Modelling upstream migration of Chinook salmon and steelhead trout

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Abstract

Upstream adult Chinook and steelhead migration is characterized primarily by swim speed and secondarily by river velocity and temperature. A fitted model of fish velocity as a function of in-river water velocity and temperature is developed.

Introduction

Theoretically, fish migration is motivated by the need to optimize spawning fitness, yet controlled by environmental conditions encountered during passage. River discharge, spill, temperature conditions and dam configurations have been shown to affect their passage rate to varying degrees.

Keefer *et al.* (2004) reviewed the important factors affecting travel rates and completed a multi-year radio-tagging study on spring-summer Chinook. They found differences in migration rates that varied over time and in response to environmental conditions. Migration rates were related to location, date of passage and river discharge. Goniea *et al.* (2006) found that very warm temperatures (> 20°C) slowed migration of adult fall Chinook. Robards & Quinn (2002) associated changes in Columbia River steelhead migration timing to flow and temperature patterns. Salinger & Anderson (2006) used a unimodal swim-speed temperature model for modeling upstream swimming of Chinook and steelhead from Bonneville dam to Lower Granite dam. Chinook have been observed passing at temperatures above and below the 16.3°C optimal. Spring runs pass in cooler water than the fall run. Steelhead mostly migrate in waters that are above optimal temperature, later in the season.

In this paper, we develop a travel rate model based on water velocity and temperature for upstream migration rates and apply it to Chinook and steelhead passage at Bonneville Dam on the Columbia River for purposes of forecasting their arrival at upstream dams.

Methods

Reach passage

Previous studies have shown that flow, temperature and time of year affect upstream migration rates to a certain extent. Swimming speed has a unimodal relationship to temperature with a peak near 16°C for Chinook, and assumed to be similar for steelhead {Salinger, 2006 #254}. Spring and summer Chinook migrate before this point, while steelhead and fall Chinook migrate later in the season, during warmer temperatures. Extremely high flows can have a negative effect on travel time but in a wide range of conditions, steelhead and Chinook can exploit counter-currents and eddies to aid them in up-river travel. Travel velocity of the fish is primarily a function of swimming speed, which has a temperature component, and to a lesser extent river water velocity which is a function of flow.

Dam passage

Several dam passage studies have attempted to demonstrate a relationship between local conditions and dam passage rates. {Zabel, 2008 #452} found that dam passage rates were partially related to flow and temperature as well as fish length but the influence of these factors varied between dams. {Keefer, 2002 #453} found that spill, flow and turbidity had limited impact on steelhead passage times. {Zabel, 2008 #452} also found that passage time can be quite protracted but variable with mean passage time ranging from 0.87 to 1.93 days at the lower Columbia dams consistent with {Keefer, 2005 #455} report that radio-tagged fish pass Columbia and Snake river dams in less than two days. A strong signal is the diel variability, with most fish passing during the day {Bjornn, 2000 #454}.

Dam passage time includes two components: time required to find and enter the dam, and time required to ascend the fish ladders and exit the dam. Collectively, the dam entry delay is most of the elapsed time and the in-dam passage is typically more rapid. Time required to enter the dam is from studies of radio-tagged individuals {Zabel, 2008 #452}.

Table 1 Time for fish to find and enter the dam.

Days equivalent for 50% to enter dam during:	BON	TDA	JDA	MCN
Day	0.47	0.81	1.15	0.96
Night	11.7	10.4	34.5	6.3
Combined	0.87	1.25	1.9	1.5

Time required to ascend the dam is computed from data on elapsed time within BON and MCA of individually pit-tagged fish. At BON, there are over 187,000 Chinook and 91,000 Steelhead records through 2013.

PIT in-dam times	BON Chinook	MCA Chinook	BON Steelhead	MCA Steelhead
< 1 hour	27%	27%	21%	21%
< 2 hours	62%	69%	62%	74%
< 6 hours	83%	88%	82%	88%
< 12 hours	89%	93%	88%	93%
< 1 day	95%	97%	95%	95%

The passage data for individuals moving upstream is constrained to observations at dams and therefore has components of both swimming velocity, dam entry and dam passage. Although the in-dam times are shown to be reasonably consistent as shown above, the dam passage is highly variable and not well related to environmental conditions which makes it difficult to model with independent variables.

The available travel time data are computed from observations of an individual fish at a downstream dam followed by an observation at an upstream dam. The elapsed time therefore includes in-river swimming and passage of multiple dams, making the separate components difficult to isolate. As a result, we develop a model for upstream movements based on the overall distribution of velocities which has statistical properties that are easy to compute.

Grand mean velocity of a population is computed from the data directly. The residual velocities were then fit with a linear model using river conditions as predictor variables. A suite of linear models were considered including linear, quadratic and interaction terms for water velocity and temperature. The data are noisy and sensitivity to environmental conditions is weak. Natural variability is high.

Data

PIT-tag data on more than 150,000 individual fish and environmental conditions are from the DART database (www.cbr.washington.edu\dart). Each fish was first detected at Bonneville and then subsequently upstream at one or more locations.

Fish were initially divided into groups for analysis according to species (Chinook or steelhead) and final upstream destination (Columbia, Snake River, or Yakima). Then we examined the travel rates of these groups for additional relationships to environmental conditions. Any further distinctions were initially ignored assuming that any other differences in travel rate would be mechanistically related to an environmental factor (e.g. temperature, water velocity) or a physical factor applicable to the fish (e.g. gender, size).

PIT tag passage records were processed to determine travel-velocity over-the-ground (km/d) in the lower (BON – MCN) and/or upper river (IHR to LWG, or PRD to WEL) along with environmental conditions during their in-river passage. The individuals were grouped into cohorts based on their tagging attributes. Cohorts were also divided by destination and the Chinook separated by season (spring/summer or fall) and the upper and lower reaches modeled separately.

Velocity distributions for each cohort were then examined for unimodality. This was true for the Chinook but not the steelhead. There is no clear indicator of whether a steelhead fish will be fast or slow. Figure 1 shows the breakdown of swim velocities based on other attributes.

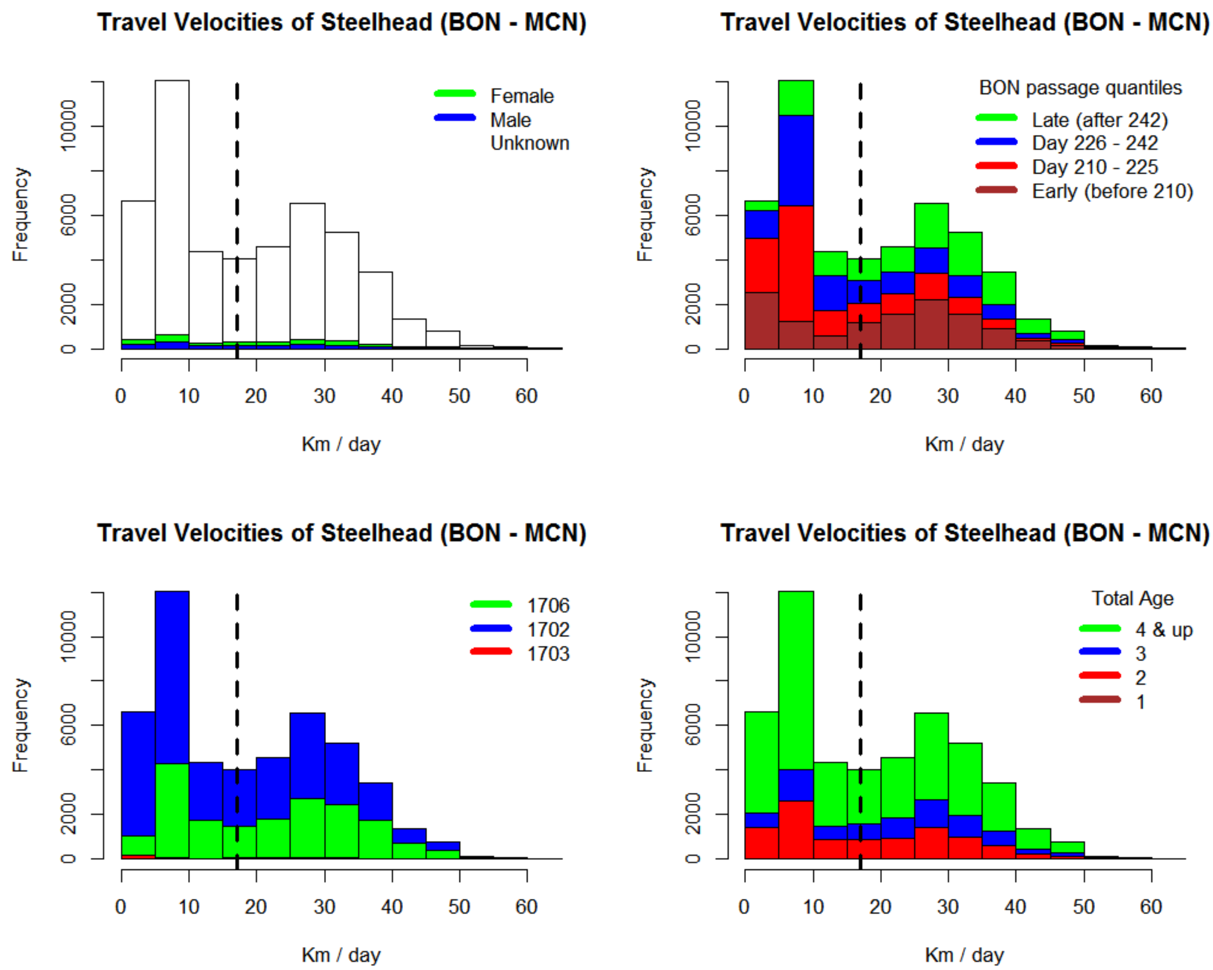

Figure 1 Bi-modal distribution of steelhead travel velocities between BON and MCN is depicted by these histograms. There is no clear predictor of which will be fast or slow based on other attributes. Upper left: sex; upper right: BON passage day-of-year; lower left: HUC; and lower right: Age in years. The median velocity is shown with the dashed vertical line.

As a result, the steelhead were also broken into two groups: fast and slow, based on their individual travel velocity relative to the population's mean velocity. Each distribution was then unimodal.

The full model is:

$$FishVel = FishVel_{mean} + Vel_{H_20} + Vel_{H_20}^{\;2} + Temp + Temp^2 + Vel \bullet Temp$$

Sub-models without one or more terms were considered and the final model for a stock was based on the one with the lowest AIC score.

Water velocity and temperature are computed with the COMPASS model. The model takes into account flow and reservoir elevations with reach-specific velocity-flow relationships in order to forecast velocities. The temperature sub-model is based on long-term averages and flow conditions. Each day that new data are available, the DART in-season process replaces forecasted values with observations, recomputes forecasted condition and runs again.

Results

Using PIT tag data from 2008 – 2014, the fitted parameters for the upstream velocity of various stocks are shown in Table 2. The difference between the observed and modelled mean travel time varied with stock and year as shown in Table 3. Grand mean error of observed minus modeled travel time is 0.02 days. Range is from -11.7 to 3.3. Years 2002 – 2007 were used as a validation set. Terms not improving AIC were omitted from the full model for the specific stocks (---).

Table 2 Linear model fitted parameters for travel velocity of 12 stocks in the lower Columbia and stock-specific upper reaches.

Stock	MedianVelMCA	MeanVelMCA	b0	bVel	bVel2	bTemp	bTemp2	bVelTemp	vVar
SnakeSpr	39.149	38.156	38.156	-0.322	-0.002	2.367	-0.114	0.014	106.320
UColSpr	37.092	35.849	35.849	-0.551	-0.001	2.872	-0.139	0.025	81.953
YakSpr	34.955	34.811	34.811	-0.111	-0.002	1.897	-0.088	---	87.592
SnakeFall	39.906	39.167	39.167	-1.089	-0.008	3.040	-0.150	0.066	75.897
UColFall	38.541	37.749	37.749	9.192	-0.019	-11.263	0.530	-0.409	54.156
YakFall	38.599	37.272	37.272	-5.044	---	7.457	-0.364	0.247	67.078
SnakeStlhd	27.196	27.771	27.771	0.089	---	1.525	-0.067	-0.014	58.359
UColStlhd	32.516	33.177	33.177	-0.419	0.004	0.914	-0.028	---	32.727
YakStlhd	30.102	30.785	30.785	-0.186	---	1.401	-0.063	---	38.879
SlowSnakeStlhd	5.890	6.426	6.426	0.218	---	-1.058	0.054	-0.010	6.575
SlowUColStlhd	9.777	11.706	11.706	0.718	-0.004	-1.105	0.041	-0.014	32.070
SlowYakStlhd	7.607	8.192	8.192	---	0.003	-2.059	0.097	---	15.493

Stock	MedianVelUp	MeanVelUp	b0up	bVelup	bVel2up	bTempup	bTemp2up	bVelTempup	vVarup
SnakeSpr	31.575	31.432	31.432	0.347	-0.008	-1.713	0.043	0.025	160.772
UColSpr	28.699	28.341	28.341	-0.148	---	0.018	-0.003	0.013	96.411
SnakeFall	31.413	31.351	31.351	-2.381	0.015	6.451	-0.292	0.072	85.126
UColFall	26.866	26.560	26.560	1.447	0.010	-2.390	0.121	-0.084	78.143
SnakeStlhd	21.175	20.584	20.584	0.148	0.008	-0.489	0.037	-0.031	83.491
UColStlhd	22.523	22.874	22.874	-0.495	0.004	1.580	-0.069	0.011	62.013
SlowSnakeStlhd	24.088	23.918	23.918	-3.065	0.013	4.599	-0.205	0.117	64.320
SlowUColStlhd	21.759	22.418	22.418	0.109	0.008	-2.290	0.135	-0.032	60.868

* Upstream is from PRA to WEL in the Columbia and from IHR to LWG on the Snake.

Table 3 Mean Error between observed traveltime and modeled travel time for PIT-tagged fish by year. Years 2008- 2014 (shaded) were used as the calibration data set. Years 2002-2007 demonstrate a validation of the model.

Stock	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
SnakeSpr	1.40	2.51	0.70	1.02	0.36	1.15	0.20	-0.08	0.31	-1.66	-1.83	0.32	-0.43
UColSpr	1.42	1.66	1.10	0.96	1.11	3.04	2.68	0.49	0.46	-0.36	-0.28	0.76	-0.14
YakSpr	2.62	3.26	0.57	0.79	-2.02	1.59	-1.75	-2.02	0.21	-3.14	-4.34	-0.74	-0.39
SnakeFall	1.83	1.60	1.16	1.89	1.77	1.56	-8.20	0.77	1.07	0.91	-0.31	2.30	0.72
UColFall	0.20	1.55	0.05	-1.58	-0.79	0.33	-11.72	0.12	0.22	-6.47	-9.00	-3.73	0.17
YakFall	3.11	2.13	0.76	1.05	1.92	0.10	-1.58	1.29	1.29	1.18	-0.09	2.29	0.53

Implementation

The AUM model is run daily during the adult Chinook migration season to forecast arrivals of adult salmon passage at upstream locations. The COMPASS model generates temperatures and velocities for each day of the year in distinct reaches of the Columbia River system. Reaches are typically divided at dams and confluences. The daily arrivals at Bonneville dam are known to consist of a mixture of stocks heading to different locations, and the distribution of fish allocated to each modelled stock are based on the Stock Separation algorithm (http://www.cbr.washington.edu/sites/default/files/papers/StockSeparationforAUM2008.pdf). They are them moved upstram according to the velocity which is function of the environmental variables, and elapsed time resolved to half a day. Since forecasted environmental variables change from day to day, passage forecasts made each day frequently vary from the previous day's prediction. The space-time state of each stock at each site is then reported and displayed as one of the Adult Passage Predictions on the CBR website (http://www.cbr.washington.edu/inseason/adult#).

References

Goniea T. M., Keefer M. L., Bjornn T. C., Peery C. A., Bennett D. H., Stuehrenberg L. C. (2006) Behavioral Thermoregulation and Slowed Migration by Adult Fall Chinook Salmon in Response to High Columbia River Water Temperatures. *Transactions of the American Fisheries Society,* **135**, 408-419.

Keefer M. L., Peery C. A., Jepson M. A., Stuehrenberg L. C. (2004) Upstream migration rates of radio-tagged adult Chinook salmon in riverine habitats of the Columbia River basin. *Journal of Fish Biology,* **65**, 1126-1141.

Robards M. D., Quinn T. P. (2002) The Migratory Timing of Adult Summer-Run Steelhead in the Columbia River over Six Decades of Environmental Change. *Transactions of the American Fisheries Society,* **131**, 523.

Salinger D. H., Anderson J. J. (2006) Effects of Water Temperature and Flow on Adult Salmon Migration Swim Speed and Delay. *Transactions of the American Fisheries Society,* **135**, 188-199.