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Project Final Product[1]

Developing tools to evaluate management strategies for sustainable exploitation of Yukon River Chinook Salmon

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II. Abstract

Canadian-origin Chinook Salmon in the Yukon River are managed jointly though an agreement between the United States and Canada on requirements for passage of sufficient numbers of salmon into Canada to maintain sustainable levels of escapement and provide for fishery needs. Uncertainty about the future dynamics of this population, effects of long-term changes in population structure and advances in assessment methodologies have motivated interest in examining this fishery using modern quantitative methods. After engaging with members of the Yukon River Panel Joint Technical Committee, we updated a state-space run-reconstruction and stock-recruitment model and developed a Management Strategy Evaluation (MSE) model for this population and its associated fisheries. We developed two models, one using traditional methods that do not consider the effect of changes in population structure on effective escapement (escapement quantity model), and a second that explicitly considered age, sex, and length dynamics in modeling escapement (escapement quality model). The two modeling approaches resulted in similar run reconstructions, but moderately different stock-recruitment relationships – the escapement quality model exhibited a larger escapement associated with maximum recruitment. However, the uncertainty associated with parameter estimates for both models was large relative to the differences on point estimate values. The MSE models revealed very limited differences in outcomes and trade-offs among management objectives between the two stock-recruitment models. Several notable trade-offs were made evident from the MSE model analysis, including trade-offs between US commercial harvest and outcomes for escapement, Canadian commercial harvest, and Canadian subsistence harvest. In general, lower harvest rates and higher escapement targets were favored for these three up-river outcomes, than would be optimal for US harvest. On the other hand, moderate US commercial harvests were achievable with policies that would be preferred for up-river stakeholders. Finally, MSE simulations demonstrated lower harvest rates and/or higher escapement targets are needed when using large mesh (e.g., 7.5”) gillnets for the fisheries rather than smaller mesh (e.g., 5.25”) gear. Future use of the evaluation tools described in this report will have greater impact if they are employed in an open, transparent manner that engages key stakeholders.

Keywords: (up to 12 terms, alphabetical)

Canadian-origin, Chinook Salmon, escapement quality, Management Strategy Evaluation, state-space model, stock-recruitment, Yukon River

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IV. Introduction

A central objective of fisheries management is to ensure the sustainable harvest of fish populations (Hilborn and Walters 1992). Management decisions are ideally informed by quantitative analyses of data, which for Pacific salmon, typically include sources such as fishery landings, escapement counts and age compositions. Fishery management decisions are often challenging due to uncertainty in system structure, dynamics, and the quantity and quality of data. For salmon fisheries of the Arctic-Yukon-Kuskokwim (AYK) region of Alaska, these uncertainties are particularly prevalent due to the vast size and remoteness of the area, which makes data collection programs difficult and expensive. This study presents a framework for the structured analysis of Chinook Salmon data with the goal of informing management decisions using cutting-edge analytical techniques that account for multiple sources of uncertainty. The framework includes a state-space approach for run reconstruction as well as a Management Strategy Evaluation model to assess policy decisions quantitatively.

This framework extends previous analyses undertaken in the AYK region. In 2012 a run reconstruction was completed for the Canadian-origin Yukon Chinook population, and used to inform a Bayesian state-space stock-recruitment analysis (S. Fleischman, Alaska Department of Fish and Game, unpublished data). This analysis served as the basis for development of a preliminary Management Strategy Evaluation (MSE) model for this stock (Quantitative Fisheries Center, MSU, unpublished data). Outputs from the 2012 run reconstruction served as inputs for the MSE. However, the MSE model was developed after only limited engagement with biologists and managers responsible for the assessment and management of this population. Consequently, it was not known if the objectives and details were fully consistent with management needs and understanding of the system. In this study we revisited both the stock-recruitment analysis and the MSE model, this time soliciting input from regional biologists and managers (members of the Yukon River Panel's Joint Technical Committee) using a structured approach. As a consequence of this input, we became particularly interested in considering aspects of population structure that have been hypothesized to influence escapement quality, which refers to the per-capita fecundity of the spawning run. Factors that result in a run comprised of large females, for example, would exhibit higher per-capita fecundity than a run of small fish and thus would be considered to have a higher quality of escapement.

Our overall goal was to use the MSE methodology to develop a tool to elucidate and quantify trade-offs among potentially conflicting management objectives, while explicitly accounting for uncertainty about system dynamics. We also sought to assess whether these tradeoffs were altered when we accounted for escapement quality in our run-reconstruction and MSE models.

4.1 State-space run-reconstruction model

Run reconstruction refers to the process of estimating annual escapement and corresponding recruits. The term state-space model refers to a dynamic (i.e., sequential in time), statistical model that includes sub-models for both process errors and observation errors. The model we developed uses time series of harvest data, 11 abundance indices and age compositions to reconstruct the run. The time series of data run from 1982 to 2015 but not all sources have complete time series (details are summarized in Table 6.1). In addition to the run abundance reconstruction, the state-space model also estimates a relationship between stock and recruits, which for this analysis we assume to follow a Ricker formulation.

Our discussions with biologists and managers revealed concerns about changes in age and sex composition of returning Chinook Salmon over time. Specifically, large, old, females comprise a smaller proportion of the run today than they did in decades past. Since these large females carry more eggs, the concern is that a run made up of smaller individuals may produce fewer eggs, which may negatively affect recruitment if egg survival remains constant. To address this issue we formulated a version of the state-space model that accounts for both age structure and sex ratio, thus accounting for the age- and time-specific fecundity of the escaped stock. Hereafter this model will be referred to the escapement quality model. We additionally fit a more standard abundance-based model that does not incorporate age- and time-specific fecundity (stock = total number of adults returning). Below, we refer to this model as the escapement quantity model.

4.2 Management Strategy Evaluation

MSE allows an objective appraisal of policy options that explicitly considers uncertainty. Inputs to the MSE include (1) management options to be evaluated and (2) population and fishery characteristics. The policy options considered here were escapement goal (in numbers of fish) and the harvest rate on the surplus stock (surplus being the difference between the estimated run size and the escapement goal). The harvest rate was included as a policy lever in recognition of the fact that in fisheries like the Yukon Chinook Salmon fishery the total harvest taken is generally less than the total surplus above the escapement target. The population characteristics we included were obtained from outputs of the state-space model (Figure 4.1), such as the Ricker α and β parameters and their uncertainties and the initial population estimated by the run reconstruction. Fishery characteristics included simulations of alternative mesh size restrictions.

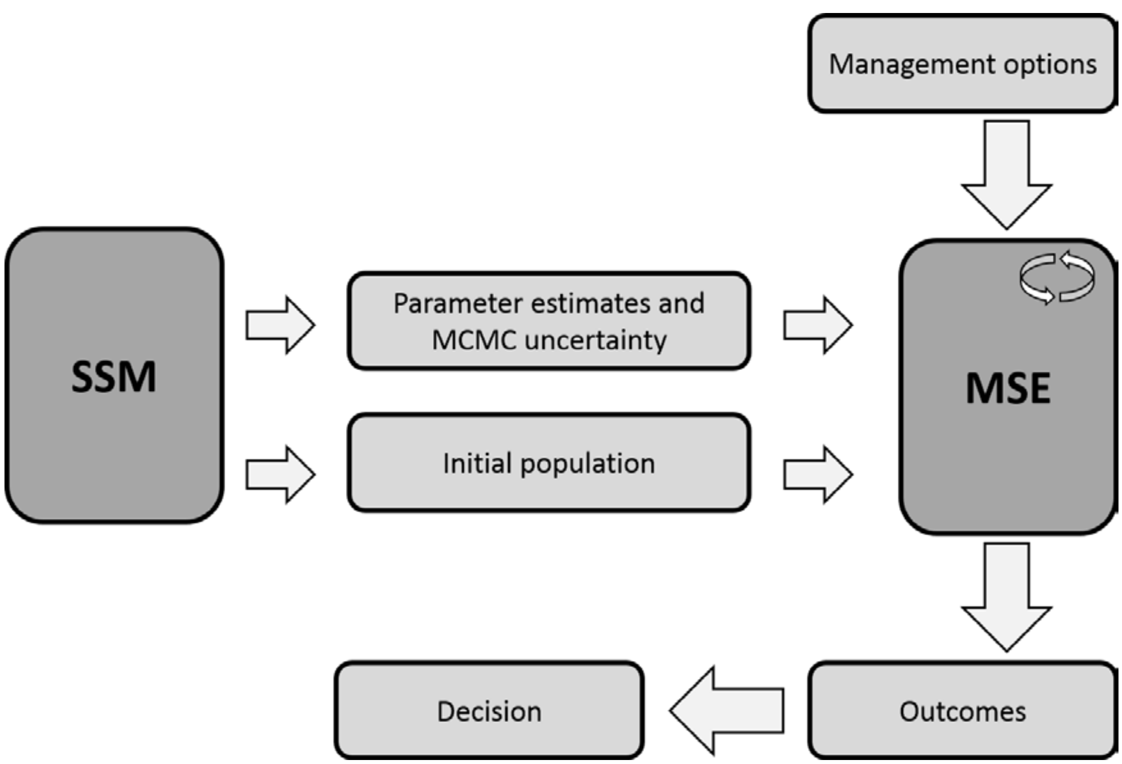


Figure 4.1. Schematic of the relationship between the state-space model, the Management Strategy Evaluation and decision-making.

Metrics of interest to decision makers (e.g., catch, total escapement, etc.) were calculated and used to inform management decisions. Uncertainty is an important component of the MSE so both the expected value and the distribution of a metric can be important. Because uncertainty is built-in, statistics such as the probability of meeting management objectives can be calculated. Most fisheries include competing objectives (e.g., catch and escapement) so the analysis of these tradeoffs is an important use of MSE models.

V. Objectives

Objective 1. In consultation with Yukon River salmon managers and biologists, identify important management objectives and issues of concern for Yukon River Chinook Salmon.

Objective 2. Review, update, and document the Canadian-origin Yukon River Chinook Salmon run-reconstruction and Bayesian state-space stock-recruitment model.

Objective 3. Develop and apply an MSE model that incorporates the results of the revised stock-recruitment analysis, to examine trade-offs among management objectives identified through completion of objective 1.

Objective 4. Engage biologists and managers throughout the project (1) to ensure an appropriate set of management objectives guides our analysis, and (2) to inform them of the MSE process, including – as appropriate – training of biologists in the analytical methods used.

VI. Methods

6.1. Consultation

We met with the Yukon River Panel Joint Technical Committee (JTC) in November 2015 in Seattle WA. During a full-day engagement we presented background material on Structured Decision Making and Management Strategy Evaluation, and briefly introduced the technical methods we intended to use for Objectives 2 and 3. We followed this with an interactive discussion of management options, objectives and critical uncertainties for Canadian-origin Yukon River Chinook Salmon, and solicited suggestions from JTC members for sources of data to inform our analysis.

6.2 State-space model

6.2.1 Data

Data for the most basic of stock-recruit models include time series of the spawning stock and matching numbers of recruits. However, in this model there are few complete observations for either of these measures (save Eagle telemetry during 2002-2004 and Eagle sonar during and after 2005 for border passage). Instead, multiple indices are used along with harvest removals and age compositions to "reconstruct" the run while simultaneously estimating the parameters of a Ricker stock-recruit curve. The data that are observed include abundance indices, harvest data and size/age/sex composition data. See Appendix 1 for a summary of all the data that are used in the state-space model.

6.2.1.1 Relative index data

The values for all index data reflect the standardized counts of fish observed at each index location. Sources include aerial surveys on the Little Salmon, Big Salmon, Nisutlin, Wolf, and Ross rivers and Tincup Creek. The Tatchum Creek index is a foot survey and the Blind Creek and Whitehorse fishways are weirs. For the state-space model, index data do not have to occur in every year and do not need to occur in contiguous years (Table 6.1).

6.2.1.2 Absolute indices of border passage

Telemetry and sonar data at Eagle are treated as absolute indices of abundance (i.e., no catchability is estimated in the model – catchability is a scalar that relates the index to the magnitude of the population). Telemetry data were available during the period 2002-2004 and sonar data were available during 2005 to 2015.

6.2.1.3 Harvest data (and CVs)

Fishery-dependent data are composed of U.S. and Canadian annual harvests and harvest age compositions from the US fishery. All the fisheries data run from 1982-2015. These data were obtained from Yukon River panel JTC reports.

6.2.1.4 Composition data

Composition data refers to the proportions of individuals that are in each age, sex or age-sex category each year. The age and sex composition data come from surveys near the US-Canada border as well as from the US harvest.

6.2.1.4.1 Age compositions

The age composition data used in the model are the weighted sums from border passage and US harvest data. The raw age compositions were estimated by counting scale annuli from fish sampled at the border or in U.S. commercial and subsistence harvests. The border passage data were sampled using fish-wheels (1982-2006) and in-river gillnets (2007-2016) while harvest was sampled at commercial fish processing facilities and during subsistence fishery surveys. The model input age compositions were calculated as

$$\breve{\boldsymbol{A}}_y = \lambda_{y,US}\dot{\boldsymbol{A}}_{y,US} + \lambda_{y,CA}\dot{\boldsymbol{A}}_{y,CA} \tag{6.2.1}$$

$$\boldsymbol{A}_y = \text{round}\left(\frac{\breve{\boldsymbol{A}}_y}{\sum \breve{\boldsymbol{A}}_y} ESS_y\right)$$

Where $\breve{\boldsymbol{A}}_y$ is the year-y weighted age compositions, $\lambda_{y,US}$ and $\lambda_{y,EG}$ are the annual weighting factors for the US harvest and Canadian border passage run components, and $\dot{\boldsymbol{A}}_{y,US}$ and $\dot{\boldsymbol{A}}_{y,CA}$ are the raw age

Table 6.1. Inclusion of each of the 12 indices for each year of the state-space model data.

Year	Index Number											
	1	2	3	4	5	6	7	8	9	10	11	12

1982			X	X	X	X	X	X	X		X	
1983			X	X	X	X	X	X	X	X	X	
1984			X	X	X	X	X	X	X	X	X	
1985			X	X	X	X	X	X	X	X	X	
1986			X	X	X	X	X	X	X	X	X	
1987			X	X	X	X	X	X	X	X	X	
1988			X	X	X	X	X	X	X	X	X	
1989			X	X	X	X	X	X	X	X	X	
1990			X	X	X	X	X	X	X	X	X	
1991			X	X	X		X		X		X	
1992			X	X	X	X	X	X	X	X	X	
1993			X	X	X	X	X	X	X		X	
1994			X	X	X	X	X	X	X	X	X	
1995			X	X	X	X	X	X	X	X	X	
1996			X	X	X	X	X	X	X	X	X	
1997			X	X	X	X	X	X	X	X		X
1998			X	X	X	X	X	X	X	X		X
1999			X	X	X	X	X	X	X			X
2000			X	X	X	X	X	X	X	X		
2001			X	X	X	X	X		X	X		
2002		X	X	X	X	X	X		X			
2003		X	X	X	X	X	X		X			X
2004		X	X	X	X	X	X		X			X
2005	X		X	X	X	X	X		X		X	X
2006	X		X	X	X	X	X		X			X
2007	X		X	X	X	X	X		X			X
2008	X		X	X	X		X		X			X
2009	X			X	X	X	X		X			X
2010	X				X	X	X		X			X
2011	X				X		X		X			X
2012	X				X		X					X
2013	X						X					X
2014	X						X					X
2015	X						X					X

Index Key:

1. Sonar
2. Telemetry
3. Mark Recapture
4. Little Salmon[1]
5. Big Salmon[1]
6. Nisutlin[1]
7. Whitehorse Fishway[1]
8. Tatchum[2]
9. Wolf[1]
10. Tincup[1]
11. Ross[1]
12. Blind[3]

[1]Aerial survey
[2]Foot survey
[3]Weir survey

composition data from the US harvest and Canadian border passage. $\lambda_{y,US}$ and $\lambda_{y,CA}$, which are equal to the estimated magnitudes of the US harvest and Canadian border passage, respectively, are determined from previous model runs (i.e., these weights are derived iteratively). $\boldsymbol{A}_y$ are used as observed multinomial age counts, which serve as surrogate data to inform the model about annual age composition. They sum to the annual effective sample size ESS_y, which was set to 100. Previous analyses have found that key results from state-space analyses of Pacific salmon data are generally not sensitive to the choice of effective sample size (e.g., Fleischman and McKinley 2013).

6.2.1.4.2 Female proportions-at-age (age-sex compositions)

The escapement quality version of the model requires further composition data that describe the proportion of females by age class in the escaping component of the run. Female proportions-at-age composition data are derived from fish wheel sampling during 1982-2004 at the White Rock and Sheep Rock sampling locations and from gill net sampling at Eagle from 2005-2016. Gillnet samples (which used a range of mesh sizes) were assumed to accurately represent the age composition of the run, however this assumption could not be made for fish wheels. Those data were corrected for the selectivity patterns of the fish wheels relative to gillnets. This could have been implemented inside the model but instead the corrections were made before preparing the model's data file. Thus the composition "data" that enter into the model (for all years, regardless of gear type) represent actual escapement composition as opposed to uncorrected sampled compositions.

Selectivity is the relative rate of capture of the age classes. Thus the product of numbers-at-age ($\dot{N}_a$) and selecticvity-at-age (S_a) gives the relative catch-at-age ($\dot{C}_a$; e.g., from a gillnet)

$$\dot{C}_a = S_a \dot{N}_a \qquad (6.2.2)$$

Therefore, if S_a and $\dot{C}_a$ are known it is possible to determine $\dot{N}_a$, the run age composition.

6.2.1.4.3 Selectivity function

Selectivity is a fixed function (i.e., it is not estimated in the model) that comes from previous research on the lower Yukon River (Bromaghin 2005). That function is

$$f(x) = \left(1 + \frac{\lambda^2}{4\theta^2}\right)^{\theta} \left[1 + \frac{\left(x - \frac{\sigma\lambda}{2\theta} - \tau\right)^2}{\sigma^2}\right]^{-\theta} \exp\left\{-\lambda\left[\tan^{-1}\left(\frac{x - \frac{\sigma\lambda}{2\theta} - \tau}{\sigma}\right) + \tan^{-1}\left(\frac{\lambda}{2\theta}\right)\right]\right\} \qquad (6.2.3)$$

where τ (1.920), σ (0.204), θ (0.622) and λ (-0.547) are the parameters as estimated by Bromaghin (2005) for Chinook Salmon. Bromaghin's x is a measure of fish size, expressed as

$$x = \frac{l}{2m} \qquad (6.2.4)$$

Where l is fish length and m is the mesh size in mm. The term $2m$ represents the perimeter of a mesh in mm and Eqn. 6.2.4 is meant to represent the geometric similarity (Bromaghin 2005). This allows Bromaghin's equation (6.2.3) to be used for different mesh sizes without re-parameterization. Using this method the selectivity for each length class can be estimated for gill nets.

Both ages and lengths are known for individuals of both sexes in the age-sex-length database. Thus the size composition for each returning age-class can be estimated (fish lengths are necessary to apply the selectivity function). First the data are aggregated into 20 mm length bins by sex within each age class. Second the counts-at-length are divided by the selectivity-at-length (from equation 6.2.3), giving a selectivity-corrected estimate of the returning counts by age and length. Finally the length bins are summed for each age, resulting in an estimate for the returning age composition by sex.

Age-3 and age-8 fish were uncommon in returns and they were re-assigned to age-4 and age-7 respectively to simplify calculations. Selectivity-at-age is estimated differently for the fishwheel data set and the gill net data set (see Sections 6.2.1.4.4 and 6.2.1.4.5 below).

6.2.1.4.4 Fish wheel data

Fish wheel data (1982-2004) were collected from the White Rock and Sheep Rock sampling locations, and all the data were used. Before standardization, the fishwheel data were converted from snout-to-fork length to mid-eye-to-fork length. This conversion made them comparable to the gillnet data collected at Eagle. The conversion was

$$MEF_i = 1.446 + 0.898FL_i \tag{6.2.5}$$

where MEF_i and FL_i represent the mid-eye-fork length and snout-to-fork length for individual i.

In order to use the fish wheel and gillnet abundance data together (treating them identically) in the state-space model, the fish wheel data were assumed to have the same selectivity as a 5.25 in gillnet (MacDonald and Labelle, unpublished data; Hamazaki, unpublished data). This mesh size was then used to calculate x (Eqn. 6.2.4) and subsequently selectivity-at-size (Eqn. 6.2.3) for each age group.

6.2.1.4.5 Gillnet data

Gillnet age composition data (2005-2016) were collected from the Eagle test fishery. The mesh sizes used ranged from 2.75 to 8.5 in, and both age and size information were collected. The data were combined with the selectivity-corrected fish wheel composition data.

6.2.1.5 Fecundity data

Fecundity-at-age estimates were necessary for the escapement quality version of the state-space model. The average fecundity-at-size was found using a relationship for Yukon River Chinook developed by Bromaghin et al. (2011). That relationship was

$$G_i = 11.23MEF_i^F + 4631 \tag{6.2.6}$$

where G_i is the fecundity for individual I and MEF_i^F is the mid-eye-fork length for sampled female i. After fecundity was estimated for each individual the fish were grouped and the average fecundity by year and age was calculated.

6.2.2 Age-structured stock-recruitment framework

6.2.2.1 Base Ricker model

The Ricker model predicts recruitment in year y (R_y) using the equation

$$R_y = S_y \alpha e^{-\beta S_y} e^{\varepsilon_{Wy}} \quad (6.2.7)$$

where S_y is the spawning stock (numbers of individuals in the case of the escapement quantity model and numbers of eggs in the case of the escapement quality model), α and β are parameters to be estimated and $\varepsilon_{Wy} \sim N(0, \sigma_W^2)$. This model is expressed within the assessment in its log-transformed form, as

$$\ln R_y = \ln S_y + \ln \alpha - \beta S_y + \varepsilon_{Wy} \quad (6.2.8)$$

6.2.2.2 Including autocorrelation

Since some processes that influence recruitment show evidence of trending over time (e.g., ocean productivity conditions) the stock-recruitment model can be improved by accounting for such temporal variability. Ignoring (i.e., not modeling) these processes can lead to residual trends. Following Fleischman et al (2013), we modeled these trends using a lag-1 autoregressive parameter ϕ such that the total error ε becomes $\varepsilon = \phi v_{y-1} + \varepsilon_{Wy}$ where the lag-1 residuals are v_{y-1}. The model including this trend is then

$$\ln R_y = \ln S_y + \ln \alpha - \beta S_y + \phi v_{y-1} + \varepsilon_{Wy} \quad (6.2.9)$$

where ϕv_{y-1} Is the autoregressive component of the error and ε_{Wy} is the random component.

6.2.2.3 Age Structure

Age-at-maturity (which governs the age composition in the run) was modeled hierarchically: i.e., it was allowed to vary among cohorts to a specified extent. Age-at-maturity vectors[2] $\mathbf{p_y}$ = (p_{y4}, p_{y5}, p_{y6}, p_{y7}) from year *y* returning at ages 3–7 were drawn from a *Dirichlet* (γ_3, γ_4, γ_5, γ_6, γ_7) distribution. The Dirichlet parameters can also be expressed in an alternate form where

$$D = \sum_a \gamma_a \quad (6.2.10)$$

is the (inverse) dispersion[3] of the annual age-at-maturity vectors, reflecting consistency of age at maturity among brood years. The location parameters

$$\pi_a = \frac{\gamma_a}{D} \quad (6.2.11)$$

are proportions that sum to one, reflecting the age-at-maturity central tendencies.

The abundance *N* of age-*a* Chinook Salmon in calendar year *y* is the product of the age proportion scalar *p* and the total return (recruitment) *R* from year *y*–*a*:

[2] These age proportions are maturity and survival schedules for a given brood year (cohort) across calendar years. In contrast, Equation 6.1.14 describes age proportions in a given calendar year across brood years.

[3] A low value of *D* is reflective of a large amount of variability of age-at-maturity proportions $\mathbf{p}$ among brood years, whereas a high value of *D* indicates more consistency in $\mathbf{p}$ over time.

$$N_{ya} = R_{y-a} p_{y-a,a} \,. \qquad (6.2.12)$$

The total run during calendar year *y* is the sum of abundance-at-age across ages:

$$N_y = \sum_a N_{ya} \,. \qquad (6.2.13)$$

Annual age composition proportions in the run ($\boldsymbol{\psi}$) are

$$\boldsymbol{\psi}_{y,a} = \frac{N_{y,a}}{N_y} \qquad (6.2.14)$$

6.2.2.4 Harvest removals

Both US and Canadian harvest rates are parameters estimated by the model. US harvest in year y, $H_{US,y}$, is

$$H_{US,y} = \mu_{US,y} N_y \qquad (6.2.14)$$

where μ_{US} is the US harvest rate and N_y is the run in year y. $\mu_{US,y}$ is estimated annually, and is assigned an uninformative beta prior distribution

$$\mu_{US,y} \sim Beta(1.0,1.0) \qquad (6.2.15)$$

Canadian harvest differs only in that the rate μ_{CA} applies only to fish that have survived the US fishery. Thus

$$H_{CA} = \mu_{CA,y} P_y \qquad (6.2.16)$$

where

$$P_y = N_y - H_{CA,y} \qquad (6.2.17)$$

P_y represents border passage in year y. As with US harvest rate, Canadian harvest rate is assigned a beta prior distribution

$$\mu_{CA,y} \sim Beta(1.0,1.0) \qquad (6.2.18)$$

6.2.2.5 Abundance metrics

6.2.2.5.1 Unbiased sonar estimates

The 2005-2015 sonar estimates $\hat{P}$ are treated as unbiased estimates of border passage:

$$\log(\hat{P}_y) = \log(P_y) + \varepsilon_{Sy} \qquad (6.2.19)$$

where $P_{y,}$ is the true border passage in year y, and $\varepsilon_{Sy} \sim N(0, \sigma_S^2)$.

6.2.2.5.2 Indices of relative abundance

Two indices of border passage (1982-2008 mark-recapture-based abundance estimates, 2002-2004 radio telemetry-based estimates) and nine indices of escapement were included in the model. Note that indices of border passage measure escapement plus Canadian harvest.

For each observed abundance index I, the index-specific catchability q_i (i.e., the proportion of the stock that is observed by survey i) was allowed to vary by year according to an autoregressive lag 1 (AR(1)) process:

$$\ln(I_{iy}) = \ln(q_i X_y) + \varphi_i v_{i,y-1} + \varepsilon_{iy} \qquad (6.2.20)$$

where X_y is the quantity being indexed (either true escapement or border passage) in year y, the residuals are

$$v_{i,y} = \ln(I_{i,y}) - \ln(q_i X_y) \qquad (6.2.21)$$

and $\varepsilon_{iy} \sim N(0, \sigma_i^2)$ where σ_i^2 are estimated in the model with uninformative inverse gamma priors with shape and scale both equal to 0.01. AR(1) coefficients ϕ_i were also estimated in the model with prior distributions

$$\phi_i \sim N(0, 1.0e^4) \qquad (6.2.22)$$

censored such that $-1 < \phi_i < 1$.

6.2.3 Model likelihood[4]

Each observed data point has a corresponding associated model estimate; the relationship between the data and estimates with respect to the error distributions that are assumed tunes the parameters in the model.

6.2.3.1 Age composition data

Age composition data are fit assuming a multinomial distribution

$$\mathbf{A}_y \sim \mathrm{MN}(\boldsymbol{\psi}_y, ESS_y) \qquad (6.2.23)$$

where $\mathbf{A}_y$ is a vector of sample counts-at-age, $\boldsymbol{\psi}_y$ is a vector of predicted proportions-at-age (see Eqn. 6.2.14) and ESS_y is the effective sample size for year y (i.e., in the observed data; see section 6.2.1.4.1).

6.2.3.2 U.S. and Canadian harvest

U.S. and Canadian harvest are also fit assuming lognormally distributed observation errors, identically to Section 6.2.3.2 where

$$C_{i,y} \sim \mathrm{LN}(\log \hat{C}_{i,y}, \sigma_i^2) \qquad (6.2.24)$$

Where $C_{i,y}$ is the observed value for harvest i (representing either the U.S. or Canadian fishery) in year y, $\hat{C}_{i,y}$ is the corresponding model estimate and σ_i^2 is the lognormal variance for U.S. or Canadian catch represented by i. The σ_i^2 are given the same uninformative prior as for the index data (Eqn. 6.2.20).

6.2.4 Model fitting

The model was fit in a Bayesian framework using JAGS version 4.3 (Plummer 2017) and R version 3.4.1 (R Core Team 2017). The Bayesian approach allowed for a full characterization of the uncertainty of

[4] Note that while sex data are included in the data file, sex composition is not estimated by the escapement quality model – the annual proportion of females is used directly with no assumption of uncertainty.

parameters and derived quantities by sampling from their joint probability distribution. Two 500,000-iteration MCMC chains were run after an adaptive phase of 2,000 iterations where the parameters of the Gibbs sampling algorithm were optimized. A burn-in period of 500,000 iterations was used for each chain and the final MCMC results were thinned by 100. The MCMC results, including the initial stock status (i.e., numbers-at-age) and the Ricker model parameters, were then available as inputs to the MSE.

6.3 Management Strategy Evaluation

Section 6.2 describes the Management Strategy Evaluation model. Note that the variable names in this section may not have exactly the same meaning as in section 6.2.

6.3.1 Initial conditions and stock characteristics

The MSE simulated the future dynamics of the fishery and fish population for a projection period of 50 years, across a range of policy alternatives. To account for uncertainty, a single policy simulation was repeated 500 times, with a new draw from the posterior distribution of model parameters (outputs from the state-space model MCMC run: α, β, ϕ and σ_W^2). Each simulation started with 120,000 fish divided into age classes using the age composition defined by the estimated dirichlet composition parameters from each posterior sample.

6.3.2 Dynamic operating model

The dynamic model overall order of events is given in Figure 6.1. Each year the simulation began with an estimate of the run size

$$\widehat{N}_y = \widetilde{N}_y e^{\varepsilon_N} \tag{6.3.1}$$

where $\widehat{N}_y$ was the estimated total run size in year y (summed over ages), $\widetilde{N}$ was the true run size, and $\varepsilon_N \sim \mathrm{N}(0, \sigma_N^2)$. The value $\widetilde{N}$ was generated with equation 6.1.9. The value ε_N represents observation error in the estimate of the run size, which was calculated from the differences between annual in-season run-size projections near the mouth of the river and the final estimates of run size from the state-space model.

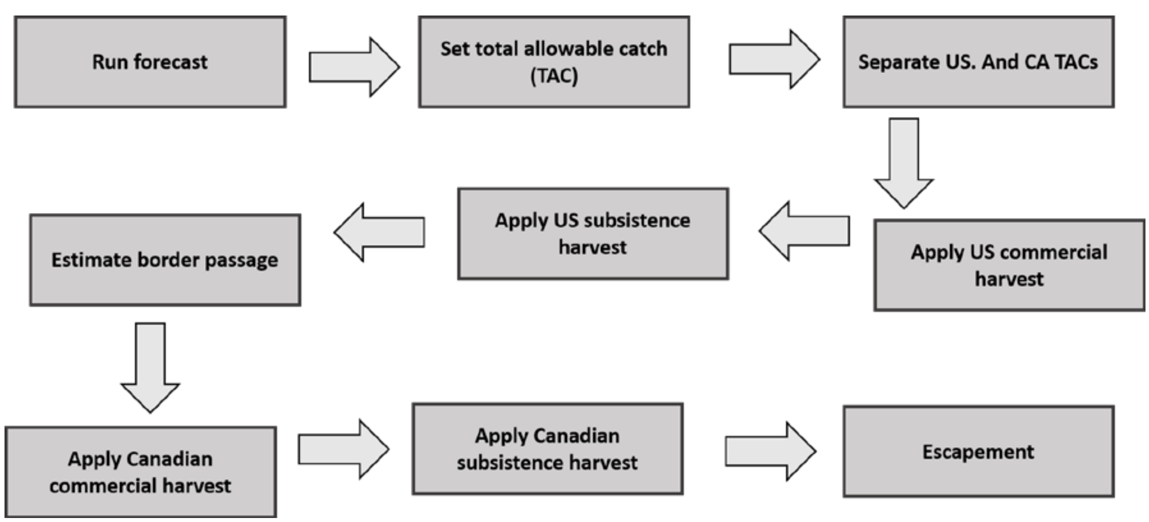


Figure 6.1 Flow chart for Management Strategy Evaluation model.

6.3.3 Allowable harvest calculation

The annual total combined (US + Canada) allowable harvest in each year was calculated as the difference between the estimated run size and the escapement goal:

$$TAC_y = \widehat{N}_y - G \tag{6.3.2}$$

where TAC_y was the total allowable catch in year y, and G was the escapement goal. The escapement goal is a policy parameter that was varied systematically across simulations to make up a complete scenario. The TAC was then split into Canadian (TAC_{CA}) and US (TAC_{US}) components based on the allocation rules in the Yukon River Salmon Agreement:

$$TAC_{CA} = \begin{cases} 0.24TAC_y & if\ TAC < 110000 \\ 0.24 \times 110000 + 0.5(TAC_y - 110000) & else \end{cases} \tag{6.3.3}$$

and

$$TAC_{US} = TAC - TAC_{CA} \tag{6.3.4}$$

6.3.4 Canadian and US total harvest

Total catch for a given fishery is not necessarily equal to the pre-season TAC share because there is error in the pre-season estimates, the order of the fisheries must be considered, and there is a maximum possible harvest rate beyond which further harvest would be unrealistic. Thus the equations for realized harvest involved the target harvest as well as other terms that represented surplus catch after removals by other fisheries and the maximum harvest rate.

For example, the calculation of total US commercial harvest was comprised of several terms. The total number of fish available for US commercial harvest was the US TAC minus subsistence needs: $(TAC_{US} - \dot{H}_{USS})$ where $\dot{H}_{USS}$ was the US subsistence harvest target. Further, the target harvest rate (U_G – a second policy parameter that was systematically varied across a range of values for each scenario) must be accounted for: $U_G(TAC_{US} - \dot{H}_{USS})$. However, the target harvest will never exactly be met because there is implementation error involved, so the TAC becomes $U_G(TAC_{US} - \dot{H}_{USS})e^{\varepsilon_{USC}}$. Finally, because there is uncertainty involved it was necessary to ensure that the final harvest did not remove more individuals than the maximum possible harvest rate relative to the population size, which was $N_{y,a}U_{MAX}$ where U_{MAX} was the maximum possible harvest rate and $N_{y,a}$ was the true number of total available fish. The $\min()$ function was used to satisfy this condition. Thus the total US commercial harvest (in numbers) in year y, $H_{USC,y}$, was

$$H_{USC,y} = \min\left[U_G(TAC_{US} - \dot{H}_{USS})e^{\varepsilon_{USC}}, (N_{y,a}U_{MAX})\right] \tag{6.3.5}$$

where

$$\varepsilon_{USC} \sim \mathrm{N}(0, \sigma^2_{USC}) \tag{6.3.6}$$

and σ^2_{USC} is the variance for the implementation error of US commercial harvest.

US subsistence harvest in year y ($H_{USB,y}$) was calculated from:

$$H_{USB,y} = \min\left[U_G\left(TAC_{US} - H_{USC,y}\right)e^{\varepsilon_{USS}}, \left(\left(N_{y,a} - H_{USC,y}\right)U_{MAX}\right), \dot{H}_{USS}e^{\varepsilon_{USS}}\right] \qquad (6.3.7)$$

where

$$\varepsilon_{USS} \sim \mathrm{N}(0, \sigma_{USS}^2) \qquad (6.3.8)$$

and σ_{USS}^2 is the variance for the implementation error of US subsistence harvest. Equation 6.3.7 is similar to 6.3.5 except $N_{y,a}$ was replaced by $N_{y,a} - H_{USC,y}$ and $\dot{H}_{USS}e^{\varepsilon_{USS}}$ has been added. $N_{y,a} - H_{USC,y}$ represents the available number of fish, but after the US commercial harvest had occurred. $\dot{H}_{USS}e^{\varepsilon_{USS}}$ is the target harvest rate but with implementation error included. Again, the minimum of these three terms was used to ensure that the number of individuals that are taken was realistic.

Subsistence needs for the Canadian fishery depended on the estimated border passage in year y ($\hat{P}_y$) which was a function of the number of returns and the realized US commercial and subsistence harvest

$$\hat{P}_y = \left[N_y - \left(H_{USC,y} + H_{USB,y}\right)\right]e^{\varepsilon_P} \qquad (6.3.9)$$

where

$$\varepsilon_P \sim \mathrm{N}(0, \sigma_P^2) \qquad (6.3.10)$$

and σ_P^2 is the variance for estimated border passage.

Commercial Canadian harvest depended on the anticipated Canadian subsistence harvest in year y, $\dot{H}_{CAB,y}$, which was

$$\dot{H}_{CAB,y} = \begin{cases} 0 & \text{If } \hat{P}_y < 42{,}500 \\ 1{,}000 & \text{If } 42{,}500 \le \hat{P}_y < 48{,}750 \\ 4{,}000 & \text{If } 48{,}750 \le \hat{P}_y < 55{,}000 \\ 8{,}000 & \text{else} \end{cases} \qquad (6.3.11)$$

The commercial harvest ($H_{CAC,y}$) was then

$$H_{CAC,y} = \min\left[U_G\left(\hat{P}_y - \dot{H}_{CAB,y}e^{\varepsilon_{CAS}} - EG\right)e^{\varepsilon_{CAC}}, U_{MAX}P_y - \dot{H}_{CAB,y}e^{\varepsilon_{CAS}}\right] \qquad (6.3.12)$$

where EG is the escapement goal in year y, P_y is the true border passage and ε_{CAS} and ε_{CAC} are implementation errors for the Canadian subsistence and commercial fisheries

$$\varepsilon_{CAS} \sim \mathrm{N}(0, \sigma_{CAS}^2) \qquad (6.3.13)$$

and

$$\varepsilon_{CAC} \sim \mathrm{N}(0, \sigma_{CAC}^2) \qquad (6.3.14)$$

and σ_{CAS}^2 and σ_{CAC}^2 are the variances of these implementation errors. Equation 6.3.12 is split into two parts. The first part, $U_G\left(\hat{P}_y - \dot{H}_{CAB,y}e^{\varepsilon_{CAS}} - EG\right)e^{\varepsilon_{CAC}}$, is the remainder of fish that are estimated to have passed the border after the escapement and subsistence harvest were accounted for, multiplied by the target harvest rate U_G and accounting for uncertainty in harvest. The second part, $U_{MAX}P_y - \dot{H}_{CAB,y}e^{\varepsilon_{CAS}}$, ensured that the actual removals are not larger than the maximum possible fishing rate multiplied by border passage and accounting for the target subsistence removals.

The realized Canadian subsistence harvest was

$$H_{CAS,y} = \min\left[\left(\hat{P}_y - EG\right)e^{\varepsilon_{CAS}}, \dot{H}_{CAS,y}e^{\varepsilon_{CAS}}, U_{MAX}P_y\right] \quad (6.3.15)$$

The first part of Eqn. 6.3.15, $\hat{P}_y - EG$, implies that removals should not be larger than border passage minus the escapement goal. The middle part, $\dot{H}_{CAS,y}e^{\varepsilon_{CAS}}$, is the targeted removals plus uncertainty and the final part, $U_{MAX}P_y$, ensures that more fish were not harvested than was reasonable according to the maximum fishing rate.

6.3.5 Age-specific harvest

The equations above give the numbers of fish taken by the components of the US and Canadian fisheries. However, not all ages are equally selected by the commercial and subsistence fisheries. Determining the age composition of the escaping fish is necessary for the escapement quality version of the model. For each of the fishery sectors, age-specific removals are determined. The total available numbers-at-age depend on the fishery – for example, the Canadian commercial fishery occurs after border passage so the total available numbers-at-age in year y are $P_{y,a}$. The example below is for the US commercial fishery where the available numbers-at-age are from the total run. The numbers-at-age are updated as the various fisheries remove the harvest-at-age. Thus the $\ddot{N}_{y,a}$ given below depend on which fishery is currently under harvest. To determine the age-specific harvest first the total vulnerable available numbers are calculated

$$\ddot{N}_y = \sum\nolimits_a v_a N_{y,a} \quad (6.3.16)$$

where $\boldsymbol{v}$ is fixed vector of age-specific vulnerabilities, each with a maximum value of 1.0. The realized annual exploitation rate for the US fishery ($\ddot{U}_y$) is then

$$\ddot{U}_y = \sum \boldsymbol{H}_{US,y} / \ddot{N}_y \quad (6.3.17)$$

Finally, the US harvest by age, $\boldsymbol{H}_{US,y}$, is

$$\boldsymbol{H}_{US,y} = \boldsymbol{v}\boldsymbol{N}_{\boldsymbol{y}} \quad (6.3.18)$$

However, this harvest is conditional on the actual availability of individuals in each of the size classes. If insufficient individuals in any size class are available for the harvest the vulnerability schedule needs to be adjusted. This process, which is applied to commercial and subsistence US and Canadian fisheries, follows the steps below (again using the US commercial fishery as an example):

1. Fish are removed from all age classes at the same rate until all have been removed from a particular age class. The remaining number of fish that need to be removed to meet the specified level of harvest, $\ddot{H}_{USC,y}$, is

   $$\ddot{H}_{USC,y} = H_{USC,y} - \sum\nolimits_a \breve{H}_{USC,y,a} \quad (6.3.19)$$

   Where $\breve{H}_{USC,y,a}$ is the number of individuals that were harvested up until all had been removed from a particular age class (depending on the available numbers and vulnerability schedule).
2. The vulnerability schedule is adjusted to exclude the most highly selected age class

   $$\dot{\boldsymbol{v}}^* = \boldsymbol{v}^* / \sum \boldsymbol{v}^* \quad (6.3.20)$$

   where $\boldsymbol{v}^*$ is the baseline vulnerability schedule but excluding the age class with insufficient individuals for harvest (which is the most highly vulnerable age class; for example, if age-5 is most highly selected then $\boldsymbol{v}^*$ is a vector of length three that represents ages 4, 6 and 7) and $\dot{\boldsymbol{v}}^*$ is the standardized version of this abridged schedule.

3. The new adjusted vulnerability schedule is used to determine the remaining fishable abundance

$$\ddot{N}_y^* = \sum_a \dot{v}_a^* N_{y,a} \quad (6.3.21)$$

where $\ddot{\boldsymbol{N}}_{\boldsymbol{y}}^*$ is the temporary updated fishable abundance in year y. The new harvest rate-by-age on the remaining individuals, U_a^*, is

$$U_a^* = \ddot{H}_{US,y} / \ddot{N}_{y,a}^* \quad (6.3.22)$$

and the additional catch-at-age ($\ddot{H}_{US,y,a}$) is

$$\ddot{H}_{US,y,a} = U_{y,a}^* \ddot{N}_{y,a}^* \quad (6.3.23)$$

4. Finally the catch-at-age before the vulnerability adjustment is added to the catch-at-age on the surplus after the adjustment

$$\breve{H}_{US,y,a} = \left[N_{y,a} - \breve{H}_{US,y,a}\right] + \ddot{H}_{US,y,a} \quad (6.3.24)$$

Where $\breve{H}_{US,y,a}$ above is the current updated harvest needed to satisfy the annual harvest level of H_y. Steps 1-4 are repeated until $\sum_a \breve{H}_{US,y,a} = H_y$.

6.3.6 Population updates after harvest and subsequent recruitment.

The total escaped stock in numbers-at-age ($\boldsymbol{S}_{\boldsymbol{y}}$) is

$$\breve{\boldsymbol{S}}_{\boldsymbol{y}} = \boldsymbol{N}_{\boldsymbol{y}} - \boldsymbol{H}_{\boldsymbol{USC}} - \boldsymbol{H}_{\boldsymbol{USS}} - \boldsymbol{H}_{\boldsymbol{CAC}} - \boldsymbol{H}_{\boldsymbol{CAS}} \quad (6.3.25)$$

and in numbers of eggs-at-age ($\widetilde{\boldsymbol{E}}_{\boldsymbol{y}}$) is

$$\tilde{\boldsymbol{S}}_{\boldsymbol{y}} = \left[\boldsymbol{N}_{\boldsymbol{y}} - \boldsymbol{H}_{\boldsymbol{USC}} - \boldsymbol{H}_{\boldsymbol{USS}} - \boldsymbol{H}_{\boldsymbol{CAC}} - \boldsymbol{H}_{\boldsymbol{CAS}}\right]\boldsymbol{G} \quad (6.3.26)$$

where $\boldsymbol{G}$ is a vector of numbers of eggs-at-age. The total escapement is then used to produce recruits in subsequent years (depending on the proportion of individuals that return at age, an input to the MSE). Eqn. 6.1.8 is used to determine the number of recruits, where α, β, ϕ and ε_{Wy} are inputs from an MCMC sample from the state-space model. The state-space model parameters differ depending on whether the MSE uses the escapement quantity or the escapement quality version, but the model structure is the same.

6.3.7 Population metrics

Finally, population metrics necessary to summarize the impact of management decisions (e.g., escapement goal, harvest rate, Table 6.2) on the population are calculated.

Table 6.2. Management Strategy Evaluation performance measures.

Performance measure	**Note**
Mean US commercial catch	
Median US commercial catch	
Mean US subsistence catch	
Median US subsistence catch	
Mean Canadian commercial catch	
Median Canadian commercial catch	
Mean Canadian subsistence catch	
Median Canadian subsistence catch	

Probability of US commercial closure	Number of years with no catch in the fishery divided by the total number of years.
Probability of US subsistence closure	
Probability of Canadian commercial closure	
Probability of Canadian subsistence closure	
CV US commercial catch	
CV US subsistence catch	
CV Canadian commercial catch	
CV Canadian subsistence catch	
CV escapement	
Mean escapement	
Probability of meeting US ANS goal	ANS (annual subsistence needs) is specified in the control file. This probability is the number of years that US subsistence catch is greater than ANS divided by the total number of years.
Average total harvest rate	Total harvest across all fisheries divided by the number of years
Median total harvest rate	
Mean returns	
Median returns	
Probability border goal not met	Border goal specified in control file
Probability escapement goal not met	Escapement goal is the management control. There is a hard-coded buffer of 14% so the definition of being short of the escapement goal is when escapement is less than 86% of the goal.
Probability of 5 contiguous years under escapement goal	
Median sex ratio of escaped fish	
Median proportion of age 6 fish	
Median number of eggs	
Mean number of times escapement is adjusted because of a series of low returns	

6.3.8 Policy Scenarios

Each policy scenario for the MSE model consists of three elements: the escapement target, the rate of harvest on the estimated surplus returns after accounting for escapement and subsistence needs, and the mesh sizes used in the fishery. We simulated a grid of 121 escapement target x harvest rate combinations, with escapement targets ranging from 0 to 50,000 fish in increments of 5,000 fish and harvest rates ranging from 0 to 100% in increments of 10%. We repeated this grid of policies for three mesh size options: 5.5, 7.5, and 8 inches.

6.4 Engagement

In addition to our initial meeting with the JTC in November 2015, we met with this group on two subsequent occasions. At the spring 2017 JTC meeting in Whitehorse, we presented our preliminary results for the state-space models and the MSE. During this meeting, we received helpful feedback that enabled us to implement further changes, particularly to the MSE model, that added realism to our approach for modeling the within-year management process. For example, in consultation with

Canadian JTC members we developed more realistic rules for modeling commercial and subsistence harvest in Canada.

We also presented our results at the fall 2017 JTC meeting in Fairbanks. Additionally, we hosted a one-day technical workshop during which we explained the methods used to develop both the run-reconstruction and stock-recruitment analysis, and subsequently the MSE model. During the first half of the workshop, participants learned how the multiple data sources that inform the run-reconstruction are integrated together in an estimation model using joint likelihood functions. During the second half, the process of developing an MSE model was explained and workshop participants were given the opportunity to construct and then game with a simple version of the MSE model described in this report.

VII. Results

7.1 Consultation

The November 2015 workshop held in association with the fall 2015 JTC meeting resulted in the generation of a set of management options, objectives, and critical information needs that were identified by JTC members in consultation with project team members Jones and Syslo. Notes from this meeting, including a list of attendees, are reproduced as Appendix 1.

7.2 State-space model

7.2.1 Evidence for trends in escapement quality

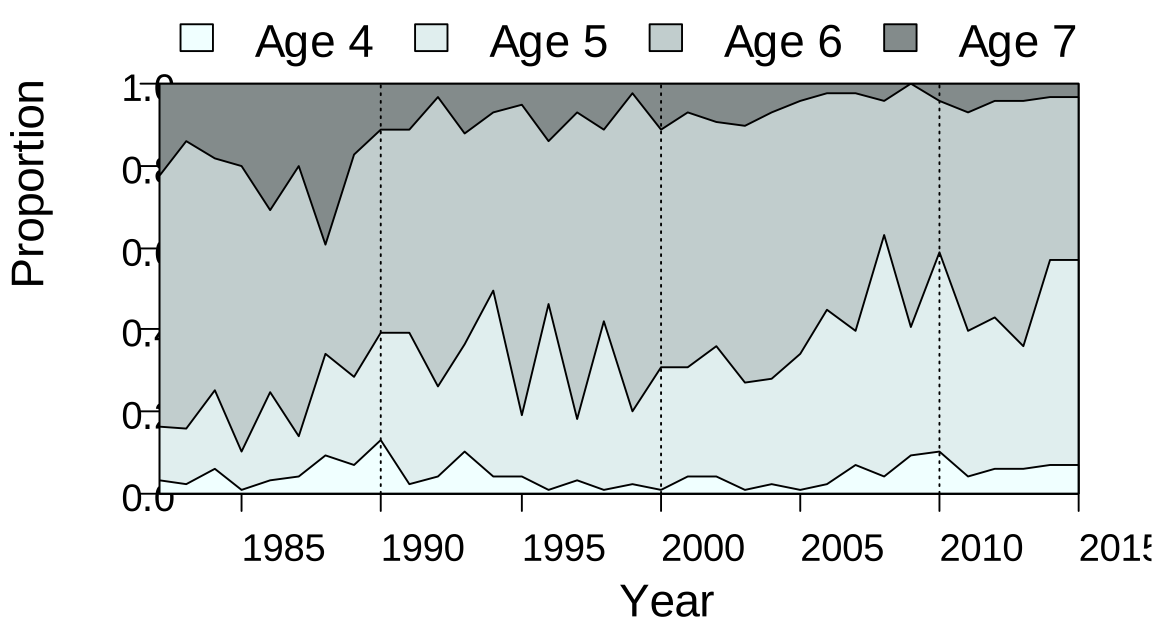
Age-sex-length data for Yukon River Chinook Salmon bound for Canadian tributaries showed evidence of a decline in the proportion of age 6 and 7 fish in the returning population from the 1980s to recent years (Figure 7.1 – top panel). In the early 1980s over 80% of escaped fish were age 6 or 7, but since 2007 the proportion has been closer to 50%. Age 6 and 7 tend to have a higher proportion of females, resulting in a sex ratio skewed towards males when these age classes are less abundant. The average fecundity of an escaped spawner has varied over time although there was not evidence for a consistent trend. Average number of eggs per spawner peaked in the late 1980s, then decreased to a low in the early 2000s, but has since rebounded (Figure 7.1 –lower panel). These trends in average fecundity of escaped fish prompted an evaluation of the impact of these patterns on the state-space run reconstruction by explicitly accounting for escapement quality.

7.1.2 State-space model diagnostics

It is customary to examine diagnostics from Bayesian estimation model outputs to ensure the parameter estimates are reliable. The primary model diagnostics used here were trace plots and autocorrelation plots for the MCMC samples; here we report on diagnostics from the escapement quality model, but the diagnostics for the escapement quantity model were similar. Trace plots show parameter estimates from MCMC chains plotted as if they were time series. The desirable features of a trace plot are that: (1) the chains are “well mixed,” indicating that a parameter estimate varies without a trend around some median value and that the different chains have similar characteristics (i.e., mean and variance); and (2) the chains are not “sticky,” meaning that the value for an estimate in the chain is not related to the previous value in the series. Autocorrelation plots give a more complete picture of the relationship between contiguous values in the chain. The desirable characteristics of those plots are low autocorrelation at all lags.

The escapement quality model estimated 951 parameters and derived values so only a sample of diagnostics are presented here. Trace and autocorrelation plots for the Ricker α and β are given. The trace plot for α (Figure 7.2 – top left panel) showed three extreme outliers. The outliers make visual evaluation of mixing and autocorrelation difficult; excluding these three values from the trace plot (Figure 7.2 – lower panel) revealed two well-mixed chains. If the mean α estimate were used in subsequent analyses from the MSE model the outliers would be a concern, but the MSE output focuses on the median so the outliers would not greatly affect policy decisions. As an example of the impact of outliers, the mean α from the escapement quality model was 0.0010 while the median was 0.0009 – a small difference but with the potential to propagate through the MSE. We did not test the sensitivity of using the mean versus the median. The β trace plots showed two well-mixed chains (Figure 7.2 – top right panel).

The autocorrelation plots for α and β (Figure 7.3) indicated that the MCMC chains have been thinned enough to remove any correlations among successive samples. Only the plots for a single chain for α and β are given in the results but in each case the autocorrelation figure was representative of both chains. The maximum positive or negative correlation for the α chains was 0.06 and the maximum for the β chains was 0.07.



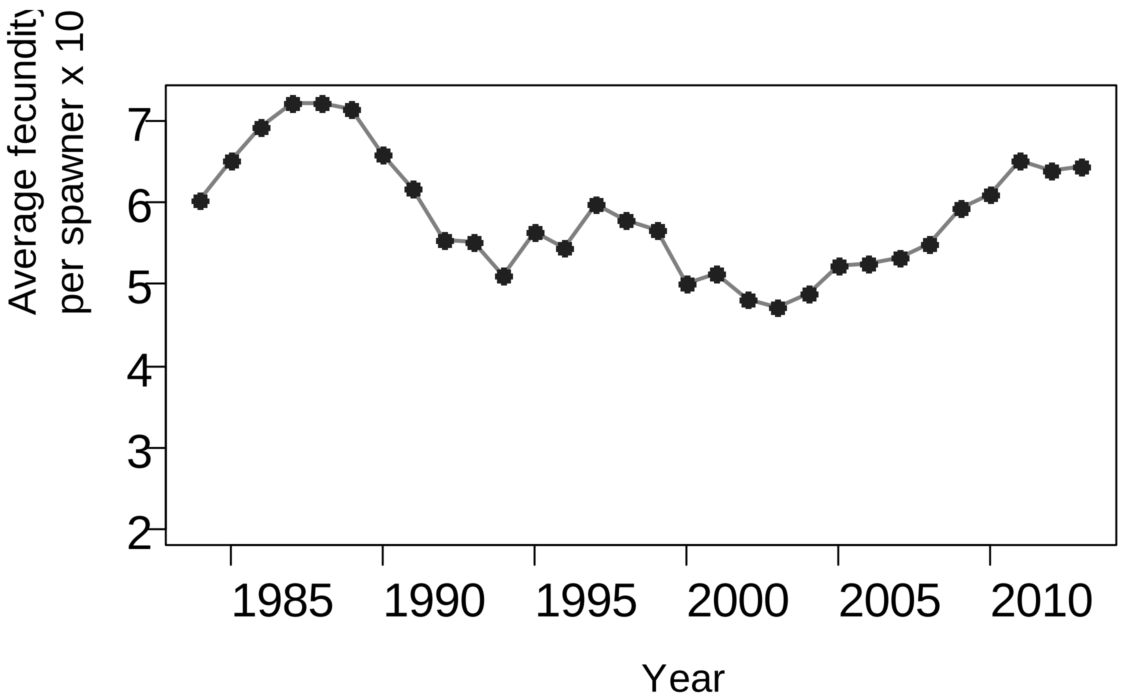


Figure 7.1. Top: Age composition for returning Yukon River Chinook Salmon (Canadian portion only) from 1982-2015. Bottom: Estimated average fecundity per spawner (females and males combined) for returning Yukon River Chinook Salmon (Canadian portion only) from 1982-2015.

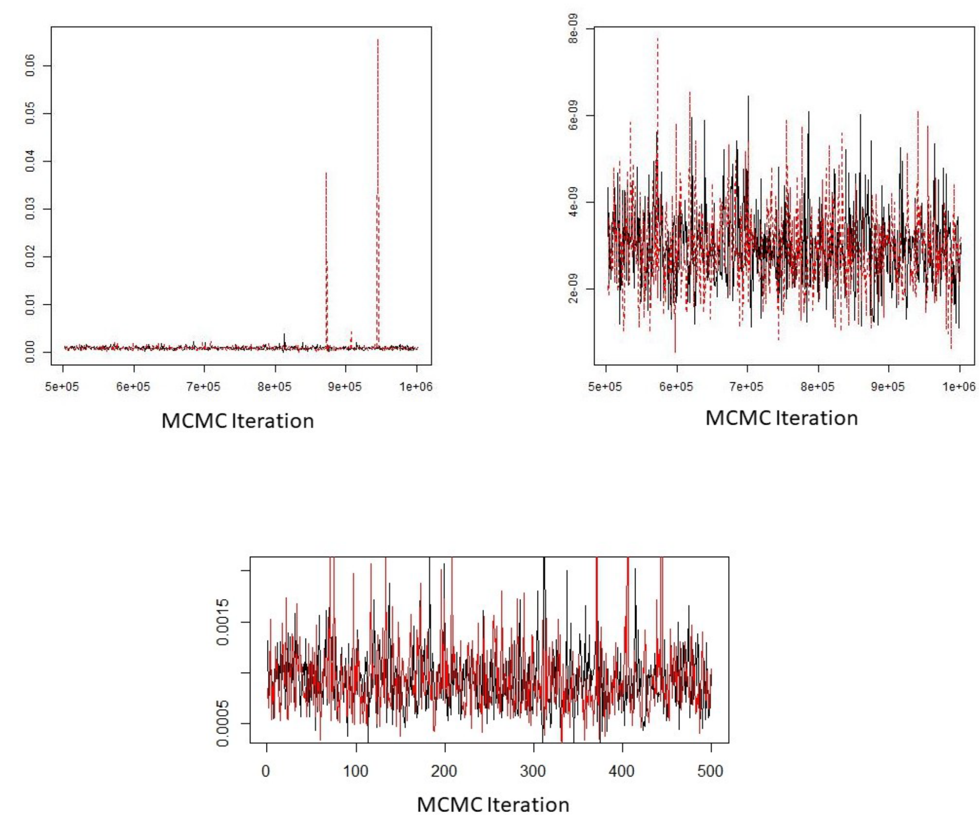


Figure 7.2 MCMC sample traceplots of Ricker alpha and beta parameters from the escapement quality SSM. Top left: alpha chain including three anomalously high outliers. Top right: beta chain. Bottom: alpha chain with three outliers filtered out.

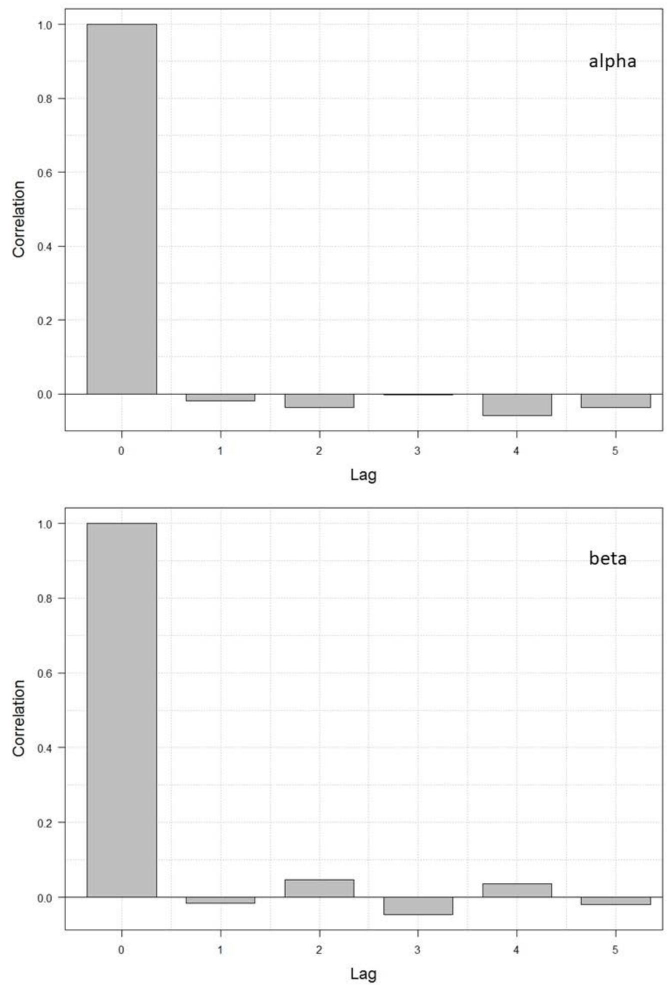


Figure 7.3 Autocorrelation plots for alpha (top) and beta (bottom) using one of the two MCMC chains displayed in Figure 7.2.

7.1.3 Stock-recruitment models

Observation and process uncertainty from the Yukon River was reflected in the MCMC chain variability of the estimated stock-recruitment relationship for both models (Figure 7.4). The 90% credible interval for the expected maximum number of recruits in the escapement quality model was (81,000-178,000) and for the escapement quantity model was (81,000-161,000). The 90% credible interval for the number of eggs to achieve maximum recruitment from the escapement quality model was (210-660 million eggs) and for the number of escaped individuals in the escapement quantity model was (31-89 thousand).

To compare the two models, we rescaled escapement for the escapement quality model by dividing the total number of eggs by the mean number of eggs per spawner, which allowed us to plot both models with the same x-axis (Figure 7.5). The shapes of the two models were similar, with a somewhat (~20%) higher escapement at maximum recruitment for the escapement quality model. As expected, reconstructed run sizes for the two models were very similar (Figure 7.6).

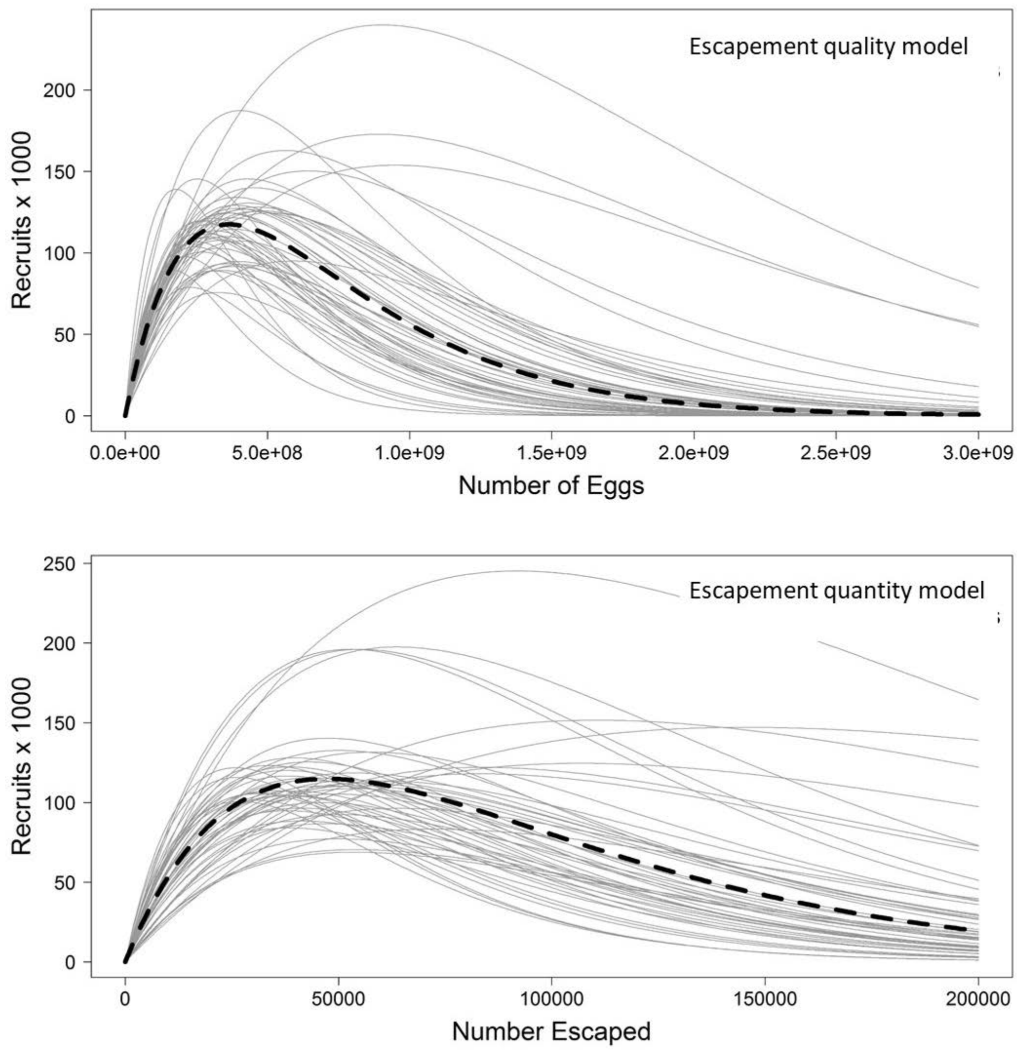


Figure 7.4 Stock-recruitment model fits, including the posterior median estimates of alpha and beta (thick dashed line), and 50 MCMC samples (light grey lines). The top panel shows the escapement quality model, with total egg production as the stock metric; the bottom panel shows the escapement quantity model, with total spawners (females + males) as the stock metric.

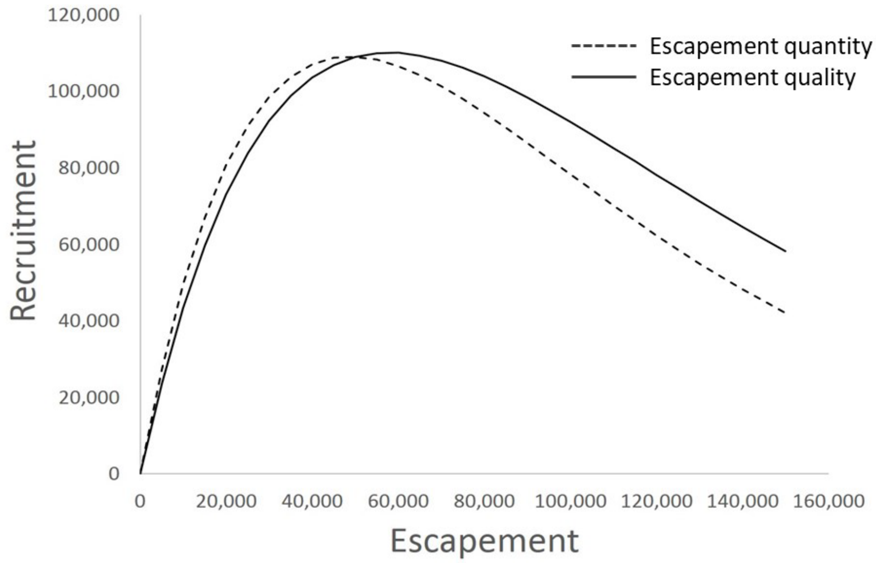


Figure 7.5. Comparison of the estimated stock recruitment relationships, based on posterior median parameter estimates for the two models considered here. Escapement values for the escapement quality model were calculated by dividing escapement in eggs by the mean number of eggs per spawner.

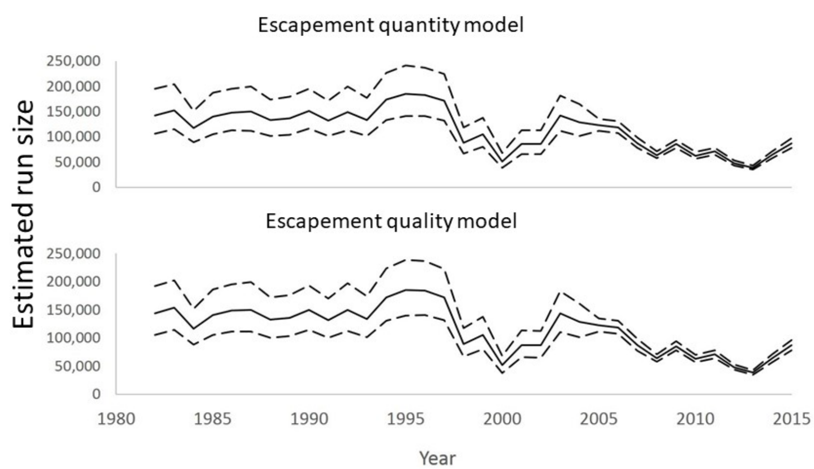


Figure 7.6 Reconstructed total run size for Canadian origin Yukon River Chinook Salmon, based on the escapement quantity model (top) and escapement quality model (bottom).

7.2 Management Strategy Evaluation model

The MSE model simulated future abundance of Chinook Salmon and calculated the performance metrics listed in Table 6.2 over a 50 year future time horizon. A single simulation of a single policy scenario (i.e., escapement target – harvest rate combination) results in a 50-year time series for all model outputs (Figure 7.7). To reflect uncertainty in model input parameters and processes (initial numbers, stock-recruit parameters, fishery outcome uncertainty) each policy scenario was repeated 500 times, generating a

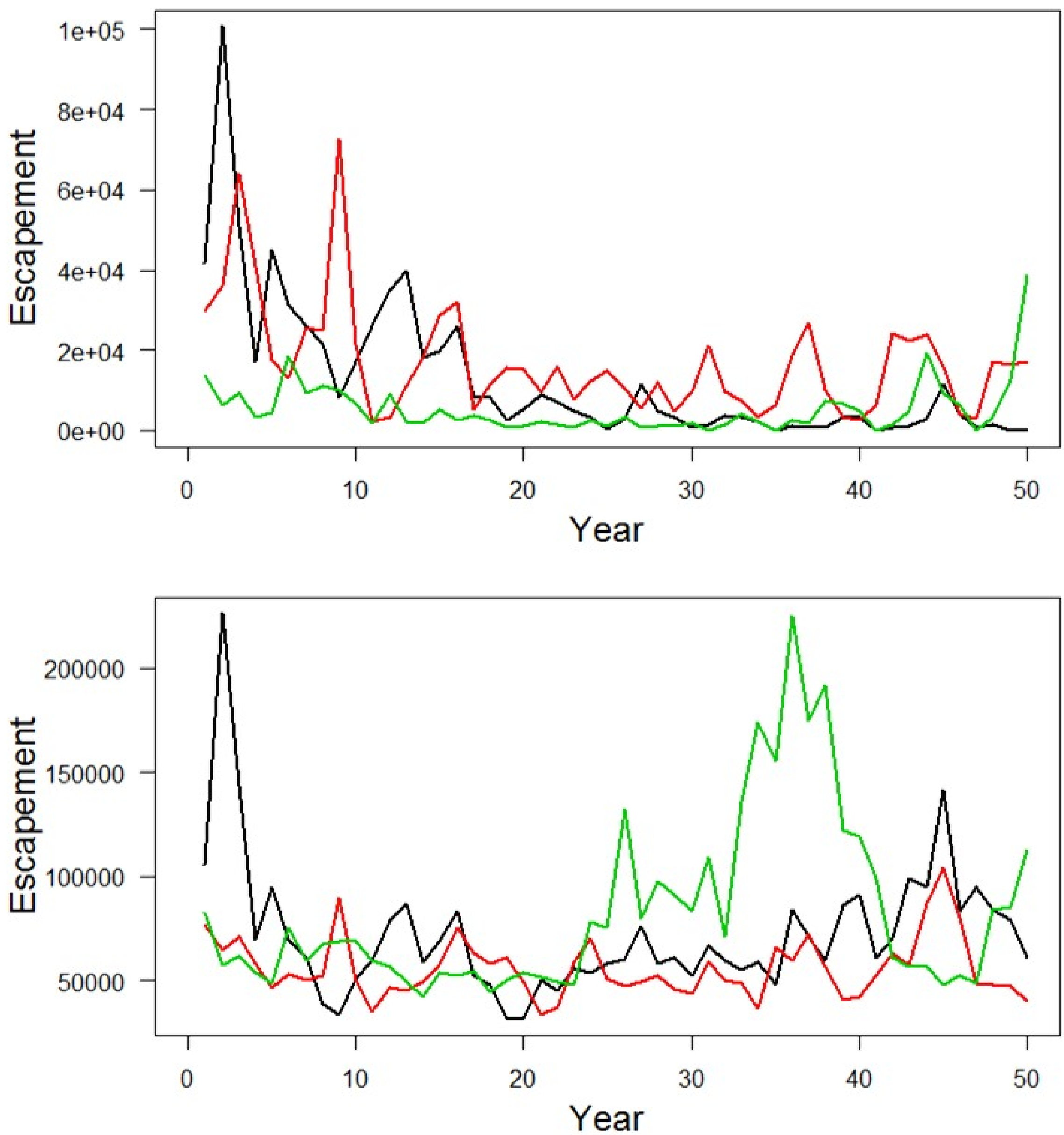


Fig 7.7. Three example MSE escapement time series from the escapement quantity model for two different policy scenarios. Upper panel – escapement target = 0; surplus harvest rate = 0.5. Lower panel – escapement target = 50,000; surplus harvest rate = 0.5.

large set of results (50 years x 500 simulations x 121 policy scenario options x 30 possible performance metrics). To facilitate interpretation of these results, we used contour plots to display median (across years and replicate simulations) outcomes for individual performance metrics across the complete range of policy scenarios considered (Figure 7.8).

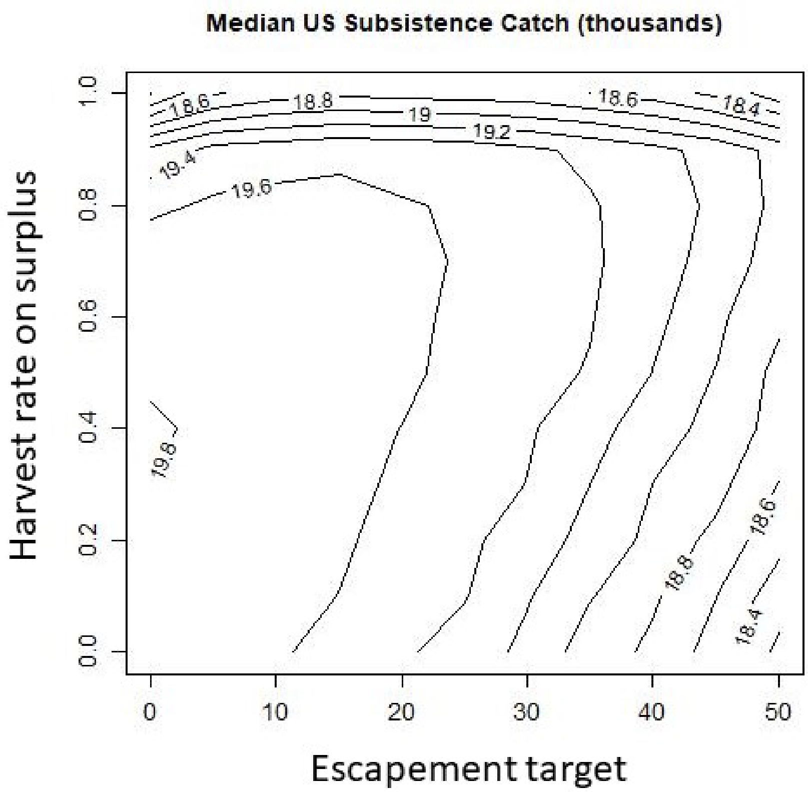


Figure 7.8. An example contour plot showing results for U.S. subsistence harvest from the escapement quality model with the 5.25 inch mesh scenario. The x-axis represents a range of escapement targets and the y-axis represents a range for the proportion of the surplus, above escapement+subsistence targets, that is harvested by the US commercial fishery. The contours were generated from the results of 500 simulations for 121 different policy combinations including escapement targets from 0-50,000 fish and harvest rates from 0-100% of the available surplus. The labels on the contours represent subsistence harvest levels in thousands of fish. In this example the highest subsistence harvest occurs at a small escapement target and moderate harvest rate (~ 40%). This would be the equivalent of a fixed harvest rate policy where 40% of the estimated total returns, after subtracting subsistence needs in the U.S. and Canada, would be harvested each year.

7.2.1 Comparison of escapement quantity and escapement quality models

The two models produced similar outcomes for all performance metrics when the smaller mesh size (5.25 inches) was simulated for the escapement quality model (note, mesh size does not affect the outcome for the escapement quantity model). Median US commercial harvest peaks at an escapement target of roughly 20,000 fish and a high harvest rate on the surplus (Figure 7.9 upper), which corresponds to a realized median escapement of approximately 25,000 fish (Figure 7.9 lower). Median Canadian commercial harvest is highest at low escapement targets (10,000 fish) and moderate (~ 0.5) surplus harvest rates (Figure 7.10 upper). This scenario results in a median escapement of 35-40,000 fish (Fig 7.9 lower). Median Canadian subsistence harvest increases with higher escapement targets and lower surplus harvest rates (Figure 7.10 lower). Note this harvest rate applies to US commercial harvest only. Policy scenarios that maximize Canadian commercial harvest result in Canadian subsistence harvests below their maximum levels. Probability of closure of US commercial fisheries (no fishing allowed due to the absence of a forecasted surplus) is generally low, except at very low surplus harvest rates or high escapement targets (Figure 7.11 upper). Probability of closure of Canadian commercial fisheries is generally higher than that for US commercial fisheries, and lowest at relatively high escapement targets and moderate surplus harvest rates. Finally, median US subsistence fishery harvests are highest at escapement targets below 20,000 fish and surplus harvest rates below 0.75 (Figure 7.8). Differences in the outcomes for the different fisheries are in part a result of the timing of the fisheries relative to one another and the rules in the model for determining whether a harvest can be taken.

7.2.2 Escapement quality model: comparison of mesh size policies

For many performance metrics the pattern of response to the range of harvest policy alternatives does not greatly depend on the simulated mesh size, but there are notable exceptions. A similar magnitude of escapement, measured in terms of eggs, can be achieved at a higher harvest rate and lower escapement goal under a fishery that uses 5.25-inch mesh than one that uses 7.5-inch mesh (Figure 7.12 upper panel). For example, to achieve 350 million eggs at a surplus harvest rate of 0.2, the escapement target needed to be 35,000 fish for the 7.5-inch mesh fishery, but only 10,000 fish for the 5.25-inch mesh fishery. This is because more large individuals (with greater fecundity) are removed under a 7.5-inch mesh harvest. This difference is not evident when escapement is quantified in terms of numbers of spawners (Figure 7.12 lower panel).

Mesh sizes also affected outcomes for US commercial harvests and Canadian subsistence harvests (Figure 7.13). Median commercial harvest of greater than 30,000 fish were forecasted for the 5.25-inch mesh fishery, but not for the 7.5-inch mesh fishery (Figure 7.13 upper panel). With a 7.5-inch mesh fishery more eggs are removed because the harvest targets larger fish, especially at low escapement goals and high surplus harvest rates; this makes it difficult for the population to be as productive as it might otherwise be. For the Canadian subsistence fishery, lower surplus harvest rates or higher escapement targets are required to achieve similar harvest rates when the mesh size is 7.5 inches than when it is 5.25 inches (Figure 7.13 lower panel).

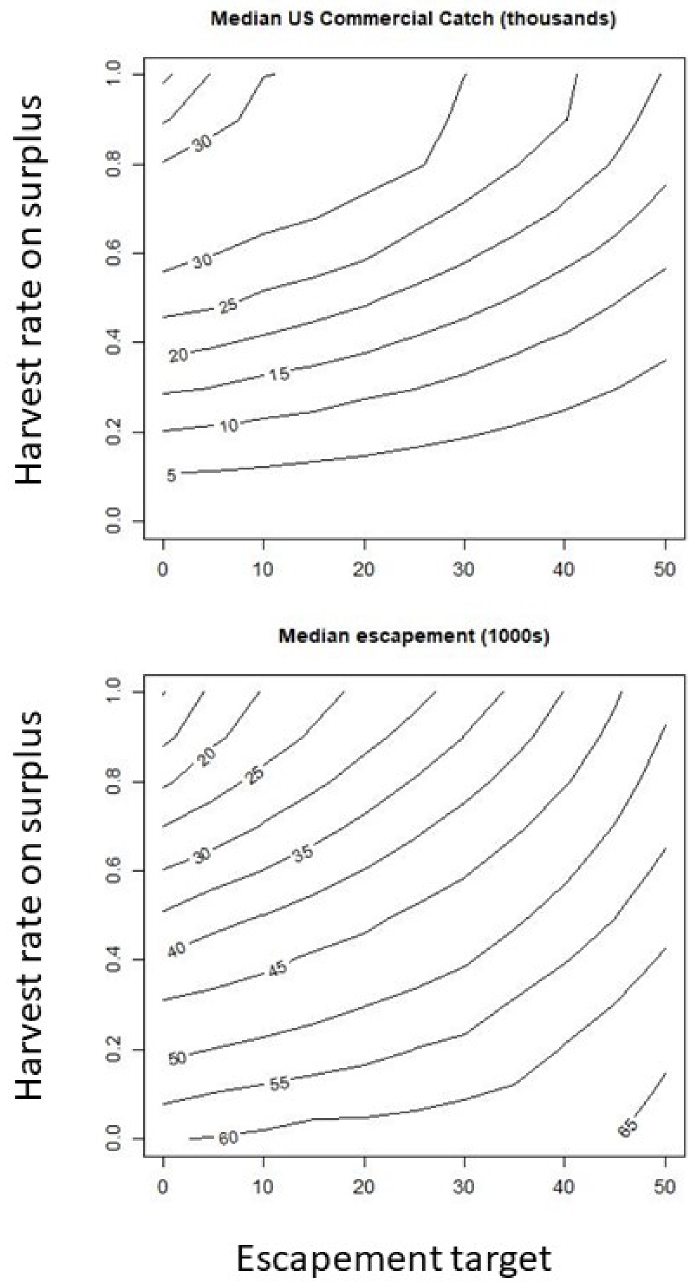


Figure 7.9. Escapement quality model results for the 5.25” mesh scenarios. Upper panel – median US commercial harvest. Lower panel – median realized escapement in numbers of spawners.

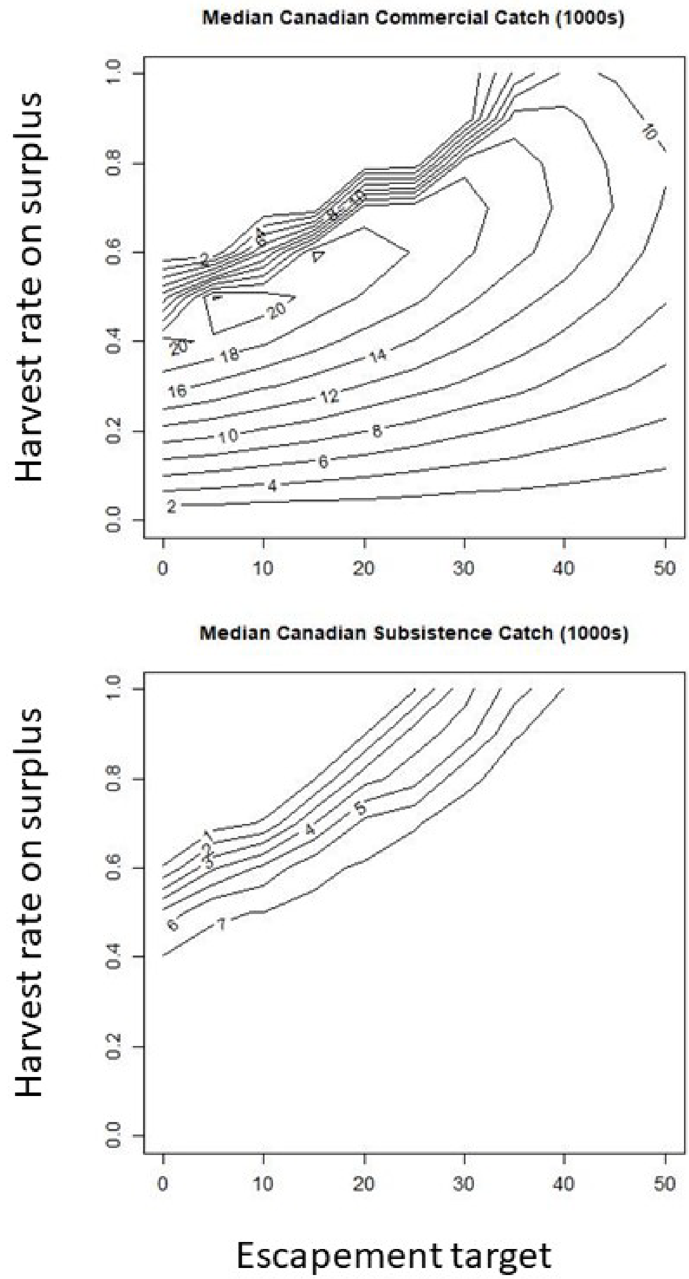


Figure 7.10. Escapement quality model results for the 5.25” mesh scenarios. Upper panel – median Canadian commercial harvest. Lower panel – median Canadian subsistence harvest.

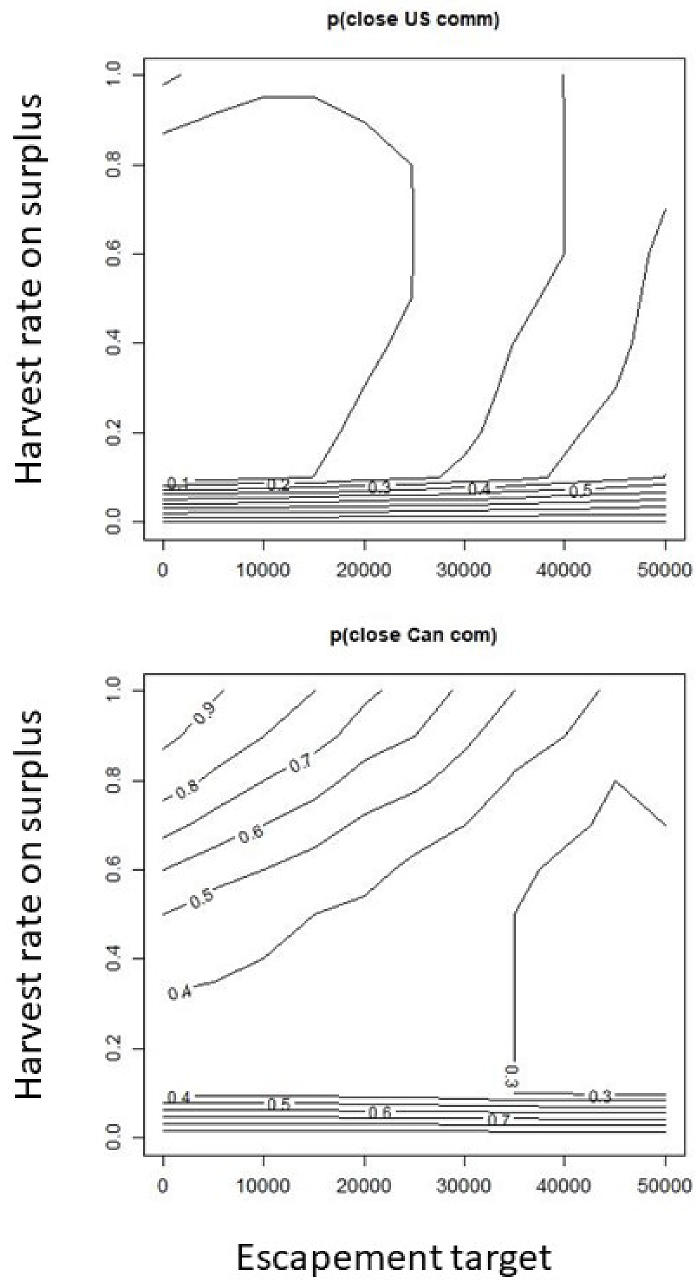


Figure 7.11. Escapement quality model results for the 5.25" mesh scenarios. Upper panel – probability of closure for the US commercial fishery. Lower panel – probability of closure of the Canadian commercial fishery. These probabilities are calculated as the number of years during a 50 year simulation when no fishing was allowed, averaged across 500 replicate simulations.

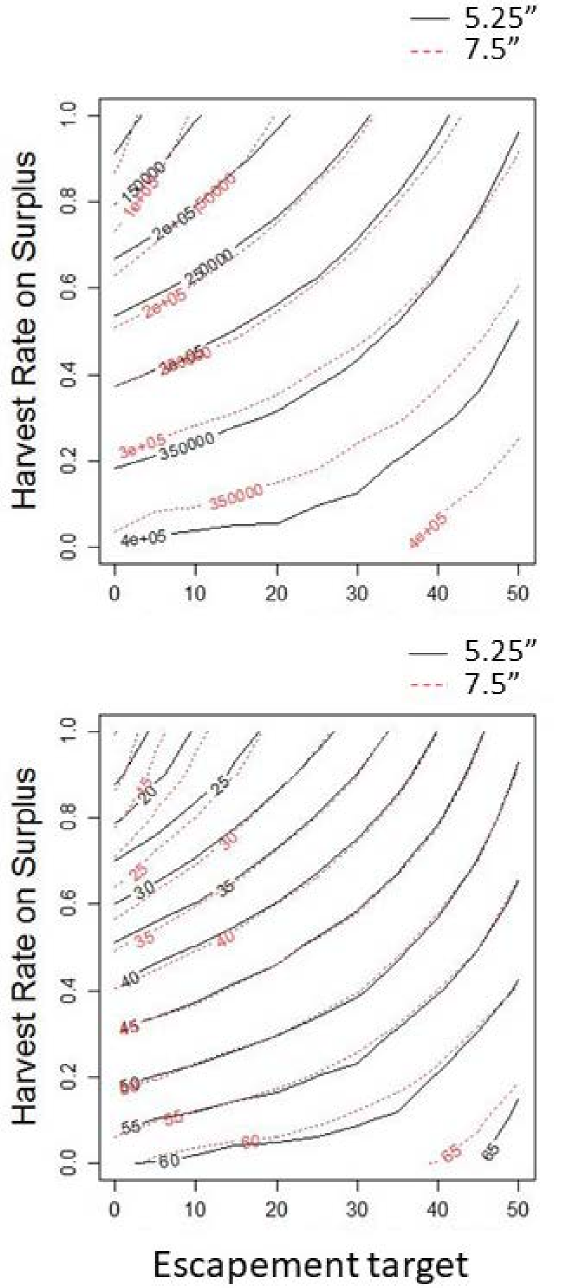


Figure 7.12. Comparison of two mesh size scenarios for the escapement quality model. Upper panel – median total escapement in units of eggs (1000s). Lower panel – median total escapement in units of spawners.

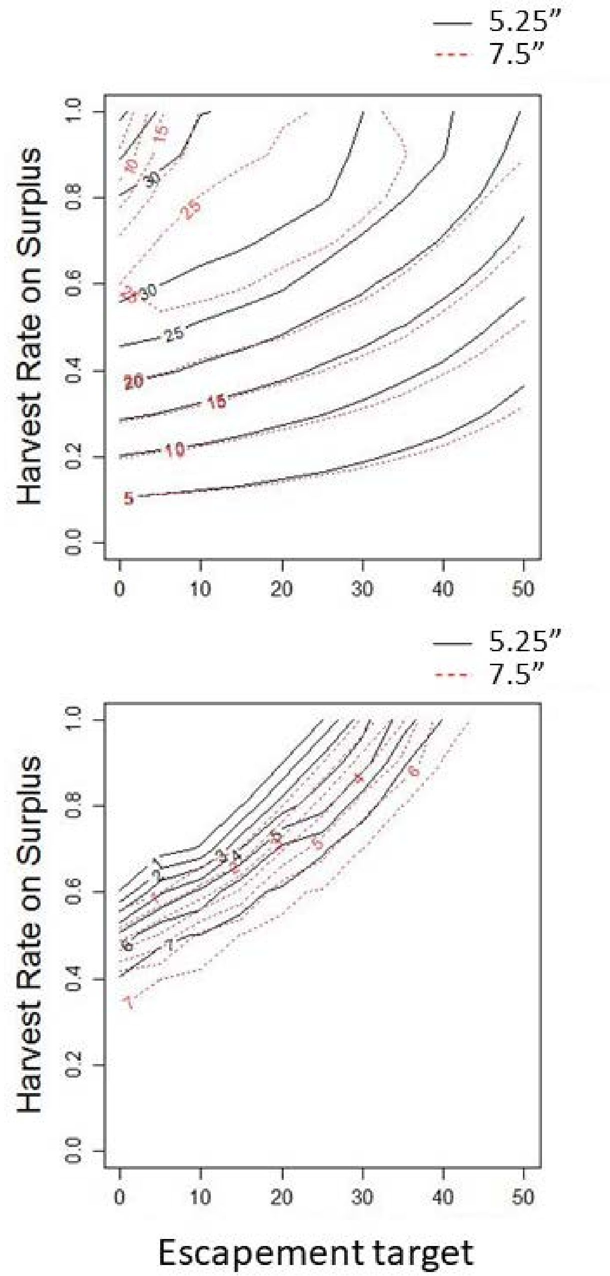


Figure 7.13. Comparison of two mesh size scenarios for the escapement quality model. Upper panel – median US commercial harvest (1000s). Lower panel – median Canadian subsistence harvest (1000s).

VIII. Discussion

Earlier versions of the state-space run-reconstruction and MSE models described here were developed for Canadian-origin Yukon River Chinook Salmon in prior projects (S. Fleischman, ADF&F unpublished analysis; Jones et al. 2012). The consultation and engagement activities that occurred at the beginning and the end of this project led to significant revisions to these models that increased the salience of the analyses and facilitated greater understanding of the purpose of the work and its strengths and limitations. In our view, it is difficult to overstate the value of this type of engagement for modeling projects whose purpose is to develop tools to assist decision-making.

State-space models are becoming a standard tool for fisheries assessment. They have considerable appeal because they are able to represent both observation and process uncertainty in the same model, thereby enabling a more complete and informative evaluation of the uncertainty associated with inferences about stock status, demographic parameters, and fishery characteristics. Estimation of state-space model parameters in a Bayesian framework allows generation of joint posterior probability distributions for all model parameters as well as derived quantities such as candidate reference points (e.g., S_{MSY}). These distributions are well suited as inputs to an MSE model that aims to properly reflect the uncertainty about system dynamics, which in turn allows formal characterization of risks associated with alternative management strategies.

Despite their appeal as a tool to inform stock assessments, stock-recruitment analyses or MSE simulations, the accuracy of state-space models remains vulnerable to erroneous assumptions about model structure or unrecognized biases in the data that the model uses to estimate uncertain quantities. In this case, a critical assumption in our analysis is that the data used to describe the time series of salmon returns to Canadian waters of the Yukon River accurately (if not precisely) represent the actual population of interest. During the project we learned of concerns that the ASL data collected near the US/Canada border might not accurately characterize the sex composition of the actual run passing the border. Sex is assigned to fish sampled in fish wheels, and more recently test fishery gillnets, using non-lethal methods. The possibility exists that this method tends to overestimate the proportion of large females and underestimate the proportion of small females, because of a prior expectation that smaller fish tend to be male and larger fish tend to be female. We have begun an investigation of this by looking at sex composition data from a downstream sampling location (Rapids fish wheel) where lethal sampling was used. However, this analysis was not completed by the conclusion of this project. It is important to note that the critical question is less whether biases exist than whether the biases are large enough to lead to different conclusions about management strategies such as a desired escapement goal.

The two state-space models we estimated for this project resulted in similar run reconstructions (Figure 7.6) and stock-recruitment relationships (Figure 7.5). When we re-scaled the escapement quality stock-recruitment model to facilitate comparison with the escapement quantity model, the peak of the stock-recruitment curve corresponded to a higher escapement level (~45,000 versus 60,000 spawners). Uncertainty about the true stock-recruitment relationship for both models is large relative to this difference (Figure 7.4). Nevertheless, accounting for changes over time in the age, size, and sex composition of the returning fish did influence our assessment of the relationship between escapement and subsequent recruitment, to an extent that could have management implications. Whether this is in fact the case depends on a comparison of the performance of alternative management strategies between the two population models.

The MSE model was able to reasonably represent the dynamics of the fishery and the management process that determines border passage and escapement to spawning grounds. In practice, the rules used to determine whether a commercial fishery is allowed or whether restrictions on subsistence harvest are necessary in a particular year are not so unambiguously defined that simulating them is straightforward. However, the MSE model reflected the sequence of management decisions that have to be made each year as the fishery progresses up-river, and the priority of, first, the border passage and escapement goals and, second, subsistence needs. While commercial exploitation of Yukon River Chinook Salmon has not taken place in recent years, the MSE model needed to reflect decisions that would be made across a wide range of possible future run sizes; consequently, our evaluation of management strategies needed to consider outcomes for commercial fisheries as well as subsistence fisheries and escapement.

One aspect of the MSE model that was difficult to implement for the escapement quality model concerned the effect of mesh sizes of commercial and subsistence gillnets on selective harvest of each age class of returning fish. Combining a target harvest level for a fishery with differential age-based vulnerability would sometimes lead to all fish in an age group being removed by that fishery, with the relative impact on different age groups depending on the mesh size being used. A prediction of complete removal of all fish in an age group is likely unrealistic, and future refinements to the MSE model could include simulating this process using a depletion method where the exploitation rate on the most vulnerable age group would approach but not reach 100%. Nevertheless, we do not believe the method used in the simulations reported here resulted in qualitatively unrealistic forecasts of outcomes.

The MSE simulation results reveal potentially important trade-offs among management objectives. The most obvious trade-off is between harvest and escapement. Policies that result in the largest sustained US commercial harvest (Figure 7.9 top panel) call for high harvest rates on the surplus (> 80%) at relatively low escapement targets (~20,000), but substantially higher escapement outcomes (35-45,000 versus 25-30,000; Figure 7.9 bottom panel) can be achieved at lower harvest rates (~50-60%) without a large reduction in expected US commercial harvest. Another important trade-off is evident between US commercial harvest and Canadian subsistence harvest. Moderate to large subsistence harvests in Canada are only possible at harvest rates well below 100% of the surplus or escapement targets above 30,000 (Figure 7.10 bottom panel). This outcome requires US commercial harvest to be at least 30% lower than could be achieved at the optimal level of escapement and harvest for this sector. There is a similar trade-off between US and Canadian commercial harvest (Figure 7.10 top panel), with the best outcomes for Canadian commercial fisheries occurring at low escapement targets but also moderate harvest rates on the surplus. Careful examination and discussion of these trade-offs is the key to using MSE simulations to inform decision making for a socially and ecologically complex issue.

Mesh size policies did influence the performance of alternative management strategies. When large mesh fisheries were simulated, we found that higher escapement targets and/or lower harvest rates were required to achieve similar outcomes, both for escapement in units of eggs (Figure 7.12 top panel) and for fisheries (Figure 7.13). The larger mesh scenario also resulted in lower maximum achievable harvests for the US commercial fishery. This outcome is explained by the effect of large mesh fisheries on the size and sex composition of spawning fish, with similar levels of effort and catch overall resulting in lower numbers of large, high fecundity spawners when the large mesh gear was used. This result illustrates the importance of not just specifying safe harvest levels but also considering the effect of the fishery on escapement quality.

Wise, equitable management of economically and culturally important fisheries is invariably a challenging undertaking. Two of the most important reasons for this are (1) that there are nearly always multiple, potentially conflicting objectives for a fishery, held by a diverse group of stakeholders, and (2) that many sources of uncertainty contribute to our inability to accurately and precisely anticipate the consequences of any management strategy. Scientific tools that facilitate consideration of uncertainty and management trade-offs are therefore of great value to decision making. However, a third, equally important ingredient of a good decision-making process is transparency. If the parties responsible for determining future management strategies for Yukon River Chinook Salmon decide that the technical methods described in this report could play a useful role in future deliberations on border passage goals or other such matters, we urge them to also consider embedding the MSE work in an open, transparent process that engages representatives from all key stakeholder groups. Experience with other contentious fisheries (Jones et al. 2016) has illustrated the critical importance of engagement in the development of a well-informed management strategy.

IX. References

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X. Deliverables

Deliverables from this project include this completion report and four semi-annual progress reports. As described herein, we also presented our work at three JTC meetings (Nov 2015, March 2017 and November 2017), and hosted two workshops in association with the first and last of these JTC meetings. Copies of code for the state-space and MSE models will be made available to interested parties on request.

XI. Project Data

The data used as input to the state-space run-reconstruction model are summarized in Appendix 2. An Excel workbook containing these data will be made available to interested parties on request.

XII. Acknowledgements

We would like to thank all members of the Yukon River Panel Joint Technical Committee for the willingness to engage with us during the course of this project. Their early input helped frame the analysis appropriately, and their interest at the end ensured its salience to future discussions about the management of this fishery. We would particularly like to thank Jan Conitz and Zach Liller from ADF&G and Nathan Miller and Joel Harding from DFO for their support and assistance with local arrangements and communications. Finally, we'd like to thank Joe Spaeder and Katie Williams of BSFA for their encouragement and unfailing support of our work.

XIII. Appendices

13.1 Appendix 1: Notes from the November 19-20 meeting with the Yukon River Panel Joint Technical Committee

Developing Tools to Evaluate Management Strategies for the Sustainable Exploitation of Yukon River Chinook Salmon
Notes from 11-19/20-15 meeting in Seattle

In attendance: Jan Conitz, Holly Carroll, Bonnie Borba, Sean Larson, Jeff Estensen, Sabrina Garcia, Caroline Brown, Jim Murphy Randy Brown, Fred Bue, Gerald Maschmann, Chris Stark, Bill Bechtol, Nathan Miller, Trix Tanner, Mary Ellen Jarvis, Michael Crowe, Maggie Wright, Don Toews, Elizabeth McDonald, Michael Jones, and John Syslo

These notes summarize the discussions that took place on Friday morning (Nov 20) only. Powerpoint slides for the presentations on Thursday afternoon (Nov 19) have already been distributed to meeting participants.

Discussion of Objectives, Options and Information Sources

1) **Overall objectives** of Management Strategy Evaluation for Canadian-origin Yukon River Chinook Salmon

- a) What are our objectives? We distinguished between:
    - a. fundamental objectives
        - -ultimate goal of management
    - b. means objectives

-means for achieving fundamental objectives

2) What are the **fundamental objectives** for the project?

a) Sustain wild Chinook population at a level of abundance to allow harvest

b) Sustain Chinook populations at historical levels to provide ecosystem services

a. What is a historical level? Jan says we have records over 100 years back, but we still don't know what a historical level is because there was a lot of harvest back then. We have a hard time defining what this is.

b. Is a historical level something we can ever get back to? It is likely that we are going to manage for a given state. Mike says the purpose of this exercise to is to evaluate trade-offs that we will be living with.

c. Other ecological benefits (e.g., marine-derived nutrients, etc.) might be inherent in a "historical level."

c) Sustain abundance in all conservation units to allow harvest

d) Sustain historical escapement quality

a. historical levels of age, sex, and size composition

e) Allow traditional fishing opportunities

f) Maintain abundance at a level that allows commercial, recreational and subsistence harvest and non-consumptive use (wild fish have intrinsic) value. Broad public awareness – people just like knowing the fish are there. There is also a large wildlife-watching component.

g) Maintain equitable distribution of harvest among users

h) Allow summer chum fishery while reducing effects on Chinook

3) What are the **means objectives**?

a) Maintain (or restore where degraded) high-quality habitat

a. spawning/rearing habitat

b) Managing harvest of Canadian versus US stocks separately (we might also think about individual conservation units. Kuskokwim example where they might consider management of individual stocks)

c) minimize restrictions on traditional harvest methods

d) maintain high accuracy in stock assessments

e) ensuring management flexibility

f) maintain or increase productive capacity

g) maintain stakeholder engagement and participation

4) **Performance measures** (what do we need to be able to model/predict to answer the question of whether we are meeting fundamental objectives?)

a) Returns (escapement + harvest) (fundamental obj a)

b) Escapement (historical levels; fundamental obj b)

c) returns (or escapement) to conservation units (fundamental obj c)

d) age, sex, and size composition of the escapement (fundamental obj d)

e) subsistence harvest level (this performance measure does not explicitly consider the means by which people harvest fish (fundamental obj e)

f) population size: returns or escapement – which is more important, and the level that is considered sufficient to meet the objective, depends on the user (fundamental obj f)

g) spatial distribution of harvest (fundamental obj g)

5) **Management options**

Objectives define model outputs. Management options define model inputs.

a. Escapement target – useful construct because it can be set to zero to consider harvest <u>rate</u> policies

- a. Overall target
- b. Conservation unit-specific

b. Harvest rate on surplus above the target (a)

- a. Normally this would be a fixed rate (e.g., 25, 50, or 75%), but…
- b. …could have policy where harvest rate varies based on size surplus rather than being constant regardless of the surplus. Jan said this is unlikely because we don't know the surplus ahead of time. Mike responded this may be difficult in the real world but easy to do in the model. Model may show it doesn't result in a great benefit anyways.
- c. They have a forecast or test fishery, albeit a high degree of uncertainty.
- d. Escapement goal versus target. In Canada the target is the middle of the escapement goal range. Which part of escapement goal range will be evaluating? We will consider values from 0 to 100 percent – so we will evaluate all possible strategies.

c. Gear

- a. Mesh size

d. Bycatch in summer Chum fishery gill nets (not sure what we're going to do with this, but want to be comprehensive)

- a. In recent years other fisheries have been restricted to protect Chinook

e. In-season component

- a. Seasonal openings and closures (i through iv are US policies)
  - i. Current thinking is to protect the first pulse so that it gets to Canada (first pulse has a larger proportion of Canadian fish – local knowledge and genetics support this). Sometimes the second pulse is also protected.
  - ii. Precisely timed openings with gear restrictions for summer chum. Strategically target the chum and protect kings until about 75% of the way through the run. Then they allow targeting of kings – typically smaller males (smaller mesh gill nets). Males move ahead of females in within-stock runs. Allowing harvest towards end of run harvests more females.
  - iii. It's not just timing of kings, harvest relates to timing of chums. Chum abundance has an effect in addition to timing.
    1. Are there ways to think about scenarios with high versus low chum abundance (e.g., high chum abundance means more incidental harvest?)
    2. Jan - Could we use summer chum model with incidental harvest rate?
  - iv. First pulse has to be protected, even if you forecast a large run. This is a mandate. We should allow for scenarios in which we don't fish the first pulse, but we should also look at scenarios where we allow fishing the first pulse.
    1. Thus far, forecasting hasn't been good. However, we can model this uncertainty.
  - v. In the Yukon, an abundance-based management decision is used
    1. Let first quarter of the run pass (sometimes half)
       - a. this is the run measured at Eagle (sonar)
       - b. there is a 28-day lag between Pilot and Eagle
    2. Aboriginal fisheries open first
    3. They err on the side of being conservative if abundance is low
  - vi. If there is a strong return they do not wait until the first quarter of the run passes

6) **Information availability**

a) How much information on run-timing of US vs Canadian portions in the pulses?

a. If we're going to develop a model we're going to need to know about this

i. Coarsest level of resolution is Canadian vs. US

b. Genetics and radio telemetry (tagged at Pilot station – published papers by Eiler et al.- Transactions and PLOS one).

Holly said they (ADFG) can send GSI data on this too (Pilot versus sonar). Scale-pattern analysis.

b) How much information of basin-scale stock information?

a. We are interested in a more qualitative sense of subtle differences in run timing of the stock complex that passes in to Canada. Who would we talk to for this information?

b. Eagle sample historic run composition through time. Annual reports by Beacham and Candy on genetic samples by time stratum. Point of contact for run timing is Holly for ADFG and Trix for Canada.

c) Escapement quality

a. Spawner-recruit analysis might need sex ratio or size of individual spawners. We would at least like to look at it.

i. Jan says they have data for 30 years or so at Eagle (sex for escapement at Eagle). Hamachan has looked at it. Quality of data has improved through time. Hamachan has written a paper but it is not published/available yet.

ii. Whitehorse fishway data from when they select broodstock –might have some biases. 30-40 fish per year?

iii. Carcass work? Big Salmon River age/sex/length of carcasses

iv. In the spring/summer, John, Mike, and Matt will go to Anchorage and meet with Steve Fleischmann to talk about data sources and modeling. We might be following up with people about these data sources.

d. We will continue to treat the environment as a black box (production parameter).

e. Need to update run reconstruction component up to last year, are the escapement surveys continued or are there any new data sources?

a. Jan gave Steve up to the last year
b. Steve might send a list to see what they can add.
c. Everything is in the JTC report

f. Any additional sources of data we should look at?

a. Papers/reports on fecundity in the Yukon – raw data tabulated (Randy Brown)

h. We will be model building through spring/summer. We may communicate through Jan to provide an update at the Fall JTC meeting.

7) **Additional questions**

a. Are we ignoring long term effects (i.e., genetics)?

a. Yes.

b. How will we account for sex-ratio?

a. We will change the x variable to be fecundity.

c. Will this project result in a publication?

a. Yes, this is an end result of the project.

13.2 Appendix 2: State-space model data sources

Table 13.1. Data for the escapement quality version of the state-space model. See end of table for explanation of column headers.

year	harvUS	cvUS	harvCA	cvCA	snr	tlm	cvbp	cbmr
1982	87241	0.25	16808	0.1	NA	NA	1	36598
1983	96994	0.25	18751	0.1	NA	NA	1	47741
1984	44735	0.25	16295	0.1	NA	NA	1	43911
1985	85773	0.25	19152	0.1	NA	NA	1	29881
1986	97593	0.25	20064	0.1	NA	NA	1	36479
1987	115258	0.25	17564	0.1	NA	NA	1	30823
1988	84649	0.25	21328	0.1	NA	NA	1	44445
1989	86798	0.25	17419	0.1	NA	NA	1	42620
1990	72996	0.25	18980	0.1	NA	NA	1	56679
1991	61210	0.25	20444	0.1	NA	NA	1	41187
1992	97261	0.25	17803	0.1	NA	NA	1	43185
1993	78815	0.25	16468	0.1	NA	NA	1	45027
1994	95666	0.25	20790	0.1	NA	NA	1	46680
1995	99028	0.25	20091	0.1	NA	NA	1	52353
1996	88898	0.25	19546	0.1	NA	NA	1	47955
1997	92162	0.25	11516	0.1	NA	NA	1	53400
1998	46947	0.25	6575	0.1	NA	NA	1	22588
1999	60908	0.25	12354	0.1	NA	NA	1	23716
2000	22143	0.25	4829	0.1	NA	NA	1	16173
2001	23325	0.25	9774	0.1	NA	NA	1	52207
2002	30058	0.25	9069	0.1	NA	51428	0.2	49214
2003	59939	0.25	9446	0.1	NA	90037	0.15	56929
2004	57832	0.25	10946	0.1	NA	59415	0.13	48111
2005	44650	0.1	10977	0.1	78962	NA	0.06	42245
2006	48097	0.1	8758	0.1	71388	NA	0.06	36748
2007	48201	0.1	4794	0.1	39698	NA	0.06	22120
2008	28754	0.1	3399	0.1	37282	NA	0.06	14666
2009	16186	0.1	4297	0.1	69575	NA	0.06	NA
2010	27423	0.1	2647	0.1	34465	NA	0.06	NA
2011	20826	0.1	4594	0.1	50901	NA	0.06	NA
2012	13842	0.1	2000	0.1	34656	NA	0.06	NA
2013	6604	0.1	1922	0.1	30573	NA	0.06	NA
2014	1398	0.1	100	0.1	63431	NA	0.06	NA
2015	3681	0.1	1000	0.1	83674	NA	0.06	NA

year	Little_Salmon	Big_Salmon	Nisutlin	WHFW	Tatchum	Wolf	Tincup	Ross	Blind
1982	403	758	578	473	73	104	NA	155	NA
1983	101	540	701	905	264	95	100	43	NA
1984	434	1044	832	1042	153	124	150	151	NA
1985	255	801	409	508	190	110	210	23	NA

1986	54	745	459	557	155	109	228	72	NA
1987	468	891	183	327	159	35	100	180	NA
1988	368	765	267	405	152	66	204	242	NA
1989	862	1662	695	549	100	146	88	433	NA
1990	665	1806	652	1407	643	188	83	457	NA
1991	326	1040	NA	1266	NA	201	NA	250	NA
1992	494	617	241	758	106	110	73	423	NA
1993	184	572	339	668	183	168	NA	400	NA
1994	726	1764	389	1577	477	393	101	506	NA
1995	781	1314	274	2103	397	229	121	253	NA
1996	1150	2565	719	2958	423	705	150	102	NA
1997	1025	1345	277	2084	1198	322	193	NA	957
1998	361	523	145	777	405	66	53	NA	373
1999	495	353	330	1118	252	131	NA	NA	892
2000	46	113	20	677	276	32	19	NA	NA
2001	1035	1020	481	988	NA	154	39	NA	NA
2002	526	1149	280	605	NA	84	NA	NA	NA
2003	1658	3075	687	1443	NA	292	NA	NA	1115
2004	1140	762	330	1989	NA	226	NA	NA	792
2005	1519	952	807	2632	NA	260	NA	363	525
2006	1381	1140	601	1720	NA	114	NA	NA	677
2007	451	601	137	427	NA	54	NA	NA	304
2008	93	303	NA	399	NA	22	NA	NA	276
2009	821	1827	497	828	NA	134	NA	NA	716
2010	NA	656	288	672	NA	94	NA	NA	270
2011	NA	405	NA	1534	NA	81	NA	NA	360
2012	NA	NA	NA	1030	NA	NA	NA	NA	157
2013	NA	NA	NA	1139	NA	NA	NA	NA	312
2014	NA	NA	NA	1601	NA	NA	NA	NA	602
2015	NA	NA	NA	1465	NA	NA	NA	NA	964

year	**Age4**	**Age5**	**Age6**	**Age7**	**F4**	**F5**	**F6**	**F7**
1982	3	13	60	22	0.025445	0.022901	0.208651	0.137405
1983	2	14	70	14	0.00068	0.055744	0.263086	0.061183
1984	6	19	57	18	0.00034	0.039854	0.317015	0.062544
1985	1	9	69	20	0	0.023964	0.370944	0.063904
1986	3	21	44	30	0.000727	0.03516	0.336081	0.14937
1987	4	10	66	20	0	0.006064	0.468924	0.073269
1988	9	24	26	38	0	0.012333	0.124358	0.38335
1989	7	21	54	17	0.005544	0.052664	0.330151	0.127502
1990	13	26	50	11	0.003141	0.068153	0.329146	0.062186
1991	2	37	50	11	0.000379	0.123983	0.306833	0.068332
1992	4	22	71	3	0.010447	0.05345	0.280126	0.015306
1993	10	26	51	12	0.000334	0.051402	0.270027	0.068425
1994	4	46	44	7	0.001797	0.055422	0.197723	0.040743

1995	4	15	76	5	0.002841	0.033381	0.385298	0.029474
1996	1	45	39	14	0.005692	0.121229	0.175299	0.051224
1997	3	15	75	7	0.001821	0.043039	0.451415	0.053468
1998	1	41	47	11	0	0.074451	0.214342	0.04232
1999	2	18	79	2	0	0.058313	0.434243	0.005376
2000	1	30	58	11	0.013362	0.050342	0.278434	0.042884
2001	4	27	62	7	0	0.023256	0.240152	0.04224
2002	4	32	55	9	0.002082	0.051624	0.238135	0.029142
2003	1	26	63	10	0.002709	0.042118	0.270936	0.049507
2004	2	26	65	7	0.000591	0.020378	0.308328	0.039279
2005	1	33	62	4	0	0.099415	0.22807	0.011696
2006	2	43	53	2	0.046875	0.167969	0.160156	0.003906
2007	7	33	59	2	0.005141	0.064267	0.359897	0.005141
2008	4	59	33	4	0	0.085333	0.245333	0.037333
2009	9	31	59	0	0	0.035549	0.360124	0
2010	10	49	37	4	0	0.107143	0.264881	0.032738
2011	4	36	54	7	0.002387	0.066826	0.389021	0.054893
2012	6	37	53	4	0	0.061224	0.4	0.036735
2013	6	30	60	4	0	0.079245	0.403774	0.033962
2014	7	50	40	3	0	0.069421	0.26281	0.019835
2015	7	50	40	3	0	0.078007	0.326111	0.018418

year	**Fec4**	**Fec5**	**Fec6**	**Fec7**
1982	10560.44	12167.58	13494.48	14500.92
1983	10695.2	13472.57	14129.2	14293.79
1984	10695.2	12970.59	13930.44	14452.73
1985	0	12468.6	13731.68	14611.66
1986	10919.8	12594.23	13868.61	14604.19
1987	0	12754.03	14058.63	14671.39
1988	0	13615	13847.03	14535.68
1989	12791.47	13433.74	14066.5	14481.39
1990	12020.34	13254.81	13947.19	14118.65
1991	10807.5	12892.85	13874.1	14502.82
1992	13447.86	13259.72	14000.11	14181.85
1993	10919.8	12976.2	13947.04	14606.53
1994	12492	12886.57	14015.54	14320.18
1995	10246	12936.42	13890.32	14305.04
1996	12761.52	13087.77	13806.78	14303.77
1997	12369.49	13620.18	13918.91	13849.34
1998	0	13068.87	13806.34	14118.27
1999	0	13253.41	13571.58	13563.17
2000	13040.44	12885.74	13489.16	14223.7
2001	0	13142.88	13713.98	14180.29
2002	10829.96	12702.11	13815.65	14593.61
2003	10388.93	12934.63	14177.32	14597.21

2004	11369	12924.92	14079.26	14577.57
2005	0	13548.28	14043.76	15748.7
2006	11621.68	13100.51	13969.7	13951.9
2007	11397.08	13356.71	14216.37	14738
2008	0	13128.95	14247.91	14344.95
2009	0	13873.78	14129.99	0
2010	0	13211.03	14044.64	14452.15
2011	11088.25	12782.78	14322.63	14117.91
2012	0	13279.6	14041.97	14323.74
2013	0	13066.87	14178.07	14641.92
2014	0	13027.83	14098.17	14333.72
2015	0	13403.19	14059.91	14473.1

year	Year the data were collected
harvUS	US harvest (numbers of fish)
cvUS	CV of US harvest
harvCA	Canadian harvest (numbers of fish)
cvCA	CV of Canadian harvest
snr	Sonar index
tlm	Telemetry index
cv.bp	CV of border passage
cbmr	Canadian border mark recapture index
Little_Salmon	Little Salmon tributary index
Big_Salmon	Big Salmon tributary index
Nisutlin	Nisutlin tributary index
WHFW	Whitehorse fish wheel index
Tatchum	Tatchum tributary index
Wolf	Wolf tributary index
Tincup	Tincup tributary index
Ross	Ross creek index
Blind	Blind creek index
Age4-Age7	Annual escapement age compositions
F4-F7	Percentage females of each age (e.g., F4 is the percentage of age-4 females out of all fish – males and females combined – in a given year)
Fec4-Fec7	Annual average female fecundity