Technical Memorandum

To: Columbia River CWR Project Team

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Subject: HexSim migration corridor simulation model results

Background

To explore how cold water refuge (CWR) use influences fish fitness outcomes we developed a migration corridor simulation model in the HexSim modeling platform (Snyder et al. 2019) and used it to understand how CWR availability could potentially influence fish fitness in the Columbia River. HexSim is a dynamic, spatially-explicit individual-based modeling platform which has been frequently used to study the effect of landscape disturbance on a wide range of taxa (Schumaker and Brookes 2018). In HexSim, we developed a part probabilistic and part mechanistic model using the best available knowledge and data. The migration corridor simulation model tracks an individual's thermal exposure, energy consumption, and survival during migration. The model incorporates fish behavior, natural history, and bioenergetics and allows us to scale up from individual behaviors to population level effects. In the model, thermal conditions and fish behavior interact to determine overall fish exposure which is translated into fish fitness metrics.

The model runs on an hourly time step from July 1 to October 31. Individuals in the model migrate through the Columbia River passing through three hydropower structures starting upstream of the Bonneville dam and ending at the Snake River confluence. Swim speed and bioenergetic activity cost vary by location: hydropower tailrace, fish ladder, open reservoir, or cold water refuge. Actual fish must swim through some upstream section of the Columbia or Snake Rivers and up into adjacent tributaries to reach spawning grounds. The cost of doing so will vary depending on the individual's time of arriving at the confluence, remaining distance to and location of their spawning grounds. At present, our model cannot forecast the energetic cost of this segment of migration, and we do not have data sufficient to construct an analytic approximation. For more detailed information on model function, parameterization, and calibration see Snyder et al. 2019 and the associated Appendices.

Assumptions/Simplifications

In a system this complex there will be some simplifications based on limited understanding and availability of information. Simulation modeling is meant to approximate the important system drivers not be an exact replica. Following, we list a few important simplifications. However, this is not a comprehensive list of assumptions.

- Simulated fish do not distinguish between CWR based on quality. Warm, lower oxygen, small, or low substrate quality refuges are equally available and desirable to the fish in the model. While, temperature does not influence the selection of cold water refuges it does influence the outcome of the selection on fish fitness.
- Some fish behaviors, such as residence times in cold water refuges, are simulated probabilistically in the model and thus are simplifications of actual fish behavior.
- Simulated fish swim speeds are drawn from a distribution, but are fixed for any individual. Actual fish may adjust their swim speed in an attempt to lower exposure to high temperatures.
- Further, our bioenergetics equations do not take into account the fish swim speed, but instead account only for temperature and body size. We made the simplifying assumption that the possible thermal benefits of swimming faster were matched by the energetic cost of exerting extra energy.
- In addition, to simplifications to fish behavior and physiology, the simulated riverscape which includes temperature, volume, and depth maps, all have associated temporal and spatial uncertainties.

Experimental Approach

We used the model to explore how thermal conditions and the availability of CWR influenced fish fitness measures. These experiments were designed to assess the potential of CWRs to improve the condition of the migrating salmon and trout. We simulated the migration performance of four fish populations under differing thermal conditions.

To simulate differing thermal conditions, we varied either the temperature of the Columbia River or the availability of CWRs, or both. We created hourly thermal conditions for the experiments based on two different temperature time series for the current Columbia River. One is based on a long-term average of recent temperatures (average from 1992-2016) and the other is based on more recent temperatures (2017). The more recent temperature condition, from 2017, is not an average and therefore has a greater range of values than the long-term average. The future Columbia River year 2040 conditions were created by adding 1 °C to the current temperature time series for the Columbia River. The historic Columbia River conditions were created by subtracting 2 °C from the current temperature time series for the Columbia River.

Table 1. Table summarizing the temperature conditions of the scenarios run in the HexSim migration corridor simulations.

	CWR available	***CWR not available***
Current Columbia River temperature long term average (1992-2016)	Historic	Historic
	Current	Current
	Future Year 2040	Future Year 2040
Current Columbia River temperature recent condition (2017)	Current	Current
	Future Year 2040	Future Year 2040
	Additional CWRs Added	

Our experiments examined how the availability of CWRs can influence fish condition at the Snake River confluence by simulating thermalscapes under historic, current, and predicted future Columbia River temperatures with CWRs and with CWRs unavailable. Additionally, we evaluated how additional CWRs in the reaches of the migration corridor with low quantities of coldwater refuges (John Day and McNary pools) would influence fish conditions. Additionally, we simulated an uncertainty analysis of the relationship between acute temperature stress and survivorship.

The four populations we simulated are specified in the model using distinct entry time and initial weight distributions:

1. Tucannon Summer Steelhead
2. Grande Ronde Summer Steelhead
3. Snake River Fall Chinook salmon
4. Hanford Reach Fall Chinook salmon

Table 2. Entry time and initial weight distributions as specified in HexSim migration corridor simulation model. Distributions were summarized from Jepson et al. 2010, Keefer et al. 2009, and Keefer (unpub) data.

	Mean weight (g)	**Standard deviation Weight (g)**	**Median run timing**	**Standard deviation run timing (d)**
Tucannon Summer Steelhead	4836	1060	July 17	15
Grande Ronde Summer Steelhead	5092	1674	August 5	15
Snake River Fall Chinook salmon	4279	2088	September 3	6.5
Hanford Reach Fall Chinook salmon	5320	2720	September 10	8

For simulations with the Columbia River temperature based on year 2017 only Grande River summer steelhead and Snake River Fall Chinook Salmon populations were modeled.

Results

The following figures and tables summarize some of the results from these experiments. For each scenario, populations were simulated separately because volume of cold water does not seem to be limiting use of the majority of cold water refuges. Simulated fish condition outputs are typically depicted as a distribution of values. Results are organized by population, i.e. all results for Grande Ronde River steelhead from the six scenarios based on Columbia River long-term average are analyzed and displayed together. For each population and scenario, cumulative temperature exposure, then, energy remaining, acute mortality, and exit dates are summarized. First included are results from the Columbia River long term average scenarios. Then, we append, summary results, for the four scenarios based on the Columbia River year 2017 temperatures.

Sections

Long-term average Columbia River temperatures:

1. Cumulative degree days summary results for Tucannon River summer steelhead under long-

term average temperatures for the Columbia River

2. Energy use, CWR use, and survivorship results for Tucannon River summer steelhead under long-term average temperatures for the Columbia River

3. Cumulative degree days summary results for Grande Ronde River summer steelhead under long-term average temperatures for the Columbia River

4. Energy use, CWR use, and survivorship results for Grande Ronde River summer steelhead under long-term average temperatures for the Columbia River

5. Cumulative degree days summary results for Snake River Fall Chinook Salmon under long-term average temperatures for the Columbia River

6. Energy use, CWR use, and survivorship results for Snake River Fall Chinook Salmon under long-term average temperatures for the Columbia River

7. Cumulative degree days summary results for Hanford Reach Fall Chinook Salmon under long-term average temperatures for the Columbia River

8. Energy use, CWR use, and survivorship results for Hanford Reach Fall Chinook Salmon under long-term average temperatures for the Columbia River

Year 2017 Columbia River temperatures:

9. Cumulative degree days summary results for Grande Ronde River summer steelhead under year 2017 temperatures for the Columbia River

10. Energy use, CWR use, and survivorship results for Grande Ronde River summer steelhead under year 2017 temperatures for the Columbia River

11. Cumulative degree days summary results for Snake River Fall Chinook Salmon under year 2017 temperatures for the Columbia River

12. Energy use, CWR use, and survivorship results for Snake River Fall Chinook Salmon under year 2017 temperatures for the Columbia River

Acute temperature stress sensitivity:

13. Sensitivity testing of acute temperature stress curve

Additional simulated coldwater refuges:

14. Cumulative degree days summary results for Grande Ronde River summer steelhead under year 2017 temperatures for the Columbia River with simulated additional coldwater refuges

15. Energy use, CWR use, and survivorship results for Grande Ronde River summer steelhead under year 2017 temperatures for the Columbia River with simulated additional coldwater refuges

16. Cumulative degree days summary results for Snake River Fall Chinook Salmon under year 2017 temperatures for the Columbia River with simulated additional coldwater refuges

17. Energy use, CWR use, and survivorship results for Snake River Fall Chinook Salmon under year 2017 temperatures for the Columbia River with simulated additional coldwater refuges