Interactive Object-oriented Salmon Simulation (IOS) for the NODOS

by

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Introduction

It is widely recognized by both fisheries scientists and management agencies that the overall viability of the ESA-listed winter-run Chinook salmon population in California's Central Valley is impacted by water management actions which affect temperature, flow, and exports (*see* Kjelson and Brandes 1989; NMFS 1997; Brandes and McLain 2001; Brown and Kimmerer 2002; NRDC 2008; NMFS 2009), and which also influence route selection for salmon migrating through the Delta (*see* Perry et al 2010). However, there is also considerable disagreement over the nature and magnitude of management actions taken to aid in population recovery, as evidenced most recently by ongoing litigation over a 2009 Biological Opinion from the National Marine Fisheries Service (NMFS 2009).

It has been acknowledged for some time that modeling can play a powerful role in evaluating the interrelationships among individual factors that give rise to broad patterns in population dynamics, and that understanding the processes that produce such patterns is key to developing principles of management (Levin 1992). Ruckelshaus et al. (2002) even go so far as to say that using better models in making management decisions is one obvious way to change how risks to salmon populations are managed.

Recently, multiple efforts have been undertaken to develop effective models for Central Valley salmon. Williams (2006) classifies these models into two general categories: estimation models, which estimate parameter values by directly fitting the model to available data; and simulation models, which take parameter values from literature or other sources. An example of an estimation model is the Bayesian hierarchical state-space model developed by Newman and Lindley (2006), which incorporates multiple data sources to roughly predict juvenile out-migration based on data for juveniles from the preceding year. An example of a simulation model is the SALMOD model (Bartholow et al. 1997; Bartholow 2004), which combines information regarding run timing with fine-scale data regarding spatial and temporal variations in flow and temperature to define computational units which are then used to assess the effects of river flow and water temperatures on the production of Chinook salmon in the upper Sacramento River.

While the results of such models have provided valuable insights, their narrow focus and limited area reduce their utility in assessing the relative impact on overall population viability of actions at different locations and affecting different life stages. A framework is needed for organizing the body of information regarding the impact of changes in flow, temperature, exports, harvest, physical habitat, and other environmental variables; for quantifying the effects of these changes on the abundance of salmon at each stage in their development, migration, and maturation; and for evaluating the resulting impact on overall population viability. Life-cycle models provide such a framework. They enable, to the extent allowed by available data, the integration of information regarding each stage of the salmon life-cycle, and they synthesize data, equations, and other information into cause-effect relationships for each key environmental variable at each life stage. Life-cycle models utilize parameter values estimated by fitting the available data as well as parameter values taken from literature or other sources, thereby incorporating characteristics of both estimation and simulation models. By taking this approach, life-cycle models are able to dynamically simulate overall population response to changes in environmental variables or combinations of environmental variables at specified locations over time. Both scientists and managers are increasingly realizing the importance of life-cycle approaches (Ruckelshaus et al. 2002), and a recent review of salmon recovery efforts in California's Central Valley recommended the use of life-cycle models for evaluating the potential effects of different management scenarios (Good et al. 2007).

The Interactive Object-oriented Simulation (IOS) model detailed here is a life-cycle model developed by Cramer Fish Sciences. It is used for comparing the relative impact of different flow, temperature, and water export scenarios on the winter-run Chinook population that spawns in the upper reaches of California's Sacramento River, migrates downriver and through the Sacramento-San Joaquin Delta to the Pacific Ocean, and returns to the upper Sacramento River to spawn. We applied IOS in order to assess how winter run Chinook salmon might be influenced by NODOS operational scenarios.

IOS is a life-cycle model that simulates all life stages of winter-run Chinook salmon and models individual daily cohorts of fish through their entire life cycle. Individual life stages are modeled using functional relationships, whose form and parameters values are informed by the best available information from literature. These functional relationships for each life stage are then linked together to form a complete life cycle model that estimates the daily number of eggs for each brood year and progresses them through life stage transitions until spawning at age 3, 4 , or 5, where the process begins again for the next generation. Uncertainty is explicitly modeled in the IOS model by incorporating environmental stochasticity and estimation error where data is available.

Survival and abundance estimates generated by IOS are not intended to predict future outcomes or to predict actual survival. Rather, IOS provides an estimate of relative of survival and abundance which is useful for making comparisons between proposed operation alternatives. While IOS has been calibrated to the best available information, in most cases it is not possible to validate IOS results against actual fish abundance or survivals values because such data does not exist. Where suitable data is available (e.g. spawning escapement abundance) observed values are the result of past habitat conditions, predator abundance and other factors which are not representative of future conditions expected with NODOS proposed alternatives. Generally, IOS results are appropriately reported as averages or as probability distributions by years, by months, and/or by Water Year Type, but not as comparisons between specific days, months or years.

Model Description

In the following section we provide a brief description of the methods used in the construction of the IOS model.

Flow Data: Modeled flow and temperature data output for each of the 5 NODOS scenarios were used to inform the daily conditions experienced by salmon in the model. CALSIM, SRWQM, and DSM2 environmental data for the following locations (with corresponding life stages) were input into the model:

Location	Input Data	Life Stage
Sac River - Bend Bridge	Temperature	Egg/Alevin
Sac River - Bend Bridge	Flow	Egg/Alevin
Yolo Bypass	Flow	Smolt Delta Migration
Sac River - Hood	Flow	Smolt Delta Migration
Sutter and Steamboat Sloughs	Flow	Smolt Delta Migration
Sac River - above DCC	Flow	Smolt Delta Migration
Delta Cross Channel	Flow	Smolt Delta Migration
Sac River - below Georgiana Slough	Flow	Smolt Delta Migration
Georgiana Slough	Flow	Smolt Delta Migration
Sac River - Below Rio Vista	Flow	Smolt Delta Migration
San Joaquin River at Mossdale	Flow	Smolt Delta Migration

San Joaquin River at Stockton	Flow	Smolt Delta Migration
Old River at head of Old River	Flow	Smolt Delta Migration
Total Exports	Flow	Smolt Delta Migration

Spawning: We fit a Ricker stock-recruitment curve to determine the total number of emergent fry using both the estimated number of female spawners from carcass survey data as well as the number of juveniles caught at the rotary screw traps at RBDD (between 1996-1999 and 2002-2007). The Ricker curve is used to predict the current year's fry production based off of the estimated number of female spawners from the carcass survey. In order to ensure that developing fish experience the correct environmental conditions, the daily observed proportion of carcasses observed from carcass surveys are used to determine the distribution of egg deposition in each year current year. A total of 8 years of carcass survey data are included in the model and the particular distribution of carcasses in each year is a randomly selected variable that is resampled for each year of the simulation.

Egg to Fry (survival and maturation): Although the Ricker Stock-recruitment curve predicts the annual fry production, we wanted to account for temperature-related egg mortality and variation in maturation times of incubating eggs in response to daily temperatures. Daily maturation and survival of incubating eggs was modeled as a function of daily mean water temperature, utilizing data from Murray and McPhail (1988) and Beacham and Murray (1989), who conducted experiments in which Chinook salmon embryos and alevins were incubated under constant water temperatures. Analyses were performed to confirm that there were indeed significant relationships between temperature, survival and maturation time for the combined published data used in the JPE model. Due to the observed non-linear relationship between temperature and survival, we performed a generalized additive model (GAM). Generalized additive models are useful because they fit non-parametric smoothers to the data without requiring the user to specify any particular mathematical model to describe the non-linearity. Our analyses of the published data revealed that temperature was a significant predictor of survival ($P < 0.001$). 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 Ricker model (1996-1999, 2002-2007). The 95th percentile of the mean daily temperatures observed during the incubation period (May-August) was 57^{o}F for the years used to construct the Ricker model. Therefore, we adjusted the intercept of the daily mortality function so that temperature-related mortality begins at temperatures above 57^{o}F.

For analyses of maturation, we performed a general linear model with normal error structure. Again we found a significant positive relationship between temperature and maturation for the published data (fertilization to emergence; $P < 0.001$). Predicted values from this functional relationship were used to inform the model. Each day the proportional maturation of the incubating eggs is predicted from the daily temperature.

Downstream migration from spawning/rearing areas to Delta entry at Freeport: In order to make predictions for the number of juvenile winter-run Chinook that survive to the Delta, we used estimates based on survival of late-fall run Chinook through the Sacramento River (Michel 2010). Late-fall run and winter run migrate at a similar size and the timing of migration overlaps. Thus, late-fall run are often used as surrogates for endangered winter run. The study by Michel (2010) used acoustic tags to estimate survival of late-fall run Chinook in well defined segments of the migration route from the Coleman National Fish Hatchery to the Golden Gate. The three year study did not find a significant relationship between flow and survival, thus we based estimates of survival in the IOS model on the mean and standard error of survival between the spawning/rearing grounds and Delta entry at Freeport.

Since the fish used in the acoustic experiments were smolts, we entered in a delay element in the model which allowed 60 days for the fry in the model to develop into smolts; this delay thus allows the fish to experience the correct flow conditions in their outmigration to the Delta. Similarly, we applied an additional delay of 20 days, which was the average travel time of the acoustic tagged Chinook between their release and detection at Freeport.

Delta Migration: The smolt Delta migration portion of the life cycle is identical to that described for winter run Chinook in the Delta Passage Model (DPM). A detailed description of the DPM is provided in a separate document.

Ocean Survival: Following Cramer et al. (2007) we utilize the following values for ocean mortality and sexual maturation:

- Winter Mortality for age 3 and 4 groups is 20% (Grover *et al.*, 2004). Winter mortality for age 2 fish is modified by ocean productivity as described in Wells et al. (2007). The value of Wells' index of ocean productivity in the IOS model is a randomly selected variable based on values from 1979-2006 and is resampled for each year of the simulation.
- Smolt to Age 2 Mortality is 96%.
- Age 2 Ocean Harvest Mortality is 0% (Grover *et al.*, 2004).
- The proportion of Age 2 Returning Spawners (precocious) is 8% (Grover *et al.*, 2004).
- Age 3 Ocean Harvest Mortality is 21% (Grover *et al.*, 2004).
- The proportion of Age 3 Returning Spawners is 96% (Grover *et al.*, 2004).
- Age 4 Ocean Harvest Mortality is 66% (Grover *et al.*, 2004).
- The proportion of Age 4 Returning Spawners is 100% (Grover *et al.*, 2004)

Model Runs: Winter-run Chinook salmon were modeled across 81 years under 5 different NODOS flow scenarios. The first four years of the model run were each seeded with 3,000 adult spawners.

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