Appendix N OCAP Modeling Software, Application, and Results

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Winter Run Chinook IOS Population Model, Cramer Fish Sciences

The IOS (Interactive Object-Oriented Salmon Simulation) winter-run Chinook life cycle model was developed to help understand population-level effects of water project operations and alternative fishery management strategies. The California Department of Water Resources (CDWR) contracted with Cramer Fish Sciences to develop life cycle models in order to evaluate potential effects and design alternatives for the North-of-Delta-Offstream-Storage project. Life cycle models are well-suited for such evaluations because they integrate survival changes at multiple life stages and across the multiple habitats used by anadromous salmonids. Thus the IOS model was designed to serve as a quantitative framework for estimating the long-term response of Sacramento River Chinook populations to changing environmental conditions (e.g. river discharge, temperature, habitat quality at a reach scale). By tracking the abundance, size, and survival of Chinook salmon through successive life-stages, this life cycle model allows environmental effects to be examined at various temporal and spatial scales.

Using simulated daily flow and water temperature inputs, the IOS model tracks daily salmon numbers from seven different life stage categories (eggs, alevins, fry, parr, smolts, subadults, and adults). The model is spatially explicit including 22 reaches of the Sacramento River, the Delta, and the Pacific Ocean. Within each reach functional relationships were identified consistent with the best available science, including both research data and ecological theory. Where possible, we used experimental and field data obtained from Sacramento River populations to parameterize the functional relationships, but other data were used in their absence. In addition to calculating numbers of individuals by life stage and geographic area, IOS tracks average fry and parr size in each reach using temperature and density dependent growth functions. Juvenile salmon migration occurs as a function of maturation, habitat capacity, flow, temperature and season. Additional variables that influence life cycle processes include habitat availability (spawning and rearing), Delta conditions/water project operations, adult harvest, and the status of upstream migration barriers.

The IOS model was seeded with 5,000 spawners for the first four years then allowed to cycle through multiple generations during years 1923-2002. A single run of the IOS model was completed for each water operation scenario (Studies 7.0, 7.1 and 8.0). The effect of different water operation scenarios on the Sacramento River winter-run Chinook salmon population was evaluated by comparing abundance and survival trends at various life stages among the three runs of the IOS Model.

i. GoldSim Software (used to create IOS salmon model)

1. Reliability and acceptability of software

IOS model has been developed through an object-based, dynamic system simulation software (GoldSim). GoldSim software was initially developed as a simulation tool for complex engineering systems associated with radioactive waste management and has since been used in hundreds of high stakes applications related to water resources, human health, hazardous waste management, business modeling, and national defense (visit www.goldsim.com for detailed examples). Since GoldSim is an object-oriented software, source code is not necessary for model validation. GoldSim models (including IOS) provides complete transparency for all model attributes including structure, mathematical functions, and parameters. In addition, full software documentation is available in the help system if users require more information regarding any particular GoldSim function.

2. Quality Assurance and Quality Assessment for model calculations

Accuracy and reliability of calculations are assured by broad acceptance and varied application of GoldSim software (in which IOS model has been built). GoldSim software was initially developed as a simulation tool for complex engineering systems associated with radioactive waste management and has since been used in hundreds of high stakes applications related to water resources, human health, hazardous waste management, business modeling, and national defense (visit www.goldsim.com for detailed examples). GoldSim developers conduct regular and rigorous software verification testing to assure that all model calculations are consistent with the highest quality standards.

3. Documentation

Detailed documentation for GoldSim software may be found at www.goldsim.com.

ii. IOS Model features and application

1. Key processes and model characteristics

• *Key processes* (see model documentation below for further details)

- Egg/alevin incubation
- Juvenile growth & maturation
- Juvenile migration
- Delta survival
- Ocean survival
- Ocean harvest

- Adult migration
- In-river harvest

• *Model characteristics*

The IOS model calculates the number of individuals in each salmonid lifestage (eggs, alevins, fry, parr, smolts, subadults, and adults) in each of its geographic segments every day. These geographic segments are: 22 reaches of the Sacramento River, the California Delta, and the Pacific Ocean. In addition to calculating numbers of individuals, IOS calculates the average size of fry and parr in each of the 22 reaches using a temperature and density dependent growth function. The calculations in each segment account for all processes that move individuals into or out of a segment (or existence):

- maturation
- immigration
- emigration
- mortality

Functional relationships between these four life cycle processes and environmental variables drive the model dynamics. These functional relationships were created using the best available research. The environmental variables that influence the life cycle processes are:

- river temperature
- river flow
- habitat availability
- Delta temperature
- Delta inflow
- Delta exports
- Delta salinity
- Delta turbidity
- Delta Cross Channel (DCC) gate position
- adult harvest
- Red Bluff Diversion Dam (RBDD) status
- Anderson Colusa Irrigation District (ACID) dam status

2. Model documentation

Detailed documentation of the IOS model is available at http://www.fishsciences.net/projects/nodos.php

3. Rationale for approach and use of best available science

IOS is based on best available science, and incorporates working hypotheses for those model steps that are highly uncertain. Wherever possible, we have gathered information to check and improve reliability of the model..

Life-cycle modeling often must be completed for populations with limited empirical data, including life stages for which there are no data at all. Most life-cycle models that we have developed required that some life stages be quantitatively described by functions derived from out-of-basin studies, literature values, or professional judgment. The following list describes, in order of preference, strategies and information sources we have successfully used to parameterize our life cycle models.

(1) Use local, empirical data to derive life table values of reproduction, growth, migration, and survival. Also use local data on habitat and environmental conditions. Example: in the winter-run Chinook model, we used local data such as spawner abundance, eggs per female, and abundance of juveniles passing Red Bluff Diversion Dam to estimate the number of eggs deposited and egg-to-fry survival.

(2) Derive life-table rates from studies elsewhere, and calibrate those rates to whatever empirical data are available locally. Example: in the winter-run Chinook model, we used the function for smolt survival through the Delta derived from fall-run chinook, but used environmental values that corresponded to the dates that winter-run juveniles passed through the Delta.

(3) Simplify the model to bypass life stages lacking information. Example: in the winter-run IOS we used cohort reconstruction data to annual salmon survival and maturity, and effectively bypass finer scale processes (within-year salmon migration behavior or mortality events).

(4) When data on fish are lacking, data on habitat and environmental factors can be used to derive carrying capacity and survival. We have derived models, based on information synthesized from the literature, that relate spawning and rearing capacity for each salmonid species to habitat attributes. Example: in our coho salmon model for the Klamath Basin, we used data from habitat surveys throughout the basin to estimate rearing capacity and fry-to-smolt survival in each tributary based on a synthesis of values drawn from the published literature.

(5) The use of multiple working hypotheses is an effective approach for dealing with uncertainty. In either the presence of debate or the absence of clear understanding of an issue, there is insufficient information to eliminate competing options for how the dynamics of a life stage should be modeled. In such a case, we quantify each of the viable options and run simulations to determine how they will alter predictions of future population performance. If the options predict important differences in the future

population, then this issue must be identified as a critical uncertainty warranting study in the local population.

4. Reliability and acceptability of approach

Our life-cycle population models have been developed in collaboration with management agencies. We have used a systematic process of meetings and progress reporting to ensure full exchange of ideas and an ongoing scientific review for the functions we build into the model and for interpretations we draw from model output. For examples of these processes, see our websites for the winter-run Chinook and Klamath coho salmon modeling efforts (http://www.fishsciences.net/projects/index.php). Specifically, the Winter-run Project Work Team reviewed the winter-run integrated modeling framework (predecessor to IOS) in 2003 and our full report of response to comments is posted on the project website: (http://www.fishsciences.net/projects/cuwa/_imf/response_to_PWT_comments.pdf).

Enhancements to that model have continued since that time, and a manuscript describing the winter run model is currently being prepared for submission to a peer review fishery journal.

In 2004, our modeling of the effect of spawning habitat enhancement on fall-run Chinook salmon and steelhead embryo survival and development was published in the Canadian Journal of Fisheries and Aquatic Sciences. Throughout 2007 we have been involved in life-cycle modeling efforts for Clackamas River coho, steelhead and spring- and fall-run Chinook salmon, and Klamath River coho. On both projects, we prepared a series of technical memorandums that were widely distributed for technical review by scientists representing fisheries agencies and basin stakeholders. In both of these cases, as in the Sacramento winter-run case as well, many of the comments were helpful and led to improvements in the model. Final reviews and revisions to both the Clackamas and Klamath modeling projects are currently in process (http://www.fishsciences.net/projects/klamathcoho/).

The IOS version of the winter-run life cycle model began development in early 2007 and has been subjected to several cycles of internal review by CFS and DWR staff. In December 2007, the IOS model and hindcast model validation was presented and positively received by a large interagency audience. A series of model revisions were completed following this review, and the model is currently going through a second review process. Details on development of the winter-run Chinook IOS can be found at:
http://www.fishsciences.net/projects/nodos.php

5. Model boundaries (spatial and temporal domain)

- Spatial

  The IOS model encompasses the mainstem Sacramento River, the California Delta, and the Pacific Ocean. Tributaries to the Sacramento River are not accounted for. Bypasses (e.g., Yolo Bypass) of the Sacramento River are not accounted for.

- Temporal

As implemented for OCAP study evaluations, the IOS model encompasses 80 consecutive calendar years. The temporal resolution (i.e., timestep) is a daily one, with exception of the Delta, where environment variables only change monthly.

6. Available data sources (quality and quantity)

Experimental and field data used to parameterize the model's functional relationships were obtained from publications in peer-reviewed scientific journals, reports from resource and regulatory agencies (e.g., CDFG, NMFS), and reports from consulting firms (e.g., Stillwater Sciences, Cramer Fish Sciences). Specific details on the nature of these sources and their application in the IOS model can be found in the documentation of the IOS model available at http://www.fishsciences.net/projects/nodos.php .

7. Data gaps

The life cycle of a large anadromous fish such as Chinook salmon is sufficiently complex to make a comprehensive list of data gaps nearly endless. However, in the process of constructing and refining the IOS model, several key areas where further research is needed became apparent. Below we list some of these which are either the most critical or the most accessible to immediate research.

- Reach-specific mesohabitat availability in the Sacramento River
- Mesohabitat type usage (densities) by salmonids
- Population response to ocean conditions
- Environmental drivers of spawning site selection by adult females
- Additional influences on juvenile Delta survival (e.g., tidal currents)
- Survival of parr and fry in the Delta compared to that of smolts
- Environmental drivers of juvenile outmigration
- Relationship between density and food availability for juveniles
- In-river predation on juveniles (temperature effects?)
- Timing of juvenile migration below RBDD

8. Assumptions

All models depend on assumptions made to fill the gaps in available science. Transparency regarding such assumptions is a critical piece of knowledge for evaluating model results.

Below we provide a comprehensive list of the explicit assumptions made in the IOS life cycle model.

Adults

- The Adult sex ratio is 65% female.
- The area of available spawning habitat (gravel) in each reach is constant and best represented by the 1980 CDWR Upper Sacramento River Spawning Gravel Study.
- Spawning females each produce only one 4.5m^2 redd.
- Spawning capacity in every reach can be predicted by measures of available spawning habitat and by assuming an average redd area of 4.5m^2.
- Spawning adults first fill the capacity of the uppermost available reach and the remainder fills the next highest reach, continuing downstream until the entire escapement is distributed.
- If the RBDD is closed, 60% of the escapement is distributed above RBDD and 40% is distributed below the RBDD. If the RBDD is open, 100% of the escapement is distributed above the RBDD.
- No spawning adults pass the ACID dam when it is closed. The reach above the ACID dam is filled to capacity when the ACID dam is open.
- Fecundity stays constant at 3353 eggs/female.
- Spawning happens as an approximately normal distribution that starts April 1st and ends August 1st.

Eggs and alevins

- Average daily temperature over the period of incubation can be used as the constant temperature variable in the Temperature-dependent Incubation Time model of Beacham and Murray (1990).

Juvenile Growth

- The juvenile growth rates assume:
    - growth rate is a function of temperature and ration; ration is a function of population density
    - the shape of temperature-dependent growth curves at different rations are similar between fry and parr

- The juvenile maturation rate assumes:
  - the size distribution of juveniles within a reach is log-normal
  - juvenile growth is exponential
  - there is a constant influx of new members to a life stage at the minimum size.
- The weight-length relationship developed by Petrusso and Hayes (2001) for Chinook salmon in the Sacramento River is applicable to winter-run Chinook in the Sacramento River.

Juvenile Migration

- Downstream migration speeds estimated from juvenile Chinook on the Columbia River (Giorgi et al. 1997) are applicable to winter-run Chinook in the Sacramento River.
- Downstream migration speed of fry (but not parr or smolts) increases with increasing river flow.
- Fry and parr (but not smolts) get swept downstream during flows high enough to scour redds. Based on Williams (2006) these flows are assumed to begin at 50,000 cfs and cause 100% of fry and parr to be swept downstream each day at 60,000 cfs.
- Much of the migratory behavior of juveniles is volitional and thus independent of specific environmental triggers
- The area of each mesohabitat type in every reach can be quantified based upon habitat mapping conducted for instream flow incremental modeling by USFWS (Mark Gard, U.S. Fish and Wildlife Service, unpublished data).
- The maximum linear density of fry and parr in each mesohabitat type can be estimated based upon studies conducted on salmon abundance and mesohabitat use on the Feather River.
- Temperature-dependent scalar of capacity is assumed to be the same as that used in Cramer Fish Sciences, Population Life Cycle Model for Lower Clackamas River Salmonids.
- Emigration survival is assumed to be the same as that used in the Cramer Fish Sciences, Klamath Coho model.
- The influence of water temperature on juvenile survival through the Delta estimated by Baker et al. (1995) is applicable as a temperature scalar on migration survival of juveniles in the Sacramento River upstream of the Delta.
- Emigration survival scales down with juvenile size from 100% in smolts, to 98.5% in parr, and 97.5% in fry.

- The proportion of fry, parr, and smolts that encounter a diversion screen is proportional to the amount of flow diverted into that diversion.
- The proportion of fry, parr, and smolts encountering a diversion screen that die is 0.02

Hatchery Supplementation

- Annual hatchery supplementation was set at 200,000 smolts released into Reach 3 (Hwy 299/44 Bridge) each year

Delta passage and survival

- The average amount of time required for smolt passage through the Delta is 15 days
- The average amount of time required for parr passage through the Delta is 60 days
- The average amount of time required for fry passage through the Delta is 90 days
- Delta conditions are stable over one month intervals (CALSIM limitation)
- Delta survival is dependent only on temperature, exports, salinity, turbidity, Freeport flow, and DCC gate position.
- Delta turbidity is constant at 8.2 Formazine Turbidity Units (FTUs)
- Delta salinity can be estimated from Delta flow
- Delta survival scales down with juvenile size from 100% of the value calculated using the Newman (2003) model for smolts, to 50% of the value for parr and fry.

Ocean survival

- Smolt to Age 2 mortality in the ocean is 96%
- Age 2, 3, and 4 mortality in the ocean is 20%, respectively
- Age 3 ocean harvest is 21%
- Age 4 ocean harvest is 66%
- 8% of the surviving Age 2 population in the ocean returns to spawn
- 96% of the surviving Age 3 population in the ocean returns to spawn
- 100% of the surviving Age 4 population in the ocean returns to spawn

9. Limitations

As with any model, the explicit assumptions of the IOS model result in specific limitations for its use. These limitations should be apparent as consequences of the assumptions detailed above and will not be discussed further. However, implicit assumptions resulting from the chosen model-building approach can produce limitations to a model’s application that are less apparent. For the IOS model, the main limitations of this type are:

- The model is designed to contrast the effects of alternative water management scenarios with one another. In this application, the model is not intended to forecast future population trends.

- The model is exclusively ecological, not evolutionary and therefore cannot illustrate population-level effects that are mediated by mechanisms of selection, gene flow, mutation, or genetic drift.

- In its current formulation, the parameters of the model do not include estimates of uncertainty (i.e. the model is deterministic) and thus model results must be interpreted without the assistance of probability theory.

10. Historical comparison (hindcast)

In order to evaluate the performance of the IOS model a historical simulation (hindcast) was performed. Where available, historical data from 1968-2001 were used as yearly inputs for this hindcast. These data were:

- RBDD status
- ACID dam status
- Sport harvest rate
- Age 3 Ocean Harvest estimate
- Age 4 Ocean Harvest estimate
- Hatchery smolt releases

In addition to these yearly inputs, the hindcast simulation used historical daily hydrologic data for all 22 reaches of the Sacramento River (CH2M Hill modeling) and for the Delta (CDEC records). These data were:

- river temperature
- river flow
- Delta temperature
- Delta inflow
- Delta exports
- Delta salinity*
- Delta turbidity**

* Historical data were unavailable thus salinity was estimated from inflow.

** Historical data were unavailable thus turbidity was fixed at 8.2 FTUs.

In part one, the adult escapement was fixed at the historical value for each year, 1968-2001. This 'disconnection' of the life cycle allowed within-year comparison of model behavior with monitoring data. Specifically, data on the passage of juveniles at the RBDD (rotary screw trap [RST]; 1995-99; Martin et al. 2001) and Knight's Landing (RST & beach seine; 1996-99; Snider and Titus 2000a, 2000b; USFWS 2006) were used for this comparison.

In part two, the adult escapement was fixed for only the initial four years (1968-1971) of the hindcast simulation. For the subsequent 29 years (1972-2001) the adult escapement was determined by the life cycle model. This 'seeding' of the model allowed it to simulate forward through the historical sequence of environmental variables. The primary output used for comparison with monitoring data in this part of the hindcast was adult escapement. Specifically, annual escapement estimates from GRANDTAB (1972-2001) were used for this comparison.

11. Sensitivity/uncertainty in inputs, initial conditions

Uncertainty associated with functional relationships or their parameters within IOS can be addressed in two ways. First, users may select from a range of scientifically supportable values for uncertain functions or parameters. Such sensitivity analyses allow the user to test alternative functions and observe their influence on model results. Second, the stochastic simulation capabilities can be used to supply tabular or graphic accounting for the effects of uncertainty and variability on observed model outcomes. Simulation results for any metric of interest can be reported as a frequency distribution of outcomes rather than a simple number. The ability to quickly and easily run simulations with different functions, or different expressions of uncertainty, allows users to easily examine alternative hypotheses in situations for which local scientists or the scientific literature present conflicting interpretations.

Currently, the IOS model is configured to run on the best available and supported information and those relationships have been validated through model hindcasting. Given the complexity of the model, an evaluation of uncertainty or sensitivity for all model relationships and parameters would be impractical. Such an effort would need to be focused on those critical areas judged by area experts. We are eager to conduct such an analysis of sensitivity and uncertainty but have not yet received direction and requests for such analyses from IOS model users

12. Planned future model development

Planned future development of the IOS model includes:

- Incorporation of emerging research on survival of juveniles in the Delta (migration pathways, mortality, rearing)
- Building a population response to varying ocean conditions
- Replicating the model for other runs of Chinook in the Sacramento River

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