Fisheries Research 194 (2017) 9–21

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

# Development and evaluation of a migration timing forecast model for Kuskokwim River Chinook salmon

Benjamin A. Staton[a,b,*], Matthew J. Catalano[a], Troy M. Farmer[a], Asheber Abebe[c], F. Stephen Dobson[d]

[a] School of Fisheries, Aquaculture, and Aquatic Sciences, Auburn University, 203 Swingle Hall, Auburn, AL 36849, United States
[b] U.S Fish and Wildlife Service, Yukon Delta National Wildlife Refuge, P.O. Box 346, Bethel, AK 99559, United States
[c] Department of Mathematics and Statistics, 221 Parker Hall, Auburn University, Auburn, AL 36849, United States
[d] Department of Biological Sciences, 101 Rouse Hall, Auburn University, Auburn, AL 36849, United States

## ARTICLE INFO

Handled by Prof. George A. Rose

*Keywords:*
Pacific salmon
Phenology
Arrival timing
Forecast
Climate variable selection

## ABSTRACT

Annual variation in adult salmon migration timing makes the interpretation of in-season assessment data difficult, leading to much in-season uncertainty in run size. We developed and evaluated a run timing forecast model for the Kuskokwim River Chinook salmon stock, located in western Alaska, intended to aid in reducing this source of uncertainty. An objective and adaptive approach (using model-averaging and a sliding window algorithm to select predictive time periods, both calibrated annually) was adopted to deal with multidimensional selection of four climatic variables and was based entirely on predictive performance. Forecast cross-validation was used to evaluate the performance of three forecasting approaches: the null (i.e., intercept only) model, the single model with the lowest mean absolute error, and a model-averaged forecast across 16 nested linear models. As of 2016, the null model had the lowest mean absolute error (2.64 days), although the model-averaged forecast performed as well or better than the null model in the majority of retrospective years. The model-averaged forecast had a consistent mean absolute error regardless of the type of year (i.e., average or extreme early/late) the forecast was made for, which was not true of the null model. The availability of the run timing forecast was not found to increase overall accuracy of in-season run assessments in relation to the null model, but was found to substantially increase the precision of these assessments, particularly early in the season.

## 1. Introduction

In-season management strategies for Pacific salmon *Oncorhynchus* spp. fisheries rely heavily on indices of in-river abundance (e.g., test fisheries, sonar counts, etc.) to inform harvest control rules that attempt to attain the balance of meeting pre-determined escapement objectives while allowing adequate opportunity for harvest (Catalano and Jones, 2014). However, because indices of abundance are confounded by the phenology (i.e., timing) of the migration, their interpretation is very difficult in-season. For example, smaller-than-average index values early in the season could be due to either a small run with average timing or by a late large run, when interpreted in the context of historical years (Adkison and Cunningham, 2015). This ultimately leads to great uncertainty about how much of the incoming run has passed, which is a key piece of information that dictates fishery harvest opportunities. There exists no information in the current year's abundance index to inform the manager if (for example) 25% or 75% of the run has passed on any given day. Yet, depending which is true, the optimal management decision could be vastly different. Thus, in-season assessment typically involves some characterization of the variation in historical run timing to formulate a range of possible run size scenarios that could be representative of the current year's run size. However, given the amount of variation in historical run timing, these scenarios are rarely informative during the majority of the migration, when key harvest decisions are being made because the run scenarios may span all possible run sizes. As a result, the pre-season run size forecast remains the most precise piece of information for much of the season. If it were possible to predict the timing of the incoming run (e.g., earlier- or later-than-average) with some level of confidence, it could prove valuable for in-season assessment and decision-making by reducing uncertainty in run size predictions.

While previous research has uncovered several key physiological mechanisms that are involved with natal homing (Hasler and Scholz, 1983) and return migrations of adult salmon to freshwater environments (Cooperman et al., 2010; Cook et al., 2008; Hinch et al., 2012), the exact physiological and behavioral responses of adult salmon to

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[*] Corresponding author at: School of Fisheries, Aquaculture, and Aquatic Sciences, Auburn University, 203 Swingle Hall, Auburn AL 36849, United States.
*E-mail address:* bas0041@auburn.edu (B.A. Staton).

http://dx.doi.org/10.1016/j.fishres.2017.05.003
Received 8 February 2017; Received in revised form 3 May 2017; Accepted 5 May 2017
0165-7836/ Published by Elsevier B.V.

relatively small-scale environmental gradients within estuaries, which are likely the ultimate determinants of freshwater entry timing, are still poorly understood. Despite this uncertainty, several hypotheses have been put forth that are broadly consistent with the observed timing patterns of several species across a large geographic area (i.e., western and southwestern Alaska). Two primary influences have been suggested: genetic (Quinn et al., 2000; Anderson and Beer, 2009; O'Malley et al., 2010) and environmental (Hodgson et al., 2006; Keefer et al., 2008) mechanisms. Substantial evidence exists to suggest that both genetic and environmental controls are involved in determining migration timing, however it is broadly thought that genetic variation influences sub-stock variation (i.e., different tributary spawning groups within the same major river basin) and environmental variation influences the timing of the aggregate (i.e., basin-wide) run (Keefer et al., 2008; Anderson and Beer, 2009). This is consistent with the notion that genetically distinct components of the aggregate run behave differently as a result of their life history strategies and/or the characteristics of their specific spawning grounds (e.g., sub-stocks that must travel farther in-river to reach spawning grounds enter freshwater earlier [Clark et al., 2015]; sub-stocks that spawn in tributaries influenced by warmer lakes enable later spawning; [Burger et al., 1985]) but that certain environmental conditions act on the aggregate run to either hasten or delay freshwater entry. It has also been suggested that run size may have an influence on migration timing, although empirical support for this claim seems to be lacking. If there were indeed relationships between run timing and run size, these need to be quantified as certain combinations are particularly troublesome for managers (e.g., small/early runs and large/late runs appear the same early in-season; Adkison and Cunningham, 2015).

At the aggregate population scale, which is the focus of this paper, it has been observed that migrations occurring in the spring and summer generally occur earlier in years with warmer spring temperatures (Mundy and Evenson, 2011; Hodgson et al., 2006). Mundy and Evenson (2011) suggested that this pattern may be explained by the stability of the estuarine water column where adult salmon stage in preparation for riverine entry (or alternatively, marine exit). High estuarine water column stability was hypothesized to impede riverine entry through two mechanisms: (1) by presenting an osmotic barrier between freshwater riverine discharge and the saline ocean water which prevents osmotically incompetent individuals from crossing and (2) by preventing freshwater competent individuals from receiving olfactory cues essential to the homeward migration. Thus, Mundy and Evenson (2011) hypothesized that years in which the estuarine water column is stable over a longer period of time would be associated with later migration timing. Although water column stability is a difficult variable to measure over large spatial scales, several variables that are known to influence it are available at large scales via remote sensing (e.g., satellite observations). Such variables are sea ice cover which prevents wind-driven mixing, associated local temperature-related variables like land-based air temperature or sea surface temperature (SST), and broader scale indicators such as the Pacific Decadal Oscillation (PDO), an index of temperature anomalies in the northern Pacific Ocean. Observational studies across the North American range of Chinook salmon have found environmental-run timing correlations that are consistent with this hypothesis (Hodgson et al., 2006; Keefer et al., 2008; Mundy and Evenson, 2011). Even if the water column stability hypothesis is incorrect, observed patterns suggest that environmental variables may be used to forecast run timing with some level of accuracy and certainty.

Several efforts have been made at exploiting these environmental-run timing relationships to develop run timing forecast models for Pacific salmon migrations. Mundy and Evenson (2011) developed a model for Yukon River Chinook salmon (*O. tshawytscha*) that used air temperature, sea surface temperature, and ice cover to predict the day at which the 15th and 50th percentiles of the run passed a test fishery index location. Model predictions fit the observed data well (nearly always within seven days, usually within three days), although out-of-sample predictive ability was not presented (Mundy and Evenson, 2011). Keefer et al. (2008) developed a similar framework for Columbia River spring run Chinook salmon and found run timing relationships with river discharge, river temperature, and ocean condition indices (e.g., PDO). Their best model explained 49% of the variation in median run timing with variation in the environmental variables. Anderson and Beer (2009) continued this work on the Columbia River spring Chinook stock, but added genetic components to their analysis based on the arrival timing of precocious males. Their findings revealed that both environmental variables and changes in abundance of genetically distinct populations, which had their own distinct migration timing, affected overall run timing of the spring Chinook salmon run in the Columbia River. These advancements have shown that relationships between migration timing and environmental variables exist and may have utility for use in forecasting efforts.

The Kuskokwim River, located in western Alaska, is the second largest river system in the state and supports culturally and economically important Chinook salmon fisheries. Chinook salmon return beginning in late May and continue through early August, with the median date of passage occurring between June 14th and July 2nd. Fisheries within the region harvest salmon in-river during freshwater migrations using primarily drift gillnet gear. The Kuskokwim River salmon fishery has a distinct cultural importance: nearly all inhabitants are native Alaskans belonging to the Yup'ik group and take salmon for subsistence purposes (Linderman and Bergstrom, 2009). While commercial salmon fisheries operate within the river, these fishers often also participate in subsistence take and revenues from the sale of commercially-harvested salmon often contribute directly to participation in subsistence activities (Wolfe and Spaeder, 2009). To ensure long-term sustainable harvest, the Chinook salmon fishery is managed with a drainage-wide escapement goal derived from an age-structured state-space spawner-recruit analysis (Hamazaki et al., 2012; Staton et al., 2017). To meet these pre-determined escapement goals, in-season management strategies implement time, gear, and area closures based on limited and imprecise information regarding annual run size. The distant locations of the majority of escapement assessment projects makes direct measurement of escapement performance unavailable until late in the season. Thus, the primary sources of run size assessment information are (1) a pre-season run size forecast range (previous year's run size estimate ± approximately 20%) and (2) an in-river drift gillnet test fishery operated in Bethel, AK which has been implemented using consistent methods since 1984. The interpretation of this test fishery index suffers from the same issue of being confounded by run timing described earlier, making management decisions difficult. Without precise in-season indicators of run size, managers must often choose to either (1) trust a pre-season run size forecast for the majority of the season or (2) take their chances at deciding if the run is early or late when interpreting in-season data. Both options could lead to the wrong interpretation of the actual run size, which could have serious consequences for the management of the fishery (i.e., the unwarranted opening or closing the fishery resulting in severe under- or over-escapement). No published run timing forecast models currently exist for Kuskokwim River Chinook salmon but given the potential utility of independent run timing estimates for interpretation of in-season data, the development and evaluation of such a model is needed. The necessity of more accurate and precise in-season perceptions of run size is particularly evident in years with anticipated low runs, such as in recent years (i.e., since 2010), as this may allow managers to more effectively guard against over-exploitation while still allowing for limited harvest opportunities to support the cultural and subsistence needs of the region.

We present an analysis that develops and evaluates the performance of a run timing forecast model for Kuskokwim River Chinook salmon. The objectives were to (1) quantify historical run timing, (2) develop a run timing forecast model using environmental variables selected based