CHARACTERIZING THE MIGRATIONAL DELAY OF ADULT SALMON AT DAMS USING TIME-TO-EVENT ANALYSES

Richard W. Zabel
National Marine Fisheries Service
2725 Montlake Blvd. E.
Seattle, WA 98144 USA
phone: (206)860-3290 fax: (206) 860-3267
Rich.Zabel@noaa.gov

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Introduction

In the Columbia River Basin in the northwestern United States, adult salmonids must pass up to 9 hydroelectric dams during their return migration. Although fish ladders are provided for upstream passage, fish are delayed at dams because the attractive flows of the ladders are interspersed among several other sources of flow. Here, I present preliminary results from some new analyses to understand the delay of adult salmon at dams. I applied "time-to-event" analyses (which are analogous to survival analyses in epidemiological studies, Hosmer and Lemeshow 1999) to data derived from radio telemetry. The main focus of the research is to relate dam delay to factors such as flow and spill level, temperature, time of day, and fish length.

Methods

In 1998, spring/summer chinook were tagged at Bonneville Dam and released several km downstream. The tagging methods are the same as those presented by Burke et al. in these proceedings. The fish were detected at fixed receivers at Bonneville, The Dalles, John Day, and McNary Dams. Dam delay was defined as time elapsed between the first time a fish was detected in front of the dam to the last time the fish was detected at the entry to a fish ladder before successfully passing up the ladder (Figure 1).

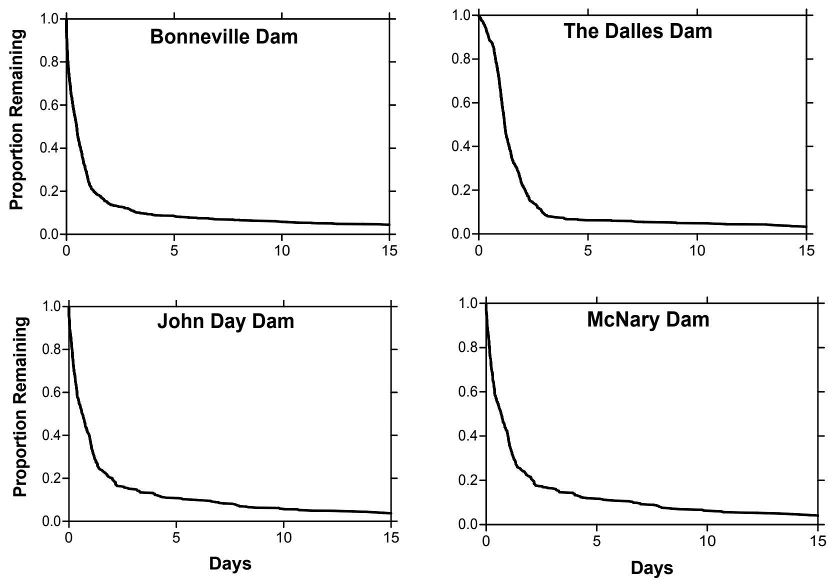

Figure 1. Proportion of adult chinook remaining versus delay time for spring (top plot) and summer (bottom plot) migrants.

Delay was modeled as a hazard function, with hazard rate, $\lambda(t)$, defined as the instantaneous rate of passage (Ross 1993). If $\lambda(t)$ is constant with respect to time, then the probability of remaining in front of a dam as a function of time is a simple exponential function:

$$\Pr(\textit{delaying t or greater days}) = \exp(-\alpha \cdot t) \qquad (1)$$

where α is the passage rate parameter. With this formulation, the mean delay time is $1/\alpha$.

The hazard rate can be elaborated as a time-varying function. In this case, the delay equation is slightly more complicated:

$$\Pr(\textit{delaying t or greater days}) = \exp(\int_0^t \lambda(\tau)d\tau \qquad (2)$$

Usually the term inside the integral is a simple function and easily integrable. As an example, I developed a diel model, where passage rate varied according to the time of day:

$$\lambda(t) = \begin{cases} \alpha_N \ \textit{during nighttime hours} \\ \alpha_D \ \textit{during daytime hours} \end{cases} \qquad (3)$$

I expanded this model to relate passage rate to predictor variables. Since the majority of passage occurred during the day, the daytime passage rate in equation (3) was modified as

(4)

where X_t is a predictor variable (which may be time-varying) and α_X is a fitted coefficient. Here I present results for the factors fish length and river temperature (measured hourly). We are currently working on applying equations (3) and (4) to spill and flow measured hourly.

Model parameters were estimated by maximizing the likelihood function. The more complex models were compared to the simple model (equation (1)) using Akaike's Information Criterion (AIC). For each model, an AIC value was calculated, and the model with the highest value was selected as the "best."

Results and Discussion

The passage rate coefficient from the simple model was similar at all four dams, with mean delay ($1/\alpha$) ranging from 2.24 to 2.93 days. For all four dams, the diel model conferred a considerable improvement over the simple model. This is consistent with observations that most fish pass during the day. Temperature was always more important than fish length in predicting delay. For two dams

(The Dalles and McNary), the effect of fish length was negligible based on comparing AIC values between the length and diel models.

Little is known about the cumulative effects of upstream passage delay at dams (NRC 1996), but the duration of delay is substantial (Figure 1). The methods presented here offer a valuable approach to understanding the factors contributing to delay, and potentially this information can be used to reduce delay.

References

Hosmer, D. W., and S. Lemeshow. 1999. Applied survival analysis: Regression modeling of time to event data. John Wiley and Sons, New York.

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Ross, S. M. 1993. Introduction to probability models, 5th edition. Academic Press, Inc., Boston

Table 1. Results from the application of the models (equations 1 through 4) to the delay data. Parameters are maximum likelihood estimates. N is the number of fish.

	Model	α or α_N	α_0 or α_D	α_X	AIC
Bonneville Dam	Simple	0.436			
	Diel	0.085	1.506		660.16
N = 860	Fish Length	0.083	4.164	-0.035	717.99
	Temperature	0.083	0.220	0.089	723.87
The Dalles Dam	Simple	0.400			
	Diel	0.108	0.678		373.50
N = 681	Fish Length	0.108	0.164	0.007	376.33
	Temperature	0.108	0.046	0.048	423.07
John Day Dam	Simple	0.341			
	Diel	0.029	0.607		421.62
N = 547	Fish Length	0.029	1.578	-0.012	446.63
	Temperature	0.029	0.94	0.036	451.65
McNary Dam	Simple	0.447			
	Diel	0.171	0.673		182.57
N = 453	Fish Length	0.172	1.446	-0.009	189.79
	Temperature	0.172	0.022	0.048	257.56