STOCK-SPECIFIC FRASER RIVER SOCKEYE SALMON RUN SIZE DETERMINATION

Sockeye Salmon adult spawning phase. DFO website.

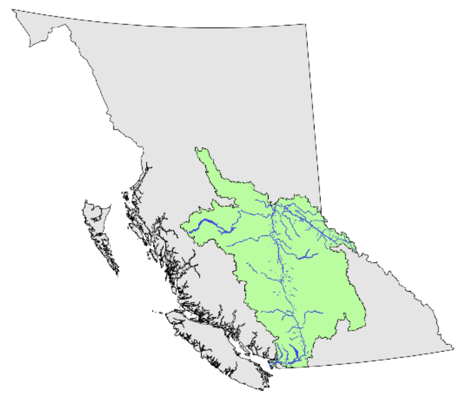

Figure 1. Map of Fraser River watershed basin (green region) based on the BC Freshwater Atlas.

CONTEXT

Fraser River Sockeye Salmon (*Oncorhynchus nerka*) management relies on preseason, in--season, and postseason abundance estimates of adult returns by stock and age, commonly referred to as run size estimates. Postseason run size estimates are used to calculate productivity and stock status for use in future harvest planning (Grant et al. 2011), to aid in recovery planning (DFO 2020a, b), and to evaluate factors limiting survival, such as en route mortality (Martins et al. 2011; Hinch et al. 2012; Doutaz et al. 2023). Despite the importance of postseason run size estimates for these analyses, there has been no consistent documentation or evaluation of the main contributing run size components—catch, spawning escapement, and en route mortality—and their summation.

Fisheries and Oceans (DFO) Fisheries Management requested that Science Branch document and review the postseason methods currently used to estimate stock-specific run sizes for Fraser River Sockeye Salmon. This work documented the current process and associated uncertainty and produced recommendations for improvements, including alternative methods for generating run size estimates, as well as guidance on the use and interpretation of run size estimates and associated derivatives (e.g., exploitation rates).

This Science Advisory Report is from the May 27-29, 2024, regional peer review on Stock-specific Fraser River Sockeye Salmon Run Size Determination. Additional publications from this meeting will be posted on the [Fisheries and Oceans Canada (DFO) Science Advisory Schedule] as they become available.

SUMMARY

- Postseason run size estimates for Fraser Sockeye stocks are used to forecast future returns, report exploitation rates and en route mortality estimates, and conduct stock assessments.
- Run sizes for most Pacific salmon stocks are the sum of catch and spawning escapement estimates; Fraser Sockeye is unique in that it also includes estimates of stock-specific en route mortality that have accounted for adverse environmental and biological conditions.
- Stock-specific estimates of en route mortality for Fraser Sockeye have been increasing and can often exceed catch and occasionally spawning escapement in overall contribution to run size calculations.
- The current Fraser Sockeye postseason run size determination process, ongoing since 2009, is designed to improve postseason run size estimates by incorporating stock-specific en route mortality and scrutinizing the main components of the run size process—catch, spawning escapement, and en route mortality.
- An in-depth documentation and review of the process used to estimate postseason stock-specific run sizes was provided with a focus on catch, escapement, and en route mortality, as well as uncertainty and input sensitivity in component error.
- Recommendations for improvements to the current stock-specific run size estimation process and guidance on use of the data sets generated by this process were provided.
- Major recommendations include the following: simplify the overall postseason run size structure; update the visual survey estimates to improve accuracy of spawning escapements; receive consistent and timely reporting of catch from all fisheries that have a reasonable potential to intercept Fraser Sockeye; update and extend en route mortality models to include all evaluated stocks; and work to quantify uncertainty in all inputs and outputs.
- A summary table of recommendations was developed along with evaluation criteria to assist with prioritization based on different end user objectives.
- Quantifying and reducing the uncertainty in run size components will support credibility for downstream uses, including exploitation rate and productivity analyses, and for estimating the impact of en route mortality.
- The postseason run size and its component data sets should be used for postseason evaluations of run size, exploitation rates, and productivity, as well as forecasting and assessments supporting long-term planning. At present, they should not be used for evaluations of in-season management or evaluations requiring underlying daily estimates.
- Large bias and imprecision of some stock-specific run size components and their derivatives require additional scrutiny for use (e.g., exploitation rates for small stocks).
- Better understanding and quantification of en route mortality will also support the Department’s recovery and rebuilding plans for Fraser Sockeye and other salmon populations, especially given the expected increased frequency of extreme migration conditions and reductions in catch and/or spawning escapements.

INTRODUCTION

Each year the management of Fraser River Sockeye Salmon (*Oncorhynchus nerka*) relies on a temporal series (preseason, in-season, postseason) of abundance estimates of adult returns to the start of coastal fisheries, commonly referred to as run size estimates. The postseason estimates are used to calculate productivity and conduct stock assessments for use in future harvest planning (Grant et al. 2011), to aid in recovery planning (DFO 2020a, b), and to evaluate factors limiting survival, such as en route mortality (Martins et al. 2011; Hinch et al. 2012; Doutaz et al. 2023). Postseason estimates are generated for 28 Fraser Sockeye stocks through an annual expert reviewed approach to run size determination (Figure 2). The derivatives of this run size determination process, such as exploitation rate, are used to informally evaluate management performance (e.g., spawner escapement targets, international/domestic catch goals; Pacific Salmon Treaty 1985). The overall approach and outputs from the run size determination process are related to First Nation treaty obligations and agreements.

Run sizes for Pacific salmon (*Oncorhynchus* spp.) stocks are most often based on the postseason summation of catch and spawning escapement estimates by age. This approach, however, does not account for en route mortality, defined as natural and human-induced mortality (excluding landed catch) between the start of the marine fishery and just prior to arriving at the spawning grounds. Postseason Fraser Sockeye run sizes are unique in that they include estimates of stock-specific en route mortality that account for adverse environmental and biological conditions. Recent changes to in-river migration conditions (e.g., high flows or high temperatures; Patterson et al. 2016) have translated into an increasing portion of Fraser Sockeye run sizes accounted for by en route mortality, with current estimates often exceeding catch and occasionally spawning escapement in overall contribution to run size calculations. This shift warrants the need to review and develop approaches to better quantify en route mortality.

The approach for including en route mortality estimates in Fraser Sockeye postseason run sizes has varied through the time series (Figure 2). From 1977 to 1992, en route mortality estimates were inconsistently included in run sizes, most commonly based on the difference between estimates (DBE) of spawning escapement (SE) and potential spawning escapement (PSE), with the latter based on lower Fraser River abundance estimates (i.e., Mission estimates) after accounting for intervening catch. These DBEs were determined for the in-season management run-timing stock aggregates—Early Stuart, Early Summer, Summer, and Lates—with the understanding that some portion of the DBEs represent uncertainties and bias inherent in the contributing stock composition, catch, and escapement estimates (Macdonald et al. 2010). From 1992 to 2008, the inclusion of en route mortality estimates became more structured, with only negative DBEs (SE < PSE) being reapportioned among co-migrating stocks and included as estimates of stock-specific en route mortality. However, the reapportioning of these aggregate DBEs to component stocks can lead to in-river loss estimates that are not necessarily related to en route mortality factors at the stock level, potentially masking the mortality relationship between loss and freshwater migration conditions. Moreover, only using DBEs when they are negative can lead to a positive bias in run size estimates, assuming the catch and SE are unbiased. Consistently selecting the higher of the SE or PSE estimates would overestimate productivity and underestimate ER. In addition, instances where DBEs are positive (SE > PSE) do not necessarily indicate that en route mortality did not occur, but rather that there is additional information on the error associated with the run size components that should be evaluated.

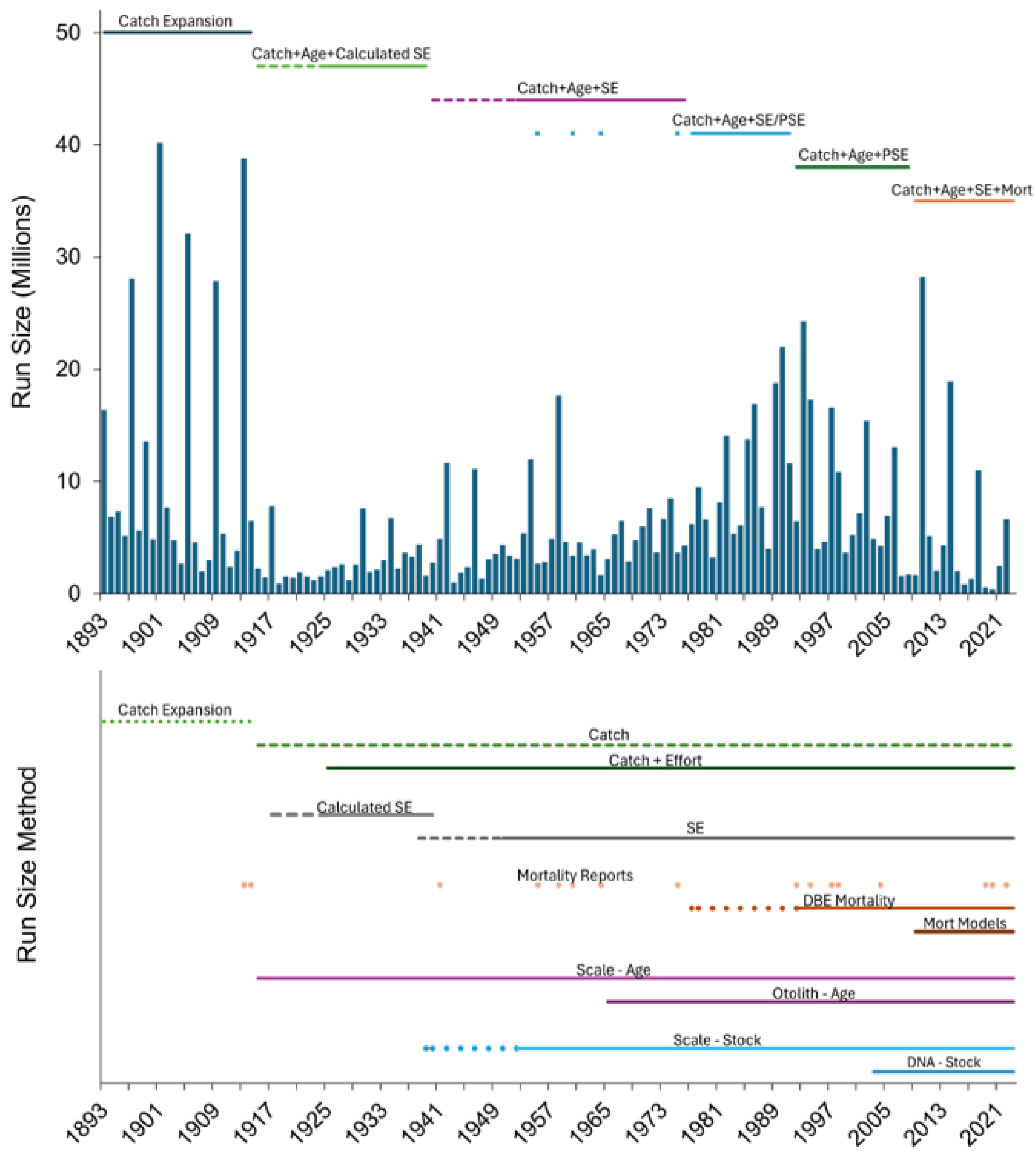

Figure 2. Overview of the different postseason run size estimation approaches for Fraser Sockeye. The top panel summarizes the run size derivation changes over the years 1893–2022; the bottom panel provides more information on changes in availability and use of stock assessment data for run size determination. Abbreviations include spawning escapements (SE) and potential spawning escapements (PSE), the latter based on lower Fraser River abundance estimates (i.e., Mission estimates) after accounting for intervening catch. Difference between estimates (DBEs) are calculated as SE minus PSE. The explicit and consistent inclusion of en route mortality estimates in run size calculations is relatively recent, beginning in 2009. Run size data sourced from the Pacific Salmon Commission (PSC) Run Size, Fishing and Escapement (RuFEs) database.

Stock-specific concerns associated with using DBEs as en route loss estimates can be highlighted by the relationship between the PSE and SE. Early Stuart and North Thompson are both examples of Fraser Sockeye stocks with consistent negative DBEs, suggesting consistent and sometimes substantial in-river mortality (Figure 3). The PSE to SE relationship for Early Stuart Sockeye is consistent with our understanding of extreme migration conditions and en route mortality (Figure 3A; Macdonald et al. 2010). In contrast, there is no biological rationale to support North Thompson Sockeye suffering disproportionately high mortality when compared to other co-migrating stocks (Figure 3B). Closer examination of spawning escapement estimates reveals that the visual assessment methods used to assess the large and turbid North Thompson are likely biased low. These cases highlight that stock-specific discrepancies between PSE and SE can be the result of biases in catch and spawning escapement and not just attributable to en route mortality.

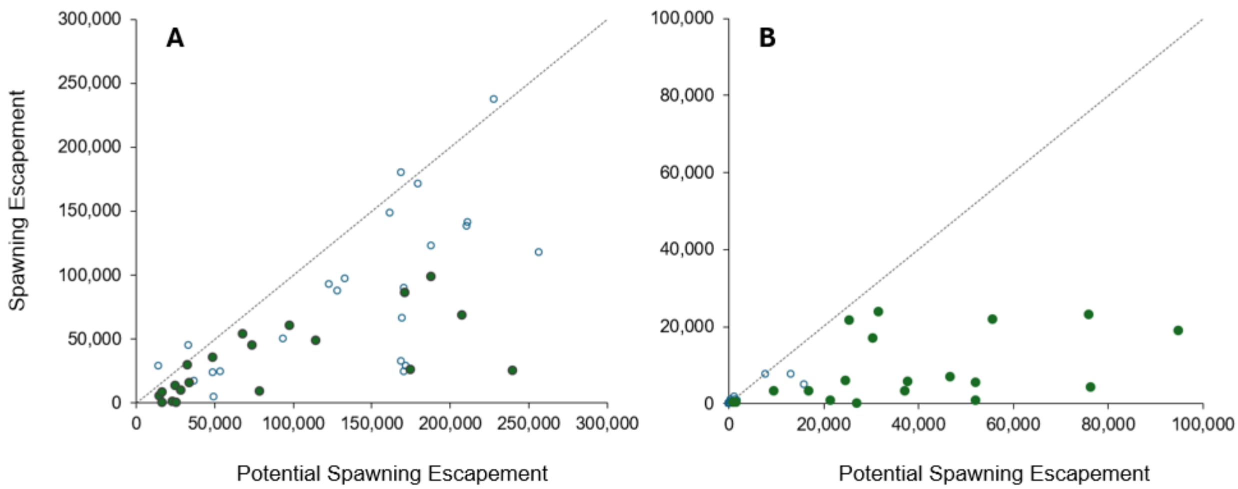

Figure 3. Comparison of potential spawning escapement (PSE; lower river Mission abundance minus upstream catch) and spawning escapement (SE) for Early Stuart (A) and North Thompson (B) Sockeye. The open dots represent data from 1977–2002; the solid dots represent data from 2003–2022, marking the transition to genetic stock assignments in PSE estimates. The dotted black line represents the 1:1 line (PSE = SE). There has been a consistent negative difference between estimates (DBE; SE - PSE) for both stocks. For Early Stuart, this is consistent with our understanding of extreme migration conditions and en route mortality. For North Thompson, there is no compelling reason to have a similarly large negative DBE associated with en route mortality. Data sourced from the Pacific Salmon Commission (PSC) Run Size, Fishing and Escapement (RuFEs) database.

An improved understanding of run sizes, run size components, and associated productivity will help in assessments of stock status. Improvements in quantifying stock-specific catch and en route mortality can help direct recovery and rebuilding efforts to focus on those factors that are contributing most to overall declines. Changes in Canadian policy (e.g., Wild Salmon Policy; DFO 2005) and legislation related to endangered species (Species at Risk Act (SARA); Committee on the Status of Endangered Wildlife in Canada (COSEWIC)) has put more emphasis on population diversity and lower abundance stocks, as well as added scrutiny on stock assessment information from low abundance stocks. Failure to recognize major biases, or to dismiss real discrepancies as simply random assessment errors associated with low precision, can lead to erroneous conclusions regarding the main factors driving changes in population abundance. For example, ignoring en route mortality in Early Stuart Sockeye over the past 30 years would imply that either productivity (return per spawner) or catch are the only serious limiting factor(s) in recovery and rebuilding potential (Figure 4). The spawner-to-spawner ratios indicate that, in 19 of the past 30 years, fewer spawners made it back to natal spawning grounds relative to their brood (Figure 4A). However, this consistent replacement failure, and hence decline, does not appear to be a function of declining productivity (returns per spawner; Figure 4B). For only 4 of the past 30 years, the estimated number of returning Early Stuart Sockeye has failed to exceed the number of brood-year spawners. This means that, in the absence of catch and en route mortality, the spawner population should be growing. If we assume no en route mortality (add all negative DBEs to SE) to isolate the impact of catch, we still only see 5 of the past 30 years without replacement levels (Figure 4C). However, if we assume no catch to isolate the impact of en route mortality, we are back to 19 of the past 30 years failing to reach replacement (Figure 4D), implying that 15 of the past 30 years would reach replacement if not for en route mortality (subtract four low productivity years).

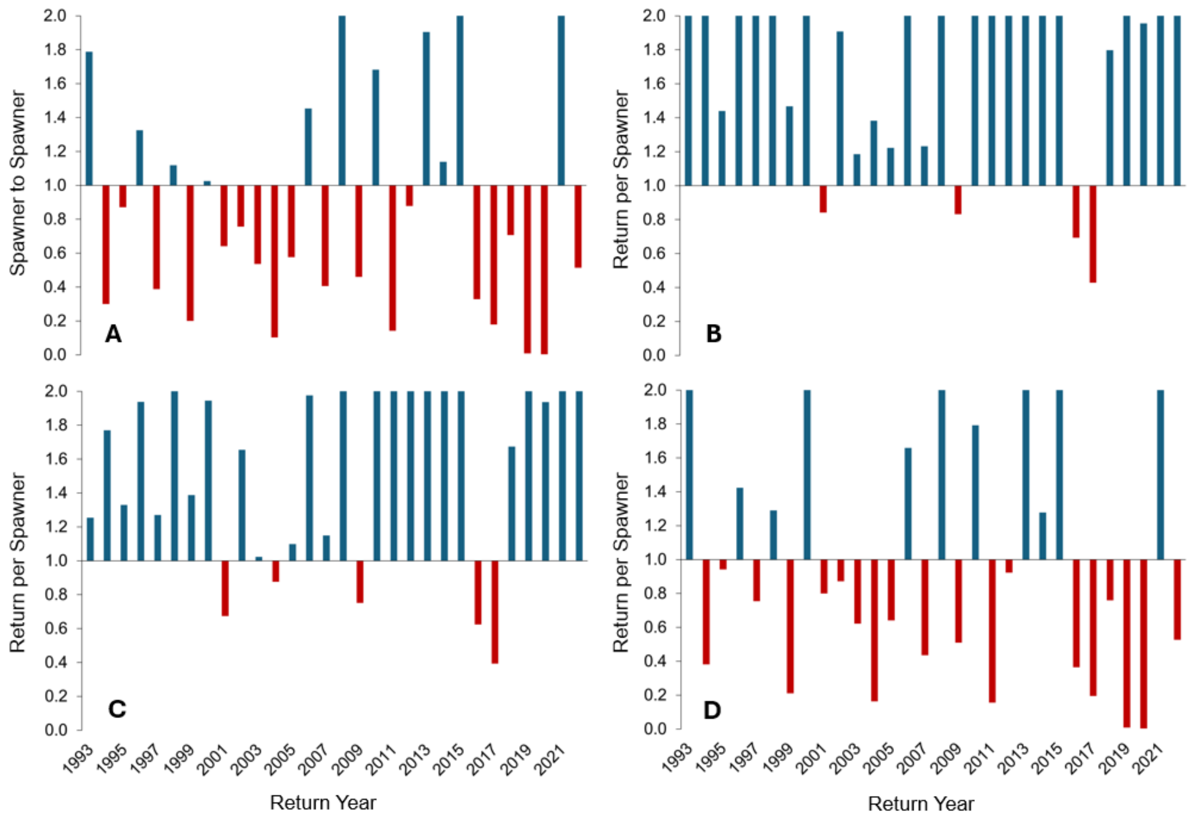

Figure 4. Annual changes in the ratio of different metrics of returns per brood-year spawners for Early Stuart Sockeye from 1993 to 2022. Each panel depicts a different metric: A) spawner to spawner, B) return per spawner, C) return per spawner assuming no en route mortality (only catch), and D) return per spawner assuming en route mortality (no catch). A value of 1 represents replacement, >1 (blue) infers population growth, and <1 (red) infers population decline relative to brood-year spawners. Spawner-to-spawner ratios were below replacement in 19 of 30 years (A), however, this was due to low productivity alone (return per spawner) in only 4 of those years (B). Failure to consider en route mortality (C) and catch (D) components in run size determination can lead to erroneous conclusions regarding the main factors driving changes in population abundance, potentially misdirecting recovery and rebuilding efforts. Total numbers have been used without adjusting to account for age class. The x-axis is capped at 2 for display purposes. Data sourced from the Pacific Salmon Commission (PSC) Run Size, Fishing and Escapement (RuFEs) database.

A working group was formed to deconstruct run size components and develop additional criteria around the appropriate use of DBEs for estimating en route loss at the stock level (Robinson and Patterson 2014, 2015). This led to the development of an annual process that includes adjustments for uncertainty in spawning escapement and total catch by stock, as well as separate estimates of en route mortality informed by the relationships between adverse migration conditions and salmon migration survival. Estimates were calculated as the sum of spawning escapement, catch and, in most cases, a Run Size Adjustment (RSA) that represented a numeric adjustment ascribed to one of four potential sources: spawning escapement, catch, en route mortality, and other. With this approach, both en route loss and assessment estimates were revisited for uncertainty and bias following in-season data procedures. The spawning escapement adjustment ($RSA_{Spawners}$) provided stock-specific adjustments based on suspected biases in terminal escapement methodologies. The catch adjustment (RSA_{Catch}) brought forth additional unassigned catch estimates that may not have fit into the existing catch accounting structures. In most cases, the en route mortality ($RSA_{Mortality}$) was a derivative of a negative DBE, however, with this approach the $RSA_{Mortality}$ values were vetted to ensure they matched with the expected mortality given the known association with environmental and biological conditions. The RSA_{Other} category was created for adjustments to the run size that could not be agreed upon to fit into one of the three established stock assessment methods (e.g., absent or incomplete SE). This interim method of postseason run size determination was in place for the 2009 to 2013 return years. The current postseason run size approach, recommendations for improvements, and guidance on use are summarized in the Assessment section below.

ASSESSMENT

Current Postseason Stock-Specific Run Size Determination Methods

The methods used to generate postseason stock-specific run size estimates from 2014 to 2022 reflect a distinct shift towards reconstructions based on spawning escapement estimates, thus avoiding the challenge of reconciling DBEs at a stock-specific level. This precipitated a central focus on the environmental and biological risk factors that impact en route mortality, prior to the evaluation of quantitative in-river mortality proxies (e.g., DBEs). The following equations are currently used to calculate Fraser Sockeye stock-specific postseason run sizes:

$$\text{Run Size} = \text{Spawners} + \text{Catch} + \text{RSA}$$

$$\text{RSA} = \text{RSA}_{\text{Spawners}} + \text{RSA}_{\text{Catch}} + \text{RSA}_{\text{Mortality}} + \text{RSA}_{\text{Other}}$$

$$\text{RSA}_{\text{Mortality}} = (\text{Spawners} + \text{RSA}_{\text{Spawners}}) * \%\text{Mortality} / (100\% - \%\text{Mortality})$$

The adjusted components (i.e., RSAs) of the equations are completed by members of the working group that gather at least once a year to discuss each component and produce postseason estimates. For each return year, experts in spawning escapement and catch estimation methods present the uncertainty in approaches used and adjustments required to develop better estimates of these components for run size determination. This is followed by the en route mortality process, in which working group members discuss the environmental and biological information available to decide on stock-specific estimates of percent mortality. These estimates are then used to reconstruct run sizes from the adjusted spawning escapement estimates.

The methods used to estimate spawning escapement (i.e., spawners) for each population vary depending on the attributes of the system and the preseason expectations of run size. Low precision techniques, such as visual surveys, are generally employed when the expected spawning escapement is less than 75,000 spawners. For populations with expected spawning escapements greater than 75,000, more intensive, higher precision methods are typically employed (i.e., enumeration fence, mark-recapture, hydroacoustics; Grant et al. 2011). Numerically, most Fraser Sockeye are counted on the spawning grounds using high intensity methods with quantifiable uncertainty estimates (i.e., low CV values). However, a high proportion of the 180+ Fraser Sockeye spawning streams are estimated using low intensity methods with unquantified uncertainty estimates. DFO Stock Assessment is responsible for evaluating their spawning escapement estimates for known or expected bias as part of the $RSA_{Spawners}$ determination process. In most cases, bias in escapement estimates is systematic and arises from the use of an inappropriate expansion factor applied to peak counts of salmon on the spawning grounds to generate escapement estimates for visually surveyed systems. The escapement adjustment decisions presented at the annual RSA working group meetings include documentation for the likely source, direction, and extent of bias for each RSA stock.

There are numerous directed and non-directed fisheries that intercept adult Fraser Sockeye through their return spawning migration. The estimation of this catch across a diverse array of fisheries depends on a suite of monitoring and reporting tools. Catch data provided by most monitoring programs are categorized by species, while catch estimates by stock and age are typically generated based on sampling programs from test fisheries, unless catches have been directly sampled. A main source of uncertainty is whether all potential fisheries that can intercept Fraser Sockeye have been evaluated to estimate total catch. The uncertainty in stock and age-specific catch estimates used in the RSA process will vary by stock group and year, which fisheries are contributing to the data, the estimation methods used, and random error. For RSA_{Catch} determination, total catch estimates for a particular fishery are evaluated for known or expected bias. Resource managers from DFO with support from Pacific Salmon Commission staff and US fisheries managers are responsible for bringing the decisions on bias to the RSA working group meetings, along with an explanation of the sources of uncertainty.

The overall goal of this $RSA_{Mortality}$ approach is to use our current understanding of how fish fate during upriver migration is influenced by environmental and biological factors to inform condition-specific en route mortality estimates. As such, the $RSA_{Mortality}$ process has been developed to incorporate a more fish-centric approach for estimating mortality based on current research on salmon migration biology. Data are presented in two summary tables and evaluated in a series of repeatable steps meant to develop a numerical range of reasonable mortality estimates prior to review of estimates derived from different stock assessment data sources.

The first table is populated with coarse mortality risk scores (1–4) that represent a range of plausible percent mortalities for each RSA stock, using the environmental and biological risk factors for a given year. The structure of the table is designed to aggregate the impact of specific drivers (or stress factors) on en route mortality, with each column representing a best estimate of the metric's independent contribution to mortality. The quantifiable relationships between high temperature or high discharge and mortality allow us to create environmental exposure profiles that are informed by stock-specific estimates of daily migration timing and lower river abundance distributions (Macdonald et al. 2010; Martins et al. 2011). The remaining environmental and biological columns are treated as modifiers to the dominant risk scores for environmental exposure. A more detailed description of the columns is provided in Table 1.

Table 1. Example of a populated environmental and biological exposure risk summary table from 2022. The overall stock-specific risk assessment values generated from this table are then input into the quantitative assessment table in the subsequent step of the RSA mortality process. NR indicates no events reported.

RUN TIMING	STOCK GROUP	STEP 1: Temperature Exposure	STEP 1: High Discharge Exposure	STEP 1: Low Discharge Exposure	STEP 1: Other Events	STEP 2: Migration Behaviour	STEP 2: Fishing Pressure	STEP 2: Fish Condition	OVERALL RISK ASSESSMENT (stock specific)	COMMENTS
Early Stuart	Early Stuart	3	4	1	NR	2	1	2	**4**	-
Early Summer	Pitt	2	1	1	NR	1	1	1	**1**	-
Early Summer	Chilliwack	1	1	1	NR	1	1	1	**1**	-
Early Summer	Nahatlatch	2	1	1	NR	1	2	1	**2**	-
Early Summer	Gates	2	1	1	NR	1	2	2	**2**	dam passage
Early Summer	Nadina	3	2	1	NR	2	2	2	**3**	-
Early Summer	Bowron	2	2	1	NR	1	2	1	**2**	-
Early Summer	Taseko	2	1	1	NR	1	2	1	**2**	-
Early Summer	Upper Barriere	3	1	1	NR	1	2	1	**2**	-
Early Summer	Scotch	3	1	1	NR	1	2	2	**3**	-
Early Summer	Seymour	3	1	1	NR	1	2	2	**3**	-
Summer	Raft	2	1	1	NR	1	2	1	**2**	-

RUN TIMING	STOCK GROUP	STEP 1: Temperature Exposure	STEP 1: High Discharge Exposure	STEP 1: Low Discharge Exposure	STEP 1: Other Events	STEP 2: Migration Behaviour	STEP 2: Fishing Pressure	STEP 2: Fish Condition	OVERALL RISK ASSESSMENT (stock specific)	COMMENTS
Summer	North Thompson	2	1	1	NR	1	2	1	**2**	-
Summer	Chilko	3	1	1	NR	2	2	1	**3**	-
Summer	Horsefly	3	1	1	NR	1	2	2	**3**	-
Summer	Mitchell	3	1	1	NR	1	2	1	**3**	-
Summer	Late Stuart	3	1	1	NR	1	2	1	**3**	-
Summer	Stellako	3	1	1	NR	1	2	1	**3**	-
Summer	Harrison	3	1	1	NR	2	2	1	**2**	early-entry 'late-run'
Late	Birkenhead	3	1	1	NR	1	2	1	**2**	-
Late	Weaver	1	1	3	NR	2	2	3	**3**	early-entry late-run
Late	Cultus	1	1	1	NR	2	2	1	**2**	early-entry late-run
Late	Late Shuswap	2	1	1	NR	2	2	1	**2**	early-entry late-run
Late	Portage	2	1	1	NR	2	2	1	**2**	early-entry late-run, dam passage

The temperature exposure risk score provides the foundation for this overall risk assessment due to the strength of the supporting research on the mechanism behind this mortality and the potential to generate a quantitative link with en route mortality estimates (Eliason et al. 2011; Martins et al. 2011; Patterson et al. 2016). The mortality risk is quantified as the mean 96-hour temperature exposure, supported by the reduction in aerobic scope that occurs at high temperatures and the associated limits on swim performance and upstream progress (Farrell et al. 2008; Eliason et al. 2011). More specifically, data collected from each real-time water temperature monitoring site are matched to the daily migration patterns of each RSA stock to evaluate the thermal exposure risk along their migratory corridor. This approach uses daily stock-specific abundance estimates at Mission to inform the migration timing and relative abundance distribution. For exposure risk assessments in the lower river, the Mission distribution is plotted against the daily mean water temperature for the lower Fraser River at Qualark (100 km upstream of Mission) and the overall site-specific risk is calculated (Figure 5). For evaluations of exposure further upstream, the Mission distribution is adjusted by a site -specific fixed migration rate to align with the location of the upstream temperature monitoring sites. The highest risk score amongst the locations available is used to populate the temperature exposure column for each stock.

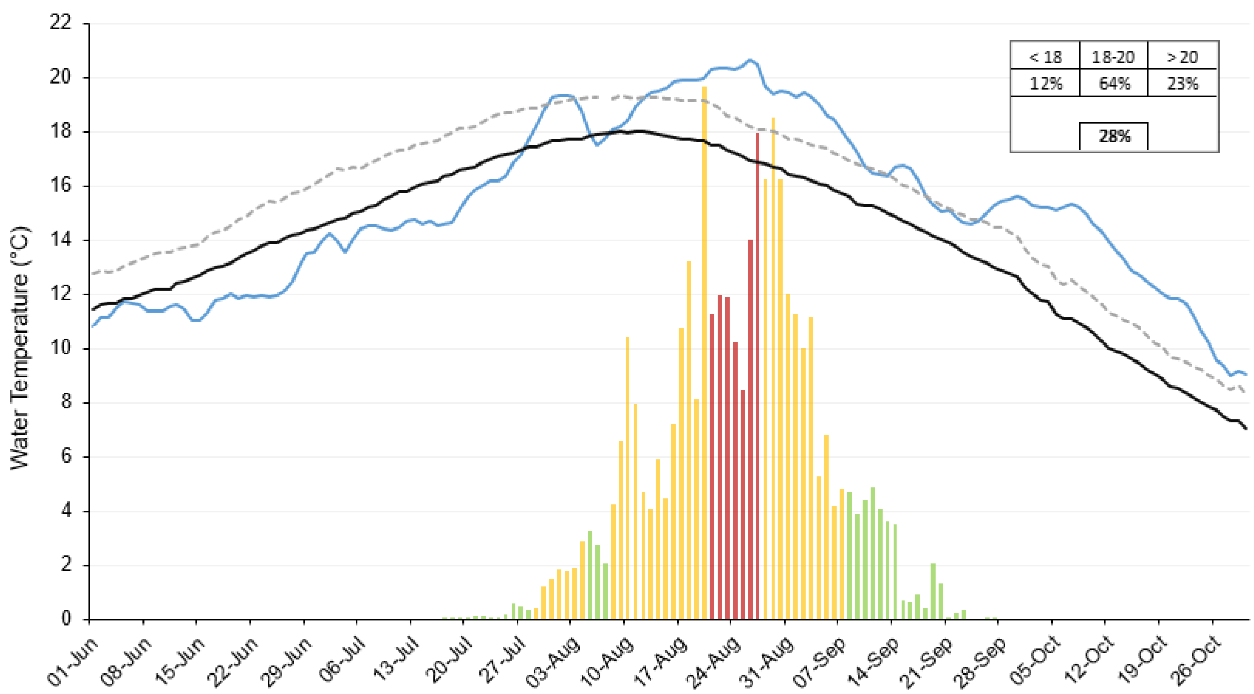

Figure 5. Example temperature exposure risk visualization for Chilko Sockeye in 2022, using Mission daily stock-specific abundance and water temperature data for the lower Fraser River (Environmental Watch Program Fraser River at Qualark). The bars present the relative abundance, where green indicates Sockeye passing the monitoring site when water temperatures are below 18°C, yellow indicates water temperature between 18 and 20°C, and red indicates water temperatures greater than 20°C. The proportional contribution of each colours to the overall abundance at Mission is presented in the table insert, with the final value in bold presenting the overall 96-hour risk, weighted by temperature category (see Robinson et al. accepted). The solid black line and dashed grey line present the daily mean and +1SD water temperature for 1941–2021. The solid blue line depicts the water temperature for the assessment year (i.e., 2022).

The next mortality risk score, high discharge exposure, mimics the high temperature exposure approach using high flow thresholds from published work (e.g., Macdonald et al. 2010) to estimate risk. Daily stock-specific abundance estimates at Mission are used to inform migration timing and relative abundance distributions and plotted against daily mean discharge for the lower Fraser River only. The remaining columns identify other environmental or biological variables that may modify the high temperature or high discharge risk scores. Low flow impacts have been noted on a few occasions, such as low flow barriers prior to reaching spawning assessment areas. The mortality risk from geomorphology events, such as landslides, are considered in a separate score. The mortality risk from adverse migration behaviour is based on stock-specific deviations in timing of marine arrival, river entry, spawning arrival, and spawn timing. For example, a higher score is given to populations exhibiting early river entry timing given its close association with high en route mortality (Hinch et al. 2012). The score for the added risk posed by fishing is based on expert opinion on the proportion of a given stock that is likely to experience an adverse fishery encounter, or FRIM (Patterson et al. 2017). The last biological column score on fish condition is evaluated based on reports of fish size, surficial fish condition, and egg retention.

The final step in the mortality risk assessment table is to estimate the most likely range of percent mortality experienced by each stock by assessing the cumulative exposure risk across table columns. There is a lack of research regarding how two or more potential drivers (e.g., stressors) will interact (i.e., antagonistic, synergistic, or additive; Côté et al. 2016) to affect overall mortality (Patterson et al. 2016, 2017). At a minimum, a dominance stressor response, a variant of antagonistic, is assumed, whereby the highest value for temperature or discharge is the default starting position for the overall score. Expert opinion is then used to determine whether additional mortality needs to be applied due to the other risk factors (e.g., dam passage), keeping in mind that fish can only die once so spatial and temporal risk is considered at this stage. Conversely, this is also where stock-specific information can be used to provide mitigation against a high value (e.g., Chilko thermal tolerance; Eliason et al. 2011). The additional information relevant to the final decision is documented.

Next, the quantitative mortality estimates available for Fraser Sockeye each year are presented in the second summary table. First, the stock-specific mortality estimates generated by in-season tagging programs and/or tagging-based models developed from the relationship between migration timing and environmental exposure risk are presented (English et al. 2005; Martins et al. 2011). These models are used to estimate mortality based on stock-specific Mission migration timing and environmental condition data for a given assessment year. Next, five different estimates of en route loss between lower river and spawning escapements (i.e., variations of DBEs) produced through existing in-season and postseason procedures are evaluated. A comparison of the mortality risk score range from the previous table with these quantitative estimates is then completed. The final point estimate of mortality normally falls within the mortality risk range agreed upon by the working group; justifications for any deviations are documented.

The final stage of the process is the complicated task of integrating all of the data sets reviewed and generated in the postseason process back into the historic production data sets. This includes applying run size components to different levels of stock aggregation, and assigning age composition to the stock-specific postseason run size estimates to inform estimates of recruits. In addition, the sex ratio and egg retention estimates collected during spawning ground surveys are integrated to calculate estimates of effective female spawners used in stock-recruit calculations. The final integration piece and data set storage is completed by Pacific Salmon Commission staff.

Recommended Improvements to Stock-Specific Run Size Determination

The current postseason run size estimation process documented in Robinson et al. (accepted) represents one of the few examples of how to incorporate en route mortality along with catch and spawning escapements into postseason estimates of run size for Pacific salmon (e.g., Potter et al. 2004; Baker et al. 2014), even though quantifying stage-specific mortality has long been recognized as important in stock assessments (Ricker 1976). In the absence of other peer reviewed processes, a detailed list of potential recommendations was compiled that spans the full spectrum of data collection, data analysis, and reporting for spawning escapement, catch, and en route mortality, as well as a review of alternative methods to estimating Fraser Sockeye run sizes drawn from related published literature (Patterson et al. accepted). This recognizes that continued improvements to postseason run size determination will be of benefit to users of this data. The main goal of each recommendation is to improve the overall quality of the data outputs and the veracity of the process used to generate those outputs. Therefore, each recommendation has been selected to meet the following improvement criteria:

1. needs to improve one of these outputs for one or more RSA stock postseason: stock-specific run size, stock-specific spawning escapement, stock-specific catch, stock-specific en route mortality, or any of the above with respect to age; and
2. needs to address one of these target improvement areas: reproducibility, transparency, documentation, best practices, uncertainty quantification, or uncertainty reduction (see Table 2).

In addition, recommendations need to focus on at least one of the following key areas:

1. a direct component input (e.g., spawner escapement),
2. an indirect component input (e.g., fish condition, fishing effort),
3. a process (e.g., risk assessment),
4. a main output (e.g., stock-specific run size), or
5. a derivative of the main output (e.g. exploitation rate).

Major recommendations for each category include the following: simplify the overall postseason run size approach; update the visual survey estimates to improve accuracy of spawning escapements; receive consistent and timely reporting of catch from all fisheries that have a reasonable potential to intercept Fraser Sockeye; update and extend mortality models to include all RSA stocks; and work to quantify uncertainty in all inputs and outputs (Table 2). A series of methods for generating estimates of spawning escapements, catch, and en route mortality when stock size is very low, or individual component data are exceptional (e.g., no catch data, extreme high mortality) were also recommended, along with a postseason run reconstruction model. An overall caution was noted for the high uncertainty in some estimates of run size, components, and derivatives (i.e., exploitation rate, stock recruitment estimates), especially for low abundance stocks. Further work is needed to evaluate the recommendations to determine if improvements will likely arise as expected and to ensure efforts are directed to serve the changing and multiple purposes of generating age-stock-specific run sizes for Fraser Sockeye. Declines in stock abundances, reductions in catch, and increases in en route mortality are not unique to Fraser Sockeye, as such, the methods and recommendations are likely of value to other Pacific salmon population assessment processes.

Table 2. Summary characterization of the run size improvement recommendations. The direct (D) and indirect (I) notations indicate the target and type of improvement for each recommendation. The effort column reflects the relative work required to complete. The process connection column refers to a subset of science and management processes each recommendation would impact (FP = Fraser Panel, RR = recovery and/or rebuilding, SSA = stock status assessments, WG = postseason run size working group). The remaining columns provide further context to help scope and prioritize recommendations in light of major science challenges and key considerations. The latter includes key dependencies to other recommendations.

Recommendation	Run Size	Spawners	Catch	En Route Mortality	Reproducibility / Transparency	Documentation	Best Practices	Uncertainty Quantification	Uncertainty Reduction	Effort	Process Connection	Major Science Challenges	Key Considerations and Dependencies (R-#)
OVERALL APPROACH													
R-1: Simplify overall postseason run size structure	D	-	-	-	D	-	I	-	-	Low	All	Unforeseen circumstances	Requires R-4 and R-11
R-2: Standardize level of population aggregation	D	-	-	-	D	-	I	-	-	Medium	All	-	Define multiple end user objectives
R-3: Standardize level of spatial scope	D	-	-	-	D	-	I	-	-	Low	All	Natural marine mortality	Spatial/temporal movement of fisheries
SPAWNING ESCAPEMENT													
R-4: Update visual survey expansion factors	I	D	-	I	-	-	-	-	D	Medium	RR, SSA	Need confidence intervals	-
R-5: Quantify the uncertainty in escapement estimates by age	-	D	-	-	-	-	I	D	-	Medium	FP, RR, SSA	Method development	-
R-6: Prioritize reduction in uncertainty for low abundance stocks	-	D	-	I	-	-	-	-	D	High	RR, SSA	-	Resource re-allocation; Pacific Salmon Treaty commitments
R-7: Remove RSA-spawning escapement	-	D	-	-	D	I	D	-	I	Low	SSA	Needs peer review; requires reassessment of spawning escapement time series	R-4

Recommendation	Run Size	Spawners	Catch	En Route Mortality	Reproducibility / Transparency	Documentation	Best Practices	Uncertainty Quantification	Uncertainty Reduction	Effort	Process Connection	Major Science Challenges	Key Considerations and Dependencies (R-#)
CATCH													
R-8: Consistent and timely reporting of all catches	I	-	D	I	D	D	D	-	D	High	FP, RR	-	Multi-group cooperation
R-9: Improve information collection for fishing-related incidental mortality (FRIM)	I	-	I	D	I	I	I	-	D	High	FP, RR	Limited information on drop-off mortality	Multi-group cooperation; R-8
R-10: Quantify uncertainty in catch estimates	I	-	D	-	-	I	-	D	-	High	RR	Large scope	Capacity limits; R-8
R-11: Improve assignment of age and stock	I	-	D	-	-	-	-	-	D	Medium	FP, SSA	Genetic stock assignment limits	Mult-group cooperation; R-8
R-12: Remove RSA-catch	I	-	D	-	D	I	D	-	-	Low	WG	-	Database updates; R-8, R-9, R-11
EN ROUTE MORTALITY													
R-13: Generate mortality estimates for all RSA stocks at annual review	I	-	-	D	I	-	I	-	D	Medium	RR, SSA	Limited data on lower Fraser stocks	R-2
R-14: Regular literature reviews for adult salmon migration biology	-	-	-	D	-	-	D	-	-	Low	All	-	-
R-15: Improve temperature exposure scores and mortality models	-	-	-	D	-	-	-	I	D	Medium	All	Trade-offs between stock-specific and more general species model	R-22
R-16: Improve discharge exposure scores and mortality models	-	-	-	D	-	-	-	I	D	Medium	All	Needs peer review	R-22

Recommendation	Run Size	Spawners	Catch	En Route Mortality	Reproducibility / Transparency	Documentation	Best Practices	Uncertainty Quantification	Uncertainty Reduction	Effort	Process Connection	Major Science Challenges	Key Considerations and Dependencies (R-#)
R-17: Update migration behaviour and timing mortality models	-	-	-	D	-	-	-	I	D	Medium	FP, RR	Linked to thermal exposure	R-22
R-18: Quantification of fishing-related incidental mortality (FRIM)	-	-	-	D	-	-	-	I	D	Medium	All	Cumulative impacts	R-8, R-9, R-15, R-22
R-19: Quantification of fish condition related to mortality	-	-	-	D	-	-	D	I	D	Medium	All	Inconsistent results to date	R-22
R-20: Re-evaluate the use of MA model and DBE estimate variants	-	-	-	D	I	-	-	-	-	Medium	All	-	-
R-21: Quantification of uncertainty in mortality estimates	-	-	-	D	-	-	D	D	I	High	RR	Multiple sources of uncertainty; method development	-
R-22: Multi-factor and cumulative impacts modeling	-	-	-	D	-	-	D	I	D	High	RR	-	R-14
R-23: Re-evaluate the overall risk assessment process	-	-	-	D	D	-	I	-	-	Medium	RR	Limited extreme mortality events to model	-
R-24: Generate independent estimates of mortality	-	-	-	D	-	-	D	-	D	High	RR	Multiple ideas, difficult, in some cases unproven	R-14
R-25: Generate spatial and temporal resolution of mortality	-	-	-	I	-	D	I	I	I	High	RR	Method development	R-8, R-9
DATA INTEGRATION													

Recommendation	Run Size	Spawners	Catch	En Route Mortality	Reproducibility / Transparency	Documentation	Best Practices	Uncertainty Quantification	Uncertainty Reduction	Effort	Process Connection	Major Science Challenges	Key Considerations and Dependencies (R-#)
R-26: Provide data quality indicators	I	-	-	-	-	-	-	I	-	Low	All	-	R-5, R-10, R-21
R-27: Documentation for core component inputs and outputs	I	-	-	-	I	D	I	-	-	Low	WG	-	-
DIAGNOSTICS													
R-28: Re-evaluation of the effectiveness of current diagnostics	I	I	I	I	I	-	D	-	-	Medium	FP, SSA	Difficult to quantify performance metrics	R-5, R-10, R-21
ROLES AND RESPONSIBILITIES													
R-29: Articulation of detailed information and timeline requirements	I	I	I	I	-	D	-	-	-	Low	WG	-	-
OTHER IMPROVEMENTS													
R-30: Explore considerations for updating historic time series	D	-	-	-	I	-	-	-	-	High	RR, SSA	-	Impacts historical data sets
R-31: Document overall confidence in run size and components	D	I	I	I	-	-	-	D	-	High	All	Method development	R-26
R-32: Link postseason mortality work to in-season MA work	-	-	-	D	I	I	-	-	-	Medium	FP	-	-
SMALL RUN SIZES AND EXCEPTIONAL DATA													

Recommendation	Run Size	Spawners	Catch	En Route Mortality	Reproducibility / Transparency	Documentation	Best Practices	Uncertainty Quantification	Uncertainty Reduction	Effort	Process Connection	Major Science Challenges	Key Considerations and Dependencies (R-#)
R-33: Develop general approaches to small run sizes	D	-	-	-	D	-	-	-	-	Medium	RR	Method development	-
R-34: Methods for very low spawning escapement estimates	-	D	-	-	D	-	-	-	I	Medium	SSA	-	-
R-35: Approach for absence of spawning escapement estimates	-	D	-	-	D	-	-	-	I	Medium	SSA	Review infilling methods	-
R-36: Methods for very low estimates of catch from small run sizes	-	-	D	-	D	-	-	-	I	Medium	RR	-	Update data integration systems
R-37: Approach for absence of relevant catch data	-	-	D	-	D	-	-	-	I	Medium	All	Review infilling methods	R-8
R-38: Methods for mortality estimates for small run sizes	-	-	-	D	D	-	I	-	I	Medium	RR, SSA	-	R-15
R-39: Approaches for extreme mortality estimates	-	-	-	D	D	-	I	-	I	Medium	RR	Method development; limited data to model	Update data integration systems; R-30

Guidance on Use of Different Run Size Data Sets

Stock-specific postseason run size estimates for Fraser Sockeye were generated and made publicly available before guidelines for appropriate use were developed. Moreover, there is the added complication of co-existing with a similar set of stock-specific run sizes (and derivatives) generated based on in-season methods (Michielsens and Martens 2022). Failure to recognize the appropriate use of each data set could have unintended consequences regarding conclusions drawn about stock status, en route mortality, productivity and/or harvest impacts. Guidance and rationale for which specific run size estimates should be used in particular situations (e.g., productivity estimates vs. in-season management evaluations) were provided. Advice on the limits of the run size components and how best to interpret the derivatives of the process, such as productivity and exploitation rates, was also provided.

In general, postseason run size estimates should be used when historical time series of run sizes and run size components are of most interest (Table 3). This includes a postseason evaluation of exploitation rates and mortality for stock status assessments and recovery planning. However, if the primary intention is to evaluate in-season fisheries management performance, then Mission-based estimates of run sizes should be used. This would include potential simulations of the efficacy of alternative in-season management measures, such as window closures, that require daily reconstructions of abundance and catch.

Table 3. Overview of key differences and guidance on use between postseason runs sizes developed after the RSA process and Mission-based run size estimates generated immediately after the season (abridged version from Table 2 in Patterson et al. accepted).

-	Postseason run size	Mission-based run size
Derivation	Spawning escapement + Catch + En route mortality (plus bias adjustment for spawners and catch)	Mission abundance + seaward catch
Temporal resolution	Annual estimates	Annual estimates derived from daily abundance estimates
Stock resolution	28 RSA groups (most aligned with CUs and forecasted stocks)	52 Catch & Racial (C&R) groups
Availability	~6 months postseason	Immediately following the season with updates being made as more information become available
Recommended types of uses	Postseason evaluation Stock-recruitment forecasting Exploitation rate Productivity analyses En route mortality Assessments supporting long-term planning and management such as benchmarks, status evaluations, evaluations of stock rebuilding plans,	Post-season evaluations of in-season management Potential spawning escapements (PSEs) Interim run size before postseason values available Difference Between Estimates (DBEs) Daily migration timing, spread and diversion rate estimates Gear and area specific harvest rates Stock-specific fishery vulnerability assessments

Ecosystem Considerations

There has been an increase in the frequency and magnitude of reports of natural en route mortality of many Pacific salmon stocks (Patterson et al. 2016; Westley 2020). For many Fraser Sockeye stocks, annual estimates of en route mortality can often exceed catch and or spawning escapement values (e.g., Early Stuart; Figure 6). Therefore, the common practice of ignoring estimates of en route mortality, or assuming it to be negligible, as with other Pacific salmon (Branch and Hilborn 2010; Cunningham et al. 2018; Peacock et al. 2020; Atlas et al. 2023), is not a defensible position for assessments of Fraser Sockeye. However, there has also been an increased shift from multi stock to more single stock management; which has generally reduced catch contributions and increased spawning escapement estimates for Pacific salmon (Cunningham et al. 2018; Freshwater et al. 2020). Therefore, efforts have been undertaken to improve estimates of all components of run size to better reflect the current reality of lower catches, higher en route mortality, and more scrutiny on variable spawner escapement estimates. Many of the methods described to quantify en route mortality and associated recommendations to improve mortality estimates are in specific relation to Fraser Sockeye, however this work may help inform other salmon assessments that are dealing with similar challenges. In particular, en route mortality is likely to play a larger role in future salmon assessments with predicted changes in environmental migratory stressors (von Biela et al. 2020; Crozier and Siegel 2023). This work represents an uncommon example of using ecosystem information to help inform the potential role that environmentally driven en route mortality will have in future stock recovery and rebuilding efforts.

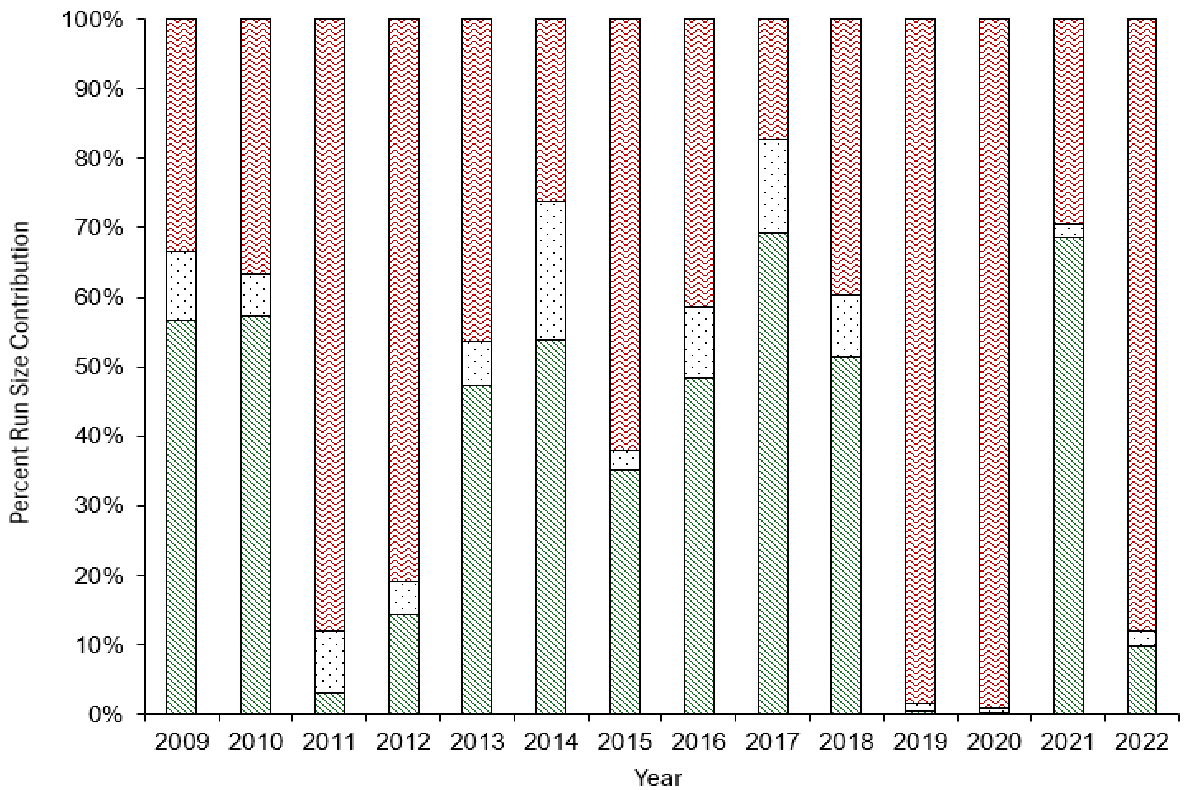

Figure 6. Spawning escapement (green diagonal stripe), catch (black dot), and en route mortality (red wave) contributions to Early Stuart Sockeye postseason run sizes from 2009 to 2022. Estimates of en route mortality often exceed spawning escapement and catch components, demonstrating the importance of annual en route mortality estimation. Data sourced from PSC RuFEs database.

Sources of Uncertainty

Sources of uncertainty are discussed in detail in both the postseason run size determination review and the recommendations for improvements table above (e.g., Table 1; Patterson et al. accepted). Key sources of uncertainty that were highlighted during the review process for each major area include:

- Spawning escapement – precision of spawning escapement estimates typically vary as a function of expected run size
- Catch – directed and non-directed interception coverage can change over time and space
- Mortality – there are very few independent estimates of mortality (e.g., telemetry)
- Small run sizes – are associated with a general increase in the uncertainty in all component values and require caution in interpretation of run size derivatives (e.g., exploitation rate)
- Run size process – adjustments to run size components are based in part on expert opinion, and therefore final values are not always reproducible with new or different expertise and knowledge regarding the stocks
- Climate change – increase variability in environmental conditions can impact the uncertainty of not only mortality models predicting outside their parameterized conditions, but also in estimates of spawning escapement and catch

CONCLUSIONS AND ADVICE

This Science Advisory Process provides background information on run size estimation and sensitivity to input uncertainty and reviews the current methods for postseason stock-specific run size determination. The current methods produce postseason estimates of stock and age-specific run size, spawning escapement, catch, and en route mortality through complex data analysis and integration across science and management bodies. This collaborative process is designed to scrutinize the uncertainty in all input components and account for climate change impacts in stock assessments for fisheries management by using ecosystem information to inform en route mortality estimates.

Guidance on the use of the data sets generated by this postseason run size process is also provided. The outputs from the current postseason approach are used in other science and management processes with varying objectives. It is recommended that these run size and component data sets are used for postseason stock-specific evaluations of run size, exploitation rates, and productivity, as well as in forecasting and long-term planning assessment. They should not be used for evaluations of in-season management or for evaluations requiring underlying daily estimates; the Mission-based run size estimates are currently suited to these objectives.

Numerous recommendations for improvements to the current stock-specific run size estimation process were provided through this process. A detailed list of recommendations to improve postseason run sizes was provided (Table 2). Meeting participants highlighted the recommendations below and refined the evaluation criteria used in Table 2 to inform prioritization of recommendations depending on user objectives.

- R-1: Simplify the overall post season run size structure
- R-4: Update the visual survey expansion factors
- R-8: Receive consistent and timely reporting of all catches

- R-13: Generate en route mortality estimates for all RSA stocks at annual review
- R-5, R-10, R-21: Quantify the uncertainty in stock and age-specific estimates of spawning escapement, catch, and en route mortality

The following considerations and advice for postseason run size determination were emphasized by participants of this peer review process:

- Final postseason run size estimates are typically presented as point estimates only, while the three main components – spawners, catch and en route mortality – include unquantified uncertainty which adds to the overall sensitivity of run size determination
- Large bias and imprecision of some stock-specific run size components and their derivatives require additional scrutiny for use (e.g., exploitation rates for small stocks)
- It is advisable to consider aggregation of assessment data for co-migrating stocks to reduce bias and imprecision of run size components and derivatives for small abundance stocks
- Quantifying and reducing the uncertainty in run size components will support credibility for downstream uses, including exploitation rate and productivity analyses, and for estimating the impact of en route mortality on stock recovery and rebuilding programs
- En route mortality can be higher than catch in some years; therefore, to rebuild stocks under current and future climate conditions, considerations beyond just harvest management are likely necessary
- Continued effort is needed to make improvements to methods for postseason run size determination to adapt to changing management and sciences uses
- Assessment of other Pacific salmon stocks should consider the work herein as a potential approach to deal with climate change impacts on changes in salmon mortality, harvest, and escapement patterns

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Centre for Science Advice (CSA)
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ISSN 1919-5087
ISBN 978-0-660-77126-7 Cat. No. Fs70-6/2025-021E-PDF

Correct Citation for this Publication:

DFO. 2025. Stock-Specific Fraser River Sockeye Salmon Run Size Determination. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2025/021.

Aussi disponible en français :

MPO. 2025. Détermination de la taille de la remonte propre au stock de saumon rouge du fleuve Fraser. Secr. can. des avis sci. du MPO. Avis sci. 2025/021.