

# SacPAS Fish Model: A model for emergence, migration and survival of Sacramento River salmon

<http://www.cbr.washington.edu/sacramento/migration/>

## User's Manual

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## Introduction and Overview

The Sacramento Prediction and Assessment of Salmon (SacPAS) data and analysis tools were developed specifically to assist managers and interested parties in understanding and forecasting salmon emergence, migration and survival. It is a suite of integrated tools for data selection and manipulation, coupled to a spawning-to-emergence model and a juvenile migration model. This document provides background on the SacPAS Fish Model. The public, web-based model is found at:

<http://www.cbr.washington.edu/sacramento/migration/> .

The SacPAS Fish Model begins with egg deposition at the time of spawning where development rate and survival are controlled by various methods to determine fry emergence timing and survival. The user controls temperature inputs, redd/carcass/adult counts, and survival details for egg development modeling. The output of this emergence sub-model becomes the input for a migration sub-model, based on the NOAA/NMFS COMPASS model (Zabel et al. 2008) for the Columbia River where flow drives movements and consequently, survival. COMPASS itself is based on the Columbia River Salmon Passage model (CRiSP) developed with funding from Bonneville Power Administration by the University of Washington Columbia Basin Research Group (<http://www.cbr.washington.edu/analysis/archive/crisp>). Figure 1 illustrates the interactions of these model components.

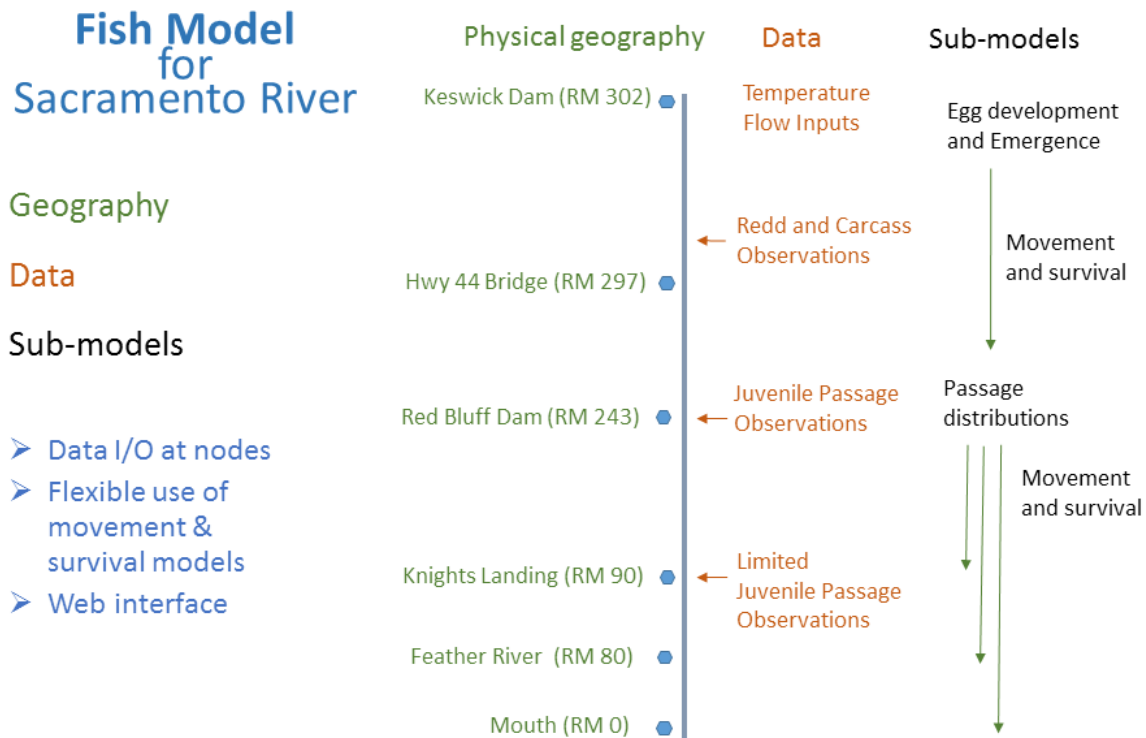


Figure 1 Schematic of physical geography, data and sub-models comprising the Fish Model component of SacPAS.

## Essentials for a model run

Emergence modeling requires:

- Temperature profiles. Time series of daily temperatures from historical observations at a selection of locations or user-specified, uploaded data.
- Spawning timing and numbers new redds or fish carcasses per day from observations or uploaded by user.
- Egg development model and parameter selection.
- Egg survival model and parameter selection.

Smolt passage modeling requires:

- Output from the emergence sub-model with date and counts of fish OR User-provided dates and counts uploaded.
- Daily flows from historical observations or uploaded.
- Migration rate model and parameter selection.
- Migration survival model and parameter selection.

This model is still under development; new features, controls, and data are being planned for and added on a regular basis.

## Terminology

*Spawning* is the action of depositing *eggs* in a *redd* (nest) which begins the *egg development* period. The salmon die shortly after spawning and their carcasses are found along the river. The number and location of redds are observed during regular surveys of the spawning grounds, or are inferred from carcass counts. When an egg *hatches*, the *embryo* inside becomes an *alevin*, which has an attached yolk sac. The alevin remains in the gravel and grows on its remaining yolk at a rate that is very strongly related to temperature. It then moves out of the gravel (*emergence*) into the free-flowing river as a *fry*. Fry rear in the local environment and/or move downstream. Fry that rear sufficiently and are ready for active migration to the ocean are known as *smolts*. When juvenile fish (either fry or smolts) are observed at a point on the river their *passage* is enumerated as counts per day. The aggregated counts per day comprise a *release* used as input to the passage model. The release can be based on the modelled emergence of the fry, or can be input directly by the user. The passage model simulates the downstream movement and survival of the release through subsequent river *reaches* which span arbitrary sections of river (they are not constrained by length, etc.). Reaches are typically delineated by confluences, points of interest, monitoring locations, weirs, dams, etc. Each reach is spatially explicit, described primarily by its length, but also having unique reach-wide characteristics, e.g. a relationship between flow and water velocity. *Travel time*, *survival*, and *passage* of the fish in the release as a whole are tracked through each reach and the entire system. *Sub-models* are used for different parts of the emergence or passage processes, and the user has choices on which sub-model and *parameters* to use. Model and parameter adjustments influence the sensitivity of each particular process to temperatures and/or flows. Flow and temperature inputs can come from historic data or be specified by the user.

Warning: Units for numerical values are from a mixture of systems. COMPASS inputs include: flow in 1000 foot<sup>3</sup>•sec<sup>-1</sup> (KCFs or TCFS), velocity of fish and/or water in miles•day<sup>-1</sup>, temperature in °C. CDEC temperature data are in Fahrenheit and flow data are in CFS.

Some useful conversions:

$1 \text{ ft} \cdot \text{sec}^{-1} = 16.364 \text{ miles} \cdot \text{day}^{-1} = 26.3 \text{ km} \cdot \text{day}^{-1}$ ,  $1 \text{ mile} \cdot \text{hour}^{-1} = 1.4667 \text{ foot} \cdot \text{second}^{-1}$ ,  
 $1 \text{ KCFS} = 28.32 \text{ m}^3 \cdot \text{sec}^{-1}$ ,  $1^\circ\text{C} = 1.8^\circ\text{F}$ ,  $1000 \text{ ATU } (^\circ\text{C}) = 1800 \text{ ATU } (^\circ\text{F})$ .

There are many interactive unit conversion calculators on the internet that will convert specific measurement into appropriate units for input.

## Web Interface of the SacPAS Fish Model

The various components of the web interface are described here. The interface includes an HTML document with text boxes, selections, radio buttons and file uploads for controls. Outputs begin with HTML pages that include options for viewing and downloading results for external analysis.

The SacPAS fish modeling process can begin at either of two start points (see Figure 2).

- 1) Egg deposition at the time of spawning.
- 2) Fish passage at beginning of migration.

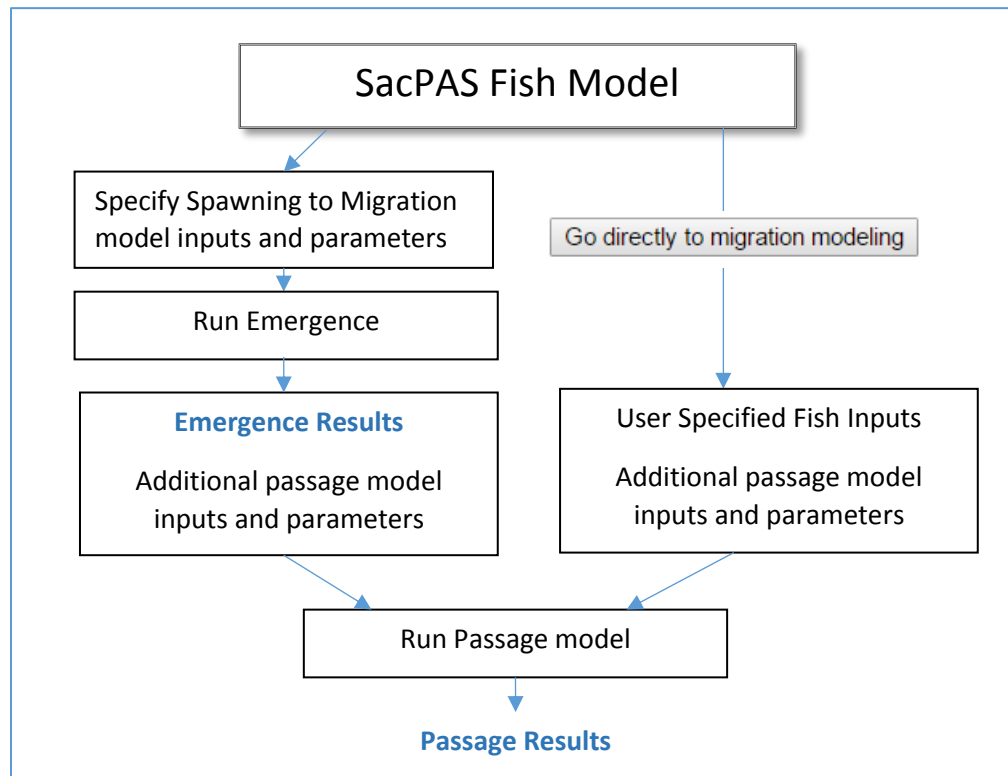


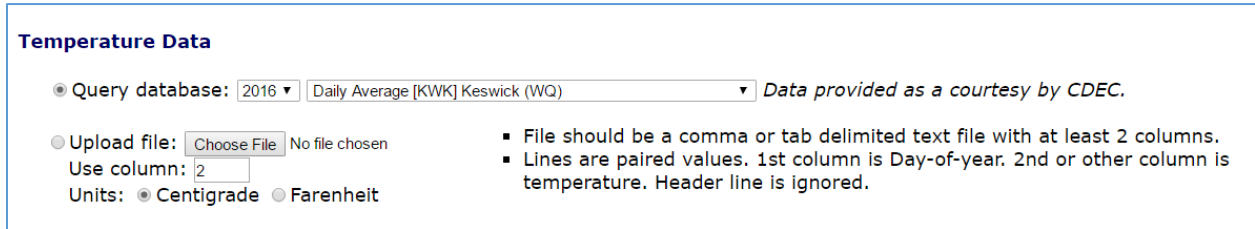
Figure 2 Schematic of modeling process.

### Egg and juvenile fish (spawning to migration)

Development rate and survival are modeled by a user-selected method to determine fry emergence from the gravel. The egg development sub-model is controlled with temperature inputs, redd/carcass/adult counts, and survival details for the eggs. Critical outputs of this process are displayed for the user and become inputs for the migration model.

### Specify temperature data

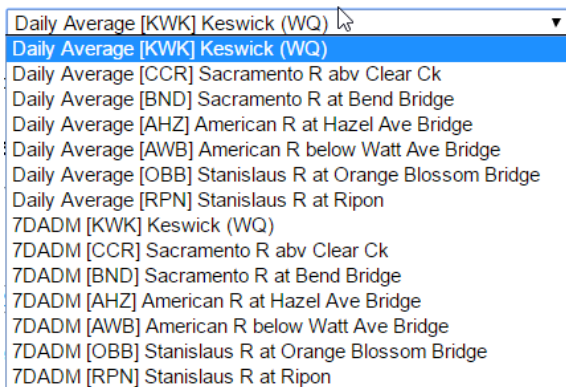
Temperature data may be specified from observed data (2000-present) queried directly from the SacPAS database or user-generated custom files can be uploaded to the model. The current model does not specify temperature at individual redds. The emergence models use Celsius (°C) temperatures; inputs can be converted from Fahrenheit (°F) as needed.



The screenshot shows a form titled "Temperature Data". It includes a "Query database:" section with a year dropdown set to "2016" and a location dropdown set to "Daily Average [KWK] Keswick (WQ)". A note states "Data provided as a courtesy by CDEC." Below this is an "Upload file:" section with a "Choose File" button and the text "No file chosen". There is a "Use column:" input field with the value "2" and "Units:" radio buttons for "Centigrade" (selected) and "Fahrenheit". To the right, a list of instructions specifies: "File should be a comma or tab delimited text file with at least 2 columns." and "Lines are paired values. 1st column is Day-of-year. 2nd or other column is temperature. Header line is ignored."

Figure 3 Specify temperature data.

For database temperatures, location can be specified as being from any of a number of CDEC sites and values selected as either daily average or 7DADM (7 day average of daily maximum) (see Figure 4). Database temperatures are available at sites that are *not* contiguous with the smolt passage portion of the model. Users can still model emergence in these locations and future versions of the passage model may include migration from other rivers.



The screenshot shows a dropdown menu with the following options: "Daily Average [KWK] Keswick (WQ)", "Daily Average [CCR] Sacramento R abv Clear Ck", "Daily Average [BND] Sacramento R at Bend Bridge", "Daily Average [AHZ] American R at Hazel Ave Bridge", "Daily Average [AWB] American R below Watt Ave Bridge", "Daily Average [OBB] Stanislaus R at Orange Blossom Bridge", "Daily Average [RPN] Stanislaus R at Ripon", "7DADM [KWK] Keswick (WQ)", "7DADM [CCR] Sacramento R abv Clear Ck", "7DADM [BND] Sacramento R at Bend Bridge", "7DADM [AHZ] American R at Hazel Ave Bridge", "7DADM [AWB] American R below Watt Ave Bridge", "7DADM [OBB] Stanislaus R at Orange Blossom Bridge", and "7DADM [RPN] Stanislaus R at Ripon".

Figure 4 Dropdown menu of current locations and temperature values to use for emergence modeling.

### Specify Spawning data

Spawning data is selected for specific years representing combined counts from Keswick to A.C.I.D dams for Winter Chinook redds or carcass data, earliest 2000 and 2003, respectively. These are temporally, but not spatially (river mile) specific. In addition to selecting redds from historical years, 10 and 20 year averages are available.

Like the temperature data, there is the option of uploading a user-generated file of redd, carcass, or adult data. Files should be comma or tab delimited text files with 2 columns of paired values (day-of-year and count). To upload a file for model use: select the "Upload file" option, click the "Browse..." button, and select the appropriate file from your computer.

The use of carcasses requires two other inputs. First, the number of redds to be modeled is a fraction of the number of carcasses observed. The "Adults/carcasses per redd" number is applied to the carcass count to get redds. Positive integer only is allowed. E.g., if males and females are equal in the population and every female spawns, use 2. However, in years 2004 to 2015, carcasses outnumbered redds by a

factor of 8.9 (average) on the Sacramento River winter Chinook spawning grounds. Many redds are missed during surveys for a variety of reasons, and not all fish spawn successfully. Note that if there are an insufficient number of carcasses to allocate to a redd, you will be warned and prompted to adjust the number.

Second, there is a timing offset in days because redds are constructed and spawning occurs prior to the death of the adults and carcass recovery. The mean offset for peak redd day to peak carcass day was -11.8 days over the period 2004 to 2015 on the Sacramento River winter Chinook spawning grounds. For adult counts (e.g., at a weir), use a positive offset because spawning is delayed until redds are built.

Additional modeling for American River fall Chinook carcasses is also implemented and future versions of the model will allow users to select other spawning grounds.

### Spawning Data

Winter Chinook redds:  Combined counts from "Keswick Dam to A.C.I.D. Dam" and "A.C.I.D. Dam to Highway 44 Bridge" for Winter Run Chinook.

Winter Chinook carcasses  (Sacramento River) *Redd and Carcass database provided as a courtesy by CDFW and USBR. [Data Disclaimer](#)*

Fall Chinook carcasses  (American River) 2011 not available.

Upload file:  No file chosen  
Use column:   
Units:  Redds  Adults or Carcasses.

- File should be a comma or tab delimited text file with at least 2 columns.
- Lines are paired values. 1st column is Day-of-year. 2nd or other column is redd, adult or carcass count. Header line is ignored.

**Adult and Carcass Handling**

Adults/carcasses per redd:   

- This divides the count to get redds. Positive integer only. If you are uploading adult or carcass counts, this will adjust those counts to get the correct number of redds. E.g., if males and females are equal in the population and every female spawns, use 2. More importantly, redds are missed. In years 2004 to 2015, carcasses outnumbered redds by an average of 8.9 on the Sacramento River winter Chinook spawning grounds.

Timing offset:  days.  

- Integer days only. For *carcasses* use a negative value because spawning is prior to carcass detection. The mean offset for peak redd day to peak carcass day is -11.8 days over the period 2004 to 2015 on the Sacramento River winter Chinook spawning grounds. For *adult* counts (e.g., at a weir), use a positive offset because spawning is delayed until redds are built.

Figure 5 Specify spawning data.

### Specify egg development

Egg development can be modeled with one of four different sub-models, each of which uses the temperature and spawning data specified in the previous steps. They have each been adapted from published sources: Beacham and Murray (1990), Beer and Anderson (1997), Jensen et al. (1999), and the default linear model of Zeug et al. (2012). They all use temperature to model the duration of development such that each daily temperature value advances development until it is 100% complete. This is done for each day that one or more redds are specified. All the fry that emerge from a redd will share the same development rate and survival rate, but each redd is handled separately.

In practice, for each day at a given temperature, the percentage development is computed and aggregated until a fish reaches 100%. This allows any arbitrary sequence of temperatures to be used. All of the fish from a single redd are handled identically.

[View egg growth models comparison](#)

**Egg Development model**

- Chinook Mechanistic (Beer and Anderson 1997): Egg mass  mg. (Allowed Range:  $100 \leq x \leq 400$ )
- Chinook Empirical (Jensen et al. 1999)
- Chinook Power law (Beacham/Murray 1990) Days =  $e^{10.404 - 2.043 \cdot \log(T_{\text{°C}} + 7.575)}$
- Chinook Linear (Zeug et al. 2012): Target ATUs  degree C days. (Allowed Range:  $700 \leq x \leq 1200$ )
  - Default linear value 958 is centigrade equivalent of ATUs accumulated at the published daily rate:  $0.00058 * T_{\text{Fahrenheit}} - 0.018$
  - Enter a value in either box to convert between ATU-Centigrade  and ATU-Fahrenheit .
  - Fahrenheit ATUs are accumulated above 32. This calculation is NOT a temperature conversion tool.

Eggs per Redd  Oppenheim (2014) (Allowed Range:  $1000 \leq x \leq 6000$ )

Figure 6 Specify egg development.

### Specify Egg survival

Two basic models are available for egg to fry survival. Importantly, they both include the in-gravel phase of egg/alevin survival and the early fry rearing survival prior to arrival at Red Bluff Dam. The first specifies a constant survival characterized from emergence to RBDD (Oppenheim 2014). The second model includes temperature-dependent and temperature-independent mortality components. Note that the temperature dependent parts are driven by the previously selected river temperature values. There are two options for the temperature-independent survival rates that are associated with density on the spawning ground and these are based on Martin et al. 2016a, 2016b. The published parameters are defaults and the user has the option to modify them by typing numbers into the input boxes (see Figure 7). The user also has the option to examine the functional forms of the model by clicking the “Explore Egg/Fry survival models” link.

[Explore Egg/Fry survival models](#)

**Survival model**

- Constant survival (Oppenheim, 2014): Spawning to emergence:  Fry to RBDD:  (Allowed Ranges:  $0.0 < x \leq 1.0$ )
- Survival modeling from spawning to fry passing RBDD.
 

Temperature-dependent mortality parameters.

$T_{\text{crit}} =$   °F or  °C. Temperature below which there is no temperature dependent mortality.

$b_T =$   °F<sup>-1</sup> or  °C<sup>-1</sup>. Rate at which an increase of 1° increases daily mortality.

  - To remove the temperature related parameters from survival modeling, set  $T_{\text{crit}}$  to a high value (max: 80).
- Use linear non-temperature-related mortality parameters. Sacramento River Temperature Task Group model (SRTTG)
 

$\mu_0 =$   Density-independent base survival rate (i.e. maximum survival)

$\mu_1 =$   Density-dependent survival per female spawner
- Use beverton-holt non-temperature-related mortality parameters. (Martin et al. 2016)
 

$S_0 =$   Density-independent base survival rate (i.e. maximum survival)

$K =$   Carrying capacity of female spawners.

  - To remove the density related parameters from survival modeling: Let  $\mu_0 = 1$  and  $\mu_1 = 0$  or  $S_0 = 1$  and  $K =$  extreme value (1000000).

Figure 7 Egg survival model selection

### Analysis and Results Display controls

The user has additional controls over how the results are processed and presented. First is the option to “smooth” the redd and/or carcass data. Given that redd surveys are done intermittently, smoothing will allocated redds observed on a single day back in time to the previous non-zero-count day, or one week if this is the first record for the season. The timeframe for output presentation can be controlled with the dropdown Date Range menu.



Outputs from the model run come in various forms. All include a summary with and without details and graphics as histograms of counts per day or as cumulative emergence over time. Finally, the model can be run and results presented in one of two ways. Either send the results to an output tab which will be overwritten if the form is re-run by pressing the **Run Emergence (to an output tab)** button, or send results to a unique tab each time by pressing the **Run Emergence (new tab each click)** button. The Reset button restores all values on the page to their defaults. See Figure 8.

**Analysis and Results Display**

Use redd or carcass value data set *as is*.
  Smooth redd or carcass values.
 [See Notes](#)

Date Range:

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Summary and graphics only.
  Summary, graphics and details.
  Show histograms.
  Show cumulative.

Figure 8 Analysis and results controls

### Emergence model results

Pressing a “Run Emergence ...” button applies all of the previously selected inputs to the emergence model and computes development for the entire population of redds. A new page opens with a summary of the run, and a graphic depiction of the redds, temperature profile, and emergence. The user is reminded of all the controls that were used for this modeling session (Figure 9) and given summary results.

Notes: “Expansion” in results refers to the emergence season compared to the spawning season. In the example here, the emergence season was four days shorter than the spawning season. In warming waters, later-spawned fish developed more quickly.

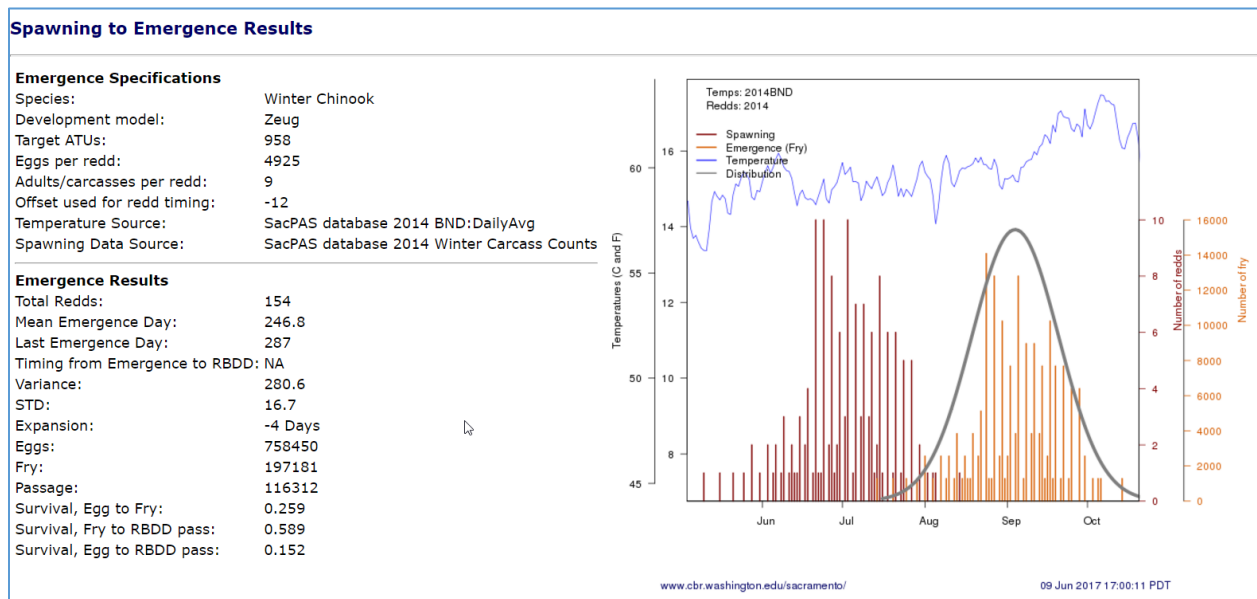


Figure 9 Sample results page after running the emergence model. This shows the Emergence Summary and Graphics.

If “details” was selected in the Analysis and Results Display area, then below the summary is a table with details on the fate of redds on each day of the spawning season. The day, redd count, duration of incubation, emergence day (as day-of-year), passage day (currently same as emergence day), Accumulated Temperature Units (ATUs) mean incubation temperature (°C), the count of eggs and potential fry, and the number surviving to Red Bluff Diversion Dam is reported. The graphics appear below this table.

### In-River Migration

The passage component of SacPAS Fish Model can be run using output of the emergence model or directly with user provided inputs. The model is a reconfiguration of the NMFS COMPASS smolt passage model developed for Columbia River salmon and steelhead (Zabel et al. 2008) which in turn was based on the [CRISP](#) model developed and maintained at the University of Washington from 1988 to 2006.

The model is very flexible and can be configured to any river system through a dynamic river description file that characterizes the system as a network of tributaries using latitude and longitude coordinates and river cross-sectional areas. A river is a series of connected segments (reaches) that preserve continuity of water flow while accounting for the inputs from tributaries and losses from irrigation withdrawals. The water velocity in each reach is determined with a power curve relationship between flow and velocity in a free-flowing reach. There is no modeling of passage through impoundments anywhere in the current configuration of the model. Fish passage time over a reach (travel time) is a function of the water velocity and survival is a function of the distance travelled and the time required to complete it.

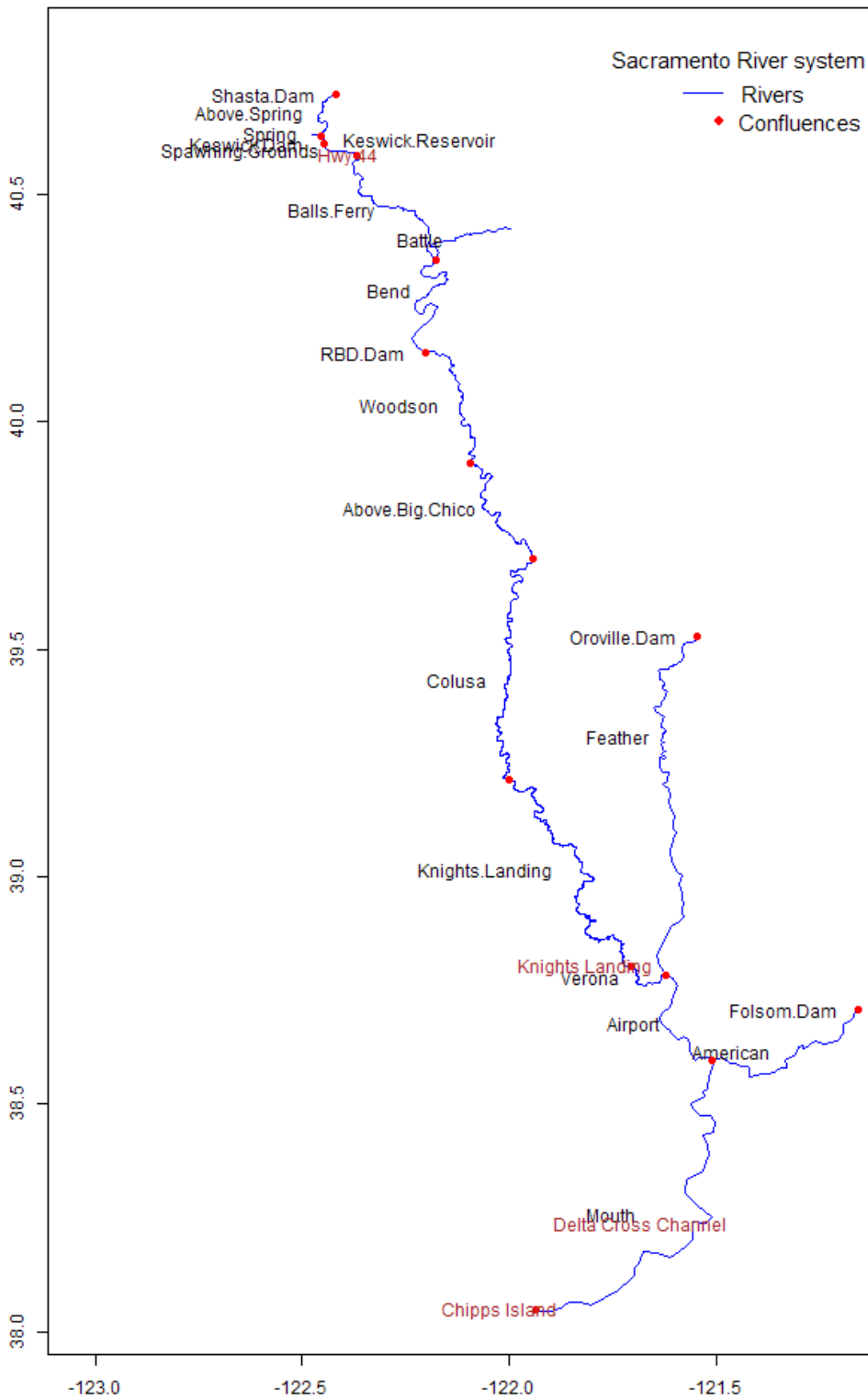


Figure 10 Map of major features along the Sacramento River system used in the spatially explicitly passage model including reach names and select landmarks.

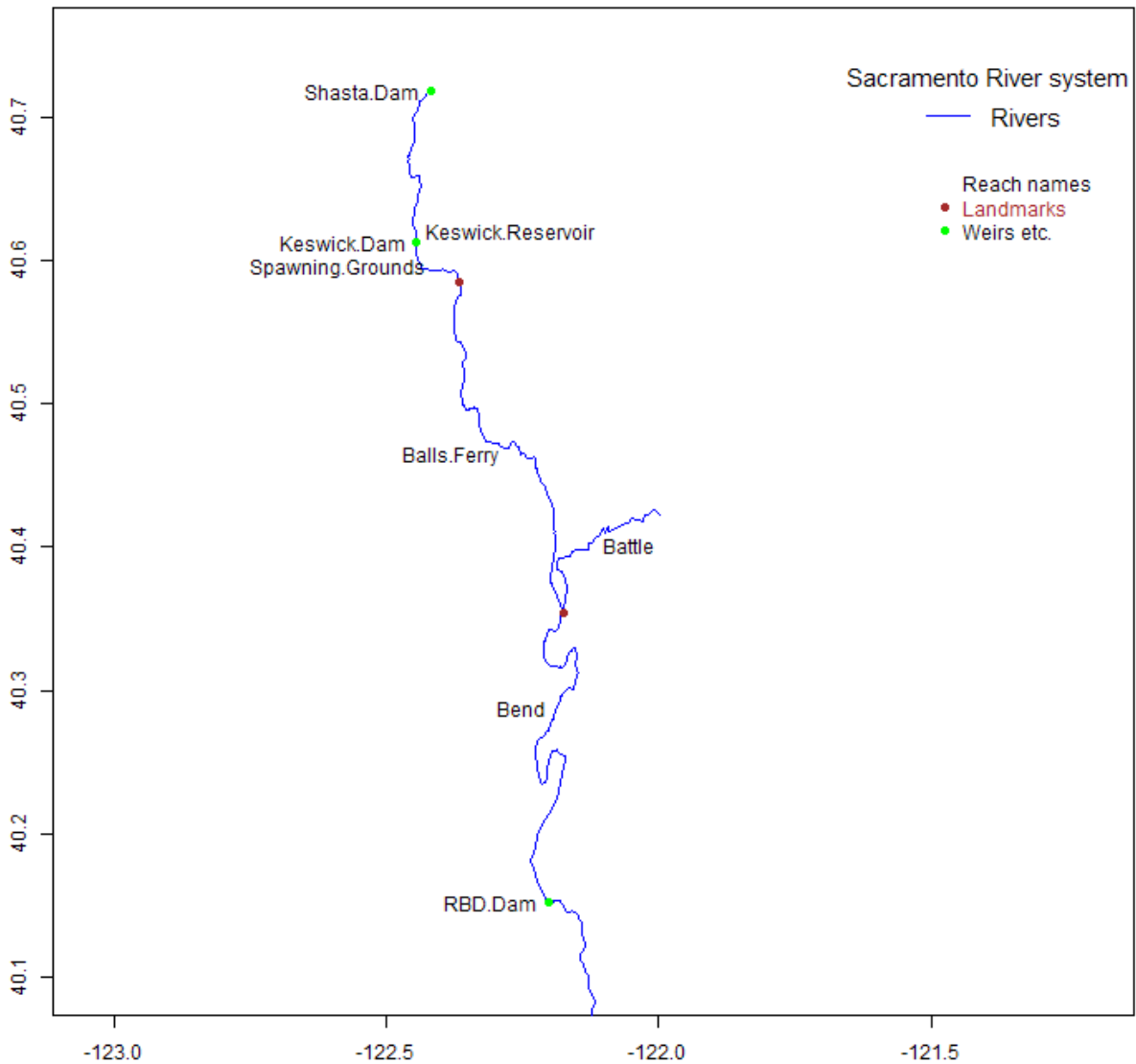


Figure 11 Details of major Sacramento River features used in the spatially explicitly passage model including reach names and select landmarks.

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). Several sub-models for movement and mortality are implemented in the passage model.

Currently, the survival sub-model is calibrated with data from survival studies of fall chinook tagged with hydroacoustic tags (data courtesy of Steel et al. unpublished manuscript). However, the underlying model is very flexible and has the capacity to include more detail and covariates that affect movement and survival. As a predictive tool, migration and survival need to be characterized in terms of forecastable environmental conditions.

## Specify flow

Flow is an important input to the model and must cover a two year period for at least one location. Flow inputs to the passage model can be made in three possible ways:

- 1) Historical System Conditions: a pre-formed data set of observations with both spatial and temporal resolution. Necessarily, the most recent archive is at least one year old. The current model configuration can account for spatial variation in flow due to tributary inputs and irrigation withdrawals<sup>1</sup>. However, this is only available for these Historical System Conditions data sets.
- 2) Fixed point flow for recent years. These would act as surrogates for actual flow in the river. These data are obtained from the SacPAS database and there are several possible configurations of sites and years-of-record. When modeling scenarios with incomplete flow records, the 10-year average flow is post-pended to the available data. Examples: The 2017 cohort of Winter Chinook salmon are being modeled on October 1, 2017, with fixed flow for 2017-2018 at BND. The database provides observations from the station for Jan 1, 2017 – September 30, 2017, and uses the historic daily average for each missing day October 1, 2017 – December 31, 2018 to complete the time series.
- 3) User provided flow. This allows any hypothetical scenario to be modeled. Some care must be taken to format the flow file appropriately. A plain text file with space or comma delimited records is required with an optional header row. Each subsequent row corresponds to a day beginning Jan 1 and continuing for two years for a total of 731 values. This allows for a leap year. “Dummy” values can be used at either end of the time series. A spreadsheet or text file with multiple columns for years/scenarios/etc. can be used.

### Specify Flow

- Historic System Conditions: Use an existing data set: 2016 to 2017 ▼
- Fixed Flow: flow observations at a single site with 10 year averages for missing/future values: 2017 - 2018 ▼ Obs. and/or 10 year avg. flow at: BND ▼
- User Provided Flow: Choose File No file chosen  
Use column: 2 Needs 731 values beginning Jan.1 of the spawning year. First column is day and other columns are values. Comma or space delimited. Units: ● CFS ● KCFS/TCFS.

## Specify migration rate

Juvenile fish migration rate in miles/day is calculated as a function of river velocity

### Optional: migration rate configuration

- Use the linear migration rate equation with option to modify these default parameters. (Note: net migration rate adjusted to be  $\geq 1$  mile/day)

Above Red Bluff, Fish velocity (miles/day) = 1 + 0.05 x River\_Velocity

Below Red Bluff, Fish velocity (miles/day) = 1 + 0.07 x River\_Velocity

- Use a non-linear migration rate with flow and date threshold triggers. See: [Explore Flow Pulse Migration Model parameters](#)

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

Fish velocity (miles/day) = 0 + 1 x River\_Velocity // (1 + exp(-0.85 x (Flow - 15 KCFS) - 0.1 x (Day - 150))) (May 30 is the critical day.)

<sup>1</sup> These are inferred from differences between downstream and upstream flows at flow monitoring sites.

## Survival below RBDD

Survival is calculated for each reach using the distance and travel time with the XT migration survival model of Anderson et al. (2005). Mortality parameters were adjusted to fit results of a Fall Chinook radio telemetry study reported by Steel et al. (unpublished manuscript).

Current survival model based on reconciled XT fit to LFRCS data (Steel, A. et al. unpublished data).

See: [Survival Model](#)

Adjust the survival rate equation below Red Bluff. See: [Explore Survival Model parameters](#)

Distance(x) parameter =

Time(t) parameter =

Survival between emergence and RBDD passage depends on the selected emergence model. However, the travel time between the spawning ground and RBDD is determined from the SacPAS passage model.

## Passage Model Results

Passage model results can be output in graphical form, as a CSV data file, or as a PDF file. In Figure 12, emergence of fish that seed the model is shown as a Gaussian distribution (gold color) with passage timing and numbers to RBDD (green) and Knights Landing (purple). For a selected year, observed arrival at RBDD is shown as a dashed histogram and flow is shown as blue line.

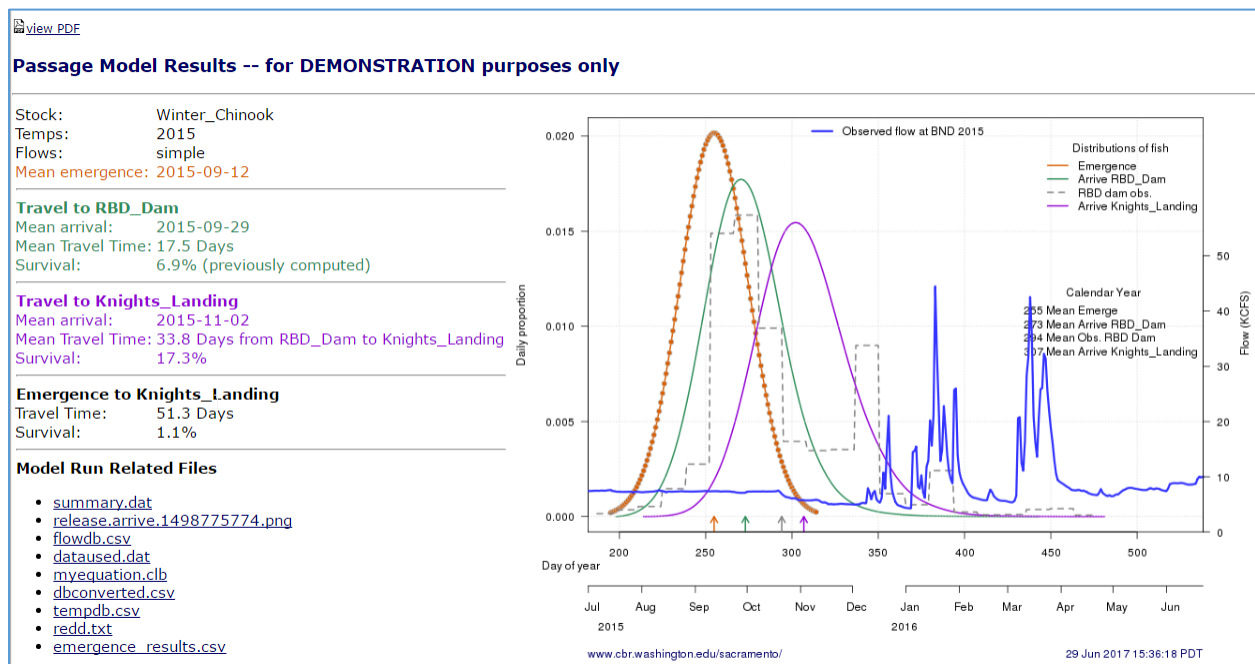


Figure 12 Graphical output window showing results of the passage model.

## Model Details

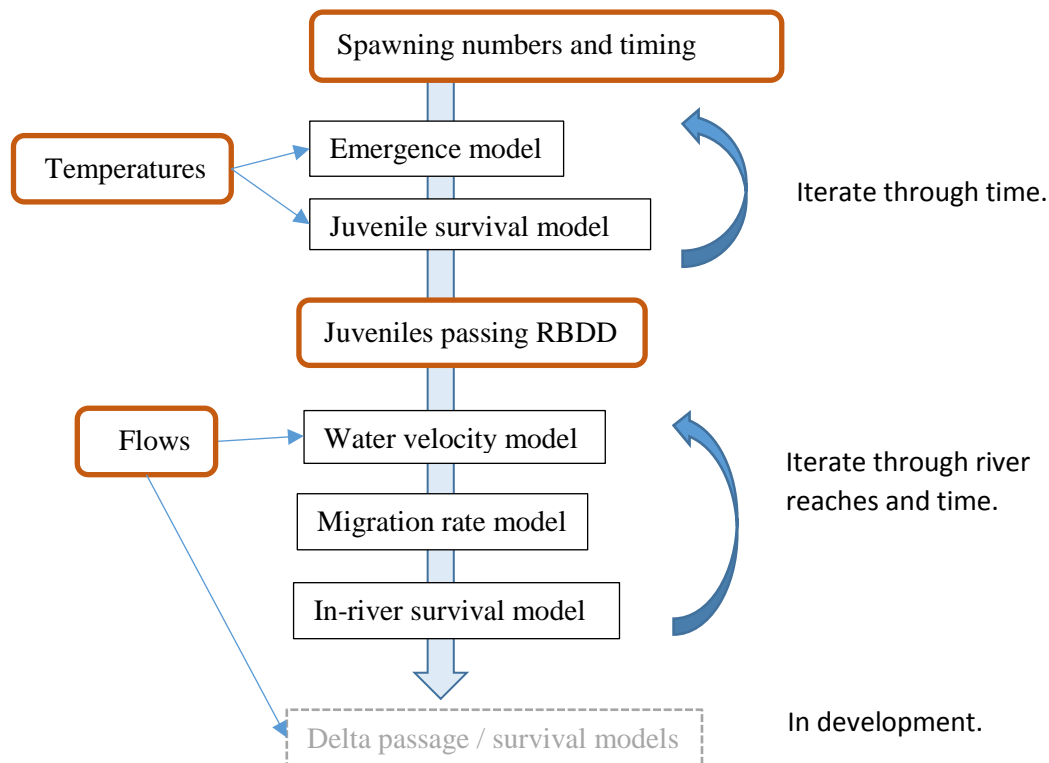


Figure 13 Sub-model components and data relationships overview.

## Sub models

### Emergence timing model

Egg development begins at the time of spawning and proceeds at a rate that is related to temperature. Four options are available for modeling Chinook egg development. They are illustrated in Figure 14. It is not possible to modify the parameters in these models (except the ATU model).

- 1) A mechanistic model (Beer and Anderson 1997). This model does not have a closed form. The egg mass and embryo mass are coupled and temperature drives the rate and efficiency of growth. When the yolk is sufficiently depleted, the fish emerges.
- 2) An empirical model (Jensen and Jensen 1999). Each day, the fraction of total development is related to temperature as:  

$$0.002755949 + 6.340096 \times 10^{-5} \cdot T + 9.564633 \times 10^{-5} \cdot T^2 - 5.250954 \times 10^{-6} \cdot T^3 + 3.046699 \times 10^{-7} \cdot T^4$$
- 3) A power law model (Beacham and Murray 1990). At a fixed temperature, the number of days for development is:  $Days = e^{10.404 - 2.043 \cdot \log(T^{\circ}C + 7.575)}$ . To use this in fluctuating temperatures, development rate (1/Days) is computed each day, and these fractions are summed until they add up to one at emergence.
- 4) Accumulated Temperature Units (ATU) model (Zeug et al. 2012). Every day, temperature units are accumulated until the total number of degree days exceeds a specified

threshold. The published value (in °C units) is 958. Development rate per day is  $0.001044 * \text{Temp}_C$  or  $0.0058 * \text{Temp}_F - 0.018$ . The user can change the ATU threshold.

Additional models and parameterizations on demand are limited for this version. Adjusting the ATU threshold is possible. It is planned that future versions of the model will allow the user more control over the exact model being used.

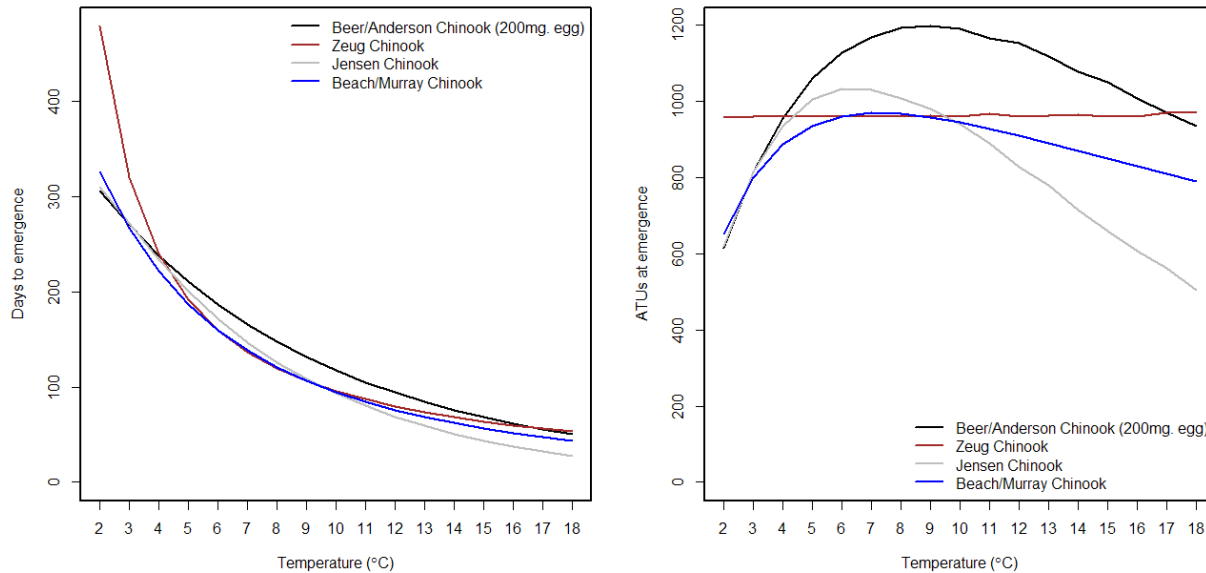


Figure 14 Chinook egg development time and ATUs according to four unique models. In practice, daily fraction of total growth is computed for each day's average temperature and these daily fractions are summed until they reach one.

### Egg/Juvenile survival model

There are three models available for egg/juvenile survival.

- 1) Constant survival where egg survival and fry survival are distinct but unvarying (Oppenheim 2014).
- 2) Threshold-temperature survival with a linear spawner density effect (Martin et al. 2016a). In this case there is no temperature effect below the threshold. Above the threshold, survival decreases with increasing water temperature. There is a maximum survival level specified and this is unaffected by temperature, but the number of spawners on the spawning grounds reduces survival.
- 3) Threshold temperature survival with a beverton-holt type spawner density effect (Martin et al. 2016b). In this case there is no temperature effect below the threshold. Above the threshold, survival decreases with increasing water temperature. There is a maximum survival level specified and this is unaffected by temperature, but the number of spawners on the spawning grounds reduces survival relative to the carrying capacity of the river.

The two models with threshold temperatures are similar but compute the density effect differently.

The constant survival model is unaffected by the temperature or number of spawners, but the other two can be explored by clicking the "Explore Egg/Fry survival models" link which will open a Shiny App in a



new browser window allowing the user to manipulate all the inputs to the survival equations and visualize the results (Figure 15).

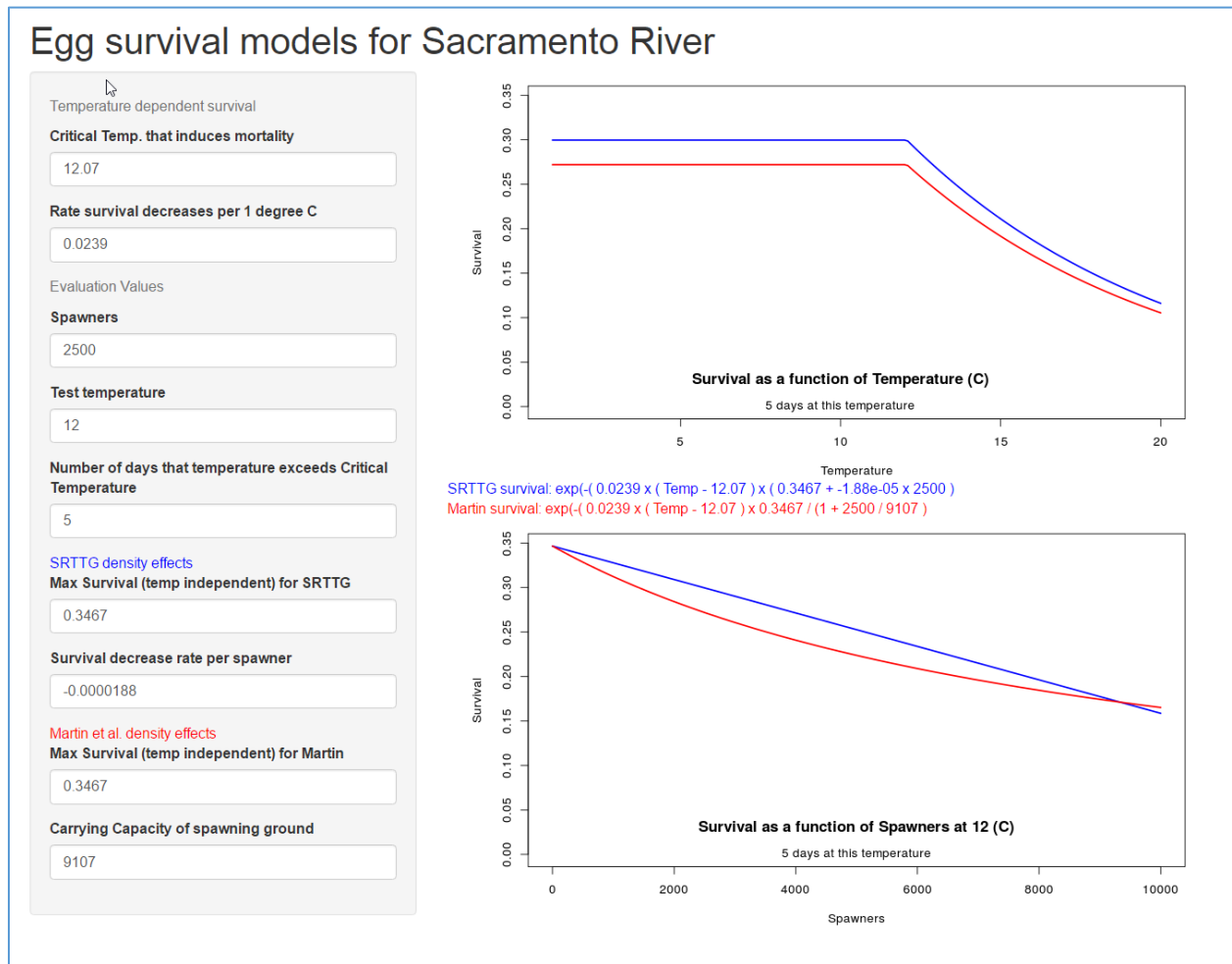


Figure 15 Shiny app allowing user to explore sensitivity of egg/fry survival models, [https://nicko.shinyapps.io/EGG\\_SURV/](https://nicko.shinyapps.io/EGG_SURV/).

### Water velocity model

The water velocity relationship to flow is based on the Hec-RES model, maintained by the US-ACOE <http://www.hec.usace.army.mil/software/hec-ressim/>. Flow vs. velocity data were provided by Andrew Pike (pers. communication February 12, 2016). See Figure 16.

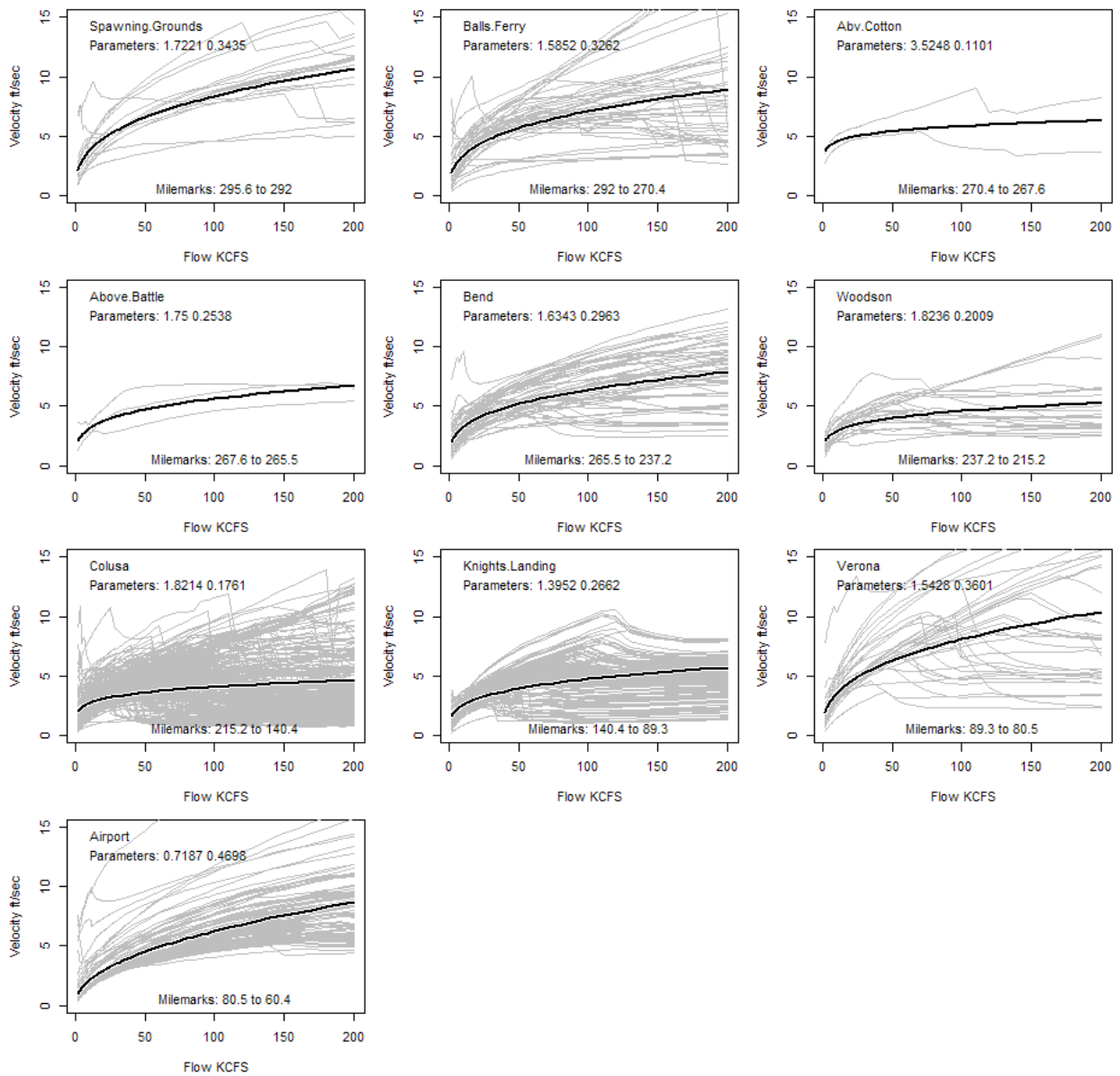


Figure 16 Flow velocity relationships used for the passage model. Transects are organized by reaches. Each gray line is a flow velocity relationship at a cross section within the reach. The black line is a fit to the available data and provides the parameters required for each reach in the passage model.

### In-river survival model

The in-river survival model calibration is ongoing. It is a multi-stage process including selection of the model, data acquisition to support the functional form of the model, and calibration of model parameters.

The basic assumption is that the fish are relatively the same between cohorts, but the environment varies greatly. Thus, the survival model needs to be sensitive to environmental conditions and specific to Winter Chinook. Most notably, flow varies spatially and temporally, and influences travel time directly. The consequence for real fish is that: although slow travel may reduce daily predator encounters, it increases the number of days spent in the river. The tradeoff between the distance (X) and the time spent (T) is referred to as the “X-T model” Anderson et al. 2005. Its functional form and current

parameterization (unpublished data Steel A. and Anderson J. personal communication) are shown in Figure 17. Implementation of this model into the current configuration of COMPASS involves a mapping of the X-T parameters to the internal survival model. These are compared in Figure 17. For a detailed exploration of the tradeoffs between the time and distance, there is an interactive tool for examining the sensitivity of the passage survival model to the input parameters. See <https://nicko.shinyapps.io/SURVDEMO/> and illustration in Figure 18.

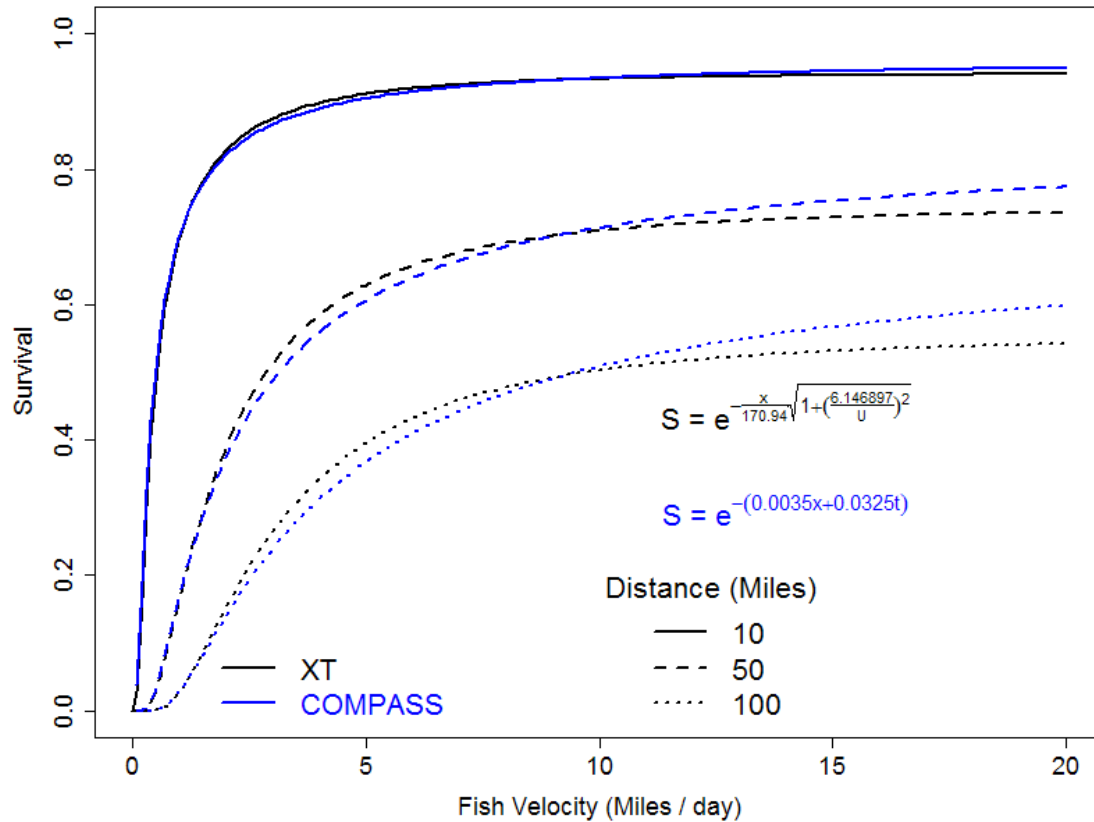


Figure 17 Survival is a function of both distance (X) and travel time (T) in the passage model. This illustration shows the relationship between the XT model and the COMPASS-ready model.

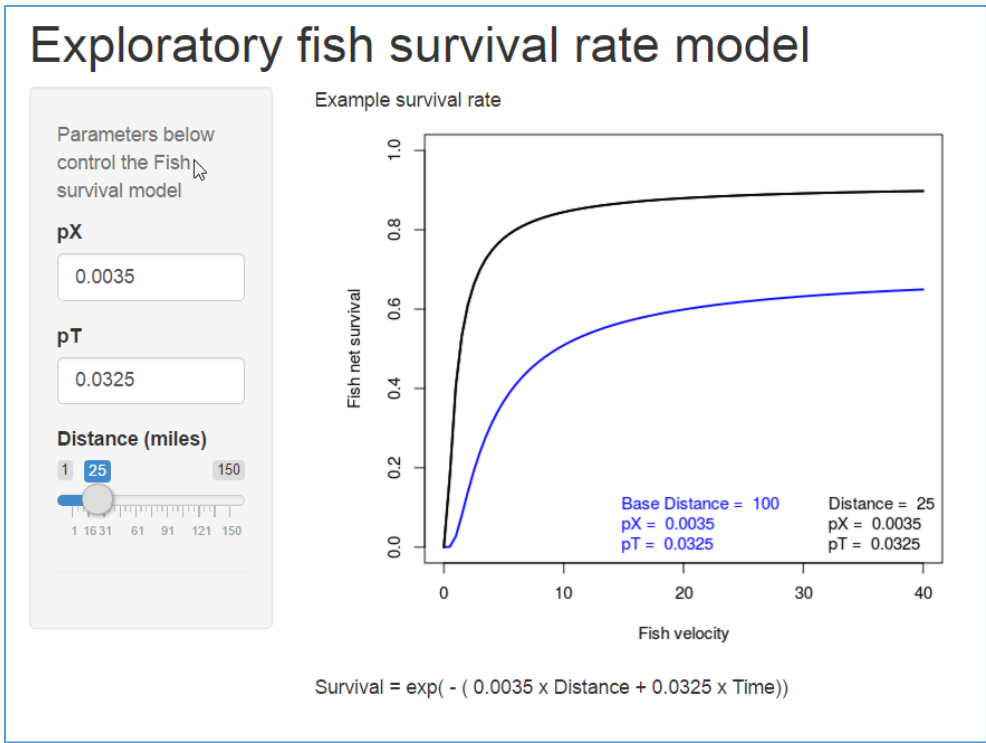


Figure 18 Interactive tool for examining sensitivity of the passage survival model to the parameters. See <https://nicko.shinyapps.io/SURVDEMO/>

### Migration model

Migration rate is modeled as a function of water velocity which in turn is a function of flow. There are currently two options: a linear and a non-linear type. The effective migration rate is adjusted, as needed, to be  $\geq 1$  mi/day.

*A linear migration rate model:* Fish.velocity = param<sub>0</sub> + param<sub>1</sub> x River.velocity. The default equation is 1 (mi/day) + 0.05\**River.velocity* (mi/day) above Red Bluff and 1 (mi/day) + 0.07 \* *River.velocity* (mi/day) below Red Bluff.

*A non-linear migration rate model:* This form has a slow base velocity but jumps to a much higher value under one or both of these conditions: the day of the year approaches a threshold, or the flow approaches a threshold. The sensitivity of the rate to these thresholds is controlled by two parameters. This allows fish to migrate very rapidly on freshets, and/or after sufficient time has passed since migration began:

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

The equation parameters (and base values used for sensitivity analysis) are:

- $V_{Fish}$  = mean migration rate on day  $D$
- $\beta_0$  = parameter that determines the flow-independent migration rate. (0)
- $\beta_1$  = parameter relates fish velocity to river velocity. For freshet-movements (non-swimming), this parameter is probably  $\sim 1.0$ . (1.0)
- $\alpha_1$  = sensitivity to flow-effect changes (0.2)

$\alpha_2$  = sensitivity to day-effect changes (0.03). This will be smaller than  $\alpha_1$  and will reflect both the units (days vs. KCFS), and also the sensitivity of fish to time. Ultimately they will move downstream, even without an episodic flow trigger.

Q = flow volume on day  $D$

D = day-of-year

$Q_{crit}$  = flow level above which the fish move with the velocity of the water. (15 KCFS). In the Sacramento, a lot of the flow is unregulated, so freshets can be significant. Winter flow events exceed base flows by factors of 2 – 5 or more.  $400 \text{ m}^3\text{s}^{-1} = 14 \text{ KCFS}$  may be a useful starting value (del Rosario et al. (2013).

$D_{crit}$  = threshold for day-of-year influence on fish velocity. (425 = March 1). This is a surrogate for biotic and abiotic triggers that become more likely as time goes on: growth, size, age, smoltification, day length, etc.

$\bar{V}$  = mean water velocity in the reach computed with  $\bar{V}_D = p_0 \cdot Q^{p_1}$ .

The flow-velocity relationships are well established for the Sacramento River, and the parameters  $p_0$  and  $p_1$  vary with each reach (see Figure 16).

In the early season, Winter Chinook are known to move quite unremarkably, unless there is a large freshet. This model has the property that late season and/or high flow can trigger rapid migration. Additionally, since the two exponential terms 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 will be triggered. To examine this model, with full functional control, see: [https://nicko.shinyapps.io/MIGR\\_DISTRI/](https://nicko.shinyapps.io/MIGR_DISTRI/) (Figure 19).

# Exploratory fish migration rate model

Parameters below control the Fish velocity relationship to water velocity

alpha

alpha2

B0

B1

Critical Flow

Example Flow




Critical Day

Example Day

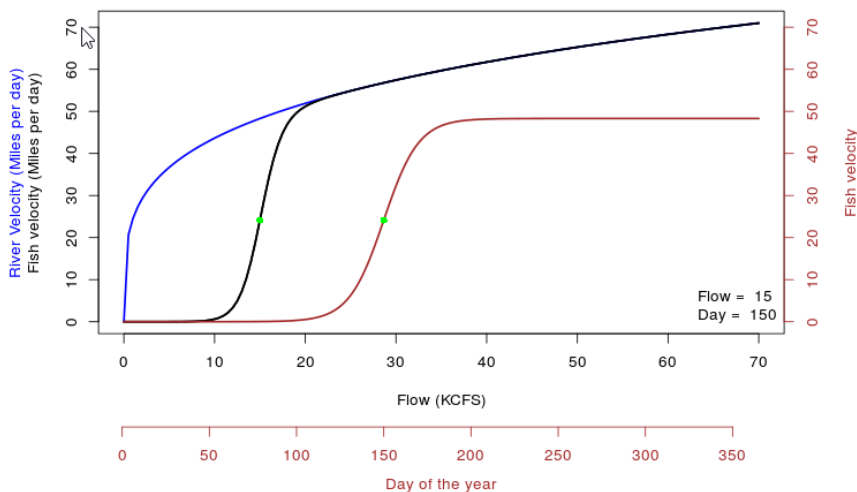



Velocity of water is related to flow volume:

p0 (exponent)

p1

Example migration rate model that initiates rapid migration at a critical flow and/or after a certain time in the year



Water velocity =  $1.5 * \text{Flow}^{0.25} * 16.34 \text{ (Miles / Day) / (Foot / Second)}$

Migration Rate =  $0 + 1 * \text{River\_Velocity} / (1 + \exp(-0.85 * (\text{Flow} - 15) - 0.1 * (\text{Day} - 150)))$

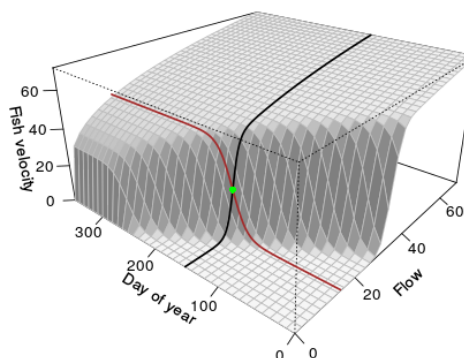


Figure 19 Interactive tool for examining sensitivity of the passage migration rate model to the parameters. See: [https://nicko.shinyapps.io/MIGR\\_DISTRI/](https://nicko.shinyapps.io/MIGR_DISTRI/)

## Calibration

The calibration process is on-going at time of writing. No specific migration or survival rate models have been published for winter Chinook. The default survival rate and migration rate parameters are described above in the sections: “In-river survival model” and “Migration model”. Currently, the state of the data includes indices of winter Chinook counts at various locations along the Sacramento River. Based on [Cohort Juvenile Monitoring](#) and [Migration Timing and Conditions](#) SacPAS data queries, the median passage days were computed for each cohort at RBDD and the Sacramento trawls for the last 10

years. These were used to compute an index of the cohort travel time (see Table 1 ). Exploring the mechanisms that produce such highly variable travel time data (from 51 to 165 days) will help make the SacPAS Fish Model a better predictive tool. Notes on interpretation: These 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.

For details, we recommend viewing the SacPAS Juvenile Monitoring & Sampling queries [Cohort Juvenile Monitoring](#) and [Migration Timing and Conditions](#). The ratio of the Sacramento Beach Seines catch index to the RBDD estimated passage varies from 0.000013 to 0.003128 over the last 10 years.

Table 1 Juvenile Winter Run Chinook Monitoring Data.

Cohort Year	RBDD median passage	Sacramento River Beach Seines median passage	Travel time (Days)
2007	10/2/2007	1/8/2008	98
2008	9/18/2008	3/3/2009	165
2009	9/18/2009	11/20/2009	63
2010	10/5/2010	12/17/2010	73
2011	10/7/2011	1/30/2012	115
2012	10/20/2012	12/10/2012	51
2013	10/28/2013	2/15/2014	110
2014	9/27/2014	12/17/2014	81
2015	10/6/2015	1/20/2016	106
2016	10/5/2016	12/12/2016	68

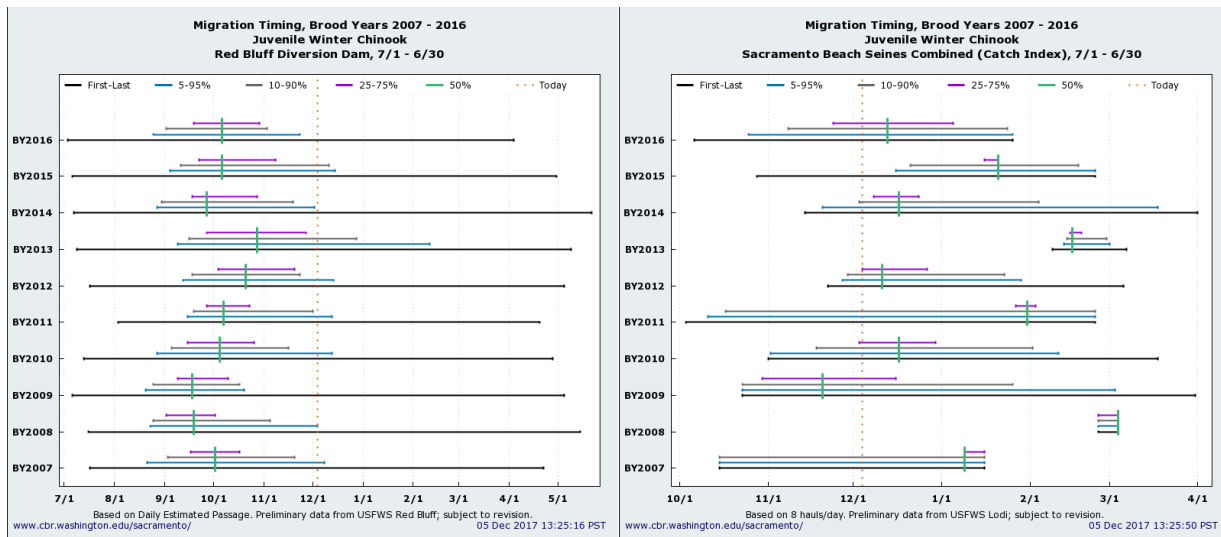


Figure 20 Migration timing of winter Chinook for 10 years at RBDD and Sacramento beach seines from [Migration Timing and Conditions](#) SacPAS database query.

## Sensitivity

### Emergence model sensitivity to temperature.

Sensitivity of emergence to temperature is essential to the emergence modeling process. **Error!**

**Reference source not found.** compares the four current options in terms of accumulated temperature units (ATUs) and days to emergence. Currently the parameters of the models cannot be altered, except to select the final ATU value for the linear model.

### Sensitivity of the migration model to annual differences and use of base, historic 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 historic base conditions over the years 2008 through 2016, and then compared to results with alternative parameters as inputs.

The historic 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 historic 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. This is easy to see in Figure 21 as an example of the spatial variability in flows at four sites on the Sacramento River over the years 2012 and 2013. The historic 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 historic base data and the surrogates are depicted in Figure 22 and Figure 23. A note on interpretation: Keswick flows are highly regulated and result in very consistent survivals and travel times, regardless of the year (black line represents KWK in Figure 21 through Figure 23). The flows have low variability between years as do the corresponding survival and travel time based on this. Downstream at Verona (VON), the Feather River can contribute significant flow in certain years. With VON flow as a surrogate, the inter-annual survival and travel time predictions vary widely, and survival is generally higher and travel is more rapid due to the greater flow.



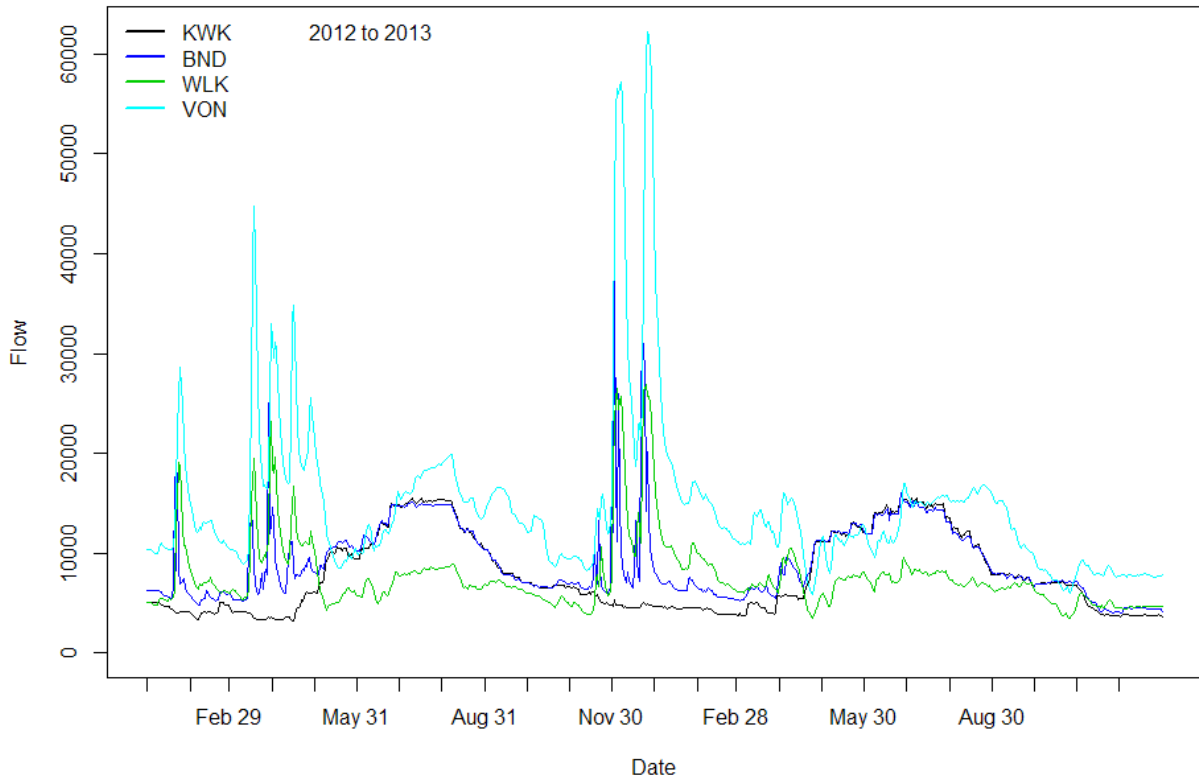


Figure 21 Hydrographs (average daily flow in CFS) at four sites on the Sacramento River during 2012 and 2013.

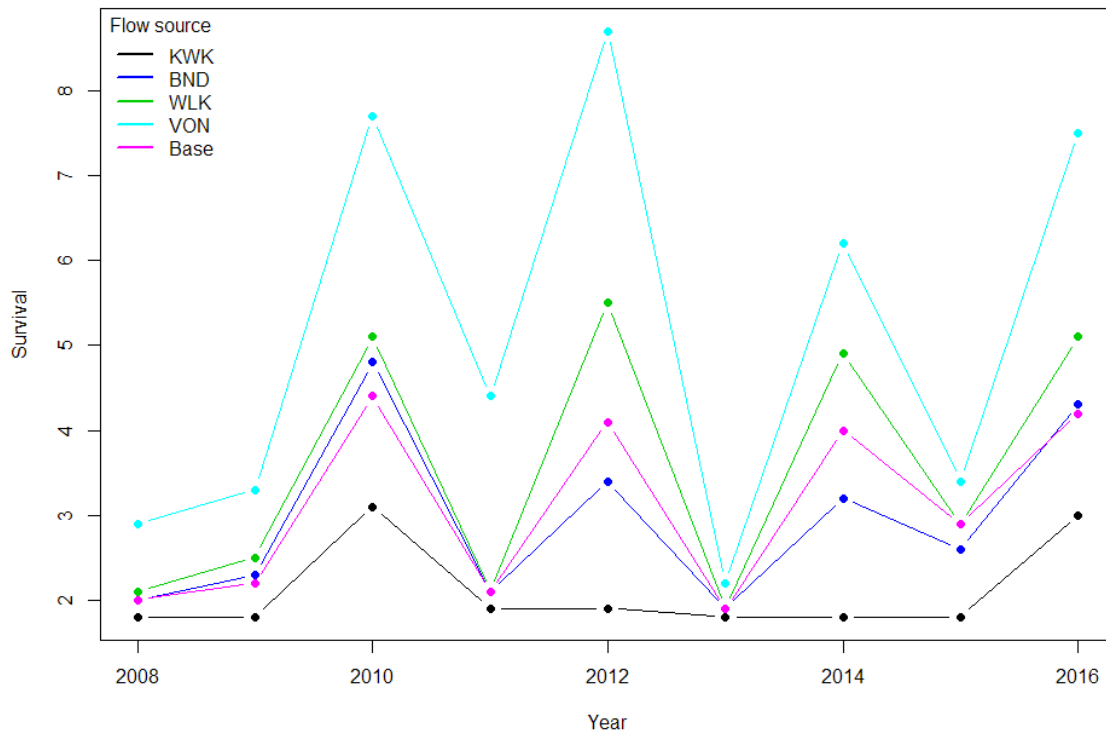


Figure 22 Sensitivity of survival to flow sources and annual variation. "Base" conditions have time and space-varying flows based on observed historic conditions. Single site conditions (BND=Bend, KWK = Keswick, WLK = Wilkins, and VON = Verona) have the observed flow at the site applied to the entire river.

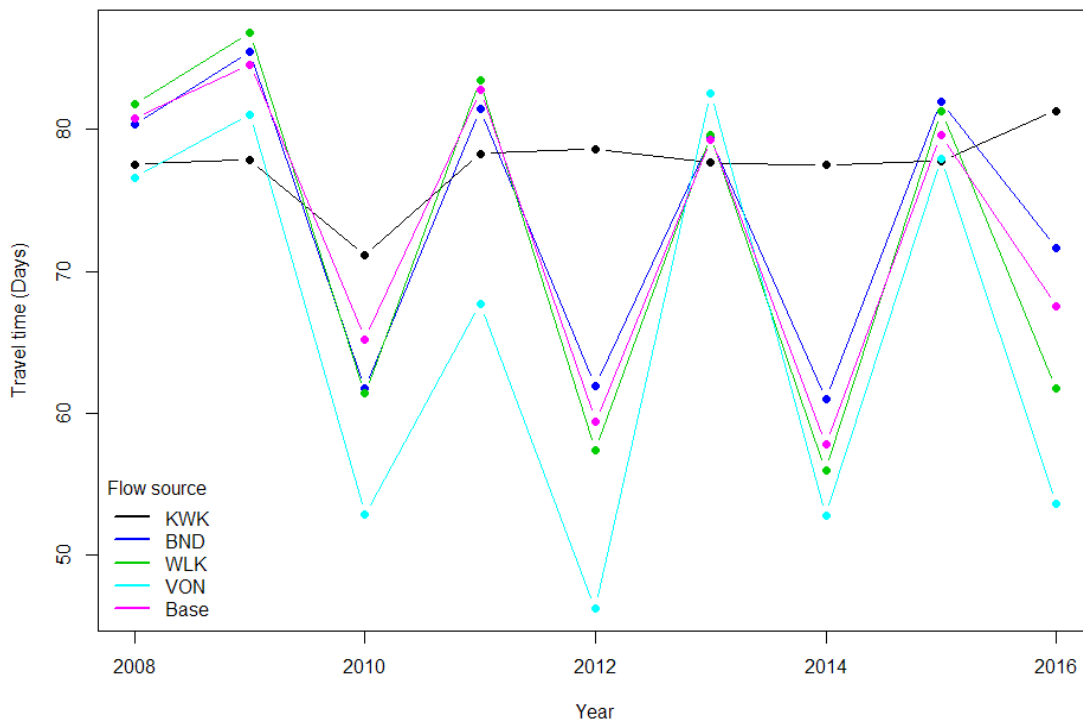


Figure 23 Sensitivity of travel time (days) to flow sources and annual variation. Travel time modelled from RBDD to Verona. "Base" conditions have time and space-varying flows based on observed historic conditions. Single site conditions (BND=Bend, KWK = Keswick, WLK = Wilkins, and VON = Verona) have the observed flow at the site applied to the entire river.

## Sensitivity to migration rate parameters

The general non-linear, migration rate equation has the following form:

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

The linear model is a special case of this when the bracketed term is equal to one. The bracketed term allows thresholds of time and/or flow to trigger rapid migration. For the sensitivity analysis, a base set of migration parameters was chosen and then each parameter in turn was varied over a range. There are many possible combinations of changes that could be illustrated, but one-at-a-time sensitivity is shown here. The timeframe for a model run spans two calendar years because the Winter Chinook spawn in the late 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). Base values are:  $B_0 = 0$ ;  $B_1 = 1$ ;  $\alpha_1 = 0.2$ ;  $\alpha_2 = 0.03$ ;  $Q_{crit} = 15$  KCFS;  $D_{crit} = 425$ .  $B_0$  is the constant, background migration rate;  $B_1$  is the rate of migration proportional to the flow. When  $B_1 = 1$  and the bracketed term = 1, fish move at the velocity of the river ( $V$ ) on that day in their location. The terms  $\alpha_1$  and  $\alpha_2$  control the sensitivity of the exponential expression to flow ( $Q$ ) and day-of-year ( $D$ ).

We encourage the use of the interactive visualization tool [https://nicko.shinyapps.io/MIGR\\_DISTRIB/](https://nicko.shinyapps.io/MIGR_DISTRIB/) to see how the parameters affect the interaction of time and flow to generate fish velocity. See Figure 19.

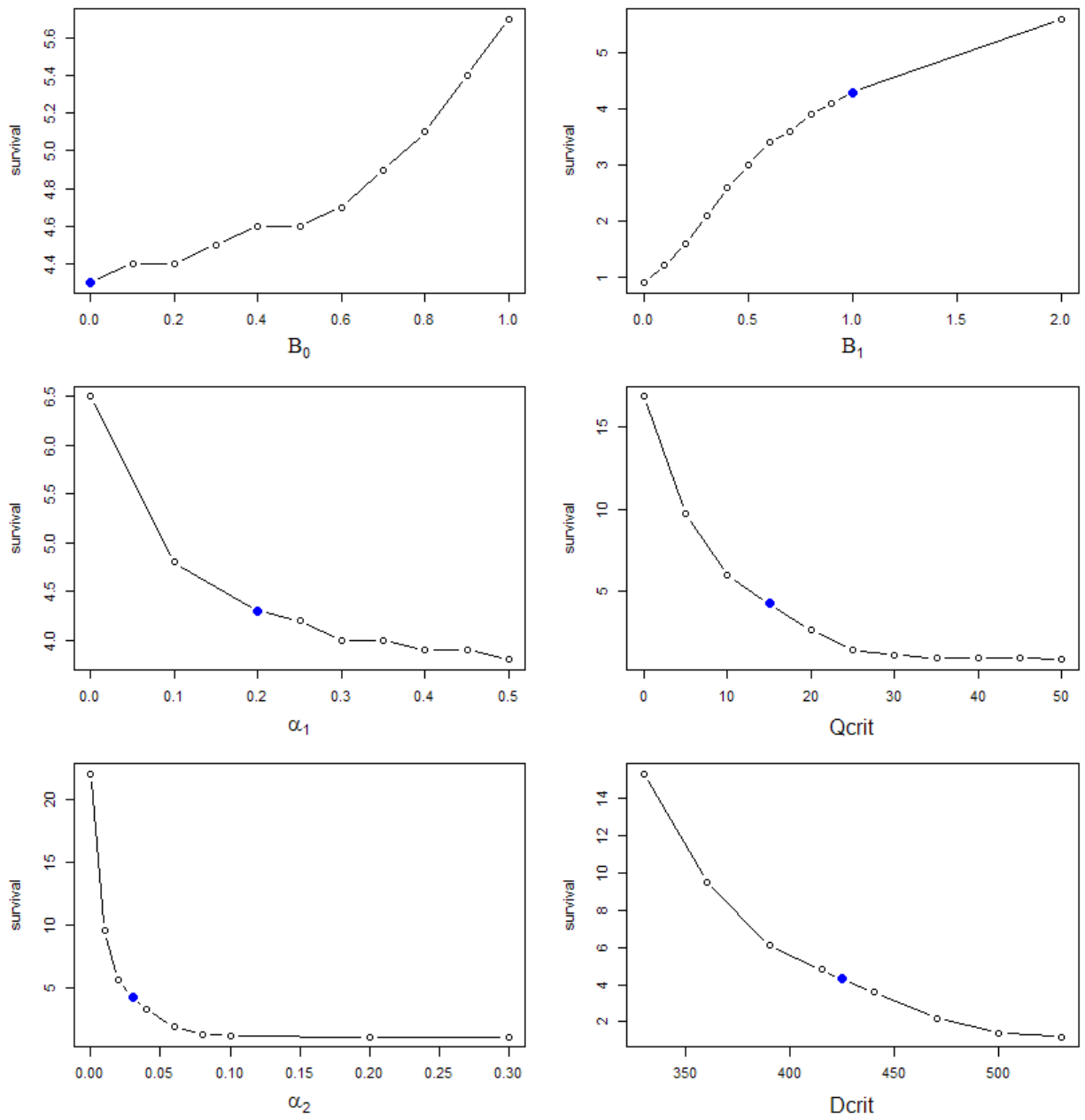


Figure 24 Sensitivity of survival to migration rate parameters for a cohort of fish in the Sacramento River released on day 300 in 2010 (October 27) from Red Bluff dam to the mouth of the Feather River. Larger solid dot shows the mean response at the nominal value of the parameter. This is verified by their identical y-axis values in each panel.

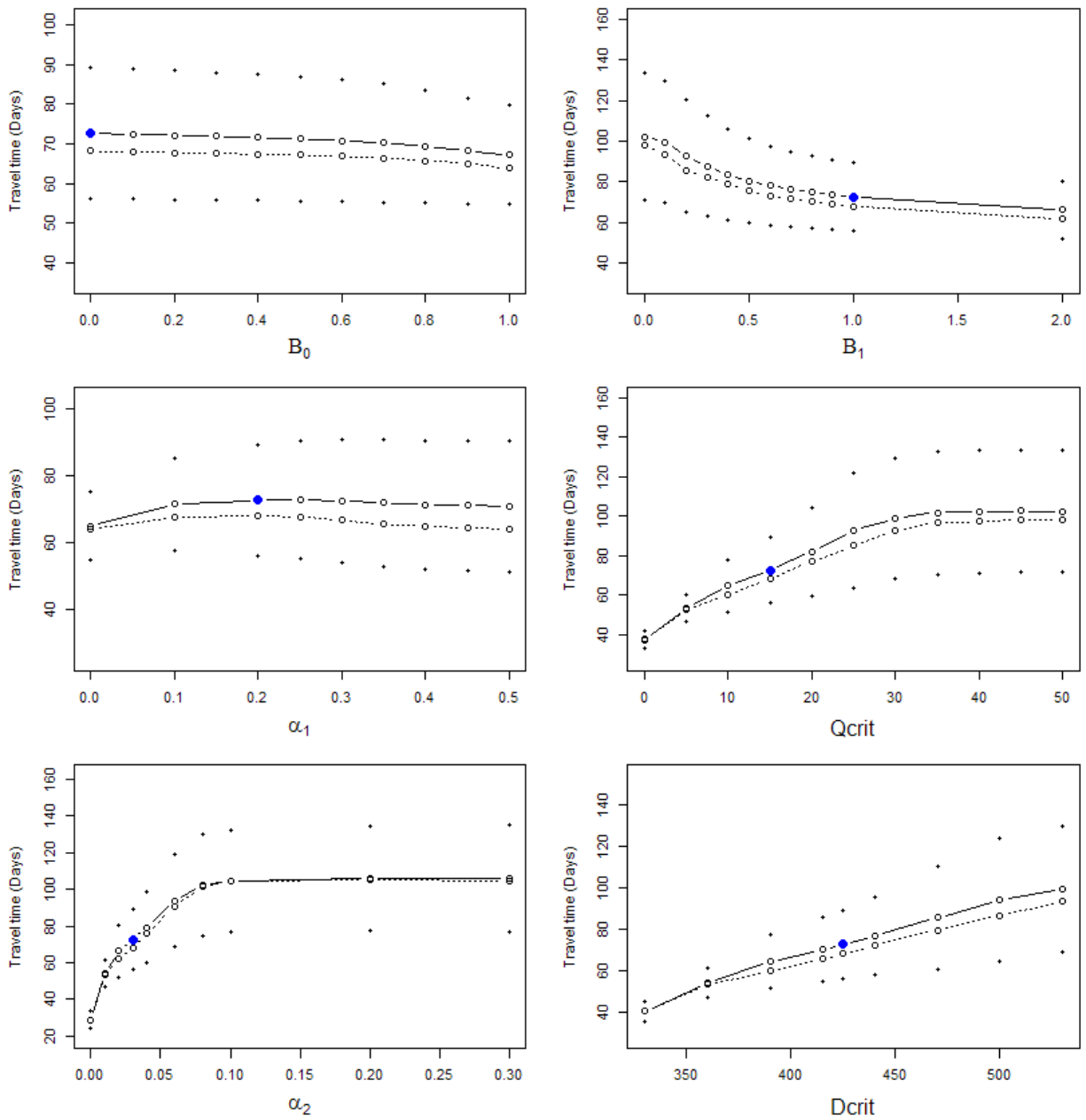


Figure 25 Sensitivity of travel time to migration rate parameters for a cohort of fish in the Sacramento River released on day 300 in 2010 (October 27) from Red Bluff dam to the mouth of the Feather River. The mean travel time (solid line) the median travel time (dotted line) and the mean  $\pm$  standard deviation (small dots) are shown. Larger solid dot shows the mean response at the nominal value of the parameter. This is verified by their identical y-axis values in each panel.

### Sensitivity to survival equation parameters

Survival is a function of distance travelled and time elapsed. 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 do 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 26 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 be killed 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 26 right panels).

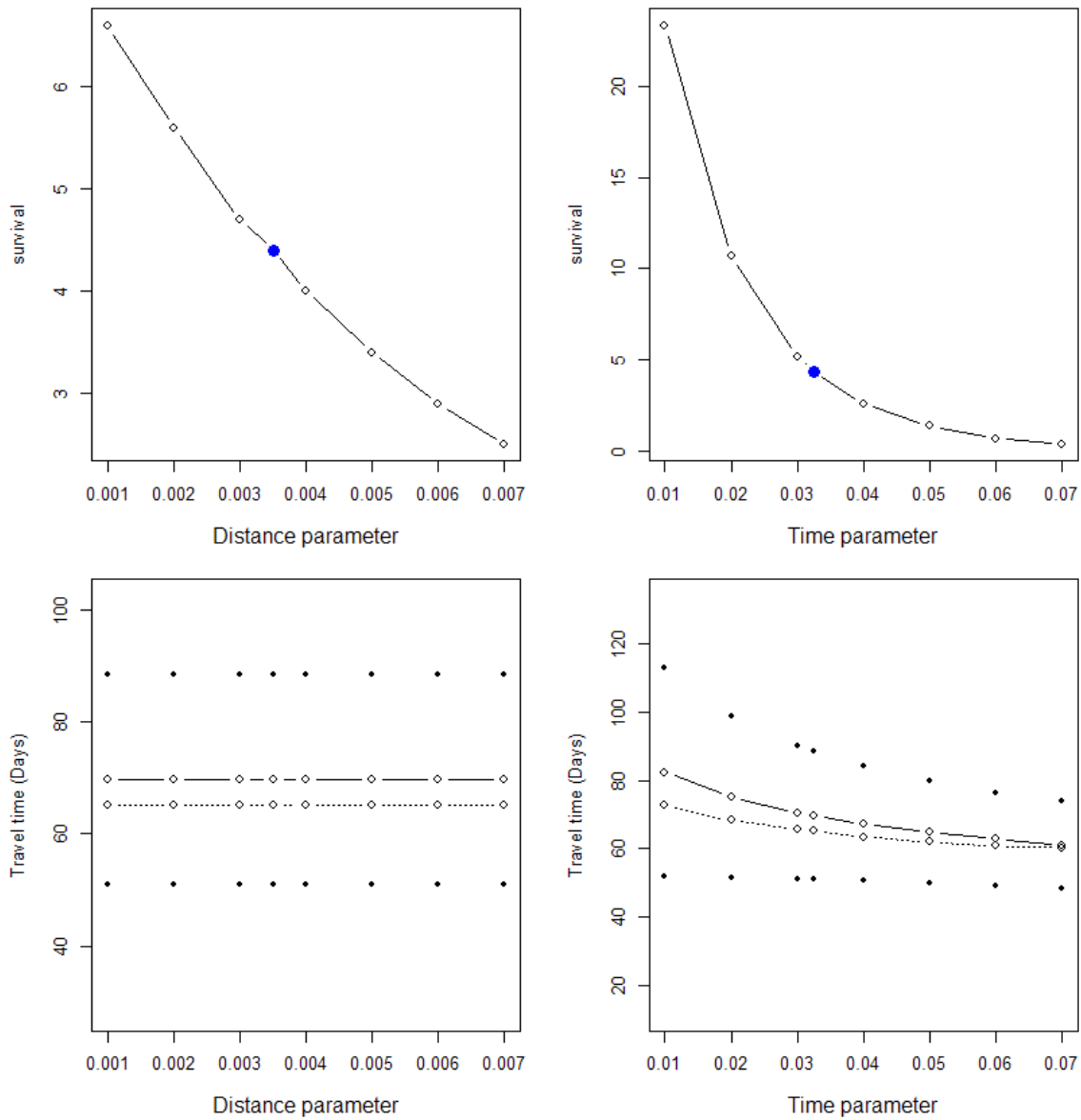


Figure 26 Sensitivity of survival (%) and travel time to the survival equation parameters. The mean travel time (solid line) the median travel time (dotted line) and the mean  $\pm$  standard deviation (dots) are shown.

## Acknowledgements

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## Citations

- Anderson JJ, Gurarie E, Zabel RW. Mean free-path length theory of predator-prey interactions: Application to juvenile salmon migration. *Ecological Modelling*. 2005;186(2):196-211. doi: DOI 10.1016/j.ecolmodel.2005.01.014. PubMed PMID: ISI:000230636400004.
- Beacham, T.D., C.B. Murray. 1990. Temperature, egg size, and development of embryos and alevins of five species of Pacific salmon: A comparative analysis. *Transactions of the American Fisheries Society*. 119(6):927-945.
- Beer, W.N., J. Anderson. 1997. Modelling the growth of salmonid embryos. *Journal of Theoretical Biology*. DOI 10.1006/jtbi.1997.0515
- CFS. 2010. A Revised Sacramento River Winter Chinook Salmon Juvenile Production Model. Cramer Fish Sciences. Available 9 May 2016 from: <http://deltacouncil.ca.gov/sites/default/files/2014/11/November-2010-A-Revised-Sacramento-River-Winter-Chinook-Salmon-Juvenile-Production-Model.pdf>
- del Rosario, R.B., (six other authors). 2013. Migration patterns of juvenile winter-run-sized Chinook salmon through the Sacramento-San Joaquin Delta. *San Francisco Estuary and Watershed Science*. 11(1). <http://escholarship.org/uc/item/36d88128>. Available June 15 2017.
- Jensen J. O. T., Jensen M. E., Aquaculture Assoc. of Canada S. A. N. B., Waddy S. 1999. IncubWin: A new Windows 95/98/NT computer program for predicting embryonic stages in Pacific salmon and steelhead trout *Contributed Papers - Aquaculture Canada '99 Victoria BC*, 28 pp.
- Martin, B., John S., Pike A., Roberts J., Danner E. 2016. Modeling temperature dependent mortality of winter-run Sacramento River Chinook salmon. In: [http://www.westcoast.fisheries.noaa.gov/publications/Central\\_Valley/Water%20Operations/nmfs\\_concurrence\\_on\\_the\\_bureau\\_of\\_reclamation\\_s\\_sacramento\\_river\\_temperature\\_management\\_plan-june\\_28\\_2016.pdf](http://www.westcoast.fisheries.noaa.gov/publications/Central_Valley/Water%20Operations/nmfs_concurrence_on_the_bureau_of_reclamation_s_sacramento_river_temperature_management_plan-june_28_2016.pdf). Available June 20, 2017.
- Martin, B., (six other authors). 2016. Phenomenological vs. biophysical models of thermal stress in aquatic eggs. *Ecology Letters*. DOI 10.1111/ele.12705
- Oppenheim, B. 2014. Juvenile Production Estimate (JPE) Calculation and Use/Application of Survival Data from Acoustically-tagged Chinook Salmon Releases. Report prepared for the 2014 Annual Science Panel Review Workshop, November 6-7.
- Zabel R.W., Faulkner J., Smith S., Anderson J., Van Holmes C., Beer W. N., Iltis S., Krinke J., Fredricks G., Bellerud B., Sweet J., Giorgi A. 2008. Comprehensive passage (COMPASS) model: a model of downstream migration and survival of juvenile salmonids through a hydropower system. *Hydrobiologia*. 609(1):289-300.
- Zeug, S., P. Bergman, B. Cavallo, and K. Jones. 2012. Application of a Life Cycle Simulation Model to Evaluate Impacts of Water Management and Conservation Actions on an Endangered Population of Chinook Salmon. *Environmental Modeling and Assessment*. DOI 10.1007/s10666-012-9306-6.