MortSim: A Tool for Investigating In-river Mortality of Salmonids

Tyler Pilger FISHBIO
Matt Peterson FISHBIO
Shaara Ainsley FISHBIO

Introduction

Managing in-river mortality of anadromous species is complicated by the numerous extrinsic (e.g., water quality, predator density, anthropogenic habitat alteration) and intrinsic (e.g., behavior and life history, density-dependent effects) factors that influence species survival. For example, juvenile Central Valley Chinook Salmon (*Oncorhynchus tshawytscha*) migrating from tributaries of the Sacramento and San Joaquin rivers through the Delta and out to the ocean have experienced high mortality rates owing to entrainment in irrigation diversions and pumping stations, physical habitat alterations, native and introduced predator species, and reduced life history diversity (Rieman et al. 1991, Lindley et al. 2009, Perry et al. 2010). Mitigation for high in-river mortality can be costly (e.g., habitat restoration in migration corridors) and in some cases (e.g., predator management, levee setbacks), is controversial among stakeholders. Thus, there is a need for a decision support tool to help resource managers prioritize and investigate the effectiveness of different management actions.

Plate 1. Sources of mortality

Computer simulations provide a useful platform for integrating species-specific biological characteristics with management strategies because they allow users to test various scenarios and evaluate outcomes prior to implementing management strategies. Simulations are also useful in the planning phases of projects to help identify sources of uncertainty, direct sampling efforts, and sometimes reveal possible unintended consequences of management actions.

Objectives:
- Develop a simulation-based decision support tool for restoration focused on minimizing combined sources of mortality. Such a tool could help managers plan and prioritize restoration activities to provide the most effective results.
- Perform multiple simulation scenarios to explore the parameter space and identify the limits of the simulation tool.
- Illustrate the simulation tool by focusing on two alternative management actions aimed at increasing juvenile survival: wide-spread restoration efforts that would increasing overall survival or targeted restoration to increase survival at mortality hot spots.

Purpose

Provide a decision support tool for resource managers that are interested in restoration activities focused on minimizing in-river mortality of juvenile anadromous fishes

Design Concepts

- Stochasticity
  - Survival – binomial probability
- Observation – daily cohort
  - Survival and mortality rates
  - Per capita loss for each river km.
  - Hot spot location and survival

State Variables and Scales

- Population scale – Tracks numbers of daily cohort that survive and die
- Spatial scale – Kilometers
- Temporal scale – Days

Initialization

- Size of each daily cohort

Submodels

- Hot spot – survival probability reduced
- Modified hot spot – hot spot modified to reduce mortality and survival increased relative to baseline survival
- Compensatory mortality – proportion of fixed survival rate at hot spot redistributed to remaining river kilometers

Methods

We developed a stochastic survival model for simulating mortality of fish species through a river reach (Figure 1). Using the R environment, we wrote a simulation routine that mimics the natural type III survivorship curve exhibited by many salmonid species. In the program, we allowed for the overlay of mortality hot spots that mimic the effects of areas of intense localized mortality. We define mortality generally as fish that die at any particular time or location, but we do not assign a cause to mortality. We also included the ability to "fix" hot spots to mimic remediation or mitigation in areas of increased mortality. In order to explore possible unintended consequences of fixing the hotspot, we included an option to simulate compensatory mortality. Lastly, we packaged this simulation program using a dynamic interactive platform that can be accessed online using a web browser; therefore, no software is required to use this tool.

Process Overview and Scheduling

- Day 1
  - i. Cohort 1 enters reach (Figure 1)
  - ii. Mortality function
  - iii. Surviving fish move to next river km
  - iv. Mortality function
  - v. …
- Day 2
  - i. Cohort 2 enters reach
  - ii. …

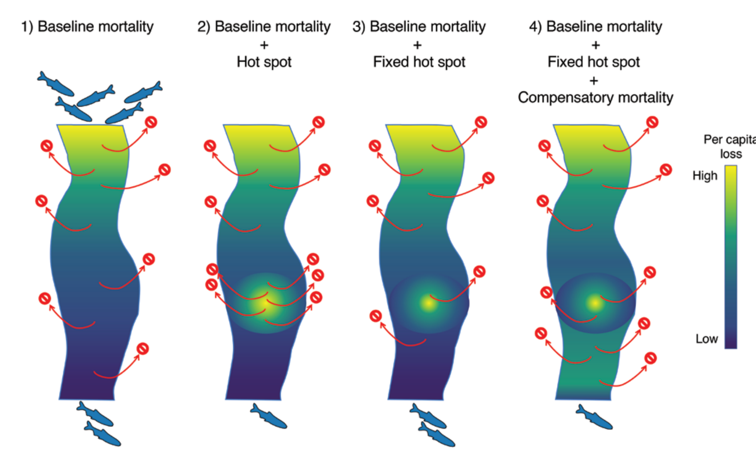


Figure 1. Stochastic survival model depicting the baseline mortality model and each additional submodel. Red "no" symbols represent loss of individuals from the daily cohort as they move downstream.

Input

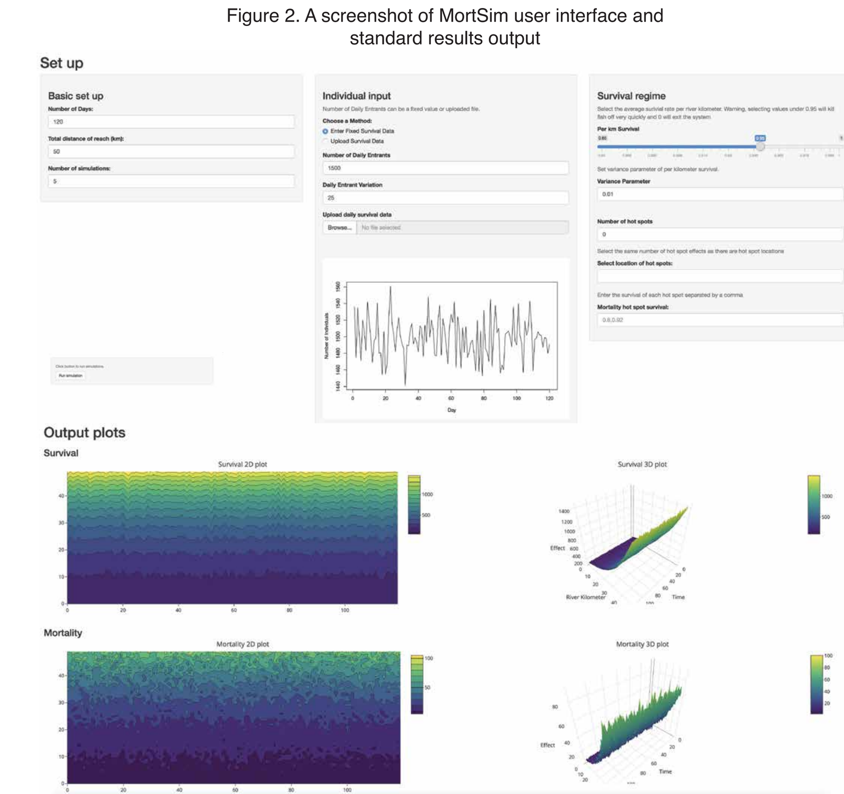
Table 1. Parameter input table

Parameter or constant	Description	Value or range
N_d	Size of daily cohort entering the reach	Constant, Uniformly distributed, User-defined [249 - 27,584]*
N_{tot}	Total number of individuals migrating through the reach.	500,000*
S_{rkm}	Survival rate, per kilometer	0.95 - 0.995
rkm	Total distance of reach	50 - 150
n_{days}	Number of days of Migration period	120
HS_n	Hot spot number	0 - 10
HS_{loc}	Location of mortality hot spots	User-defined, Randomly placed in reach
S_{HS}	Survival at hot spot(s)	$0 < S_{HS} < S_{rkm}$
HS_{fix}	Proportion of fish saved by fixing a hot spot	0 - 1
M_{comp}	Proportion of fish saved by fixing a hot spot that are subject to compensatory mortality	0 - 1

*User defined data was pulled from rotary screw trap catch on the Stanislaus River truncated to 120 trapping days

Model Assumptions:
- Individual survival is random and independent from other individuals
- Survival is not dependent on discharge
- Survival is not dependent on fish size
- There are no density-dependent effects on survival
- Survival is independent of how long it takes to move through the reach
- All individuals move through the reach during the migration period, i.e., no rearing

Figure 2. A screenshot of MortSim user interface and standard results output



Test out MortSim! **ASK ME!**

Test the application! **Copy** link or **Scan code** to email link to yourself!

https://tjpilger.shinyapps.io/MortSim_app/

Plate 2. Juvenile salmon and different reaches of the Stanislaus River.

Results from Development and Model Testing

Scenarios:
- Baseline survival rates, $0.88 \leq S_{rkm} \leq 0.98$
- Reach length, $50 \leq rkm \leq 150$
- 50 simulations each

Results:
- Run time = 4.8 minutes
- If $S_{rkm} < 0.95$, no fish survive a 50 km reach
- Mortality greatest upstream where numbers of individuals greatest

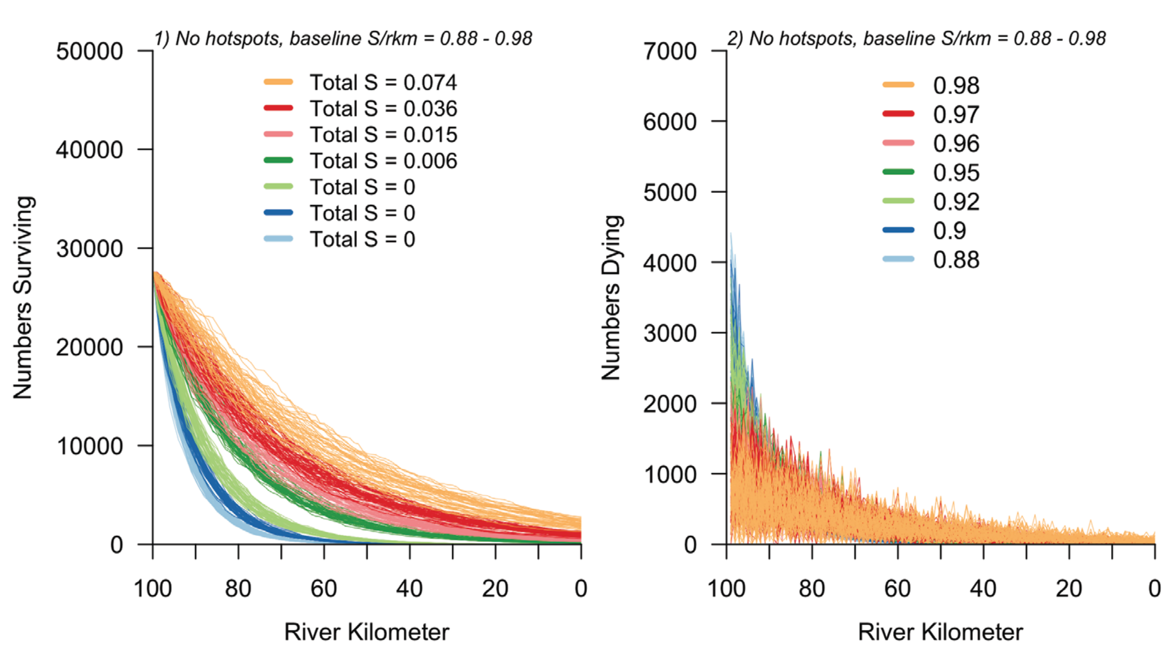


Figure 3. Effect of varying baseline survival (S_{rkm}) on numbers of individuals that survive (left) or die (right) from a single daily cohort. Each line represents the result of a single simulation

Scenarios
1) Baseline survival, $S_{rkm} = 0.95$, 50 km reach
2) $HS_n = 2$, $S_{HS} = 0.8$, $HS_{loc} = 4$ and 43 km from start
3) Modify only upstream hot spot by 100%
4) Modified hot spot with 99% compensatory mortality

50 simulations each

Results:
- Run time = 2 minutes
- Hot spot mortality greater upstream than downstream
- Modifying hot spot can increase daily cohort survival
- Compensatory mortality function reduced daily cohort survival

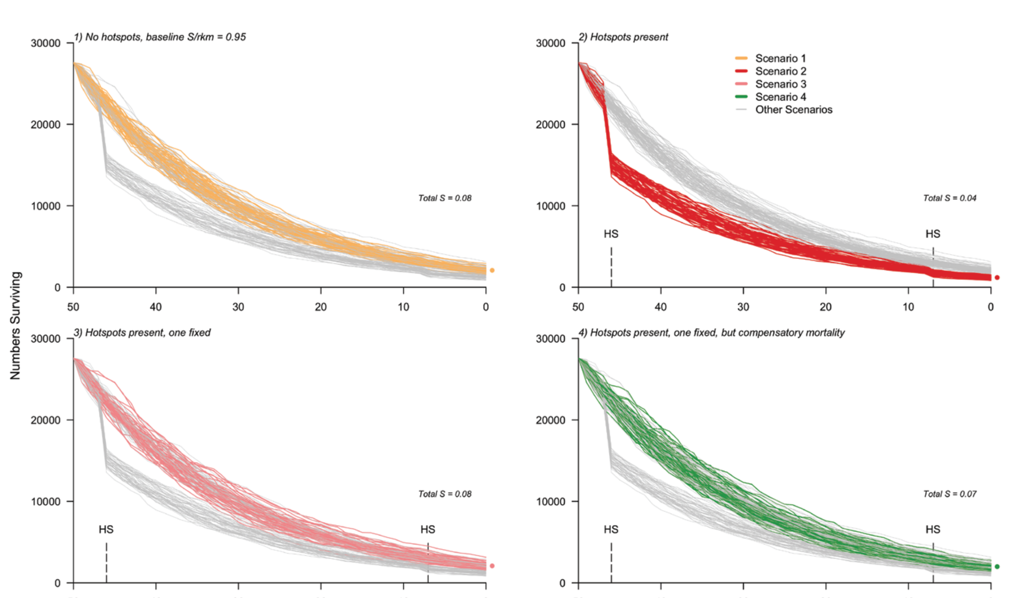


Figure 4. Survival of a single daily cohort from each of the four possible MortSim scenarios. Each line represents the result of a single simulation.

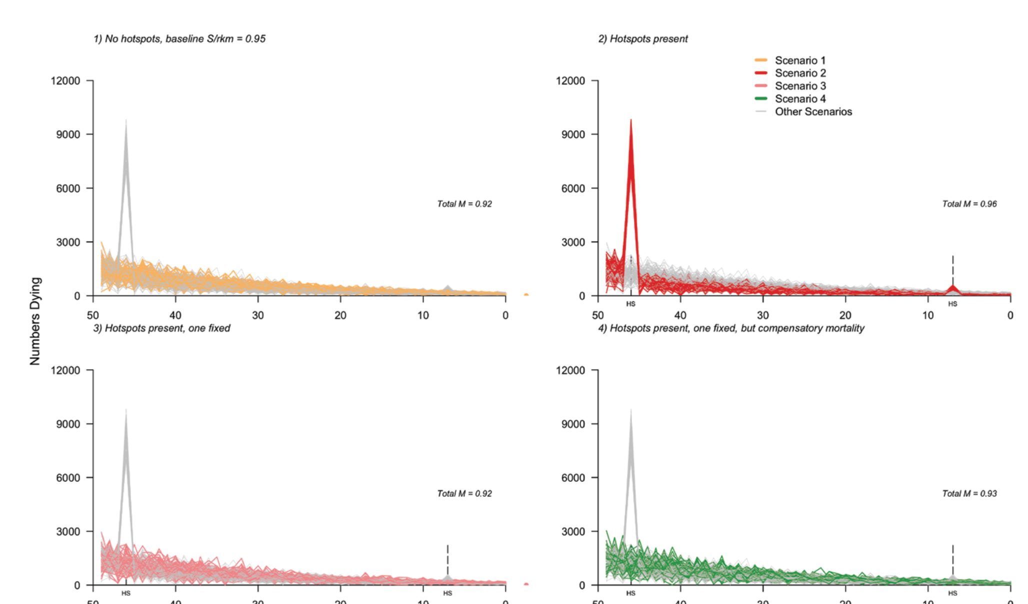


Figure 5. Mortality of a single daily cohort from each of the four possible MortSim scenarios. Each line represents the result of a single simulation.

Applied Example

We applied the decision support tool to help prioritize two alternative management strategies aimed at increasing juvenile fall-run Chinook survival on the Stanislaus River. Possible strategies include widespread restoration efforts that would increase overall survival (e.g., flow and temperature management, or widespread suppression of predators) or targeted restoration to increase survival at mortality hot spots (e.g., predator hot spot remediation, or fish screening at intakes and diversions).

Questions - With respect to baseline survival and hot spot number, intensity, and location:
1) Are there conditions where per capita loss is more sensitive to increasing baseline survival than hot spot intensity or number?
2) Are there conditions where per capita loss is more sensitive to reducing hot spot intensity or number than to increasing baseline survival?

We performed simulations over a range of baseline survival rates, with increasing number of hot spots. Hot spot location and intensity were allowed to vary randomly.

Hypotheses:
1) When baseline S_{rkm} is low, modifying hot spots will not substantially improve per capita loss.
2) When baseline S_{rkm} is high, modifying hot spots will improve per capita loss.

Simulation Set Up

Input: 2014 Daily abundance estimates from a rotary screw trap on the Stanislaus River

Scenario
- S_{rkm} = {0.95, 0.96, 0.97, 0.98, 0.99}
- HS_n = {1, 2, 5},
- S_{HS} = random uniform distribution (0 - 0.8)
- HS_{loc} = Random uniform distribution (1 - 50)
- 500 simulations per S_{rkm} HS_n combination

Results:
- Run time = 1.5 hours
- Upstream hotspots cause greater loss than downstream
- Loss from hot spots dependent on baseline survival

Summary:
- Remediation of downstream hot spots under low baseline S_{rkm} will have little effect on decreasing per capita loss
- Remediation of hot spots under high baseline S_{rkm} will have greater effect on decreasing per capita loss
- Remediation of hot spots higher in the system will have greater effect on decreasing per capita loss than remediation of hot spots lower in the system.

Per Capita Loss (Number Died per 10,000)

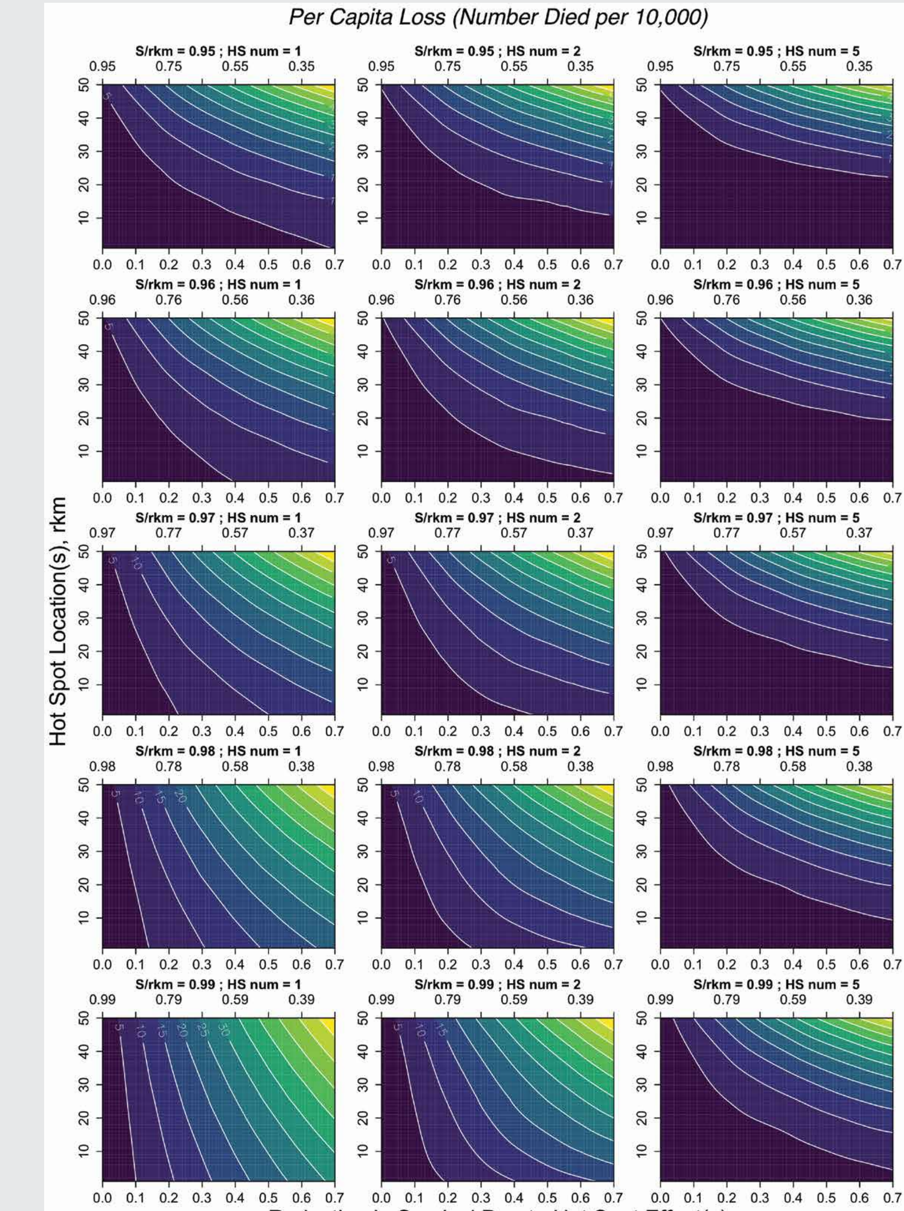


Figure 6. The effects of hot spot intensity and river kilometer position on per capita loss of individuals during an entire migration season.

Summary

- For a given daily migration cohort at a given baseline S_{rkm}, there is a finite distance over which all individuals will die.
- There is a spatial effect on mortality, particularly with hot spots

Future Work:
- Continue fixing bugs, exploring parameter space, and adding summary information
- Convert to agent-based model
- Develop additional submodels: different sources of mortality, predator behavior, etc.
- Incorporate other agent-based models, e.g., inSALMO

Literature Cited:

Lindley, S.T., Grimes, C.B., Mohr, M.S., et al., 2009. What caused the Sacramento River fall Chinook stock collapse?. US Department of Commerce, NOAA, NMFS, Southwest Fisheries Science Center, Fisheries Ecology Division.

Perry, R.W., Skalski, J.R., Brandes, P.L., et al., 2010. Estimating survival and migration route probabilities of juvenile Chinook salmon in the Sacramento–San Joaquin River Delta. NAJFM, 30: 142-156.

Rieman, B.E., Beamesderfer, R.C., Vigg, S. and Poe, T.P., 1991. Estimated loss of juvenile salmonids to predation by northern squawfish, walleyes, and smallmouth bass in John Day Reservoir, Columbia River. TAFS, 120: 448-458.

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Contact: Tyler Pilger, FISHBIO, 180 E. Fourth Street, Suite 160, Chico, CA 95928, USA. | E-mail: tylerpilger@fishbio.com | Phone: (530) 892 - 9686

www.FISHBIO.com