Technical Memorandum

Long-Term Operation of the Central Valley Project and State Water Project

Winter-Run Life Cycle Model Sensitivity Analyses on Delta Mortality

Introduction

The Winter-run Life-Cycle Model (WRLCM) is a stage-structured, spatially explicit life cycle model that reflects the population dynamics of winter-run Chinook salmon in the Sacramento River, California. The objectives of this modeling study were to provide an understanding of how the 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, revisions were made to the analysis that were not included in the Study Plan.

Methods

The WRLCM includes several habitats for each of the life history stages of spawning, rearing, smoltification (physiological and behavioral process of preparing for seaward migration as a smolt), outmigration, and ocean residency. The WRLCM uses discrete geographic regions of Upper River, Lower River, Floodplain, Delta, Bay, and Ocean to track juveniles and subadults through their life cycle (Appendix B Figure 1). In the Delta, juvenile survival is calculated by an enhanced particle tracking model (ePTM), which runs on a 15-minute time step using DSM2 hydrology and a fish behavioral model. Those results are integrated across the monthly freshwater time step of the WRLCM to provide survival estimates of smolts originating in the River, Delta, and Floodplain habitats. The WRLCM has been calibrated to adult and juvenile indices of abundance from 1995 to 2020 through a statistical fitting approach that incorporates the survival calculations from the ePTM as well as other sub-models (Hendrix et al. 2024, Appendix B p. 4).

To evaluate the effect of additional Delta mortality on the population dynamics of winter-run Chinook salmon, a counterfactual analysis can be performed with the WRLCM model. A counterfactual approach uses a baseline historical run using observed environmental conditions and then modifies some aspect of the dynamics to evaluate what could have happened if the conditions had been different. A counterfactual approach was used with the WRLCM over its calibration period 1995 – 2020. To evaluate the effect of additional Delta mortality, the mortality of juvenile Chinook through the Delta was increased by several hypothesized levels over the range (0 - 10%) on top of the estimated ePTM survivals in the Delta. The WRLCM model was then run for the 1995 – 2020 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. Abundance metrics were based on natural origin production only (adults produced from spawning in the Sacramento River) and based on natural and hatchery production (adults produced from artificial spawning in the hatchery and released as smolts). Additional details are provided in Appendix B.

Six different scenarios were developed for this analysis, which differed 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.

A detailed description of the WRLCM model and how it was modified for this study are included in Appendix B.

Results

The WRLCM was used to calculate the escapement abundance across the modeled time series of 1995 to 2020 under each of the through-Delta mortality scenarios. For illustration, the trend in modeled escapement was generated under the 10% mortality scenario as a bookend on the population response (Figure 1). The Scenario 10% diverged from the baseline after the first four years, due to the Baseline and all Scenarios using the same values to initiate the WRLCM in the first four years of the simulations. The spread between the trajectory of the Scenario 10% and the Baseline tended to increase over the modeled time period due to the cumulative effects of reduced cohort survival in the Scenario 10% relative to the Baseline (Figure 1 – compare 2003 to 2019). Due to variation in the hydrologic conditions, there are years where differences between Baseline and the five mortality scenarios are compressed, however. For example, escapement in 2017 is similar in the Baseline and Scenario 10% due to low levels of escapement from the 2014 brood year, which was a critical dry year (Figure 1).

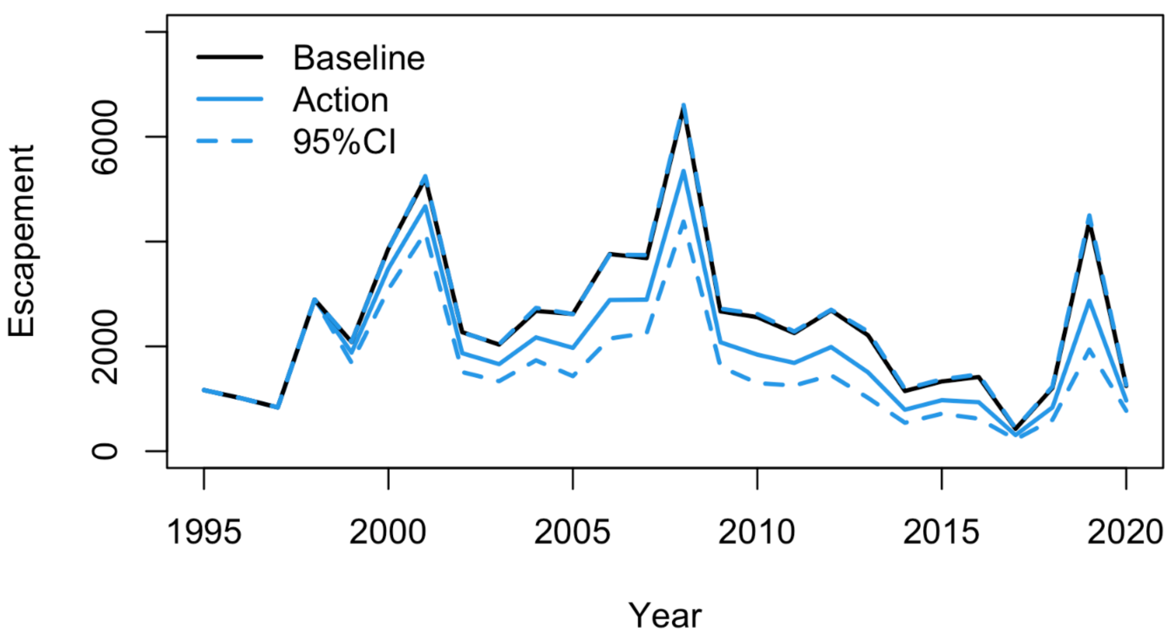

Figure 1. Baseline Mean Escapement and Scenario 10% Mean Abundance (line) and 95% Central Interval (dashed line) over the Modeled Period of 1995 – 2020

The productivity metrics provided information on how the individual cohorts were affected by the additional through-Delta mortality. The natural origin winter-run Chinook salmon population was not productive from 1995 to 2020, and the average cohort replacement rate (CRR) was less than 1.0 under the baseline (Table 1). Average CRR values of 1.0 or greater are necessary for the population to sustain itself. The additional mortality in through-Delta survival decreased productivity, and the effect on CRR was an approximately equivalent level of reduction relative to Baseline. For example, Scenario 1% resulted in an approximately 0.9% reduction in CRR relative to Baseline (Table 1). Likewise, Scenario 5% had a reduction of 4.6% on average 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	0.827 (0.745, 0.912)	NA
Scenario 1%	0.819 (0.738, 0.904)	-0.9% (-0.9, -0.9)
Scenario 2.5%	0.808 (0.727, 0.892)	-2.3% (-2.4, -2.2)
Scenario 5.0%	0.789 (0.709, 0.872)	-4.6% (-4.8, -4.5)
Scenario 7.5%	0.769 (0.691, 0.851)	-7.0% (-7.2, -6.7)
Scenario 10.0%	0.75 (0.673, 0.830)	-9.4% (-9.6, -9.0)

Key: CI = Central Interval CRR = Cohort Replacement Rate

The abundance metrics provided information on the cumulative effects of the scenarios over the modeled 1995 – 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 1,879 male and female spawners (Table 2). 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 percentage 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 Baseline and Scenario 1% was 3.5%. In general, the mean abundance was reduced by approximately three 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 0.17 (Table 2). Increasing the through-Delta mortality caused this viability metric to increase. At the highest level of through-Delta mortality, the probability that winter-run natural origin spawners would fall to below 2,500 in at least one year was 0.81.

Finally, the probability that the 10-year average abundance would be below the 10-year average abundance observed in the baseline (1,879) indicated an increasing trend with higher through-Delta mortality. The abundance under Scenario 1% through-Delta mortality had a 0.61 probability of being lower than the Baseline, whereas the abundance under Scenario 10% through-Delta mortality had a 0.97 probability of being below Baseline. The result under Scenario 10% is consistent with the trends in abundance depicted in Figure 1.

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 < 2,500)[b]	Probability (Scenario < Baseline[c])
Baseline	1879 (1258, 2767)	NA	0.17	NA
Scenario 1%	1813 (1219, 2663)	-3.5% (-3.8, -3.1)	0.22	0.61
Scenario 2.5%	1719 (1163, 2513)	-8.4% (-9.2, -7.6)	0.31	0.71
Scenario 5.0%	1572 (1075, 2282)	-16.2% (-17.5, -14.6)	0.49	0.84
Scenario 7.5%	1438 (993, 2069)	-23.3% (-25.2, -21.1)	0.66	0.93
Scenario 10.0%	1315 (918, 1876)	-29.8% (-32.2, -27.1)	0.81	0.97

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 (1,879).

Key:

CI = Central Interval

NA = not applicable

Discussion

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. As a result, this analysis represents a type of sensitivity analysis of the WRLCM to through-Delta survival. Cohort productivity, as indicated by the CRR, decreased at a rate roughly equivalent to the through-Delta mortality. This result occurred due to the largely linear model structure for all life stages after the Delta in the WRLCM. In contrast, the abundance-related metrics reflected the cumulative effects of the through-Delta mortality over multiple cohorts. This analysis indicated a greater impact on abundance metrics than productivity metrics. Abundance of the winter-run population was reduced by approximately three times the level of the through-Delta mortality. For example, a 1% increase in through-Delta mortality resulted in a 3.5% average reduction in abundance, when comparing Scenario 1% to Baseline. The abundance related metrics are dependent upon the length of the modeled time series and period over which the abundances were averaged, however. In the analysis presented here, the scenario-specific abundances reflected the effects of the through-Delta survival over approximately 5 generations (1999 start year and averaged over the final 10-year period 2011-2020).

There are some important caveats to this analysis. This application of the WRLCM assumed that all rearing locations and therefore outmigration routes would be equally impacted by the levels of through-Delta mortality. Depending upon the implementation of operations that would affect through-Delta survival, there are some outmigration routes that would be less affected (e.g., Yolo originating smolts). The 3-year rolling abundance metric was calculated on the natural origin escapement and did not include hatchery-origin fish. When hatchery-origin fish were included in the calculations (hatchery returns started in 2003), the probability of falling below the 2,500 moderate risk threshold was 0.0 across all scenarios (Appendix B).

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. Namely, if the operational scenarios can be reflected in CalSim and DSM2 hydrodynamic models outputs, both the ePTM (Sridharan et al. 2023) and the EcoPTM (Wang et al. 2024) run on the DSM2 hydrodynamic modeling platform, and they are capable of providing estimates of through-Delta survival at a monthly time-step. As we have shown here, the impacts of those operations on a specific cohort is approximately equivalent to the additional through-Delta mortality relative to a Baseline. To understand the cumulative effects on abundance, the WRLCM would incorporate the monthly survival estimates to evaluate the population level effects. The results of such an analysis would provide a more accurate estimate of the through-Delta mortality, and the cumulative population impacts under specific operational scenarios.

Key Findings

1. WRLCM results indicated that additional through-Delta mortality causes a decrease in productivity and abundance of the winter-run Chinook salmon population on the Sacramento River.

2. Productivity of the winter-run Chinook salmon population was reduced by approximately the level of mortality in through-Delta mortality. For example, a 1% increase in through-Delta mortality resulted in a 0.9% average reduction in the productivity metric (cohort replacement rate) relative to the baseline.

3. Abundance of the winter-run population was reduced by approximately three times the level of the through-Delta mortality. For example, a 1% increase in through-Delta mortality resulted in a 3.5% average reduction in abundance. The larger impact on the abundance metric was due to the cumulative effects of reducing the productivity of individual cohorts over time.

References

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Appendix A

Study Plan

Winter-Run Life Cycle Model Sensitivity Analyses on Delta Mortality

Appendix A
Study Plan

Background

The winter-run life-cycle model (WRLCM) is structured spatially to include several habitats for each of the life history stages of spawning, rearing, smoltification (physiological and behavioral process of preparing for seaward migration as a smolt), outmigration, and ocean residency. The WRLCM uses discrete geographic regions of Upper River, Lower River, Floodplain, Delta, Bay, and Ocean to track juveniles and subadults through their life cycle. The life-history stages are represented within the WRLCM by using developmental stages of eggs, fry, smolts, ocean sub-adults, and mature adults (spawners). In the Delta, juvenile survival is reflected in the enhanced particle tracking model (ePTM), which runs on a 15-minute time step using DSM2 hydrology and a fish behavioral model; those results are integrated across the monthly freshwater time step of the WRLCM to provide survival estimates of smolts originating in the River, Delta, and Floodplain habitats. The WRLCM has been calibrated to adult and juvenile indices of abundance from 1995 to 2020 through a statistical fitting approach.

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 WRLCM model. The approach would increase the mortality of juvenile Chinook through the Delta by several hypothesized levels (0-10%) on top of the estimated ePTM survivals in the Delta. The WRLCM 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 are 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

Winter-Run Life Cycle Model Sensitivity Analyses on Delta Mortality

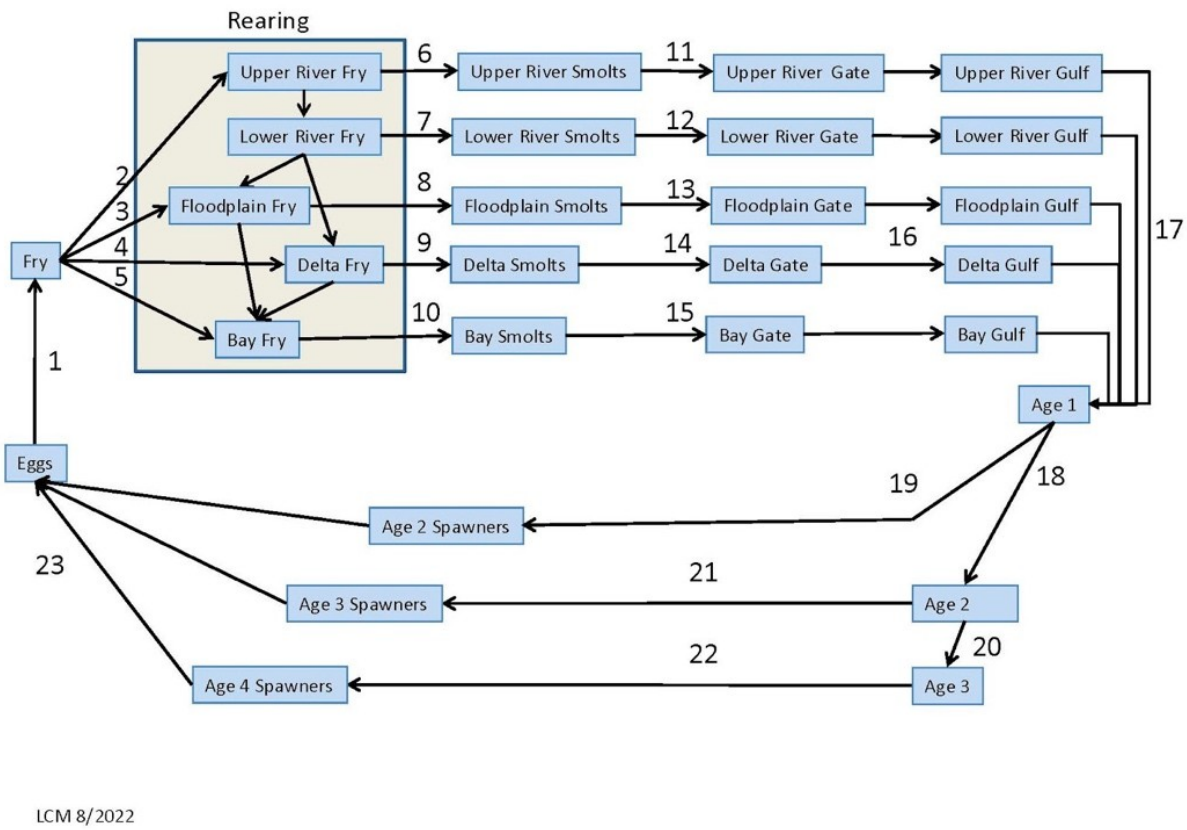
Appendix B
Model and Scenario Descriptions

Model Description

The Winter-Run Life Cycle Model (WRLCM) model description follows closely with the description provided in Hendrix et al. (2024) with several important exceptions. To simplify the life stage dynamics, a tidal fry component to the life cycle was not modeled. Few data are available on this life stage making parameterization of the tidal fry survival and movement rates difficult. As a result, the tidal fry dynamics were largely defined by expert opinion in Hendrix et al. (2024). Furthermore, it was assumed that only a small portion of the population (0.05) utilized this life history variant, thus the winter-run Chinook salmon population dynamics on a whole are relatively insensitive to the dynamics of this stage.

The egg- to-fry survival uses the results of a temperature-dependent mortality model (Martin et al. 2017) to reflect monthly exposure of eggs to thermal mortality. The smolt survival model uses an enhanced particle tracking model (ePTM) that tracks the fate of juvenile salmon through the Delta by using a hydrodynamic model (DSM2) and intelligent agents to navigate the Delta (Sridharan et al. 2023). The ePTM model runs under historical conditions to provide a monthly estimate of survival for fish originating from the Sacramento River, the Yolo Bypass, and the Delta that is incorporated into the smolt outmigration survival in the WRLCM.

For the remaining life history stages, the WRLCM is similar in form to that specified in Hendrix et al. (2024). The interested reader can find more details in Hendrix et al. (2024) and Osterback et al. (in Press). The WRLCM is composed of a set of states that are defined by life stage and geographic location and a set of transitions among the states (Figure B1).



Note: The number represents a transition equation by which survival and movement among geographic areas of life stages are defined by mathematical equations. Each box represents a state, and each arrow is a transition between states.

Figure B1. Transition Stages for the Winter-run Chinook Salmon Life Cycle Model

The WRLCM is linked to several sub-models that supply inputs to the overall dynamics, which include physical data of flow, temperature, and modeled outputs such as habitat capacity and smolt survival (Figure B2). Each of these sub-models is further defined in Hendrix et al. (2024), but the enhanced particle tracking model is described in more detail here due to its importance in modeling through-Delta survival.

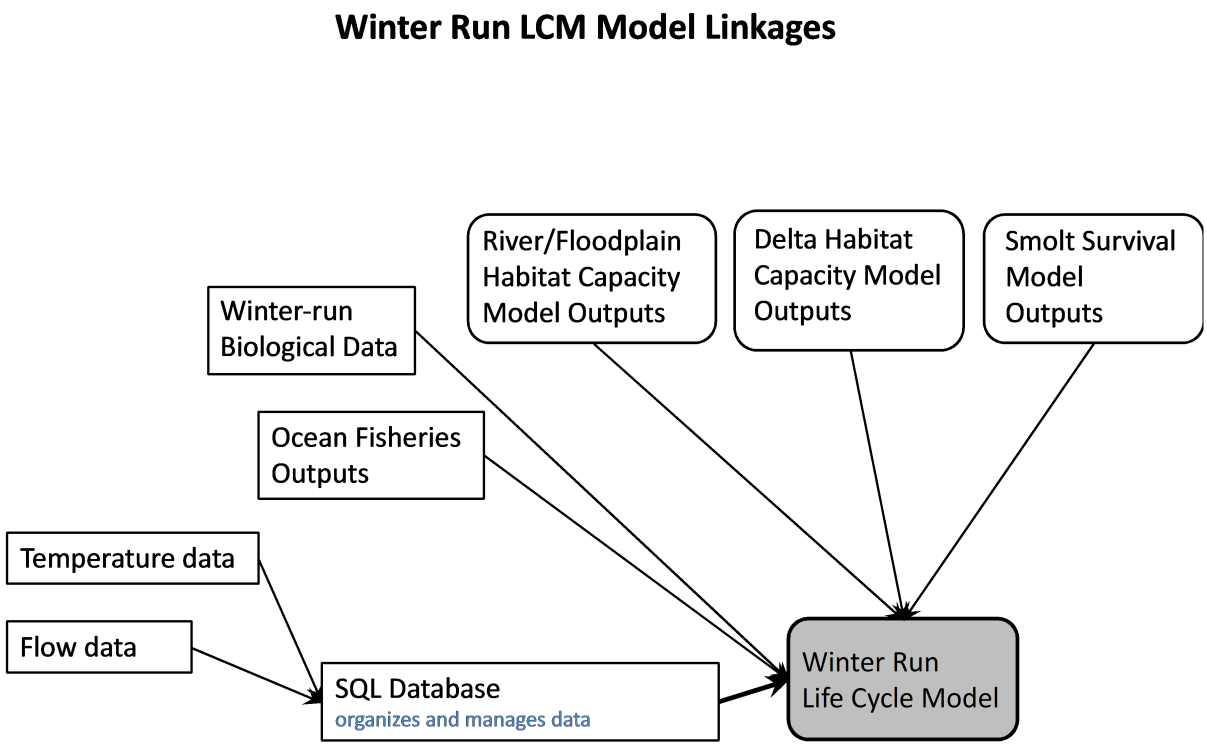


Figure B2. Data and Submodels that Support and Provide Physical Drivers and Parameters that Feed into the Life Cycle Model

Enhanced Particle Tracking Model for Smolt Survival

The ePTM is an individual-based model of routing, travel time, and survival of Chinook salmon smolts outmigrating through the Delta to the ocean. It simulates the movement of individual fish through the Delta's complex channel network using a combination of advection, diffusion, active swimming behaviors, and flow-based routing at channel junctions. Mortality is modeled as a function of both travel time and distance following the functional form of the XT Mean Free-path Length model (Anderson et al. 2005) but parameterized at the scale of the ePTM's 15-minute time step.

The ePTM is an extension of the original particle tracking model (PTM) developed by the California Department of Water Resources as part of the Delta Simulation Model 2 (DSM2) software suite3. In DSM2, the Delta is represented by a network of 1D channels connected at nodes. The original PTM simulated passive, neutrally buoyant particles using random walk movement in a quasi-3D flow field derived from the 1D flows provided by the DSM2 HYDRO module, with advection dominating in the streamwise direction and diffusion in the cross-stream and vertical directions.

The ePTM adds active swimming in the streamwise direction, with swimming speed and direction (with or against the prevailing flow) varying spatially within the Delta. Additional behaviors include selective tidal stream transport and a probabilistic orientation oceanward or landward depending on the relative strengths of the tidal and net flows. In lieu of the original PTM's flow-split routing model, which routes fish at junctions (nodes) according to the proportion of outflow in the channels, the ePTM uses a bifurcating streamline algorithm that routes fish according to their position relative to the streamlines that divide flow entering the alternative channels. Fish behaviors and the parameters of the mortality model were calibrated using acoustic telemetry data from late fall-run Chinook salmon smolts (Sridharan et al. 2023).

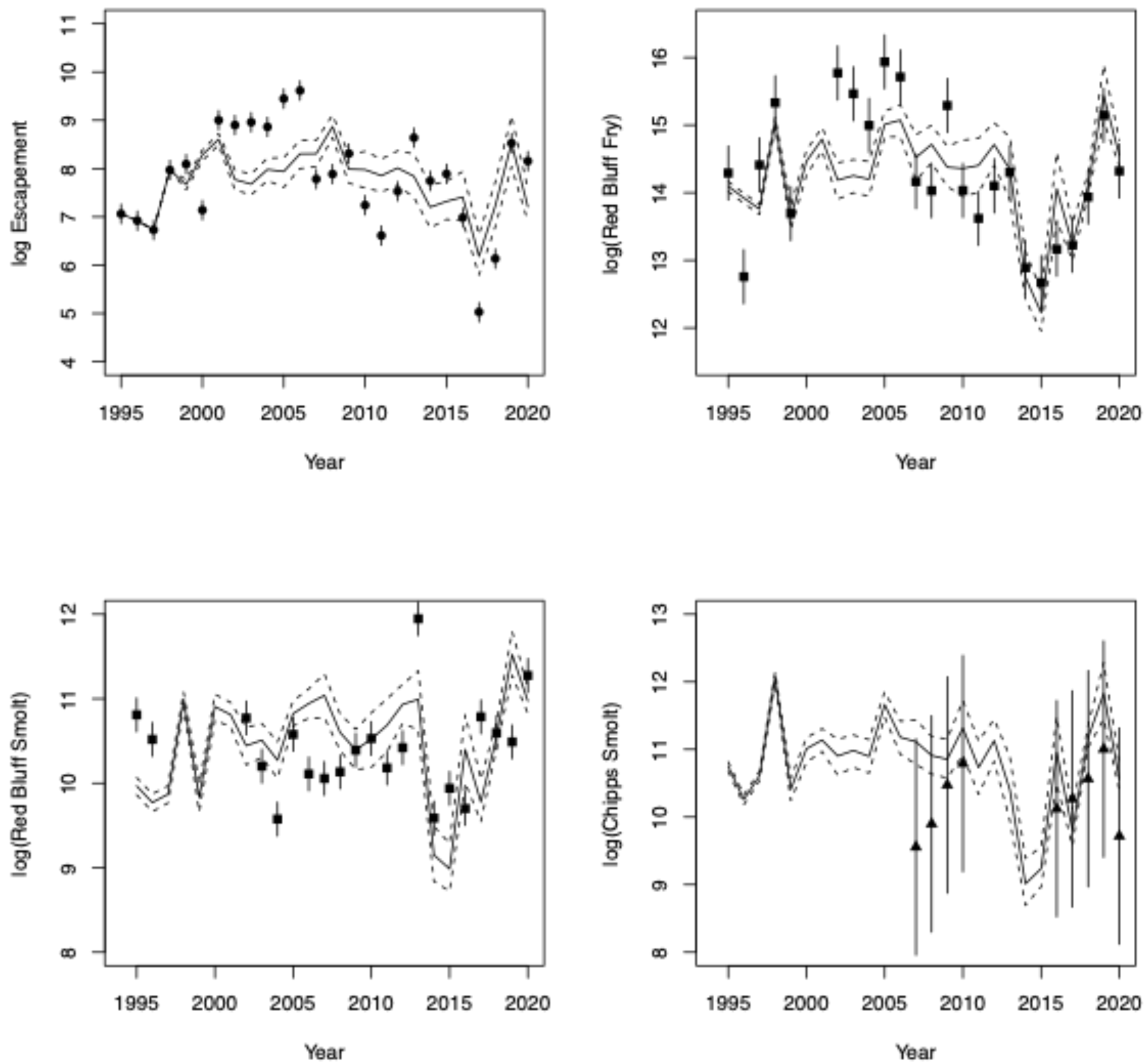
WRLCM Calibration

The monthly and annual dynamics of the WRLCM were calibrated by using an initial escapement estimate, the transition equations defined in the WRLCM structure with known coefficients (Hendrix et al. 2024) and a set of estimated model coefficients. As an example of the sub-model inputs, the TDM model defines the change in egg to fry survival and the ePTM defines the through Delta survival for smolts originating in all rearing areas except the Bay. While these sub-models can reflect monthly variation in survival due to changing environmental conditions, the WRLCM needs to be calibrated to observations of winter-run abundance at multiple life stages to ensure that is reflecting Sacramento winter-run Chinook dynamics. The set of estimated model coefficients performs this task. We utilized abundance of spawner escapement (both natural origin and hatchery origin), abundance of fry passage at Red Bluff Diversion Dam (RBDD) (defined as those fish passing between October and December of their brood year), and abundance of smolt passage at RBDD (defined as those fish passing between January and May of the calendar year following their brood year) and juvenile estimates at Chipps Island (in the calendar year following their brood year). Specifically, the data used to calibrate the WRLCM included:

- Escapement abundance: 1995 – 2020
- RBDD juvenile abundance for fry (September – December) and smolts: (January – June) 1995 – 1999, 2002 – 2020
- Chipps Island juvenile abundance: 2007-2010, 2016-2020

An optimization routine was used to maximize the log likelihood of the model predictions relative to the observations to estimate the model coefficients. The model structure was written in the NIMBLE programming language (deValpine et al. 2017) using NIMBLE version 1.3.0 (deValpine et al. 2024) and the optimization was completed in R (R Core Team 2024).

Calibration of the WRLCM to the four data time series indicated that the model captured annual variation in abundance at multiple life stages from 1995 to 2020 (Figure B3). The set of estimated model coefficients were described by the maximum likelihood mean and a standard deviation, which was calculated via the Fisher information matrix. Uncertainty in the model predictions was obtained by drawing 1,000 samples from a normal distribution constructed from the mean and standard deviation and running the model over 1,000 simulations to make predictions. The predictions for the abundances of the life stages were summarized by the mean and 95% prediction intervals (Figure B3).



Note: Observed log abundance in each life stage (points) and 95% measurement uncertainty (vertical lines through points) for escapement (circles), juvenile counts at Red Bluff Diversion Dam (squares) and juveniles in Chipps Island trawls (triangles).

Figure B3. WRLCM predictions at maximum likelihood estimates (solid lines) and 95% prediction intervals (dashed lines) of log adult escapement (top left), log juvenile fry counts (passage prior to Jan) at Red Bluff Diversion Dam (top right), log smolt counts (passage in Jan and after) at Red Bluff Diversion Dam (bottom left), and annual log juvenile abundance estimates at Chipps Island (bottom left)

Scenario Definitions

There were 5 Scenarios developed for analysis, which differed 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.

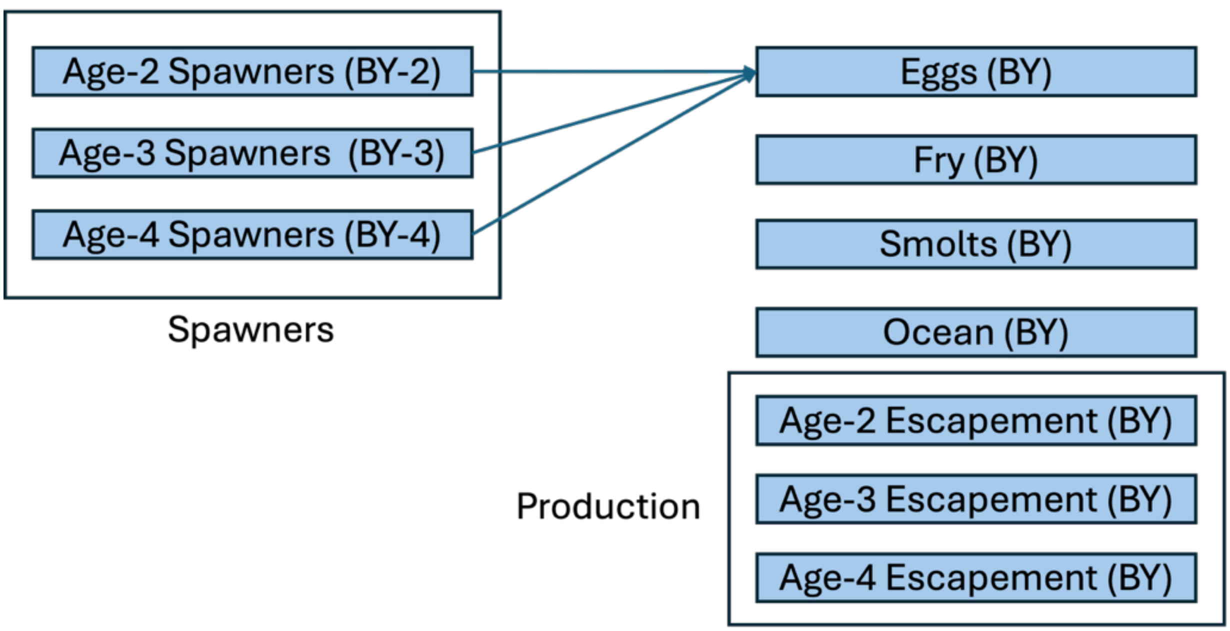
Metrics

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 B4). The Spawners in Figure B4 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 B4. 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 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 = 5:26 are used as the viability metric for productivity for each simulation *s*

$$CRR_s = 1/22 \times \sum_{y=5}^{26} CRR_{y,s}$$

The first viability metric for productivity was the average cohort replacement rate for model years *t* = 5 to 26.

$$VM_{P1} = CRR_s$$

Percent difference in CRR

The percent difference in the CRR for the scenario relative to the baseline was also calculated. The percent 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 (17:26) was the first abundance viability metric. Because winter-run return at age-3 predominantly, the 10-year average represents approximately 3 years of returns from each of the underlying 3 components.

$$N10_s = 1/10 \times \sum_{17}^{26} \sum_{a=2}^{4} Esc_{m:f,n,a,t,s}$$

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.

$$VM_{A1} = N10_s$$

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.

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

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

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

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 *N3t* 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 24 of these years (years 3:26) 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.

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

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