A Revised Sacramento River Winter Chinook Salmon Juvenile Production Model

Prepared by:
Kristopher Jones
Paul Bergman
Brad Cavallo

Prepared for:
The National Oceanic and Atmospheric Administration (NOAA)
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INTRODUCTION

There are four runs (or “races”) of chinook salmon (*Oncorhynchus tshawytscha*) present in the upper Sacramento River California, which can be distinguished by the season adults return to spawn. Over the past 25 years, all four runs of chinook have experienced declining numbers. Winter chinook salmon abundance was estimated as high as 53,089 in 1970, but abundance estimates for the most recent years (2007-2009) were between 2,542 and 4,658 (CDFG 2010).

Historically, winter chinook spawned in spring-fed streams which provided cool summertime habitat for spawning, incubation and rearing (Yoshiyama et al. 1998). The upper Sacramento River drainage once provided ideal conditions for winter chinook due to the cool water, which would last year round from glacier and snow melt from Mount Shasta and Mount Lassen. However, following the construction of numerous small dams in the upper Sacramento River and its tributaries during the early part of the 20th Century, the reproductive potential of winter chinook were greatly reduced (e.g., after the dams prevented them from reaching their historic spawning grounds; Yoshiyama et al. 1998). Moreover, fluctuating water temperatures from dam operations have also reduced reproductive success of winter-chinook, by resulting in poor conditions for incubating eggs (NMFS 1997).

Since receiving endangered status in 1994, a number of measures have been taken to assist in the recovery of winter-run chinook. For example, in order to limit entrainment of juvenile winter-run chinook during their outmigration through the Delta, water exports are being adaptively managed from the Central Valley Project’s Tracy Pumping Plant and the State Water Project’s Harvey Banks Delta Pumping Plant in the Sacramento-San Joaquin Delta. In order to make quantitative assessments for entrainment of winter-chinook, the National Oceanic and Atmospheric Administration’s National Marine Fisheries Service (NOAA Fisheries) has annually estimated the abundance of juvenile winter-chinook entering the Delta. However, there are limitations to the methods used to derive these estimates. For example, the methods used previously to obtain juvenile production estimates (JPEs) did not account for environmental factors which are known to be important for the development and survival of juvenile salmonids. Although the JPE calculations did account for egg loss due to temperature effects, these estimates did not account for daily fluctuations that affect individual cohorts of fish developing through the season. Moreover, previous work has demonstrated that flow is a key predictor of juvenile survival during their outmigration in the Snake River (Williams and Mathews 1995) and Sacramento River (Brandes & McLain 2001). Yet, differences in survival associated with flow conditions were not accounted for in the original JPE calculations.

Lastly, uncertainty in juvenile production estimates was not included in the previous JPE models. For a model to be useful, predicted values need to be accompanied by measures of precision.
McCullagh and Nelder 1999). Three major categories of uncertainty exist in fisheries data: random fluctuations (‘noise’), uncertainty in parameter estimates, and structural uncertainty (Charles 1998). Error associated with random fluctuations of observed data and parameter estimation error can be incorporated into predictive models to inform the precision of predicted values. Structural uncertainty, or uncertainty in the basic nature of the fishery system, its dynamics and internal interactions, can have a considerable effect on fisheries models (Charles 1998). Instances of structural uncertainty include: uncertainty in fish migration patterns, predator-prey effects, effects of environmental conditions (Charles 1998). Because structural uncertainties reflect a fundamental lack of knowledge about the fishery system (Charles 1998), their associated error is usually unknown. The best that modelers can do is hope to reduce the level of structural uncertainty by using the best available information from literature to inform model function and form.

The goals of this study were to develop an improved JPE model, which would (1) develop a more robust production model by incorporating the best available information on juvenile chinook salmon production and incorporating model error wherever data on uncertainty was available (2) enable NMFS to derive JPE values with associated error; and (3) allow flexibility for making calculations sequentially as updated data becomes available. At the end of this document we provide a user manual which details directions for use of the revised JPE model.
METHODS

The JPE model uses a systems dynamics computer simulation modeling framework, a technique that is used for framing and understanding the behavior of complex systems over time. System dynamics models are made up of stocks (e.g. number of fish) and flows (e.g. sources of mortality) that influence the stocks and are informed by mathematical equations (Ford 1999). The JPE model was implemented in the software GoldSim, which enables the simulation of complex processes through creation of simple object relationships, incorporates Monte Carlo stochastic methods, and includes interactive, user-friendly interfaces (Rizzo et al. 2006). The model is composed of three submodels: Spawning, Development, and Downstream Migration (Figure 1).

Model Components

![Diagram of model components]

Figure 1. Diagram depicting the components of the JPE model. See text for further description (Steps 1-5)
The model is first seeded with the number of female spawners for the current spawning year. In order to ensure that developing fish experience the correct environmental conditions, spawn timing mimics the observed spawning distribution during carcass surveys (Step 1). Eggs deposited on a particular date are treated as cohorts which experience environmental conditions on a daily time step in the model. A stock-recruitment function is applied in Step 2 to predict the number of emergent fry from the number of female spawners. Even though the stock-recruitment relationship already accounts for temperature effects on egg mortality, in Step 3 additional daily temperature-induced mortality is imposed on incubating eggs for temperatures that go beyond those experienced during the years used to develop the stock-recruitment model (1996-1999, 2002-2007). Each day the proportional maturation of the incubating eggs is predicted from the daily temperature, and eggs continue to mature until 100% maturation is reached (Step 4). Following a 90-day delay for fry-smolt maturation, mean downstream migration survival of smolts to Chipps Island (entrance to bay) is scaled by the average Sacramento River flow experienced during each individual cohort’s migration period (Step 5).

**Spawning**

**Spawning Distribution**

Model timing is initiated with the distribution of female spawners corresponding with observed spawn timing during carcass surveys (Figure 2). The daily number of female spawners was calculated by multiplying the daily proportion of the total carcasses observed from April-September for the main-stem Sacramento River (Doug Killam, personal communication) by the total Jolly Seber estimate of female spawners (Poytress and Carillo 2007).
Figure 2. Spawning distribution of winter-run Chinook on the main-stem Sacramento River. Values shown are the proportion of the total female spawners observed on particular dates in brood year 2009.

*Ricker Stock-Recruitment Relationship*

A Ricker stock-recruitment curve (Ricker 1975) was fit to estimate the total number of winter chinook salmon emergent fry produced each year \( R \) from the number of female spawners \( S \):

\[
R = \alpha S e^{-\beta S} + \varepsilon;
\]

where \( \alpha \) is a parameter that describes recruitment rate at low spawner abundance, and \( \beta \) is a parameter that measures the level of density dependence. Estimates of female spawners are from carcass surveys from the mainstem Sacramento River and estimates of fry production are from juvenile production index (JPI) values calculated from rotary-screw trap catches at Red Bluff Diversion Dam (RBDD)(Poytress and Carillo 2007). All years with available data were included in the analysis (1996-1999 and 2002-2007). Model coefficients were estimated from the loge-transformed version of the stock-recruitment model:

\[
\log_e \left( \frac{R}{S} \right) = \log_e \alpha - \beta S + \varepsilon.
\]

The loge-transformed model describes the per capita recruitment rate \( \log_e(R/S) \) as a function of the number of female spawners \( S \). The number of female spawners explained less than 0.01% of the variation in winter chinook salmon recruitment rate \( \log_e(R/S) \) in the Sacramento River (\( F = 0.03; \text{df} = 1,8; P = 0.866 \)):

\[
\log_e \left( \frac{R}{S} \right) = \log_e 1089 - 4.47 \times 10^{-6} S + \varepsilon.
\]

The density-dependent parameter \( \beta \) did not differ significantly from zero (95% CI = -6.3x10^{-6} – 5.5x10^{-6}), indicating that the relationships between emergent fry and female spawners is linear (density independent). Therefore, \( \beta \) was removed from the equation and a linear version of the model was estimated:

\[
R = \alpha S.
\]

The number of female spawners explained 86% of the residual variation in fry production (\( F = 268; \text{df} = 1,9; P < 0.001 \))(Figure 3):

\[
R = 1043 \times S.
\]
In the JPE model, the mean fry production is predicted from the number of female spawners using the Ricker stock-recruitment relationship. The standard error of the regression between fry production and female spawners ($1.01 \times 10^6$; Figure 3) is used along with the predicted mean fry production to define a normal probability distribution that is randomly sampled from at the beginning of the model simulation to determine the annual fry production.

**Juvenile Development**

In reviewing available literature, temperature emerged as one of the most important environmental factors affecting maturation and survival of developing fishes (Embody 1934; Bailey and Evans 1971; Tang et al. 1987). In addition, temperature is an environmental factor for which there is ample data to associate with cohorts of fish developing in the mainstem Sacramento River. We used data from two experimental studies which explored the relationship between temperature and the survival and maturation time for developing chinook under controlled conditions (Murray and McPhail 1988; Beacham and Murray 1989). Mean daily temperatures from Bend Bridge, CA were used in the JPE model (California Department of Water Resources CDEC website).
Temperature-induced mortality

The stock-recruitment relationship described above already accounts for temperature effects on mortality. In order to account for extreme temperatures, analyses were performed to account for temperatures that go beyond those experienced during the years used in the stock-recruitment model. We used combined data from the experimental work of Murray and McPhail (1988) and Beacham and Murray (1989), which explored the relationship between temperature and the survival of developing chinook (from fertilization to emergence). Due to the observed non-linear relationship between temperature and survival, we tested for a polynomial relationship. Proportional survival (Survival) of incubating Chinook salmon (fertilization to emergence) was not significantly related to water temperature (Temp) (F = 0.816; df = 2,15; P = 0.459):

\[
\text{Survival} = -0.0032 \times \text{Temp}^2 + 0.3085 \times \text{Temp} - 6.5181.
\]

However, in the absence of a better-fitting relationship and because a bell-shaped curve was consistent with the shape of the survival-temperature relationship seen in literature (Murray and McPhail 1998; Beacham and Murray 1989; Beacham and Murray 1990), we proceeded with the best-fit polynomial relationship between survival and water temperature (Figure 4).

![Figure 4. Proportional survival from fertilization to emergence for incubating Chinook salmon at different constant water temperatures (Murray and McPhail 1988; Beacham and Murray 1989). Dots are observed values and solid line is best-fit polynomial model: y = -0.0032x^2 + 0.3085x – 6.5181.](image-url)
In order to apply these temperature effects to the JPE model, we needed to convert the predicted proportional mortality (1 - proportional survival) over the entire incubation period to a daily mortality rate. This conversion allowed us to apply the temperature-mortality relationship on a daily time step in the JPE model. Daily mortality was calculated using methods described in Bartholow and Heasley (2006) as follows:

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

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

Daily mortality (mortality) was significantly related to daily water temperature (Temp) ($F = 9.6; df = 2,15; P = 0.002$):

$$mortality = 0.000035 \cdot (Temp^2) - (0.00326 \cdot Temp) + 0.0753.$$  

We adjusted the intercept of the daily mortality function from the laboratory data to have temperature-induced mortality only occur at temperatures outside the range observed during the period used to develop the stock-recruitment model (1996-1999, 2002-2007); the 95th percentile of the mean daily temperatures observed during the incubation period (May-August) was 57°F for the years used to construct the stock-recruitment model. Therefore, we adjusted the intercept of the daily mortality function so that daily mortality begins at water temperatures above 57°F (Figure 5).

Figure 5. Relationship between daily proportional mortality and mean daily water temperature (°F) at Bend Bridge. Data are displayed as the predicted daily proportional mortality (solid line), with the intercept adjusted to 57°F; 57°F.
was the 95th percentile of the mean daily temperatures observed during the incubation period (May-August) for the years used to construct the stock-recruitment model. Dashed lines depict the standard error of the regression.

In the JPE model, each day the mean proportional mortality of the incubating eggs is predicted from the daily temperature using the above polynomial relationship. The standard error of the regression between daily proportional mortality and daily water temperature (0.0028; Figure 5) is used along with the mean proportional mortality to define a normal probability distribution that is randomly sampled from each day to determine the daily egg mortality.

**Temperature effects on maturation time**

In many previous studies salmon egg maturation time has been found to be negatively related to water temperatures (Murray and McPhail 1988; Beacham and Murray 1989; Crisp 1988; Geist et al. 2006). Using data from the aforementioned experiments looking at temperature effects on development (Murray and McPhail 1988; Beacham and Murray 1989) we examined the relationship between maturation time and water temperature. First we converted *maturation time* (days) to *daily maturation rate* (1/day):

\[
\text{daily maturation rate} = \frac{1}{\text{maturation time}}.
\]

Next, we tested for a significant linear relationship between maturation rate and water temperature. Daily water temperature (*Temp*) explained 99% of the residual variation in *daily maturation rate* (*F* = 2188; df = 1,15; *P* < 0.001) (Figure 6):

\[
\text{daily maturation rate} = 0.00058 \times \text{Temp} - 0.018.
\]

In the JPE model, each day the mean maturation rate of the incubating eggs is predicted from the daily temperature using the above linear function. The standard error of the regression between daily maturation rate and daily water temperature (0.00039; Figure 6) is used along with the predicted mean maturation rate to define a normal probability distribution that is randomly sampled from each day to determine the daily maturation rate.
Figure 6. Relationship between mean daily water temperature (°F) and daily proportional maturation. Data are displayed as the observed daily proportional maturation and their predicted values (solid line). Dashed lines depict the standard error of the regression.

Survival to Chipps Island

Previous studies have found flow during the migration period to be a significant predictor of smolt migration survival (Kjelson and Brandes 1989; Williams and Mathews 1995; Brandes & McLain 2001). Although the shapes of the relationships were not tested, a logarithmic relationship appears evident for fall-run Chinook hatchery smolts released in the north Sacramento-San Joaquin Delta (Kjelson and Brandes 1989; Brandes & McLain 2001) and for spring and summer-run Chinook smolts in the Snake River Basin (Williams and Mathews 1995). Therefore, in the JPE, model mean downstream migration survival of smolts to Chipps Island (entrance to bay) is scaled by the mean Sacramento River flow experienced during each individual cohort’s migration period.

In order to model the downstream migration of smolts in the Sacramento River, we used data from release experiments of coded-wire tagged (CWT) late-fall hatchery Chinook salmon smolts released at Battle Creek, CA (released to mimic wild winter chinook), which were recovered in the Chipps Island Trawl (1994-2006). Since the fish used in the CWT experiments were smolts, we entered in a delay element in the model which allowed 90 days for the fry in the model to develop into smolts. The 90 day delay thus allows the fish to experience the correct flow
conditions in their outmigration to the Delta. Similarly, we applied an additional delay of 59 days, which was the average travel time of the CWT chinook smolts between their release and capture in the Chipps Island Trawl. Mean daily flow at Freeport (California Department of Water Resources CDEC website) was used in the model to represent flow conditions during the smolt outmigration.

We examined the relationship between the USFWS smolt survival index (SSI) and mean Sacramento River Flow at Freeport, CA during the migration period for CWT surrogate winter Chinook hatchery smolts released at Battle Creek, CA. The SSI is calculated by expanding the number of smolts captured by the Chipps Island mid-water trawl to account for time spent sampling and the ratio of the net width to channel width to form an estimate of absolute abundance (Baker and Morhardt 2001). The expanded recovery is then divided by the number of smolts originally released and reported as the SSI (Baker and Morhardt 2001). Although not significant at an alpha of 0.05 (F = 2.86; df = 1,126; P = 0.093), winter chinook SSI exhibited a positive relationship with log-transformed mean flow (flow) (Figure 7):

\[
SSI = 0.0913 * \text{flow} - 0.4829.
\]

![Figure 7. Coded-wire tagged winter Chinook surrogate SSI as a function of log-transformed mean Sacramento River flow during the migration period. Dots are observed values, solid line is best-fit linear regression, dashed lines depict the standard error of the regression.](image_url)
In the JPE model, each day the mean SSI of migrating smolts is predicted from the log-transformed mean flow during the future 59 day migration period using the above linear function. The standard error of the regression between SSI and log-transformed mean flow (0.282; Figure 7) is used along with the predicted mean SSI to define a normal probability distribution that is randomly sampled from each day to determine the daily SSI.

Next, the predicted SSI is converted into a scalar that adjusts the default mean survival of migrating smolts (53%; USFWS, unpublished data). The predicted values from the SSI-flow relationship described above is divided by the mean predicted survival to calculate a daily scalar on migration survival (Figure 8). The scalar is then multiplied by 53% (default migration survival) to calculate the survival of the current day’s cohort of migrating smolts.

![Figure 8. Daily survival scalar as a function of the daily predicted winter Chinook smolt survival index.](image-url)
REFERENCES


USER MANUAL

Goldsim Player Download

In order to update and run the JPE model, the user must first download the player version of GoldSim. To download this software, go to the following link:

http://www.goldsim.com/content.asp?pageid=44

The GoldSim player will allow you to view, navigate and run the JPE model. Using the player version you will also be able to modify the components of the model as described in the sections below.

Updating the Model

On the model dashboard, there is a brief description of the model detailing the time frame during which the model operates along with details regarding its use. Each tab also has a brief description, which provides relevant information for the user.

Under the ‘Input Data’ section, the user is able to update the model with the current year’s temperature and flow data, as well as information about the total estimated number of female spawners and observed carcasses. These data will be used to inform the model, as described in the previous section. When the ‘modify data’ button is selected, this will open a window to the time series data where the daily average temperatures for Bend Bridge (CDEC) can be entered; as described in the window description, Day 0 = April 1. Similarly, data for flow can also be modified using the mean daily flow at Freeport (CDEC). Alternatively, the user can select ‘dummy’ data based on water year type (listed by water year type and the year from which the data were derived).

Under the ‘Female Spawners’ section, the user can enter the estimated total number of female spawners derived from the Jolly-Seber estimates, as well as the observed carcasses during the survey. It is important to note that the sum of all daily values (used for the spawning distribution) must equal the total carcasses observed during the carcass surveys.

In the “Downsteam Survival” box the mean smolt migration survival proportion can be entered. The default value is 53%. Once this data is entered, the model can be run to obtain the current year’s JPE.
Model Use and Results

On the dashboard, you will see the ‘GoldSim Run Controller’. Once the data has been updated, select ‘run’ on the controller. The model will take a few minutes to run through the 100 Monte Carlo simulations used to get the results. Once it is finished, the user can get the JPE results by selecting the ‘Show Chart’ button under Juvenile Production Estimate header. The following window will appear:

The value circled in red (above) is the juvenile production estimate, with the associated error circled in blue. To obtain the JPE results from the 100 Monte Carlo simulations, click on the ‘table view’ button (circled in orange above). The following window will open, which provides those results:
These 100 Monte Carlo simulations are the values that were used to come up with the mean JPE value (as well as the associated error). These data can be copied into Excel in order to keep a copy of the results from each model run (Note: the player version of GoldSim will not allow you to save model runs). If necessary, these data can also be used to run further analyses.

Also under the results section of the Dashboard, results are provided for the temperature induced egg mortality, egg to fry survival, and survival of smolts to the delta. Result outputs for the egg to fry survival and downstream migration survival (e.g., survival values and associated error) are provided in windows similar to those shown above.

**Concluding Remarks**

The above report should provide the fundamental details regarding the methods and data used in constructing the JPE model. In addition, the descriptions (both in this document and in the model) should guide you in its use.

Although error is incorporated in the model wherever data on uncertainty was available, some parameter values were informed by limited data from literature or scientific inference where information to inform uncertainty was lacking (e.g. 53% downstream migration survival).
model validation or sensitivity analysis of the current form of the JPE model has yet to be completed, and therefore the reliability of absolute estimates of salmon production is unknown. The JPE model should not be viewed as a static or definitive product, but a framework that can be modified or expanded upon as new information becomes available. In the future, we plan on improving model functionality by applying recent predator-prey logic to the downstream survival portion of the model (e.g. Anderson et al. 2005).