Interactive Object-Oriented Simulation Model for Winter-Run Chinook Salmon Sensitivity Analyses on Delta Mortality

Introduction

A modeling study was conducted to assess the effects of additional juvenile salmonid mortality (i.e., juvenile production removal) in the Delta on salmonid population performance metrics utilizing the Interactive Object-Oriented Simulation (IOS) Model for Winter Run Chinook Salmon (Zeug et al. 2012). A series of sensitivity analyses utilizing the IOS Model was applied to simulate the impact of increased Delta mortality (ranging from 0-10% of juvenile production) on several population performance metrics. 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.

The IOS Model is a lifecycle model composed of six model stages defined by a specific spatiotemporal context arranged sequentially to account for the entire life cycle of winter-run Chinook salmon, from eggs to returning spawners. The IOS Model operates on a daily timestep for the first five stages (spawning, incubation, fry rearing, river migration, and Delta passage) and an annual time step in the sixth (ocean stage) to track the fate of individual cohorts of non-hatchery Winter-Run Chinook salmon throughout the different life stages.

In the spawning stage, the temporal distribution of spawning is determined by water temperatures prior to the onset of reproduction. During the egg incubation stage, development time and survival are applied daily as a function of daily mean temperatures. Fry rearing occurs for 60 days post emergence, and daily survival rate is a function of temperature.

River migration is initiated after 60 days of fry rearing. The river migration reach extends from Red Bluff to the City of Sacramento. Survival and travel time in this reach are both a function of flow at Bend Bridge. The Delta Passage stage describes routing, survival and travel time through multiple reaches between Freeport and Chipps Island. The specific hydrologic influences on each of these outputs varies among reach based on statistical modeling of >10 years of acoustic tag detections. Hydrologic variables that influence outcomes include flow, exports and flow splits at junctions.

When fish enter the ocean, the time step switches from daily to annual. Fish may leave the ocean at ages 2, 3, or 4 with proportions determined from hatchery returns. Both harvest and natural mortality are applied to all ages.

Methods

The IOS Model was modified to allow an additional source of Delta mortality beyond losses attributed to environmental conditions. This loss was assessed on simulated cohorts of fish exiting the Delta on a percentage basis. Before the simulation study was conducted, extensive testing was conducted to ensure validity and stability of the IOS Model. Due to the stochastic nature of the IOS Model, this testing consisted of two different approaches. First, to test model validity, simulations were run under varying levels of additional Delta loss to ensure the median simulated outcomes responded as expected (e.g., additional Delta loss resulted in fewer ocean adults, returning adults, and eggs deposited), as well as analyzing the bounds of the simulated outcomes for extreme outcomes. Second, to test stability, the model was run with 100,000 random input values of additional Delta loss from 0 to 100%, with each iteration being checked for degenerate output values.

After testing, the model was run under the assumptions of additional Delta loss values ranging from 0 (baseline) to 10% in 2.5% increments plus a 1% additional benchmark. One thousand replicated simulations were run for each loss value, where a single simulation consisted of Chinook life cycles over a 100-year period from 1922 to 2021 under Action 5, the current regulatory condition (Reclamation 2025).

Results and Discussion

As expected, increased Delta loss values resulted in fewer simulated adult Chinook salmon returning to the system each year (female escapement; Figure 1). In absolute terms, the reduction in female escapement compared to the 0% additional Delta loss simulations varied from 0 to nearly 3,000 female Chinook salmon (Figure 2). The differences between additional loss levels were greatest in years that are favorable for survival (e.g., wet water year types with high river flows and low river water temperatures) and years when escapement was high (e.g., 1970) and smallest in unfavorable years (e.g., Critical water year types with low river flows and high water temperatures) and in years when escapement was low (e.g., 1934).

The IOS Model simulated that additional Delta loss compounded over the course of several simulated years before settling into an equilibrium. The equilibrium state, expressed in percentage difference from the 0% loss simulations, was a multiple of roughly three times the Delta loss (Figure 3). For example, the 2.5% simulations resulted in a roughly 10% decrease in female escapement and the 10% loss resulted in a roughly 30% reduction. These differences were less in low escapement years. This pattern might be an artifact of how the additional Delta loss is being applied in the model (as a percentage of the successful out-migrants).

To account for simulation variability, the female escapement values were summarized by how often the simulated value for female escapement fell below the 2,500 threshold (Figure 4). The number of simulations where the female escapement values fall below 2,500 individuals increased with increased Delta loss. All Delta loss levels experienced nearly 100% simulated female escapement levels below 2,500 in years with poor conditions for survival, e.g., critical water years. In these years, baseline mortality was high enough that additional mortality made a lower difference relative to other years. However, the higher the Delta loss level, the more frequently the simulated female escapement fell below the threshold. The 10% Delta loss level had on average 16% more simulations cross the threshold compared to the baseline, with a maximum difference of 36% more simulation runs crossing the threshold (Figure 5).

The cohort replacement rate (CRR) was approximately 1 across simulations (median 1.0, Inner Quantile Range 0.6 - 1.7), thought the CRR was above 1 for the majority of simulation years (51%) even when juvenile mortality was increased (Figure 6). This seems counter intuitive as there were substantial reductions in the annual number of adult spawners when juvenile mortality increased, suggesting the population was struggling to replace itself. It appeared that the effects of increased juvenile mortality were realized within a single generation (within the first four years) and then stabilized at a lower level. This might be an example of a disturbance leading to a regime shift to an alternative stable state. For these reasons, CRR may not be a very useful metric to examine these changes because it is standardized to a per-capita rate. For example, a population of 100 individuals can have a CRR of 1 and so can a population of 1,000,000. Comparing those rates does not tell you anything about population size. Other metrics presented here appear to be more effective for quantifying changes in adult abundance as a function of increasing juvenile mortality.

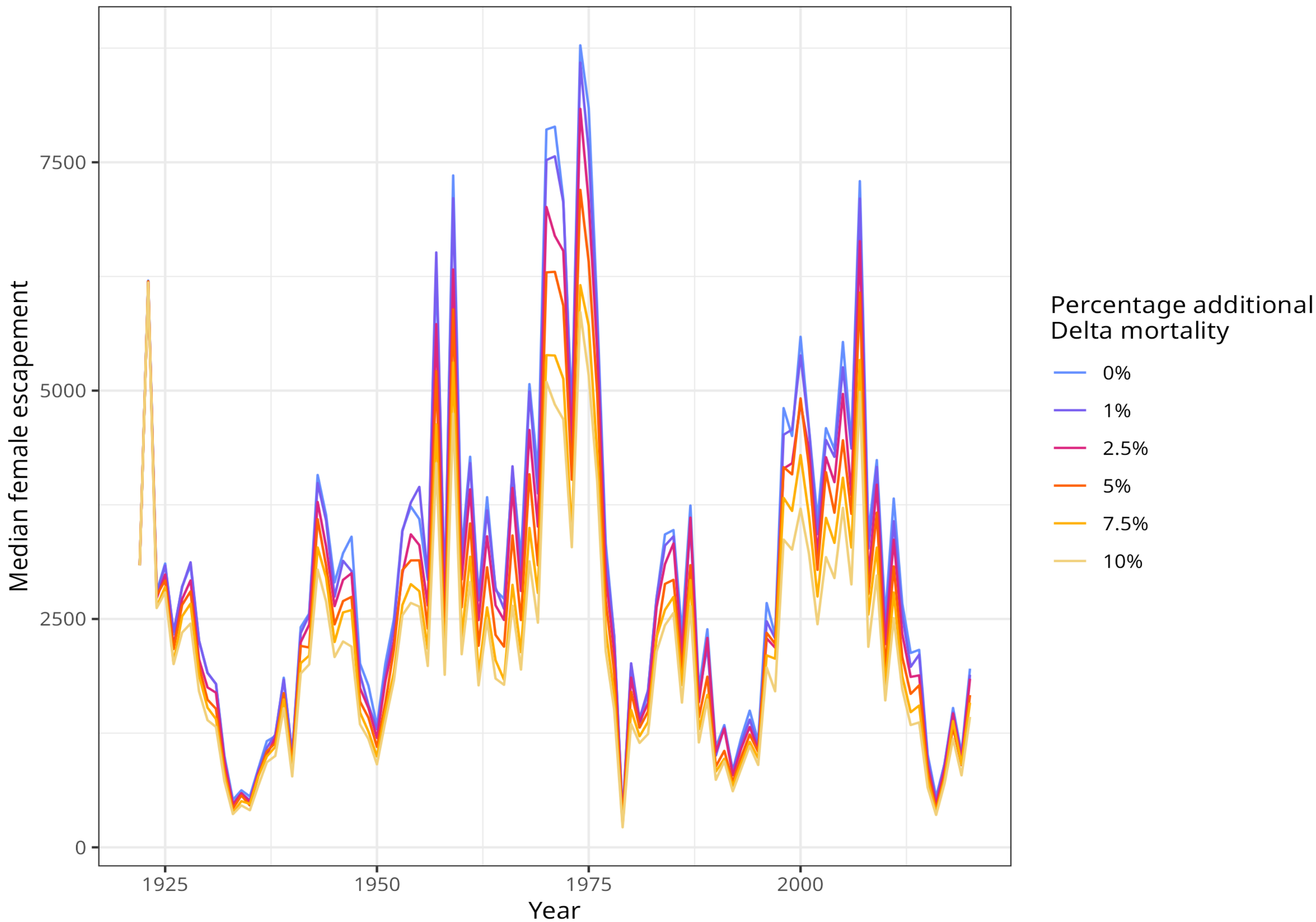


Figure 1. Median Number of Female Winter-run Chinook Salmon Returning from the Ocean (Female Escapement) under Various Modeled Additional Delta Mortality Levels over the Period 1922 to 2020

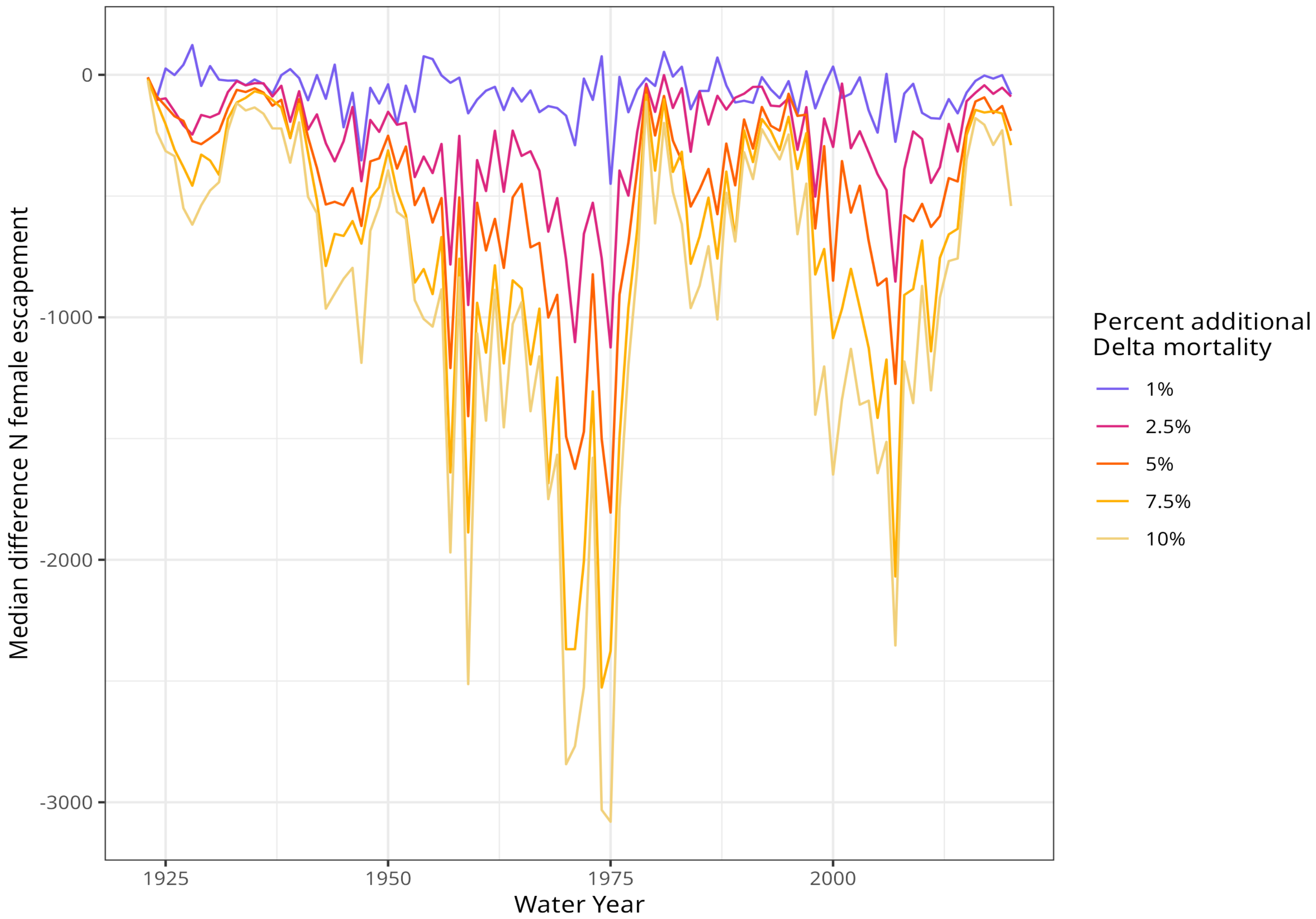


Figure 2. Median Difference in the Number of Female Winter-run Chinook Salmon Returning from the Ocean (Female Escapement) from the 0% (Baseline) Delta Mortality Levels Simulations over the Period 1922 to 2020

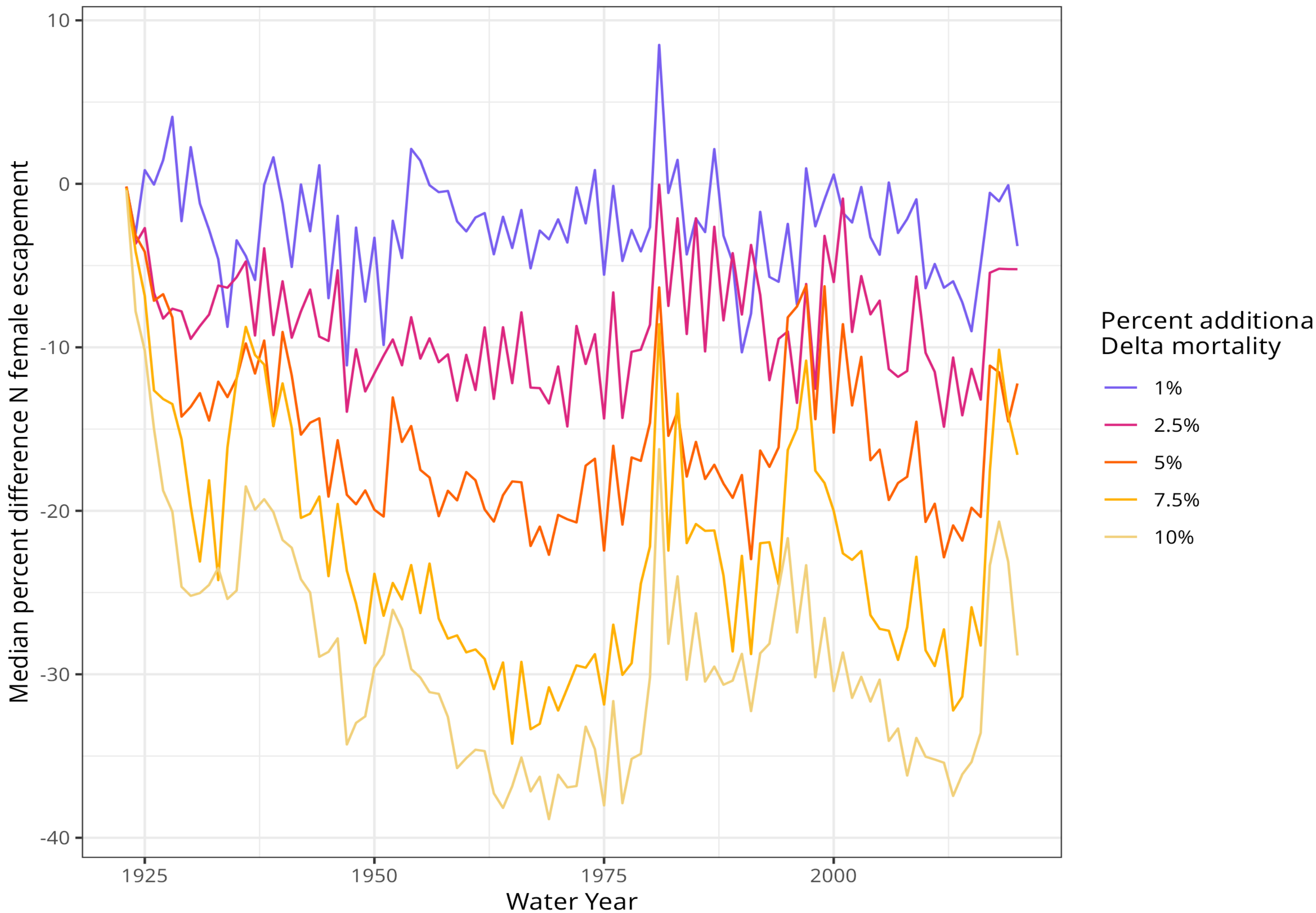


Figure 3. Median Percent Difference in the Number of Female Winter-run Chinook Salmon Returning from the Ocean (Female Escapement) from the 0% Delta Mortality Levels Simulations during the Period 1922 to 2020.

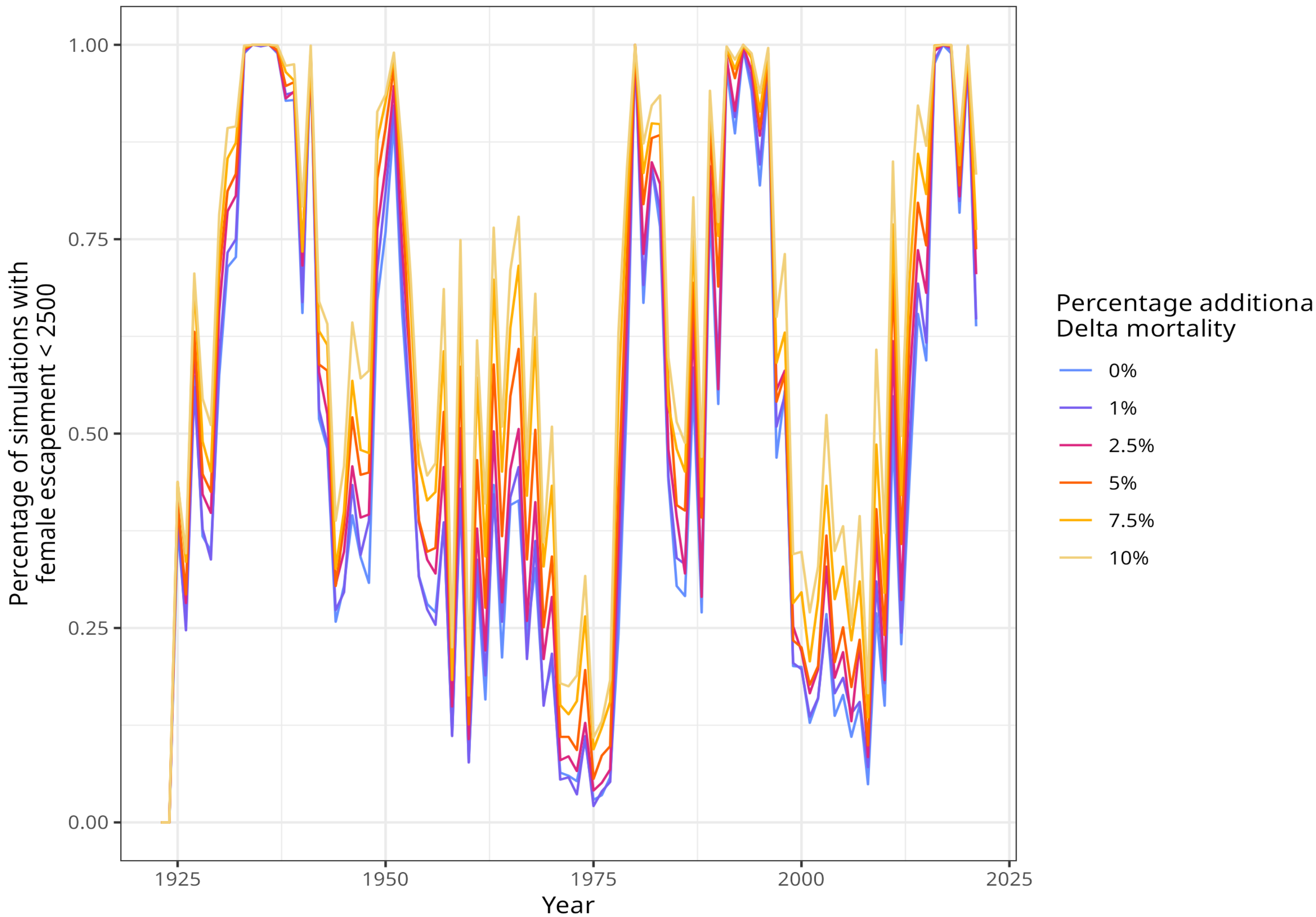
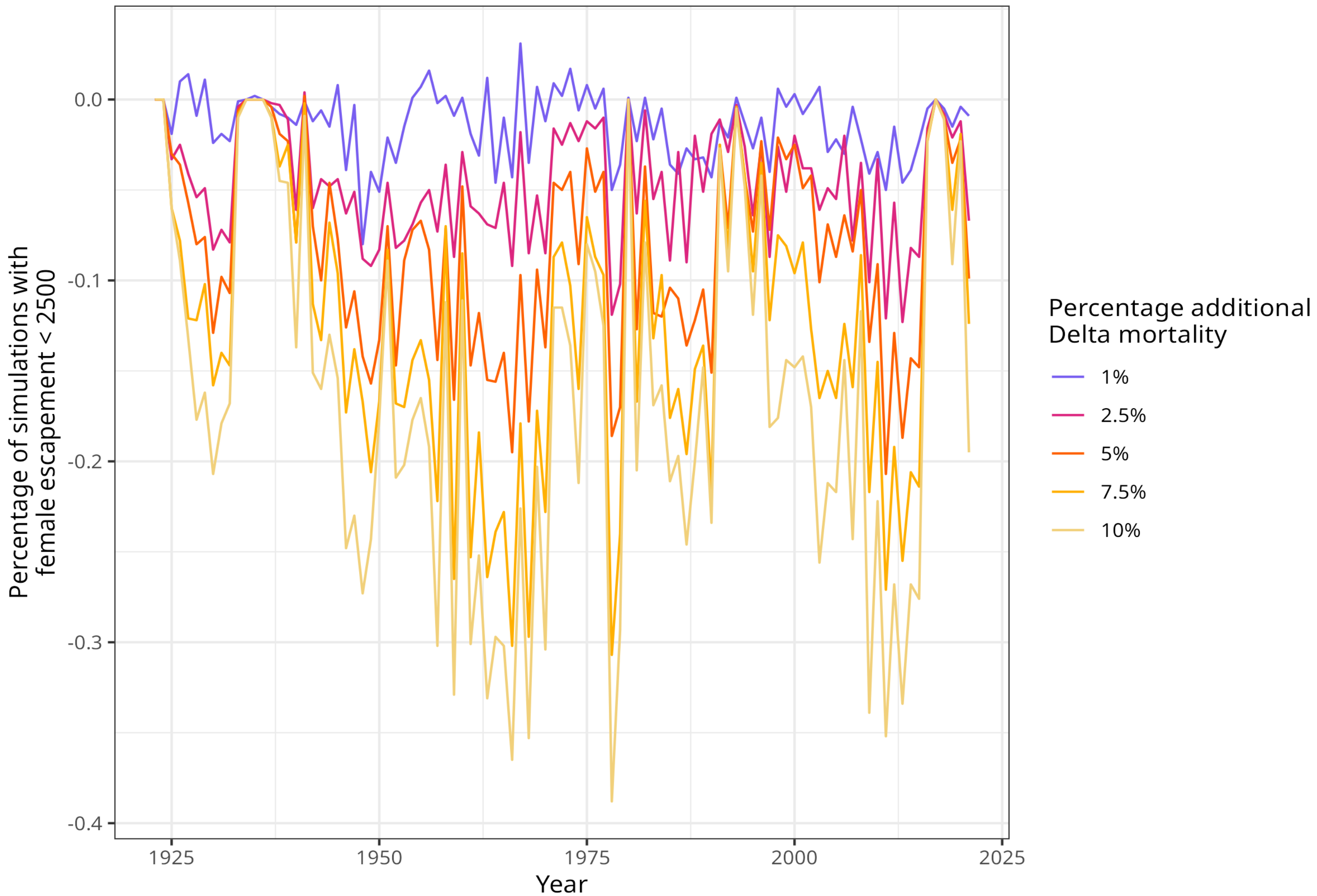


Figure 4. The Percentage of Simulated Outcomes for Each Simulated Additional Delta Mortality Levels where the Number of Female Winter-run Chinook Salmon Returning from Ocean (Female Escapement) was Less Than the Threshold of 2,500 Individuals over the Period 1922 to 2020



Note: More negative values mean more simulations crossed the threshold compared to the baseline.

Figure 5. The Percent Difference Compared to Baseline of Simulated Outcomes where Less Than 2,500 Winter-run Chinook Salmon Females Returned from the Ocean by Year of Simulation Based on 1,000 Simulated 100-year Periods

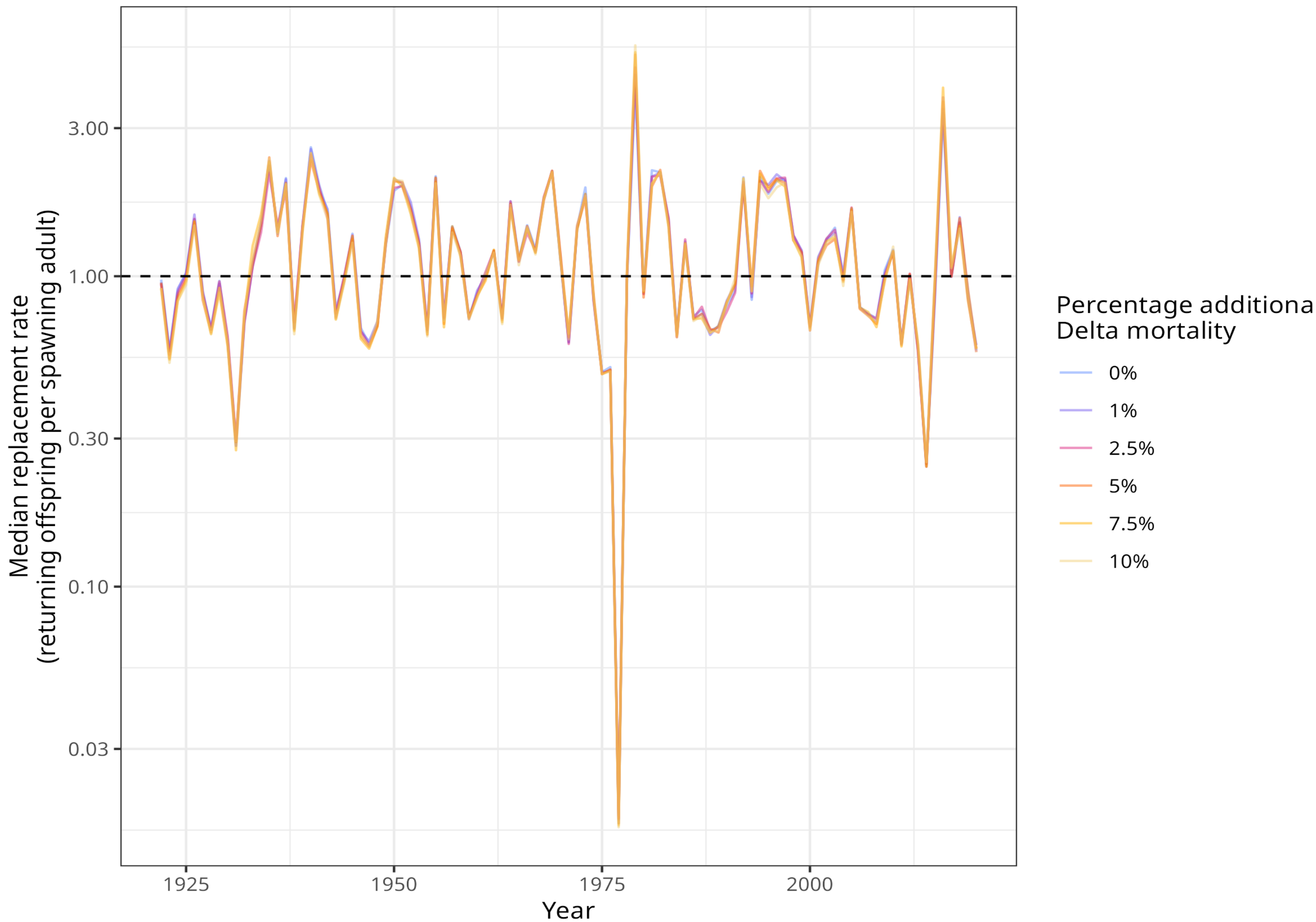


Figure 6. The Winter-run Chinook Salmon Cohort Replacement Rate (Number of Returning Offspring per Spawning Adult) Over Time.

Key Findings

1. Changes in female escapement compound over several years before reaching a new equilibrium state. Under the most severe simulation of an additional 10% Delta loss, the reduction in female escapement stabilizes to approximately 30% lower than baseline abundance.
2. Unfavorable conditions (e.g., Critical water years) result in the smallest differences between modeled scenarios, though this might be an artifact of the Delta loss being modeled as a flat percentage reduction.
3. Favorable conditions resulted in the largest modeled differences in female escapement between Delta loss levels.
4. Simulated female escapement values often fell below the 2,500 individual threshold under all Delta loss scenarios, but more frequently under the highest modeled Delta loss of 10%.
5. Cohort replacement rate appears to be a poor metric for examining potential changes in escapement as a function of juvenile mortality.

References

Zeug, S., P. Bergman, B. Cavallo, and K. Jones. 2012. Application of a Life Cycle Simulation Model to Evaluate Impacts of Water Management and Conservation Actions on an Endangered Population of Chinook Salmon. Environmental Modeling and Assessment. DOI 10.1007/s10666-012-9306-6.

Reclamation. 2025. U.S. Department of Interior, Bureau of Reclamation. Record of Decision, Long-Term Operation of the Central Valley Project and State Water Project. Available here: https://www.usbr.gov/mp/nepa/includes/documentShow.php?Doc_ID=57167. December.

Appendix A

Study Plan

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Background

The Interactive Object-Oriented Simulation (IOS) Model for Winter Run Chinook Salmon (Zeug et al, 2012) is a lifecycle model composed of six model stages defined by a specific spatiotemporal context arranged sequentially to account for the entire life cycle of winter-run Chinook salmon, from eggs to returning spawners. The IOS Model operates on a daily timestep to track the fate of individual cohorts of Winter Run Chinook salmon throughout the different life stages.

The Delta Passage stage describes routing, survival and travel time through multiple reaches between Freeport and Chipps Island. The specific hydrologic influences on each of these outputs varies among reach based on statistical modeling of >10 years of acoustic tag detections. Hydrologic variables that influence outcomes include flow, exports and flow splits at junctions.

Approach

The Stantec team will conduct a modeling study to assess the effects of additional juvenile salmonid mortality (i.e., juvenile production removal) in the Delta on salmonid population performance metrics. A series of sensitivity analyses utilizing the IOS Model to simulate the impact of increased Delta mortality (ranging from 0-10% of juvenile production) will be used on several population performance metrics. These performance metrics will include the maintenance of a replacement population (defined as escapement of 2500 adults), the cohort replacement rate, and abundance recovery rates.

To complete this work, alterations are needed to the IOS Model to enable a flat percentage of the Delta cohort to be removed. These alterations will necessitate code expansion, refactoring, testing, accuracy validation, and documentation. To that end, we propose the following work:

- Modify the IOS Model to enable the sensitivity tasks outlined above
- Validate and document the modifications
- Conduct simulations for a range of extraneous juvenile salmonid Delta removal, from zero to ten percent.
- Produce a draft report outlining the findings from the sensitivity analysis above
- Integrate comments from BOR and produce a final report.

Reference

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