PRODUCTIVITY DYNAMICS IN SPRING-RUN CHINOOK SALMON IN ADJACENT DAMS

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It is intuitively to assume that spatially adjacent stocks or populations have similar productivity (e.g., Malick & Cox, 2016; Peterman et al., 2003) and that diversity of migratory groups are essential to maintaining a self-sustainable wild population (Schroeder et al., 2016). However, this is not always true (e.g., Korman and English 2013). Where it has been found that there exist marked differences in productivity and stock status between adjacent stocks, it is not always immediately obvious why these differences have arisen and attention can often be focused on stocks that are doing poorly (Korman et al. 2019). It is helpful to focus attention also on salmon stocks that are doing better than their neighbors to help to improve understanding about reasons for the differences and which measures, if any, could be taken to improve populations that are performing poorly.

In the Willamette River System, for example, contrary to other spring-run Chinook salmon (*Oncorhynchus tshawytscha*) populations in the Willamette River, that in Fall Creek in the past decade appear to have become a self-sustaining population (Murphy et al., 2019). A focused analysis of the Fall Creek spring Chinook salmon population might create new insights regarding dam operation effects in population declines/recovery on spring-run Chinook salmon. To address this, a life cycle model using the multistage Beverton-Holt model (msBHM) (Moussalli & Hilborn, 1986) was developed for Fall Creek to assess the present and future self-sustainability for spring Chinook:

$$N_{s+1}=\frac{N_s}{\frac{1}{p}+\frac{1}{c}N_s}$$

where N_{s+1} are the individuals alive at the life stage s, p is the productivity or survival rate from s to s +1 and, c is the capacity for the life stage s. The msBHM predicts abundances from one life stage to another based on productivity (or survivorship) and stage capacity, and the number of stages usually is determined by available data.

Uncertainty is typically propagated in msBHMs by using statistical distributions (e.g., uniform, lognormal) for the survival rates capacity and functional relationships (e.g., PSM=f(temperature), where f can take any form) parameters from which the model will draw random variates at each time step (Scheuerell et al., 2006). Contrary to this typical approach, we used a statistical framework to fit available time series of data to the msBHM. In addition, prior knowledge from other studies or analyzes were incorporated as a prior probability distribution to estimate key survival rates as part of the model estimation. Time series of the total adult returns (1965-2022), redd counts expanded to Fall Creek (2002-2017), juvenile stocking above the dam (1965-1968; 1990-2005), and above-dam pre-spawn mortality estimates (2010-2018) were used. A Cormack-Jolly-Seber (CJS; Cormack, 1964; Seber, 1965) model based on Fall Creek data was used to derive a prior distribution for smolt-to-adult survival (SAS). Other survival or productivity

capacity parameters (e.g., egg and spawner capacity, fry-smolt survival, smolt-reservoir-dam-freshwater survival, etc.) were estimated (e.g., from CJSM) or derived from the literature.

The model was fitted using penalized likelihood estimation (ML). Penalized ML estimation minimizes an objective function, i.e., a log-posterior function of the log-likelihood(s) and additional information given by the (log) prior(s) distribution. The model included process and observation errors. Different models were constructed to assess the fit. Overall, there is little information to estimate time-varying parameters to accommodate possible changes in productivity or capacity other than SAS.

SAS shows significant interannual variability across many salmon stocks (e.g., Beamish, 1993; Mantua et al., 1997; Welch et al., 2021). To conform to this hypothesis, the msBHM estimated annual deviates for SAS to explain changes in adult returns. Other parameters, such as above-dam PSM, were freed up when possible. We assumed that adult returns at Fall Creek dam and redd counts contained sufficient information to estimate above-dam PSM, and we developed priors for PSM from a short time series of PSM estimates (derived from a statistical model fit to data). The msBHM fitted the estimated annual deviates for SAS, SAS, and above-dam PSM (for most recent years).

The msBHM fitted the total adult returns well but (as with any model) depended on the model/parameter assumptions (e.g., the log-likelihoods and model parameters included in the model estimation). The model predicted two periods of high adult returns. First, after the dam was built in 1965 and juvenile stocking was established, which produced returns of sometimes over 2,000 adults (with a maximum of 4696 adults in 1969).

The second period of abundance occurred in 2002-2004 (with adult return abundance estimated over 1,300). In this case, the stocking program started in 1990, indicating that the stocking program/dam passage was initially ineffective. Interestingly, the two peaks were quite abrupt, like declines, with rapid increases from low adult returns in previous years. The first period of high abundance might be explicated by the stocking program and dam operations that effectively passed juveniles through the dam. For the second peak, however, it is possible that changes in dam operations improved adult returns from juveniles only stocked in 1999-2001 (assuming a mean return at age is 4 –years old). The stocking program was discontinued in 2005.

This empirical information and model outputs show that the Fall Creek reservoir has a high juvenile survival/capacity (Homolka & Smith 1991). Thus, given optimistic dam passage conditions (e.g., during 1965-1968), the Fall Creek reservoir could produce significant adult returns. In the presence of only wild Chinooks (i.e., after 2009, where only wild fish are outplanted and no stocking), the population can produce, on average, 400 adult returns (range 103-874; twice the number than during the stocking program 1990-1998).

As is typically found in fish stock assessment (Schnute & Hilborn, 1993), the time series showed contradictory information (e.g., the model cannot simultaneously fit the time series of total adult and redd counts). This could indicate that important processes occur after adults are outplanted, and outplantings are not a good indicator of resulting redd counts (and vice versa); however, there are cases where outplants are a good indicator of redd counts; Gallagher & Gallagher, 2005). Alternatively, the redd counts could have considerable bias and/or uncertainty; e.g., the time series of redd counts showed high interannual variability.

Model projections used the mean SAS estimate and the most recent annual mean SAS deviations and PSM estimates. The results show that the adult returns by 2032 could reach an average of 580 if the model weights adult returns more highly, or 760 if it weights redd count more highly. In both situations, the mean SAS prior was updated to 0.037. Recent estimates (e.g., SAS deviations) reflect present productivity conditions unless persistent autocorrelated deviations are observed in the time series, which was not detected. In addition, before 2009, juvenile stocking above Fall Creek might still be "influencing" SAS estimates, so those were not included in the projections. After 2009 only wild chinook are outplanted; thus, the projections reflect better the wild population dynamics.

Most juvenile dam passage appears to occur during fall drawdown (Murphy et al., 2019), and tagging studies show high reservoir survival and dam passage at Fall Creek (Homoka & Smith, 1990). It seems that a limited diversity of migratory groups (e.g., fry and subyearling) could maintain a wild self-sustainable population if dam passage is adequate. The SAS estimates for Fall Creek contrast with the adjacent DEX-LOP Chinook population, where SAS is very low (e.g., <<0.01). This indicates that substantial improvement in reservoir survival, dam passage, and/or SAS is needed at Dexter dam to match the adult returns from the Fall Creek population. Therefore, adjacent Chinook stocks or populations do not necessarily have similar productivity, especially as dam operations can significantly impact population recovery.

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