit conditions with the site-specific flow used as the fish move through the river.

Survival and travel time comparisons based on the historical base data and the surrogate flows are depicted in Figure 62 and Figure 63, respectively. Because the KWK flows are regulated, they result in consistent survivals and travel times, regardless of the year (black lines in Figure 62 and Figure 63) due to the relatively low variability between years. In contrast, downstream at Verona (VON), tributaries may have contributed significant flow in certain years such that when VON flow as a surrogate, the inter-annual survival and travel time predictions vary widely, survival is generally higher, and travel is more rapid due to the greater flow. Use of the spatially explicit flows (Base) results in an in-between survival and travel time computation because it is using the lower upstream flows and higher downstream flows as the fish are moved through the river.

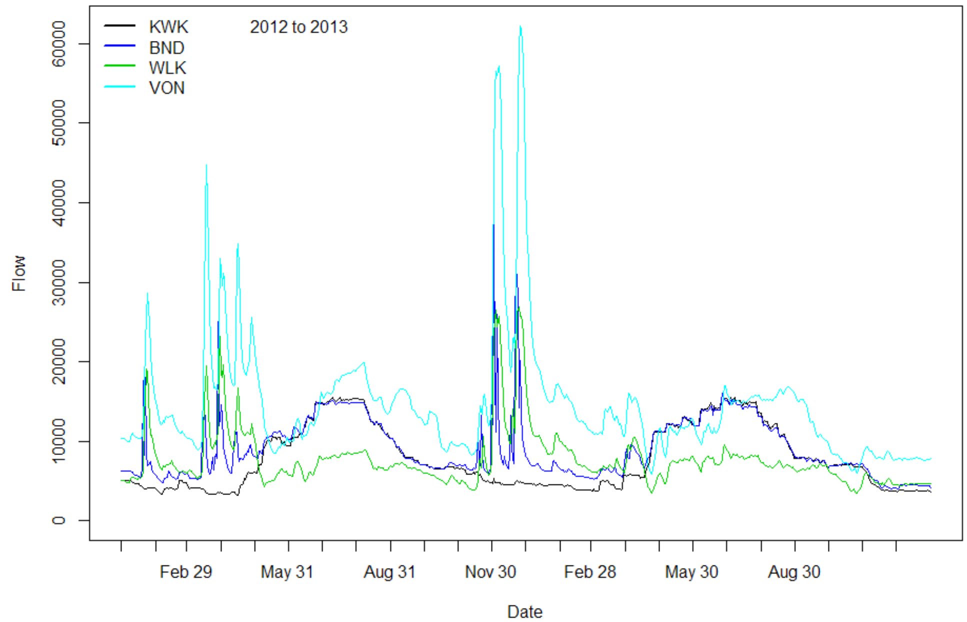


Figure 61. Hydrographs (average daily flow in CFS) at four sites on the Sacramento River during 2012 and 2013. The sites are ordered from upstream (KWK) to downstream (VON). Pulses of water are apparent as tall spikes in the hydrograph, and depict additional flow from tributaries at successive downstream locations.

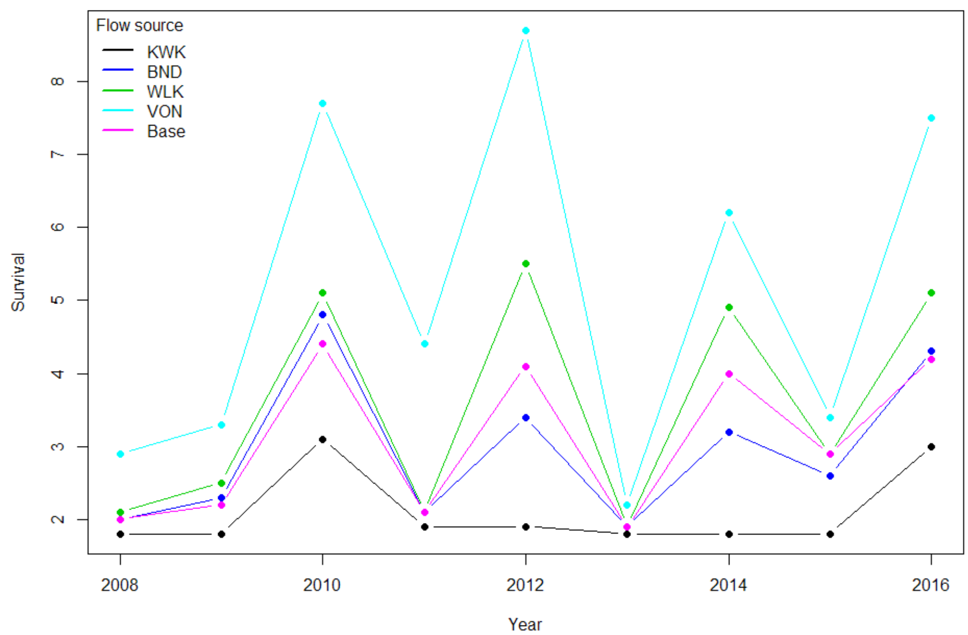


Figure 62. Sensitivity of survival to flow sources and annual variation. "Base" conditions have time and space-varying observed historical flows. Single site condition model runs (BND=Bend, KWK = Keswick, WLK = Wilkins, and VON = Verona) have the observed flow (https://cdec.water.ca.gov/river/rivcond.html; https://www.cbr.washington.edu/sacramento/data/query_river_graph.html) at the specific site applied to the entire river.

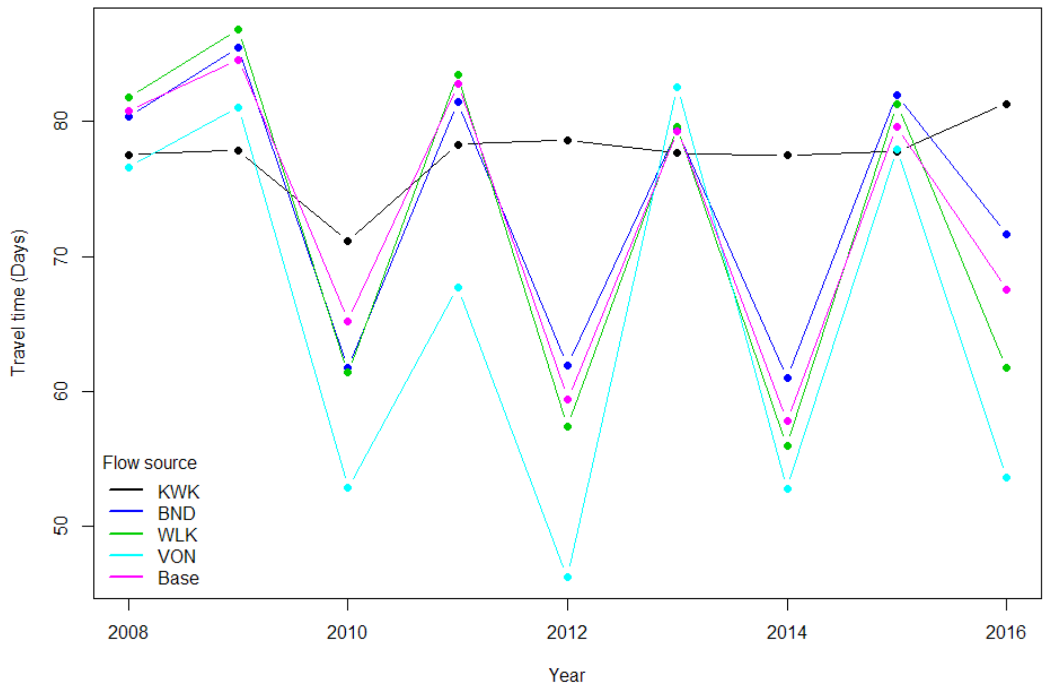


Figure 63. Sensitivity of travel time (days) to flow sources and annual variation. "Base" conditions have time and space-varying observed historical flows. Single site condition model runs (BND=Bend Bridge, KWK = Keswick Dam, WLK = Wilkins Slough, and VON = Verona) have the observed flow (https://www.cbr.washington.edu/sacramento/data/query_river_graph.html; https://cdec.water.ca.gov/river/rivcond.html) at that specific site applied to the entire river.

6 Acknowledgements

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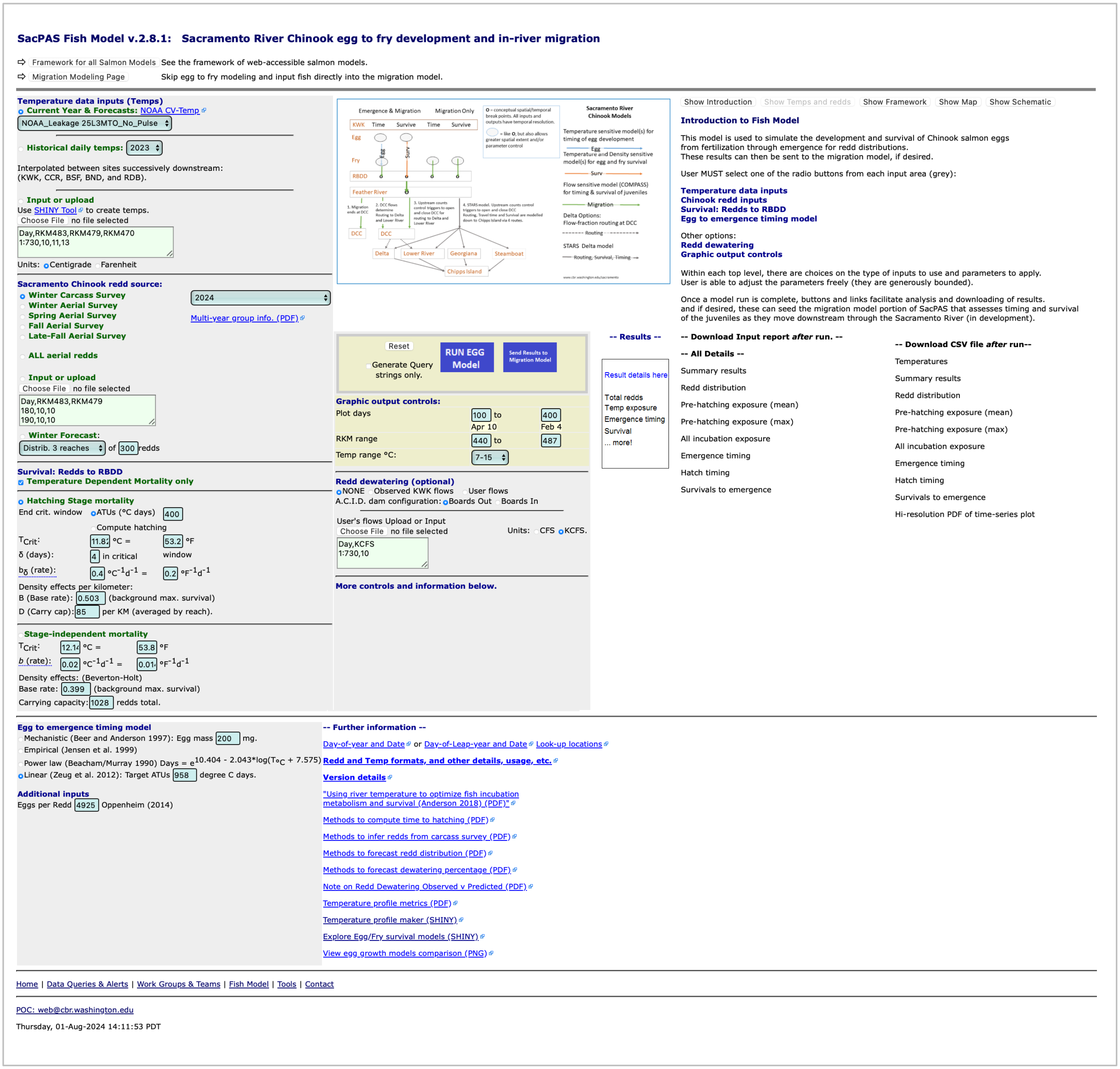
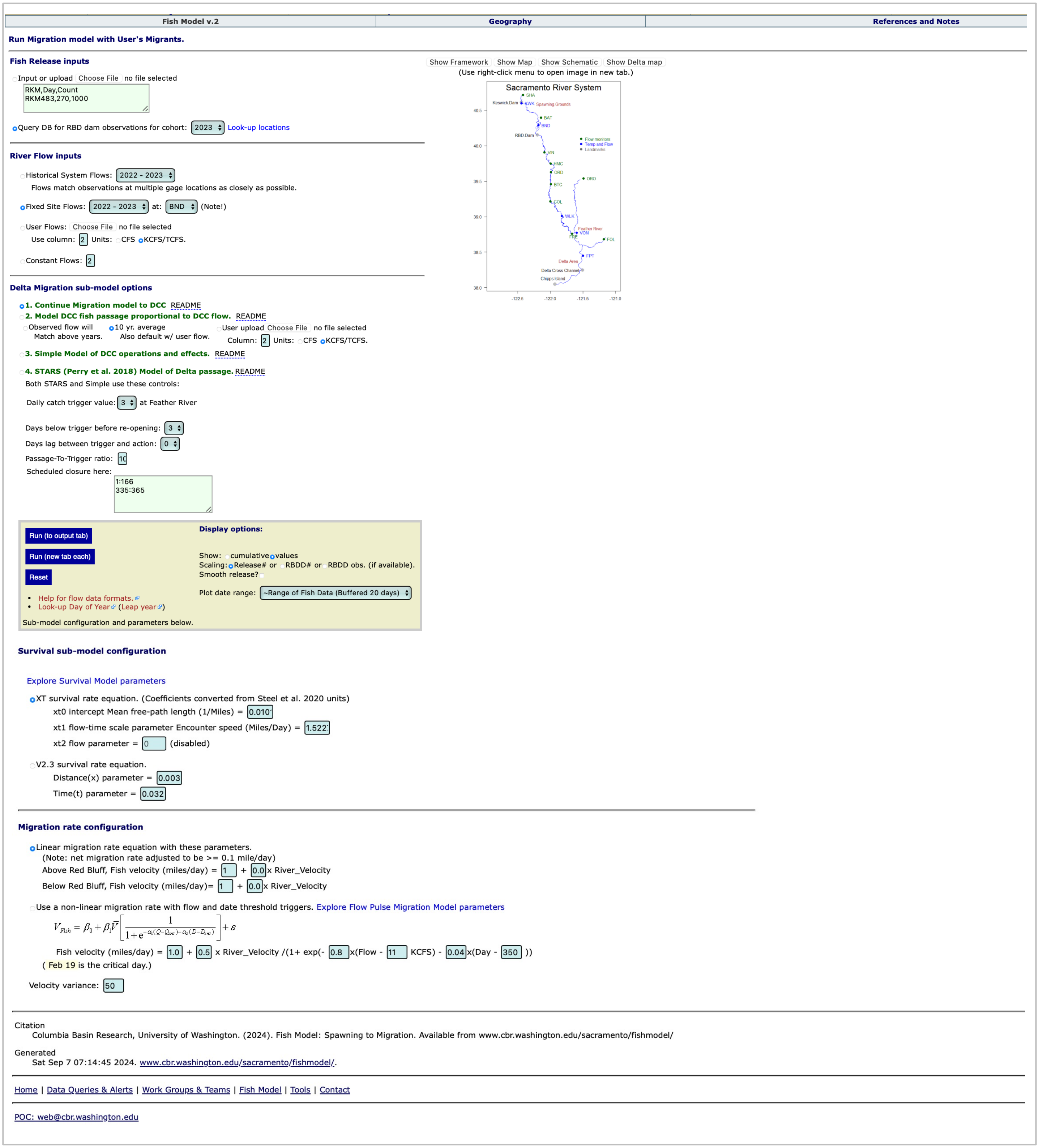
8 Appendix

Appendix 1. General User Interface of SacPAS Fish Model v. 2.8.1, Egg-to-Fry Model.



Appendix 2. General User Interface of SacPAS Fish Model v. 2.8.1, Migration Model.



Fish Model v.2	Geography	References and Notes

Run Migration model with User's Migrants.

Fish Release inputs

Input or upload Choose File no file selected

RKM,Day,Count
RKM483,270,1000

Query DB for RBD dam observations for cohort: 2023 Look-up locations

River Flow inputs

Historical System Flows: 2022 - 2023
Flows match observations at multiple gage locations as closely as possible.

Fixed Site Flows: 2022 - 2023 at: BND (Note!)

User Flows: Choose File no file selected
Use column: 2 Units: CFS KCFS/TCFS.

Constant Flows: 2

Delta Migration sub-model options

1. Continue Migration model to DCC README
2. Model DCC fish passage proportional to DCC flow. README
Observed flow will Match above years. 10 yr. average Also default w/ user flow. User upload Choose File no file selected Column: 2 Units: CFS KCFS/TCFS.
3. Simple Model of DCC operations and effects. README
4. STARS (Perry et al. 2018) Model of Delta passage. README
Both STARS and Simple use these controls:

Daily catch trigger value: 3 at Feather River

Days below trigger before re-opening: 3
Days lag between trigger and action: 0
Passage-To-Trigger ratio: 10
Scheduled closure here:
1:166
335:365

Run (to output tab)
Run (new tab each)
Reset

- Help for flow data formats.
- Look-up Day of Year (Leap year)

Display options:
Show: cumulative values
Scaling: Release# or RBDD# or RBDD obs. (if available).
Smooth release?
Plot date range: ~Range of Fish Data (Buffered 20 days)

Sub-model configuration and parameters below.

Show Framework Show Map Show Schematic Show Delta map
(Use right-click menu to open image in new tab.)

Survival sub-model configuration

Explore Survival Model parameters

XT survival rate equation. (Coefficients converted from Steel et al. 2020 units)
xt0 intercept Mean free-path length (1/Miles) = 0.010
xt1 flow-time scale parameter Encounter speed (Miles/Day) = 1.522
xt2 flow parameter = 0 (disabled)

V2.3 survival rate equation.
Distance(x) parameter = 0.003
Time(t) parameter = 0.032

Migration rate configuration

Linear migration rate equation with these parameters.
(Note: net migration rate adjusted to be >= 0.1 mile/day)
Above Red Bluff, Fish velocity (miles/day) = 1 + 0.0 x River_Velocity
Below Red Bluff, Fish velocity (miles/day)= 1 + 0.0 x River_Velocity

Use a non-linear migration rate with flow and date threshold triggers. Explore Flow Pulse Migration Model parameters

$$V_{Fish} = \beta_0 + \beta_1 \bar{V}\left[\frac{1}{1+e^{-\alpha_1(Q-Q_{crit})-\alpha_2(D-D_{crit})}}\right] + \varepsilon$$

Fish velocity (miles/day) = 1.0 + 0.5 x River_Velocity /(1+ exp(- 0.8 x(Flow - 11 KCFS) - 0.04 x(Day - 350))
(Feb 19 is the critical day.)

Velocity variance: 50

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