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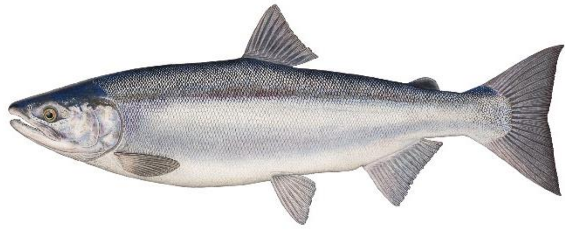
ESTIMATES OF A BIOLOGICALLY-BASED SPAWNING GOAL AND MANAGEMENT BENCHMARKS FOR THE CANADIAN-ORIGIN TAKU RIVER SOCKEYE SALMON STOCK AGGREGATE



Adult Sockeye salmon (Source: Paul Vecsei/ Fisheries and Oceans Canada)

Figure 1. Map of the Taku River watershed, a transboundary river in northwest British Columbia and Southeast Alaska (map provided by Alaska Department of Fish and Game).

Context:

Taku River Sockeye salmon (Oncorhynchus nerka) comprise a transboundary stock managed cooperatively by Canada and the United States under the Pacific Salmon Treaty (Treaty). The Transboundary Chapter of Annex IV of the Treaty requires Parties to develop of a “bilaterally-agreed maximum sustainable yield (MSY) escapement goal prior to the 2020 fishing season.” In light of this, work was undertaken to estimate biological benchmarks for the Canadian-origin Taku River Sockeye salmon stock aggregate, including the spawner abundance that maximizes sustainable yield over the long-term in average conditions (S_{MSY}). Additional work was undertaken to consider management targets based on the various profiles (e.g. using overfishing profiles, recruitment profiles, and yield profiles), as well as candidate management benchmarks based on bilaterally-agreed definitions.

This Science Advisory Report is from the November 5-6, 2019 regional peer review on the Development of a Biological Escapement Goal for Taku River Sockeye Salmon. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

February 2020

SUMMARY

- The Transboundary Panel requires a maximum sustainable yield (MSY)-based escapement goal recommendation at the aggregate level to support the management and stock assessment regime that has been developed by the Parties' joint Transboundary Technical Committee for implementation prior to the 2020 fishing season.
- The specific objectives of this review are to:
  1. Identify the spawning escapements that would produce maximum sustainable yields for the Canadian-origin Taku River Sockeye salmon *Oncorhynchus nerka* stock aggregate.
  2. Identify the appropriate biological benchmarks for the management of the Canadian-origin Taku River Sockeye salmon stock aggregate.
- A Bayesian state-space Ricker model that included age-structure and a one year-lag autoregressive component was fit to 1980–2014 brood years for Canadian-origin Taku River Sockeye salmon greater than 349 mm (mid eye to fork length).
- Data for the state-space model included:
  1. harvest estimates of Canadian-origin Taku River Sockeye salmon in terminal areas;
  2. capture-recapture estimates of above-border abundance Canadian-origin Taku River Sockeye salmon; and
  3. weighted age composition estimates of Taku River Sockeye salmon harvested in the U.S. District 111 traditional commercial drift gillnet fishery and Sockeye salmon captured in the Canyon Island fish wheels in the lower Taku River.

  Estimates of uncertainty were included in these data sources. These data were reviewed and updated in a bilateral process starting in 2018.
- Capture-recapture abundance estimates were calculated with the *BTSPAS* package (Bonner and Schwarz 2020; Schwarz et al. 2009) which generates both Bayesian time-stratified Petersen estimates and pooled Petersen estimates. Bayesian time-stratified estimates explicitly account for several common sources of potential bias (e.g., tags missed while the fishery is closed) by extrapolating a run-timing curve from the tag data. However, Bayesian estimates are computationally complex, and can be sensitive to prior assumptions. The simple pooled Petersen and variations of the Bayesian time-stratified Petersen were generally very close. Based on this observation, the bilateral review process chose to use pooled Petersen estimates for the state-space model inputs.
- Pooled Petersen capture recapture abundance estimates for Canadian-origin Taku River Sockeye salmon were adjusted for dropout rate and for size bias. A dropout adjustment of 25.5% was used for 1984 to 2016, which was based on a weighted average dropout observed in radiotelemetry studies from 1984, 2015, 2017 and 2018. Year-specific dropout rate estimates were applied for 2017 and 2018. A size-bias adjustment of 6.4% (based on the 2003 to 2018 average) was applied to 1984 to 2002 estimates and adjustments for 2003 to 2018 were year-specific size-stratified estimates.
- Historical annual terminal run abundance and inriver run abundance, spawning abundance, stock-recruitment parameters, and biological benchmarks were estimated from this model.
- Specific biological benchmarks estimated from the model are as follows: S_{MSY} = 43,857 (90% CI from 30,422 to 99,699) fish, 80% S_{MSY} = 35,086 (24,337 to 79,760) fish, S_{MAX} =

59,145 (35,843 to 164,901) fish, S_{EQ} = 124,106 (97,418 to 252,655) fish, and S_{GEN} = 5,873 (1,967 to 25,146) fish.

- Limited contrast in spawning escapement estimates resulted in large uncertainty in biological benchmarks. Sensitivity tests of the prior distribution on the density-dependence parameter (β) resulted in similar median estimates of key model outputs.

BACKGROUND

The Taku River is a transboundary river system originating in the Stikine Plateau of northwestern British Columbia. The merging of two principal tributaries, the Inklin and Nakina rivers, approximately 50 km upstream from the border, forms the mainstem of the Taku River. The river flows southwest from this point through the Coast Mountain Range eventually draining into Taku Inlet in Southeast Alaska, about 30 km east of Juneau (Subdistrict 111-32) (Figure 1). A majority of the 17,000 km^2 Taku River watershed lies within Canada (Neal et al. 2010). The river produces one of the largest runs of Sockeye salmon in Northern British Columbia and Southeast Alaska and Sockeye salmon spawn throughout the drainage in both river and lake habitats.

Sockeye salmon returning to the Taku River drainage are primarily harvested in the U.S. District 111 traditional commercial drift gillnet fishery (hereafter referred to as D111 gillnet fishery) in Taku Inlet (Subdistrict 111-32) and in the inriver Canadian commercial fishery (Pacific Salmon Commission Joint Transboundary Technical Committee 2019). Other harvests occur in the inriver U.S. personal use fishery, in test/assessment fisheries, and in Canadian Aboriginal food, social, and ceremonial fishery (hereafter referred to as Aboriginal fishery).

The Taku River Sockeye salmon stock aggregate is jointly managed by Fisheries and Oceans Canada (DFO), the Alaska Department of Fish and Game (ADF&G), and the Taku River Tlingit First Nation. The Pacific Salmon Commission, via the Pacific Salmon Treaty (Treaty) of 1985, commits Canada and the U.S. to conservation and allocation obligations for salmon originating in the waters of the Canadian portion of the Taku River. The Treaty mandates cooperative international management and has established conservation (via a spawning escapement goal) and harvest sharing (percentage sharing of the allowable catch) obligations for Taku River Sockeye salmon. Taku River Sockeye salmon are managed as an aggregate under provisions of Chapter 1, Annex IV of the Treaty.

The purpose of this paper is to provide science advice with respect to development of a biologically-based spawning escapement goal for the Canadian-origin Taku River Sockeye salmon stock aggregate. The escapement goal is to be based on maximum sustainable yield (MSY) and have biological benchmarks that are consistent with DFO’s Precautionary Approach and Wild Salmon Policy (see Holt 2009, Grant et al. 2011, DFO 2005), and the Alaska Sustainable Salmon Fisheries Policy (Alaska Board of Fisheries’ regulations, the *Policy for the Management of Sustainable Salmon Fisheries* (Sustainable Salmon Policy: 5 AAC 39.222) and the *Policy for Statewide Salmon Escapement Goals* (Escapement Goal Policy: 5 AAC 39.223)). Terminal harvests and above-border inriver run estimates spanning nearly four decades form the basis of this work. Advice regarding biological benchmarks will contribute to a future assessment of status to meet Canada’s Precautionary Approach and Wild Salmon Policy commitments and the Alaska Sustainable Salmon Fisheries Policy commitments.

The specific objectives of this work are to:

Objective 1: Identify the spawning escapements that would produce maximum sustainable yields for the Taku River Sockeye salmon stock aggregate.

Objective 2: Identify the appropriate biological benchmarks for management of the Taku River Sockeye salmon stock aggregate.

These tasks primarily emerged from an obligation in the most recent provisions of Chapter 1, Annex IV of the Treaty that calls for the development of a bilaterally-agreed MSY escapement goal prior to the 2020 fishing season. Paragraph 3(b)(i) states:

(B) "The Parties shall develop a joint technical report and submit it through the Parties' respective review mechanisms with the aim of establishing a bilaterally-approved maximum sustainable yield goal for Taku River Sockeye salmon prior to the 2020 fishing season."

The Transboundary Panel requires escapement goal recommendations at the aggregate level to support the management and stock assessment regime that has been developed by the Parties through the joint Transboundary Technical Committee. The historical spawning escapement objective, established in 1985, was from 71,000 to 80,000 fish with a point goal of 75,000 fish. In February 2019, a revised "interim" objective, based on the historical objective, but adjusted downward by 22% to account for historical dropout rates observed through radiotelemetry studies conducted in 1984, 2015, 2017, and 2018 (Pacific Salmon Commission Joint Transboundary Technical Committee 2019), was agreed to by the Parties for the 2019 fishing season. The interim goal specified was 55,000 to 62,000 fish with a management target of 59,000 fish.

The Taku River Sockeye salmon populations are grouped into conservation units for Canadian domestic status assessments under DFO's *Wild Salmon Policy* (DFO 2005), but Taku River Sockeye salmon conservation units are currently aggregated into a single Taku River Sockeye salmon stock aggregate for management purposes (e.g., in-season run size, spawning escapement objective; *see section 1.2.4 Canada's Wild Salmon Policy;* DFO 2005). The analyses in this report are primarily at this aggregate stock level. All references to "border" in the document pertain to the U.S./Canada border in the lower Taku River. The capture-recapture abundance estimates of the aggregate stock exclude fish smaller than 350 mm as measured from mid-eye to fork-of-tail (MEF). In keeping with this, the escapement goal and associated benchmarks refer to naturally spawning fish greater than 349 mm in MEF length.

DATA

Canadian-origin Taku River Sockeye salmon data used in the state-space spawner-recruit model included:

1. estimates of harvest of naturally spawned and enhanced (hatchery-produced) fish above and below the border, and associated coefficients of variation (CVs);
2. capture-recapture estimates of above-border abundance, and associated CVs; and
3. weighted age composition estimates of D111 gillnet fishery harvests and lower Taku River (Canyon Island) fish wheel catches.

Harvest included in this analysis is only from directed fisheries within terminal marine areas (U.S. District 111), which includes Taku River Sockeye salmon harvested incidentally in the hatchery purse seine fishery at Amalga harbor in D111, the U.S. inriver personal use fishery, and Canadian inriver fisheries (test/assessment, commercial, and Aboriginal fisheries), and therefore run abundance is terminal and germane to the Canadian-origin Taku River Sockeye salmon.

Canadian-origin inriver Sockeye salmon abundance was estimated using data generated in capture–recapture studies conducted annually from 1984 to 2018 and implemented within the R environment (R Core Team 2019; version 3.6.0) using the *BTSPAS* package with custom extensions (Bonner and Schwarz 2020; Schwarz et al. 2009; Schwarz 2006). Sockeye salmon greater than 349 mm MEF length were captured and marked at fish wheels located at Canyon Island, in the lower Taku River, and subsequently recaptured in commercial fisheries upstream of the border. A detailed review of telemetry data and other data associated with the program resulted in substantial corrections for dropout and size selectivity during the experiments (i.e., size bias). Inriver abundance from 1984 through 2002 (excluding 1986) was based on pooled Petersen estimates with no size stratification. These inriver estimates were adjusted downward by 6.4% which represented the average bias observed between size-stratified and non-size-stratified pooled Petersen estimates from 2003 to 2018. Inriver abundance from 2003 onward was based on year-specific size-stratified Petersen estimates. All estimates (1984–2018, excluding 1986) were adjusted to account for dropout; fish not available for recapture due to mortality of marked fish due to predation, fish spawning below the border, or due to capture, handling, and tagging at the Canyon Island fish wheels. For years 2016 and prior, a weighted-average dropout rate of 25.5% was applied to the capture-recapture abundance estimates. The dropout rate was based on a weighted average of results from radiotelemetry studies conducted in 1984, 2015, 2017, and 2018. Year-specific dropout rates were applied to 2017 and 2018 (32.1% in 2017 and 14.6% in 2018) based on radio-telemetry studies conducted in those years.

Age compositions were estimated from a weighted combination of age data from the D111 gillnet fishery harvest of Sockeye salmon in Taku Inlet and age data from the Canyon Island fish wheels.

ANALYSIS

Taku River Sockeye salmon spawner-recruit data were analyzed using a Bayesian state-space Ricker spawner-recruit model (Ricker 1954) that included age-structure and a one year-lag autoregressive component. State-space models are time series models that feature both observed variables and unobserved states to describe the uncertainty introduced into the estimate of spawning size that produces MSY (Fleischman et al. 2013).

Use of a Bayesian age-structured state-space model allows for consideration of process variation (natural fluctuations) in stock productivity, recruitment, and age-at-maturation independently from observation error (uncertainty in measurements of observed data) in run size, harvest, and age composition. Such models have been used with increasing frequency in place of traditional methods in spawner-recruit analysis of Pacific salmon (e.g., Bernard and Jones III 2010; Schmidt and Evans 2010; Eggers and Bernard 2011; Fleischman et al. 2013; Fleischman and Reimer 2017).

Biological benchmarks (e.g., 80% of S_{MSY}, S_{MSY}, S_{MAX}, S_{GEN}, S_{EQ}) were estimated based on samples of posterior distributions.

The expected performance of alternative spawning goals was summarized in three probability profiles:

- Optimal yield profiles: probabilities that a given level of spawning escapement will produce average yields exceeding X% of MSY (Fleischman et al. 2011).
- Overfishing profiles: probability of overfishing the stock such that sustained yield is reduced to less than a percentage (70%, 80%, 90%) of MSY by fishing too hard and supplying too few spawners (Bernard and Jones III 2010).
- Maximum recruitment profiles: probability that a given level of spawning escapement will produce average recruits exceeding X% of maximum recruitment (Hamazaki et al. 2012).

Sensitivity analysis to the prior distribution for the beta parameter

Sensitivity analyses were performed on the prior distribution for the beta parameter from the spawner-recruit function. The base prior distribution for the beta parameter was a normal distribution with mean 0, precision (inverse of the variance) 0.000001, and constrained to be greater than 1.0 x 10^{-6}. An alternative prior distribution for the beta parameter, beta_1 (β_1), was a uniform distribution from 0.000001 to 1.0. A second alternative prior distribution for the beta parameter, beta_2 (β_2), was a normal distribution with mean 0 and precision 0.000001 without constraints.

Sensitivity analysis on the early years of missing capture-recapture abundance estimates (1980-1983)

Sensitivity analyses were also performed on the early years of missing capture-recapture abundance estimates. For all scenarios, 1984–1985 and 1987–2018 capture-recapture abundance estimates were the input capture-recapture estimates of above-border abundance with the associated coefficients of variation from the base model. There was no inriver abundance estimate for 1986. Five scenarios were explored for the sensitivity analysis. For scenarios 1a, 1b, and 1c, the inriver abundance estimates for years 1980–1983, and 1986, were the median capture-recapture abundance estimates output from the posterior distribution of the base model. The coefficients of variation were adjusted by the scenario (0.90, 0.50, and 0.10, respectively) to represent varying degrees of confidence in these estimates. For scenario two, median capture-recapture abundance estimates from the posterior distribution of the base model for years 1980–1983, and 1986 were multiplied by 0.75 to represent potentially lower abundance than the base model for these years. The coefficients of variation were set to 0.10 for these years. For scenario three, median capture-recapture abundance estimates from the posterior distribution of the base model for years 1980–1983, and 1986 were multiplied by 1.33 to represent potentially higher abundance than the base model for these years. The coefficients of variation were set to 0.10 for these years.

RESULTS

Stock Productivity, Capacity, and Yield

Results of the Ricker spawner recruit relationships take into account measurement error in both spawners (*S*) and recruits (*R*) when derived from the age-structured state-space model fitted to capture-recapture abundance estimates, harvest data, and age composition data; these results are depicted as the error bars in Figure 2, which weight the individual data pairs based on how precisely they were estimated. Some of the plausible relationships (grey shaded regions) varied greatly from the posterior medians of $\ln(\alpha')$ and β (Figure 2; dark dashed line). The median estimate of $\ln(\alpha')$ was 2.11, corresponding to $\alpha' = 8.17$ (high productivity stock; $\alpha \geq 4$; Su and Peterman 2012) and the median estimate of the density dependent parameter β was 1.69 x 10^{-5}. Uncertainty about β is reflected in variability in the values of S leading to maximum recruitment $S_{MAX} = 1/\beta$, and uncertainty about equilibrium abundance, S_{EQ} is reflected by variability in the values of S where the curves intersect the replacement line. The contrast in the spawner data used in the spawner-recruit analysis (1980–2014) was low (3.8; Clark et al. 2014). The estimated AR(1) parameter ϕ was 0.24, suggesting weak positive lag-1 serial correlation in residuals.

Estimates of escapement obtained by fitting a state-space model to Taku River Sockeye salmon data ranged from 24,075 fish in 1982 to 102,456 fish in 2016 (Figure 3). To incorporate uncertainty about the plausible spawner-recruit relationships (Figure 2), the success or failure of a given number of spawners to achieve biological reference points across plausible spawner-recruit relationships were tallied to create overfishing profiles (Figure 4; top panel), maximum recruitment probability profiles (Figure 4; middle panel), and optimal yield profiles (Figure 4, bottom panel). The maximum recruitment profiles, which are highest near S_{MAX} = 59,145 fish, display the probability of achieving at least 70%, 80%, or 90% of maximum recruitment for specified levels of escapement. Optimal yield profiles show the probability of a given number of spawners achieving at least 70%, 80%, or 90% of MSY. These probabilities, which are highest near S_{MSY} = 43,857 fish can be used to quantify the yield performance of prospective escapement goals taking into consideration uncertainty about the true abundance and productivity of the stock (Figure 4). Overfishing profiles show the probability that sustained yield would be reduced to less than 70%, 80%, or 90% of MSY by allowing too few fish to spawn.

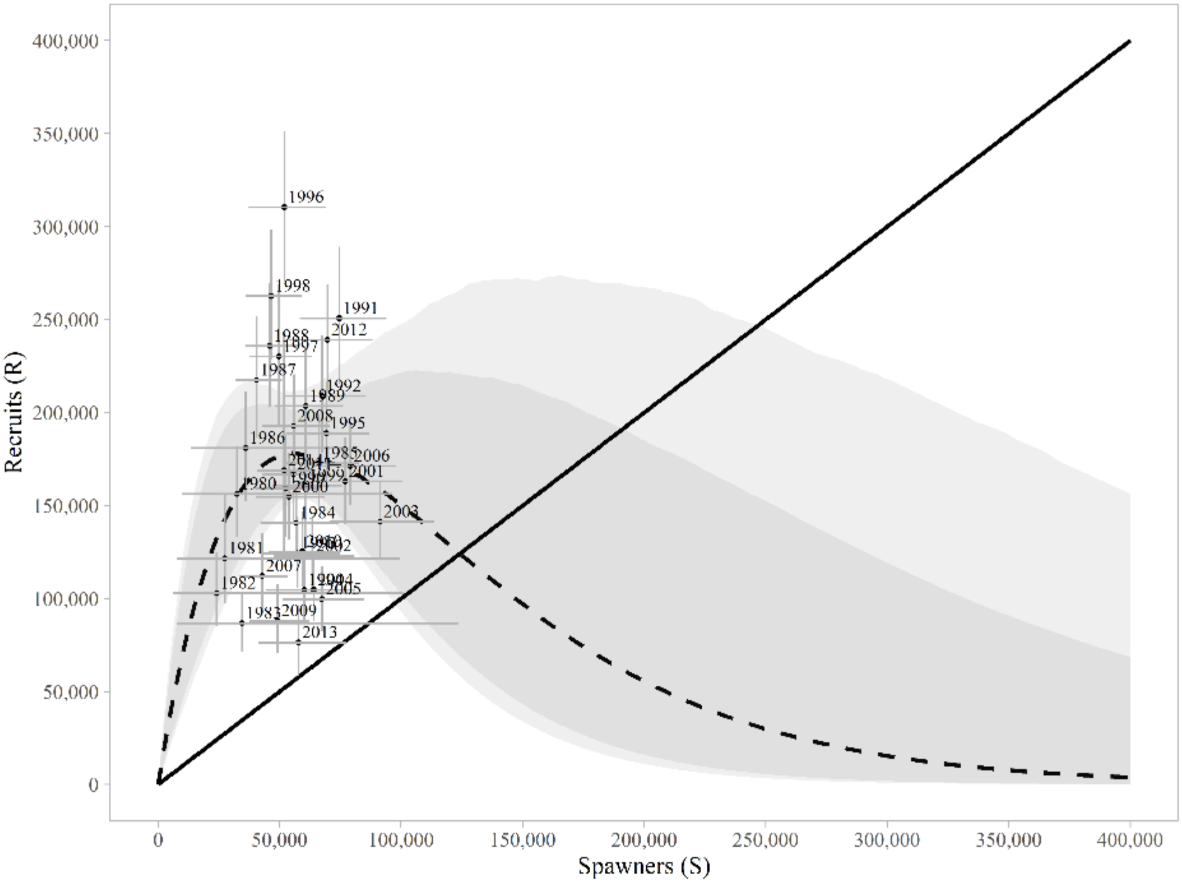


Figure 2. Plausible spawner-recruit relationships (shaded regions around the dashed line) for Taku River Sockeye salmon as derived from a Bayesian state-space model fitted to abundance, harvest, and age data for calendar years 1980–2018. Posterior medians of recruits and spawners are plotted as brood year labels with 95% credible intervals (grey lines). The heavy dashed line is the Ricker relationship constructed from ln(α') and β posterior medians with 90% and 95% credible intervals (shaded areas). Recruits replace spawners on the solid diagonal line.

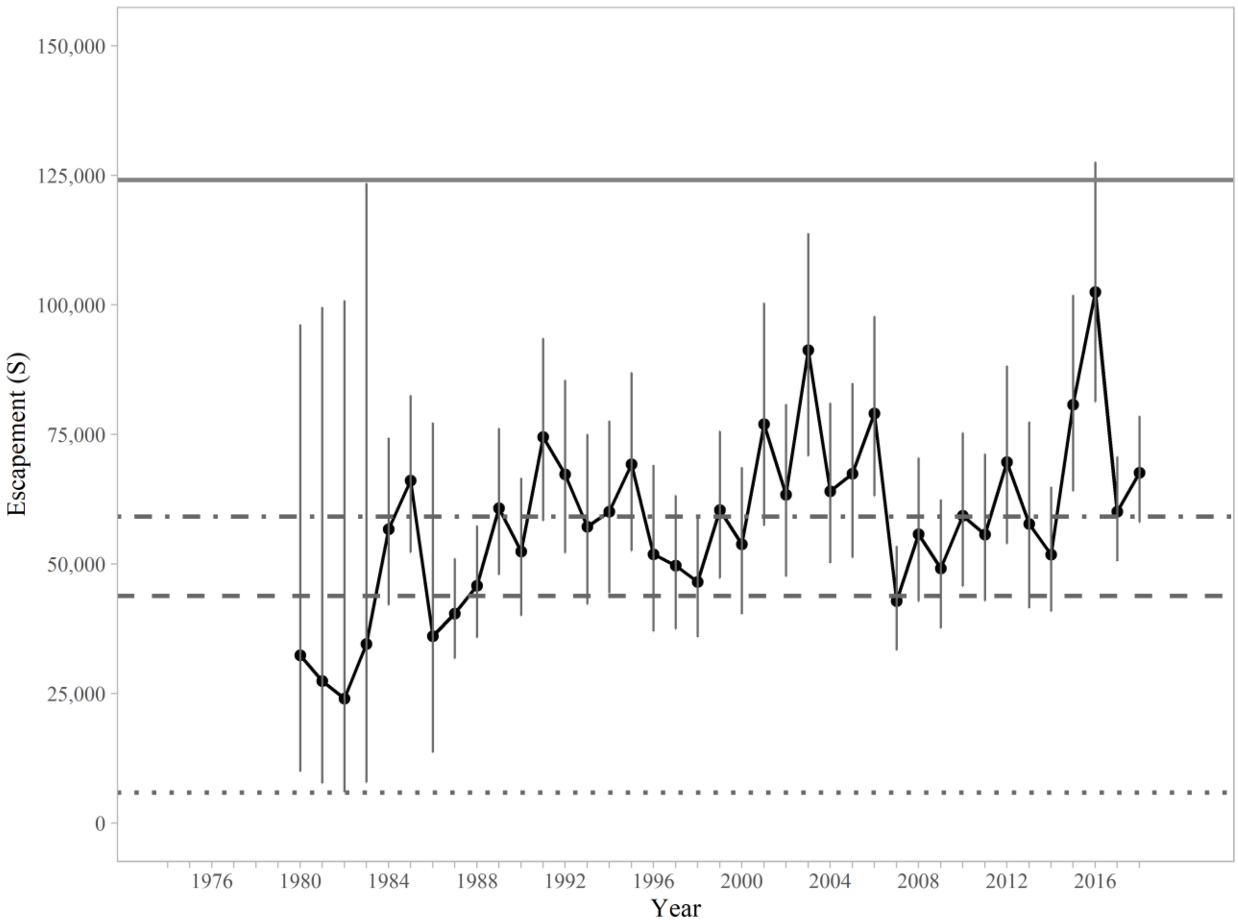
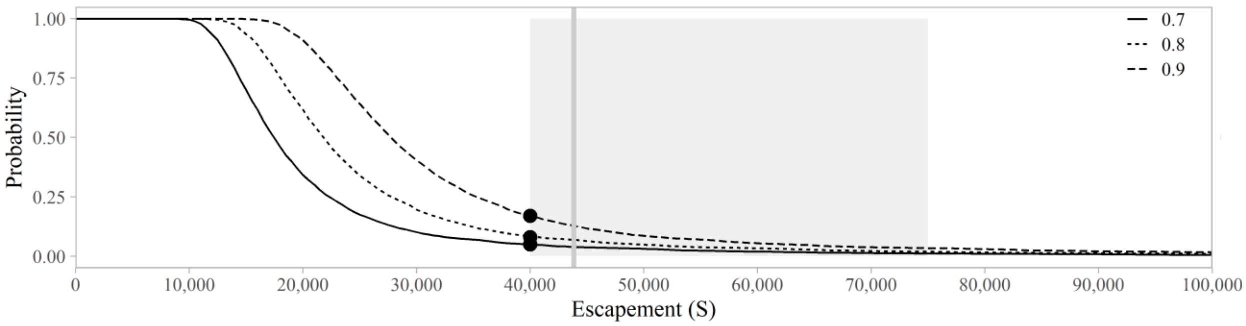
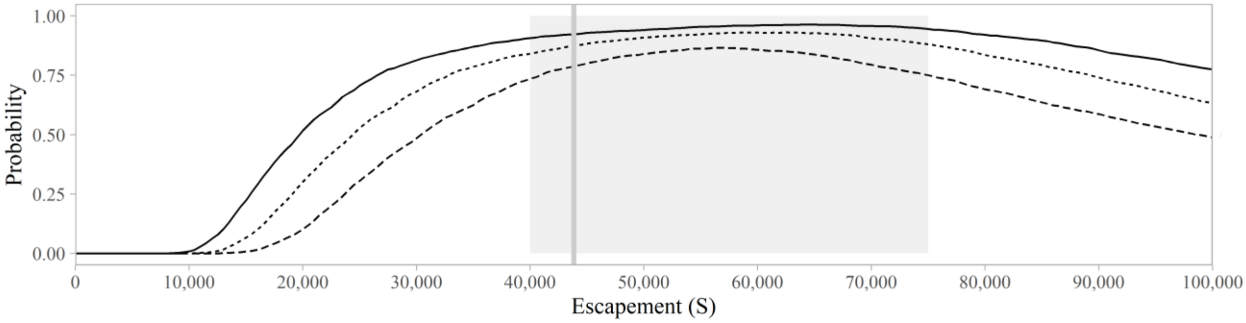


Figure 3. Posterior medians of escapement estimates and 95% credible intervals (vertical lines) for Sockeye salmon obtained by fitting a Bayesian state-space model to Taku River Sockeye salmon data, 1980–2018. Posterior medians of S_{MAX} (horizontal dashed line with dots), S_{MSY} (horizontal dashed line), S_{GEN} (horizontal dotted line), and S_{EQ} (horizontal solid line) are plotted as reference lines. Years with higher uncertainty corresponded to years with missing capture-recapture abundance estimates (1980–1983, 1986).

a) Overfishing Profile



b) Recruitment Profile



c) Yield Profile

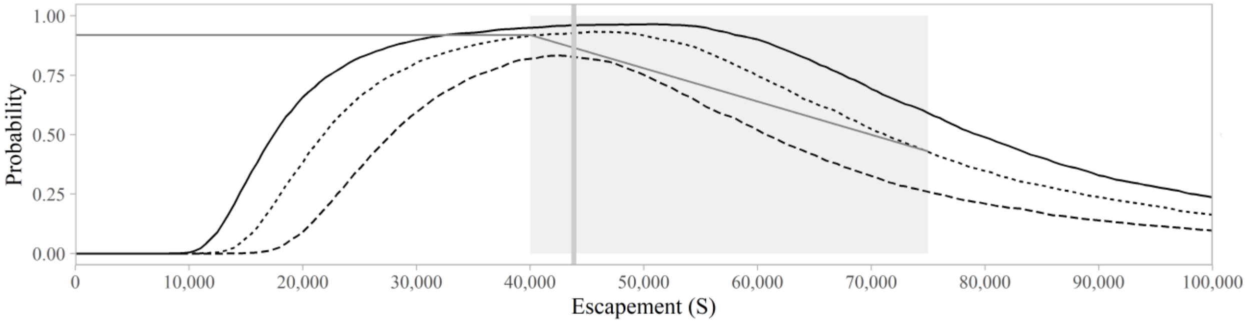


Figure 4. Overfishing profiles (OFPs), maximum recruitment probability profiles (MRPs), and optimal yield profiles (OYPs) for Taku River Sockeye salmon. The OFPs show the probability that reducing escapement to a specified level will result in less than specified fractions of maximum sustained yield. The OYPs and MRPs show the probability that an escapement will result in specified fractions (0.70, 0.80, and 0.90 line) of maximum sustained yield or maximum recruitment. The Taku River Sockeye Salmon Working Group recommended an escapement goal range (40,000-75,000 fish; grey box) where the probability of average optimal yields exceeding 0.80 MSY is 0.92 (lower bound; horizontal line in the yield profile) and 0.43 (upper bound; diagonal line in the yield profile). Overfishing profiles show the probability that sustained yield is reduced to less than a fraction (0.70, 0.80, 0.90) of MSY given a fixed level of escapement. This probability refers to the lower bound of the hypothetical escapement goal range (40,000 fish or lower bound of grey region). The overfishing probability of the stock is 0.05, 0.08, and 0.17 based on 0.70, 0.80, and 0.90 MSY, respectively (solid black points in the overfishing profile). The light grey vertical line in all three figures is the S_{MSY} value of 43,857 spawners.

Sensitivity analysis to the prior distribution for the beta parameter

The results of a sensitivity analysis on the prior distribution for the beta parameter of the Ricker model show that a uniform prior distribution (beta$_1$) produced similar median estimates of key model outputs and biological reference points as the normal prior distribution, although the computation time was greatly increased with the uniform prior distribution. Likewise, a normal prior distribution on beta that was not constrained to be greater than 1.00 x 10^{-6} (beta$_2$), greatly increased the uncertainty of the estimated reference points, but produced similar median estimates of key model outputs. Therefore, the base prior distribution, a normal distribution, mean 0, precision 0.000001, and constrained to be greater than 1.00 x 10^{-6}, was used for median estimates of key model outputs and biological reference points (Table 1).

Table 1. Posterior medians and coefficients of variation (CVs) for key model quantities, with base and alternative versions of prior distributions on the parameter beta.

			Alternative priors			
			Medians		CVs	
Parameter	Median	CV	β_1	β_2	β_1	β_2
α	7.63	0.42	7.63	7.56	0.41	0.44
ln(α)	2.03	0.20	2.03	2.02	0.20	0.20
ln(α')	2.11	0.19	2.11	2.10	0.19	0.20
β	1.69 x 10^{-5}	0.39	1.68 x 10^{-5}	1.68 x 10^{-5}	0.39	0.40
S_{EQ}	124,106	0.64	124,370	123,505	0.49	3.67
S_{MAX}	59,145	0.85	59,509	59,197	0.83	5.37
S_{MSY}	43,857	0.67	44,032	43,692	0.59	4.05
$S_{\text{MSY 80\%}}$	35,086	0.67	35,226	34,953	0.59	4.05
U_{MSY}	0.75	0.11	0.74	0.74	0.11	0.12

Note:
β_{Base}~ Normal (0, 1.00 x 10^{-6}) and constrained to be greater than 1.00 x 10^{-6}
β_1~ Uniform (1.00 x 10^{-6}, 1.0)
β_2 ~ Normal (0, 1.00 x 10^{-6})

Sensitivity analysis on the early years of missing capture-recapture abundance estimates (1980-1983)

A sensitivity analysis of the estimated inriver abundance for the early years (scenarios 1a, 1b, and 1c; median capture-recapture abundance estimates output from the posterior distribution of the base model used as input inriver abundance data for years 1980–1983, and 1986 and coefficients of variation adjusted by the scenario (0.90, 0.50, and 0.10, respectively) indicated that arbitrarily reducing the uncertainty in inriver abundance data from the early years increased the posterior estimate of S_{MSY}. The increase in S_{MSY} varied from approximately 2,900 fish to 15,100 fish (S_{MSY} varied from 46,720 fish to 58,987 fish) as the coefficients of variations of the capture-recapture abundance estimates decreased from 0.90 to 0.10 (Table 2); although the coefficients of variations of S_{MSY} were relatively stable (range from 0.62 to 0.72 for the three scenarios and 0.67 for the base model). If the coefficients of variation of the 1980–1983 and 1986 capture-recapture abundance estimates were set at 0.10 (i.e., similar to the other inputs from years 1984, 1985, 1987–2018), but the inputs for years 1980–1983 and 1986 were multiplied by 0.75 (scenario two), the estimate of S_{MSY} remained relatively unchanged from the base model although the precision on the reference point increased (CV decreased to 0.43; Table 2). If the coefficients of variation of the 1980–1983 and 1986 capture-recapture abundance estimates were set at 0.10 (i.e., similar to the other inputs from years 1984, 1985, 1987–2018), but the inputs for years 1980–1983 and 1986 were multiplied by 1.33 (scenario three), the estimate of S_{MSY} increased by about 20,600 fish, but the precision on the reference points remained similar to the base model (0.74; Table 2).

Table 2. Posterior medians and coefficients of variation for key model quantities, with base and alternative versions of assumptions on the early years of capture-recapture abundance estimates. The coefficients of variation (CVs) for the S_{MSY} reference point for the different scenarios are in parentheses.

	Base Model						
Parameter	Median	CV	*Scenario1a*	*Scenario1b*	*Scenario1c*	*Scenario2*	*Scenario3*
α	7.63	0.42	7.06	6.59	5.55	7.66	4.95
$\ln(\alpha)$	2.03	0.20	1.95	1.88	1.71	2.04	1.60
$\ln(\alpha')$	2.11	0.19	2.03	1.96	1.79	2.11	1.68
β	1.69×10^{-5}	0.39	1.56×10^{-5}	1.45×10^{-5}	1.14×10^{-5}	1.66×10^{-5}	9.96×10^{-6}
S_{MSY}	43,857	0.67	46,720 (0.62)	48,991 (0.65)	58,987 (0.72)	44,811 (0.43)	64,412 (0.74)

Biological Benchmarks

Using base case assumptions and data from the 1980–2014 brood years, the estimated biological benchmarks (5th and 95th percentiles of the posterior distribution, capturing the central 90% of parameter samples) were:

- Spawner level that produces maximum sustainable yield (S_{MSY}) estimated at 43,857 spawners (30,422 to 99,699 spawners);
- Spawner level that is 80% of that needed to produce maximum sustained yield (80%S_{MSY}) estimated at 35,086 spawners (24,337 to 79,760 spawners);
- Spawner level that produces the maximum adult recruits (S_{MAX}) estimated at 59,145 spawners (35,843 to 164,901 spawners);
- Equilibrium spawner level in the absence of fishing (S_{EQ}) estimated at 124,106 spawners (97,418 to 252,655 spawners);
- Spawner level with a high probability of rebuilding to S_{MSY} in one generation in the absence of harvest (S_{GEN}) estimated at 5,873 spawners (1,967 to 25,146 spawners).

Considerations for Choosing A Spawning Goal

Fishery policy guides the frame of reference, which determines how we present and interpret the results of biological analyses. ADF&G and DFO operate under independent policies and the results of our analyses may be applied in different ways.

Although the median estimate of S_{MSY} was 43,857 fish, a variety of escapement goal ranges can be considered that encompass this value. Given the uncertainty in the outputs of the spawner-recruit model, the minimal contrast within the time series, and lack of information at high spawner abundances, the Taku River Sockeye Salmon Working Group recommended a conservative approach be applied when considering the tradeoff between achieving MSY and guarding against overfishing the stock. We recommend basing the potential MSY-based escapement goal range against the following risk criteria that were developed from the performance profiles:

- The recommended escapement goal should provide a greater than 90% probability that sustained yield would be at least 80% of MSY; a probability of “overfishing” of less than 10%.

- The recommended escapement goal should provide a greater than 50% probability of achieving at least 70% of MSY over the long-term if the stock is managed to the proposed escapement goal range.

Table three can be used to directly identify candidate bounds for an escapement goal range, once a probability level has been identified. Shaded areas delineate the spawner abundances that meet the two proposed criteria (above). Any spawner abundance above 38,000 has a less than 10% probability of achieving less than 80% of MSY (6th column of Table 3). A lower bound for the escapement goal range could be selected at any point above this value and be consistent with the first stated risk criterion above. Any spawner abundance between (and including) 28,000 and 79,000 has a probability of 50% or higher of achieving 70% of MSY (4th column of Table 3). An upper bound for the escapement goal range could be selected at any point in this range and be consistent with the second stated risk criterion. Additional qualitative considerations could be used to further narrow down the candidate values for lower and upper bounds.

Table 3. Sensitivity of yield-based reference escapements to alternative definitions. The optimal yield probabilities (probability of achieving at least x% of MSY) are the probabilities that a given level of spawning escapement will produce average yields exceeding 70%, 80%, or 90% of MSY. Overfishing probabilities (probability of overfishing below x% of MSY) are the probabilities that sustained yield is reduced to less than a fraction (70%, 80%, 90%) of MSY. The percent probability for the overfishing profiles refers to the lower bound of the escapement goal range. Values that meet the criteria suggested by the authors are shaded. The values in bold are the biological escapement goal range of 40,000–75,000 fish recommended by the Taku River Sockeye Salmon Working Group.

Escapement	**Probability of achieving at least x% of MSY**			**Overfishing probability of yields below x% of MSY**		
	90%	**80%**	**70%**	**90%**	**80%**	**70%**
28,000	51%	76%	88%	49%	25%	12%
29,000	56%	78%	89%	44%	22%	11%
30,000	60%	80%	90%	40%	20%	10%
31,000	63%	82%	91%	37%	18%	9%
32,000	67%	84%	92%	33%	16%	8%
33,000	69%	85%	92%	31%	15%	8%
34,000	72%	87%	93%	28%	13%	7%
35,000	74%	88%	93%	26%	12%	7%
36,000	76%	89%	93%	24%	11%	7%
37,000	78%	90%	94%	22%	10%	6%
38,000	80%	90%	94%	20%	10%	6%
39,000	81%	91%	95%	18%	9%	5%
40,000	**82%**	**92%**	**95%**	**17%**	**8%**	**5%**
41,000	83%	92%	95%	16%	8%	5%
42,000	83%	92%	96%	15%	7%	4%
43,000	83%	93%	96%	14%	7%	4%
44,000	83%	93%	96%	13%	7%	4%
45,000	82%	93%	96%	12%	6%	4%
46,000	81%	93%	96%	11%	6%	4%

Escapement	Probability of achieving at least x% of MSY			Overfishing probability of yields below x% of MSY		
	90%	**80%**	**70%**	**90%**	**80%**	**70%**
47,000	81%	93%	96%	10%	6%	4%
48,000	79%	93%	96%	10%	5%	3%
49,000	77%	93%	96%	9%	5%	3%
50,000	75%	92%	96%	9%	5%	3%
51,000	73%	91%	97%	8%	5%	3%
52,000	71%	90%	96%	8%	4%	3%
53,000	68%	89%	96%	8%	4%	3%
54,000	66%	87%	96%	7%	4%	2%
55,000	63%	86%	95%	7%	4%	2%
56,000	61%	84%	94%	7%	4%	2%
57,000	59%	82%	93%	6%	4%	2%
58,000	57%	79%	92%	6%	4%	2%
59,000	54%	77%	91%	6%	3%	2%
60,000	52%	75%	90%	6%	3%	2%
61,000	50%	72%	89%	5%	3%	2%
62,000	47%	70%	87%	5%	3%	2%
63,000	45%	68%	85%	5%	3%	2%
64,000	43%	65%	83%	5%	3%	2%
65,000	41%	63%	81%	5%	3%	2%
66,000	39%	61%	79%	4%	3%	2%
67,000	38%	60%	76%	4%	2%	2%
68,000	36%	57%	74%	4%	2%	1%
69,000	34%	55%	72%	4%	2%	1%
70,000	33%	52%	69%	4%	2%	1%
71,000	31%	51%	67%	4%	2%	1%
72,000	29%	48%	65%	4%	2%	1%
73,000	28%	47%	63%	4%	2%	1%
74,000	27%	45%	61%	4%	2%	1%
75,000	**26%**	**43%**	**59%**	**3%**	**2%**	**1%**
76,000	25%	41%	57%	3%	2%	1%
77,000	24%	39%	55%	3%	2%	1%
78,000	23%	38%	52%	3%	2%	1%
79,000	22%	36%	51%	3%	2%	1%
80,000	21%	35%	49%	3%	2%	1%
81,000	20%	33%	47%	3%	2%	1%
82,000	19%	32%	45%	3%	2%	1%
83,000	19%	30%	44%	3%	2%	1%
84,000	18%	29%	42%	3%	1%	1%

SOURCES OF UNCERTAINTY

The following sources of uncertainty were identified in this assessment.

Process and observation error

Use of a Bayesian age-structured state-space model allowed for consideration of process variation (natural fluctuations) in stock productivity, recruitment, and age-at-maturation independently from observation error (uncertainty in measurements of observed data) in run size, harvest, and age composition.

Alternative estimation approaches

The derived estimates of the reference points S_{MSY}, 80% S_{MSY}, and U_{MSY} based on the calculations of Lambert W (Scheuerell 2016), Peterman et al. (2000), and Hilborn (1985) approximations all produced similar results. Therefore, only reference points using the more explicit Lambert W function were shown for simplicity.

Alternative model assumptions on the prior distribution for the beta parameter

Sensitivity analysis on the choice of prior distribution for the beta parameter were explored and biological benchmarks were estimated for each model for comparison. The base case for beta was a prior distribution which is a normal distribution, mean 0, precision 0.000001, and constrained to be greater than 1.00×10^{-6}. An alternative prior distribution, beta_1, was a uniform distribution from 0.000001 to 1.0. A second alternative prior distribution, beta_2, was a normal distribution, mean 0, and precision 0.000001. Median estimates of key model outputs such as $\ln(\alpha')$, β, and reference points were similar across the base case and the two alternative prior distributions on beta, although the precision on the reference points was much lower on the model that was implemented with the beta_2 prior (Table 1).

Uncertainties in environmental variability

Temporal changes in ocean conditions (e.g., sea surface temperature, acidification, freshwater discharge) can potentially affect salmon survival rates and cause large year-to-year variations in Northeast Pacific salmon productivity (Mueter et al. 2002; Adkison et al. 1996). Time-varying management policies (target spawner abundance changing in response to changes in the Ricker productivity parameter), may have the potential to result in higher escapement and more harvest while reducing the risk across a range of harvest rates (Collie et al. 2012).

Expansions of Capture-Recapture Abundance Estimates

Expand the capture-recapture abundance estimates by fish wheel catch per unit effort in years with low tag recovery and effort or early removal of the fish wheel during early or late statistical weeks; or use the Bayesian time-stratified estimate (*BTSPAS*; Bonner and Schwarz 2020; Schwarz et al. 2009; Schwarz 2006). The *BTSPAS* estimate is a hierarchical model that will extrapolate the run curve before the commercial catch occurred and after the fishery ended, or if the fish wheel is removed early due to low water or other unforeseen reason.

Uncertainties in data

Unreported harvest and incidental fishing mortality such as escape mortality (mortality of fish that actively escape after contact with fishing gear such as a hook or gillnet prior to landing), depredation (fish that die as a result of predators directly removing fish from fishing gear during the capture process; not including predation of released fish), and fishery drop-out (fish that die and drop out of fishing gear such as gillnets prior to landing) were not accounted for in this analysis (Patterson et al. 2017). This unaccounted harvest can bias available harvest estimates. Second, total fish numbers from the U.S. commercial fisheries are based on total harvest weight converted to numbers of fish, not individual fish counts. Third, an unknown number of Taku River Sockeye salmon are harvested in non-directed interception fisheries in Southeast Alaska outside of the terminal area (defined as District 111). Pursuant to the Treaty, this analysis only included directed harvest of Taku River Sockeye salmon in terminal areas. Therefore, run abundance and return only encompassed Taku River Sockeye salmon inside the Taku River drainage and in the terminal areas adjacent to the outlet. Future analyses could include harvest in non-terminal areas to better represent the total run abundance and total return of Taku River Sockeye salmon.

Years with higher uncertainty corresponded to years with missing capture-recapture abundance estimates (1980–1983, 1986), missing age composition data (1980–1982), and missing harvest data below the border (1980–1982). Modeled escapements from these years were some of the lowest in the time series (24,075 to 36,106). Subsequent productivity and yields from these escapements are highly uncertain (see *Sensitivity Analysis on the Early Years (1980–1983);* Table 2). Future analyses of an MSY-based escapement goal and estimation of biological benchmarks based on a state-space modeling framework could consider providing additional information for these early years with the potential for added bias with the accompanying additional assumptions. Finally, the low contrast in escapements results in uncertainty in parameter estimates and derived estimates of biological benchmarks.).

CONCLUSIONS AND ADVICE

Based on the analyses from the state-space model and given consideration for the low contrast and high uncertainty of data, parameter, and biological benchmarks, the recommendation from the Taku River Sockeye Salmon Working Group is a biological escapement goal range of 40,000 to 75,000 fish. Based on the lower bound of this range, the probability of overfishing, where sustained yield is reduced to less than 80% of MSY, is 8% (Table 3). At the upper bound, this range has a minimum 59% probability of a given number of spawners achieving at least 70% of MSY and a minimum 43% probability of a given number of spawners achieving at least 80% of MSY (Table 3).

SOURCES OF INFORMATION

This Science Advisory Report is from the November 5-6, 2019 regional peer review on the Development of a Biological Escapement Goal for Taku River Sockeye Salmon. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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