SacPAS Fish Model v.2: A model for emergence, migration and survival of Sacramento River salmon

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 second version of the interface to these coupled models: SacPAS Fish Model v.2. The public, web-based model is found at: http://www.cbr.washington.edu/sacramento/fishmodel/ .

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 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.

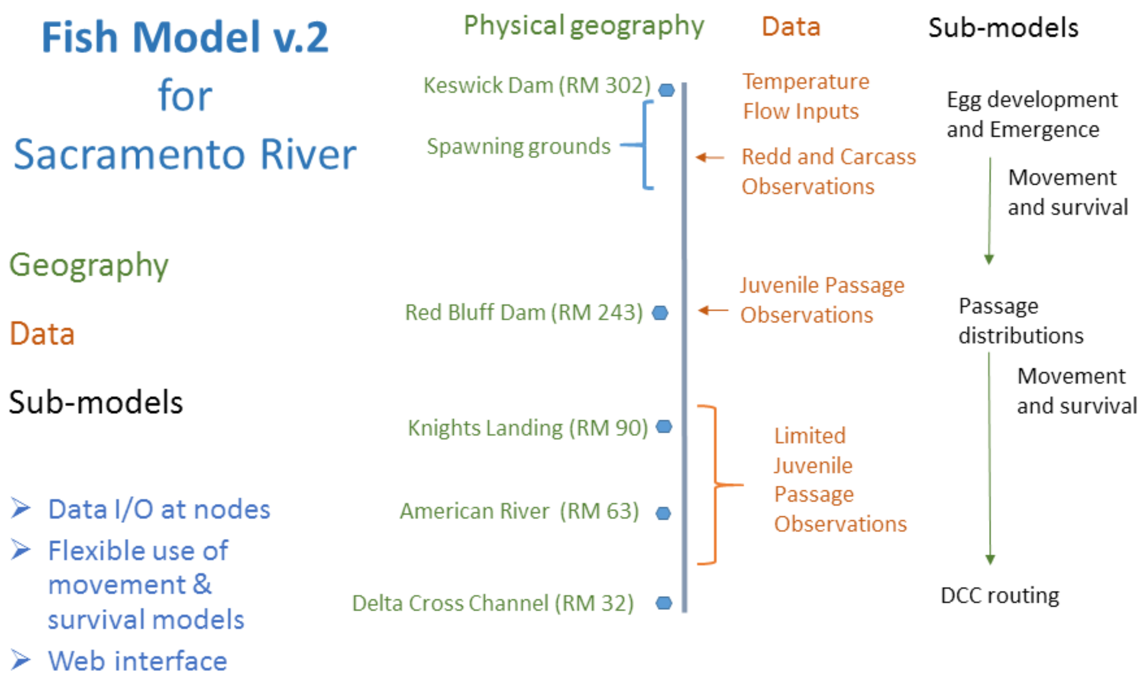


Figure 1 Schematic of physical geography, data and sub-models comprising the Fish Model component of SacPAS.

Important changes to Fish Model since version 1

1. Temperatures can vary across the spawning ground.
2. Use of carcasses or adult counts is removed. User must now pre-process these data.
3. No release "smoothing".
4. Additional egg survival models based on temperature and/or density.
5. Spatial depiction and control is enhanced.
6. Mode details on emergence are presented
7. Migration model tracks fish to the Delta Cross Channel.
8. DCC operations are modeled.
9. User interface is reorganized.

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 of new redds 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 RBDD passage based on the bi-weekly estimates, or user-provided dates and counts.
- Daily flows from historical data sets on the Sacramento River, daily flows from a single location or user-provided.
- 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 adult 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 *passage distribution.* The passage distribution or other time-count data is called a *release* when used as input to the passage model. 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 $\text{foot}^3 \bullet \text{sec}^{-1}$ (KCFS or TCFS), velocity of fish and/or water in $\text{miles} \bullet \text{day}^{-1}$, temperature in °C.
CDEC temperature data are in Fahrenheit and flow data are in CFS.

Some useful conversions:
$1\ \text{ft} \bullet \text{sec}^{-1} = 16.364\ \text{miles} \bullet \text{day}^{-1} = 26.3\ \text{km} \bullet \text{day}^{-1}$ $1\ \text{mile} \bullet \text{hour}^{-1} = 1.4667\ \text{foot} \bullet \text{second}^{-1}$
$1\ \text{KCFS} = 28.32\ \text{m}^3 \bullet \text{sec}^{-1}$ 1°C = 1.8°F 1000 ATU (°C) = 1800 ATU (°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 control of the inputs and computations. 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.

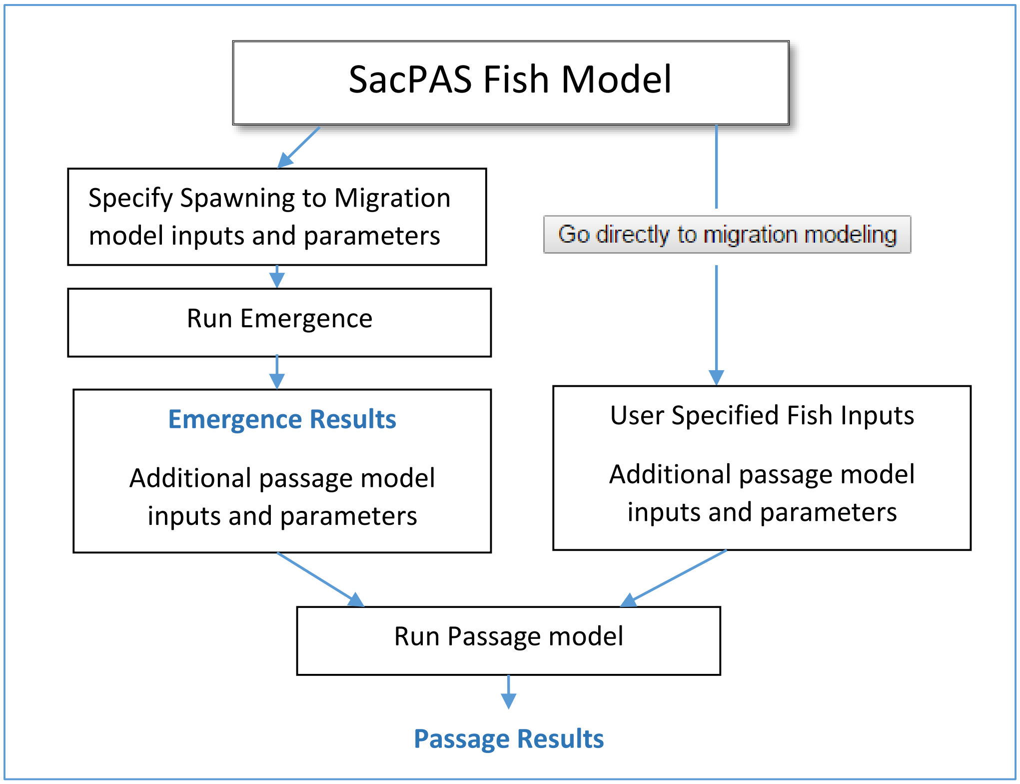


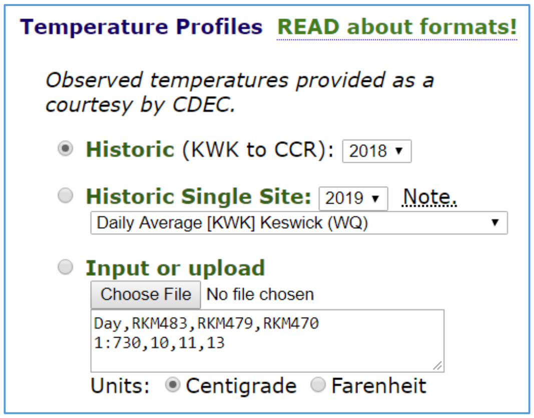
Figure 2 Schematic of modeling process.

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 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 historic data (2000-present) queried directly from the SacPAS database or user-generated custom files can be uploaded to the model. Database temperatures are either from a single site and apply to all redds, or are computed for every location using the observed gradient between KWK and CCR (CDEC data sites). The emergence models use Celsius (°C) temperatures; inputs can be converted from Fahrenheit (°F) as needed.



Temperature Profiles READ about formats!

Observed temperatures provided as a courtesy by CDEC.

● **Historic** (KWK to CCR): 2018 ▾

○ **Historic Single Site:** 2019 ▾ Note.
Daily Average [KWK] Keswick (WQ) ▾

○ **Input or upload**
Choose File No file chosen

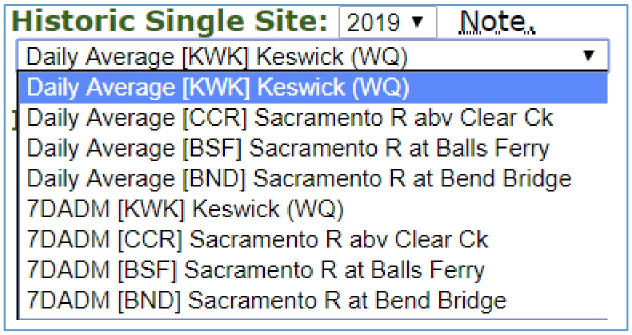
```
Day,RKM483,RKM479,RKM470
1:730,10,11,13
```

Units: ● Centigrade ○ Farenheit

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 only available at sites on the Sacramento River mainstem.

Input or uploaded temperatures follow certain guidelines described below.



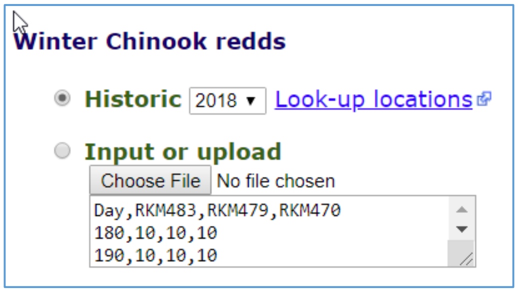
Historic Single Site: 2019 ▾ Note.

Daily Average [KWK] Keswick (WQ) ▾
Daily Average [KWK] Keswick (WQ)
Daily Average [CCR] Sacramento R abv Clear Ck
Daily Average [BSF] Sacramento R at Balls Ferry
Daily Average [BND] Sacramento R at Bend Bridge
7DADM [KWK] Keswick (WQ)
7DADM [CCR] Sacramento R abv Clear Ck
7DADM [BSF] Sacramento R at Balls Ferry
7DADM [BND] Sacramento R at Bend Bridge

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

Specify Winter Chinook redds (Spawning data)

Spawning data is selected for specific years for Winter Chinook redds (Figure 5). These are temporally and spatially specific. Through 2015, spatial resolution to the nearest kilometer is available. Like the temperature data, there is the option of uploading or inputing user-generated data. See section below on input and upload guidelines. All allowed redd/release locations are shown in Figure 6.



Winter Chinook redds

● **Historic** 2018 ▾ Look-up locations

○ **Input or upload**
Choose File No file chosen

```
Day,RKM483,RKM479,RKM470
180,10,10,10
190,10,10,10
```

Figure 5 Specify spawning data.

Input and Upload Guidelines

1. Spawning and Temperature inputs are similar.
2. Files should be comma delimited text files with at least 2 columns.
3. The first column is the Day of the year with “Day” in the first row.
4. Subsequent columns have the location in the first row and the data in remaining rows.
5. For redds, the data are “counts”.
6. For temperature, the data are “degrees”.
7. Zeroes are acceptable for redds. If an entire row or column is zero consider omitting it prior to uploading or typing it in.
8. If you upload a file from your computer, the input will be written directly into the textarea. There must be one or more redds at an allowed location on at least one day.
9. Temperatures should span two years. Dummy values can be used outside of the period of interest. A range of days can be specified in the first column with a colon between the first and last day.
10. If you want to change your input or upload values after a Run, use the “Reset” button first, then re-upload or edit the textarea.
11. Fish Release inputs have three columns labelled “RKM”,”Day”, and “Count”.
12. For each release location the day of the year and the number of fish are specified row by row. The model will consolidate duplicate days at a location if necessary.
13. Flow inputs for migration or Delta Cross channel losses from the river can be uploaded in a two column format with “Day” and “Value” in two, comma-separated columns.

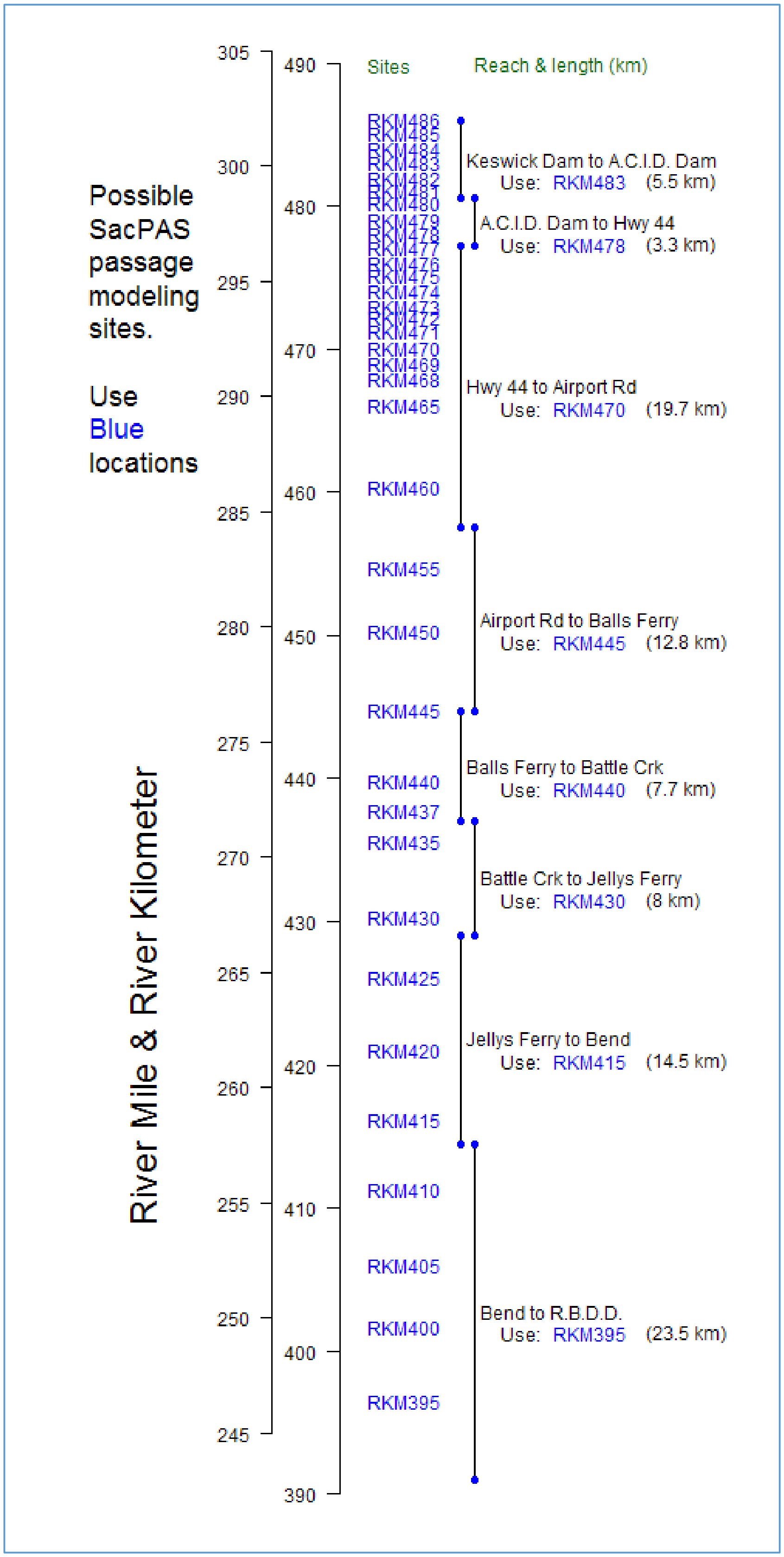
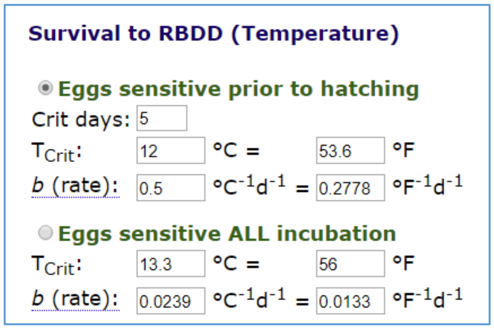


Figure 6 Accepted spawning and/or release locations in the Sacramento River.

Specify Survival to RBDD due to temperature

Two models are available for temperature effects on 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 using the previously selected river temperature profiles. Both of them apply a high mortality rate for each day that the temperature exceeds a threshold. In one model this applies to the entire period pre-emergence. In the second case this only applies to a critical period just before hatching (5 days is the default).



Survival to RBDD (Temperature)

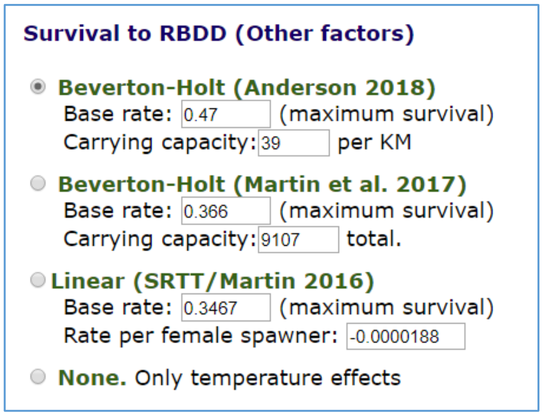
● **Eggs sensitive prior to hatching**
Crit days: 5
T_{Crit}: 12 °C = 53.6 °F
b (rate): 0.5 $°C^{-1}d^{-1}$ = 0.2778 $°F^{-1}d^{-1}$

○ **Eggs sensitive ALL incubation**
T_{Crit}: 13.3 °C = 56 °F
b (rate): 0.0239 $°C^{-1}d^{-1}$ = 0.0133 $°F^{-1}d^{-1}$

Figure 7 Egg survival due to temperature effects selection.

Specify Survival to RBDD due to maximum survival rates and density

There are three options for the temperature-independent survival rates that are associated with density on the spawning ground (Anderson 2018, Martin et al. 2017, 2016). The published parameters are defaults and the user has the option to modify them by typing numbers into the input boxes (see Figure 8). The user also has the option to examine the functional forms of the model by clicking the “Explore Egg/Fry survival models” link under “Further information”.



Survival to RBDD (Other factors)

● **Beverton-Holt (Anderson 2018)**
Base rate: 0.47 (maximum survival)
Carrying capacity: 39 per KM

○ **Beverton-Holt (Martin et al. 2017)**
Base rate: 0.366 (maximum survival)
Carrying capacity: 9107 total.

○ **Linear (SRTT/Martin 2016)**
Base rate: 0.3467 (maximum survival)
Rate per female spawner: -0.0000188

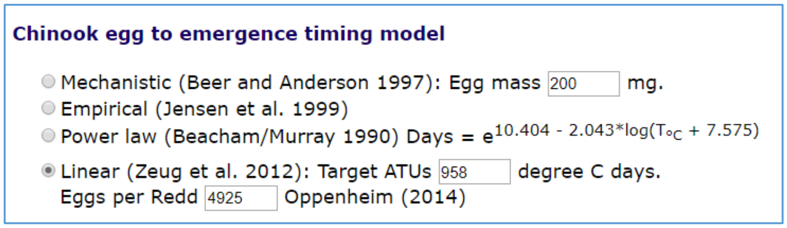
○ **None.** Only temperature effects

Figure 8 Egg survival due to non-temperature effects selection

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.



Chinook egg to emergence timing model

○ Mechanistic (Beer and Anderson 1997): Egg mass 200 mg.
○ Empirical (Jensen et al. 1999)
○ Power law (Beacham/Murray 1990) Days = $e^{10.404 - 2.043*\log(T_{°C} + 7.575)}$
● Linear (Zeug et al. 2012): Target ATUs 958 degree C days.
Eggs per Redd 4925 Oppenheim (2014)

Figure 9 Specify egg development rate.

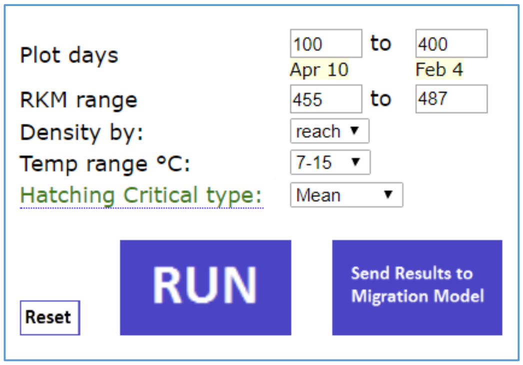
Analysis and Results Display controls

There are a few additional controls that apply to each run. See Figure 10. The range of “Plot days” specifies the window of time over which results are displayed. The “RKM range” specifies the spatial window over which results are displayed. Adjust these to cover the ranges of the inputs. Density can be computed by reach or river kilometer (through 2015). The temperature range of output graphics can be selected as broad (4-20°C), moderate (7-15°C) or narrow (10-14°C). Conditions at hatching can be depicted as the mean during the critical period or the maximum during the critical period.

The “Reset” button restores all values on the page to their defaults. Use this prior to re-uploading data to redd or temperature input textareas.

The “Run” button sends all parameters and controls to the emergence model and returns the results to the the user on the same page.

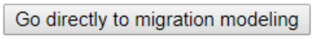
The “Send Results to Migration Model” sends all parameters and controls to the emergence model and opens a new page where the results and additional data are prepared to send to the migration model.



Plot days 100 to 400
Apr 10 Feb 4
RKM range 455 to 487
Density by: reach
Temp range °C: 7-15
Hatching Critical type: Mean

Figure 10 Analysis and results controls

In-River Migration

The in-river migration component of SacPAS Fish Model v.2 can be run using output of the emergence model or directly with user-provided inputs. To skip emergence modelling, click the  button.

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.

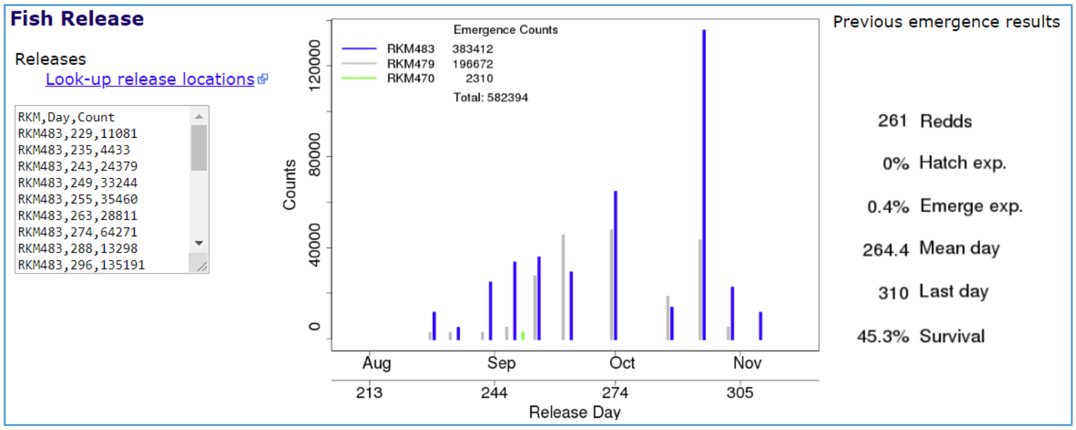
To visualize the spatial extent of the model click on the link: “Download a KML file to visualize with Google Earth/Maps” to download a file named sacramento.desc.kml. Once downloaded, this file can be opened with Google Earth, Google Maps and other compatible programs.

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 the Fish Release

There are two presentations for controlling the Fish Release. Either the emergence results are presented with the details ready for the migration model as in the example of Figure 11 or if the user skips emergence modeling, the presentation is like Figure 12 where the release can be uploaded (see “Input and Upload Guidelines” above) or the observed bi-weekly estimates at RBDD can be selected.



Fish Release

Releases

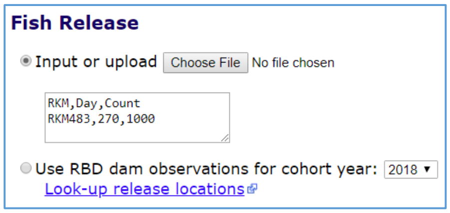
Look-up release locations

```
RKM,Day,Count
RKM483,229,11081
RKM483,235,4433
RKM483,243,24379
RKM483,249,33244
RKM483,255,35460
RKM483,263,28811
RKM483,274,64271
RKM483,288,13298
RKM483,296,135191
```

Previous emergence results

261	Redds
0%	Hatch exp.
0.4%	Emerge exp.
264.4	Mean day
310	Last day
45.3%	Survival

Figure 11 Example of fish release presentation after emergence modeling.



Fish Release

● Input or upload Choose File No file chosen

```
RKM,Day,Count
RKM483,270,1000
```

○ Use RBD dam observations for cohort year: 2018

Look-up release locations

Figure 12 Example of fish release presentation if user skips emergence modeling.

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[1]. 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. See "Input and Upload Guidelines" above. 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.

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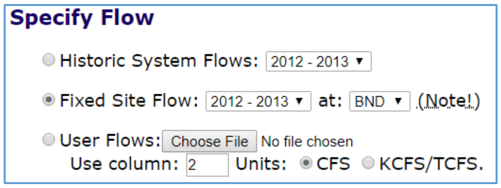
[1] These are inferred from differences between downstream and upstream flows at flow monitoring sites.



Specify Flow

○ Historic System Flows: 2012 - 2013 ▾

● Fixed Site Flow: 2012 - 2013 ▾ at: BND ▾ (Note!)

○ User Flows: Choose File No file chosen
Use column: 2 Units: ● CFS ○ KCFS/TCFS.

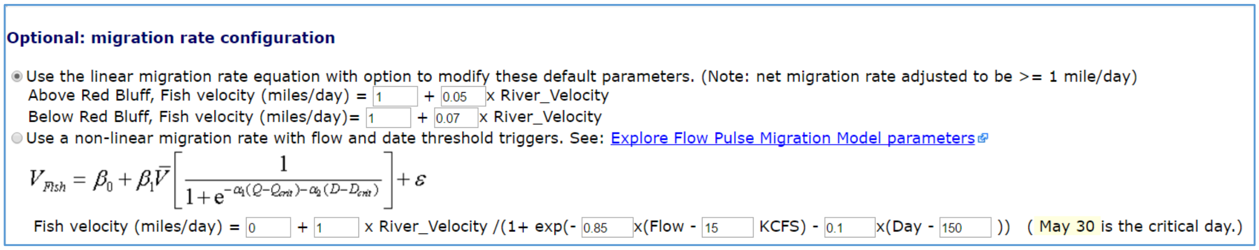
Figure 13 Three methods for specifying flow inputs to the migration model.

Model the Delta Cross Channel (Optional)

When the migration model determines the number of fish that arrive at the Delta Cross Channel (DCC), the user can continue to model what will happen to them at this point in the river. Either the specified DCC flows can be used to route fish into the delta, or the arrival of the fish at a specified point upstream can be used to control water, and therefore fish, flowing into the delta

Specify migration rate

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



Optional: migration rate configuration

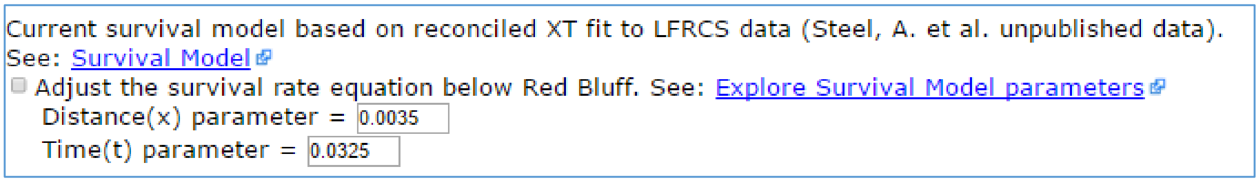
● Use the linear migration rate equation with option to modify these default parameters. (Note: net migration rate adjusted to be >= 1 mile/day)
Above Red Bluff, Fish velocity (miles/day) = 1 + 0.05 x River_Velocity
Below Red Bluff, Fish velocity (miles/day)= 1 + 0.07 x River_Velocity
○ Use a non-linear migration rate with flow and date threshold triggers. See: Explore Flow Pulse Migration Model parameters

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

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.)

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).

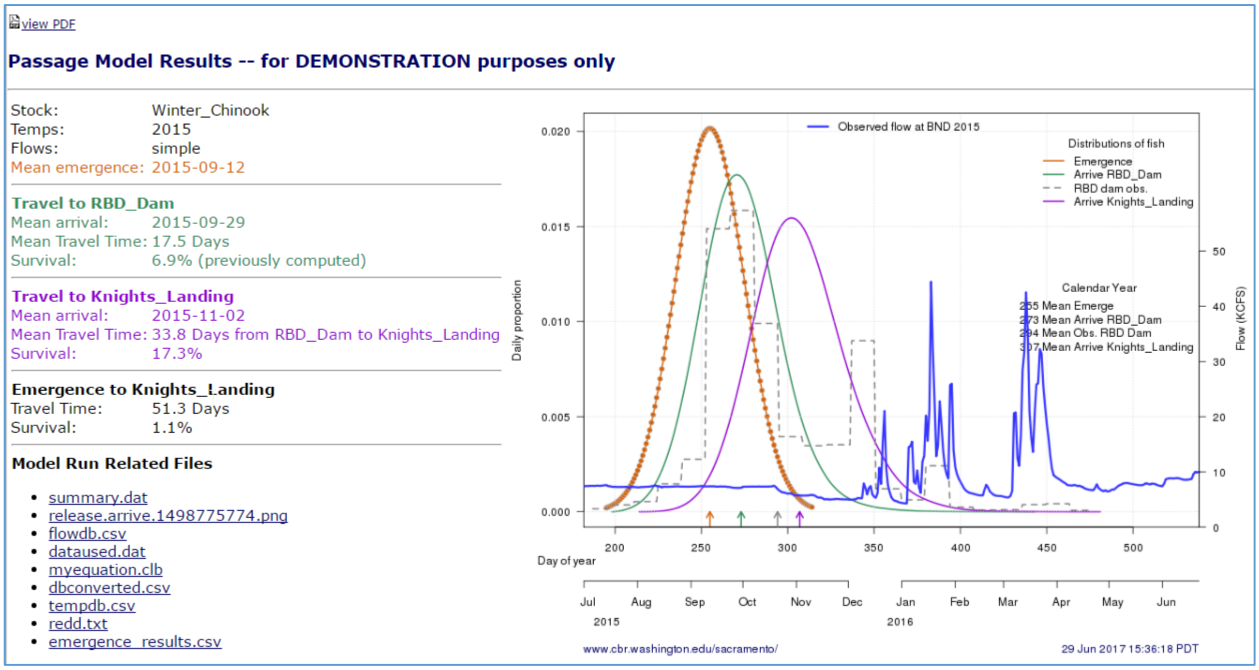


Current survival model based on reconciled XT fit to LFRCS data (Steel, A. et al. unpublished data).
See: Survival Model
☐ Adjust the survival rate equation below Red Bluff. See: Explore Survival Model parameters
Distance(x) parameter = 0.0035
Time(t) parameter = 0.0325

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 14, 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.



view PDF

Passage Model Results -- for DEMONSTRATION purposes only

Stock: Winter_Chinook
Temps: 2015
Flows: simple
Mean emergence: 2015-09-12

Travel to RBD_Dam
Mean arrival: 2015-09-29
Mean Travel Time: 17.5 Days
Survival: 6.9% (previously computed)

Travel to Knights_Landing
Mean arrival: 2015-11-02
Mean Travel Time: 33.8 Days from RBD_Dam to Knights_Landing
Survival: 17.3%

Emergence to Knights_Landing
Travel Time: 51.3 Days
Survival: 1.1%

Model Run Related Files

- summary.dat
- release.arrive.1498775774.png
- flowdb.csv
- dataused.dat
- myequation.clb
- dbconverted.csv
- tempdb.csv
- redd.txt
- emergence_results.csv

Figure 14 Graphical output window showing results of the passage model.

Model Details

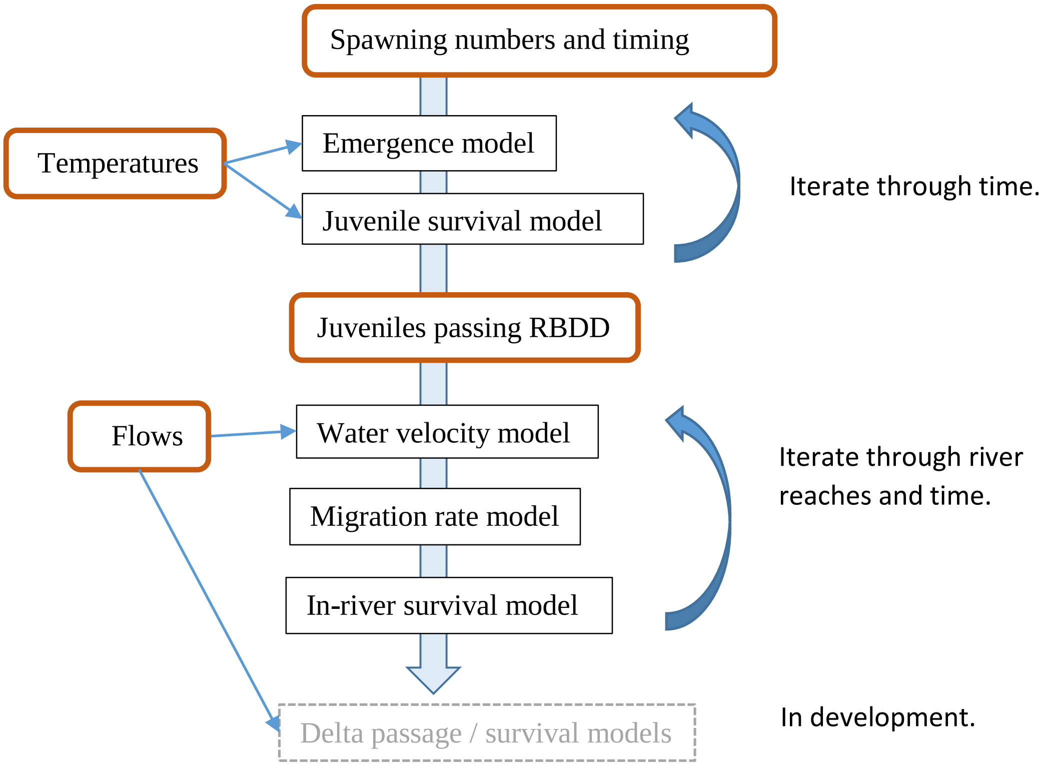


Figure 15 Sub-model components and data relationships overview.

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 16. 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:

   $$0.002755949 + 6.340096\text{x}10^{-5} \cdot T + 9.564633\text{x}10^{-5} \cdot T^2 - 5.250954\text{x}10^{-6} \cdot T^3 + 3.046699\text{x}10^{-7} \cdot T^4$$
3) A power law model (Beacham and Murray 1990). At a fixed temperature, the number of days for development is: $Days = e^{10.404 - 2.043*log(T°C + 7.575)}$. 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*$Temp_C$ or 0.0058*$Temp_F$ – 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.

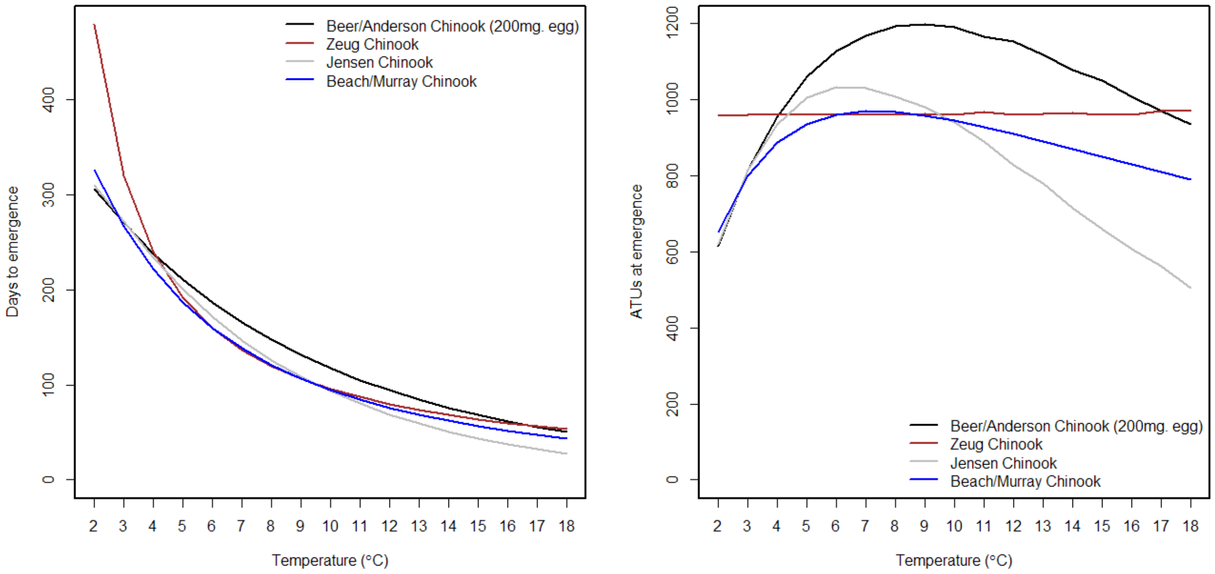


Figure 16 Chinook egg development time and ATUs according to four unique models. In practice, daily fraction of total growth is computed for each day's average temperature and these daily fractions are summed until they reach one.

Egg/Juvenile survival models

Survival due to temperatures and survival due to other factors are separated. User selects one of two temperature-related survival models and optionally includes one of three non-temperature survival models.

Temperature effects

The temperature effects models are functionally identical, but vary in the time-frame to which they apply. Survival is reduced for each day that the temperature is above a specified threshold. In the Anderson (2018) model this applies to a critical period (default: 5 days) just prior to hatching. In the Martin (2017) model this applies at any time during incubation.

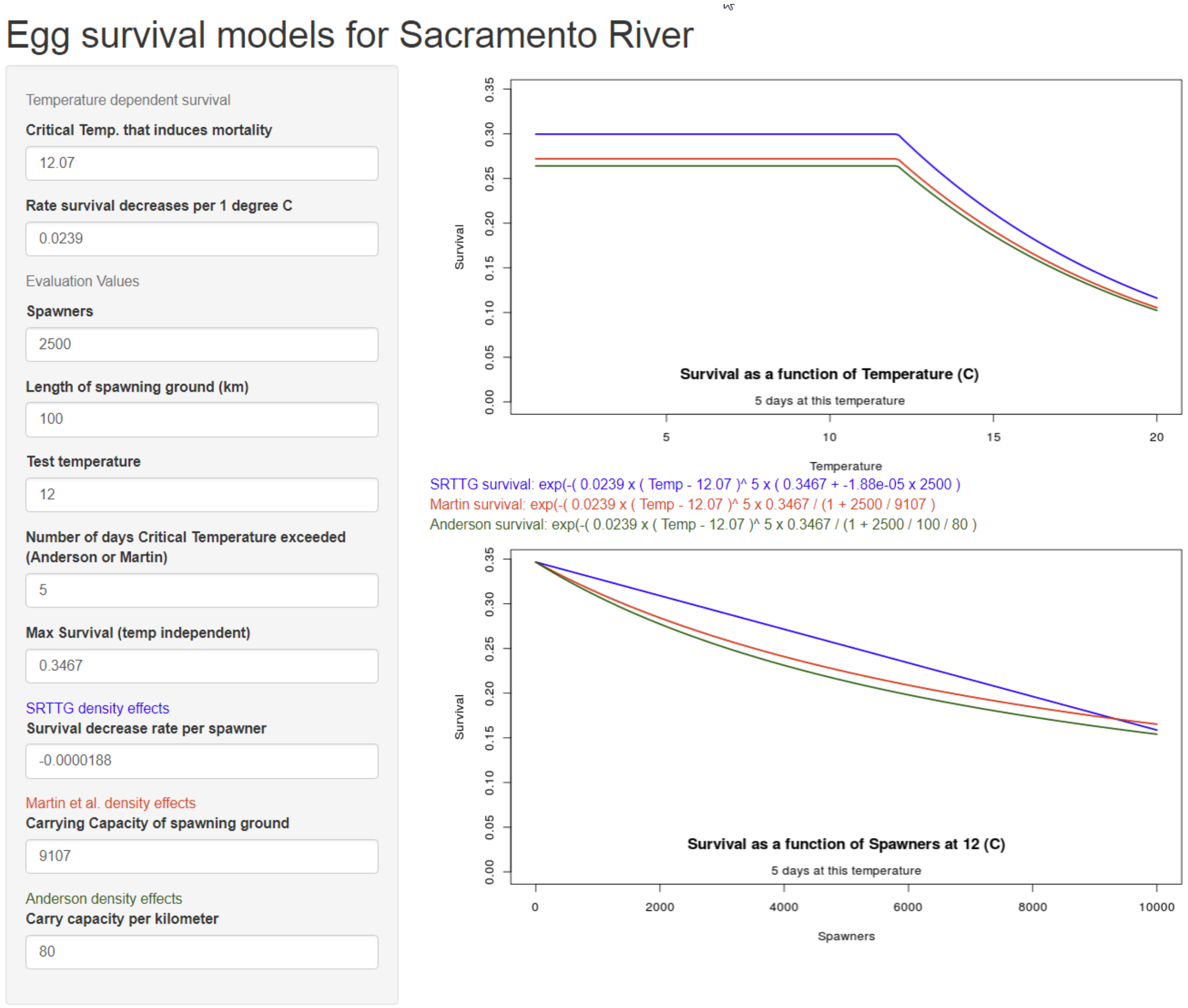
Non-temperature effects egg/juvenile survival models

These models set a survival base rate and include density of spawners in some way.

1) A linear spawner density effect (Martin et al. 2016) where each additional spawning female reduces survival (default -0.0000188 per female).
2) The number of redds on the spawning grounds (Martin et al. 2017) reduces survival relative to the carrying capacity of the river (default 9107 redds).
3) The number of redds on the spawning grounds (Anderson 2018) reduces survival relative to the local density (default 39 redds per km.)

4) For constant survival, use the Martin et al. 2016 model and set "Rate per female spawner" = 0 .

To explore the sensitivity of these models, click the "Explore Egg/Fry survival models" link. This opens an interactive "Shiny App" in a new browser window allowing you to manipulate the inputs in order to visualize the results (Figure 17).



Egg survival models for Sacramento River

Temperature dependent survival

Critical Temp. that induces mortality: 12.07

Rate survival decreases per 1 degree C: 0.0239

Evaluation Values

Spawners: 2500

Length of spawning ground (km): 100

Test temperature: 12

Number of days Critical Temperature exceeded (Anderson or Martin): 5

Max Survival (temp independent): 0.3467

SRTTG density effects

Survival decrease rate per spawner: -0.0000188

Martin et al. density effects

Carrying Capacity of spawning ground: 9107

Anderson density effects

Carry capacity per kilometer: 80

SRTTG survival: exp(-(0.0239 x (Temp - 12.07)^ 5 x (0.3467 + -1.88e-05 x 2500)

Martin survival: exp(-(0.0239 x (Temp - 12.07)^ 5 x 0.3467 / (1 + 2500 / 9107)

Anderson survival: exp(-(0.0239 x (Temp - 12.07)^ 5 x 0.3467 / (1 + 2500 / 100 / 80)

Figure 17 Shiny app allowing user to explore sensitivity of egg/fry survival models, https://nicko.shinyapps.io/EGG_SURV/.

Water velocity model

Water velocity is assumed to contribute to migration velocity. Water velocity, in turn, is a function of flow based on results of 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 18.

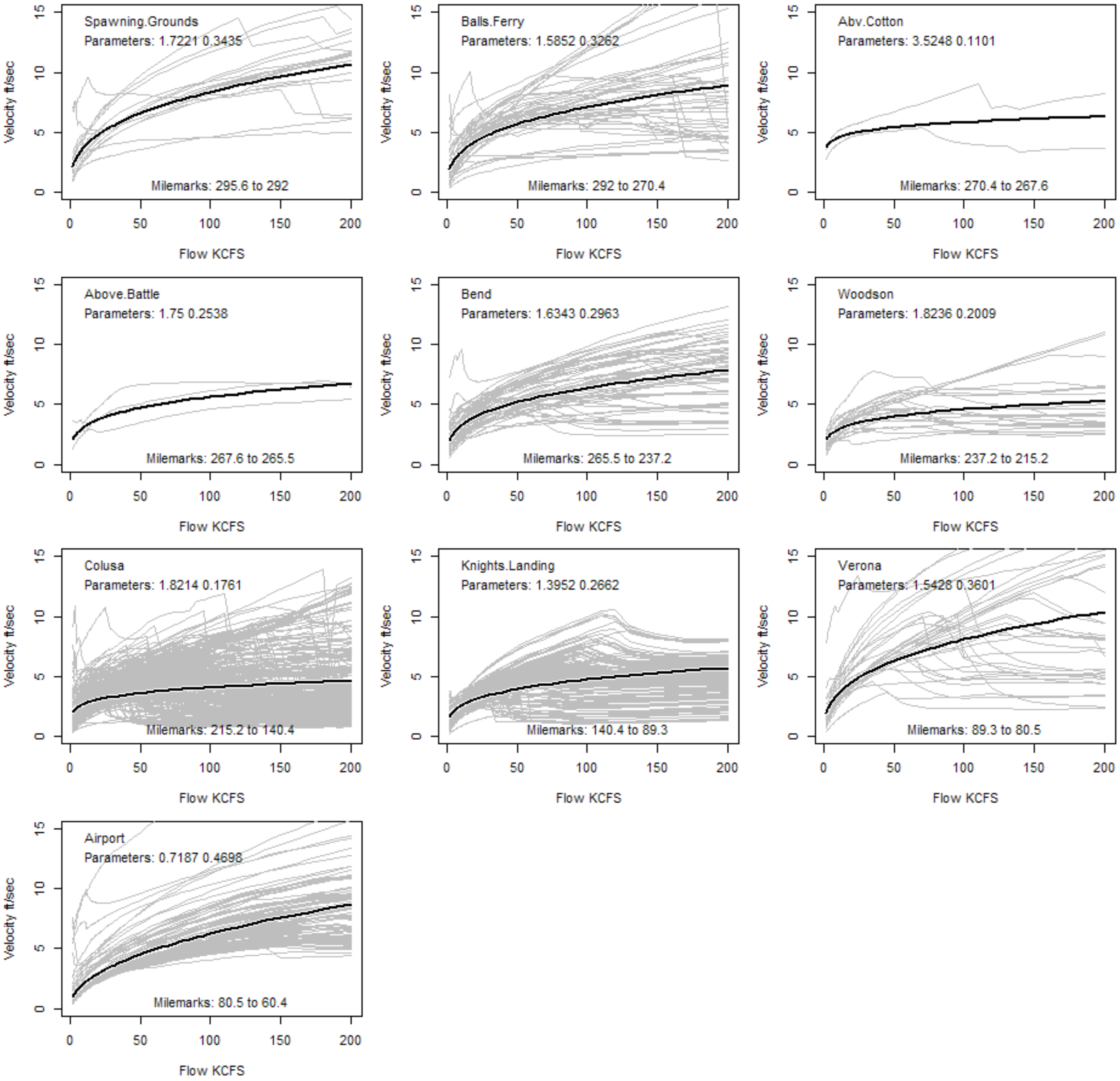


Figure 18 Flow-velocity relationships used for the passage model. Transects are organized by reaches. Each gray line is a flow velocity relationship at a cross section within the reach. The black line is a fit to the available data and provides the parameters required for each reach in the passage model.

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 19. 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 19. 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 20.

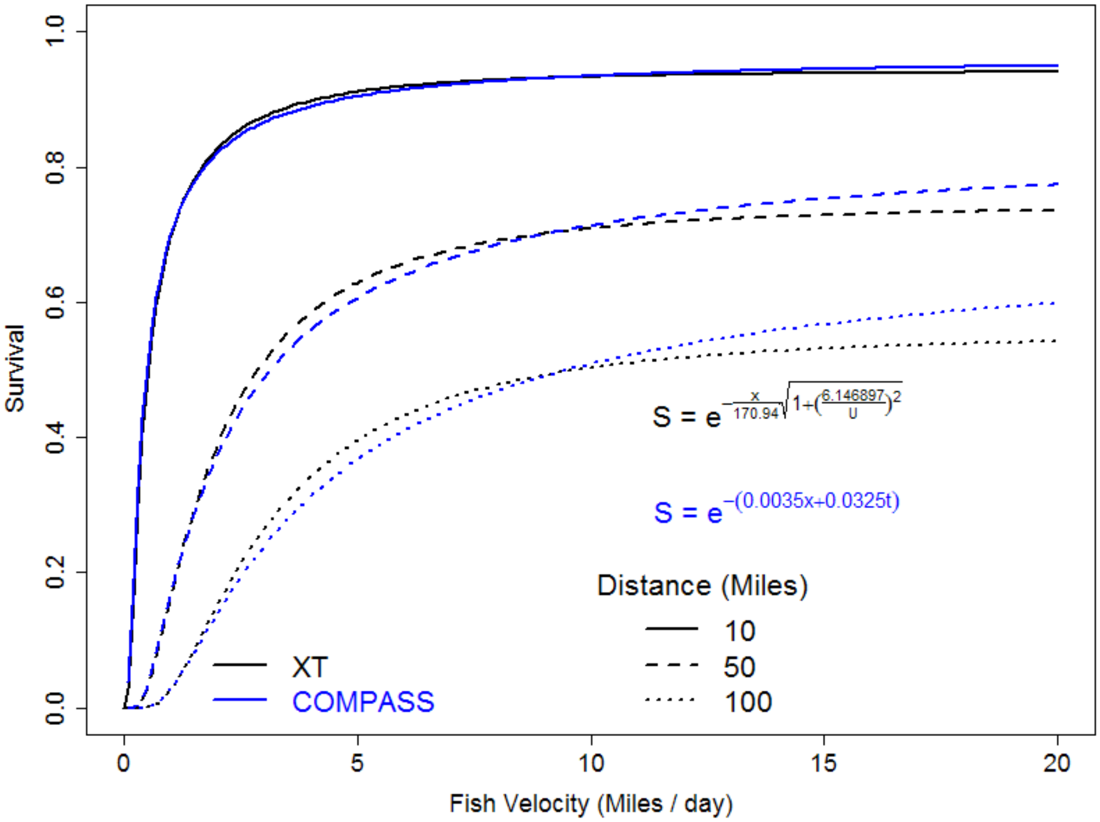
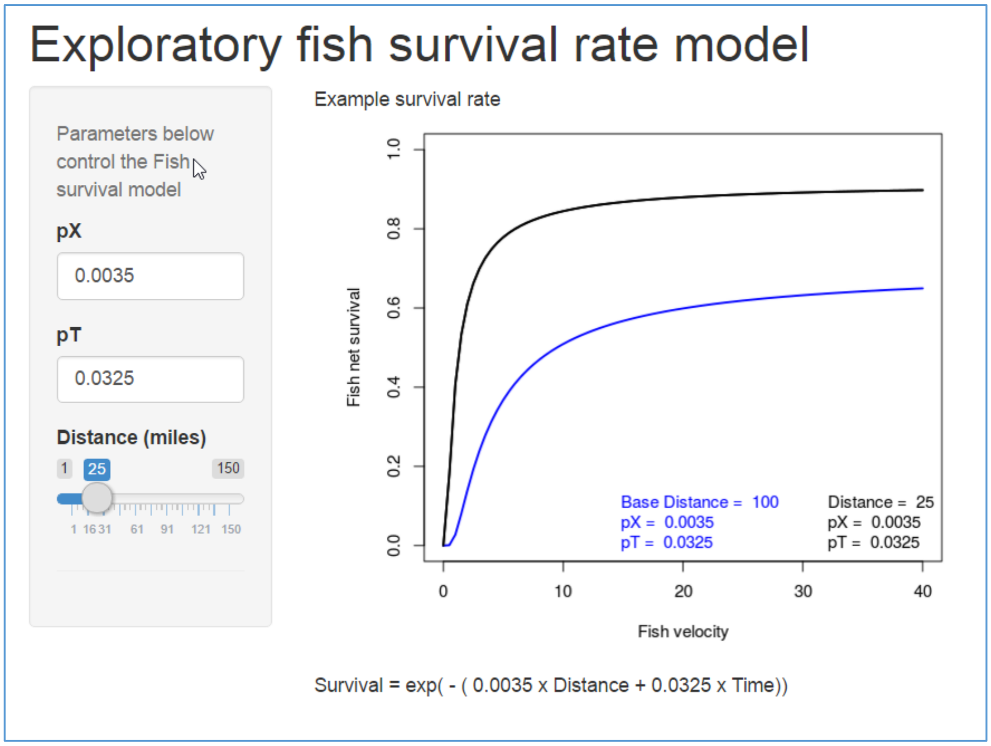


Figure 19 Survival is a function of both distance (X) and travel time (T) in the passage model. This illustration shows the relationship between the XT model and the COMPASS-ready model.



Exploratory fish survival rate model

Parameters below control the Fish survival model

pX: 0.0035

pT: 0.0325

Distance (miles): 25

Survival = exp(- (0.0035 x Distance + 0.0325 x Time))

Figure 20 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 ≥ 1 mi/day.

A linear migration rate model: Fish.velocity = $\text{param}_0 + \text{param}_1$ 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:

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

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

V_{Fish} = mean migration rate on day *D*
β_0 = parameter that determines the flow-independent migration rate. (0)
β_1 = parameter relates fish velocity to river velocity. For freshet-movements (non-swimming), this parameter is probably ~1.0. (1.0)
α_1 = sensitivity to flow-effect changes (0.2)

α_2 = sensitivity to day-effect changes (0.03). This will be smaller than α_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

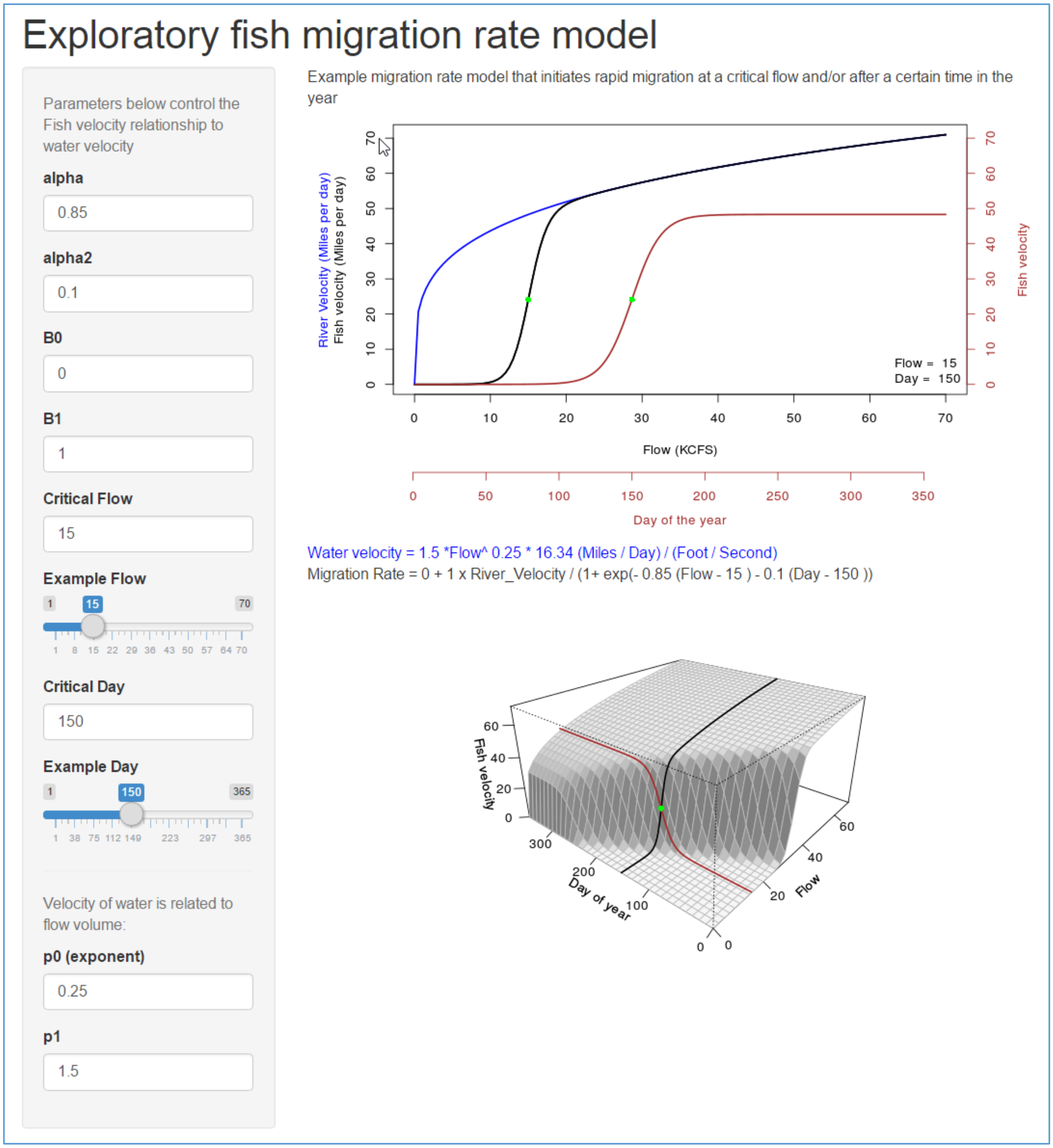
Q_{crit} = flow level above which the fish move with the velocity of the water. (15 KCFS). In the Sacramento, a lot of the flow is unregulated, so freshets can be significant. Winter flow events exceed base flows by factors of 2 – 5 or more. 400 m^3s^{-1} = 14 KCFS may be a useful starting value (del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

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

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 18).

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_DISTRIB/ (Figure 21).



Exploratory fish migration rate model

Parameters below control the Fish velocity relationship to water velocity

alpha
0.85

alpha2
0.1

B0
0

B1
1

Critical Flow
15

Example Flow
15

Critical Day
150

Example Day
150

Velocity of water is related to flow volume:

p0 (exponent)
0.25

p1
1.5

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 *Flow^ 0.25 * 16.34 (Miles / Day) / (Foot / Second)
Migration Rate = 0 + 1 x River_Velocity / (1+ exp(- 0.85 (Flow - 15) - 0.1 (Day - 150))

Figure 21 Interactive tool for examining sensitivity of the passage migration rate model to the parameters. See: https://nicko.shinyapps.io/MIGR_DISTRIB/

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

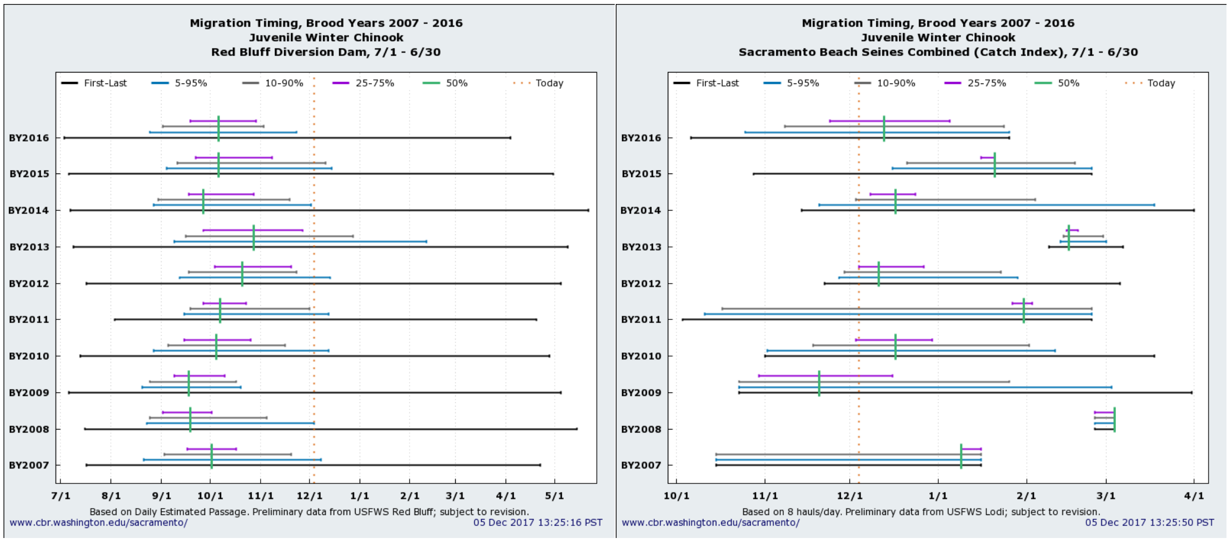


Figure 22 Migration timing of winter Chinook for 10 years at RBDD and Sacramento beach seines from Migration Timing and Conditions SacPAS database query.

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 withdrawls and/or tributary contributions can alter the hydrograph significantly. This is easy to see in Figure 23 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 24 and Figure 25. 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 23 through Figure 25). 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.

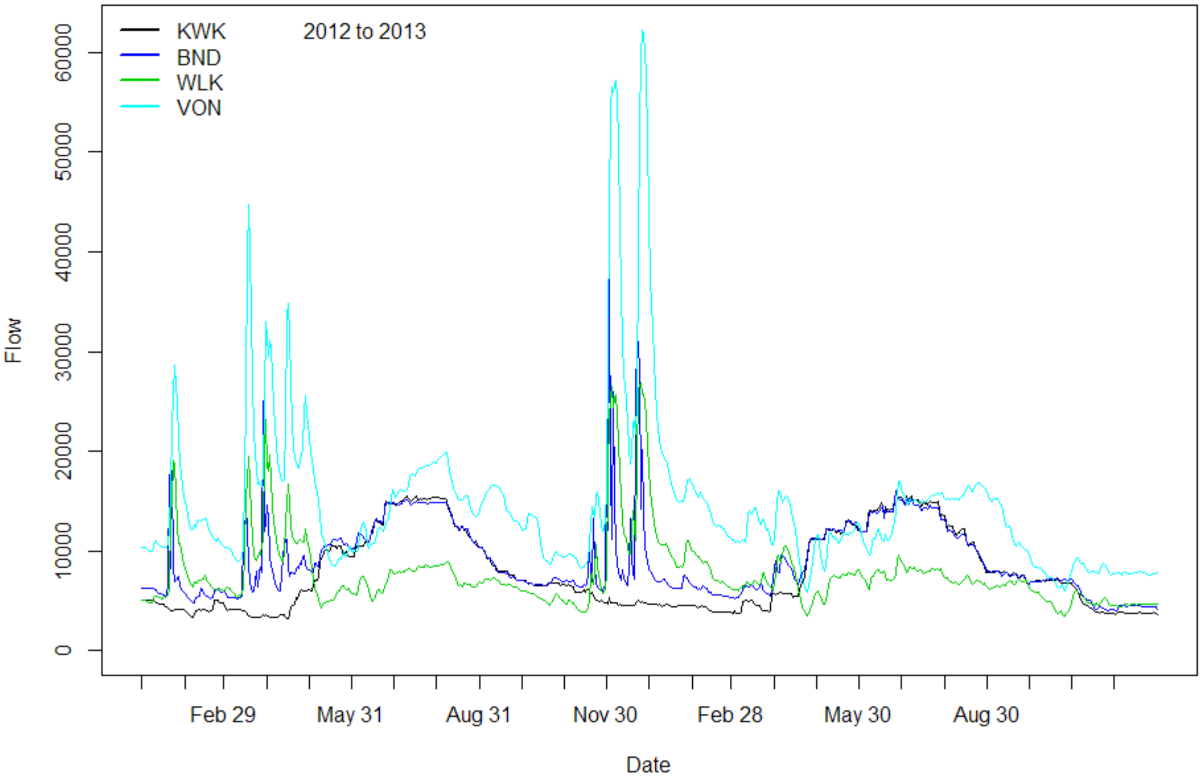


Figure 23 Hydrographs (average daily flow in CFS) at four sites on the Sacramento River during 2012 and 2013.

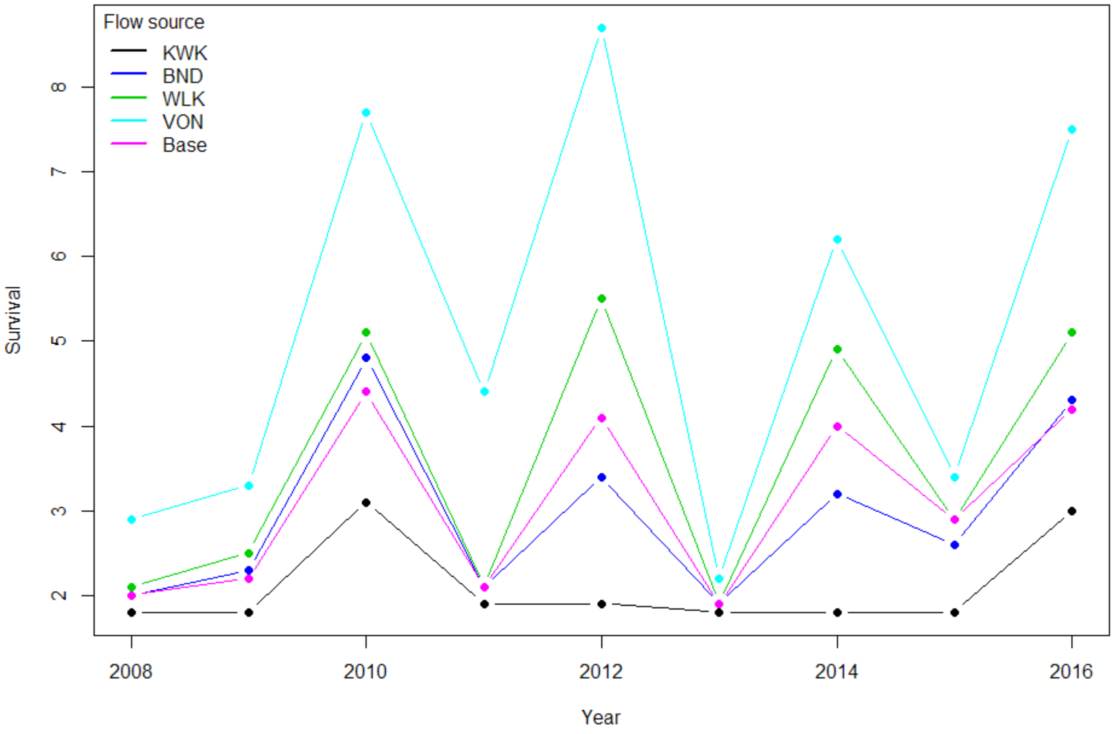


Figure 24 Sensitivity of survival to flow sources and annual variation. "Base" conditions have time and space-varying flows based on observed historic conditions. Single site conditions (BND=Bend, KWK = Keswick, WLK = Wilkins, and VON = Verona) have the observed flow at the site applied to the entire river.

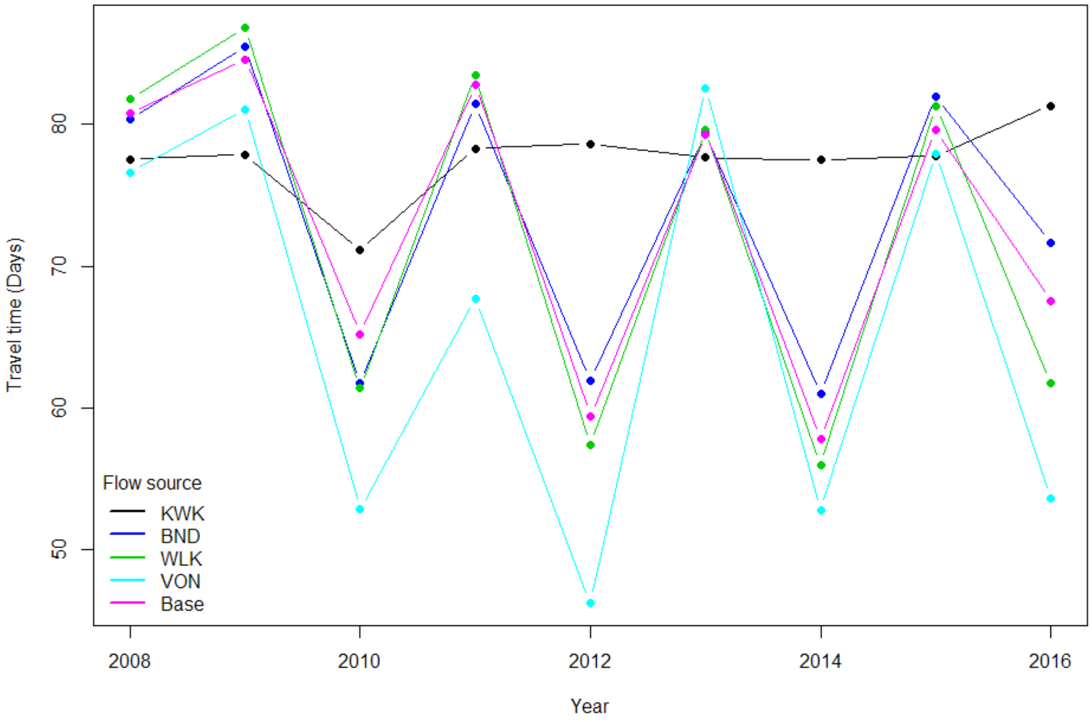


Figure 25 Sensitivity of travel time (days) to flow sources and annual variation. Travel time modelled from RBDD to Verona. "Base" conditions have time and space-varying flows based on observed historic conditions. Single site conditions (BND=Bend, KWK = Keswick, WLK = Wilkins, and VON = Verona) have 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: $B_0 = 0$; $B_1 = 1$; $\alpha_1 = 0.2$; $\alpha_2 = 0.03$; Qcrit = 15 KCFS; Dcrit = 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 α_1 and α_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/ to see how the parameters affect the interaction of time and flow to generate fish velocity. See Figure 21.

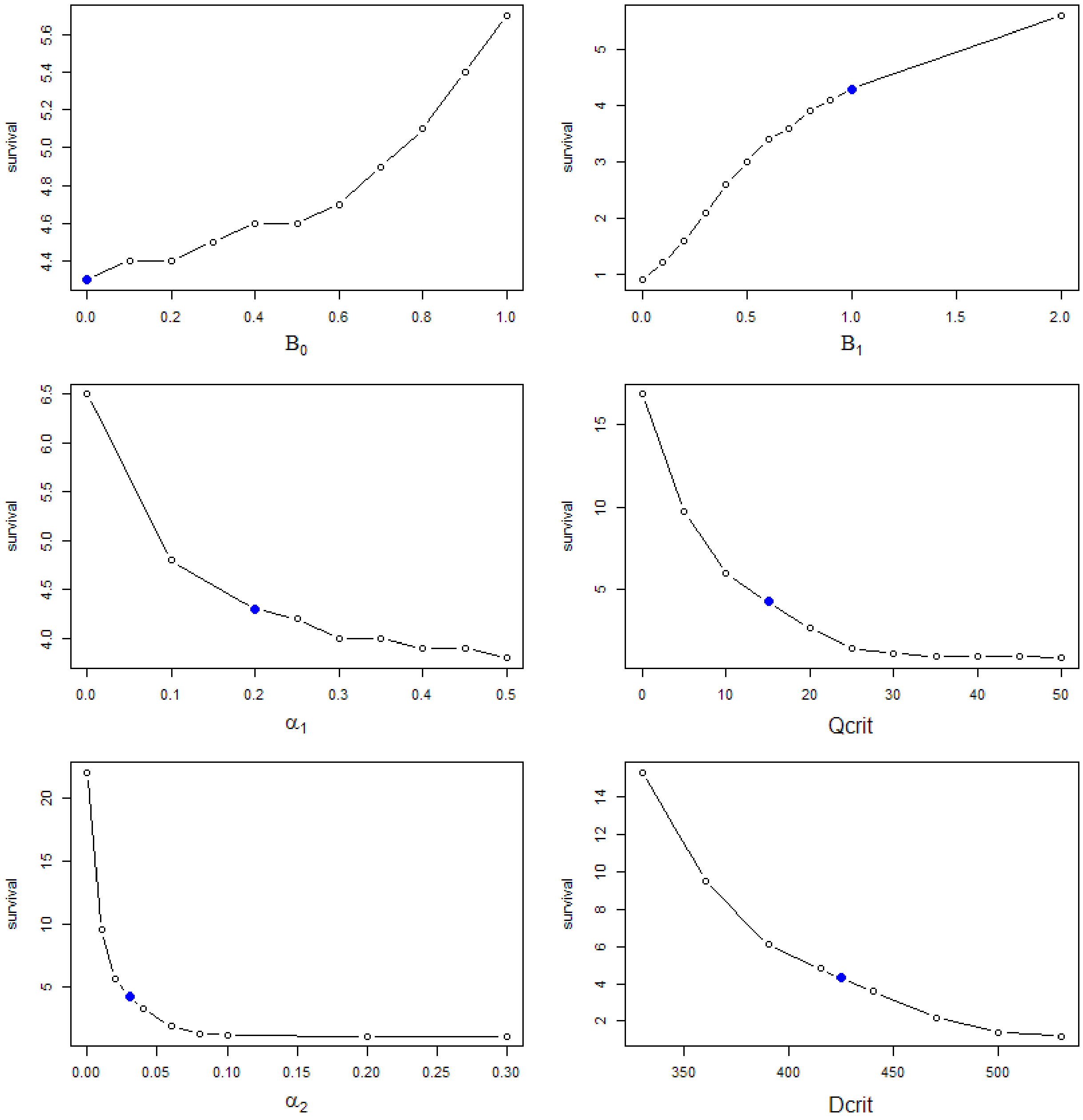


Figure 26 Sensitivity of survival to migration rate parameters for a cohort of fish in the Sacramento River released on day 300 in 2010 (October 27) from Red Bluff dam to the mouth of the Feather River. Larger solid dot shows the mean response at the nominal value of the parameter. This is verified by their identical y-axis values in each panel.

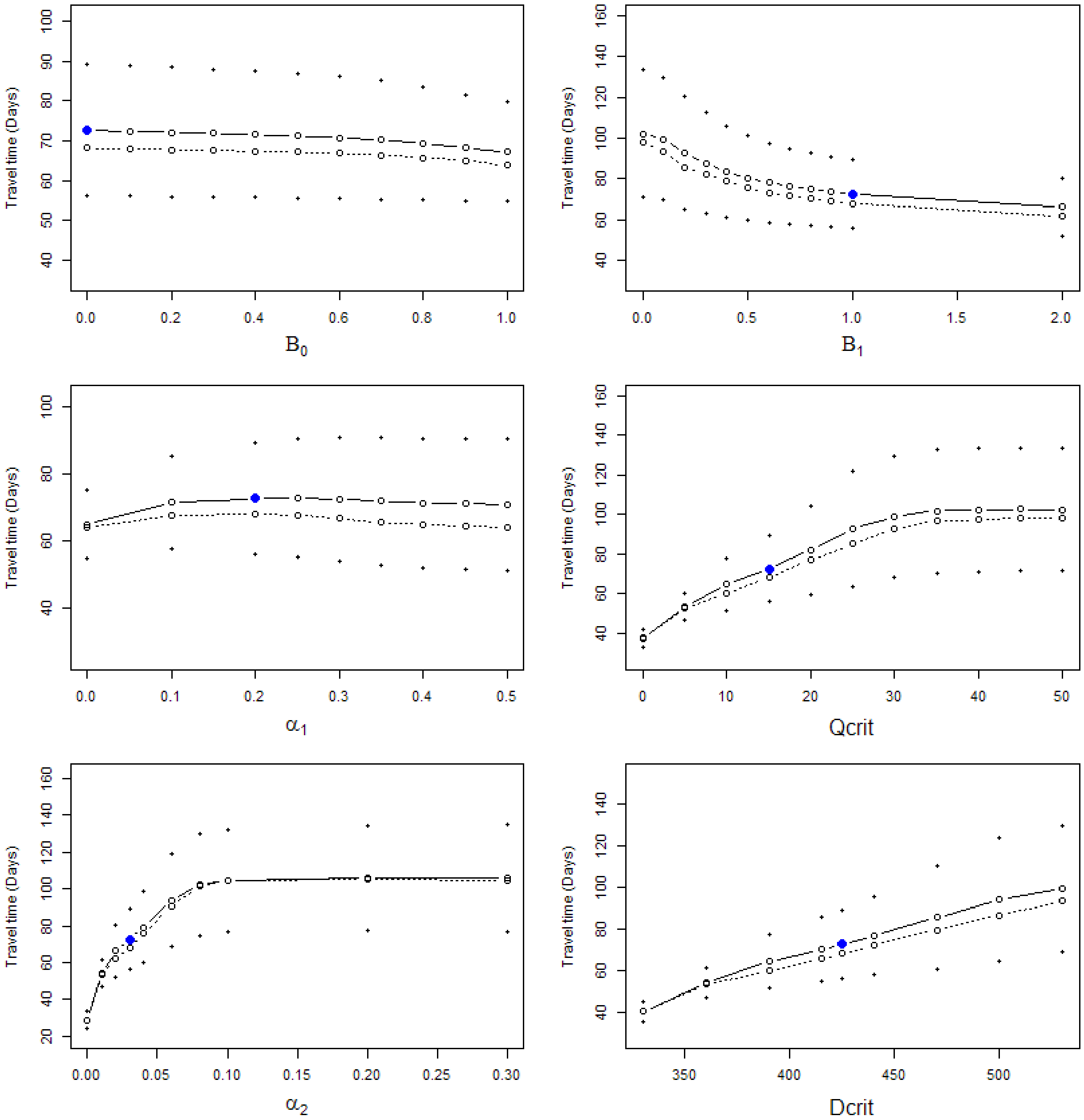


Figure 27 Sensitivity of travel time to migration rate parameters for a cohort of fish in the Sacramento River released on day 300 in 2010 (October 27) from Red Bluff dam to the mouth of the Feather River. The mean travel time (solid line) the median travel time (dotted line) and the mean ± standard 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 28 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 28 right panels).

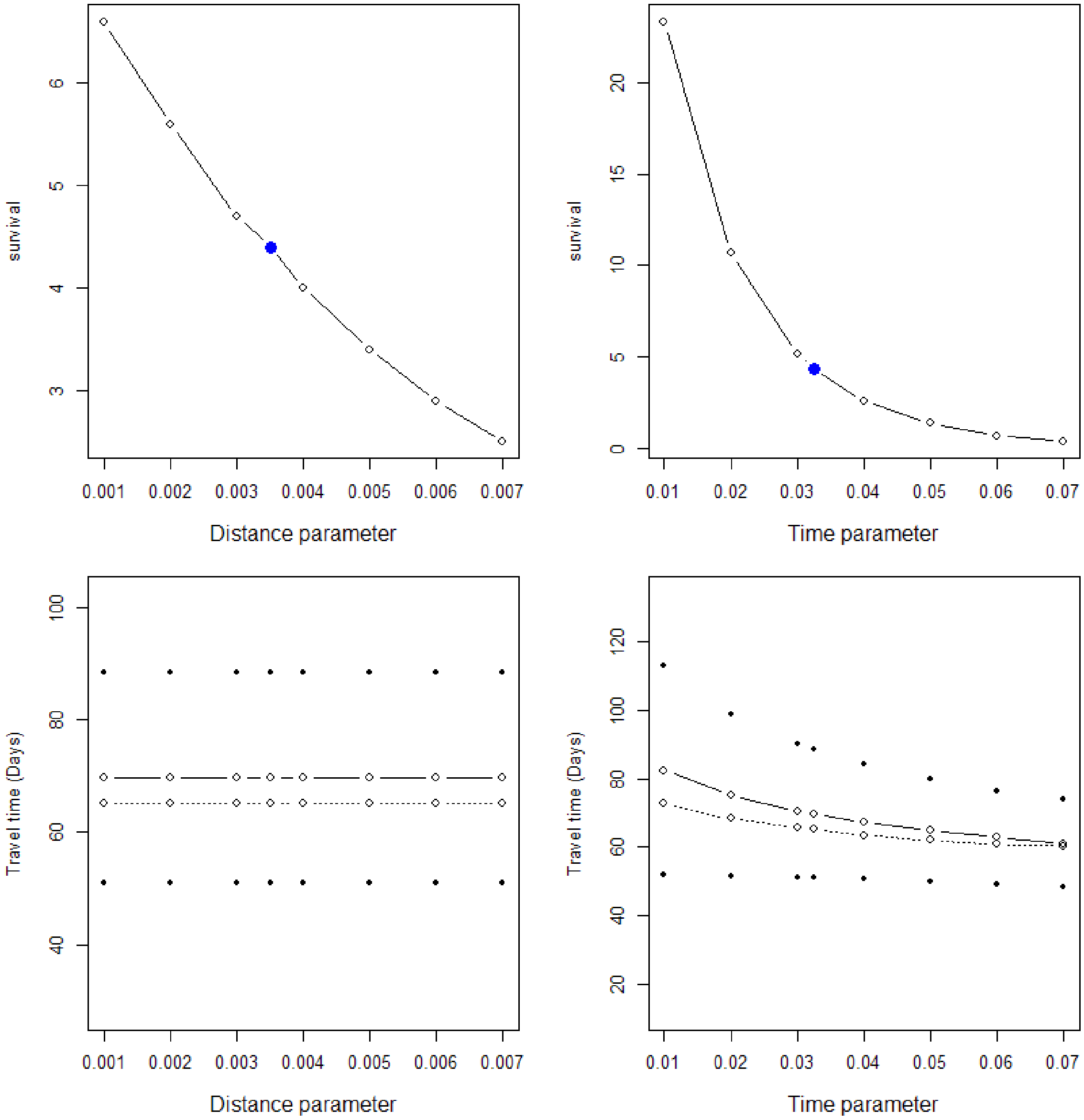


Figure 28 Sensitivity of survival (%) and travel time to the survival equation parameters. The mean travel time (solid line) the median travel time (dotted line) and the mean ± standard deviation (dots) are shown.

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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. 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.