Oncorhynchus Basian Analysis Model for Winter-Run Chinook Salmon Sensitivity Analyses on Delta Mortality

Introduction

The Oncorhynchus Bayesian Analysis (OBAN) model is a stage-structured, spatially explicit life cycle model that reflects the population dynamics of Sacramento River winter-run Chinook salmon. The objective of this modeling study was to provide an understanding of how additional Delta mortality affects the productivity and abundance of the winter-run Chinook salmon population both in absolute terms and relative to the baseline. Appendix A includes the initial Study Plan for this analysis, however there were revisions to the analysis that were not included in the Study Plan.

Methods

The OBAN model includes three freshwater life history stages, spawning, eggs, and juveniles, at Red Bluff Diversion Dam (RBDD); juveniles in their first year in the ocean after rearing and outmigration; age-2 returning adults, age-3 returning adults; and age-4 returning adults. The OBAN model uses statistical relationships to evaluate the role of freshwater drivers on the egg to RBDD juvenile survival, and on the RBDD juvenile survival to first year in the ocean. The OBAN model has been calibrated to adult estimates of total adult escapement from 1967 to 2011 and to juvenile indices of abundance at RBDD from 1995 to 2011 through a Bayesian statistical fitting approach that incorporates parameter uncertainty.

To evaluate the effect of additional Delta mortality on the population dynamics of winter-run Chinook salmon, a counterfactual analysis was performed with the OBAN model over the period of 1970 – 2020. A counterfactual approach uses a baseline historical run using observed environmental conditions and then modifies an aspect of the dynamics to evaluate what could have happened if the conditions had been different. To evaluate the effect of additional Delta mortality, the mortality of juvenile Chinook salmon in the juvenile life stage from RBDD to the first ocean year was increased by several hypothesized levels over the range (0 - 10%) on top of the estimate survival in this stage. The OBAN model was then run for the 1970-2020 period under each of the mortality levels to evaluate how the population productivity and abundance respond to these levels of through-Delta mortality over the model period.

Six different scenarios were developed for this analysis, which differed in the level of through-Delta survival (Baseline, 1.0%, 2.5%, 5.0%, 7.5%, 10%). The scenarios were developed in the same manner and only differed in the level of mortality applied.

Detailed descriptions of the OBAN model and the scenarios are included in Appendix B.

Results

All scenarios used the same values to initiate the winter-run Chinook salmon population in the OBAN model in the first four years of the simulations. To understand the effect of the through-

Delta mortality scenarios, the mean escapement for the final 10 years of the modeled time-period were used in the metrics of abundance. Mean estimates of abundance for each Scenario and the Baseline showed similar patterns in abundance (Figure 1). The Scenario 10% diverged from the baseline to the largest degree of the scenarios with the other scenarios diverging to an intermediate degree in order of their level of additional Delta mortality. Due to variation in the hydrologic conditions, there are years where differences between Baseline and the five mortality scenarios are compressed. For example, escapement in 2017 is similar in the Baseline and mortality scenarios due to low levels of escapement from the 2014 brood year, which was a critical dry year. In contrast the variation between mean escapement is more pronounced in 2015 and 2019 when overall escapement was higher across all scenarios (Figure 1).

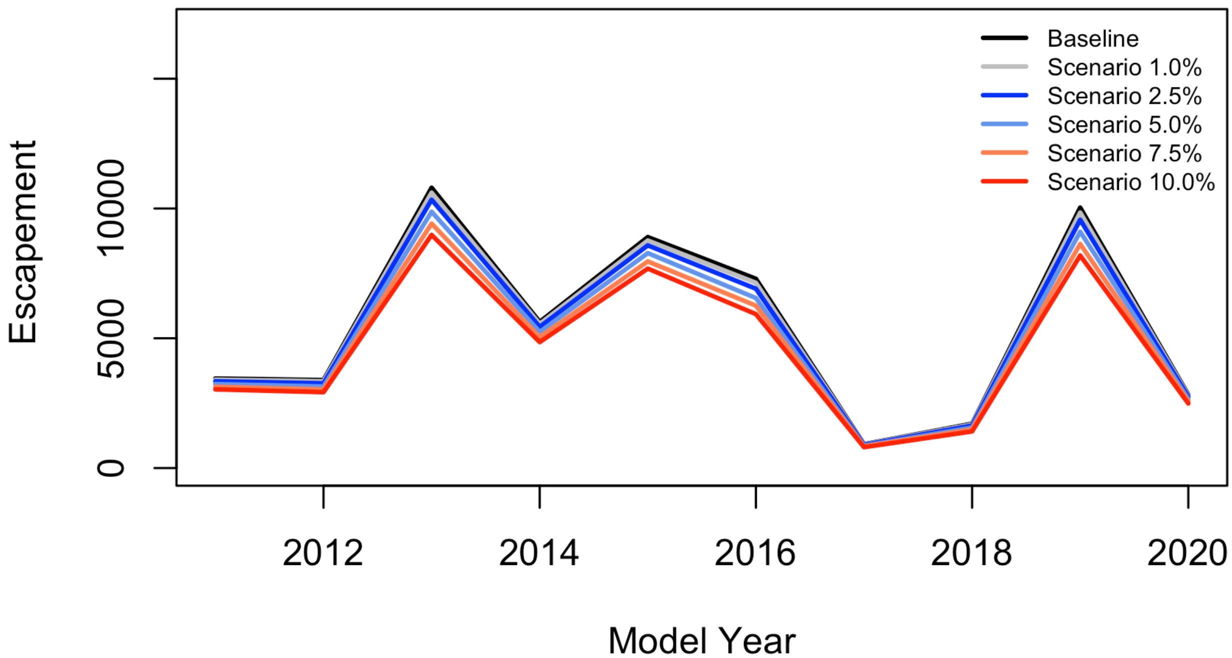

Figure 1. Baseline and Scenario Mean Escapement Abundance over the Last 10 Years (2011-2020) of the Modeled Period of 1970 – 2020

The productivity metrics provide information on how the individual cohorts were affected by the additional through-Delta mortality. The natural origin winter-run Chinook salmon population under baseline conditions had a cohort replacement rate (CRR) that averaged 1.32 (Table 1). Average CRR values of 1.0 or greater are necessary for the population to sustain itself. The CRR values greater than 1.0 were due largely to the general increase in abundance that occurred between the early 1980's and the mid-2010s.

The additional mortality in through-Delta survival decreased the productivity relative to the Baseline scenario (Table 1). The level of reduction in the CRR was small, with changes in CRR of less than 1% relative to Baseline (Table 1).

Table 1. Cohort Replacement Rate Metrics for Scenarios with Different Levels of Delta Mortality

Scenario	CRR mean (95% CI)	Percent difference in CRR relative to Baseline mean (95% CI)
Baseline	1.321 (1.124, 1.692)	NA
Scenario 1%	1.320 (1.124, 1.690)	-0.0% (-0.2, 0.1)
Scenario 2.5%	1.319 (1.123, 1.686)	-0.1% (-0.2, 0.1)
Scenario 5.0%	1.318 (1.121, 1.680)	-0.2% (-0.8, 0.4)
Scenario 7.5%	1.316 (1.119, 1.674)	-0.3% (-1.2, 0.7)
Scenario 10.0%	1.315 (1.119, 1.668)	-0.4% (-1.6, 0.9)

Key:
CI = Central Interval
CRR = Cohort Replacement Rate

The abundance metrics provided information on the cumulative effects of the scenarios over the modeled 1970 – 2020 period due to the consistent reduction in productivity across multiple cohorts. The mean 10-year abundance (calculated over the final 10 years of the modeled time series) for the Baseline was 8,004 male and female spawners combined (Table 2). This value was used to evaluate the probability of each mortality scenario having a 10-year mean abundance under the Baseline in the this viability metric (viability metrics are described in Appendix B). The 10-year mean abundance was inversely proportional to the level of through-Delta mortality with lower mean abundances for scenarios with higher mortality (Table 2). The percent difference in mean 10-year abundance between each of the mortality scenarios and the Baseline indicated the degree of the cumulative effects from each through-Delta mortality scenario. For example, the difference in mean abundance between the Baseline and Scenario 5% was -8.1%. In general, the mean abundance was reduced by approximately 1.5 times the through-Delta mortality over the modeled time series (Table 2).

The probability that the three-year sum of natural origin abundance would be below the threshold of 2,500 spawners increased with through-Delta mortality. The probability of surpassing the threshold under the baseline was 0.396 (Table 2). Increasing the through-Delta mortality caused this viability metric to increase. In Scenario 10% the probability that winter-run natural origin spawners would fall to below 2,500 in at least one year was 0.485.

Finally, the probability that the 10-year average abundance would be below the baseline (8,004) indicated an increasing trend with higher through-Delta mortality. The abundance under Scenario 1% through-Delta mortality had a 0.703 probability of being lower than the Baseline, whereas the abundance under Scenario 10% through-Delta mortality had a 0.787 probability of being below Baseline.

Table 2. Abundance Metrics for Scenarios with Different Levels of Delta Mortality

Scenario	Abundance[a] mean (95% CI)	Percent difference in abundance relative to Baseline mean (95% CI)	Probability (3-year sum < 2500)[b]	Probability (Scenario < Baseline[c])
Baseline	8,004 (2,308, 24,992	Not Applicable	0.396	Not Applicable
Scenario 1%	7,861 (2,282, 24,513)	-1.7% (-2.1, -1.2)	0.403	0.703
Scenario 2.5%	7,649 (2,242, 23,805)	-4.1% (-5.1, -3.0)	0.418	0.722
Scenario 5.0%	7,304 (2,157, 22,652)	-8.1% (-10.0, -6.0)	0.443	0.748
Scenario 7.5%	6,969 (2,086, 21,534)	-12.0% (-14.8, -9.0)	0.467	0.768
Scenario 10.0%	6,644 (2,024, 20,450)	-15.9% (-19.4, -11.9)	0.485	0.787

Notes:

a The average abundance in the final 10-years of the simulation study.

b The number of simulations in which one or more of the 3-year rolling sum of escapement abundance fell below the 2,500 threshold.

c The baseline mean of the average abundance in the final 10-years (8,004).

Key: CI = Central Interval

Discussion

- This relatively small reduction in CRR was due to the Delta and early ocean stages being combined, and the overall survival through these two stages was low. As a result, a 1-10% decrease on a rate of 0.001 will have an overall small effect on the dynamics.
- A similar analysis was completed for the Winter-run Life Cycle Model (WRLCM). The OBAN results showed a similar direction of impacts of Delta mortality, but a smaller magnitude of change in both the CRR and the abundance metrics relative to the baseline. The baseline CRR under the OBAN model for 1995-2020 (the same period used in the WRLCM) was 1.1 (95%CI: 0.75, 1.80) indicating both a lower CRR and more uncertain CRR for that period relative to the results from 1970 – 2020.

The OBAN model provides a longer time series compared to the WRLCM counter factual analysis and thus more environmental conditions. However, due to the structure of the life cycles in the OBAN model, it is not sensitive to the levels of through-Delta mortality used in this study. The OBAN model would likely be more sensitive to specific changes in operational conditions and the drivers – e.g., changes in exports, rather than sensitivity to changes in the intercept of the logistic regression for the life history stages. This could occur if the changes to the drivers caused a shift in through-Delta life stage that was greater than 0.10 from the baseline (the largest magnitude used in this scenario analysis). Also, the OBAN model was calibrated to the adult escapement and juvenile fry abundance estimates at RBDD through 2011. Recalibrating the OBAN model with additional years of abundance data that could change the relationships between driver variables and population response, thus changing the results of this analysis.

This study explored the impact of hypothetical levels of through-Delta mortality ranging from 1% to 10% on the productivity and abundance of Sacramento River winter-run Chinook salmon using the OBAN model. As a result, this analysis represents a type of sensitivity analysis of the OBAN model to changes in the RBDD to first year ocean survival, which includes Delta mortality. Productivity of the winter-run population in the OBAN model were affected by the additional Delta mortality (Table 1); however, the effects on CRR were small relative to the levels of additional Delta mortality. For example, a 10% increase in Delta mortality resulted in an approximate 0.4% reduction in CRR relative to the Baseline (Table 1). This occurred due to the multiple covariates that were included in the life stage from fry at RBDD to the end of the first year in the ocean. Survival through these life stages is low (on the order of 4% to 0.4%) and thus a reduction in survival of 10% leads to a small absolute change in survival. The sensitivity analysis that is being performed here is essentially modifying the intercept in the regression equation that relates fry at RBDD to end of the first-year ocean survival. As a result of the underlying construction of the OBAN model, the population productivity metric CRR is not particularly sensitive to changes in Delta mortality.

The abundance related metrics reflected the cumulative effects of the through-Delta mortality over multiple cohorts. This analysis indicated an approximately 1.5 times decrease in abundance relative to the Baseline for a given level of through-Delta mortality. Thus, the abundance of modeled winter-run was more sensitive to through-Delta mortality than productivity. Small changes in productivity due to the additional Delta mortality (0.1-0.4%) lead to a larger impact on abundance (1.5% - 16%) due to the cumulative effects occurring over the 51-year period of the model runs. This is approximately 17 generations given the 3-year dominant age at return for winter-run. The probability that a scenario was less than the Baseline was greater than 0.7, even under Scenario 1%, due to the cumulative effects reflected in the abundance metric. The probability that the scenarios were below the average Baseline increased for each subsequent level of Delta mortality (Table 2). The probability of the population falling below the 2,500 threshold in 1 or more years was 0.396 under the Baseline scenario. For each additional level of Delta mortality the probability of surpassing the 2,500 threshold in 1 or more years increased approximately 1.5% for an additional 2.5% increase in Delta mortality e.g., 0.418 to 0.433 for Scenario 2.5% versus Scenario 5.0% (Details on calculations of the probability of surpassing the 2,500 threshold are described in Appendix B). The probability of falling below the abundance threshold of 2,500 occurred during the 1980 - 2000 model period, which had low abundance (Appendix B, Figure B-4). As a result, this abundance metric reflects the levels of abundance in that time frame of the full model runs (1970 – 2020).

There are some important caveats to this analysis. This application of the OBAN model is dependent upon the historical hydrologic and operational time series from 1970 – 2020. The OBAN model was calibrated to the adult escapement and juvenile fry abundance estimates at RBDD through 2011, and the relationships between driver variables and survival rates were derived from that calibration. Additional abundance data are available for calibration and could be used to improve the relationships between driver variables and population responses over more recent years. After including those additional years of abundance data, the relationships and their magnitude could vary given any updates in the relationships to the driver variables. Finally, future work using similar tools to those applied in this analysis could provide a more refined estimate of the through-Delta mortality associated with specific operational scenarios. For example, modeling the changes to flow (e.g., Yolo access), DCC operations, and exports could be linked directly to the Delta mortality rates. This would allow the analysis to reflect annual variation in the Delta mortality rate due to those actions, rather than the constant mortality rates applied here.

Key Findings

1. OBAN results indicated that additional through-Delta mortality causes a small decrease in cohort productivity across variable rates of through-Delta mortality in the modeled population of winter-run Chinook salmon on the Sacramento River.

2. The OBAN model calculated the effect of the cumulative reduction in productivity on the abundance of winter-run over approximately 17 generations. Population abundance was reduced by approximately 1.5 times the level of the through-Delta mortality. For example, a 1% increase in through-Delta mortality resulted in a 1.7% average reduction in mean abundance.

Appendix A

Study Plan

Appendix A
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Background

The Oncorhynchus Bayesian Analysis (OBAN) model is a stage structured model that incorporates factors affecting early life stage survival (e.g., temperature and flow in the Sacramento River) and factors affecting Delta survival (e.g., exports, access to Yolo Bypass, etc.). The model tracks the abundances of juveniles through two freshwater stages to reflect the effects of these factors chronologically, tracks the subadults through the ocean, and tracks mature adults returning to spawn. The OBAN model was fit to historical data to reflect the population dynamics of winter-run Chinook salmon in the Sacramento River. The approach to fitting used a Bayesian statistical framework to evaluate the strength of each environmental driver on the freshwater survival of juvenile winter-run Chinook, and to account for uncertainty in the parameter estimates in the OBAN model.

Approach

To evaluate the role of hypothetical additional Delta mortality on the overall survival of winter-run Chinook, a counterfactual analysis can be performed with the OBAN model. The approach would increase the mortality of juvenile Chinook through the Delta by several hypothesized levels (0-10%). The OBAN model would then be run for the historical period under each of the mortality levels to evaluate how the population abundance would have changed over the model period.

Metrics

- **Absolute:** This evaluation can compute the annual spawner abundances and the juvenile life stage abundances under the baseline condition and under each of the hypothesized Delta mortality levels. This metric provides an estimate of abundance that can be compared to abundance viability criteria persistence (2,500 adults) in addition to calculating the cohort replacement rate (CRR) under each of the hypothesized mortality levels. Care should be taken in interpreting the results due to the results being sensitive to the specifics of the time-period being modeled, such as the initial abundance of the population and the specific ordering of the wet and dry water year types in the historical period.

- **Relative:** A slightly more robust metric is the relative abundance of the annual spawner abundances and the juvenile life stage abundances. Under this metric, the change in the abundances is compared to the baseline. This metric is less sensitive to the initial abundances of the population but still sensitive to the specific ordering of the wet and dry years.

Appendix B

Model and Scenario Descriptions

Appendix B – Model and Scenario Descriptions

Model Description

The winter-run Chinook salmon Oncorhynchus Bayesian Analysis (OBAN) model uses statistical approaches to understand how a series of environmental driver variables (e.g., temperature and flow) that are under management control may affect winter-run Chinook salmon population dynamics. The model was developed by first determining which of a suite of parameters (e.g., water temperature, harvest, exports, striped bass abundance, and offshore upwelling) covaried with historical abundance data. The OBAN model incorporates uncertainty by estimating the influence of covariates on population abundance in a Bayesian estimation framework. The set of covariates that provided the best model fit were then retained for the predictive model. The OBAN model can be used to evaluate how hypothetical changes to management can affect the population of winter-run Chinook in the Sacramento River.

The OBAN model uses values of the covariates to predict patterns in winter-run Chinook salmon population dynamics. Furthermore, uncertainty in the predicted winter-run abundance is then incorporated into model output through Monte Carlo simulations (1,000 simulations per model run). Under a counterfactual analysis the alternatives can be compared in terms of the population abundance. The alternatives can also be compared to a baseline condition to provide inference on the relative performance of the alternatives to the baseline, which is a more robust approach for evaluating alternatives than absolute prediction.

Specifically, the OBAN model:

- Accounts for mortality during all phases of the winter-run Chinook salmon life history, including environmental and anthropogenic factors;
- Evaluates covariates that may explain dynamic vital rates (e.g., thermal mortality reduces alevin survival rates in spawning reaches);
- Estimates model coefficients by fitting predictions of the population dynamics model to observed indices of abundance in a Bayesian framework

The OBAN model is composed of several life history stages:

- Alevin – incubation in the gravel below Keswick Dam
- Fry – rearing above Red Bluff Diversion Dam (RBDD)
- Delta – from RBDD to Chipps Island
- Bay – from Chipps Island to the Golden Gate

- Gulf – Gulf of Farallones
- Ocean 1 – first year in the ocean, return to spawn as 2-year olds
- Ocean 2 – second year in the ocean, return to spawn as 3-year olds
- Ocean 3 – third and final year in the ocean, return to spawn as 4-year olds
- Escapement – composed of all spawners on the spawning ground

General OBAN Model Structure

The OBAN model was developed from the conceptual life-cycle model of winter run Chinook salmon, and it uses a Bayesian statistical estimation algorithm to find a statistical "best fit" to empirical trends by matching model predictions to empirically observed juvenile and adult abundances. The model is capable of fitting any number of abundance data sources and estimating any number of coefficient values to find the best statistical prediction.

The transition between life history stages occurs with a Beverton-Holt recruitment function:

$$\boldsymbol{N_{j+1} = N_j \times \frac{p_j}{1 + \frac{p_j N_j}{K_j}}}$$

where N_j is the abundance at life stage j, p_j is the productivity in the absence of density dependence for life stage j, K_j is the capacity at life stage j. The two parameters of the Beverton-Holt transition equation are p_j and K_j , and they can be user defined constants, estimated parameters fixed across all years, or dynamic, i.e., $p_{j,t}$ and $K_{j,t}$ can be modeled as changing in each year t. Note that density dependence can be effectively removed from the formulation by setting K_j to a very large value.

In the case of dynamic productivity ($p_{j,t}$) and dynamic capacity ($K_{j,t}$), parameter values, the values of the productivities and capacities in a given year can be modeled from a set of time-varying covariates. By using this formulation, the influence of anthropogenic and environmental factors on specific life history stages can be incorporated into both the productivity and capacity terms.

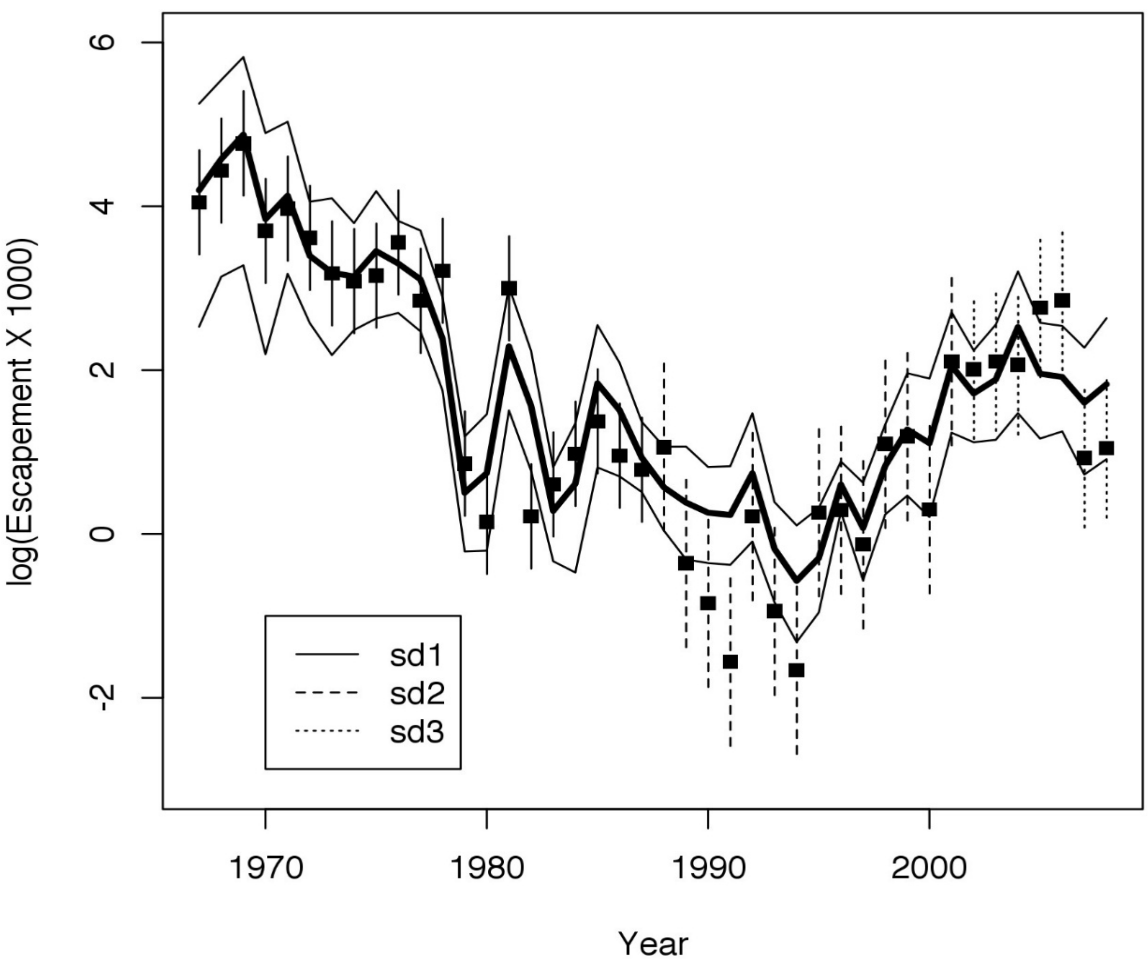
Each productivity parameter (survival in the OBAN model) can be influenced by independent covariates acting simultaneously on the life history stage to drive demographic rates. The dynamic productivities used a logit transformation, which caused the productivities to remain between 0 and 1. This interval is the sample space for the survival for all stages from alevin to spawner:

$$\text{logit}(\boldsymbol{p_{j,t}}) = \boldsymbol{\beta_{0,j} + \beta_{1,j}X_{1,t} + \beta_{2,j}X_{2,t} + \cdots + \beta_{5,j}X_{5,t}}$$

The dynamic capacities used a natural log transformation, which caused the capacities to remain between 0 and infinity. This interval is the sample space for the abundance for all stages from alevin to spawner:

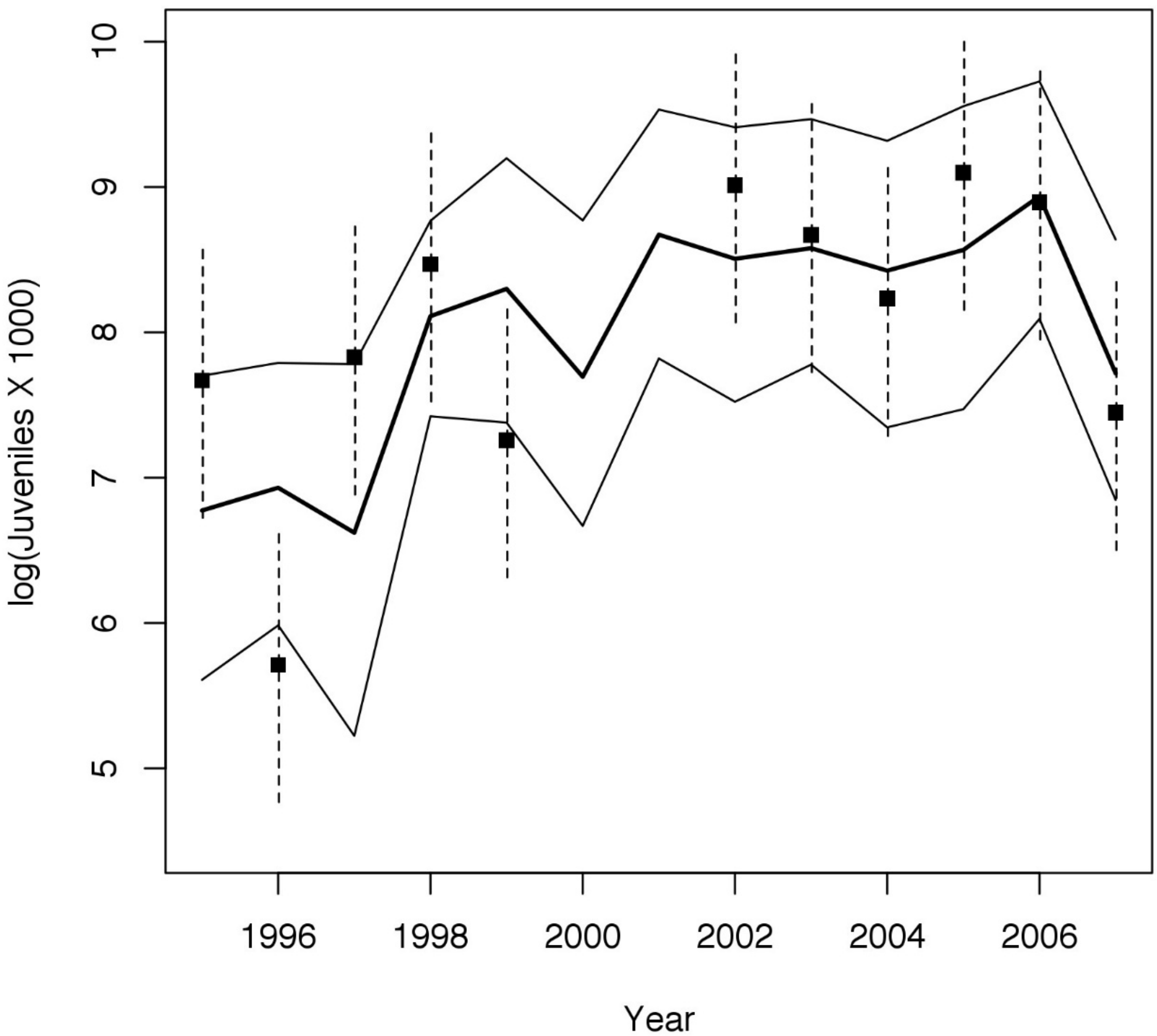
$$\ln(K_{j,t}) = \beta_{0,j} + \beta_{1,j}X_{1,t} + \beta_{2,j}X_{2,t} + \cdots + \beta_{5,j}X_{5,t}$$

The estimation of *pj,t* and *Kj,t* involves estimating the coefficients on the right hand sides of the equations (the β terms in the equation). The X1:5,t are environmental covariates that represent water conditions such as temperature or flow, biotic factors such as predator abundance, food abundance, or anthropogenic factors such as water export levels or harvest rates. The model has the ability to estimate as few or as many of the parameters as desired, and covariates were incorporated into the OBAN model based on their ability to explain historical patterns in winter-run escapement (Figure B-1) and juvenile abundance data at RBDD (Figure B-2).



Note: Observed escapement (squares) under three different sampling designs with one standard deviation of measurement error (sd 1, sd 2, sd3) in vertical lines

Figure B1. Median OBAN Model Predictions of Escapement (dark line) and 95% Credible Intervals (thin line)



Note: Observed juvenile fry abundance (squares) and one standard deviation in measurement error (vertical lines).

Figure B2. Median OBAN Model Predictions of Red Bluff Diversion Dam Fry Juvenile Abundance (dark line) and 95% Credible Intervals (thin line).

Covariates

The following covariates were retained in the model and their coefficients were estimated:

- *TEMP*: July through September mean daily water temperature in the Sacramento River at Bend Bridge. This covariate affects survival of the alevin life history stage.

- *FLMIN*: August through November minimum monthly flow (cubic feet per second (cfs)) in the Sacramento River at Bend Bridge (USGS Gauge 11377100 data). This covariate affects survival of the fry life history stage.

- *EXPT*: Total water exports in the south Delta (CVP and SWP) during December through June, derived by taking average daily export rate (cfs), multiplying by the number of days in the month, and then summing over December-June (IEP Dayflow data). This covariate affects survival in the Delta life history stage.

- *YOLO*: Number of days during December through March (December of the brood year and January – March of the year following) with flows at Verona greater than 56,000 cfs (the flow required to initiate flooding in the Yolo Bypass). This covariate affects survival in the Delta life history stage.

- *DCC*: Proportion of time that the Delta Cross Channel gates were open between December and March (December of the brood year and January – March of the year following) (US Bureau of Reclamation data). This covariate affects survival in the Delta life history stage.

- *UPW* and *FARA* - *ocean productivity indexes*. Nearshore ocean processes can have important consequences for Chinook salmon (Wells et al. 2007, Woodson et al. 2013), and here we use upwelling from April to June in a region south of the entrance to San Francisco Bay, *UPW* (Station 36 N 122 W Pacific Fisheries Environmental Laboratory https://oceanview.pfeg.noaa.gov/products/upwelling/dnld) and the mean sea surface temperature from February to April in the Gulf of the Farallones, *FARA* (Gulf of Farallons sea surface temperature data - NOAA buoy 46026 18 NM west of San Francisco, 37.750 N 122.838 W, https://www.ndbc.noaa.gov/station_history.php?station=46026).

- *Harvest*: Ocean harvest of Ocean 2 and Ocean 3 individuals (Ocean 1 are assumed to be too small to be vulnerable to the fishery) as the proportion of the total Ocean 2 and Ocean 3 individuals available for harvest. The harvest rate index was constructed by using the California Department of Fish and Wildlife ocean and recreational fishing regulations. Until 1987, there was little regulation of the Central Valley Chinook fishery and estimates of the mortality rate on winter-run Chinook in the ocean fishery was approximately 0.7 of the mortality rate experienced by fall-run Chinook. The harvest rate of fall-run Chinook is estimated annually as the Central Valley Index (CVI) by calculating the proportion of the fall run that were captured in the fishery versus those that escaped the fishery and returned back to the rivers (harvested/(harvested + escaped). In 1989, winter-run Chinook salmon were listed as threatened and the following year the ocean fishery regulations were shifted to open two weeks later (NMFS 1997). It was assumed that this had an effect on the winter-run harvest mortality and reduced the impact to 0.5 of the CVI. In 1994, winter-run were reclassified as endangered and, in 1997, a biological opinion was released by NMFS (1997) initiating a delayed opening of the ocean fishery from mid-March to mid-April and eventually to late April in 2001. Using coded wire tagged winter run from 1998 through 2000 cohorts, Grover et al. (2004) estimated ocean harvest rates of 0.22. The effect of the fishery is not the same for Ocean 2 and Ocean 3 stages, however. The rates described above were generated for the Ocean 2 stage. Ocean 2 and Ocean 3 fish are not captured at the same rate. Most winter-run Chinook return to spawn as three-year olds (after the Ocean 2 phase); however, the Ocean 3 stages are more likely to be captured in the commercial fishery due to their larger size. Grover et al. (2004) found that the harvest related mortality of Ocean 3 winter run Chinook was 2.5 to 3.7 times the rate of Ocean 2 winter run. For OBAN, it assumed that the harvest rates experienced by Ocean 3 stage winter run were 2.7 times the harvest rates experienced by Ocean 2 stage. In order to make sure that the harvest rate could not surpass 1, a logistic regression approach was used to incorporate the harvest rates.

Harvest also occurs in the Sacramento River, and the best available published rates were used. Between 1967 and 1975, estimates of winter-run harvest in the recreational river fishery varied from 0.04 to 0.14 (Hallock and Fisher 1985). For OBAN, it was assumed that the in-river fishery harvest rates were 0.09 from 1975 to 1982, which was the average of the Hallock and Fisher (1985) estimates. NMFS (1997) published in-river harvest rates from 1983 to 1990 that varied between 0.013 and 0.087. For OBAN, it was assumed that the in-river harvest was constant at 0.05 from 1991 to 2007. The 0.05 river harvest rate was used in combination with the 0.22 ocean harvest rate to equal the average harvest impact rate identified by Grover et al. (2004) for the 1998, 1999, and 2000 cohorts.

Scenario Development and Descriptions

The OBAN analysis incorporates uncertainty in the predicted response of winter-run Chinook salmon to each scenario. The estimation phase of the OBAN model generates samples from the posterior distribution of parameters that relate physical covariates to survival rates. Monte Carlo simulation is used to run the OBAN analysis phase for each of the 1,000 samples to incorporate parameter uncertainty.

To simulate winter-run Chinook salmon population dynamics under each scenario, covariate data were used for the model period 1970 – 2020. All covariates were normalized by subtracting the mean and dividing by the standard deviation of empirical data that were used in the estimation of the OBAN model coefficients (values for standardization of freshwater covariates provided in Table B-1).

Table B-1. Measured Physical Freshwater and Marine Covariates Used in the Calibration of the Winter-run Chinook Salmon OBAN Model

Covariate	Mean	Standard Deviation
STEMP (°C)	14.26	1.29
FLMIN (cfs)	6,534	1,504
EXPT (cfs)	1,250,000	320,900
YOLO (days)	22.88	24.74
DCC	0.46	0.42
FARA (°C)	11.83	0.89
UPW (unit?)	210.5	49.85

Key:
°C = degrees Celsius
cfs = cubic feet per second
DCC = Proportion of time that the Delta Cross Channel gates were open between December and March
EXPT = Total water exports at the CVP and SWP during December through June
FARA = Sea surface temperature in the Gulf of the Farallones between February and April
FLMIN = August through November minimum monthly flow
STEMP = Mean daily water temperature in the Sacramento River at Bend Bridge in July through September
UPW = Upwelling in a region south of the entrance to San Francisco Bay (m3/s/100 m of coastline)
YOLO = Number of days during December through March with flows at Verona greater than 56,000 cfs

Five scenarios were developed for analysis, each differing in the level of through-Delta survival (Baseline, 1%, 2.5%, 5%, 7.5%, 10%). All of the scenarios were developed in the same manner and only differed in the level of mortality applied.

The outputs of the OBAN analysis are the performance metrics of each scenario both in absolute terms and relative to the Baseline. Because each iteration of the 1,000 Monte Carlo simulation uses the same set of parameter values, the OBAN effects analysis generates the performance of each scenario despite incorporating parameter uncertainty. Performance metrics are calculated as the relative increase or decrease compared to the Baseline; thus, there are 1,000 values of the relative performance metrics that are summarized using point estimates (e.g., median or mean) and ranges (e.g., 95% confidence interval) of the metrics.

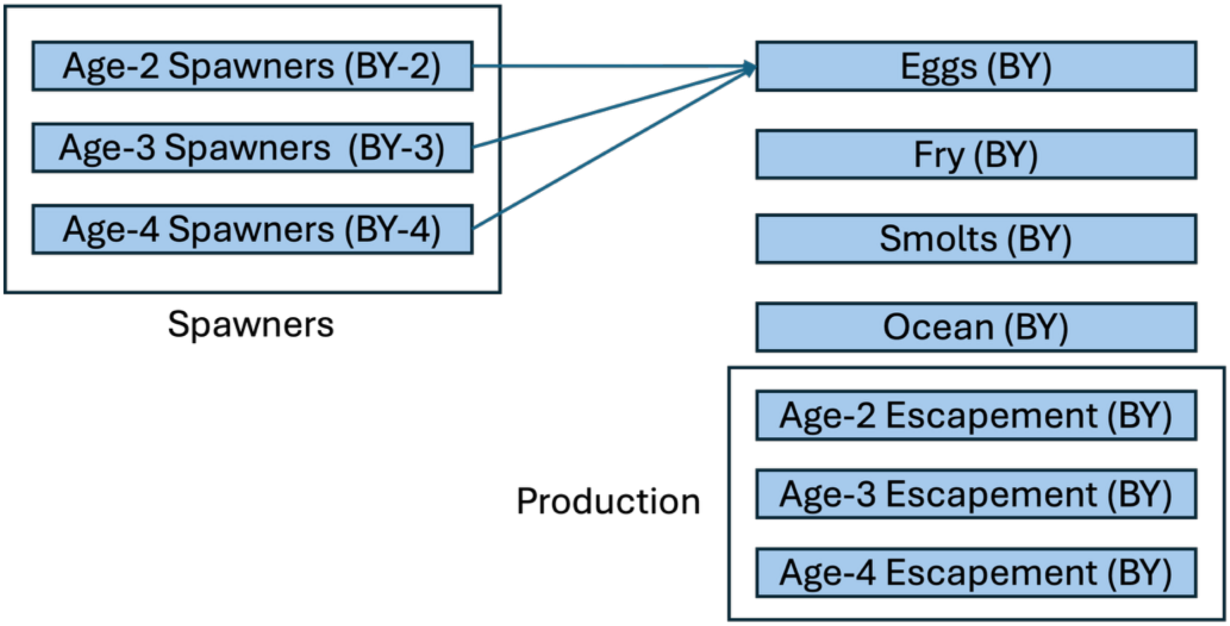
Metrics

Productivity and abundance metrics were calculated to evaluate the through-Delta scenarios.

Productivity Metrics

Cohort Replacement Rate

The cohort replacement rate (CRR) evaluates the productivity of natural-origin winter-run Chinook salmon; that is, the production that occurred from the part of the population spawning in the Sacramento River (Figure B-3. The Spawners in Figure 4 can be both natural origin and hatchery origin that spawn in the Sacramento River. The Production for brood year (BY) by those Spawners creates eggs that ultimately return as age-2, age-3, and age-4 Escapement. The CRR is the ratio of Production/Spawners.



Note: Spawning by hatchery and natural origin winter-run Chinook in the river (Spawners) in brood year (BY) produce eggs, fry, that return as escapement at age-2, age-3, and age-4 (Production)

Figure B3. Schematic of the Cohort Replacement Rate

The CRR for brood year y was calculated as a function of the females (as they are the ones producing eggs) using the following equation (subscript for simulation *s* is suppressed):

$$CRR_y = \frac{\sum_a Esc_{f,a,y+a}}{\sum_a Sp_{f,n,a,y} + Sp_{f,h,a,y}}$$

where $Esc_{f,a,y+a}$ is the female escapement of females from brood year y that returned at age a in calendar year $t = y + a$, $Sp_{f,n,a,y}$ is the female spawners of age a in brood year y of natural origin and $Sp_{f,h,a,y}$ is the female spawners of age a in brood year y of hatchery origin. The average CRR over model years t = 5:50 are used as the viability metric for productivity for each simulation s, calculated as:

$$CRR_s = 1/22 \times \sum_{y=5}^{50} CRR_{y,s}$$

The first viability metric (VM) for productivity was the average cohort replacement rate for model years t = 5 to 50:

$$VM_{P1} = CRR_s$$

Percent Difference in Cohort Replacement Rate

The percentage difference in the CRR for the scenario relative to the baseline was also calculated. The percentage difference was calculated as:

$$VM_{A2} = \frac{CRR_{scenario,s} - CRR_{base,s}}{CRR_{base,s}} \times 100\%$$

Similarly, the mean and 95% central interval (0.025 and 0.975 quantiles) were calculated across simulations to summarize the viability metric.

Abundance Metrics

The natural origin escapement, which is defined as the sum of all male and females that are 2-year, 3-year, and 4-year fish that were spawned in the river (their parents may have been natural or hatchery origin) was used to calculate the abundance metric.

Average Abundance in Final 10 Years

The average natural origin escapement from the last 10 years of the modeled period (42 to 51) was the first abundance viability metric. Because winter-run Chinook salmon predominantly return at age-3, the 10-year average represents approximately 3 years of returns from each of the underlying 3 components, calculated as:

$$N10_s = 1/10 \times \sum_{17}^{50} \sum_{a=2}^{4} Esc_{m:f,n,a,t,s}$$

where *Esc m:f,n,a,t,s* is the male and female escapement of natural origin of age *a* in model year *t* and simulation *s*. The first viability metric for abundance was the 10-year average natural origin escapement as calculated:

$$VM_{A1} = N10_s$$

The mean and 95% central interval (0.025 and 0.975 quantiles) was calculated across simulations to summarize the viability metric.

Percent Difference in 10-Year Average Abundance

The percent difference in the average abundance of the final 10 years of the model run was also calculated for the scenario relative to the baseline. The percent difference was calculated as:

$$VM_{A2} = \frac{N10_{scenario,s} - N10_{base,s}}{N10_{base,s}} \times 100\%$$

Similarly, the mean and 95% central interval (0.025 and 0.975 quantiles) was calculated across simulations to summarize the viability metric.

Probability that 10-Year Abundance is Below Baseline Mean

The probability that the average abundance in the simulations under each scenario will be below the global average abundance in the Baseline (averaged over simulations) to evaluate the probability that the Scenario abundance would be below the mean Baseline abundance, calculated as:

$$\Pr\left(N10_{scenario} < \overline{N10}_{baseline}\right) = \sum_{s=1}^{1000} I(N\,10_{scenario,s} < \frac{N10_{baseline,s}}{1000})$$

where the bar indicates that it is the global average of the 10-year mean abundance of the baseline scenario.

$$M_{A3} = Pr(N10_{scenario} < \overline{N10}_{baseline})$$

3-year Sum of Escapement

The final abundance viability metric is the three-year sum of fish returning to spawn relative to a threshold. Lindley et al. (2007) identified a moderate risk of extinction occurring if the three-year sum of abundance is less than 2,500, thus that threshold was used here. The three-year sum for calendar year t is computed as the sum of all fish of natural origin escaping between years *t-2* and *t* (subscript for simulation s suppressed):

$$N3_t = \sum_{t-2}^{t} \sum_{a=2}^{4} Es\,c_{m:f,n,a,t}$$

The viability metric compares this quantity $N3_t$ to a value of 2,500 (Lindley et al. 2007). For the purposes of this analysis, an indicator function *I*( ), which returns a value of 1 if the expression in the parenthesis is true, and a 0 if the expression is false was used. For the 26-year time series of escapements, the rolling three-year sum for 48 of these years (model years 1973 to 2020) was calculated. The indicator function to identify whether the three-year rolling natural origin abundance was below the 2,500 threshold was used. The quantity was calculated for each of the s = 1,000 simulations.

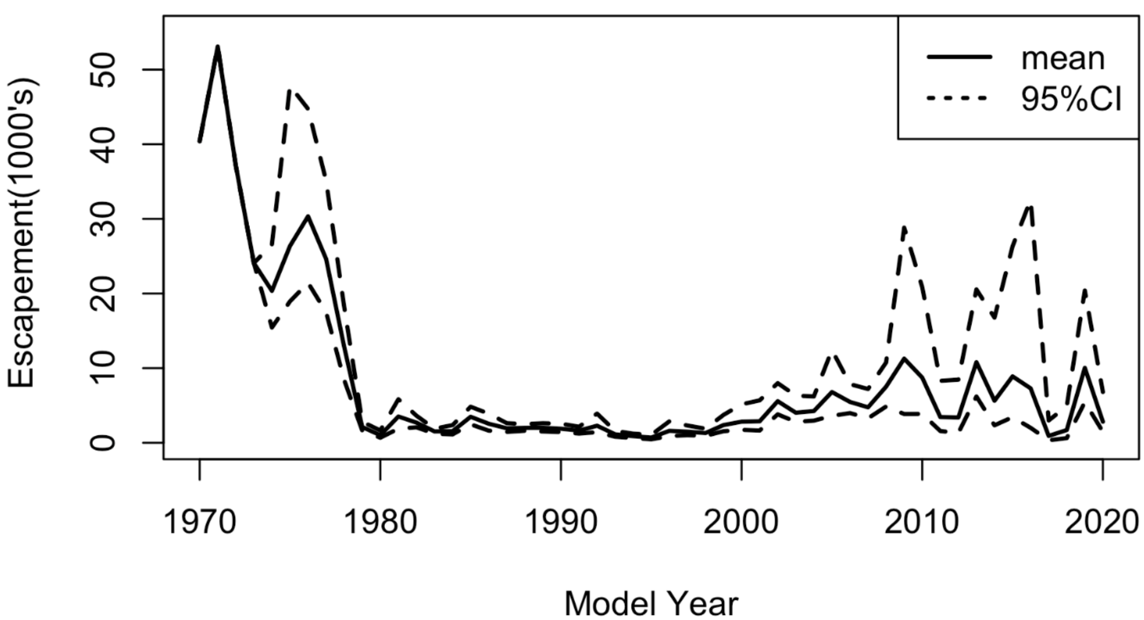
$$T2500_{t=3:26,s} = \sum_{t=3}^{26} I((N\,3_t, s) < 2500)$$

The viability metric was the proportion of scenarios in which the natural origin escapement falls below the 2,500 threshold in one or more years.

$$VM_{A4} = 1/1000 \times \sum_{s=1}^{1000} I(T\,2500_{t=3:26,s} > 0)$$

Additional Figures

Figure B-4 is included to support the OBAN analysis. The baseline model run indicated an initial drop in modeled winter-run abundance from the early 1970's to a low level in the early 1980's and a subsequent increase in abundance through the mid-2010's (Figure B-4).



Note: Mean and 95% intervals are plotted

Figure B4. OBAN Modeled Abundance of Winter-Run Chinook Salmon from 1970 to 2020 under Observed Historical Covariate Values

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