Preliminary analysis of hydroacoustically tagged salmon smolt survival and migration rates in the mid-Columbia River

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1 Introduction

This is a brief report on some preliminary results of analyses on travel timing and survival of salmon smolt in several reservoirs of the mid-Columbia. The data was collected in 2005 by Chelan County Public Utility District 1 using hydroacoustic tags implanted in juvenile chinook (*O. tshawytscha*), sockeye (*O. nerka*) and steelhead (*O. mykiss*) salmon. Whereas the bulk of outmigrating salmon survival data comes from PIT tags which are detected only at dams, hydroacoustic detecting arrays were placed in several mid-reservoir locations, allowing for an analysis of migration timing and survival within a reservoir. Detection probabilities are quite high with hydroacoustic arrays, as they cover the entire width of the river. The data also provides longitudonal distribution of migration paths across the river and three dimensional tracks of the fish at the dams themselves, though these dimensions are not analyzed in this report.

The purpose of the analysis is to identify some of the inter-reservoir structure of the migration and survival patterns. Hopefully, the results can motivate a more detailed and process oriented understanding and modeling of salmon migration, and can be at least conceptually applied to other reservoirs in the Columbia River. The ultimate goal is to guide management decisions that mitigate salmon survival.

Commonly, probability of survival is assumed to decay exponentially with time, a common model of time-dependent mortality. However, studies have shown that, in fact, distance travelled is posssibly a stronger indicator of survival. This can be explained by the number of predators encountered depending more strongly on distance travelled downstram than time spent in a reservoir, a process referred to as the "gauntlet effect". Anderson et al. (2005) have proposed a simple model where the strength of the time and distance dependence of survival is determined by a parameter which reflects the net amount of randomness in the trajectories of both the smolt and their predators. Their model is referred to as the XT-model, reflecting dependence on space (x) and time (t). The XT-model is in some ways the conceptual framework that guides this analysis.

2 Data

Hydroacoustic tags developed by HTI were implanted by Chelan County Public Utility District 1 in a total of 4476 juvenile chinook (*O. tshawytscha*), sockeye (*O. nerka*) and steelhead (*O. mykiss*) salmon during spring outmigration between April 18 and June 9, 2005. The juveniles were released in groups of 24 individuals (chinook and steelhead) or 20 individuals (sockeye) from various locations on the Columbia River in Chelan county, WA: the tailrace of Wells dam (river mile 515.8), the juvenile salmon bypass system at Rocky Reach dam (r.m. 473.7), the tailrace of Rocky Reach dam, and the tailrace of Rock Island dam (r.m. 453.4). Detector arrays were located at Rocky Reach and Rock Island dams in a manner that allows for 3-d tracking of the salmon as it approaches either the bypass system, the turbines or the spillway at each dam. Arrays of detectors were also placed across the river a locations in the mid-reservoirs. These were: Beebe Bridge (r.m. 503.9) between Wells and Rocky Reach, Hydro Park station (r.m. 462.7) between Rocky Ridge and Rock Island and Crescent Bar (r.m. 442.52) and Sunland Estates (r.m. 431.08) downstream from Rock Island. The mid-reservoir arrays are designed to detect the passing fish, but do not provide 3-d tracking resolution. Each hydroacoustic tag emits a pulse at a frequency specific to each fish, thereby identifying fish singly, as well as providing the exact time of passage. Lengths and weights were also obtained for each indivudial. See Figure 1 for detector locations, Table 1 for details about the releases and Figures 2 for passage tracks of all the fish.

3 Results

3.1 Mortality intensity

When a fish ceases to be detected, a mortality event can be infered. From these events, probabilities of mortality can be calculated, as can a mortality intensity, defined as the probability of death per mile traveled. In total, out of 5820 total implanted fish 774 mortality events occured: 158 of 984 chinook (16%), 198 of 1991 sockeye (10%), and 418 of 2845 steelhead (15%). The distribution of mortality events over reservoirs is, however, not uniform. Table 2 summarizes the mortality data while Figure 3 gives a graphical representation of the distribution of mortality over the study area.

In most reservoirs, the highest mortality intensity occurs in the reaches immediately after a dam. This effect is most striking for sockeye. In the Rocky Reach reservoir, the mortality intensity drops from 0.432 % per mile in the initial 11.6 mile reach between Wells dam and Beebe Bridge by nearly an order of magnitude to 0.048 % per mile in the remaining 30 miles to Rocky Reach dam. Chinook smolt on the other hand show an insignificant increase in mortality intensity within the first reservoir. In general chinook and steelhead, display a net increase in mortality intensity as they migrate downstream, with slight increases immediately after passing dams. Steelhead in particular show a significant rise in mortality after passing Rock Island dam.

It should be noted that specific causes of mortality are unknown. Presumably, in the mid-reservoir the bulk of mortality is due to predation (REFS?). In the tailraces, however, it is difficult to separate the effects of mortality due to dam passage from the possibility of greater predation in the tailraces (more REFS!?). A good explanation for the differences in the mortality distribution of the three species requires greater knowledge of the biology of the organisms and the mechanisms of mortality. It should be noted that the sockeye are the smallest of the three species ($\hat{\mu}$ =117 mm, $\hat{\sigma}$=7.26 mm, compared to chinook: $\hat{\mu}$ =163 mm, $\hat{\sigma}$=13.1 mm, and steelhead mean $\hat{\mu}$ =184 mm, $\hat{\sigma}$=18.7 mm), possibly resulting in greater stress-induced mortality during dam passage. The large size of the steelhead might make them more susceptible in general to predation. Differences in predator concentrations (pikeminnow, bass, walleye, birds) in the reservoirs, as well as differences in swimming behavior might futher explain these differences. The later migration of the sockeye relative to the other species by a month might also be a factor. ALL OF THESE HYPOTHESES REQUIRE FURTHER RESEARCH EITHER IN THE LITERATURE OR IN THE RIVER.

The take-home message from this analysis is that when modelling survival for migrating salmon, one cannot assume that mortality is distributed uniformly between reservoirs, or even within a single reservoir. The results suggest that an aggregate model of down-migrating salmon survival would benefit from separating mortality at the dams from mortality in the mid-reservoir, with the general implication and the per mile mortality in the mid-reservoir is less than at the dam. This holds especially true for sockeye salmon.

3.2 Velocity distributions

The arrival time distributions of the migrating smolt for all species in all reservoirs conforms to the inverse gaussian travel time distribution proposed by Zabel and Anderson (1997). The inverse gaussian distribution is given by the pdf:

$$\mathrm{IG}\{L, v, \sigma\} : f(t) = \frac{L}{\sqrt{2\pi\sigma^2 t^3}} \exp\left(\frac{(-L - vt)^2}{2\sigma^2 t}\right) \tag{1}$$

where L represents a distance travelled at mean velocity v with a spread coefficient $\sigma > 0$. The inverse gaussian is a unimodal, positively skewed distribution. Two basic processes can yield the inverse gaussian distribution. The distribution of arrival times for a single random walker moving with mean advective velocity v_r and variance σ_r at time step τ_r will be $\mathrm{IG}\{L, L/v_r, \sigma_r^2/\tau_r\}$. Alternatively, the distribution of arrival times for a group of organisms each moving deterministically but with velocities distributed normally among the population (i.e. $V \sim \mathrm{Normal}\{\mu_v, \sigma_v^2\}$) will be $\mathrm{IG}\{L, L/\mu_v, \sigma_v^2\}$. The converse of the last statement is that if a sequence of random arrival times T_i has an inverse gaussian distribution, then L/T_i will return a normal distribution of velocities. A combination of the two processes will yield an inverse gaussian that is a mixture of the intrinsic randomness of an organism's movement and the dispersion of the population's velocities.

There is little biological reason for migrating smolt to move with any significant randomness. This is supported both by theoretical arguments against increasing encounter probabilites with predators and with empirical evidence that suggests that survival of migrating smolt is dominated by a non-random 'gauntlet'-like process (in the context of the XT-model). The discussion in following section depends (I think) on this assumption.

The distribution of travel velocities for the mid-Columbia salmon data does conforms well to the normality assumption, and is consequently far simpler to analyze than the raw travel time data (see Figure 4). Boxplots of velocities (see Figure 5) for all three species over all reaches show remarkably consitent patterns. Mean velocities per reach range widely between 15 and over 80 miles a day. Sockeye travel on average faster than steelhead, which are on average faster than chinook. All species slow down significantly after the reaches that immediately follow a dam. Though it is possible that this is partially due to milling in forebays, the fact that the effect is as strong for the final reach (Crescent Bar to Sunland Estates), which is well above the following dam (Wanapum) seems to suggest that travel does actually slow down in the mid reservoir. The fact that all three species respond identically to each of the reservoirs seems to indicate that travel for smolt is controlled to a large extent by the physical and hydrological characteristics of the reservoirs. It is possible that a thorough analysis of the factors that determine the travel velocity of smolt can be applied more widely to reservoirs throughout the Columbia River.

The reaches of the river where velocities are highest tend to correspond with those where mortality intensity is also highest. This contradicts a widely held assumption that mortality is most closely correlated to amount of time spent in a reservoir, and provides some indirect support for an gauntlet-like process.

3.3 Testing for selection

Because the fates of individual salmon are tracked through the system, we can compare some of the statistics of the population that survives versus the population that doesn't. It turns out that the distribution of length and weight for the survivors is identical to that of the victims (see Table 3), indicating that there is no selective pressure on size one way or the other. It also begs the question: what exactly causes discrepancies in the mortality between species if size does not appear to play any role in survival?

Finally, the mean travelling velocities of the surviving fish can be compared with those that died. The interaction plot in Figure 6 shows that, again, there is no difference in the mean velocities of fish that survive and those that die. This is possibly the most compelling evidence that travel velocity itself plays less of a role in survival than distance travelled.

4 Concluding comments

There are two somewhat contradictory messages that emerge from this analysis regarding salmon smolt survival. The first is that, not surprisingly, the processes of migration and survival are complicated and heterogeneous. There are significant differences between the species, with sockeye in particular displaying the greatest response to dam passage while simultaneously showing the highest overall survival. The significant differences in survival probabilities and travel velocities between the upper and lower reaches of the dams should be taken into account as most models of survival assume a homogenous process, a constraint due in part to the lack previously of higher resolution migration data.

The second important message is that some things might actually be simpler than one might have guessed. For example, the differences in travel velocities are exceptionally consistent between species. This seems to indicate that migration might be less determined by differences in behavior and rather by the hydrological conditions of the river. This gives hope that a robust physical model of migration might be obtainable which could be generalizable to multiple reservoirs. The apparent lack of any kind of apparent selection on the fish, either for size or migration speed, similarly simplifies modeling of predation.

It is clear from the distribution of mortality events that predation is indeed an important source of mortality. The lack of any strong dependence of mortality on time spent in the reservoir is compelling evidence for a gauntlet-like process of survival. The juvenile salmon must necessarily move through a reservoir in a way that appears to be largely determined by the features of the reservoir. It is my own hunch that the spatial distribution of predators is the most significant factor in determining survival. If this is the case, then that is probably the most fruitful direction to focus work on: isolating the sources of mortality and separating the effects and distributions of the various predators.

An analysis of the 3d tracks of salmon approach to the dams might also be fruitful, if only to explore how mortality depends on the path the smolt chooses (bypass, turbine, spillway). It might also suggest the extent of mortality at the dam, though the power of the inference will be relatively diminished.

While PIT-tag data necessarily lacks the high detections and finer resolution of hydroacoustic data, it is far more voluminous and spatially wide-ranging. Elsewhere, efforts are being made to relate survival estimates of migrating smolt obtained from PIT-tag data to factors such as migration distance, travel time, spill and flow at dams, temperature, turbidity and season. Hopefully, the information that can be obtained from hydroacoustic data can provide some process-based motivations for guiding the modeling that is done basin-wide.

5 Aknowledgements

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References

James J. Anderson, Eliezer Gurarie, and Richard W. Zabel. Mean free-path length theory of predator-prey interactions: application to juvenile salmon migration. *Ecological Modelling*, in press, 2005.

Richard W. Zabel and James J. Anderson. A model of the travel time of migrating juvenile salmon, with an application to Skanke River spring chinook. *North American Journal of Fisheries Management*, 118:558–560, 1997.

A Tables

Species	Dates	Wells tailrace		R.R. bypass		R.R. tailrace		R.I. tailrace		N
		R	n	R	n	R	n	R	n	
Chinook	4/18-5/28	20	483	-	-	20	500	-	-	983
Steelhead	4/18-5/29	20	984	-	-	20	1000	20	501	2485
Sockeye	5/15-6/9	24	499	24	498	24	497	24	496	1990

Table 1: Table of hydroacoustically tagged salmon smolt releases in spring and summer 2005. R refers to the number of releases at each location. The smolt were released into the river typically every other day in the date interval indicated in teh *Date* column.

A: Chinook

Reach of river	Distance (miles)	N	Events	MI (%/mile)	SE
A: W to BB	11.6	483	8	0.143	0.050
B: BB to RR	30.12	475	23	0.161	0.033
C: RR to HP	16.73	952	48	0.301	0.042
D: HP to RI	3.55	904	7	0.218	0.082
E: RI to CB	10.88	897	37	0.379	0.061
F: CB to SE	11.44	860	35	0.356	0.059
TOTAL	84.32	984	158	M total:	0.161

B: Sockeye

Reach of river	Distance (miles)	N	Events	MI (%/mile)	SE
A: W to BB	11.6	499	25	0.432	0.084
B: BB to RR	30.12	474	7	0.049	0.018
C: RR to HP	16.73	1462	77	0.315	0.035
D: HP to RI	3.55	1385	4	0.081	0.041
E: RI to CB	10.88	1877	51	0.250	0.034
F: CB to SE	11.44	1826	34	0.163	0.028
TOTAL	84.32	1991	198	M total:	0.099

C: Steelhead

Reach	Distance (miles)	N	Events	MI (%/mile)	SE
A: W to BB	11.6	984	29	0.254	0.046
B: BB to RR	30.12	955	40	0.139	0.022
C: RR to HP	16.73	1915	66	0.206	0.025
D: HP to RI	3.55	1849	18	0.274	0.064
E: RI to CB	10.88	2332	147	0.579	0.046
F: CB to SE	11.44	2185	118	0.472	0.042
TOTAL	84.32	2845	418	M total:	0.147

Table 2: Table summarizing mortality events and mean intensity of mortality. N refers to the number of smolt entering a reservoir and MI represents intensity of mortality presented as percent probability of mortality per river mile. Standard errors are measured using the variance from a standard binomial model $\hat{\sigma} = \sqrt{p(1-p)/N}$ scaled to the length of the reach.

	Surviving Fish		Dead Fish	
	mean length	sd	mean length	sd
Ch	162.65	13.09	161.01	12.97
Sk	117.37	7.35	118.15	6.44
St	184.69	18.56	181.74	18.87

Table 3: Comparison of lengths of surviving and dead fish. Statistically, the lengths are identical.

B Figures

Figure 1: Map of release and detection locations along the mid-Columbia river

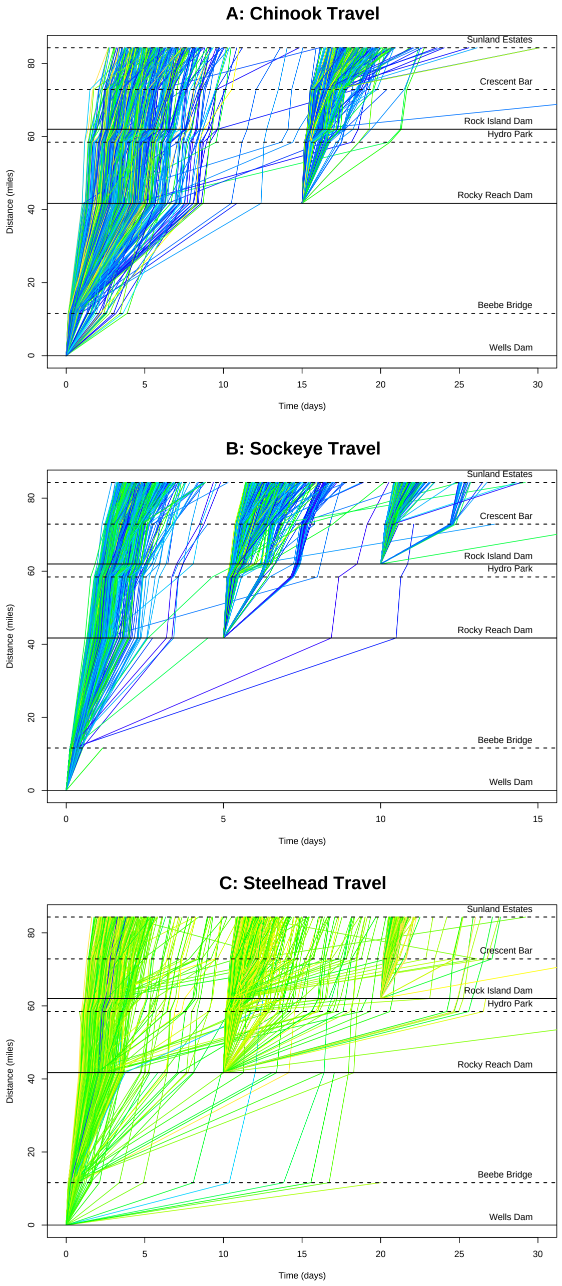


Figure 2: Travel tracks for (A) chinook, (B) sockeye and (C) steelhead juveniles. Darker blue colors represent smaller fish, while yellower colors represent larger fish. While the separate locations of release are separated for clarity, the actual date of release of is not reflected in the plot. Distance traveled is presented along the y-axis while days of travel are on the x-axis; a steeper track represents a fish that spends relatively little time in a given stretch. A track that terminates is a mortality event.

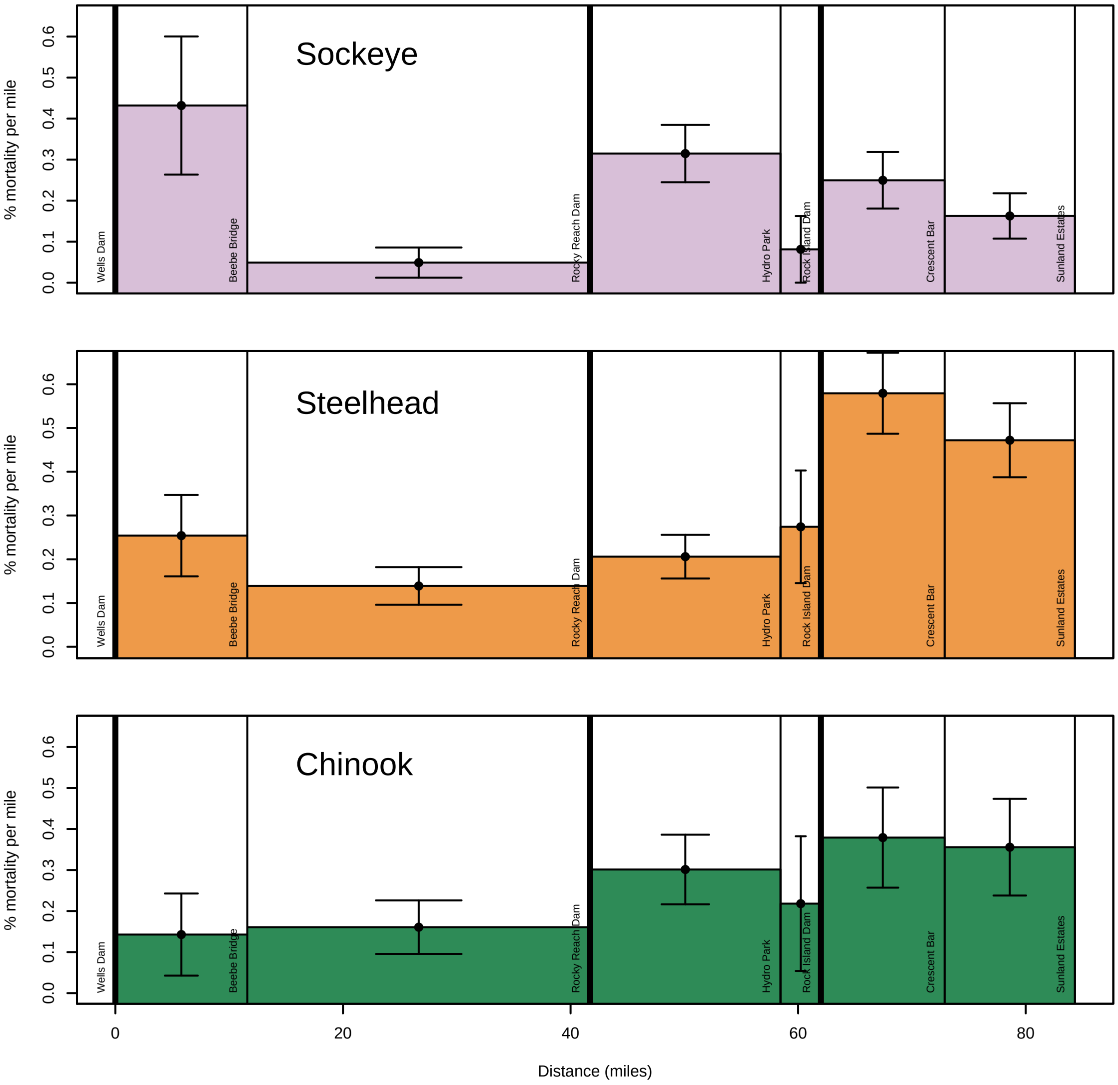
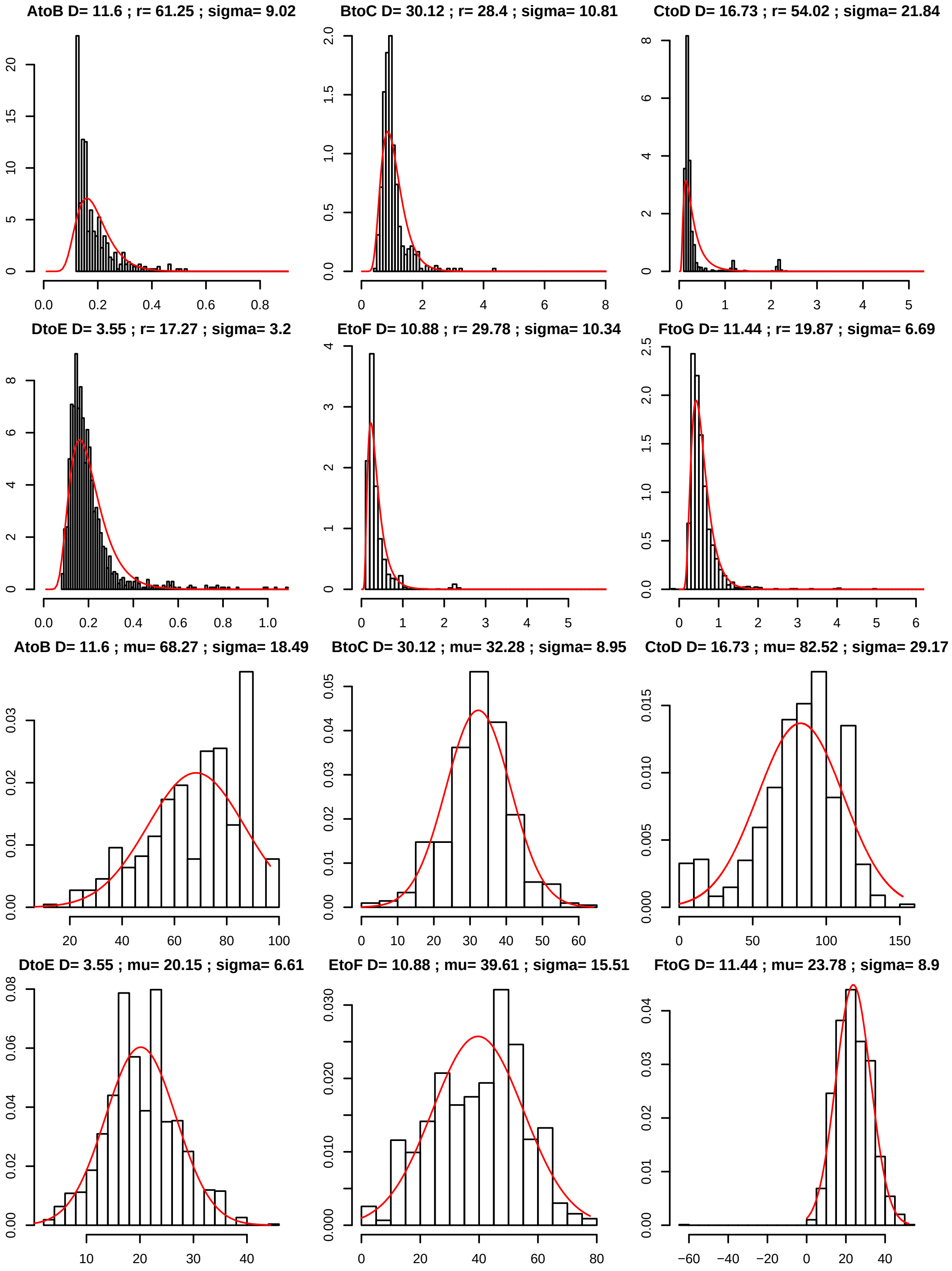


Figure 3: Intensity of mortality per stretch of each species' travel. Bold faced vertical lines indicate dams. Error bars indicate 95% confidence intervals calculated using the estimated variance from a binomial mortality model (see Table 2). The area of each rectangle is proportional to the total probability of mortality in the corresponding section.


AtoB D= 11.6 ; r= 61.25 ; sigma= 9.02

BtoC D= 30.12 ; r= 28.4 ; sigma= 10.81

CtoD D= 16.73 ; r= 54.02 ; sigma= 21.84

DtoE D= 3.55 ; r= 17.27 ; sigma= 3.2

EtoF D= 10.88 ; r= 29.78 ; sigma= 10.34

FtoG D= 11.44 ; r= 19.87 ; sigma= 6.69

AtoB D= 11.6 ; mu= 68.27 ; sigma= 18.49

BtoC D= 30.12 ; mu= 32.28 ; sigma= 8.95

CtoD D= 16.73 ; mu= 82.52 ; sigma= 29.17

DtoE D= 3.55 ; mu= 20.15 ; sigma= 6.61

EtoF D= 10.88 ; mu= 39.61 ; sigma= 15.51

FtoG D= 11.44 ; mu= 23.78 ; sigma= 8.9

Figure 4: Histograms and fits of inverse gaussian fits to travel times and normal fits to velocity distributions for Chinook travel times across all six stretches.

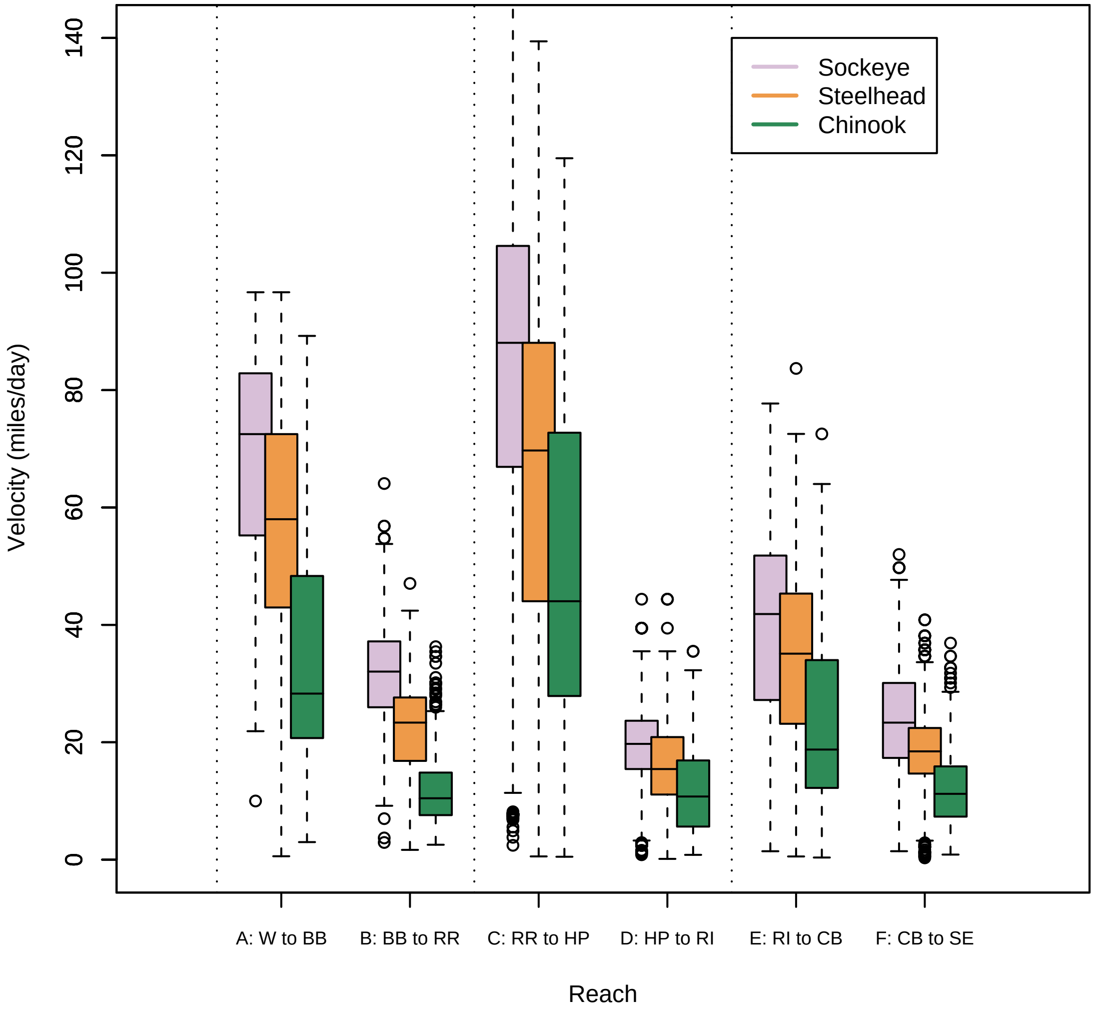


Figure 5: Boxplots of travel velocities for all three species over six reaches. Dotted vertical lines indicate passage through dams.

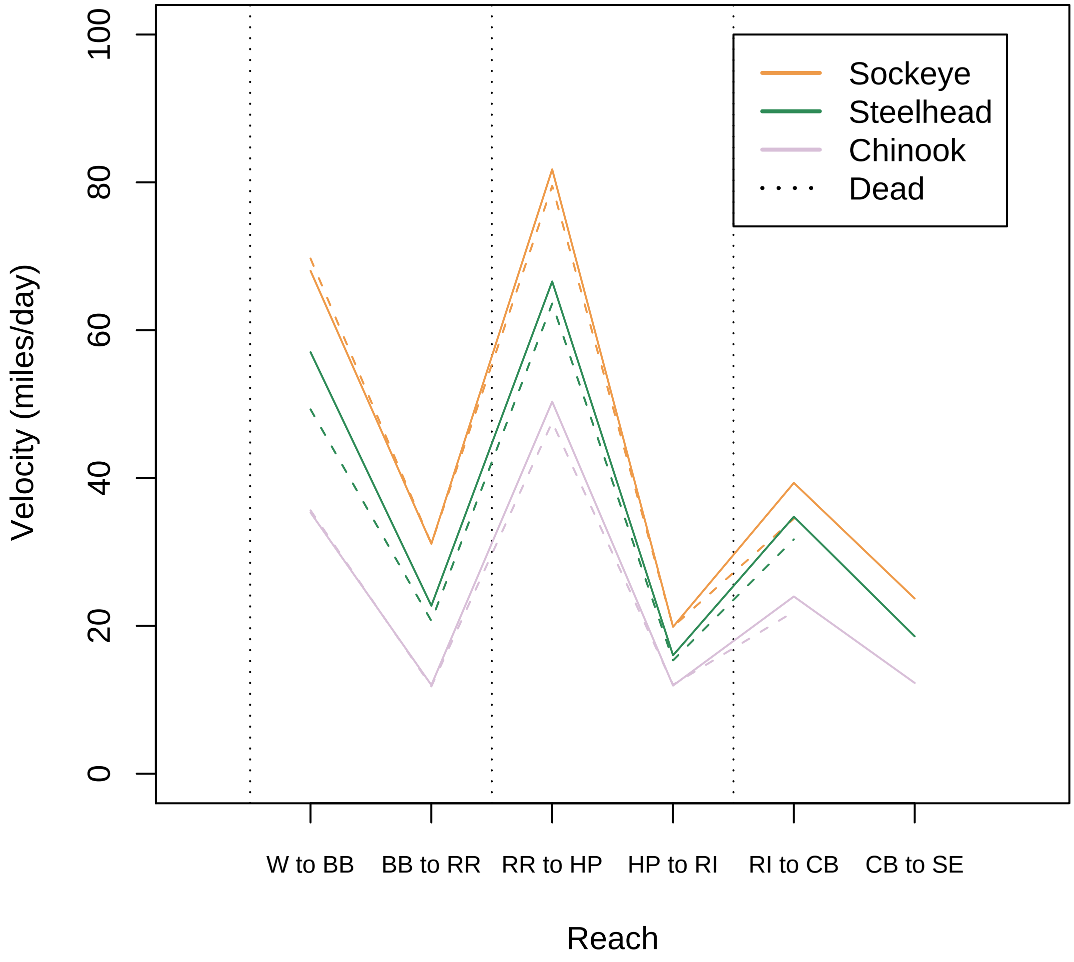


Figure 6: Interaction plot comparing the mean velocities of surviving fish (solid line) with fish that died. There are no detectable differences between the two groups. Dotted vertical lines indicate passage through dams.