# Overview of pre-season and inseason assessment methods for Fraser River sockeye salmon 

C.G.J. Michielsens
F.J. Martens, Editors

June 2022


## Pacific Salmon Commission Technical Report No. 49

The Pacific Salmon Commission is charged with the implementation of the Pacific Salmon Treaty, which was signed by Canada and the United States in 1985. The focus of the agreement are salmon stocks that originate in one country and are subject to interception by the other country. The objectives of the Treaty are to 1) conserve the five species of Pacific salmon to achieve optimum production, and 2) to divide the harvests so each country reaps the benefits of its investment in salmon management.

Technical Reports of the Pacific Salmon Commission present results of completed or ongoing investigations carried out by the Pacific Salmon Commission that are deemed of sufficient interest to be made available to the scientific community and the public.

The contents of these reports may be reprinted, and reference to the source will be appreciated.

> Pacific Salmon Commission
> $600-1155$ Robson Street
> Vancouver, B.C.V6E 1B5
> (604) 684-8081
> www.psc.org


## Data Disclaimer

The Pacific Salmon Commission (PSC) obtains data from a number of agencies. Values posted in this report are the most up to date at the time of publication. The user of this data assumes all responsibilities on its usage and for verifying the completeness and accuracy of this data for both critical and non-critical uses and applications. In no event will PSC be in any way held liable to the user or any third parties who use this data or any derivatives.

## Terms of Use

Use of any data, graphs, tables, maps or other products obtained through Pacific Salmon Commission (PSC), whether direct or indirect, must be fully acknowledged and/or cited. This includes, but is not limited to, all published, electronic or printed documents such as articles, publications, internal reports, external reports, research papers, memorandums, news reports, radio or print. Proper citation (subject to the documents' citing style) includes: "Pacific Salmon Commission (PSC) http://www.psc.org (month and year when data was retrieved)". If the document contains an acknowledgment section, then it must be noted that data was provided by the Pacific Salmon Commission, found at http://www.psc.org.

## Contact Information

Please email any inquiries to info@psc.org.

Correct citation for this report:
Michielsens, C.G.J. and Martens, F.J. Editors. 2022. Overview of pre-season and in-season assessment methods for Fraser River sockeye salmon. Pacific Salmon Comm. Tech. Rep. No. 49, 217 p.

Correct citation for individual chapters in this report, example:
Gill, J.A., Hague, M.J. and Phung, A. 2022. Run size forecast. In: Michielsens, C.G.J. and Martens, F.J. Editors. Overview of pre-season and in-season assessment methods for Fraser River sockeye salmon. Pacific Salmon Comm. Tech. Rep. No. 49, 9-16 p.

## Acknowledgements

This report would not have been possible without the support of Pacific Salmon Commission Secretariat staff, past and present. We would like to thank current Commission staff: Angela Phung, Benia Nowak, Catherine Ball, Christina Langlois, Dejan Brkic, Eric Taylor, Jacqueline Nelitz, Julie Sellars, Mark McMillan, Maxine Forrest, Merran Hague, Mike Bartel Sawatzky, Rachael Hornsby, Serena Wong, and Steve Latham, as well as staff that have left the PSC: Bruce White, Cory Lagasse, Jessica Gill, Erica Jenkins, Jim Cave, Jim Gable, Jim Woody, Keith Forrest, Ian Guthrie, Mike Lapointe, Pasan Samarasin, Yunbo Xie. We would also like to acknowledge Julie Ehrmantraut for collating this report, as well as special thanks to lan Guthrie for providing the photo for the cover page. And finally, thank you to the Fraser River Panel members who reviewed certain chapters of this report and provided helpful feedback.

## TABLE OF CONTENTS

Acknowledgements ..... 1
Introduction ..... 4
Assessment Overview of Fraser River Sockeye ..... 5
A. Preseason Management Information ..... 8
Pre-season Management Information
Run Size Forecast. ..... 9
Timing and Diversion Rate Forecasts ..... 17
Fraser River Sockeye Management Adjustments ..... 24
Pre-season Fraser River Sockeye Spawning Escapement Plan ..... 29
Test Fishing Catch Forecasts ..... 36
Assessment of Fisheries Plans
Planning Model - General Overview ..... 38
Planning Model Inputs ..... 44
Planning Model - Biological Assumptions ..... 51
Harvest Rate Parameterisation and Catch Dynamics ..... 57
B. In-Season Assessments ..... 65
Fisheries Information
PSC Test Fisheries ..... 66
Catch-per-unit-effort (CPUE) Calculations ..... 71
In-river Catchability Estimates ..... 75
Marine Catchability Estimates ..... 82
Biological Information
Sampling Protocol ..... 89
Length, Weight, and Sex ..... 94
In-Season Scale and Age Reading Methods ..... 99
Stock Composition Estimates Based on Scale Pattern Analyses ..... 103
DNA-based Stock ID Method ..... 109
Hydroacoustic Information
Daily Estimation of Salmon Passage at the Mission site ..... 116
Left Bank Salmon Passage Based on Shore-based Split-beam Sonar ..... 121
Flux Model for Fish Passage Based on Split-beam System ..... 126
Shore-based Imaging Sonar Systems ..... 131
Offshore Salmon Passage Based on Mobile Transecting Split-beam System ..... 135
Length-based Mixture Model for Imaging Sonars ..... 140
Daily Abundance Estimates
Species Information: Overview ..... 145
In-season Application of Stock ID Information ..... 151
In-season Marine Reconstructions ..... 155
Run Size Assessment
In-season Time-density Model ..... 160
In-season SMURF Model ..... 167
Gulf Troll-based Run Size ..... 173
Environmental Information
Management Adjustments ..... 179
EWatch Temperature and Discharge Forecasts ..... 185
DBE Temperature and Discharge Model ..... 191
DBE Run Timing Model and Upstream Migration Timing Model ..... 198
Fisheries Assessment
Total Allowable Catch (TAC) ..... 202
Glossary of Terms. ..... 207
Acronyms and Abbreviations ..... 215

## Introduction

Fraser River sockeye and pink salmon are managed according to Chapter 4 of the Pacific Salmon Treaty which has been in effect since 1985. Ensuring Treaty obligations are met and implementation is followed correctly entails gathering data and information for assessment purposes. This is done in support of Fraser River Panel management actions aimed at meeting objectives pertaining to (1) achieving spawning escapement targets, (2) meeting international catch allocation goals and (3) meeting domestic catch allocation objectives. As a result, data and information are collected throughout the year and analyzed from the perspective of pre-season planning, in-season management and post-season review. This technical report serves to document the pre-season and in-season assessment methods supporting Fraser River Panel management of Fraser River sockeye salmon.

This technical report is a compilation of short chapters that document different data collection and assessment methods for Fraser River sockeye salmon, with special reference to 2018 given the data collection and assessment methods are most comprehensive on this cycle line. Each chapter can potentially be used as a separate, stand-alone document or sub-report when wanting to provide others with information on the topic and are also accessible in this format to Fraser River Panel and Technical Committee members on the PSC SharePoint site or to others upon request. Each chapter/sub-report contains all the technical details required to understand, critique and replicate the methods. This includes among others an overview of the data and the methods used and planned changes or areas for improvement. To ensure the accessibility of the individual chapters and prevent readers from being overwhelmed by details, the individual chapters are restricted to about five pages. If the information on a topic is too lengthy, it is spread over several chapters, either by providing first a more general overview followed by one or more chapters that go into further detail (e.g., a chapter discussing the overall hydroacoustic program at Mission followed by several chapters of the different components of the hydroacoustic program), or by spreading one topic over several chapters (e.g., separate discussion of marine versus in-river catchability estimates). The use of individual chapters as sub-reports allows more flexibility in terms of adding additional documentation for new methods or revising documentation of existing methods instead of republishing an entirely updated technical report. It is anticipated that future published versions of this technical report will also incorporate post-season assessment methods as well as methods to assess Fraser River pink salmon.

This technical report aims to inform members of the Fraser River Panel and technical committee, academia and the general public about the different data collection and assessment methods for Fraser River sockeye salmon. This report does not aim to provide the results of these assessments, which can be found in the Fraser River Panel annual reports available on the PSC website (www.psc.org). Further questions regarding this technical report and its content can be directed to info@psc.org.

## Assessment Overview of Fraser River Sockeye

Annual pre-season planning of the fisheries management season for Fraser River sockeye starts by gathering the necessary inputs for the PSC Planning Model (Chapter A6), a simulation tool used by the Fraser River Panel to assess the ability of different fisheries plans to reach management targets given the information and forecasts available preseason (Chapter A7). Fisheries and Oceans (DFO) provides some of this information: run size forecasts for the different management groups (Chapter A1), marine timing and northern diversion rate forecasts (Chapter A2), and the spawning escapement plan (Chapter A4), while PSC Secretariat staff provide forecasts of test fishing catches (Chapter A5) and forecasted estimates of en route losses, i.e., differences between predicted and observed escapement estimates (DBEs, differences between estimates). The latter inform the Management Adjustment (MA, Chapter A3) which refers to the additional fish added to an escapement target to increase the likelihood of achieving that target. The Planning Model relies on a forward reconstruction with assumptions on fish movement and migration behaviour (Chapter A8) as well as assumptions about the vulnerability of sockeye to different fisheries operations (Chapter A9). The Planning Model helps create pre-season fisheries schedules and assesses the sensitivity of fishery plans and the achievement of management targets to alternative biological and management scenarios. This helps guide pre-season planning for stakeholders and informs early in-season management prior to the availability of updated in-season information.

In-season fisheries management relies on real time data of returning sockeye to adjust and refine preseason fisheries plans and helps guide fisheries management decisions. One of the key data sources in-season are the test fisheries (Chapter B1) that provide information on abundance, timing, and diversion rates as well as species and stock composition information for use in stock assessments. Test fishing occurs in marine approaches to the Fraser River (Johnstone Strait and Juan de Fuca Strait) and within the Fraser River. While purse seine and gillnets form the main gear types used for quantitative assessments, the PSC test fisheries also include troll/hook and line test fisheries to assess delaying sockeye in the Strait of Georgia, and reef net test fisheries. One key data set collected by these test fisheries is the catch-per-unit-effort (CPUE) data (Chapter B2), which is used to estimate daily sockeye abundances in the test fishing area. For marine test fisheries in Johnstone Strait and Juan de Fuca Strait, the CPUE data along with an expansion line estimate (the inverse of the catchability coefficient) are used to derive daily abundances (Chapter B4). At the start of the season, historical expansion line estimates are applied, derived from data from past years. Because abundances predicted this way may deviate substantially from the true abundance to the high variability in expansion lines, both between years and within a season, expansion lines are updated once sufficient in-season observations have been obtained. The abundance estimates based on marine CPUE data are considered early indicators of the expected in river abundance given that it takes sockeye approximately 6 to 8 days to migrate from marine areas to the Fraser River. In the Fraser River, daily sockeye abundance estimates are primarily based on hydroacoustic data collected at Mission (Chapter B10). If Mission hydroacoustic data are unavailable or unreliable to estimate sockeye abundance due to the dominance of other species, the CPUE data collected at the Whonnock test fishing site can be used in combination with in-river expansion lines (Chapter B3).

Fish caught by the test fisheries, and by commercial fisheries when they occur, are sampled on a regular basis to collect a range of biological information used for in-season assessments (Chapter B5). Biological information includes length, weight and sex information (Chapter B6). Length measurements can be used to supplement stock identification and they are used as inputs into hydroacoustic models to differentiate fish species. Weights are important for understanding fish condition and provide the fishing
industry with information on potential value of fishing opportunities. Biological samples also include DNA and scales that are collected in a procedural manner to ensure up-to-date stock identification data are available for each Panel meeting. Scale data (Chapter B7) provides information about fish age, growth rate and stock identification when DNA estimates are not (yet) available. For stock identification, scales are compared against scales of known stock origin using a linear discriminant analysis in combination with a principal component analysis (Chapter B8). The output from this model provides stock proportions for each sample and stock assignment probabilities for individual sockeye salmon. DNA-based stock identification (Chapter B9) is however the preferred method for identifying salmon stocks. DNA has been used by the PSC since 2002 and uses genetic profiles from fishery catches of unknown stock composition and compares this to a genetic baseline with known stock origin using a Bayesian statistical framework. The genetic identification of salmon stocks is essential for stock-specific reconstructions to assess the total run size and timing by management group (Early Stuart, Early Summer, Summer and Late run sockeye).

Another in-season assessment program operated by the PSC is a hydroacoustics program which provides daily estimates of salmon passage in the Fraser River throughout the summer (Chapter B10). Because of the large 400 m river width, a combination of four hydroacoustic systems are deployed to adequately monitor the salmon migration past the area. The left bank area, where most of the upstream migration typically occurs, is monitored by a stationary split-beam system (Chapter B11) and an ARIS imaging sonar (Chapter B13) deployed at the end of a fish deflection weir. The ARIS system collects more visually intuitive data but only covers the first 30 meters of the left bank while the split-beam system extends coverage by an additional 30m. The left bank ARIS system increases the accuracy of the left bank, especially during periods of high abundance when the split-beam system has been known to underestimate abundances. The nearshore right bank area is monitored using another ARIS imaging sonar, covers up to 30 meters and typically observes less than $20 \%$ of the daily upstream salmon migration. The remaining offshore region is monitored by a mobile, downward-looking split-beam system deployed from a sampling vessel that transects the river (Chapter B14). The information collected from the left-bank and mobile split-beam systems are input into a flux model to estimate fish passage (Chapter B12). These estimates are combined with the data collected by the shore-based imaging sonars to derive the daily salmon estimates. In addition to abundance information, the ARIS systems on both the left and right bank also provide estimates of salmon species composition using a mixture model based on acoustically observed fish lengths (Chapter B15).

The total salmon estimates when combined with species composition estimates provide daily sockeye abundance information. Several different data sources and methods exist to derive species composition (Chapter B16) and each has its own shortcomings depending on sample size and the number of species migrating in the river at that time. The daily sockeye abundance estimates can be further split up into abundance of the four different management groups through the application of stock proportion estimates derived from test fishing catch samples taken in the same area (Chapter B17). Stock proportion estimates are also applied to catch and CPUE data. The resulting stock-specific estimates of catch and escapement past Mission are then used in reconstructions (Chapter B18), applied both forwards and backwards. Forward reconstructions predict stock-specific escapement into the river based on marine daily abundances derived from stock-specific CPUE data from marine test fisheries combined with assumptions about migration speed and delay behaviour. Backward reconstructions add stock-specific daily estimates of marine and lower river catches to stock-specific daily escapement estimates to reconstruct the total daily abundance in marine areas. The resulting estimates are used to derive the total run size, marine migration timing and diversion rate.

Prior to all sockeye salmon passing by the riverine hydroacoustic site, in-season run size and timing estimates are obtained through the application of a Bayesian time-density model (Chapter B19) fit to CPUE data from marine gillnet and purse seine test fisheries in Johnstone Strait and Juan de Fuca Strait and reconstructed daily marine abundance estimates. For Harrison and Late run stocks that delay their upstream migration, only marine CPUE are used to assess the run, resulting in larger run size uncertainty in comparison to stocks that also rely on marine reconstructed data. Given the larger uncertainty associated with these Late-run run size estimates and the fact they make up a substantial portion of the total Fraser River sockeye run on the 2018 cycle line, two additional models are used on high abundance years. One of these assessments is referred to as SMURFing (Smolt Method for Updating Run-size Forecasts, Chapter B20) and relies on an in-season run size estimate for Early Thompson and relative smolt abundance estimates collected two years prior for Late Shuswap/Portage versus Early Thompson stocks to predict the run size for Late Shuswap/Portage. It assumes the same marine survival for Late Shuswap/Portage as for Early Thompson. While it does not provide the final in-season run size for Late run stocks, it does provide an early indicator if the run size is smaller or larger than the pre-season forecast. The other assessment method employed on large Late run years relies on CPUE data of a troll test fishery in the Strait of Georgia (Chapter B21) which helps estimate the number of Late run sockeye delaying their upstream migration into the Fraser River. Information collected from this test fishery provides an alternative run size estimate based on escapement into the Fraser River to date, estimated number of delaying fish and estimated abundance seaward of the troll test fishery. Both these assessment methods are only used on years with large Late-run abundances, i.e., Late Shuswap return years, and help with the in-season planning of potential fisheries.

An additional component the Fraser River Panel considers when planning fisheries are potential en route losses due to adverse migration conditions within the Fraser River. To increase the likelihood of achieving spawning escapement targets for the four management groups, the Panel uses Management Adjustments (MA, Chapter B22) which are the additional fish allocated to escape fisheries for the purpose of increasing the likelihood of achieving these targets. To select appropriate MA values, the Panel will take into account observed and predicted estimates of temperature and discharge within the Fraser River (Chapter B23) and other factors that can cause adverse migration conditions and differences between predicted and observed spawning ground estimates (DBEs, difference between estimates). In-season DBE predictions for Early Stuart, Early Summer and Summer run sockeye are also generated through a DBE temperature and discharge model (Chapter B24) where 19-day mean water temperature and discharge observations in the Fraser River are related to historical DBE data. Late run sockeye, excluding Birkenhead and Big Silver, traditionally delay their upstream migration. Early entry into the Fraser River since 1995 has however resulted in extended freshwater residence times, increased exposure to higher river temperature and discharge and increased mortality (Lapointe et al. 2003, Cooke et al. 2004). The DBE run timing model (Chapter B25) to predict the DBE for these stocks relates upstream migration timing to migration success, i.e., to DBE estimates. Early predictions of upstream migration timing in turn are based on the historic relationship between the proportion upstream migration to-date and upstream timing.
In-season fisheries opportunities are determined by the availability of International total allowable catch (TAC, Chapter B26). This is calculated as the Fraser River sockeye abundance available after the spawning escapement target (SET), the Management Adjustment (MA), the agreed Aboriginal Fisheries Exemption (AFE) and the expected catch in panel authorized test fisheries are deducted. If there is sockeye abundance available for harvest, the United States share will not exceed 16.5 percent of the sockeye TAC. The remaining TAC in addition to AFE catches are assigned to Canada.

## A.Preseason Planning

# A1. Run Size Forecast 

J.A. Gill, M.J. Hague, and A. Phung

## Summary

Fisheries and Oceans Canada (DFO) provides run size forecasts to the Pacific Salmon Commission (PSC) as part of their obligations under the Pacific Salmon Treaty (Chapter 4, Paragraph 4). Forecasted returns of Fraser River sockeye salmon (Oncorhynchus nerka) stocks based on historical stock-recruitment data are a key input into pre-season planning for fisheries. Prior to the start of the season, run size forecasts are used directly in calculations of management objectives (e.g. spawning escapement targets, total allowable catch, Chapter A4) and in simulations of alternative fishing scenarios (Chapter A6). These forecasts also play an important role in the early in-season management of Fraser River sockeye salmon, prior to the availability of updated estimates based on in-season information and are utilized throughout the fishing season as informative prior distributions for stock assessment models (Chapter B19).

Individual return forecasts are generated for 27 component stocks, and then aggregated into four management groups: Early Stuart, Early Summer, Summer and Late run. Run sizes are forecasted using traditional stock-recruit models (e.g. Ricker, Larkin) unless recruitment data are lacking, in which case average survival estimates from related stocks are relied upon (Cass et al. 2006). Selection of the model used to forecast a stock is based on a retrospective evaluation of the performance of the multiple models and subsequent ranking of the models based on various performance and selection criteria. Given the uncertainty in the modelled stock-recruit relationships, a Bayesian approach is used to generate posterior probability distributions of run size for the various component stocks. Sensitivity of management decisions to alternative run size scenarios can then be evaluated by drawing different quantiles from the posterior distributions.

## Introduction

Fisheries and Oceans Canada (DFO) provides run size forecasts prior to the fishing season to the Pacific Salmon Commission (PSC) as part of their obligations under the Pacific Salmon Treaty (PST 2020, Chapter 4). Individual return forecasts are generated for 27 component stocks, and then aggregated into four management groups: Early Stuart, Early Summer, Summer, and Late run. Despite the uncertainty associated with run size forecasts based on historical stock-recruitment data, the forecasted distributions of run size for different stocks and management groups of Fraser River sockeye play an important role in the pre-season planning and in-season assessments of stock size. Run size forecasts for Fraser River sockeye are a key input into DFO's Integrated Fisheries Management Plan, or IFMP (DFO 2018b). Key management objectives such as total allowable catch (TAC), spawning escapement targets (SET), management adjustments (MAs), low abundance exploitation rates (LAERs), and aboriginal fisheries exemptions (AFEs) are all directly influenced by the size of aggregate returns for each management group. In addition, the PSC utilizes both the run size forecasts and associated management inputs to evaluate the sensitivity of fishing plans and the probability of achieving management objectives across a range of run size scenarios using a fisheries simulation model. Prior to the availability
of in-season data which are used to refine estimates of run size and timing, early management decisions rely on the results of the pre-season simulations to evaluate catch proposals made by each country. Finally, while the Fraser River Panel typically adopts updated run sizes based on in-season stock assessments, the stock-specific forecasts and the mean and standard deviation (SD) of the probability distributions provided by DFO pre-season continue to be used as priors in Bayesian run size assessments.

## Data

Detailed descriptions of the data used to forecast Fraser River sockeye salmon run size can be found in Grant et al. (2010) and Cass et al. (2006). Time series of stock recruit data are currently available for 20 of the 27 forecasted stocks. The majority rely on spawning escapement and estimates of returns by age, while some also have historical time series of juvenile abundance in terms of fry or smolts (Grant et al. 2010, Table 1). Spawning escapement is usually quantified as the number of females contributing to the spawning population based on potential egg deposition (i.e., effective females spawners (EFS), Cass et al. 2006). The one exception is the Cultus Lake population where estimates of EFS are poorly determined; therefore, total adult escapement data are used instead (Cass et al. 2006). Stocks identified in the forecast as miscellaneous rely solely on historical timeseries of escapement data to generate the forecast given their lack of sufficient recruitment information (Table 1).

Most Fraser sockeye stocks are comprised of four year old salmon that entered the ocean at age 2 ( 42 sockeye) and five year old salmon that have spent an additional year in the ocean ( $5_{2}$ ). The total forecasted recruitment in a given year is therefore based on the sum of the estimated number of 4 and 5 -year-old recruits from different brood years. For Fraser River sockeye salmon, only the Harrison stock has a different age structure as they enter the ocean as one-year old smolts and the resulting recruitment forecast is comprised of forecasted estimates of 3 and 4 -year-old salmon ( $3_{1}$ and $4_{1}$ sockeye).

In addition to biological data, environmental covariates are used to improve the fit of traditional stockrecruit models. These variables include mean winter (November-March) indices from the Pacific Decadal Oscillation (PDO), mean spring-summer (April-July) sea surface temperatures collected at Entrance or Pine Island, and Fraser River peak and mean discharge from April to June measured in Hope (Grant et al. 2010).

## Methods

A wide range of different models are considered for the forecast (Tab) of Fraser River sockeye salmon run size. Detailed descriptions and model structures of the pre-season run size forecast models can be found in MacDonald and Grant (2012), Grant et al. (2010) and Cass et al. (2006). The complexity of the forecast models is dependent on data available for each stock. Non-biological models, which are also termed naïve models as they assume no underlying biological mechanism, calculate return forecasts based on historical estimates of returns or returns per effective female spawner or per juvenile (MacDonald and Grant 2012). These models rely on historical years or a subset of years or, in case data for a stock are missing (e.g., miscellaneous stocks), on historical data from other stocks are used as proxy (DFO 2018a).

Biological models are used when sufficient stock-specific spawner-recruitment data are available. Biological models are based on a relationship between spawning escapement or juvenile abundance and subsequent recruitment and include: 1) Ricker models (Ricker 1954); 2) power models; 3) Larkin models; 4) Kalman filter models; and 4) sibling models (MacDonald and Grant 2012). The Kalman filter models account for changes in productivity over time while the sibling models rely on the return of a younger
age class one year prior to predict returns of the older age class to account for shared productivity between siblings. The various biological models may also include environmental variables as covariates, which are especially of use when recruits encountered extreme environmental conditions during earlier parts of their life history. Uncertainty in parameter estimates and the resulting return size forecasts are quantified by estimating Bayesian posterior probability distributions using Markov Chain Monte Carlo (MCMC) simulations run through WinBUGS software (DFO 2015).
Both non-biological and biological models produce estimates of the total number of recruits, irrespective of the age and year in which they return to the Fraser River for spawning. To determine the total number of returning sockeye salmon in a given year, the recruitment forecasts need to be split up by age using age proportion estimates based on historical data. Age-specific recruitment is calculated by multiplying the total return forecast by historical age proportions (Appendix 3 in Grant et al. 2010, MacDonald and Grant 2012). In years of high expected proportions of age-five fish (or age-four fish for the Harrison stock), sibling models are used to forecast returns of the older age group based on the productivity calculated for their younger siblings that returned the previous year.

The selection of the model used to forecast a stock is based on a retrospective evaluation of the performance of the different models and subsequent model ranking based on various performance criteria. A jack-knife cross validation analysis is used to simulate forecasted time series of each stock and model based on historical data. In the jack-knife analysis, data are sequentially removed for the single year being forecast and the remaining stock-recruitment data are used to fit the model and generate a forecasted run size (MacDonald and Grant 2012). For each model, the resulting time series of forecasted run sizes are compared against historical observations through the calculation of a suite of model performance measures: 1) mean raw error (MRE), 2) mean absolute error (MAE), 3) mean proportional error (MPE), and 4) root mean square error (RMSE; Grant et al. 2010). For each stock, the relative performance across models is calculated by applying a rank (from best to worst) for each metric (Grant et al. 2010), and then averaging the ranks of individual model ranks across the performance metrics to generate a single performance index for each model (MacDonald and Grant 2012). In addition to the quantitative selection process, the forecast methodology also relies on a set of additional model selection criteria (MacDonald and Grant 2012, Hawkshaw et al. 2020). The results of the top ranked models are presented to a group of technical experts, who will review the model results for the individual stocks as well as the model selection criteria across stocks. These expert driven model selection criteria are adjusted annually as needed and reported in the forecast document (Hawkshaw et al. 2020).

## Results

Uncertainty in the forecast results is expressed in terms of a probability distribution which is described in the forecast document (i.e., DFO 2019) in terms the following percentiles: $10 \%, 25 \%, 50 \%, 75 \%$, and $90 \%$. The median forecast ( $50^{\text {th }}$ percentile, or p50) represents an equal chance (i.e., a one in two chance) that the return will fall above or below the forecast value for each stock (Grant et al. 2010, DFO 2018a; Table 3). In comparison, there is a one in four chance that the actual number of returning sockeye salmon will fall at or below the forecast associated with the $25^{\text {th }}$ percentile (p25 probability level). Within the current forecast methodology, the p50 forecast assumes long term average productivity will be maintained, the p 10 and p 25 forecasts assume below average productivity, while the p 75 and p 90 forecasts assume above average productivity (Grant et al. 2010).

Table 3 list the various forecasted stocks, the model used to generate that forecast, and percentiles that define the forecast. For example, the Weaver stock (Table 3) in the Late run management group was forecasted using a Ricker model with the PDO as an environmental covariate. At the $10 \%$ (p10)
probability level, there is a one in ten chance that the actual return will fall at or below 38,000 fish, while at the $90 \%$ (p90) probability level, there is a one in ten chance the actual return will be above 655,000.

## Planned Changes and Potential Areas for Improvement

As additional years of stock-recruit data become available, the performance of the pre-season run size models are subject to change. Sockeye returns in recent years have been well below the median forecast, which has resulted in overly optimistic pre-season plans and which points to a need to reevaluate model performance and/or adjust expectations for pre-season planning (DFO 2019). The positive bias in recent run size forecasts could be a result of many different factors, but DFO recommends a re-evaluation of the model performance given the lower than average productivity observed across most stocks in recent years (DFO 2019). The ability to relate changes in marine survival to environmental indices could also help improve forecasts (DFO 2019). A CSAS review of the forecast methodology has been planned for the near future.

In addition, advances in DNA technology, in combination with increased abundance of some stocks, has allowed the number of stocks for which spawner-recruitment are available to increase (e.g. Chilliwack). These advances allow for additional forecasting methods be used for these stocks, potentially lowering uncertainty associated with the forecast.

Finally, there has been some criticism of the simplified approach of summing total returns across individual forecasts by summing the probability levels. For example, the p25 forecast for all Fraser River sockeye stocks combined is currently based on the sum of the p25 forecast of the individual stocks. This approach assumes that stocks will all return at the same probability level (i.e., variation over time is fully correlated). A more statistically valid approach would be to incorporate the observed correlation in run size estimates between the component stocks (DFO 2019).

Table 1. Available data for each Fraser River sockeye salmon stocks included within the annual forecast (Grant et al. 2010, MacDonald and Grant 2012).

| Management Group | Name of forecasted stock | PSC Catch and Racial (C\&R) group name | Years of available data (by return year) | Additional data |
| :---: | :---: | :---: | :---: | :---: |
| Early Stuart | Early Stuart | Early Stuart | 1952-2015 | Fry (not used in forecast) |
| Early Summer | Bowron | Nadina/Bowron | 1952-2015 |  |
|  | Upper Barriere (Fennell) | North Barriere | 1971-2015 |  |
|  | Gates | Gates/Nahatlatch | 1972-2015 | Fry (not used in forecast) |
|  | Nadina | Nadina/Bowron | 1973-2015 | Fry |
|  | Pitt | Pitt/Alouette/Coquitlam | 1956-2015 |  |
|  | Scotch | Early South Thompson | 1984-2015 |  |
|  | Seymour | Early South Thompson | 1952-2015 |  |
|  | Misc (EShu) ${ }^{1}$ | Early South Thompson | 1952-2015 | Scotch/Seymour R/EFS used as proxy |
|  | Misc (Taseko) ${ }^{1}$ | Taseko | 1952-2015 | Chilko R/EFS used as proxy |
|  | Misc (Chilliwack) ${ }^{2}$ | Chilliwack | 1952-2015 | Early Summer-run stocks R/EFS used as proxy |
|  | Misc (Nahatlatch) ${ }^{1}$ | Gates/Nahatlatch | 1952-2015 | Early Summer-run stocks R/EFS used as proxy |
| Summer | Chilko | Chilko | 1952-2015 | Smolt |
|  | Late Stuart | Late Stuart | 1952-2015 |  |
|  | Quesnel | Horsefly/Mitchell | 1952-2015 | Fall Fry |
|  | Stellako | Stellako | 1952-2015 | Fry (not used in forecast) |
|  | Harrison | Harrison | 1952-2015 |  |
|  | Raft | Raft/North Thompson | 1952-2015 |  |
|  | Misc (N. Thomp. Tribs) ${ }^{1}$ | Raft/North Thompson | 1952-2015 | Raft and Fennel R/EFS used as proxy |
| Summer continued | Misc (N. Thomp. River) ${ }^{1}$ | Raft/North Thompson | 1952-2015 | Raft and Fennel R/EFS used as proxy |
|  | Misc (Widgeon) ${ }^{1}$ | Widgeon Slough | 1952-2015 | Birkenhead R/EFS used as proxy |
| Late | Cultus | Weaver/Cultus | 1952-2015 | Smolt |
|  | Late Shuswap | Late Shuswap/Portage | 1952-2015 | Fall Fry |
|  | Portage | Late Shuswap/Portage | 1957-2015 |  |
|  | Weaver | Weaver/Cultus | 1970-2015 | Fry |
|  | Birkenhead | Birkenhead/Big Silver | 1952-2015 |  |
|  | Misc <br> (Harrison/Lillooet) ${ }^{1}$ | Birkenhead/Big Silver | 1952-2015 | Birkenhead R/EFS used as proxy |

[^0]Table 2. List of candidate models organized by two categories (non-biological and biological) with descriptions. Adapted from Cass et al. (2006).

| MODEL ACRONYMN | MODEL DESCRIPTION |
| :---: | :---: |
| A. Non-biological Models |  |
| RS (used for miscellaneous stocks) | Product of average survival on time series for specified stocks and the forecast brood year EFS |
| RSC (or RJC) | Product of average cycle-line survival (entire time-series) and the forecast brood year EFS (or juvenile/smolt) |
| R1C | Return from 4 years before to forecast year |
| R2C | Average return from 4 and 8 years before the forecast year |
| RAC | Average return on the forecast cycle line for all years |
| TSA/TAC | Average return across all years |
| RS1 (or RJ1) | Product of average survival from 4 years before the forecast year and the forecast brood year EFS (or juvenile/smolt) |
| RS2 (or RJ2) | Product of average survival from 4 and 8 years before the forecast year and the forecast brood year EFS (or juvenile/smolt) |
| RS4yr (or RJ4yr) | Product of average survival from the last 4 consecutive years and the forecast brood year EFS (or juvenile/smolt) |
| RS8yr (or RJ8yr) | Product of average survival from the last consecutive 8 years and the forecast brood year EFS (or juvenile/smolt) |
| MRS (or MRJ) | Product of average survival for all years and the forecast brood year EFS (or juvenile/smolt) |
| B. Biological Models |  |
| Power | Power function combining all cycle lines |
| Power-cyc | Power function combining one cycle line |
| Ricker | Ricker function combining all cycle lines |
| Ricker-cyc | Ricker function combining one cycle line |
| Larkin | Larkin function combining all cycle lines |
| Kalman Filter Ricker | Ricker function with a Kalman filter on the Ricker $\alpha$ parameter combining all cycle lines |
| Smolt-jack | Considers both smolt abundance and the age-3 (jack) returns from the same brood year ${ }^{1}$ |
| Sibling model (4 year old) | Considers relationship between returning year classes, applying additional information from age-3 (jack) survival to forecast age-42 sockeye |
| Sibling model (5 year old) | Considers relationship between returning year classes, applying additional information from age $-4_{2}$ survival to forecast age- 5 2 sockeye |

Table 3. 2018 Fraser River sockeye forecasts. Forecasts are presented from their $10 \%$ to $90 \%$ probability levels. Adapted from DFO (2018a).

| Run Timing Group Stock | Forecast Model | Probability that Return will be at/or Below Specified Run Size |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | 10\% | 25\% | 50\% | 75\% | 90\% |
| Early Stuart | Ricker (Ei) ${ }^{+}$ | 37,000 | 54,000 | 84,000 | 133,000 | 199,000 |
| Early Summer |  | 584,000 | 1,102,000 | 2,155,000 | 3,765,000 | 6,587,000 |
| (total excluding miscellaneous) |  | 393,000 | 674,000 | 1,175,000 | 2,168,000 | 3,750,000 |
| Bowron | Ricker (Pi) ${ }^{+}$ | 7,000 | 12,000 | 20,000 | 35,000 | 59,000 |
| Upper Barriere (Fennell) | Power | 9,000 | 14,000 | 25,000 | 46,000 | 80,000 |
| Gates | Larkin | 11,000 | 20,000 | 38,000 | 76,000 | 149,000 |
| Nadina | MRJ | 45,000 | 81,000 | 153,000 | 291,000 | 518,000 |
| Pitt | Larkin | 22,000 | 32,000 | 53,000 | 84,000 | 130,000 |
| Scotch | Larkin | 89,000 | 166,000 | 330,000 | 750,000 | 1,513,000 |
| Seymour | RickerCyc | 210,000 | 349,000 | 556,000 | 886,000 | 1,301,000 |
| Misc (EShu)* | R/S | 186,000 | 416,000 | 956,000 | 1,546,000 | 2,736,000 |
| Misc (Taseko)* | R/S | - | - | - | 1,000 | 1,000 |
| Misc (Chilliwack)* | Ricker | 2,000 | 5,000 | 11,000 | 25,000 | 53,000 |
| Misc (Nahatlatch)* | R/S | 3,000 | 7,000 | 13,000 | 25,000 | 47,000 |
| Summer |  | 1,470,000 | 2,473,000 | 4,344,000 | 7,669,000 | 13,173,000 |
| (total excluding miscellaneous) |  | 1,442,000 | 2,417,000 | 4,250,000 | 7,473,000 | 12,778,000 |
| Chilko | 4-PowJuvPi; 5-Sib | 833,000 | 1,345,000 | 2,259,000 | 3,801,000 | 6,098,000 |
| Late Stuart | R1C | 55,000 | 88,000 | 149,000 | 251,000 | 401,000 |
| Quesnel ${ }^{1}$ | RickerEi ${ }^{+}$ | 292,000 | 573,000 | 1,148,000 | 2,223,000 | 4,152,000 |
| Stellako | Larkin | 229,000 | 347,000 | 559,000 | 895,000 | 1,454,000 |
| Harrison | 3-Ricker; 4-sibling | 13,000 | 33,000 | 87,000 | 225,000 | 548,000 |
| Raft | Ricker (PDO) ${ }^{+}$ | 20,000 | 31,000 | 48,000 | 78,000 | 125,000 |
| Misc (N. Thomp. Tribs)* | R/S | 2,000 | 4,000 | 7,000 | 15,000 | 31,000 |
| Misc (N. Thomp. River)* | R/S | 25,000 | 50,000 | 84,000 | 175,000 | 354,000 |
| Misc (Widgeon)* | R/S | 1,000 | 2,000 | 3,000 | 6,000 | 10,000 |
| Late |  | 3,174,000 | 4,794,000 | 7,398,000 | 11,370,000 | 16,934,000 |
| (total excluding miscellaneous) |  | 3,164,000 | 4,776,000 | 7,363,000 | 11,303,000 | 16,818,000 |
| Cultus | power (juv) (Pi) ${ }^{+}$ | 0 | 1,000 | 1,000 | 3,000 | 6,000 |
| Late Shuswap | RickerCyc | 3,045,000 | 4,548,000 | 6,923,000 | 10,415,000 | 15,091,000 |
| Portage | Larkin | 22,000 | 44,000 | 102,000 | 234,000 | 479,000 |
| Weaver | Ricker PDO ${ }^{+}$ | 38,000 | 78,000 | 150,000 | 318,000 | 655,000 |
| Birkenhead | Ricker (Ei) ${ }^{+}$ | 59,000 | 105,000 | 187,000 | 333,000 | 587,000 |
| Misc (Harrison/Lillooet)* | R/S | 10,000 | 18,000 | 35,000 | 67,000 | 116,000 |
| Total Sockeye Salmon |  | 5,265,000 | 8,423,000 | 13,981,000 | 22,937,000 | 36,893,000 |
| (total excluding miscellaneous) |  | 5,036,000 | 7,921,000 | 12,872,000 | 21,077,000 | 33,545,000 |

[^1]Ei : Entrance Island spring sea-surface temperature
Pi : Pine Island spring sea-surface temperature
PDO : Pacific Decadal Oscillation

## References

Cass, A., Folkes, M., Parken, C., and Wood, C. 2006. Pre-season run size forecasts for Fraser River sockeye for 2006. DFO Can. Sci. Advis. Sec. Res. Doc. 2006/060.

Hawkshaw, M., Xu, Y., and Davis, B. 2020. Pre-season Run Size Forecasts for Fraser River Sockeye (Oncorhynchus nerka) Salmon in 2020. Can. Tech. Rep. Fish. Aquat. Sci. 3392: vi +52 p.

DFO. 2015. Pre-season run size forecasts for Fraser River Sockeye (Oncorhynchus nerka) and Pink (Oncorhynchus gorbuscha) salmon in 2015. DFO Can. Sci. Advis. Sec. Sci. Resp. 2015/014.

DFO. 2018a. Pre-season run size forecasts for Fraser River Sockeye (Oncorhynchus nerka) salmon in 2018. DFO Can. Sci. Advis. Sec. Sci. Resp. 2018/034.

DFO. 2018b. 2018/2019 Salmon Integrated Fisheries Management Plan - Southern BC. Fisheries and Oceans Canada.

DFO. 2019. Pre-season run size forecasts for Fraser River Sockeye (Oncorhynchus nerka) and Pink (Oncorhynchus gorbuscha) salmon in 2019. DFO Can. Sci. Advis. Sec. Tech. Memo 2019.

Grant, S.C.H., Michielsens, C.G.J., Porszt, E.J., and Cass, A. 2010. Pre-season run size forecasts for Fraser River Sockeye salmon (Oncorhynchus nerka) in 2010. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/042.

MacDonald, B.L. and Grant, S.C.H. 2012. Pre-season run size forecasts for Fraser River Sockeye salmon (Oncorhynchus nerka) in 2012. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/011.

PST. 2020. Treaty between the government of Canada and the government of the United States of America concerning Pacific salmon as modified through January 2020.

Ricker, W.E. 1975. Computation and interpretation of biological statistics of fish populations. Fish. Res. Board. Can. Bull. 191.

Wood, C.C., and Parken, C.K. 2004. Forecasted status of Cultus and Sakinaw Sockeye salmon in 2004. DFO Can. Sci. Advis. Sec. Res. Doc. 2004/127.

# A2. Timing and Diversion Rate Forecasts 

J.A. Gill, M.J. Hague and A. Phung


#### Abstract

Summary Fisheries and Oceans Canada (DFO) provides the Pacific Salmon Commission with annual forecasts of the migration timing, and migration route around Vancouver Island in accordance with the Pacific Salmon Treaty. These forecasts are based on a series of different statistical models that include various environmental covariates. These models are evaluated retrospectively to assess the bias and precision of the forecast. The results of the top performing models are reduced to single forecasts by bootstrap sampling from the probability distributions of the different model forecasts. The uncertainty around the forecast is presented by reporting the $95 \%$ probability interval in addition to the median. The resulting preseason forecasts of timing and migration routes are important for pre-season expectations of abundance and planning of fisheries (Chapter A6) and serve as informative prior probability distribution inputs into the in-season stock assessment models (Chapter B19). DFO provides timing forecasts for Early Stuart and Chilko stocks, while diversion rates are produced for the aggregate Fraser River sockeye run. Work to increase the stock resolution of the timing and diversion rate forecasts is ongoing.


## Introduction

Fisheries and Oceans Canada (DFO) produces annual forecasts of the marine migration timing and migration route around Vancouver Island as part of their obligations under the Pacific Salmon Treaty (PSC 2019, Chapter 4, Folkes et al. 2018). Marine timing for Fraser River sockeye is defined as the date when $50 \%$ of a stock has passed through the marine areas on route to their natal freshwater stream for spawning (Folkes et al. 2017, Figure 1). It is common to use the DFO statistical area 20 (Area 20) in Juan de Fuca Strait as the reference location for the marine timing (Chapter B18). The Area 20 timing then refers to the date when $50 \%$ of a stock has passed Area 20 assuming the entire run migrated through Juan de Fuca Strait. The use of the Area 20 as a refence point for timing is largely due to the fact that IPFSC historically used catch data collected from the southern migration route to derive marine migration timing (Folkes et al. 2018). DFO only produces timing forecasts for the Early Stuart and Chilko stocks. PSC staff uses the correlations between timing estimates or the timing offsets between stocks to derive timing forecast of the other Fraser River sockeye stocks. The diversion rate refers the route an individual salmon might take to return to the Fraser River to spawn (Folkes et al. 2018). More specifically, the (northern) diversion rate indicates the proportion of the salmon that migrates through Johnstone Strait (northern approach) as opposed to Juan de Fuca Strait (southern approach, Figure 2). Estimates may reflect the diversion over a week or a few days or across the entire migration season. Diversion rates have traditionally been derived for the total Fraser River sockeye aggregate but could also be derived for individual stocks or management groups. The forecasts of timing and diversion rate can be combined with the pre-season run size forecasts and historical estimates of the length of the returning run (spread) to derive forecasts of daily abundances migrating through Juan de Fuca and Johnstone Strait.


Figure 1. Example of the method used to estimate marine timing, based on reconstructed abundance data. The marine timing is the date when the cumulative daily abundance exceeds $50 \%$ of the total abundance (horizontal dashed line) and is denoted by the vertical arrow (adapted from Folkes et al. 2018).


Figure 2. Southern B.C. coast map depicting the two routes taken by adult Fraser sockeye when returning to the Fraser River. The proportion of total run returning via the northern route is considered the diversion rate.

## Data

Annual estimates of marine migration timing for Early Stuart and Chilko are derived from post-season daily reconstruction abundances estimates (Chapter B18) based on daily hydroacoustic estimates obtained at Mission (Chapter B10) plus seaward catches. The timing is defined as the date when the cumulative abundance of these stock exceeds $50 \%$ of the total run size. Annual post-season estimates of northern diversion rate of the aggregate Fraser River sockeye population are estimated by dividing the total abundance migrating through the northern (Johnstone Strait) approach by the total abundance. (Folkes et al. 2018). Prior to 1995, estimates of diversion rate were based on commercial fishery catches along both migration routes (Folkes et al. 2018). Commercial catches of Fraser River sockeye started declining after 1995. Therefore, recent estimates of diversion are based on catch per unit effort (CPUE) data from test fisheries operating in Juan de Fuca and Johnstone Straits (Putman et al. 2014).

In addition to relying on historical estimates of migration timing and diversion rate, the methods to forecast these estimates also rely on environmental data that are assumed to impact timing and diversion. The full suite of environmental data used in Folkes et al. (2018) include three El Niño indices (Oceanic Niño Index (ONI), Southern Oscillation Index (SOI), and the Bivariate ENSO Timeseries (BEST)), Fraser River discharge, relative sea level, sea surface temperature (in the open ocean and near-shore), sea surface salinity, wind stress, ocean current velocity (from both the NEPSTAR (North East Pacific Salmon Tracking and Research) ocean model and the OSCAR (Ocean Surface Current Analysis Real-time) data series), and earth magnetic field estimates (intensity and inclination, Table 1).

Table 1. Environmental variables used as predictors of Fraser River sockeye salmon marine timing and northern diversion rate (adapted from Folkes et al. 2018).

| Forecast | Variable | Observed/ <br> Modelled | Description | Temporal Resolution | Time Period |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  <br> Diversion | Sea Surface Temperature (SST) | Observed | Shore station | Daily \& Monthly | 1987-2013 |
|  |  |  | NOAA OI SST V2 (interpolated from weekly to daily) | Daily \& Monthly | 1982-2013 |
|  | Sea Surface <br> Salinity (SSS) | Observed | Shore station | Daily \& Monthly | 1987-2013 |
|  | Surface Ocean Currents | Modelled | POM finite difference prognostic model configured with 29 vertical layers and forced by three-hourly oceanic winds and monthly temperature and salinity from the GODAS | Daily | 1983-2012 |
|  |  |  | OSCAR | Monthly | 1993-2013 |
|  | Surface Wind Stress | Modelled | NCEP and NCAR Reanalysis-1 | Daily | 1983-2012 |
|  | Sea Surface <br> Temperature <br> Anomallies (SSTA) | Modelled | Monthly values of the Pacific Decadal Ocillation (PDO) | Monthly | 1951-2013 |
| Diversion Only | River discharge | Observed | Sum of the monthly average Fraser river discharge at Hope, British Columbia, for April, May, and June | Monthly | 1953-2013 |
|  | Sea level | Observed | Mean sea level for February-June at Tofino, B.C. | Monthly | 1953-2013 |
|  | Geomagnetic field intensity | Modelled | Difference between estimate at the Fraser River mouth during April-May of smolt year and the estimates at either Queen Charlotte Strait or Juan de Fuca Strait during June of the return year | Monthly | 1952-2013 |
|  | Geomagnetic field inclination angle | Modelled | As for geomagnetic intensity | Monthly | 1952-2013 |

## Methods

A set of different models are used to produce the timing and diversion rate forecast (Table 2). These models range from naïve models that rely on historical data to linear regression models, generalized additive models (GAM) and shape constrained additive models (SCAM) that include environmental covariates (Table 1) at different levels of resolution (Folkes et al. 2017, Folkes et al. 2018). Using jackknife and retrospective analyses, models are ranked annually against five performance measures to determine their ability to provide precise and unbiased predictions: mean raw error, absolute mean raw error, absolute mean error, mean square error, root mean squared error. The models to derive the forecasts are selected based on user tolerance of model uncertainty (Folkes et al. 2018). The results of the various models are reduced to a single forecast by bootstrap sampling from the probability distributions of the different model forecasts. The uncertainty around the forecast is presented by reporting the $50 \%$ and $95 \%$ probability intervals in addition to the median.

Table 2. The statistical models used to forecast migration timing or diversion rate (from Folkes et al. 2018).

| Forecast | Model Type | Statistical Model |
| :--- | :--- | :--- |
| Timing or Diversion | Naive | Series mean |
| Timing or Diversion | Naive | Four year mean |
| Timing or Diversion | Naive | Eight year mean |
| Timing or Diversion | Naive | Series median |
| Timing or Diversion | Naive | Four year median |
| Timing or Diversion | Naive | Eight year median |
| Timing or Diversion | Naive | Like last year |
| Timing or Diversion | Fitted | Auto regressive integrated moving average (ARIMA) |
| Timing or Diversion | Fitted | Single variable linear regression |
| Timing or Diversion | Fitted | Single variable GAM |
| Timing or Diversion | Fitted | Single variable shape constrained generalized additive model (SCAM) |
| Timing or Diversion | Fitted | Nepstar MLR |
| Timing or Diversion | Fitted | non-Nepstar MLR |
| Diversion | Fitted | MLR (Wickett model) |

Forecasts in each year are dependent on the performance of individual models and the available data. From an assessment point of view, there are three time periods for which forecasts are required: preliminary planning in February and April, updated planning in June and in-season assessments in July and August. At the time of the preseason planning in February, the forecast of timing and diversion rates are usually based on naïve models that account for differences between cycle line years. Models that include environmental covariates are only used in June as environmental data collected closer to the season has a better ability to predict timing and diversion. In-season these forecasts will be used as informative prior probability distributions within the in-season stock assessment models.

DFO only produces timing estimates for Early Stuart and Chilko. PSC staff uses the correlations between timing estimates or the timing offsets between stocks to produce timing forecast for the remainder of the stock groups modelled preseason and in-season. The Retrospective Evaluation Framework (REF) tool was created to standardize how decisions on pre-season migration timing are made. The REF tool allows PSC staff to retrospectively evaluate methods to obtain migration timing estimates across different stocks and cycle lines.

## Results

Timing forecasts are provided by DFO for both Early Stuart and Chilko stocks. Table 3 is an example of these forecasts for Chilko (Folkes et al. 2019a). The table lists the seven models that ranked highest in terms of model performance: four were naïve models including two auto regressive integrated moving average (ARIMA) models and three were multivariate models with environmental covariates. The forecast models are described in terms of the year and month in which the environmental data was collected that they rely on to produce the forecast, e.g. March [3] of the previous year [-1] or June [6] of the current year [0]. For covariates that are model derived, the description will also include details of the data used such as northward current velocity [v], eastward current velocity [u] and wind stress [n]. The last row of the table contains the bootstrapping results that combines the forecasts from the different models. The forecast is presented in terms of the median and the 50 and $95 \%$ probability intervals (PI). In this example the median timing forecast for Chilko is August 10 and the $95 \%$ probability interval ranges from August 1 to August 19, meaning that there is a $5 \%$ chance the actual migration timing will fall outside this range. The table to describe the diversion rate forecast (Table 4) is similar to the timing forecast. In this case, one naïve model and six multivariate models were used to produce the forecast (Folkes et al. 2019b). When converting the annual Fraser River sockeye diversion rate forecast into daily estimates, it is important to take into account the general trend towards increased northern diversion as the season progresses (Figure 3).

Table 3. Chilko sockeye timing forecast. The columns Year Shift and Month indicate when the environmental data were collected in relation to the forecast year. The Data Type indicate the type of environmental data used within the forecast model. The final row is the bootstrap combination of the different forecasts (adapted from Folkes et al. 2018).

| Model | Year Shift | Month | Data Type | n | Lower 95 PI | Lower 50 PI | Median | Upper 50 PI | Upper 95 PI |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Naive3 |  |  |  |  | 04-Aug | 07-Aug | 09-Aug | 10-Aug | 13-Aug |
| Naive5 |  |  |  |  | 04-Aug | 09-Aug | 11-Aug | 14-Aug | 19-Aug |
| TimeSeriesArimaBC |  |  |  |  | 31-Jul | 07-Aug | 10-Aug | 14-Aug | 20-Aug |
| TimeSeriesArimaNoBC |  |  |  |  | $31-\mathrm{Jul}$ | 07-Aug | 10-Aug | 14-Aug | 20-Aug |
| nepstar2 | -1,0,-1 | 6,3,5 | truetemp,u,e | 31 | 29-Jul | 03-Aug | 05-Aug | 08-Aug | 12-Aug |
| nepstar1 | -1,0,-1 | 7,3,5 | truetemp,e,n | 31 | 04-Aug | 10-Aug | 13-Aug | 15-Aug | 21-Aug |
| nepstar8 | $-1,-1,0$ | 4,5,3 | $u, u, v$ | 31 | 03-Aug | 07-Aug | 10-Aug | 12-Aug | 17-Aug |
| bootstrap |  |  |  |  | 01-Aug | 07-Aug | 10-Aug | 13-Aug | 19-Aug |

Table 4. Fraser sockeye diversion model forecasts. The columns Year Shift and Month indicate when the environmental data were collected in relation to the forecast year. The Data Type indicate the type of environmental data used within the forecast model. The final row is the bootstrap combination of the different forecasts (adapted from Folkes et al. 2018).

| Model | Year Shift | Month | Data Type | n | Lower 95 PI | Lower 50 PI | Median | Upper 50 PI | Upper 95 PI |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| TS Exp Smooth |  |  |  |  | 0 | 0.43 | 0.66 | 0.9 | 1 |
| nepstar7 | -1,-1,0 | 6,1,1 | truetemp, $u, v$ | 35 | 0.36 | 0.58 | 0.69 | 0.79 | 1 |
| nepstar10 | -1,-1,0 | 1,4,1 | $u, u, v$ | 35 | 0.25 | 0.47 | 0.58 | 0.69 | 0.91 |
| nepstar1 | -1,-1,0 | 1,4,1 | $u, u, v$ | 35 | 0.24 | 0.46 | 0.56 | 0.67 | 0.89 |
| nepstar4 | -1,-1,0 | 7,1,1 | truetemp,u,v | 35 | 0.34 | 0.55 | 0.66 | 0.77 | 0.98 |
| nepstar6 | -1,-1,0 | 6,1,3 | truetemp,u,v | 35 | 0.55 | 0.74 | 0.84 | 0.94 | 1 |
| nepstar9 | -1,-1,0 | 7,1,3 | truetemp,u,v | 35 | 0.51 | 0.71 | 0.81 | 0.91 | 1 |
| bootstrap |  |  |  |  | 0.26 | 0.54 | 0.69 | 0.84 | 1 |



Figure 3. Pre-season forecasts of the annual northern diversion rate (DR) for Fraser River sockeye salmon (green dotted line), compared to in-season estimates of daily and annual rates.

## Planned Changes and Potential Areas for Improvement

Daily reconstructed abundance estimates are used to derive migration timing and diversion rate estimates. Historical reconstruction files however vary in stock-resolution, file structure, and data assumptions, leading to inconsistencies in stock specific timing and diversion rate estimates across years. Therefore, the historical reconstruction file system will be reworked with the aim to standardize file assumptions, increase the stock and spatial resolution of reconstructed abundances, and populate a run reconstruction database. Upon completion, it will be possible to query the resulting database to obtain improved yearly timing estimates at varying stock resolution as well as obtain annual and inseason diversion rate estimates at different stock resolution. The newly developed REF tool (Retrospective Evaluation Framework) will be used to analyze, validate and document differences in historical versus updated timing and diversion rate estimates.

## References

Folkes, M., Thompson, R., and Hourston, R. 2019a. Forecast of Chilko sockeye marine timing for 2019. DFO, Nanaimo.

Folkes, M., Thompson, R., and Hourston, R. 2019b. Forecast of Fraser sockeye diversion rate for 2019. DFO, Nanaimo.

Folkes, M.J.P, Thomson, R.E., and Hourston, R.A.S. 2017. Evaluating models to forecast salmon dynamics. NPAFC Doc. 1717. 11pp. Fisheries and Oceans Canada, Pacific Biological Station, and Fisheries and Oceans Canada, Institute of Ocean Sciences.

Folkes, M.J.P, Thomson, R.E., and Hourston, R.A.S. 2018. Evaluating models to forecast return timing and diversion rate of Fraser sockeye salmon. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/021.

PST. 2020. Treaty between the government of Canada and the government of the United States of America concerning Pacific salmon as modified through January 2020.

Putman, N.F., Jenkins, E.S., Michielsens, C.G.J. and Noakes, D.L.G. 2014. Geomagnetic imprinting predicts spatio-temporal variation in homing migration of pink and sockeye salmon. J. R. Soc. Interface 11: 20140542.

Wickett, W.P. 1977. Relationship of coastal oceanographic factors to the migration of Fraser River sockeye salmon (Oncorhynchus nerka W.). ICES CM M: 26: 18.

# A3. Fraser River Sockeye Management Adjustments 

M.R. Forrest and M.J. Hague


#### Abstract

Summary The Management Adjustment (MA) refers to the additional fish added to an escapement target to increase the likelihood of achieving that target and takes into account en route loss and other factors that cause differences between predicted and observed escapement estimates (DBEs, differences between estimates). Early pre-season planning relies on historic DBE data to forecast DBEs while immediately prior to the season in June, statistical models are used to predict DBEs. For Early Stuart, Early Summer and Summer-run sockeye, statistical models use forecasted Fraser River temperature at Qualark, B.C. and Fraser River discharge at Hope, B.C. fit to a historical timeseries of escapement discrepancies to generate pre-season DBE predictions. For Late-run the statistical model is fit to upstream timing (the $50 \%$ date at Mission) to generate the pre-season predictions of DBEs. Despite the associated uncertainty, preseason DBE forecasts provide managers with an early indication of the expected discrepancy between the potential spawning escapement (PSE) and the spawning escapement (SE). This facilitates a more informed decision-making process and allows the Fraser Panel to be proactive in adopting MA estimates in response to adverse environmental conditions and adjust the fishing pressure to increase the probability of achieving spawning escapement targets.


## Introduction

Under the Pacific Salmon Treaty, the Fraser River Panel has the discretion to add additional fish to the spawning escapement target (SET) set by Canada for Fraser River sockeye salmon (O. nerka) to ensure spawning requirements are met (PST, Article IV, Chapter 4, Paragraph 3b). The additional fish added to the escapement targets for the different management units of Fraser River sockeye are termed the Management Adjustments (MAs) and they are used for the purpose of increasing the likelihood of achieving the SET. The idea is that extra fish are allowed to escape upriver of Mission to account for anticipated negative differences between in-season versus post-season estimates of spawning escapement caused by en route mortality due to poor environmental conditions during upstream migration, such as high discharge levels and warmer water temperatures. The differences between inseason and post-season estimates can however also stem from biases in the in-season and post-season assessments and the resulting catch and spawner estimates. In this case, the resulting bias can both be positive or negative.

For pre-season planning, it is important to make accurate assumptions about the Management Adjustment to ensure the SETs are met. Practically, this means managers must predict the likely difference between estimates (DBE). Depending on the available data, either historical data or statistical models are used to predict DBEs. Prior to June, managers use median values from the historical dataset for each management group. In June, when long-range forecasts of temperature and discharge are available, the DBEs are predicted using statistical models that relate historical DBEs to environmental river conditions. These models are similar to the in-season DBE models that rely on shorter range temperature and discharge forecasts. Historically, when discharge levels or temperatures are above average, DBEs also tend to be high. In addition, for Early Stuart and Early Summer runs, in-season estimates are consistently higher than spawning ground estimates even when migration conditions are within normal ranges, and this tendency is also captured by the DBE models. For Late-run sockeye,
historical DBEs are related to the date when half the run has migrated past Mission (i.e., Mission 50\% date), which captures the negative impact of the early migration behaviour observed since the mid1990s on the migration success of these stocks (Lapointe et al. 2003, Cooke et al. 2004).

## Data

The in-season and post-season spawning escapement estimates, the $50 \%$ migration dates at Hells Gate and Mission and the temperature and discharge at Hells Gate are the primary biological data used to predict DBEs. These are used as inputs in the statistical models (Chapter B24). Hells Gate is used as the geographic reference point to describe Fraser River environmental conditions because it is a well-known impediment to successful upstream salmon migration.

The DBE data are derived from the historical differences between in-season projections of spawning escapement (i.e., Mission escapement minus catch above Mission, or "potential spawning escapement, PSE") and post-season estimates (i.e., spawning ground estimates, "spawning escapement, SE").

The 50\% Hells Gate date for Early Stuart, Early Summer and Summer run are used to determine the mean temperature and discharge experienced by the management group across 31 days. The 50\% date at Mission for Late run is used in the DBE run timing model (Chapter B25). The 50\% migration date at Hells Gate or Mission for the different management groups is the date at which $50 \%$ of that group has passed these locations in the Fraser River. The Hells Gate and Mission dates are derived from marine migration timing estimates in statistical Area 20, Juan de Fuca Strait (Chapter A2). The travel time from Area 20 to Mission is assumed to be 6 days for Early Stuart, Early Summer and Summer run sockeye. The Late run sockeye travel time to Mission depends on their delay before up-stream migration but is assumed to be 8 days when travelling without delay. The travel time from Mission to Hells Gate is assumed to be 5 days for the Early Stuart, Summer and Late run sockeye and only 4 days for the Early Summer run sockeye.

Pre-season, the long-range forecasts for temperature and discharge are provided to PSC staff by Fisheries and Oceans (DFO) Environmental Watch Program (Patterson et al. 2007, Chapter B23). In combination with predicted migration timing forecast, the daily estimates of the long-range forecast allow to create 31-day mean Fraser River temperature forecasts at Qualark, B.C. and 31-day mean Fraser River discharge forecasts at Hope, B.C. (Morrison 2005, Morrison et al. 2005, Hague et al. 2014). These long-range forecasts are provided by the DFO Environmental Watch Program in June in the form of 10,000 paired predictions of Fraser River discharge and temperature that capture the uncertainty associated with these forecasts. In addition to the long-range forecast, the pre-season DBE models also use historical Fraser River temperature and discharge estimates. The DFO Environmental Watch group maintains a database of these data and an updated copy of historical observed Fraser River temperature at Qualark and discharge at Hope are provided to the PSC annually.

## Methods

## PREDICTIONS USING MEDIAN VALUES

Pre-season planning begins in early February. At this time, reliable long-range environmental forecasts are not yet available and early pre-season MAs are therefore based on median values of historical datasets. Median values are calculated by using the time series of $\operatorname{In}(P S E / S E)$ data. This median is then converted to a pMA (proportional MA) using the following equation:
(1) $\quad p M A=\left[\exp \left(\frac{P S E}{S E}\right)-1\right]$

The pMA is converted to the official pDBE (proportional DBE, rounded to two decimal places) using the following equation:
(2) $\quad p D B E=\left[\frac{1}{(1+p M A)}-1\right]$

For some management groups, like Early Stuart and Summer run, there have been no substantial differences detected between the pDBEs of different cycle lines. Therefore, the median pDBE has been based on all historical years. The pDBEs for Early Summer-run and Late-run groups often vary depending on the cycle line. For example, in Dominant or Subdominant Early South Thompson years, pDBEs may differ substantially from the pDBEs on off-cycle years, indicating that the response of this group to negative environmental conditions differs depending on their abundance. Therefore, the Early Summerrun dataset might be reduced to only Dominant or Dominant and Subdominant years when calculating the median pDBE for those years. Similarly, the datasets can also be reduced to odd pink years or cycle line years if pDBEs on those years differ from other years. However, this significantly reduces the number of data points used to calculate the median.

## MODEL PREDICTIONS USING LONG TERM ENVIRONMENTAL FORECASTS

In June, pDBE predictions are based on statistical DBE models using long-range forecasts of river conditions in combination with in-river migration timing predictions to produce current year forecasts. For Early Stuart, Early Summer and Summer-run sockeye, these models are regression models relating freshwater conditions defined by temperature ( $T$ ) and discharge ( Q ) to differences between estimates (MacDonald et al. 2010). The forecasted 31-day mean T and Q centered around the 50\% date at Hells Gate is used as a model input to forecast the DBE for the current year. These DBE timing and discharge models are run separately for each management group and are based on each group's 50\% date at Hell's Gate. The 31-day model captures $90 \%$ or more of a run's exposure to environmental conditions at Hell's Gate and provides a better fit to the historical DBE data than environmental data averaged over a shorter time-period (Hague et al. 2007).

For Late-run sockeye the statistical model is a regression model that relates early upstream migration to differences between estimates. The DBE run-timing model prediction is based on a pre-season prediction of upstream timing, which is dependent on the number of days the salmon delay in the Strait of Georgia. The estimate of delay is based on historical delay patterns for the different cycle lines. Due to the uncertainty in the upstream timing estimate, the Panel is often presented with a range of DBE predictions using multiple upstream timing dates before and after the current estimate. In recent years, the Panel has agreed to use the adopted pre-season median unless in-season timing is later than a specific date. The date is determined by the date at which the DBE prediction from the run-timing model using all years is lower than the adopted median DBE.

## Results

In February, management considerations for the upcoming season are presented to the Panel. The preliminary pDBE estimates for consideration by the Fraser River Panel at this time are based on the median pDBEs. These very preliminary pDBEs are used by PSC staff to seed the planning model and by DFO in the preliminary escapement plan. In April the preliminary pDBEs are reviewed again with possible changes depending on updated information and Fraser River Panel guidance. The resulting pMAs are then used for all of the April planning model work. In June, the DFO Environmental Watch group provides the pre-season long-range forecasts of temperature and discharge and PSC staff use the environmental models to forecast the pDBE for Early Stuart, Early Summer run and Summer run sockeye. The Panel may choose to adopt (if either party accepts) or not adopt (if both parties reject) the
recommended pDBEs or may choose a different value as they see fit (by bilateral agreement). The adopted pMA is then used in the pre-season planning model for in-season fisheries management until the Panel adopts an in-season pMA.

## Planned Changes and Potential Areas for Improvement

There is quite a lot of uncertainty associated with the PDBE forecast estimates as well as the long-range preseason temperature and discharge forecast estimates used as inputs into the model. This has caused some reluctance from the part of the Fraser River Panel to adopt preseason DBEs based long-range environmental forecasts. Instead the Panel has often preferred to rely on historical data when preseason planning.

The current T \& Q models predict a DBE for each management group but do not incorporate group specific information despite known differences in tolerances to adverse migration conditions (Eliason et al. 2011).

MAs are only of relevance if there is a potential for a harvestable surplus. In years when preseason run size estimates are too low for a harvestable surplus, management adjustments have no management consequences and are therefore not adopted by the Fraser River Panel.

## References

Cooke, S.J., Hinch, S.G., Farrell, A.P., Lapointe, M.F., Jones, S.R.M., Macdonald, J.S., Patterson, D.A., Healey, M.C. and Van Der Kraak, G. (2004). Abnormal migration timing and high en route mortality of sockeye salmon in the Fraser River, British Columbia. Fisheries 29(2): 22-33.

Eliason, E. J., Clark, T.D., Hague, M.J., Hanson, L.M., Gallagher, Z.S., Jeffries, K.M., Gale, M.K., Patterson, D.A., Hinch, S. G., and Farrell, A.P. (2011) Differences in thermal tolerance among Sockeye Salmon populations. Science 332:109-112.

Hague, M.J. and Patterson, D.A. (2014). Evaluation of Statistical River Temperature Forecast Models for Fisheries Management, North American Journal of Fisheries Management, 34:1, 132-146.

Lapointe, M.F., Cooke, S.J., Hinch, S.G., Farrell, A.P., Jones, S., Macdonald, S., Patterson, D., Healey, M.C., and Van Der Kraak, G. (2003). Late-run sockeye salmon in the Fraser River, British Columbia are experiencing early upstream migration and unusually high rates of mortality: what is going on? In Proceedings of the 2003 Georgia Basin/Puget Sound Research Conference. pp. 1-14.

MacDonald, J.S., Patterson, D.A., Hague, M.J., and Guthrie, I.C. (2010). Modeling the Influence of Environmental Factors on Spawning Migration Mortality for sockeye salmon fisheries management in the Fraser River, British Columbia. Transactions of the American Fisheries Society. 139:768-782.

Morrison, J. (2005). Fraser River Temperature and Discharge Forecasting: 2004 Review. Canadian Technical Report of Fisheries and Aquatic Science 2594.

Morrison, J. and Foreman, M.G.G (2005). Forecasting Fraser River flows and temperatures during upstream salmon migration. Journal of Environmental Engineering and Science, 4: 101-111.

Patterson, D.A., Hague, M.J. 2007. Evaluation of Long Range Summer Forecasts of Lower Fraser River Discharge and Temperature Conditions. Can. Tech. Rep. Fish. Aquat. Sc. 2754: vii + 34 p.

R Core Team (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

# A4. Pre-season Fraser River Sockeye Spawning Escapement Plan 

C.G.J. Michielsens

## Summary

Fisheries and Oceans Canada (DFO) provides pre-season escapement plans to the Pacific Salmon Commission (PSC) as part of their obligations under the Pacific Salmon Treaty (Chapter 4, Paragraph 4). Long-term escapement strategies for Fraser River sockeye stocks are derived through the FRSSI (Fraser River Sockeye Spawning Initiative) process and vetted through domestic consultation. The simulation model used as part of the process evaluates the performance of different control rules and assesses their robustness to different sources of uncertainty such as assumptions about population dynamics and future patterns of productivity. The resulting escapement plan is defined in terms of a TAM (Total Allowable Mortality) rule that accounts for both fishing and natural mortality due to adverse environmental conditions en route to the spawning grounds. The TAM rules for the different management groups are defined by Lower and Upper Fishery Reference Points, TAM caps and Low Abundance Exploitation rates (LAERs). The use of TAM rules as part of the escapement plan results in dynamic escapement goals that are updated repeatedly in-season based on updated information on run size and adopted Management Adjustments (MAs). The resulting TAC (Total Allowable Catch) is calculated as the aggregated Fraser River sockeye abundance available after the escapement target, the Management Adjustment, the agreed Fraser River Aboriginal Exemption and the expected catch in Panel-authorized test fisheries are deducted from the pre-season run size forecasts.

## Introduction

As part of Fisheries and Oceans Canada (DFO) obligations under the Pacific Salmon Treaty (PST 2020, Chapter 4), escapement targets are provided to the Pacific Salmon Commission (PSC) prior to the fishing season. These spawning escapement targets are defined through an escapement plan that takes into account the run size as well as adverse environmental conditions that could reduce the probability of reaching those targets. The latter is achieved by increasing the escapement by adding fish to the target in the form of a Management Adjustment (MA, MacDonald et al. 2010). The escapement plan has been derived though the Fraser River Sockeye Spawning Initiative (FRSSI), a multi-year collaborative planning process by DFO to develop a long-term escapement strategy (Pestal et al. 2008). The simulation model that is part of the FRSSI process allows for the evaluation of the performance of different escapement strategies through the application of different harvest control rules. In addition, it explores the robustness of these strategies to different key sources of uncertainty such as possible alternative population dynamics and future patterns of productivity. The use of a harvest control rule as part of the escapement plan result in dynamic escapement goals that are updated repeatedly during the fishing season from updated information on run size and in-season environmental conditions (Pestal et al. 2012).

## Data

The simulation model used within the FRSSI process is populated using the stock-recruitment data for 19 distinct Fraser River sockeye stocks that, on average, make up $98.6 \%$ of the total sockeye run for the Fraser River (Pestal et al. 2007). These data are also used for the forecast and are described in detail in Grant et al. (2010). The majority of the stocks rely on spawning escapement and estimates of returns by age, while some stocks also have historical time series of juvenile abundance in terms of fry or smolts (Grant et al. 2010).

## Methods

The simulation model developed as part of the FRSSI process aims to evaluate the long-term performance of different harvest control rules under a wide range of alternative biological assumptions and hypothesized future states of nature (Chaput et al. 2013). The model includes 19 different stocks, grouped into 4 management units (Early Stuart, Early Summer run, Summer run and Late run). The abundance of the stocks is simulated into the future based on historical stock-recruitment relationships. The simulation models differ depending on the assumptions they make on the population dynamics of the stocks, which includes different assumptions about stock-recruit relationships and interactions between cycle lines, different future trends in productivity and natural mortality. Within the simulations, the different population dynamic scenarios are used to evaluate specific escapement strategies for the different management groups based on a control rule. The outputs from the model simulations are used to track the status of each individual stock.

For Fraser River sockeye salmon, the ability to reach escapement goals is not only impacted by fisheries but also by mortality caused by adverse environmental conditions. The control rule for Fraser River sockeye is therefore formulated in terms of a TAM (Total Allowable Mortality) rule (Figure 1) and accounts both for fishing and natural mortality. The TAM rule is defined by a Lower Fishery Reference Point, an Upper Fishery Reference Point, a TAM cap and a Low Abundance Exploitation rate (LAER). When the in-season run size is below the Lower Fishery Reference Point, no directed fisheries are allowed; only incidental harvest, directed at co-migrating stocks, is permitted. This incidental harvest needs to remain well below the Low Abundance Exploitation rate. In case the in-season run-size estimate is above the Upper Fishery Reference Point, the Total Allowable Mortality (TAM) rate remains fixed at the TAM cap. The projected MA is subtracted from the TAM to calculate the final allowable ER calculation (DFO 2018). Between the Lower and Upper Fishery Reference Points, a fixed escapement target, equal to the Lower Fishery Reference Point, is assumed. The different components of the TAM rule are derived through the simulation modelling and the FRSSI process and vetted through domestic consultation (Chaput et al. 2013). The pre-season TAC (Total Allowable Catch) is derived using the TAM rule and calculated as the aggregated Fraser River sockeye abundance available after the escapement target, the management adjustment, the agreed Fraser River Aboriginal Exemption and the expected catch in Panel-authorized test fishing catch are deducted from the pre-season run size forecast.


Figure 1. Graphical presentation of the Total Allowable Mortality rule for Fraser River sockeye salmon (DFO 2018). The Lower Fishery Reference Point is here represented as the No-Fishing Point while the Upper Reference Point is represented as the Cut-back Point. The Low Abundance Exploitation Rate (LAER) is applied after the TAM rule and is not shown in the figure.

## Results

The FRSSI process results in the creation of a pre-season spawning escapement plan (Table 1). The top table of Table 1 describes the TAM rule: the low abundance exploitation rate (LAER), the TAM Cap, the Lower and the upper Fishery Reference Points and the pre-season pMA at the p50 level Fraser River sockeye forecast. The subsequent tables illustrate the application of the TAM rule for different run size forecast levels for each of the four management groups. More specifically, at the different forecast levels, the table will provide the \% TAM implied by the forecast level (TAM rule (\%)), the number of fish added to the escapement target based on the assumed pMA (Escapement Target MA), the sum of the escapement target and the MA, the low abundance exploitation rate, and the available exploitation rate given the run size, escapement target and MA. If the run size is smaller than the escapement target plus MA, the available exploitation rate is $0 \%$. If the available exploitation rate exceeds the LAER, the allowable exploitation rate will equal the available rate. If the available exploitation rate is lower than the LAER, the allowable exploitation rate will equal the LAER but it should be emphasized that a LAER is not a target but allows for by-catch of a management group in fisheries directed at other management
groups or species with available surpluses. Table 1 also translates the allowable exploitation rate into the number of sockeye available to be harvested. In order to translate this into a TAC (Total allowable catch) for the aggregate management groups, the Aboriginal Fisheries Exemption (AFE) and test fishing catches need to be removed. Subsequent information in the table illustrates the performance of the TAM rule in terms of the resulting escapement when perfectly executed and assuming the pre-season MA forecast is correct. More specifically, it calculates the number of spawners that are predicted to reach the spawning grounds while taking into account en route loss and compares these numbers against the numbers observed in the brood year (BY spawners) and on average on the cycle, both in absolute numbers as well as in percentage.

Table 1. Spawning escapement plan for Fraser River sockeye salmon in 2018, provided to the Panel by Fisheries and Oceans Canada and based on Fraser River Sockeye Spawning Initiative (FRSSI) guidelines with input from domestic consultations.

| Management Unit | Harvest Rule Parameters |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | Low Abundance ER (LAER) | TAM Cap | Lower Fishery Reference Point | Upper Fishery Reference Point | Pre-season pMA @p50 |
| Early Stuart | 10\% | 60\% | 108,000 | 270,000 | 0.69 |
| Early Summer (w/o misc) | 20\% | 60\% | 180,000 | 450,000 | 0.23 |
| Summer (w/o misc) | 20\% | 60\% | 1,020,000 | 2,550,000 | 0.10 |
| Late (w/o misc) | 20-30\% | 60\% | 1,100,000 | 2,750,000 | 0.43 |


| Management |  | Pre-season Forecast Return |  |  |  | p90 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Unit |  | p10 | p25 | p50 | p75 |  |
| Early Stuart | forecast | 37,000 | 54,000 | 84,000 | 133,000 | 199,000 |
|  | TAM Rule (\%) | 0\% | 0\% | 0\% | 19\% | 46\% |
|  | Escapement Target | 37,000 | 54,000 | 84,000 | 108,000 | 108,000 |
|  | MA | 25,500 | 37,300 | 58,000 | 74,500 | 74,500 |
|  | Esc. Target + MA | 62,500 | 91,300 | 142,000 | 182,500 | 182,500 |
|  | LAER | 10\% | 10\% | 10\% | 10\% | 10\% |
|  | Available ER at Return | 0\% | 0\% | 0\% | 0\% | 8\% |
|  | Allowable ER | 10\% | 10\% | 10\% | 10\% | 10\% |
|  | Allowable Harvest | 3,700 | 5,400 | 8,400 | 13,300 | 19,900 |
| 2018 Performance |  |  |  |  |  |  |
|  | Projected S (after MA) | 19,600 | 28,700 | 44,600 | 70,600 | 105,700 |
|  | BY Spawners | 68,613 | 68,613 | 68,613 | 68,613 | 68,613 |
|  | Proj. S as \% BY S | 29\% | 42\% | 65\% | 103\% | 154\% |
|  | cycle avg S | 33,275 | 33,275 | 33,275 | 33,275 | 33,275 |
|  | Proj. S as \% cycle S | 59\% | 86\% | 134\% | 212\% | 318\% |


| ManagementUnit | Pre-season Forecast Return |  |  |  | p90 |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | p10 | p25 | p50 | p75 |  |
| Early Summe lower ref. pt. (w misc) | 267,500 | 294,300 | 330,100 | 312,600 | 316,200 |
| (w/o RNT) upper ref. pt. (w misc) | 668,700 | 735,800 | 825,300 | 781,500 | 790,400 |
| forecast (incl. misc) | 584,000 | 1,102,000 | 2,155,000 | 3,765,000 | 6,587,000 |
| TAM Rule (\%) | 54\% | 60\% | 60\% | 60\% | 60\% |
| Escapement Target | 267,500 | 440,800 | 862,000 | 1,506,000 | 2,634,800 |
| MA | 61,500 | 101,400 | 198,300 | 346,400 | 606,000 |
| Esc. Target + MA | 329,000 | 542,200 | 1,060,300 | 1,852,400 | 3,240,800 |
| LAER | 20\% | 20\% | 20\% | 20\% | 20\% |
| Available ER at Return | 44\% | 51\% | 51\% | 51\% | 51\% |
| Allowable ER | 44\% | 51\% | 51\% | 51\% | 51\% |
| Allowable Harvest | 255,000 | 559,800 | 1,094,700 | 1,912,600 | 3,346,200 |
| 2018 Performance |  |  |  |  |  |
| Projected S (after MA) | 266,500 | 439,200 | 858,800 | 1,500,400 | 2,625,000 |
| BY Spawners | 647,784 | 647,784 | 647,784 | 647,784 | 647,784 |
| Proj. S as \% BY S | 41\% | 68\% | 133\% | 232\% | 405\% |
| cycle avg $S$ | 330,355 | 330,355 | 330,355 | 330,355 | 330,355 |
| Proj. S as \% cycle S | 81\% | 133\% | 260\% | 454\% | 795\% |

Table 1, continued.

| Management Unit | Pre-season Forecast Return |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | p10 | p25 | p50 | p75 | p90 |
| Summer lower ref.pt. (w misc) | 1,064,300 | 1,064,300 | 1,064,300 | 1,064,300 | 1,064,300 |
| (w. RNT \& Ha upper ref. pt. (w misc) | 2,660,900 | 2,660,900 | 2,660,900 | 2,660,900 | 2,660,900 |
| forecast | 1,470,000 | 2,473,000 | 4,344,000 | 7,669,000 | 13,173,000 |
| TAM Rule (\%) | 28\% | 57\% | 60\% | 60\% | 60\% |
| Escapement Target | 1,064,300 | 1,064,300 | 1,737,600 | 3,067,600 | 5,269,200 |
| MA | 106,400 | 106,400 | 173,800 | 306,800 | 526,900 |
| Esc. Target + MA | 1,170,700 | 1,170,700 | 1,911,400 | 3,374,400 | 5,796,100 |
| LAER | 20\% | 20\% | 20\% | 20\% | 20\% |
| Available ER at Return | 20\% | 53\% | 56\% | 56\% | 56\% |
| Allowable ER | 20\% | 53\% | 56\% | 56\% | 56\% |
| Allowable Harvest | 299,300 | 1,302,300 | 2,432,600 | 4,294,600 | 7,376,900 |
| 2018 Performance |  |  |  |  |  |
| Projected S (after MA) | 1,065,300 | 1,065,300 | 1,739,400 | 3,070,700 | 5,274,500 |
| BY Spawners | 2,837,275 | 2,837,275 | 2,837,275 | 2,837,275 | 2,837,275 |
| Proj. S as \% BY S | 38\% | 38\% | 61\% | 108\% | 186\% |
| cycle avg S | 815,485 | 815,485 | 815,485 | 815,485 | 815,485 |
| Proj. S as \% cycle S | 131\% | 131\% | 213\% | 377\% | 647\% |
| Management Unit | Pre-season Forecast Return |  |  |  |  |
|  | p10 | p25 | p50 | p75 | p90 |
| Late lower ref.pt. (w misc) | 1,105,200 | 1,105,200 | 1,105,200 | 1,105,200 | 1,105,200 |
| (w/o Har) upper ref. pt. (w misc) | 2,763,100 | 2,763,100 | 2,763,100 | 2,763,100 | 2,763,100 |
| forecast | 3,174,000 | 4,794,000 | 7,398,000 | 11,370,000 | 16,934,000 |
| TAM Rule (\%) | 60\% | 60\% | 60\% | 60\% | 60\% |
| Escapement Target | 1,269,600 | 1,917,600 | 2,959,200 | 4,548,000 | 6,773,600 |
| MA | 545,900 | 824,600 | 1,272,500 | 1,955,600 | 2,912,600 |
| Esc. Target + MA | 1,815,500 | 2,742,200 | 4,231,700 | 6,503,600 | 9,686,200 |
| LAER | 20\% | 20\% | 20\% | 30\% | 30\% |
| Available ER at Return | 43\% | 43\% | 43\% | 43\% | 43\% |
| Allowable ER | 43\% | 43\% | 43\% | 43\% | 43\% |
| Allowable Harvest | 1,358,500 | 2,051,800 | 3,166,300 | 4,866,400 | 7,247,800 |
| 2018 Performance |  |  |  |  |  |
| Projected S (after MA) | 1,270,900 | 1,919,500 | 2,962,200 | 4,552,500 | 6,780,300 |
| BY Spawners | 2,303,384 | 2,303,384 | 2,303,384 | 2,303,384 | 2,303,384 |
| Proj. S as \% BY S | 55\% | 83\% | 129\% | 198\% | 294\% |
| cycle avg S | 2,652,186 | 2,652,186 | 2,652,186 | 2,652,186 | 2,652,186 |
| Proj. S as \% cycle S | 48\% | 72\% | 112\% | 172\% | 256\% |
| Allowable Harvest (TF, US, CDN) | 1,916,500 | 3,919,300 | 6,702,000 | 11,086,900 | 17,990,800 |
| Total projected spawners | 2,622,300 | 3,452,700 | 5,605,000 | 9,194,200 | 14,785,500 |

## Planned Changes and Potential Areas for Improvement

The impact of changes in productivity have been quantitatively included in the simulation model scenarios to derive the TAM rules. Due to concerns about the potential impacts of increased variability and observed trends in productivity that accompanies climate change, DFO is currently reviewing the robustness of the current and alternative harvest control rules. This is occurring within the FRSSI model by testing the TAM rules against alternative future productivity patterns to identify TAM rules that produce undesirable outcomes. DFO is targeting the incorporation of productivity changes in the evaluation of the harvest control rules in time for the 2022 Fraser River sockeye season.

Even though the simulation model used to derive escapement plans evaluates the impact of different TAM rules on individual stocks, the in-season implementation aims to ensure escapement targets are reached for each management group, not for each stock. Currently the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) has assessed 8 stocks as endangered (Early Stuart, Bowron, Taseko, Late Stuart, Quesnel, Portage, Weaver, Cultus) and 2 as threatened (North Barriere, Widgeon, (COSEWIC 2017).

## References

Chaput, G., Cass, A., Grant, S., Huang, A.-M., and Veinott, G. 2013. Considerations for defining reference points for semelparous species, with emphasis on anadromous salmonid species including iteroparous salmonids. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/146. v + 48 p.

COSEWIC. 2017. COSEWIC assessment and status report on the Sockeye Salmon Oncorhynchus nerka, 24 Designatable Units in the Fraser River Drainage Basin, in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. xli + 179 pp.

DFO. 2018. 2018/2019 Salmon Integrated Fisheries Management Plan - Southern BC. Fisheries and Oceans Canada.

Grant, S.C.H., Michielsens, C.G.J., Porszt, E.J., and Cass, A. 2010. Pre-season run size forecasts for Fraser River Sockeye salmon (Oncorhynchus nerka) in 2010. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/042.

MacDonald, J.S., Patterson, D.A., Hague, M.J., and Guthrie, I.C. (2010). Modeling the Influence of Environmental Factors on Spawning Migration Mortality for sockeye salmon fisheries management in the Fraser River, British Columbia. Transactions of the American Fisheries Society. 139:768-782

Pestal, G., Huang, A-M., Cass, A. and the FRSSI Working Group. 2012. Updated Methods for Assessing Harvest Rules for Fraser River Sockeye Salmon (Oncorhynchus nerka). DFO Can. Sci. Advis. Sec. Res. Doc. 2011/133. viii + 175 p.

Pestal, G., Ryall, P., and Cass, A. 2008. Collaborative Development of Escapement Strategies for Fraser River Sockeye: Summary Report 2003 - 2008. Can. Man. Rep. Fish. Aquat. Sci. 2855: viii + 84 p.

PST. 2020. Treaty between the government of Canada and the government of the United States of America concerning Pacific salmon as modified through January 2020.

# A5. Test Fishing Catch Forecasts 

## E. Taylor

Test fishing plans are developed pre-season by the Fraser River Panel with the objective to inform decisions of the Panel while minimizing negative implications for conservation and for other fisheries, i.e., minimizing the number of fish retained. Because test fishing catch are accounted for prior to allocating Total Allowable Catch (TAC, Chapter B26), they have a direct impact on potential harvest opportunities. Pre-season forecasts of test fishing catches are therefore important for planning and as inputs into the Fishery Planning Model (FPM, Chapter A6). They are also important to determine the financial outlook of test fishing operations. While test fishing catches are not limited to Fraser River sockeye salmon, the test fishing deduction to the TAC is an estimate of the total retained Fraser River sockeye catch from all Panel-approved test fisheries. This deduction is made up of two components: fish that are unavoidably killed when conducting test fishing operations or the fish required for biological samples (nondiscretionary catch) and additional fish retained by the test fishery to offset test fishing costs (discretionary catch, also referred to as pay fish). Forecast of non-discretionary catches are based on test fishing catches on previous cycle line years, adjusted to account for differences in run size while discretionary catch forecasts are dependent on assumed average weight and price. Pay fish however are only retained when agreed to by the Fraser River Panel and following specific conditions as set out by the PSC Test Fishing Policy (2021).

## Introduction

The Pacific Salmon Commission (PSC), or its predecessor the International Pacific Salmon Fisheries Commission, has operated test fisheries to obtain data required to inform bilateral decisions of the Fraser River Panel since the 1960s. These test fisheries implemented under the Pacific Salmon Treaty are essential for the Fraser River Panel to fulfil its responsibilities in terms of ensuring conservation objectives are met through appropriate in-season harvest management and catch allocation. Test fishing catch refers to the number of salmon caught and retained in Panel-approved test fisheries. The test fishing catch is comprised of non-discretionary and discretionary catch. Non-discretionary catch refers to the fish that are unavoidably killed when conducting test fishing operations. This catch includes all salmon caught by gill nets and those required for biological samples. Discretionary catches refer to the retention of additional salmon by the marine purse seine or reef net test fisheries to offset the costs of the test fishing program. Discretionary catch is often referred to as Pay Fish. Guidelines for the retention of test fishing catches and pay fish are described in the PSC Test Fishing Policy (2021).

Predicting test fishing catches is an important component of the pre-season planning process as reliable predictions of test fishing catches and associated revenue are important to plan for potential financial surplus or deficit scenarios. In addition, test fishing catch forecasts are also important to predict Total Allowable Catch (TAC) which is derived by deducting the agreed Fraser River Aboriginal Exemption and the predicted catch in Panel-authorized test fisheries from the harvestable surplus (Chapter A4). Test fishing catches are therefore also termed test fishing deductions when discussing TAC calculations (Chapter B26). Test fishing catch forecasts are generated several years ahead based on past catches on the same cycle years and are updated annually based on preseason run size estimates, generated before the start of the fishing season. In-season, these forecasts are replaced with actual catch observations.

## Data

Predictions of non-discretionary test fishing catches are based on historical catch data of all test fisheries combined, while weight and price information are used to predict the catch needed to cover the cost of the test fishing program.

## Methods

For non-discretionary catch, a multi-year retrospective analysis indicated that there is a strong correlation between the non-discretionary catch and historical catches over the previous three cycle years. Preseason, prior to a preseason run size forecast being available, the average of the three cycle years are used to forecast test fishing catches. Once a run size forecast is available, this estimate is used to scale the test fishing catches of the historical years by dividing the total test fishing catches by the total run sizes and calculating the non-discretionary test fishing harvest rates. These historical harvest rates, used in combination with the run size forecast, allow to predict non-discretionary test fishing catches.

When discretionary catch is authorized, it is normally with the intention of achieving cost-neutrality and therefore discretionary catch predictions are based on the number of salmon needed to pay for the test fishing program minus non-discretionary catches. The forecast of the discretionary catch is dependant on the assumed average weight and price of the salmon. Under certain conditions, additional discretionary salmon could be caught beyond the salmon needed to pay for the test fishing program in the current year with the aim to supplement the test fishing revolving fund and offset future test fishing costs. These conditions include extremely high salmon abundances and/or the ability of either country to harvest their full TAC (PSC 2021).

When test fishing catch forecasts are used as deductions in the TAC calculations, they need to be allocated to individual management groups, i.e., Early Stuart, Early Summer, Summer and Late run. For non-discretionary catches, this is achieved by multiplying the total catch forecast with the average proportion by management group as observed on the three most recent cycle years. For discretionary catches, the management group-specific estimates are obtained by multiplying the total discretionary catch estimates with the proportions of each management group within the predicted harvestable surplus for the current year.

## Planned Changes and Potential Areas for Improvement

Overall, the use of 3-year cycle line averages to predict non-discretionary and discretionary catches has been a simple and effective method and there are no changes planned to the current estimation methodology. As run sizes have declined in recent years, there has been increased attention paid to the test fishing catches as a deduction to the harvestable surplus as it determines the available TAC to be shared by Canada and the U.S. In some years, when the distribution of test fishing catch across management groups has differed substantially from the distribution based on the run size forecast, the method has been adjusted slightly to only rely on past years with similar distributions across management groups.

## References

Pacific Salmon Commission Test Fishing Policy. Feb. 10, 2021. Pacific Salmon Commission.

# A6. Planning Model - General Overview 

## M.J. Hague

## Summary

Pre-season, the Fraser River Panel uses a fisheries simulation model developed by PSC staff, hereafter referred to as the PSC Planning Model, to develop preliminary fishing plans, to identify potential limitations in achieving management objectives, and to explore the effect of uncertain biological and management inputs on proposed fisheries. The goal of these plans is to create a fisheries schedule which meets Panel objectives under key pre-season assumptions. The PSC Planning Model is a simulation tool primarily used to assess sensitivity of fisheries plans and achievement of management targets under alternative biological (e.g. run size, diversion rate) and/or management (e.g. total allowable mortality rules) scenarios. Model results are used to guide pre-season planning for stakeholders and to inform early in-season management decisions prior to the availability of updated in-season run size information (Chapter B19). This report describes the general process used to populate, run and evaluate the PSC Planning Model. Detailed descriptions of model inputs and the technical implementation of the model structure are described in the companion Chapters A7-A9.

## Introduction

Pursuant to Article IV, Chapter 4, Paragraph 9d, of the Pacific Salmon Treaty, the Fraser River Technical Committee (FRTC) and Pacific Salmon Commission (PSC) staff work jointly to develop fisheries and management plans for Fraser River sockeye salmon prior to the start of each fishing season using the PSC Planning Model. The goal of these plans is to create a provisional fisheries schedule which meets Panel objectives (PST, Article IV, Chapter 4, paragraph 10) under key pre-season assumptions. Historically, pre-season fishing plans for Fraser River sockeye salmon were based on management experiences in previous years, but as the variability in biological forecasts and the complexity of the management regimes increased, managers realised the need for a more rigorous and structured planning tool (Cave and Gazey 1994). The first version of the PSC Planning Model was created by Rod Cooke and Jim Cave (IPSFC, predecessor of the PSC) in 1984, and was used extensively beginning in 1985 (final year of the IPSFC) (J. Cave, personal communication). These models were developed in early spreadsheet software and were restricted in size and complexity due to the computer processing limitations of the day. Early run reconstruction models (Starr and Hilborn 1988) influenced later updates to the Planning Model structure and harvest rate parameterisation (Cave and Gazey 1994) and the model was re-coded in Excel in 1997 (J. Cave, personal communication).

Over time, the model has been adapted and updated to reflect changes to fishery structure and to address requests from the FRP and FRTC. Some of these changes include controls for individual transferable quota (ITQ) fisheries in Canada, separate accounting for Fisheries Induced Mortalities (FIMs), tracking of both discretionary (i.e. pay fish) and non-discretionary test fishing catch, changes in assignment of stocks to management groups, Management Adjustment (MA) deductions, inclusion of Low Abundance Exploitation Rates (LAERs), changes to the relevance of different fisheries and refinements to underlying biological assumptions. While the spreadsheet model continued to meet most pre-season management objectives, the structural framework restricted flexibility and was prone to errors during the revision process.

In 2011, the FRTC and FRP agreed to restructure the PSC Planning Model in R statistical software (R Core Team 2013) which could handle the increased complexity required to explicitly model many of the model assumptions. Over the next several years, PSC staff worked with Panel and Technical Committee members to develop the current Planning Model which is controlled by a Graphical User Interface (GUI) developed using the RShiny package (Shiny (rstudio.com)). The R model has improved the transparency of underlying model assumptions and has increased the flexibility and ease with which the modellers can make changes to fisheries and stock structure.

## Data

The PSC Planning Model relies on three different types of data inputs: biological, fisheries, and management. A more thorough description of the key inputs in the Planning Model is provided in Chapter A7, but they are also briefly described here. The biological inputs define the abundance of the expected salmon return, i.e. the run size forecast, and how these salmon are distributed in space and time. The latter is defined by the timing of the run, the number of days it takes for $95 \%$ of the run to migrate through an area (i.e., the spread), the proportion of the total run migrating through Johnstone Strait (i.e. the diversion rate), the proportion of the run that delays their upstream migration into the Fraser River and the number of days of delay. Within the Planning Model, stocks are grouped for modelling purposes based on similarities in migratory patterns (12 modelling groups) but are aggregated by management group (Early Stuart, Early Summer, Summer, Late-run, and Fraser pinks) for reporting and evaluation purposes.

The fisheries inputs relate to the anticipated amount of fishing effort or resulting catch, how that effort or catch will be distributed across the salmon season and if catches will be retained or released. In the case of test fishing catches, fisheries input also includes predicted non-discretionary catches as well as discretionary catches and the schedule when these discretionary catches will be taken to pay for the test fishing program, i.e. taken as pay fish (Chapter A5).

The management inputs differ by management group and are defined by the various components of the Spawning Escapement Plan (Chapter A4): the Spawning Escapement Target (SET), the Management Adjustment (MA) (Chapter A3), the Test Fishing Deduction (Chapter A5), the Aboriginal Fisheries Exemption (AFE) and the Low Abundance Exploitation Rate (LAER). In addition, the PSC Planning Model also requires inputs regarding the allocation of the Total Allowable Catch (TAC, Chapter B26) across the various fisheries, both internationally as well as nationally.

Model inputs are either based on medians derived from historical time series, generated by forecast models run outside of the Planning Model structure, or based on the expert judgment from within the FRTC and FRP. Because several forecast models to produce biological inputs require covariate data and these are only available immediately prior to the season, Planning Model inputs in early spring rely primarily on medians derived from historical time series (Chapter A7). Depending on the source of the data, inputs are either updated annually, multiple times annually, or as additional information becomes available. There are two key parameterisation timeframes: the first occurs in the early spring when most inputs are typically calculated from historical timeseries, and the second occurs in late spring once more covariates for forecast models become available. The updating of management and fisheries inputs typically follows the same schedule as for the biological parameters of the model. February inputs are based on historical observations, run size forecasts, and preliminary escapement plans and are typically finalised during the June meeting once the Canadian Minister of Fisheries has approved Canada's annual Integrated Fisheries Management Plan (IFMP, DFO 2018).

Under the Pacific Salmon Treaty (Article IV, Chapter 4, Paragraphs 3 and 4), Canada is responsible for producing run-size specific estimates of SETs, LAERs, and AFEs. In addition, the technical chairs provide
information relating to anticipated fishing effort levels, fishing schedules for their respective countries, and domestic catch allocations for their respective countries. Secretariat staff provide advice on preseason estimates of management adjustments, although final adoption is left to the discretion of the Panel (Chapter A3), as well as test fishery deductions and the test fishing schedule (Chapter A5). More detailed descriptions of the PSC Planning Model inputs, including responsibilities, is provided in Chapter A7.

## Model

The PSC Planning Model assumes a daily time step with salmon moving in groups (box-cars) through a series of gauntlet-style mixed gear and mixed stock fisheries (Cave and Gazey 1996). Spatially, the model covers fishing areas in both Johnstone Strait and Juan de Fuca Strait, starting with DFO statistical Areas 12 and 20 and extending into the upper mainstem of the Fraser River, DFO statistical Area 29. Daily abundances in the most seaward areas are defined by the stock group specific forecast estimates of run size, timing and spread in addition to the diversion rate. Daily "blocks" of salmon are then moved through the different fishing areas and exposed to a sequential series of fisheries (Figures 1 and 2 in Chapter A8). The different fisheries are modelled through the application of harvest rates equations. The abundance of fish exposed to a given fishery is controlled by underlying specifications of migration rate and the length of a fishing area. For example, fish that migrate through an area over the course of several days may also be exposed to multiple days of fishing. Alternatively, this means that more than one daily migratory block of fish would be exposed to a single fishery opening in a large fishing area, or in an area in which fish are assumed to delay or slow down their migration.

Using the PSC Planning Model, the FRTC annually explores alternative fishery scenarios to optimise the achievement of Pacific Salmon Treaty objectives (achievement of SETs and international as well as domestic catch allocations) under various biological and/or management assumptions. This is done during the bilateral FRTC meetings in April and June. User-inputs allow FRTC chairs to evaluate different fishing schedules and assumed different harvest efficiencies to optimise outputs and balance conservation, fishery, and domestic objectives. Biological and/or management inputs are varied across scenarios to assess the sensitivity of fishing plans to changes in underlying assumptions. PSC staff provide the necessary modelling and administrative support when running the PSC Planning Model prior to presenting results to the Fraser River Panel for further discussion.

The current PSC Planning Model runs on a joint MS Excel and R (R Core Team 2013) operating platform. Excel interfaces are used for entering baseline data inputs and summarising key model outputs. The main simulation framework is coded in the statistical software $R$ and controlled by users through an RShiny GUI.

## Results

The PSC Planning Model summarises the results of the models in a series of tables collating fisheryspecific and management related statistics (e.g. Tables 1 and 2). The FRTC chairs use these outputs to refine preseason fishing plans and to communicate results of final model runs to the Fraser River Panel. At the end of the June meeting, a Panel-approved "Base Case" model is adopted which can be referenced in-season to help guide decision making for early fisheries. The alternative model runs allow FRP and FRTC members to evaluate the sensitivity of that base case plans to different assumptions. Model results are communicated at various levels of resolution so that fishing plans can be evaluated in terms of meeting international (e.g. escapement targets and TAC) as well as domestic (e.g. appropriate allocation of or distribution of fishery opportunities) objectives. In addition, model results may be used during the domestic consultation process to help communicate anticipated fishery plans.

Table 1. Example PSC Planning Model TAC summary from 2021 based on the $90^{\text {th }}$ percentile of the pre-season sockeye run size forecast, and the median run size forecast for pink salmon.
p90 Sockeye \& p50 Pink Salmon


Table 2. Example of a catch summary table from 2021 pre-season planning, corresponding to the TAC table in Table 1.

| ALLOCATION SUMMM |  |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Sockeye |  |  |  |  |  |  |
|  | TARGET CATCH | TOTAL CATCH | TARGET \% | MODELLED \% | LANDED CATCH | FIMS |
| U.S. | 284,700 | 282,400 |  |  | 281,000 | 1,400 |
| TREATY INDIAN ALL CITIZEN | 192,500 92,100 | 201,200 | $\begin{aligned} & 67.7 \% \\ & 32.3 \% \end{aligned}$ | $71.2 \%$ $28.8 \%$ | $\begin{array}{r} 201,200 \\ 79,800 \end{array}$ | 1,400 |
| CANADA | 1,842,900 | 1,291,904 |  |  | 1,289,700 | 2,300 |
| COMMERCIAL | 773,000 | 209,400 |  |  | 207,100 | 2,300 |
| AREA B | 374,900 | 95,700 | 48.5\% | 45.7\% | 93,400 | 2,300 |
| AREA D | 167,000 | 53,200 | 21.6\% | 25.4\% | 53,200 | 0 |
| AREAE | 194,000 | 49,500 | 25.1\% | 23.6\% | 49,500 | 0 |
| AREA G | 0 | $0$ | 0.0\% | 0.0\% | 0 | 0 |
| AREA H | 37,100 | 11,000 | 4.8\% | 5.3\% | 11,000 | 0 |
| RECREATIONAL | 34,700 | 11,600 |  |  | 11,600 | 0 |
| IN-RIVER | 23,100 | 0 |  |  | 0 | 0 |
| MARINE | 11,600 | 11,600 |  |  | 11,600 | 0 |
| FIRST NATIONS | 1,050,800 | 1,070,904 |  |  | 1,071,000 | 0 |
| MARINE | 266,800 | 269,204 | 25.4\% | 25.1\% | 269,204 | 0 |
| Lower Fraser | 434,000 | 451,700 | 41.3\% | 42.2\% | 451,700 | 0 |
| BC Interior | 350,000 | 350,000 | 33.3\% | 32.7\% | 350,000 | 0 |
| TEST FISHING | 33,100 | 31,000 |  |  | 31,000 | 0 |


| Pinks |  |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | TARGET CATCH | TOTAL CATCH | TARGET \% | MODELLED \% |
| U.S. |  | 48,400 | 47,600 |  |  |
|  | TREATY INDIAN ALL CITIZEN | $\begin{aligned} & 24,200 \\ & 24,200 \end{aligned}$ | 23,700 23,900 | $\begin{aligned} & 50.0 \% \\ & 50.0 \% \end{aligned}$ | $\begin{aligned} & 49.8 \% \\ & 50.2 \% \end{aligned}$ |
| CANADA |  | 140,100 | 157,100 |  |  |
| COMMERCIAL |  | 0 | 20,500 |  |  |
|  | AREA B <br> AREA D <br> AREA E <br> AREA G <br> AREA H <br> In-River EO BS | 0 0 0 0 0 0 | 18,400 100 0 0 2,000 0 | $\begin{array}{r} \hline 82.5 \% \\ 4.0 \% \\ 3.0 \% \\ 0.5 \% \\ 10.0 \% \end{array}$ | $89.8 \%$ $0.5 \%$ $0.0 \%$ $0.0 \%$ $9.8 \%$ |
| RECREATIONAL |  | 0 | 0 |  |  |
|  | IN-RIVER MARINE | 0 | 0 0 |  |  |
| FIRST NATIONS |  | 140,300 | 136,700 |  |  |
|  | MARINE IN-RIVER | $\begin{array}{r} 39,000 \\ 101,300 \end{array}$ | $\begin{array}{r} 35,400 \\ 101,300 \end{array}$ | $\begin{aligned} & 27.8 \% \\ & 72.2 \% \end{aligned}$ | $\begin{aligned} & 25.9 \% \\ & 74.1 \% \end{aligned}$ |
| TEST FISHING |  | 3,500 | 400 |  |  |

## Planned Changes and Potential Areas for Improvement

Since the inaugural use of the R-based planning model in 2019, Staff have focussed on transitioning from a VBA to R-based GUI. Modellers continue to refine the model interface and dataflow to meet the continuing and evolving needs of the Fraser River Panel.

## References

Cave, J.D. and Gazey, W.J. 1994. A preseason simulation model for fisheries on Fraser River sockeye salmon (Oncorhynchus nerka). Can. J. Fish. Aquat. Sci. 51 :1535-1549.

DFO. 2018. Integrated fisheries management plan June 1, 2018 - May 31, 2019. Salmon, Southern BC. Fisheries and Oceans Canada, BC.

PSC. 1995. Pacific Salmon Commission run-size estimation procedures: An analysis of the 1994 shortfall in escapement of late-run Fraser River sockeye salmon. Pacific Salmon Commission Tech. Rep. 6: 179 p.

Starr, P., and Hilborn, R. 1988. Reconstruction of harvest rates and stock contribution in gauntlet salmon fisheries: application to British Columbia and Washington sockeye (Oncorhynchus nerka). Can. J. Fish Aquat Sci 45: 2216-2229.

R Core Team (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

# A7. Planning Model Inputs 

## M.J. Hague

## Summary

The PSC Planning Model (Chapter A6) is a simulation tool used by the Fraser River Panel to assess the sensitivity of fisheries plans and achievement of management targets to alternative biological (e.g. run size, diversion rate) and/or management scenarios. This report describes the key biological, management and fisheries inputs used to parameterise the PSC Planning Model and run simulations. Further details regarding model parameterisation and underlying assumptions can be found in Chapter A8 and A9.

## Introduction

Pre-season, the Fraser River Panel (FRP) and Fraser River Technical Committee (FRTC) use the PSC Planning Model to develop preliminary fishing plans, to identify potential limitations to achievement of management objectives, and to explore the effect of uncertain biological and management inputs on proposed fisheries. This simulation model requires a wide range of different inputs: biological inputs to model the behaviour of the different stocks, fisheries inputs to assess the impact of various fisheries on the stocks and management inputs to ensure management objectives are met. Early in the year, these inputs are based on historical data and preliminary schedules and plans, while just prior to the start of the season, the model inputs are replaced with improved forecasts and federally approved escapement plans. Model seeding, or parameterisation, occurs twice per year: once in February/April and a second time in June. The responsibility for providing different model inputs falls primarily onto Canada and the PSC, with the U.S. providing additional domestic-level information regarding their own fisheries as well as domestic targets and constraints. Typically, the Panel will approve the parameterisation of a "base case" model before the conclusion of their final pre-season meeting in June based on the best-available information.

## Data

## BIOLOGICAL INPUTS

The PSC Planning Model simulates the daily migration of 12 different Fraser River sockeye salmon stock groups, in addition to a single group for all Fraser River pink salmon. Table 1 provides a list of the different sockeye salmon stock groupings used in the Planning Model. Table 1 provides a guide for aggregating stock-specific information from historical reconstruction and pre-season forecast files into appropriate groupings currently utilised pre-season. These groups are structured to aggregate groups of fish with identical management constraints and migratory parameters (Chapter A6). Table 2 provides a description of the key biological inputs in the PSC Planning Model. Pre-season estimates of run size, timing, spread and diversion are used to parameterise normal distributions of daily abundance entering Johnstone Strait and Juan de Fuca Strait while delay information is used to model the upstream migration timing of various stocks which hold in the Strait of Georgia prior to moving up-river.

Table 1. Stock definitions and aggregations within the PSC Planning Model. At the finest resolution, stocks are defined as groups of fish with identical migratory and management parameters.

| Planning Model Group | Migratory Sub-group | Catch \& Racial stock groups | Management Group |
| :--- | :--- | :--- | :--- |
| Early Stuart | North, South | Early Stuart | Early Stuart |
| Early Miscellaneous <br> (above Harrison) | North, South | Nadina, Bowron, Gates, Nahatlatch <br> Taseko | Early Summer |
| Early Miscellaneous <br> (below Harrison) | North, South | Chilliwack, Pitt, Alouette, Coquitlam | Early Summer |
| Early South Thompson | North, South | Early South Thompson, North Barriere | Early Summer |
| Late Stuart, Stellako | North, South | Late Stuart, Stellako | Summer |
| Chilko | North, South | Chilko | Summer |
| Quesnel | Norsh, South | Raft, North Thompson | Summer |
| North-Thompson | North, South | North, South <br> Delay, non-delay | Harrison, Widgeon |
| Harrison | Birkenhead, Big Silver | Summer |  |
| Birkenhead | Late Shuswap | Sates |  |
| Non-Birkenhead Lates <br> (above Harrison) | North, South <br> Delay, non-delay | Weaver, Cultus <br> Non-Birkenhead Lates <br> (below Harrison) <br> Delay, non-delay | Lates |

Table 2. A description of the key biological inputs in the PSC Planning Model, including timelines for updating inputs, the data source, the relevant Chapter containing additional information on how the data are used to derive model inputs and the party responsible for providing the update.

| Input | Description | Update <br> schedule | Source | Relevant <br> Chapter | Responsible <br> Party |
| :--- | :--- | :--- | :--- | :--- | :--- |
| Run size | Preseason run size forecast | February | Stock-recruit data | A1 | DFO |
| Timing | Index of migration timing, i.e. date when <br> $50 \%$ of the run will have passed the <br> refence location | March | Historical medians | this Chapter | PSC Staff |
|  |  | June <br> DFO oceanographic <br> forecasts for Early Stuart <br> and Chilko | A2 | DFO |  |
|  | June | Historical differences in <br> migration timing | this Chapter | PSC Staff |  |
| Spread | Number of days required for 95\% of the <br> run to migrate through an area | March | Historical medians | this Chapter | PSC Staff |
| Rate | Percentage of the total return which <br> migrates through Johnstone Strait | March | Average of historical <br> daily cycle line estimates | this Chapter | PSC Staff |
|  | June | DFO oceanographic <br> forecast | A2 | DFO |  |
| Delay | The proportion of the run expected to <br> delay its upstream migration by holding <br> in the Strait of Georgia and the numer of <br> days their upstream migration is delayed | March | Historical medians | this Chapter | PSC Staff |

## Run size

Run size forecasts are a critical aspect of the modelling process, and directly affect the value of management inputs, patterns of daily abundances, and strongly influence the pattern of proposed fisheries which optimise trade-offs between conservation and fishing targets. Fisheries and Oceans Canada (DFO) provides pre-season forecasts of sockeye salmon run size using a suite of stock recruitment and naïve models (Grant et al. 2010, Chapter A1). These forecasts are provided at a finer stock resolution than used by the PSC Planning Model, and so must be aggregated to the model group level (Table 1). The uncertainty around the run size forecast is expressed in terms of a probability distribution. As stated in the PST (Chapter 4), the median forecast (p50) is used as the default input for the base case planning scenario, but the Panel may also choose to adopt a more precautionary or optimistic forecast until the in-season run size estimates are available. A key sensitivity analysis performed by the parties during pre-season fisheries planning is to vary the assumed run size from the default median (p50) estimate to either a lower (e.g., p25), or higher (e.g., p75) estimate of abundance. Preseason run size estimates are typically available in February and do not get updated until during the season.

## Marine timing

In the PSC Planning Model, marine timing is termed as the Area $2050 \%$ date, or the date by which 50\% of a run has passed the mid-point of statistical Area 20 assuming all sockeye salmon migrate through the southern approach around Vancouver Island (Chapter A2). Both the absolute timing as well as the offsets between the timings of the various management groups (Early Stuart, Early Summer, Summer and Late run) influence preseason fishing plans. During the spring, timings for the different stock groups in the PSC Planning Model are calculated based on historical timing data derived from post-season reconstructed daily marine abundance estimates (Chapter B18). Statistical and retrospective analyses are used to determine the best available estimates for each stock in a given year. Typically, all-year medians, cycle-line medians or all-year medians excluding 2016 cycle line data are used.

In June, DFO provides additional timing forecasts for Early Stuart and Chilko based on oceanographic models (Folkes et al. 2018, Chapter A2). These estimates are applied directly to update the Early Stuart and Chilko timing estimates. For all other stock groups, the historical timing is updated either earlier or later depending on the difference between the Chilko timing forecast to the Chilko historically-based timing estimate. This approach assumes the underlying oceanographic conditions affecting Chilko salmon will have the same effect on other co-migrating stocks. It is at the Fraser River Panel's discretion to utilise these updated timing forecasts, to use the historical timing estimates, or to adopt some alternative value.

## Spread

Another parameter used to define the anticipated daily abundances of fish is the spread of the run. Assuming the run follows a normal distribution, the spread indicates the number of days for $95 \%$ of the run to migrate past a reference location (i.e., the standard deviation of the normal distribution). Annual spreads are calculated from reconstructed historical marine timing profiles (Chapter B18) and are quantified using the same subset of years selected for the historical timing estimates. Spread estimates for aggregated stocks are calculated by first summing daily reconstructed abundances and then recalculating the spread of the group. The spread model inputs are only updated once a year, during the initial model seeding process.

## Northern diversion rate

The diversion rate is defined as the proportion of the run that migrates through Johnstone Strait, i.e., the northern approach. The models to predict the diversion rate have varied over time and will likely continue to evolve. In 2018, a new process of predicting the diversion rate in March was applied
whereby the daily diversion rates over the last three years on the cycle line were averaged. In June, DFO provides an additional annual forecast of the total Fraser River sockeye salmon diversion rate using a suite of oceanographic models (Folkes et al. 2018, Chapter A2). The pattern of daily diversion based on the historical data is then multiplied by a scaler to ensure the total diversion was equivalent to the DFO forecast. The daily diversion rate estimates are multiplied by the daily abundances of the various stock groups to calculate the abundances migrating through Johnstone Strait versus Juan de Fuca Strait. Unlike other Fraser River sockeye salmon stocks, Harrison sockeye migrate predominantly through the south. Given the limited amount of historical data, a Harrison-specific diversion rate is derived by adjusting the diversion rate based on the historical relationship between total Fraser and Harrison-only diversion rates.

## Delay in upstream migration

A percentage of Harrison (Summer run) and Late-run stocks (excluding Birkenhead and Big Silver) typically delay their migration in the Strait of Georgia for a variable number of days prior to continuing their upriver migration (Cooke et al. 2004). Historically, the number of days delay and the upstream timing has differed across cycle lines and except for odd cycle line years, cycle line medians are used as model input. The proportion of the run that delay their upstream migration, the Mission $50 \%$ migration date of both the delaying and non-delaying components, and the spread of the delay component are all inputs into the PSC Planning Model. Using expert judgement, these inputs are adjusted to produce results consistent with the historical median estimates of delay and the median $50 \%$ migration date at Mission.

## MANAGEMENT INPUTS

Most of the bi-lateral management parameters are provided by Canada, pursuant to guidance in the Pacific Salmon Treaty (Article IV, Chapter 4). In addition, PSC staff provide test fishing deductions (Chapter A5) and management adjustments (Chapter A3); both of which also influence the calculation of Total Allowable Catch (TAC). Preliminary escapement plans from Canada are generally aligned with rules corresponding to either the previous year, or previous year on the cycle line. Updated values are normally available by June, but Ministerial approval may be delayed until early in the fishing season.

TAMs, SETs, AFEs, and LAERs
Under the Pacific Salmon Treaty (Chapter 4, Article IV), Canada is responsible for providing harvest control rules for the management of Fraser River sockeye stocks. Prior to each fishing season, the Minister of Fisheries, Oceans and the Canadian Coast Guard must formally approve an annual Integrated Fisheries Management Plan (IFMP) following a series of consultations with key stakeholder groups. This plan includes harvest control rules that define the Spawning Escapement Targets (SET), Total Allowable Mortality (TAM), and Low Abundance Exploitation rates (LAERs) for each sockeye salmon management group (DFO 2018, Chapter A4). Fraser River sockeye salmon follow abundance-based harvest rules and so the SET and TAM values vary as a function of the assumed run size. The Aboriginal Fisheries Exemption, or AFE, is also described in the IFMP provided by Canada. This is a fixed 400,000 sockeye deduction from the bi-lateral Total Allowable Catch (TAC) to meet Canadian First Nations fishing requirements.

## Management Adjustments

Management Adjustments (MAs) represent the expected number of additional fish required to pass the Mission hydroacoustic facility to achieve the desired SET. Initial preseason MAs are based on historical discrepancies, or differences between escapements at Mission and those on the spawning grounds (DBEs), after accounting for known catch removals from historical data sets. Historical discrepancies (Chapter A3, B22) may exist because of errors in stock assessment, catch accounting, or natural en route
losses. In June, long range environmental forecasts (Chapter B23) produced by the DFO Environmental Watch Program are used to predict MAs for Early Stuart, Early Summer run and Summer run using multiple regression models fit to time series of lower river discharge and temperature data (Macdonald et al. 2010, Cummings et al. 2011). The Late-run MA is either left as the historical median or updated to a predicted MA estimate based on estimated upstream timing (Macdonald et al. 2010, Cummings et al. 2011). However, the Panel may choose alternative MAs for any of the management groups.

Table 3. A description of the key management inputs in the PSC Fisheries Planning model.
\(\left.$$
\begin{array}{|l|l|l|l|l|l|}\hline \text { Input } & \text { Description } & \begin{array}{l}\text { Relevant } \\
\text { Chapter }\end{array} & \begin{array}{l}\text { Update } \\
\text { schedule }\end{array} & \text { Source } & \begin{array}{l}\text { Responsible } \\
\text { Party }\end{array} \\
\hline \begin{array}{l}\text { Total Allowable } \\
\text { Mortality (TAM) } \\
\text { rules }\end{array} & \begin{array}{l}\text { Management group specific rules to } \\
\text { define the total allowable mortality } \\
\text { at different run size }\end{array} & \text { A4 } & \text { March } & \begin{array}{l}\text { Previous cycle } \\
\text { year }\end{array} & \text { PSC staff } \\
\hline \begin{array}{l}\text { Spawning } \\
\text { Escapement Targets } \\
\text { (SETs) }\end{array} & \begin{array}{l}\text { Run size specific SET for each of the } \\
\text { management groups }\end{array}
$$ \& A4 \& March \& Previous cycle \& PSC staff <br>

year\end{array}\right]\)| June |
| :--- |

## Test fishery deductions

Pursuant to the PST (Article 4, Chapter 4), the TAC is reduced by the amount of catch in Panel authorised test fisheries. Test fishing catches consist of nondiscretionary catch of fish that are unavoidably killed when conducting test fishing operations and discretionary catches retained to offset test fishing costs. Preseason, the Panel agrees to a draft test fishing plan put forth by PSC staff. A detailed description of how test fishery deductions are predicted for pre-season planning is provided in Chapter A5. Estimated catches by fishery are calculated from historical catchability estimates applied to simulated daily fish abundances. Gill net test fisheries are assumed to retain all fish, whereas purse seine fisheries are modelled as either non-retention (fish are only landed to meet scientific sampling requirements) vs. retention (all fish are landed and fish in excess of the sampling requirements are used to offset the cost of the test fishing program).

The distribution of test fishing catches across management groups is calculated using a combination of two approaches. First, the non-discretionary catch (i.e., all gill net test fishery catch plus scientific samples in the purse seine test fishery) is proportionally assigned to each group based on the historical distribution of non-discretionary catches average over the last 3 cycle lines and adjusted for the current proposed test fishery dates. Second, the discretionary catch (i.e., fish landed above and beyond those required for scientific samples), is proportionally distributed as a function of the available harvestable surplus for each management group (i.e., run size minus spawning escapement target and management
adjustment). These approaches are sometimes revised to meet the expected stock composition and/or test fishery schedule assumed for a given year.

## International and domestic allocations

The PST (Article 4, Chapter 4) assigns $16.5 \%$ of the TAC available for international sharing to the U.S. with the balance assigned to Canada. In addition, each country allocates their respective share across different stake-holder groups following pre-season consultations. These percentages are then used as objectives to help guide the fishing plans in the PSC Planning Model. Canada assigns allocations to different commercial fishing sectors: Area B seine, Area D gill net, Area E gill net, Area H troll, and Area G troll. Allocation targets are also specified for marine, lower river, and interior First Nations fisheries as well as marine and in-river recreational fisheries. In the US, allocation percentages are used to divide the TAC between Tribal and All Citizen fisheries.

## FISHERIES INPUTS

Fisheries inputs relate to the number of vessels expected to participate to a fishery, i.e., the fishing effort, or expected catches and the schedule when fishing is expected to occur. Table 4 provides a description of the key fisheries inputs in the PSC Planning Model.

Table 4. A description of the key fisheries inputs in the PSC Fisheries Planning model.

| Input | Description | Relevant <br> Chapter | Responsible Party |
| :--- | :--- | :--- | :--- |
| Fishing effort | Anticipated fleet size | this Chapter | FRTC chairs |
| Fixed catch inputs | Catches for fisheries that are not modelled dynamically | this Chapter | FRTC chairs, PSC staff |
| Test fishing <br> schedule | Fishing schedules of the different test fisheries, <br> including non-retention criteria of test fishing catches <br> and retention schedules of non-discretionary catches | this Chapter | FRP, PSC staff |
| Fishing schedule | Days/hours of different planned openings. Also <br> includes non-retention criteria, designation of ITQ <br> fisheries, ITQ catches, harvest rates, etc. | this Chapter | FRP, PSC staff |

## Fishing effort

Effort-based harvest rate equations are used in the PSC Planning Model to generate estimates of catch for derby-style fisheries. The model is seeded with historical estimates of fishing effort (total number of vessels) for the following fisheries: marine gillnet (Area 11, Area 12), marine purse seine (Area 12, Area 13 and Area 20), troll (Area 29), Tribal (Area 4B56C, Area 7, Area 7A), and All Citizen (Area 7, Area 7A).

## Fixed catch (for fisheries not modelled dynamically)

Some fisheries are not dynamically modelled within the PSC Planning Model, either because of unparameterized harvest equations, or because they are outside of the current geographic scope. Instead, experts provide estimates of catch by management group, including estimates of fishing induced sockeye mortalities (FIMs) in pink salmon directed fisheries. The Canadian FRTC chair provides catch estimates for the following fisheries: marine recreational catch, in-river beach seine FIMs, and gulf seine FIMs. PSC staff will provide catches estimates for the purse seine test fishing samples. These catches are relatively small and are estimated based on daily sample sizes and distributed across management groups based on historical stock composition information.

## Fishing plans

Once the model has been fully parameterised under a given set of assumptions, the FRTC works with PSC Staff to develop a fishing plan for each country. The goal of these plans is to optimise trade-offs
between conservation and fishing objectives by developing fishing scenarios that meet Spawning Escapement Targets, come as close as possible to meeting the international TAC allocations as well as domestic allocation requirements. Model input requirements vary by fishery depending on the underlying equations. At a minimum, derby-style fisheries must include a start and end date, while ITQstyle fisheries (Individual Transferable Quota) must also indicate an anticipated target catch. Users can choose to specify the hours of fishing operations, the fishing effort and if sockeye catches would be retained or not. Initial fishing plans developed in March/April are updated and finalised following an update of the model inputs in June.

## References

Cummings, J.W., Hague, M.J., Patterson, D.A., and Peterman, R.M. 2011. The impact of different performance measures on model selection for Fraser River sockeye salmon. N. Am. J. Fish. Aquat. Sci. 31: 323-334.

Cooke, S.J., Hinch, S.G, Farrell, A.P., Lapointe, M.F., Jones, S.R.M., Macdonald, J.S., Patterson, D.A., Healey, M.C., and Van Der Kraak, G. 2004. Abnormal Migration Timing and High en route Mortality of Sockeye Salmon in the Fraser River, British Columbia. Fisheries 29:2, 22-33

DFO. 2018. Integrated fisheries management plan June 1, 2018 - May 31, 2019. Salmon, Southern BC. Fisheries and Oceans Canada, BC.

Folkes, M.J.P, Thomson, R.E., and Hourston, R.A.S. 2018. Evaluating models to forecast return timing and diversion rate of Fraser sockeye salmon. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/021.

Grant, S.C.H., Michielsens, C.G.J., Porszt, E.J., and Cass, A. 2010. Pre-season run size forecasts for Fraser River Sockeye salmon (Oncorhynchus nerka) in 2010. DFO Can. Sci. Advis. Sec. Res. Doc. 2010/042.

Macdonald, J.S., Patterson, D.A., Hague, M.J., and Guthrie, I.C. 2010. Modeling the Influence of Environmental Factors on Spawning Migration Mortality for Sockeye Salmon Fisheries Management in the Fraser River, British Columbia. Transactions of the American Fisheries Society 139:768-782.

# A8. Planning Model - Biological Assumptions 

## M.J. Hague

## Summary

The PSC Planning Model (Chapter A6) is a simulation tool used by the Fraser River Panel to assess different alternative fisheries plans and their ability to achieve management targets under various biological (e.g., run size, diversion rate) and/or management scenarios. The calculations of catch and escapement by the Planning Model (Chapter A9) rely fundamentally on assumptions associated with forward run reconstructions. This report describes the key assumptions regarding the dynamics of fish movement and migration behaviour. The sources and processes underlying the annual re-parameterisation of the biological and fisheries management inputs feeding into the model are provided in Chapter A7.

## Introduction

As described in Chapter A6, and pursuant to Article IV, Chapter 4, Paragraph 9d, of the Pacific Salmon Treaty, the Fraser River Technical Committee (FRTC) and Pacific Salmon Commission (PSC) staff work jointly to develop fisheries management plans for Fraser River sockeye salmon prior to the start of each fishing season using the PSC Planning Model. The usefulness of the Planning Model as a management tool depends in part on the accuracy of biological pre-season forecasts, but also on the realism of the underlying model parameterisations, primarily those relating to fish movement and vulnerability to fishery operations.

Fundamentally, the Planning Model is a forward reconstruction model (Cave and Gazey 1996, Starr and Hilborn 1998), simulating the daily migrations of sockeye salmon as they "move" through a gauntlet of marine and freshwater fisheries. The model uses fishery-specific instantaneous mortality rates applied to vulnerable "blocks" of salmon to estimate fisheries-specific catches and escapement (Chapter A9). Since the original publication of the forward reconstruction model by Cave and Gazey (1996), the assumptions underlying the model have been changed to reflect both improved information about stock-specific differences in salmon migratory behaviour, and changes to fisheries and management strategies (Chapter A9). Biologically, a larger number of individual stock groups are modelled given the availability of more detailed stock-specific data since the advancement of DNA-based stock identification technology. Increased understanding of stock-specific fish migration behaviour has also resulted in changes to modelling approaches for diversion rate (percentage of fish migrating via Johnstone Strait vs. Juan de Fuca Strait) and delay in the Strait of Georgia. The following report describes the main biological assumptions underlying the simulation model.

## Reconstruction Model Assumptions

## NORMAL RUN TIMING DISTRIBUTIONS

Within the PSC Planning Model, 'stocks' are defined as aggregates of fish with a unique set of migration characteristics such as: migratory path, migration rates, delay behaviour, marine arrival timing, and abundance. These stock groups are based on the four different Fraser River management groups but with additional sub-groups based on migration differentiation. For example, Late-run fish are divided into additional groups depending on whether they migrate through Johnstone Strait (North) or through Juan de Fuca Strait (South), whether or not they delay their upstream migration, and whether they
spawn below or above the confluence of the Harrison River. The full suite of Planning Model stock groups and migration parameters are described in Chapter A7 (Tables 1 and 2). The biological model for each stock $(s)$ is initialised by creating a series of normally distributed daily migration profiles centred on an index of expected median marine migration timing:

$$
\begin{equation*}
N(d)=N \cdot \frac{1}{\sigma \sqrt{2 \pi}} \cdot e^{-\frac{1}{2} \cdot\left(\frac{d-\mu}{\sigma}\right)^{2}} \tag{1}
\end{equation*}
$$

where $N$ is the total forecasted abundance (run size) of a stock, $d$ is day, $\sigma$ is the standard deviation, and $\mu$ is the median marine migration date of the run (Figure 1). The marine migration date, also referred to as the Area 20 date or marine $50 \%$ date, indicates the date when half (50\%) of the run would have passed through Area 20 assuming all fish migrated via that route. The normal distributions are parameterised using pre-season forecasts of abundance, timing and standard deviation (see Chapter A7).

Next, a daily diversion rate pattern (i.e. proportion of the run migrating around the northern tip of Vancouver Island instead of through Juan de Fuca Strait) is applied to create separate entry distributions for the northern and southern approaches around Vancouver Island (Figure 1). Alternative diversion rate patterns can be applied to individual stocks to accommodate known differences in migratory routes. Fish migrating through the southern approach are initiated in Area 127 off the southwest coast of Vancouver Island, and fish migrating through the northern approach are initiated in Area 111 off the northern tip of the island (Figure 1).


Figure 1. (a) Schematic illustrating the fisheries "gauntlet" modelled by the PSC fisheries planning model. (b) A GIS map of corresponding locations.

## BOX-CAR FORWARD RECONSTRUCTION ASSUMPTIONS

Once the daily abundance estimates, representing Fraser River sockeye expected to migrate through the north and south, are derived, the model uses a set of control rules to move fish through space and time
from the tip of Vancouver Island to the Mission hydroacoustic site, and then continuing up the mainstem. Terminal fisheries harvests or catch excess to spawning escapement requirements (ESSRs) are not specifically addressed within the current modelling construct.

The forward reconstruction assumes a 'boxcar' style movement of fish occurring on a daily time-step (Cave and Gazey 1996, Starr and Hilborn 1998) over most of the migration. A 'bathtub' assumption is also applied, meaning that on a given day fish are either fully vulnerable to, or completely unaffected by, an assumed fishery opening. Migration times, and thus the exposure of a given daily migration 'block' of fish to a given fishery, are controlled by underlying stock-specific migration rates and lengths of each fishing area (Appendix A, Table A1). It is assumed that fish remain in a statistical area for a minimum of one day and migration times are rounded to full daily increments. Statistical areas associated with residency times greater than one day are represented by multiple model sub-areas, each representing roughly one day of migration time in the model (Appendix A, Table A1). In some cases, statistical areas represent parallel migration routes (e.g., Area 20, Areas 4B, 5, 6, and 6C) and for migration purposes they are considered identical but are still identified uniquely for the purposes of catch accounting (i.e., fish are assumed to migrate simultaneously through Canadian Area 20 and US Area 4B56C).

Figure 2 illustrates how the boxcar movement assumptions interact with fishery exposure during the forward reconstruction. Exposure times depend on the dates of the fishery opening, the migration rate of the fish, and the size of the fishing area. In some cases, the same group of fish could be exposed to fishing pressure across multiple days of a fishery opening, while in others, a group of fish may only be vulnerable to a fishery for part of an opening.


Figure 2. Schematic illustration of a basic boxcar run reconstruction model. The colored bars represent different statistical fishing areas, with the left most square representing the most seaward location. Each "fish/hook" represents one day of fishing. Each fish represents one daily block of fish. Black fish in each panel are not exposed to a fishery opening on a given day, while grey fish are. Each panel represents a daily time-step. The top panel represents the shape of the unfished run prior to entering marine approach fisheries. The bottom panel represents the shape of the run at Mission, with certain days of abundance reduced due to catch removals.

Following the illustration in Figure 2, the escapement of fish ( $N$ ) into area (a) on a given day (d) is reduced by an amount equivalent to the landed catches and fishing induced mortalities (FIMs) occurring on that day in that area. Assuming it takes one day for the fish to migrate through area a, the resulting escapement of fish into the downstream area $(a+1)$ on the next day $(d+1)$ is represented by:

$$
\begin{equation*}
N_{a+1}(d+1)=N_{a}(d)-C_{a}(d) \tag{2}
\end{equation*}
$$

The resulting daily escapement into the Fraser River ( $\mathrm{N}_{\mathrm{FR}}$ ), after migrating for $m$ days through all areas along the migration route and being intercepted by $k$ fisheries along the way, is given by:

$$
\begin{equation*}
N_{F R}(d+m)=N(d)-\sum_{f=1}^{k} C_{f} \tag{3}
\end{equation*}
$$

## STRAIT OF GEORGIA MIGRATION DELAY BEHAVIOUR

The exception to boxcar movement occurs in the Strait of Georgia near the Fraser River Delta, where a proportion of the Late-run and Harrison stocks delay their migration prior to moving upstream (Lapointe et al. 2003). Delaying fish are assumed to both slow down, and to redistribute when entering the Fraser River, thus violating the assumptions of a boxcar model. Subsequent to river entry, boxcar movement is assumed to resume for the remainder of the freshwater migration. A separate sub-model is applied to model stocks which hold and redistribute in the Strait of Georgia (Table 1, see also Chapter A7), for which a set of parameters that characterise the period of delay, and the new profile of upstream migration, are defined. Note that this sub-model does not apply to Late run or Harrison sockeye that do not delay their upstream migration

To mimic delay behaviour of delaying Late run and Harrison sockeye, the model adjusts the number of fish remaining in the Strait of Georgia ( $N_{S O G}$ ) and the number of fish migrating into the lower river on a daily basis. This is done by assuming that delaying salmon fish accumulate over time in the Strait of Georgia, with a proportion of the available abundance migrating upstream:

$$
\begin{equation*}
N_{F R}(d)=p(d) \cdot N_{T, S o G}(d), \tag{4}
\end{equation*}
$$

where $p(d)$ indicates the proportion of the abundance holding in the Strait of Georgia migrating into the Fraser River ( $F R$ ), and $N_{T, S O G}$ indicates the total accumulated abundance remaining in the Strait of Georgia, following fisheries removals. The daily proportion of available fish migrating upstream is derived from a normal density function representing the run timing profile of a delaying stock as it exits the Strait of Georgia and enters the Fraser River, where $\sigma$ is the standard deviation, and $\mu$ is the upstream timing:

$$
\begin{equation*}
f(d)=\frac{1}{\sigma \sqrt{2 \pi}} \cdot e^{-\frac{1}{2} \cdot\left(\frac{d-\mu}{\sigma}\right)^{2}} \tag{5}
\end{equation*}
$$

The proportion of delaying fish associated with each day of migration $(p(d))$ is then given by dividing the proportion of fish migrating upstream by the proportion of fish still present in the Strait of Georgia:

$$
\begin{equation*}
p(d)=\frac{f(d)}{\sum_{d}^{D} f(d)} \tag{6}
\end{equation*}
$$

Because sockeye are assumed to accumulate in the Strait of Georgia, the daily abundance of outmigrating delay fish cannot simply be removed by subtracting from a single day of resident abundance (i.e. cannot be treated the same as a daily catch removal). Instead, the model makes the simplifying
assumption that the total reduction in fish due to outmigration is spread proportionally across the remaining abundance in the Strait:

$$
\begin{equation*}
p_{S o G}(d)=\frac{N_{S o G}(d)}{\sum_{d}^{D} N_{S o G}(d)}, \text { with } N_{S o G}(d)=N_{S o G}(d-1)-C_{S O G}(d-1) \tag{7}
\end{equation*}
$$

The result of this assumption is that the daily stock composition of sockeye entering the river from the Strait of Georgia will not mirror the daily stock composition entering the Strait of Georgia.

The shape of the remaining distribution fish in the Strait of Georgia after each day of upstream migration ( $N_{F R}$ ) and catch ( $C_{S O G}$ ) is then calculated using:

$$
\begin{equation*}
N_{S O G}(d+1)=N_{S O G}(d)-p_{a}(d) \cdot N_{F R}(d) . \tag{8}
\end{equation*}
$$

In the next loop of the simulation, the escapement into the river is equivalent to the abundance outmigrating from the Strait ( $N_{F R}$ ) and the escapement into the Strait ( $N_{S O G}$ ) becomes re-defined by Equation 8. Due to the iterative nature of this calculation, daily escapement into the river is populated one day at a time, even in the absence of any fisheries.

## Planned Changes and Potential Areas for Improvement

The fisheries planning model and marine reconstruction model used to occur within the same framework and had a shared set of underlying assumptions. In recent years, some of the basic biological assumptions (e.g., movement rate) have diverged, and should be reconciled. There has been some interest in improving the modelling of pink salmon fisheries as well as upriver fisheries, some of which are currently entered as fixed inputs in the model. Modellers also continue to revise and improve the coding efficiency and user interfaces and address ongoing requests from the Fraser River Panel and Technical Committee.

## References

Branch, T.A., and Hilborn, R. 2010. A general model for reconstructing salmon runs. Can. J. Fish. Aquat. Sci. 67: 886-904.

Cave, J.D. and Gazey, W.J. 1994. A preseason simulation model for fisheries on Fraser River sockeye salmon (Oncorhynchus nerka). Can. J. Fish. Aquat. Sci. 51: 1535-1549.

Lapointe, M., Cooke, S.J., Hinch, S.G., Farrell, A.P., Jones, S., McDonald, S., Patterson, D., Healey, M.C., and Van Der Kraak, G. 2003. Late-run sockeye salmon in the Fraser River, British Columbia, are experiencing early upstream migration and unusually high rates of mortality - what is going on? Proceedings of the 2003 Georgia Basin/Puget Sound Research Conference.

PST. 2020. Treaty between the government of Canada and the government of the United States of America concerning Pacific salmon as modified through January 2020.

Starr, P., and Hilborn, R. 1988. Reconstruction of harvest rates and stock contribution in gauntlet salmon fisheries: application to British Columbia and Washington sockeye (Oncorhynchus nerka). Can. J. Fish Aquat Sci 45: 2216-2229.

## Appendix A: Detailed movement assumptions

Table A1. Modelled residency times within different statistical areas and offsets from the index start of Area 20.

| Statistical <br> Area(s) | Approach | Country | Model <br> Sub- <br> Area(s) | Residency Time (days) | Offset from Area 20 (Southern Approach) |  | Offset from Area 20 (Northern Approach) |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  | Summerrun | Late-run | Summerrun | Late-run |
| Area 20 | Juan de Fuca | Can | fa7, fa8 | 2 | 0 | 0 | NA | NA |
| Area 19 | Juan de Fuca | Can | fa9, fa10 | 2 | 2 | 2 | NA | NA |
| Area 18 | Juan de Fuca | Can | fa11 | 1 | 4 | 4 | NA | NA |
| $\begin{aligned} & \text { Area(s) } \\ & 4 \mathrm{~B}, 5,6 \mathrm{C} \\ & \hline \end{aligned}$ | Juan de Fuca | U.S. | fa7, fa8 | 2 | 0 | 0 | NA | NA |
| Area 6 | Juan de Fuca | U.S. | fa9 | 1 | 2 | 2 | NA | NA |
| Area 7 | Juan de Fuca | U.S. | fa10 | 1 | 3 | 3 | NA | NA |
| Area 7A | Juan de Fuca | U.S. | fa11 | 1 | 4 | 4 | NA | NA |
| Area 11 | Johnstone Strait | Can | fa13 | 1 | NA | NA | -3 | 0 |
| Area 12 | Johnstone Strait | Can | $\begin{aligned} & \text { fa14, } \\ & \text { fa15, fa16 } \end{aligned}$ | 3 | NA | NA | -2 | 1 |
| Area 13 | Johnstone Strait | Can | fa17, fa18 | 2 | NA | NA | 1 | 4 |
| Area 14 | Johnstone Strait | Can | fa19, fa20 | 2 | NA | NA | 3 | 6 |
| Area 15 | Johnstone Strait | Can | fa19 | 1 | NA | NA | 3 | 6 |
| Area 16 | Johnstone Strait | Can | fa20 | 1 | NA | NA | 4 | 7 |
| Area 17 | Johnstone Strait | Can | fa21 | 1 | NA | NA | 5 | 8 |
| Area 29A | Strait of Georgia | Can | fa22 | 1 | 5 | 5 | 6 | 9 |
| Area 29B | River | Can | fa23 | 1 | 6 | 6 | 7 | 10 |
| Area 29D | River | Can | fa24 | 1* | 7 | 8 | 8 | 12 |
| MissionHarrison | River | Can | fa25 | 1* | 8 | 9 | 9 | 13 |
| HarrisonSawmill | River | Can | fa26 | 2 | 9 | 11 | 10 | 14 |
| Above Sawmill | River | Can | fa27 | NA | 11 | 13 | 12 | 16 |

*2-day migration for Late-run sockeye salmon due to slower migration speed

# A9. Harvest Rate Parameterisation and Catch Dynamics 

M.J. Hague

## Summary

The PSC Planning Model (Chapter A6) is a simulation tool used by the Fraser River Panel to assess alternative fisheries plans and their ability to achieve management targets under various biological (e.g., run size, diversion rate) and/or management scenarios. This report describes the fisheries included in the model as well as the different approaches for calculating catch and escapement based on daily estimates of sockeye abundance in the various fishing areas. The underlying migration assumptions are described in Chapter A8. The sources and processes used to derive the biological and fisheries management inputs to parameterise the model are provided in Chapter A7.

## Introduction

As described in Chapter A6, and pursuant to Article IV, Chapter 4, Paragraph 9d, of the Pacific Salmon Treaty, the Fraser River Technical Committee (FRTC) and Pacific Salmon Commission (PSC) staff work jointly to develop fisheries and management plans for Fraser River sockeye salmon prior to the start of each fishing season using the PSC Planning Model. The usefulness of the Planning Model as a management tool depends in part on the accuracy of pre-season biological forecasts, but also on the realism of the underlying model parameterisations, such as assumed harvest rate dynamics and the vulnerability of migrating salmon to fisheries openings.

The types of fisheries targeting Fraser River sockeye salmon, and the management rules used to guide them, have changed substantially since the Planning Model was first described by Cave and Gazey (1996). For example, many Canadian commercial fisheries in marine areas have changed from high intensity "derby" style fisheries, to protracted, lower-impact, individual transferable quota (ITQ) fisheries. In addition, the Planning Model now monitors the impact of both landed catch and fishing induced mortalities (FIMs) on estimated escapements; a relatively new concern due to increased interest in Fraser River pink salmon directed fisheries and the need for accurate accounting of exploitation rates associated with vulnerable Fraser River sockeye salmon stocks.

Daily fishery catches within the Planning Model are both a function of the abundance and vulnerability of the salmon exposed to a given opening as well as a function of the assumed harvest rates of the fishery, or fisheries, operating in a given area on a given day. The following report describes the assumptions, parameterisations, and control rules used to quantify both the abundance of the vulnerable fish population and the fishery-induced mortality rates associated with individual fisheries. Resulting daily catch and escapement calculations are also defined as well as areas for future refinement.

## Planning Model Catch Assumptions

## FISHERY HARVEST RATE DEFINITIONS

A detailed description of fishery parameterisations within the Planning Model can be found in Table A1. There are four categories of fisheries within the model that are characterised by different harvest rate
equations and associated parameter requirements: derby fisheries, mixed gear fisheries, ITQ fisheries, and test fisheries. Each category is described in more detail below.

## Derby Fisheries

Harvest rate equations for many of the derby fisheries were parameterised with data from the 1980's and 1990's (Cave and Gazey 1996); Table A1. Catch is a function of the number of vessels, the assumed harvest rate per vessel, and the length of the opening. Historically, these fisheries were characterised by a short fishing window, high fishing effort ( $E$, number of vessels participating to the fishery), and often intensive fishery exploitation. As a result, original harvest rate parameterisations were sometimes characterised for 12-hour openings, in which case the 'elemental' harvest rates ( $u$ ) defined by Cave and Gazey (1996) were first re-scaled to daily harvest rates ( $h$ ):

$$
\text { (1) } \quad h=2 \cdot u+u^{2}, \text { with } u=a+b \cdot E
$$

where ' $a$ ' and ' $b$ ' are fishery-specific parameters (Table A1) relating effort to harvest rate. In other cases (Table 1), daily harvest rates were parameterised as a function of effort and fishery catchability ( $q$ ) estimated from historical reconstructions:

$$
\begin{equation*}
h=1-e^{-q E} \tag{2}
\end{equation*}
$$

Many of the FSC fisheries are modelled with a single daily harvest rate ( $h$ ), which is informed by the expert judgement of fishery managers and may change at the discretion of the Canadian Technical Committee Chair. Often, the intention of these harvest rates is not to accurately reconstruct catches, but to seed the Planning Model with reasonable harvest expectations and to meet domestic catch constraints.

## U.S. Mixed Gear Fisheries

The current harvest rate equations applied to US All Citizen and Tribal fisheries operating in statistical Areas 6, 7, and 7A were originally parameterised based on analyses performed in the 1980s (PSC 1990). The effort ( $E$; quantified as number of vessels or number of landings) in these mixed gear fisheries is quantified in terms of "purse seine equivalents". A fixed gill net to purse seine catch-per-unit-effort CPUE ratio is applied to re-scale the number of gill net vessels (GN) participating (or modelled) during a fishery opening into a "purse seine equivalent" ( $E_{P S}$ ):

$$
\begin{equation*}
E_{P S}=\frac{C P U E_{G N}}{C P U E_{P S}} \cdot E_{G N} \tag{3}
\end{equation*}
$$

where $E$ refers to fishing effort.

The Planning Model applies a fixed 0.2 CPUE ratio to "convert" the number of gill net vessels into an equivalent number of purse seine vessels (i.e., the effort associated with five gill nets is equivalent to the effort of one purse seine). The original analysis resulting in the application of the CPUE ratio for effort scaling has not been identified, although similar conversions of vessel effort to purse seine equivalents using CPUE ratios have been applied in other fisheries. e.g., herring fisheries in the North Sea (Bjorndal and Conrad 1978).

Harvest rates for the US mixed gear fisheries are also assumed to vary across the season (elemental harvest rates, $u_{\text {early }}$ vs. $u_{\text {late }}$ in Table A1). The historical analysis of purse seine equivalents from the 1980s (PSC 1990) noted that catchability in the Area 7 and 7A fisheries decreased in mid- to late August,
potentially associated with lower catchability of Late-run fish due to behavioural differences in migration patterns (e.g. swimming lower in the water column and less accessible to gear). However, PSC Staff also hypothesized that observed seasonal differences in catchability could be associated with estimation errors related to uncertainty in Late-run reconstructions (PSC 1990). The Planning Model somewhat arbitrarily assigns a date of August 12 in Area 7 and August 14 in Area 7A to switch from "early" to "late" harvest rates, as the stock composition generally becomes weighted more heavily towards Late-run stock components around this time. However, modellers have the flexibility to redefine the time periods over which to apply each harvest rate equation.

## ITQ Fisheries

Canada's Area B, E and H fisheries currently operate under an Individual Transferable Quota (ITQ) system. Their fisheries are modelled by 'spreading' the total catch target $\left(C_{T}\right)$ over the duration of the fishery opening ( $n$ ) which may last 1 to 7 days ( $d$ ):

$$
\begin{equation*}
C(d)=C_{T} / n . \tag{4}
\end{equation*}
$$

For fisheries openings spanning multiple statistical areas (e.g. Area 12 and 13 purse seine), the total daily catch is proportionally assigned to each area (a) based on fishing effort ( $E$, number of vessels):

$$
\begin{equation*}
C_{a_{1}}(d)=\frac{E_{a_{1}}}{\sum_{a_{1}}^{A} E_{a}} \cdot C_{T}(d) . \tag{5}
\end{equation*}
$$

On a given day, the catch is converted to a harvest rate ( $h$ ) by dividing the catch by the number of salmon exposed to the fishery:

$$
\begin{equation*}
h(d)=C(d) / N(d) \tag{6}
\end{equation*}
$$

The resulting harvest rate is then applied across the different stock groups, assuming equal catchability. Daily harvest rates are capped at thresholds ( $h_{T}$ ) to prevent unrealistic catches at low fish abundance:

$$
h(d)=\min \left\{\begin{array}{l}
h_{T},  \tag{7}\\
\frac{C(d)}{N(d)}
\end{array}\right\} .
$$

If daily catch targets are not met early in the opening (i.e., $C(d)<C_{T}(d)$ ), the remaining catch is redistributed across subsequent days until the total catch target $\left(C_{T}\right)$ is reached:

$$
\begin{equation*}
\text { If } C(d)<C_{T}, \text { then } C(d+1: D-1)=C_{T}-\sum_{d=1}^{D} C(d), \tag{8}
\end{equation*}
$$

where $C_{T}$ is the total target catch over the course of an ITQ opening, $d$ is fishing day, and $D$ is the number of days in an opening. This approach assumes that the fishery will operate in a manner which increases the probability of reaching the target catch applied to the opening.

## Test Fisheries

Gill net test fisheries are assumed to land all catches estimated using historically derived, time varying, harvest rates (Chapter B4). Landed catches from purse seine test fisheries to meet scientific sampling requirements are calculated outside of the Planning Model and entered as fixed catch deductions (Chapter A5). By default, all other sockeye encountered by the purse seine test fisheries are assumed to
be released. However, to offset the cost of test fishing operations in some years, the purse seine test fisheries may retain their sockeye, and/or pink salmon catch on some days. During retention periods, the purse seine test fisheries are modelled using the ITQ catch equations, with total target catches and opening dates provided by PSC Staff.

## CATCH AND ESCAPEMENT PROJECTIONS

## Fish Vulnerability

In addition to the harvest rate calculations, the catch on a given day of a fishery opening will also depend on the number of fish vulnerable to the opening. As discussed in Chapter A8, the Planning Model assumes that fish migrate through fishing areas on a daily time-step and assuming fixed order of movement (i.e. "boxcar" reconstruction). The number of daily blocks of fish migration exposed to a fishery depend on the size of the management area, the number of days a fishery is open, and the speed with which salmon migrate through the fishery. In some cases, the same group of fish might be exposed to fishing pressure over multiple days of an opening, or in sequential openings occurring in downstream areas. The Planning Model calculates the number of fish escaping from a fishery on a daily basis, so that the vulnerable population becomes smaller over multiple days of exposure.

## Instantaneous Harvest Rates

To facilitate the modelling of simultaneous fisheries and short-fishery openings (< 1 day), daily harvest rates ( $h$ ) were re-scaled in the current Planning model as instantaneous fishing mortality rates ( $F$ ) , where:

$$
\begin{equation*}
F=(-1 * \log (1-h)) \tag{9}
\end{equation*}
$$

The resulting catch for a single day is then calculated as:

$$
\begin{equation*}
C(d)=\left(1-e^{-F}\right) \cdot N(d) \tag{10}
\end{equation*}
$$

where $C(d)$ is catch on a given day, $N(d)$ is the total number of fish exposed to a given fishery (i.e., may include one or multiple daily "blocks" of fish migration) and $d$ is fishing day. The above re-scaling does not impact catch estimation when there is only a single fishery targeting a block of fish, but becomes important during simultaneous fishery modelling. Catch on subsequent days, or in subsequent areas, is then a function of the number of fish in each daily migration block escaping from the previous opening, where $N(d+1)$ is the total abundance escaping from the fishery on day $d$ :

$$
\begin{equation*}
N(d+1)=N(d)-C(d) \tag{11}
\end{equation*}
$$

Fisheries removals are indexed both by fishing day, as well as by daily migration block to calculate both daily escapements and to summarise catches. The model also summarises daily escapement from every statistical area for each stock. The impact of changes to fishing area size, partial area closures, assumed slowing or speeding up of fish through an area etc., can all be easily modelled through a simple change to the data input files.

Instantaneous fishing mortality equations can be expanded to model multiple simultaneous sources of mortality, such as when more than one fishery is operating in the same area at the same time, or with the potential future inclusion of natural sources of mortality. To do so, the total catch is first calculated using:

$$
\begin{equation*}
C(d)=\left(1-e^{-\sum_{1}^{n} F}\right) \cdot N(d) \tag{12}
\end{equation*}
$$

The catch is then partitioned across $n$ fisheries (or alternative sources of mortality) using:

$$
\begin{equation*}
C(d)_{n}=C(d) * \frac{F_{n}}{\sum_{1}^{n} F} \tag{13}
\end{equation*}
$$

While derby fisheries can operate simultaneously and for fractions of a day, an order of operations must still be assumed for ITQ fisheries. By default, ITQ fisheries operating in the same area on the same date are assumed to take place after any simultaneous derby fisheries, i.e., ITQ harvest rate equations are based on the abundance of fish escaping from concurrent derby fisheries. From a practical standpoint, this model simplification only impacts ITQ catches in scenarios of low abundance relative to target catch, in which case harvest thresholds may be triggered.

## Fishery Induced Mortalities (FIMs)

In addition to landed catch, the Planning Model also models the mortality associated with the nonretention of sockeye catches during pink-directed fishery openings i.e., fishery induced mortalities (FIMs). The assumed loss of fish is calculated by multiplying the harvest rate associated with a directed fishery by a gear-specific FIM rate (see Table A1). For the purposes of escapement calculations, FIMs are removed from daily migration blocks of salmon in the same way as landed catch; however, FIMs are tracked separately for the purposes of catch accounting.

## Planned Changes and Potential Areas for Improvement

Most harvest rate equations within the Planning Model were parameterised using data from years with very different fisheries, and fish conditions compared to current. It also has been noted that some of the US harvest rate equations produce negative values when fleet size drops below a certain threshold.
Given the changes in fish abundance, fleet size, and fishing technology over the last 40 years, the parameterisation of these fisheries (Table A1) requires updating and should be interpreted with caution.

## References

Bjorndal, T. and Conrad, J.M. 1987. The dynamics of an open access fishery. Canadian Journal of Economics (1): 74-85. e.g. Tuna fisheries: Shomura, R.S.; Majkowski, J.;Langi, S. (eds.) Interactions of Pacific tuna fisheries. Proceedings of the first FAO Expert Consultation on Interactions of Pacific Tuna Fisheries. 3-11 December 1991.

Branch, T.A. 2009. Difference in predicted catch composition between two widely used catch equation formulations. Can. J. Fish. Aquat. Sci. 66: 126-132.

Cave, J.D. and Gazey, W.J. 1994. A preseason simulation model for fisheries on Fraser River sockeye salmon (Oncorhynchus nerka). Can. J. Fish. Aquat. Sci. 51 :1535-1549.

DFO. 2018. Integrated fisheries management plan June 1, 2018 - May 31, 2019. Salmon, Southern BC. Fisheries and Oceans Canada, BC.

PSC. 1989. Review of the performance of the south coast fishery model and the input parameters for 1989. Internal Memo.

PSC. 1995. Pacific Salmon Commission run-size estimation procedures: An analysis of the 1994 shortfall in escapement of late-run Fraser River sockeye salmon. Pacific Salmon Commission Tech. Rep. 6: 179 p.

Starr, P., and Hilborn, R. 1988. Reconstruction of harvest rates and stock contribution in gauntlet salmon fisheries: application to British Columbia and Washington sockeye (Oncorhynchus nerka). Can. J. Fish Aquat Sci 45: 2216-2229.

## Appendix A：Detailed fisheries descriptions

Table A1 General characteristics of each fishery currently used in the Fisheries Planning Model．Elemental daily harvest rates（h）are converted to instantaneous fishing mortality rates（F）using the formula：$F=(-1 * \log (1-h)) * T$ ，where $T=1$ is a full fishing day．

| $\frac{\vec{U}}{\frac{\lambda}{2}}$ |  | $\begin{aligned} & \text { B } \\ & 0 \\ & 0 \end{aligned}$ | む | $$ | ジँ |  |  |  |  |  | $\sum_{I I}$ |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| A20 B | A20 | Can | Comm | B | Purse seine | 94 | 2 | $h=1-e^{(-q * E)}$ | $q=0.00685$ | 30\％ | 25\％ | n／a | n／a |
| A18 H | A18－4 | Can | Comm | H | Troll | 45 | 1 | $h$（stock－specific） | $\mathrm{n} / \mathrm{a}$ | 5\％ | 10\％ | n／a | n／a |
| A11 D | A11 | Can | Comm | D | Gill net | 29 | 1 | $\begin{aligned} & u=a+b * E \\ & h=2 * u+u^{2} \end{aligned}$ | $\begin{aligned} & a=0.006628 \\ & b=0.000346 \end{aligned}$ | n／a | 60\％ | n／a | n／a |
| A12 D | A12 | Can | Comm | D | Gill net | 96 | 2 | $\begin{aligned} u & =a+b * E \\ h & =2 * u+u^{2} \end{aligned}$ | $\begin{aligned} a & =0.0064239 \\ b & =0.000373 \end{aligned}$ | n／a | 60\％ | $\mathrm{n} / \mathrm{a}$ | n／a |
| A12 B | A12 | Can | Comm | B | Purse seine | 96 | 2 | $\begin{aligned} u & =a+b * E \\ h & =2 * u+u^{2} \end{aligned}$ | $\begin{aligned} & a=0.30342 \\ & b=0.0012 \end{aligned}$ | 65\％ | 25\％ | n／a | $\mathrm{n} / \mathrm{a}$ |
| A13 B | A13 | Can | Comm | B | Purse seine | 91 | 2 | $\begin{aligned} & u=a+b * E \\ & h=2 * u+u^{2} \end{aligned}$ | $\begin{aligned} & a=0.29159 \\ & b=0.001 \end{aligned}$ | 55\％ | 25\％ | n／a | n／a |
| A12 H | A12 | Can | Comm | H | Troll | 48 | 1 | $h=h_{\text {max }} * v$ | $\begin{aligned} & h_{\max }=0.02 \\ & v=\text { stock specific scaler } \end{aligned}$ | 8\％ | 10\％ | n／a | n／a |
| A13 H | A13 | Can | Comm | H | Troll | 91 | 2 | $h=h_{\max } * v$ | $\begin{aligned} & h_{\max }=0.04 \\ & v=\text { stock specific scaler } \end{aligned}$ | 8\％ | 10\％ | $\mathrm{n} / \mathrm{a}$ | n／a |
| A29 H | A29 | Can | Comm | H | Troll | 41 | 1 | $h=q * E$ | $q=0.004$ | 0．2\％ | 10\％ | n／a | n／a |
| A29 B | A29 | Can | Comm | B | Purse seine | 41 | 1 | $h$ | n／a | 50\％ | 25\％ | n／a | n／a |
| A29 E | A29 | Can | Comm | E | Gill net | 70 | 2 | $h$ | n／a | 80\％ | 60\％ | n／a | 425，000 |
| A20 FSC | A20 | Can | FSC | n／a | Mixed | 47 | 1 | $h$ | $\mathrm{n} / \mathrm{a}$ | n／a | n／a | n／a | 260,000 (marine FSC total） |
| A1213 <br> FSC | A12，A13 | Can | FSC | n／a | Mixed | 31 | 1 | $h$ | $\mathrm{n} / \mathrm{a}$ | $\mathrm{n} / \mathrm{a}$ | n／a | n／a | $\begin{aligned} & \text { 260,000 (marine FSC } \\ & \text { total) } \end{aligned}$ |
| StevHR FSC | Steveston <br> －Harrison | Can | FSC | n／a | Mixed | 100 | 3 | $h$ | $\mathrm{n} / \mathrm{a}$ | $\mathrm{n} / \mathrm{a}$ | $\mathrm{n} / \mathrm{a}$ | $\begin{aligned} & 95,00 \\ & 0 \\ & \hline \end{aligned}$ | 400，000 |
| HRSM FSC | Harrison－ <br> Sawmill | Can | FSC | n／a | Mixed | 73 | 2 | $h$ | $\mathrm{n} / \mathrm{a}$ | $\mathrm{n} / \mathrm{a}$ | $\mathrm{n} / \mathrm{a}$ | $\begin{aligned} & 95,00 \\ & 0 \\ & \hline \end{aligned}$ | 400，000 |
| AbSM <br> FSC | Above Sawmill | Can | FSC | n／a | Mixed | $\mathrm{n} / \mathrm{a}$ | n／a | $h$ | stock－specific | $\mathrm{n} / \mathrm{a}$ | $\mathrm{n} / \mathrm{a}$ | n／a | 190，000 |

Pre-season Planning: Assessment of Fisheries Plans

| A67 TI | A6, A7 | US | TI | n/a | Mixed | 81 | 2 | $\begin{aligned} & u_{\text {early }} \\ & =a+b * \ln (E) \\ & u_{\text {late }}=a+b * E \\ & h=2 * u+u^{2} \end{aligned}$ | $\begin{aligned} & a_{\text {early }}=-0.1823 \\ & b_{\text {early }}=0.0928 \\ & a_{\text {late }}=0.0443 \\ & b_{\text {late }}=0.00088 \end{aligned}$ | n/a | 25\% | $\mathrm{n} / \mathrm{a}$ | n/a |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| A7A TI | A7A | US | TI | n/a | Mixed | 45 | 1 | $\begin{aligned} & u_{\text {early }} \\ & =a+b * \ln (E) \\ & u_{\text {late }}=a+b * E \\ & h=2 * u+u^{2} \end{aligned}$ | $\begin{aligned} & a_{\text {early }}=-0.3602 \\ & b_{\text {early }}=0.212 \\ & a_{\text {late }}=0.0405 \\ & b_{\text {late }}=0.00378 \end{aligned}$ | n/a | 25\% | $\mathrm{n} / \mathrm{a}$ | n/a |
| A67 AC | A7, A7 | US | AC | n/a | Mixed | 81 | 2 | $\begin{aligned} & u_{\text {early }} \\ & =a+b * \ln (E) \\ & u_{\text {late }}=a+b * E \\ & h=2 * u+u^{2} \end{aligned}$ | $\begin{aligned} & a_{\text {early }}=-0.1823 \\ & b_{\text {early }}=0.0928 \\ & a_{\text {late }}=0.0443 \\ & b_{\text {late }}=0.00088 \end{aligned}$ | n/a | 25\% | n/a | n/a |
| A7A AC | A7A | US | AC | n/a | Mixed | 45 | 1 | $\begin{aligned} & u_{\text {early }} \\ & =a+b * \ln (E) \\ & u_{\text {late }}=a+b * E \\ & h=2 * u+u^{2} \end{aligned}$ | $\begin{aligned} & a_{\text {early }}=-0.3602 \\ & b_{\text {early }}=0.212 \\ & a_{\text {late }}=0.0405 \\ & b_{\text {late }}=0.00378 \end{aligned}$ | n/a | 25\% | n/a | n/a |
| A4B56C | $\begin{aligned} & \mathrm{A} 4 \mathrm{~B}, \mathrm{~A} 5, \\ & \mathrm{~A} 6 \mathrm{C} \end{aligned}$ | US | TI | n/a | Gill net | 94 | 2 | $h=q * E$ | $q=$ stock specific | n/a | 60\% | $\mathrm{n} / \mathrm{a}$ | n/a |
| $\begin{aligned} & \text { A20 GN } \\ & \text { TF } \\ & \hline \end{aligned}$ | A20 | Can | TF | n/a | Gill net | 94 | 2 | $h$ | n/a | n/a | 60\% | $\mathrm{n} / \mathrm{a}$ | n/a |
| $\begin{aligned} & \hline \text { A20 PS } \\ & \text { TF } \\ & \hline \end{aligned}$ | A20 | Can | TF | n/a | Purse seine | 94 | 2 | $h$ | n/a | n/a | 25\% | n/a | n/a |
| $\begin{aligned} & \mathrm{A} 12 \mathrm{GN} \\ & \text { TF } \\ & \hline \end{aligned}$ | A12 | Can | TF | n/a | Gill net | 48 | 1 | $h$ | n/a | n/a | 60\% | $\mathrm{n} / \mathrm{a}$ | n/a |
| $\begin{aligned} & \text { A12 PS } \\ & \text { TF } \end{aligned}$ | A12 | Can | TF | n/a | Purse seine | 144 | 3 | $h$ | n/a | n/a | 25\% | $\begin{aligned} & 50,00 \\ & 0 \\ & \text { (acros } \\ & \text { s A12, } \\ & \text { A13) } \\ & \hline \end{aligned}$ | n/a |
| $\begin{aligned} & \text { A13 PS } \\ & \text { TF } \end{aligned}$ | A13 | Can | TF | n/a | Purse seine | 91 | 2 | $h$ | n/a | n/a | 25\% | $\begin{aligned} & \hline 50,00 \\ & 0 \\ & \text { (acros } \\ & \text { s A12, } \\ & \text { A13) } \\ & \hline \end{aligned}$ | n/a |
| $\begin{aligned} & \text { A29 Cott } \\ & \text { TF } \end{aligned}$ | A29 <br> (Cottonwood) | Can | TF | n/a | Gill net | 35 | 1 | $h$ | n/a | n/a | 60\% | n/a | n/a |
| A29 <br> Whonn TF | A29 <br> (Whonnock) | Can | TF | n/a | Gill net | 35 | 1 | $h$ | n/a | n/a | 60\% | $\mathrm{n} / \mathrm{a}$ | n/a |

## B. In-Season Assessments

## B1. PSC Test Fisheries

## E. Taylor

## Summary

The Pacific Salmon Commission funds and operates test fisheries to inform bilateral decisions of the Fraser River Panel through the collection of data on Fraser River sockeye and pink salmon in southern British Columbia and northern Washington State. These test fisheries provide information on abundance, timing, and diversion rates as well as species and stock composition information for use in stock assessments to inform fisheries management. PSC Secretariat involvement in these test fisheries ranges from financial assistance to complete responsibility for day-to-day operations. This report outlines the purpose of Panel approved PSC test fisheries, administrative responsibilities, as well as funding of the test fishing program.

## Introduction

The Pacific Salmon Commission (PSC), and its predecessor the International Pacific Salmon Fisheries Commission, have operated test fisheries to obtain data required to inform bilateral decisions of the Fraser River Panel since the 1960s. These test fisheries are authorised under the Pacific Salmon Treaty to assess Fraser River sockeye and pink salmon and occur in three key geographic areas (Figure 1): the northern and southern marine approaches to the Fraser River (Johnstone Strait, and the Strait of Juan de Fuca, respectively) and the lower Fraser River.


Figure 1. Map of PSC test fisheries, consisting of marine test fisheries in Johnstone Strait (Round Island and Naka Creek gillnet test fisheries, Upper (Area 12/Blinkhorn) and Lower (Area 13) Johnstone Strait purse seine fisheries) and Juan de Fuca Strait (Area 20 gillnet and purse seine test fisheries, Neah Bay (Area 4B,5) gillnet test fishery, Area 7 US reef net test fishery), in the Strait of Georgia (Gulf troll test fishery) and in-river gillnet test fisheries at Cottonwood, Brownsville Bar, Whonnock and Qualark.

Test fishing is the deployment of fishing efforts to gather information about fish either moving through or residing in a particular area. This is done by deployment of consistent fishing effort in a particular
area so that quantitative catch and biological data can be used for fisheries stock assessments (Chapter B19). Test fisheries are sometimes equipped with specialized fishing gear in order to target or avoid certain species or stocks. Additionally, test fisheries have observers aboard the vessels to monitor effort and catch (Chapter B2) as well as collect biological data and samples (Chapter B5) for use in stock assessment. Gear types used by the PSC test fisheries include purse seines, gill nets (both single and variable mesh), troll/hook and line, and reef nets.

Table 1. Overview of PSC test fisheries, currently approved by the Fraser River Panel, in terms of the area of operation, administrative responsibility, period of operation, gear used, species and management group assessed, monitoring purpose, data use and derived abundance estimates.

\begin{tabular}{|c|c|c|c|c|c|c|c|c|c|c|c|c|c|}
\hline \& \& \& \& \& rent Pa \& anel app \& proved \& PSC tes \& t fisher \& \& \& \& \\
\hline \&  \&  \&  \&  \&  \&  \&  \&  \&  \&  \&  \&  \&  \\
\hline \begin{tabular}{l}
Region \\
Fraser River \& Georgia Strait Juan de Fuca Strait \& US Waters Johnstone Strait
\end{tabular} \& X \& X \& X \& X \& X \& X \& X \& X \& X \& X \& X \& X \& X \\
\hline \begin{tabular}{l}
Panel Area \\
Panel Area Waters \\
Non-Panel Area Waters
\end{tabular} \& X \& X \& X \& X \& X \& X \& X \& X \& X \& X \& X \& X \& X \\
\hline \begin{tabular}{l} 
Period of operation \\
1960s \\
1970s \\
1980s \\
1990s \\
2000s \\
2010s \\
2020s \\
\hline
\end{tabular} \& \[
\begin{aligned}
\& \mathrm{X} \\
\& \mathrm{x} \\
\& \mathrm{X} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \hline
\end{aligned}
\] \& \[
\begin{aligned}
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \hline
\end{aligned}
\] \& \[
\begin{aligned}
\& \mathrm{X} \\
\& \mathrm{x} \\
\& \mathrm{X} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \hline
\end{aligned}
\] \& \[
\begin{aligned}
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \hline
\end{aligned}
\] \& \[
\begin{aligned}
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \hline
\end{aligned}
\] \& \[
\begin{aligned}
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \hline
\end{aligned}
\] \& X \& \[
\begin{aligned}
\& \mathrm{X} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \hline
\end{aligned}
\] \& X
x
x
x
x \& \[
\begin{aligned}
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \hline
\end{aligned}
\] \& \[
\begin{aligned}
\& x \\
\& x \\
\& x \\
\& \hline
\end{aligned}
\] \& X
X
X
X \& \[
\begin{aligned}
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \hline
\end{aligned}
\] \\
\hline \begin{tabular}{l}
Gear \\
Gillnet \\
Purse Seine \\
Troll Reefnet
\end{tabular} \& X \& X \& X \& X \& X \& X \& X \& X \& X \& X \& X \& X \& X \\
\hline \begin{tabular}{l}
Mangement group \\
Early Stuart \\
Early Summer \\
Summer \\
Late run \\
Pink
\end{tabular} \& \[
\begin{aligned}
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x}
\end{aligned}
\] \& \[
\begin{aligned}
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \hline
\end{aligned}
\] \& \[
\begin{aligned}
\& x \\
\& x \\
\& x
\end{aligned}
\] \& X \& X \& \[
\begin{aligned}
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \hline
\end{aligned}
\] \& \[
\begin{aligned}
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x}
\end{aligned}
\] \& \[
\begin{aligned}
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \hline
\end{aligned}
\] \& X \& X
X
X \& \[
\begin{aligned}
\& x \\
\& x \\
\& x
\end{aligned}
\] \& \[
\begin{aligned}
\& x \\
\& x \\
\& x \\
\& x
\end{aligned}
\] \& X
\(\mathrm{X}^{*}\)
\(\mathrm{X}^{*}\)
\(\mathrm{X}^{*}\)
\(*\) \\
\hline \begin{tabular}{l}
Monitoring purpose \\
Core in-season assessment Qualitative \\
Quantitative Research
\end{tabular} \& X \& \[
\begin{aligned}
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X}
\end{aligned}
\] \& \[
\begin{aligned}
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X}
\end{aligned}
\] \& x \& \[
\begin{aligned}
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X}
\end{aligned}
\] \& \[
\begin{aligned}
\& x \\
\& x \\
\& x
\end{aligned}
\] \& \[
\begin{aligned}
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x}
\end{aligned}
\] \& \[
\begin{aligned}
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X}
\end{aligned}
\] \& \[
\begin{aligned}
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X}
\end{aligned}
\] \& X
x \& X \& X \& \[
\begin{aligned}
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \mathrm{X} \\
\& \hline
\end{aligned}
\] \\
\hline \begin{tabular}{l}
Data uses \\
Timing \\
Abundance \\
Stock ID \\
Diversion \\
Specie composition \\
Harvest rate \\
Late-run management \\
Pink management \\
Project Mission escapement \\
Project abundance entering US International allocation Verification
\end{tabular} \& \begin{tabular}{l}
\[
\begin{aligned}
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x}
\end{aligned}
\] \\
X \\
X \\
X
\end{tabular} \& \[
\begin{aligned}
\& \mathrm{X} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x}
\end{aligned}
\] \&  \& \begin{tabular}{l}
X \\
X \\
X \\
X \\
x \\
X \\
X \\
X
\end{tabular} \& \[
\begin{aligned}
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \mathrm{x} \\
\& \hline
\end{aligned}
\] \& \[
\begin{gathered}
\mathrm{x} \\
\mathrm{x} \\
\mathrm{x} \\
\mathrm{x} \\
\mathrm{x} \\
\mathrm{x} \\
\mathrm{x} \\
\mathrm{X}
\end{gathered}
\] \& \begin{tabular}{l}
X \\
x \\
X \\
X
\end{tabular} \& \[
\begin{gathered}
\mathrm{X} \\
\mathrm{x} \\
\mathrm{X} \\
\mathrm{x} \\
\mathrm{x} \\
\mathrm{x} \\
\mathrm{x} \\
\mathrm{X}
\end{gathered}
\] \& \begin{tabular}{l}
X \\
X \\
X \\
X \\
X
\end{tabular} \& \[
\begin{aligned}
\& \mathrm{x} \\
\& \mathrm{x}
\end{aligned}
\] \& X \& X
x
x

x

x \& | X |
| :--- |
| X |
| X | <br>

\hline | Estimate abundances in |
| :--- |
| Marine areas Commercial catches US Waters Strait of Georgia Fraser River at Mission | \& \[

$$
\begin{aligned}
& \mathrm{X} \\
& \mathrm{x} \\
& \mathrm{x} \\
& \mathrm{x}
\end{aligned}
$$

\] \& \[

$$
\begin{aligned}
& \mathrm{X} \\
& \mathrm{X} \\
& \mathrm{X} \\
& \mathrm{X} \\
& \mathrm{X}
\end{aligned}
$$

\] \& \[

$$
\begin{aligned}
& \mathrm{X} \\
& \mathrm{X} \\
& \mathrm{X} \\
& \mathrm{X} \\
& \mathrm{X} \\
& \hline
\end{aligned}
$$

\] \& \[

$$
\begin{aligned}
& \mathrm{X} \\
& \mathrm{X} \\
& \mathrm{X} \\
& \mathrm{X} \\
& \mathrm{X}
\end{aligned}
$$

\] \& \[

$$
\begin{aligned}
& \mathrm{X} \\
& \mathrm{x} \\
& \mathrm{X} \\
& \mathrm{x} \\
& \mathrm{x} \\
& \hline
\end{aligned}
$$

\] \& X \& X \& \[

$$
\begin{aligned}
& \mathrm{X} \\
& \mathrm{x} \\
& \hline
\end{aligned}
$$

\] \& X \& \[

$$
\begin{aligned}
& x \\
& x
\end{aligned}
$$

\] \& \[

$$
\begin{aligned}
& \mathrm{X} \\
& \mathrm{x}
\end{aligned}
$$

\] \& \[

$$
\begin{aligned}
& x \\
& x
\end{aligned}
$$
\] \& <br>

\hline
\end{tabular}

[^2]
## Purpose of PSC Test Fisheries

The specific purposes of each PSC test fishery varies, but collectively their data are used in conjunction with information from the in-river hydro-acoustics program to provide in-season estimates of run size, timing and diversion of Fraser River sockeye and pink salmon management units. Table 1 provides an overview of the different PSC Panel approved test fisheries. The raw data provided by the test fisheries are catch by stock and species (based on sampling), effort, and other biological information such as age, sex, and weight (Chapter B6). Collectively across the test fishery program, these data are used as inputs to the PSC models to assess abundance (Chapter B18), timing, the diversion rate, stock (Chapters B7-B9) and species composition (Chapter B16), vulnerability (which stocks are susceptible to capture by particular gear in particular areas) and catchability (the proportion of the available abundance captured per unit of effort) (Chapters B3-B4). In addition to providing inputs into the PSC's in-season modeling process, the data from various test fisheries are sometimes used to project the magnitude of catches in potential fisheries. Individual test fisheries can also provide relevant information on local abundances for certain users. Finally, many of the test fisheries also catch non-target stocks and other salmon species, which provides an incidental source of information on those stocks and species.

During 2016 and 2017, two workshops were commissioned to compile available information on historic and existing test fisheries, to gather input from a variety of experts in both Canada and the United States, as well as to undertake technical analyses. The results of these workshops and resulting technical review was published in a technical report and provides further details regarding the purpose of the various test fisheries (Nelitz et al. 2018).

## ADMINISTRATION

Panel approved test fisheries are operated in-season to provide information to the Panel in support of Fraser River sockeye and pink salmon management. All Panel approved test fisheries are overseen by PSC Secretariat staff and the Panel. They are funded and approved through the Panel process and any decisions that 1) influence the financial state of the PSC test fishing program, 2) affect mortality of Fraser River sockeye and pink salmon, or 3) affect the Panels ability to manage Fraser River sockeye and pink salmon are made by the Panel with advice from PSC staff. In general, day-to-day operations are the responsibilities of PSC staff, DFO staff, and First Nations administrators and major decisions and direction is the responsibility of the Panel.

Test fisheries fall under two categories depending on whether they occur within Panel Area waters or not (Figure 2). Test fisheries occurring in Areas 12 and 13 as well as upstream of the Mission Bridge take place in Non-Panel Area waters, are operated by Fisheries and Oceans Canada (DFO), and involve administrative assistance from First Nations whose traditional territory the test fisheries are operated within. The test fisheries within Johnstone Strait are administered by the Namgis A-Tlegay Fisheries Partnership. The Qualark Gillnet test fishery, located in the Fraser canyon near Yale, is operated by DFO with support from Yale First Nation. DFO is responsible for selecting test fishing contractors and fish buyers. The remaining test fisheries occur within Panel Area waters and are operated by PSC Secretariat staff. Selection of test fishers and buyers, as well as financial accounting for these test fisheries are all performed by PSC Secretariat staff.

## Panel approved PSC test fisheries



Figure 2. Hierarchy table of Panel approved PSC test fisheries depending on location.

## FUNDING

The funding of test fisheries has changed substantially over the years. In 2006, a decision from the Federal Court of Canada determined that it was illegal for the federal government to set aside a portion of a public resource, i.e. fish, to finance research activities (Larocque v. Canada 2006). Prior to the Larocque decision, test fishers could be paid based on a portion of the value of the test fishing catch and fish could be retained above and beyond the amount needed to pay for the test fishing program. Between 2006 and 2012, the Canadian federal government's ability to retain fish to finance research activities was in flux. These years, referred to as "The Larocque Years", were characterized by changes to fisher payments and policies regarding the retention of fish. Fishers were required to be paid a fixed daily rate, and only fish required for samples and those unavoidably killed during test fishing activities could be sold. Currently, fishers are still paid a fixed rate but additional fish retention to fund test fishing activities is possible under the Test Fishing Policy (PSC 2021a).

While the test fishing program is generally funded through the sale of fish, recently the sale of fish from the test fisheries is insufficient to cover the costs of the test fishing program in most years. In this case, Canada and the US are responsible for funding the remainder of the test fishing costs and do so through the use of the Test Fishing Revolving Fund (TFRF). The PSC maintains the TFRF to stabilize the financial status of the PSC test fishing program. Contributions to the revolving fund are either made directly by the Parties, or from surpluses from the sale of fish caught and retaining in the test fisheries. Withdrawals from the revolving fund occur in years where test fishing operational costs exceed incomes generated from the sale of fish. The Test Fishing Policy and Financial Regulation was developed by the Parties in 2021 to outline the criteria required for the discretionary retention of fish as well as to define the regulations determining how deficits and surpluses would be shared by the Parties (PSC 2021b).

## Planned Changes and Potential Areas for Improvement

Many of the planned changes and potential areas of improvement are outlined in the Summary of a Review of Fraser River Test Fisheries (Nelitz et al. 2018). In addition, there are ongoing modifications to the test fishing program to reduce costs and increase the information gained per dollar spent.

## References

Larocque v. Canada 2006. FCA 237, Décary J.A., judgment dated 23/6/06, 20 pp.
Nelitz, M., Hall, A., Michielsens, C.G.J., Connors, B., Lapointe, M., Forrest, K., and Jenkins, E. 2018. Summary of a Review of Fraser River Test Fisheries. Pacific Salmon Comm. Tech. Rep. No. 40: 155p.

PSC 2021a. Pacific Salmon Commission Test Fishing Policy. Feb. 10, 2021. 3p.
PSC 2021b. Rule 25: Test Fishing Revolving Fund. Pacific Salmon Commission Bylaws. As amended February 11, 2021. 48 pp.

# B2. Catch-per-unit-effort (CPUE) Calculations 

## E. Taylor

## Summary

Catch-per-unit-effort (CPUE) is arguably the most important test fishing data to estimate abundances. The Pacific Salmon Commission (PSC) relies on four different test fishing gear types to assess the abundance of Fraser River sockeye salmon: 1) seine nets, 2) gill nets, 3) troll/hook and line, and 4) reef nets. In most cases the calculation of CPUE is based on catch and fishing effort, whereby the effort will be gear dependent. But in some cases, the CPUE may be corrected to account for gear saturation or other factors that may bias the relationship between abundance and CPUE. The following report provides an overview of the calculation of CPUE for the different PSC test fisheries.

## Introduction

As part of the Pacific Salmon Treaty agreements (PST 2020, Chapter 4), the Fraser River Panel is responsible for conducting test fisheries on Fraser River sockeye salmon. Test fishery data include catch-per-unit-effort (CPUE) data that, when multiplied by an expansion line (inverse catchability, Chapters B3B4), provides an estimate of daily abundance. CPUE data are calculated differently depending on the type of gear and the associated measure of fishing effort. The four gear types employed by PSC test fisheries are purse seine, gill net, troll, and reef net. Additionally, the in-river gill nets differ slightly from their marine counterparts and require the use of a catchability correction factor when catches are above a certain level. The following report will describe the calculation of CPUE for each of the four gear types.

## Data

Before discussing CPUE calculations, it is important to define what catch and fishing effort data will be used in the calculation of CPUE. During test fishing operations, the quality of catch data is often negatively impacted by weather, equipment failure, and/or tides and currents. Under these circumstances, the test fishing skipper and observer are asked to assign a quality score of 2,1 , or 0 to the collected data. A score of 2 signifies that the data is of good quality and there were no issues to note. A quality score of 1 signifies that there were one or more issues with the collected data, but that the skipper and observer agreed that the issues did not result in the catch being unrepresentative of what would have been caught had there been no issues. Finally, a quality score of 0 signifies that the skipper and observer deem the catch being unrepresentative of what would have been caught had no issues occurred. All catch data with a set quality score of 0 are marked as non-assessment data and are excluded from calculations of CPUE.

## Methods

## PURSE SEINE TEST FISHERIES

The calculation of sockeye CPUE in the purse seine test fisheries is the simplest among all the gear types, as the total sockeye purse seine catch on a given day (C) is divided by the number of assessment sets performed, i.e. the fishing effort (E):

$$
\text { (1) } \quad C P U E=\frac{C}{E}
$$

Under normal circumstances, the purse seine test fisheries perform six sets per day. In case of mechanical failure or in case the quality of a set is deemed compromised, the number of sets and the catch are adjusted accordingly.

## GILLNET TEST FISHERIES

Gillnet test fishery CPUE calculations are a bit more complicated as gill net fishing effort (E) calculations consider the length of the net as well as the length of time the fishing net is in use, i.e., the soak time:

$$
\begin{equation*}
E=\frac{\text { Net Length }(\text { fathom }) \times \text { Soak Time }}{1000} \tag{2}
\end{equation*}
$$

The soak time is calculated as the time the net is entirely in the water, plus half of the time that it takes to set the net and to retrieve it:
(3) $\quad$ Soak Time $=$ Start Out Time - Full In Time


The CPUE is then calculated by the total number of sockeye caught, divided by fishing effort (equation 1).

The efficiency of salmon gill nets is affected by several technical and biological factors. One such technical factor, gear saturation, occurs when the gill net loses its efficiency as a greater number of target individuals are present in the net. In the lower Fraser River gillnet test fisheries, this saturation results in a reduced catch rate or catchability through either space limitation, or gear avoidance. Catchability corrections factors are used to adjust the catch rate when the total number of salmon caught in the gill net is so large that it restricts the catch rate of additional salmon. Historically, a catch level of 50 total salmon in a single set is thought to be the point where the relationship between total salmon CPUE and total salmon catch begins to become non-linear, to the extent that a catchability correction factor should be applied.

When the total salmon catch is larger than 50 , the sockeye CPUE is calculated as:

$$
\begin{equation*}
\text { CPUE } E_{\text {sockeye }}=C_{\text {sockeye }} \times \text { correction factor } \tag{4}
\end{equation*}
$$

The methodology used to calculate a correction factor is the slope of the regression line fitted through catch and CPUE data of sets with less than 50 salmon caught. Under these conditions, it is believed that gear saturation is minimal. The total salmon catch is the independent variable and the uncorrected total salmon CPUE is the dependant variable. When this linear regression is performed, the intercept is forced to zero. Figure 1 illustrates the derivation of the correction factor for the Whonnock sockeye gillnet test fishery.

This regression is re-run each year separately for the Whonnock and Cottonwood gillnet test fisheries. The analysis is performed on a subset of historical data, based on the fisher, the net used, and recency. Updates to the gill net correction factor are only made when it deviates substantially from other years. Analyses have not been performed to determine quantitatively the catch level where the relationship becomes non-linear.


Figure 1. Salmon catch and catch-per-unit-effort (CPUE) in Whonnock gillnet test fishery sets in the years 2010, 2014, and 2018. The blue line represents a slope of 0.15 and was generated by running a linear regression on sets where less than 50 salmon were caught. As total salmon catch increases past 50, the salmon CPUE does not continue to increase linearly. This effect is believed to be due to gear saturation of the gill net.

## TROLL TEST FISHERIES

CPUE in hook and line fisheries are tricky measures to estimate. It is obvious that effort is some function of time and the amount of gear used, however, once a hook has caught a fish, it is no longer fishing. The dynamics of the decline in effort of a fishing line with hooks was the subject of a study in 1989 (Cave, unpublished). It concluded that unbiased measures of CPUE (catch/1000 hook-minutes) were well related to gross measures of catch, total minutes fished, and average number of hooks per line. Unbiased sockeye CPUE ${ }_{s}$ was calculated as (Cave 1997):

$$
\begin{equation*}
C P U E_{S}=\frac{C_{S}}{C_{T}} e^{\left(i+a_{1} \ln C P U E_{T}+a_{2}\left(\ln C P U E_{T}\right)^{2}\right)} \tag{5}
\end{equation*}
$$

Where $C_{s} / C_{T}$ is the proportion of sockeye $(s)$ in the total catch $\left(C_{T}\right)$ and $C P U E_{T}$ is the unadjusted allspecies catch-per-unit-effort. The latter is based on the catch of all target and non-target species including shakers (under-sized juvenile salmonids) and effort in 1000 hook-minutes, calculated as:

$$
\begin{equation*}
\text { Effort }=\frac{\text { Total hooks } \times \text { total minutes fished }}{1000} \tag{6}
\end{equation*}
$$

The regression constants are $i=0.123, a_{1}=1.012$ and $a_{2}=0.0746$.
The PSC Troll test fishery fishes in six different statistical areas called quadrants. The CPUE for a survey period is estimated by weighing the CPUE of each quadrant by the proportion $\left(P_{q}\right)$ each quadrant represents of the survey area:

$$
\begin{equation*}
C P U E=\sum_{q=1 \rightarrow 6}\left(C P U E_{q} \times P_{q}\right) \tag{7}
\end{equation*}
$$

The proportions of the total survey area by quadrant are listed in Table 1.

Table 1. The six quadrants sampled by the PSC Troll test fishery and their proportion of the total Area Surveyed.

| Quadrant (q) | Proportion of total <br> survey Aera $\left(\boldsymbol{P}_{q}\right)$ | Quadrant (q) | Proportion of total <br> survey Aera $\left(\boldsymbol{P}_{q}\right)$ |
| :--- | :--- | :--- | :--- |
| Quadrant 1 | 0.148 | Quadrant 1 | 0.262 |
| Quadrant 2 | 0.171 | Quadrant 2 | 0.178 |
| Quadrant 3 | 0.176 | Quadrant 3 | 0.065 |

## REEF NET TEST FISHERIES

The CPUE in the reef net test fisheries is referred to as counts per minute ( $\mathrm{C} / \mathrm{Min}$ ). Fishing effort in the reef net test fishery is strictly the number of minutes spent counting. There are no adjustments made to CPUE based on fish abundance or counting conditions.

## Planned Changes and Potential Areas for Improvement

Under the current workflow, gill net correction factors are calculated pre-season based on historic data and this correction factor is applied to in-season catches. In the future, it may be beneficial to calculate season specific correction factors and make in-season adjustments to the daily CPUEs.

## References

Cave, J. 1997. Review of Area 29 Troll Test Fishing. PSC Memo. 17 p.
PST. 2020. Treaty between the government of Canada and the government of the United States of America concerning Pacific salmon as modified through January 2020.

# B3. In-river Catchability Estimates 

## S. Wong and M.J. Hague

## Summary

Mission hydroacoustic data is the primary source for estimating daily sockeye salmon abundances in the lower Fraser River. However, in cases when sockeye estimates based on hydroacoustic data are either (1) unavailable, or (2) unreliable due to dominance of other salmon species, catch-per-unit-effort (CPUE) data from the Whonnock test fishery can provide alternative sockeye passage estimates. However, high variability in the historical Whonnock expansion line (inverse of the catchability) results in uncertain abundance estimates when derived from CPUE data. The following report describes the derivation of the historical expansion line (EL) estimates that can be applied in-season to estimate sockeye passage in the absence of hydroacoustic assessments (Chapter B18). It also describes the criteria used to decide when historical expansion lines should be adjusted based on the information observed in-season.

## Introduction

As part of the Pacific Salmon Treaty agreements (PST 2020, Chapter 4), the Fraser River Panel is responsible for the enumeration of sockeye and pink salmon escapement in the Fraser River. Traditionally this is done through the collection of hydroacoustic data at Mission, B.C. (Chapter B10). The resulting total salmon estimates are divided among the species present through the application of species composition estimates derived from test fishing catches collected by the gillnet test fishery at Whonnock (Chapter B16). On odd years, when pink salmon are the dominant species (late August September) and the uncertainty associated with the species composition is large, sockeye abundance is instead derived directly from the Whonnock catch-per-unit effort (CPUE) by multiplying this estimate with an in-river expansion line (1/catchability). In addition, Whonnock CPUE-based abundance estimates are also used when the Mission hydroacoustic program is not operational, e.g., during high discharge periods, before the hydroacoustic program has started, or after it has shut down for the season.

CPUE-based abundance estimates rely on catchability estimates which are derived based on historical observations of CPUE and abundance. It is a well-recognized fact that catchability can vary across a multitude of factors and rarely displays a linear relationship with fish abundance (Brannian 1982). As such, Whonnock CPUE-based estimates of sockeye salmon abundance are inherently more uncertain than hydroacoustic-based estimates. An understanding of the key variables that affect the Whonnock expansion line is therefore critical to determine what expansion line estimate should be applied to inseason CPUE data to produce the best abundance estimates and reduce the associated uncertainty. The following report describes the method used to derive historical sockeye expansion line estimates for the in-river gillnet test fishery at Whonnock as well as the criteria used to decide when historical expansion lines should be adjusted based on the information observed in-season.

## Data

The primary purpose of the Whonnock gillnet test fishery in the lower Fraser River is to collect species composition information (Nelitz et al. 2018). When using CPUE data from this test fishery to derive sockeye abundance, the associated catchability or expansion line (1/catchability) needs to be estimated based on historical data. Expansion lines are calculated by dividing an estimate of "true" abundance,
such as hydroacoustic-based passage, by test fishery CPUE. For this analysis, historical CPUE data and hydroacoustic-based sockeye abundance estimates in the lower Fraser River from 2008 to 2020 were used. The CPUE data were derived by dividing the number of gilled and girthed sockeye salmon by the fishing effort. The fishing effort in turn was derived by multiplying the length of the fishing net/1000 by the fishing time, i.e., the time the whole net is in the water plus half of the setting and picking time.

In addition to the Whonnock test fishery data and sockeye abundance estimates, a series of associated metadata were included in the analyses to evaluate trends, i.e. information about the day, year, and fishing location (Whonnock Channel or Glenn Valley Bar). Additional covariates were explored to evaluate their impact on catchability: total catch, sockeye catch, sockeye passage, number of seals, discharge levels, water temperature and wind direction (Table 1).

For the in-season application of expansion line estimates, the corrected CPUE data from the test fishing database were used. The correction factor applied to gillnet CPUE data accounts for the saturation effect. In addition, only days with total gilled, girthed and tangled catch of at least five fish were used to calculate the historical expansion lines and applied to in-season CPUE data.

## Methods

The analysis of the in-river expansion line only included CPUE data for days where at least five sockeye were caught, to remove the impact of small sample sizes on the uncertainty associated with the expansion line. To further reduce the impact of the variability in test fishing catches on the analysis, expansion line estimates had been based on six days of observations, identical to the approach applied to derive expansion line estimates for marine test fisheries. Therefore, expansion line estimates for a given day were calculated using total passage and total CPUE over six days, covering three days before and two days after the day of interest. If a 6-day period contained less than 4 days with sufficient catches, the estimates for this period were not included in the analysis.

Correlation and trend analyses such as linear regressions (in case of continuous variables) and ANOVAs (in case of categorical variables) were conducted to identify covariates that could explain a significant proportion of the historical variance in expansion lines with the aim to improve in-season predictions. Because of the noted temporal trend in the expansion line estimates across the season, additional cross correlation analyses were conducted for the other covariables that removed the effect of the day of the year on the expansion line. Because the change in expansion line across the season is not necessarily linear, the expansion line data were also summarized by calculating the mean expansion line over a period of two weeks based on the geometric means of the daily estimates across subsets of years. This allowed to assess trends across all years, all years excluding the 2018 cycle line, by cycle line, even years only, and odd years only.

## Results

There is a high degree of variability in historical expansion lines - with values based on 6 days of data ranging from 558 to 109,978 after the catch threshold of $\geq 5$ sockeye salmon was applied (Figure 1). Regressions between expansion line and day demonstrated a positive correlation ( $R^{2}=0.28, p$-value $<$ 0.001 ), with expansion line increasing throughout the season (Figure 1B). This trend was consistent across years, with greater variation in expansion lines within than between years (Figure 1). In addition to the temporal trend, significant correlations were noted for several covariates: sockeye passage, total catch, discharge, fishing location, sockeye catch and water temperature, even though the correlation for the latter two were very low, with an $\mathrm{R}^{2}$ of 0.09 and 0.03 , respectively. The differences in expansion lines between fishing location was significant but this was mainly due to differences in discharge as the test fishery was most often in operation at Glen Valley Bar during periods of high discharge earlier in the
season. Year, seal presence and wind direction were unable to explain the variation in expansion lines. In the case of seal predation, this could be due to the uncertainty in the seal data, which are based on visual observations from the observer aboard the test fishing vessel.


Figure 1. Boxplot of 6-day expansion lines by year (A) and by in-season period across years (B).

Alternatively, multiple regression models with interactions between day or discharge, and catch, passage or water temperature generally explained more variation in the expansion line data than models without the interaction term. The two co-variates which explained the greatest percentage of the historical variability in Whonnock expansion line were day and sockeye passage past Mission (Table 1). Given that expansion lines are derived based on total sockeye abundance, it makes sense that sockeye passage explained a lot of the variation in expansion line, but it would not be possible to utilise this variable in-season as typically CPUE-based abundance estimates are needed in-season when hydroacoustic-based sockeye abundances are not available or unreliable. Day of the year is a good proxy for abundance, with abundances being low for Early Stuart and increasing later in the season when Summer-run and Late-run sockeye enter in the river. This explains the significant correlation of the expansion line with day.

Table 1. Overview of the relationship between expansion line and various covariates. When the variable was continuous, a linear regression was performed, and the table notes the coefficient of determination (R2) and if the correlation was significant (*, p-value < 0.001). When the variable was categorical, an ANOVA was performed and significance ( ${ }^{*}, p$-value $<0.001$ ) indicates that the variation in expansion line between groups is larger than the within-group variation.

| Variable | $\mathbf{R}^{\mathbf{2}}$ |  |  |
| :--- | :---: | :---: | :---: |
|  | Expansion Line <br> $\sim$ <br> $\sim$ | Expansion Line <br> $\sim$ <br> $\sim$ | Variable * Day <br> Variable |
| Day | $0.28^{*}$ | - | - |
| Year | 0.003 | - | - |
| Fishing location | $*$ | - | - |
| $\log _{10}$ Total catch | $0.17^{*}$ | $0.37^{*}$ | $0.30^{*}$ |
| $\log _{10}$ Sockeye catch | $0.09^{*}$ | $0.32^{*}$ | $0.22^{*}$ |
| $\log _{10}$ Sockeye passage at Mission | $0.30^{*}$ | $0.45^{*}$ | $0.36^{*}$ |
| Number of seals present $^{\text {Discharge }}$ | - | - | - |
| Water temperature | $0.15^{*}$ | - | - |
| Wind direction | $0.03^{*}$ | $0.27^{*}$ | $0.16^{*}$ |

The pattern in abundance is not consistent across years but differs by cycle line, with the dominant 2018 cycle line seeing a sharper increase in sockeye abundance compared to other cycle line years when later-timed Early Summer-run sockeye enter into the river. On 2020 cycle line years, overall abundance trends downward faster compared to other years, while on odd cycle line years it is the increase in pink abundance later in the season that increases overall salmon abundance. Summarising the historical expansion line data for two-week periods shows a stepwise increase in expansion lines across the season (Table 2) that fits well to the observations across all years (Figure 2). Across cycle lines, the 2018 cycle line shows an increase in expansion line in the beginning of August while on odd years, this increase only occurs in September when pink salmon increase overall salmon abundance in the river. In comparison, on 2020 cycle years, most of the run would have already migrated past Mission at the start of September.

Table 2. Average historical Whonnock sockeye expansion lines for 2-week periods for different year subsets based on corrected CPUE data for days with total sockeye catch $\geq 5$ salmon.

| Mission <br> date |  |  |  |  |  |  |  |  |
| :--- | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | All <br> years | Even <br> years | Odd <br> years | $\mathbf{2 0 1 8}$ <br> Cycle | $\mathbf{2 0 1 9}$ <br> Cycle | $\mathbf{2 0 2 0}$ <br> Cycle | $\mathbf{2 0 2 1}$ <br> Cycle | All excl. <br> 2018 cycle |
| Jul 1-15 | 6,799 | 6,320 | 7,744 | 7,083 | - | 5,480 | 7,744 | 6,626 |
| Jul 16-31 | 9,801 | 10,272 | 10,287 | 10,217 | 8,021 | 11,076 | 11,186 | 9,687 |
| Aug 1-15 | 12,001 | 13,093 | 10,775 | 17,661 | 10,044 | 10,546 | 12,011 | 10,639 |
| Aug 16-31 | 11,623 | 10,817 | 12,714 | 13,672 | 13,948 | 8,395 | 11,659 | 12,036 |
| Sep 1-15 | 15,553 | 15,553 | - | 15,553 | - | - | - | - |
| Sep 16-30 | 21,662 | 21,662 | - | 21,662 | - | - | - | - |



Figure 2. Average historical expansion lines across two-week periods based on geometric average 6-day expansion lines across various year subsets, i.e., all years, odd years, even years, all years excluding 2018 cycle line, 2018 cycle line. The geometric means of the 6-day expansion lines across all years are presented as grey dots. Historical expansion lines were calculated using corrected CPUE data from the test-fishing database for days with at least 5 salmon caught.

## IN-SEASON APPLICATION

In absence of other sources of in-season information, the historical expansion line estimates (Table 2, Figure 2) can be applied directly to corrected Whonnock CPUE data. Given the limited historical data available early in the season, averages should be calculated across all years until July $15^{\text {th }}$ (Figure 3). Later in the season, the expansion line applied may vary by cycle year and depend on the correspondence of the historical expansion lines with the expansion line observed in-season. In case the historical expansion line deviates substantially with the in-season estimates (for periods dominated by sockeye salmon when such comparisons can be made), the average ratio between observed and historical expansion lines can be used to rescale the historical expansion line up or down for the remainder of the season. This approach both adjusts for in-season conditions while still accounting for historical patterns of seasonality. Given the high variability in CPUE based abundance estimates, the implied species composition estimate should continuously be monitored and compared to other observations of species composition to ensure resulting sockeye abundance estimates fall within realistic ranges. A full overview of the decisions in terms of in-season expansion line estimates can be found in Figure 3.


Figure 3. A decision-flow diagram for selecting in-season Whonnock expansion line estimates to estimate daily sockeye abundances.

## Planned Changes and Potential Areas for Improvement

Current results are based on a limited dataset that only includes 2008-2020. Data are especially limited at the start and the end of the season, especially on non-dominant years (years excluding the 2018 cycle). This especially impacts sockeye abundance estimates on odd years when pink salmon are in the river as the assumed expansion line will have been mainly derived from data collected when no pinks were in the river and when Late-run stocks were dominating sockeye abundance. The potential bias this may create should be examined. In addition, while the two-week periods generally match the pattern of increasing expansion line well throughout the season, resulting abundance estimates are more likely to be biased around the time of the step increase. The impacts of using a stepped method rather than a linear increase could be further investigated. Finally, knowledge from fishers suggests that both water clarity and fish size impact catchability and thus could potentially aid in exposing patterns in expansion lines.

## References

Brannian, L.K. 1982. The estimation of daily escapement and total abundance from catch per unit effort of the sockeye salmon fishery in Togiak Bay, Alaska. Masters thesis, University of Washington, Seattle.

Nelitz, M., Hall, A., Michielsens, C.G.J., Connors, B., Lapointe, M., Forrest, K. and Jenkins, E. 2018. Summary of a review of Fraser River test fisheries. PSC Technical Report: 40.

PST. 2020. Treaty between the government of Canada and the government of the United States of America concerning Pacific salmon as modified through January 2020.

# B4. Marine Catchability Estimates 

C.G.J. Michielsens

## Summary

In-season run size assessments for Fraser River sockeye salmon rely on estimates of daily abundance (Chapter B18). The most seaward daily abundance estimates come from marine test fisheries in Johnstone Strait (Area 12) and Juan de Fuca Strait (Area 20). The catch-per-uniteffort (CPUE) data from these test fisheries (Chapter B2) can be used in combination with an expansion line estimate (inverse catchability) to derive daily abundances. At the start of the season, a historical expansion line estimate is applied, derived from data for past years. Due to the high variability in expansion lines, both between years and within a season, the predicted abundances based on CPUE data used in combination with historical expansion lines may deviate substantially from reconstructed abundances based on Mission hydroacoustic data and seaward catch. Predicted abundance estimates can be improved if the expansion line is updated using in-season observations. The following report provides an overview of the evaluation of different historical and in-season expansion line estimates for marine gillnet and purse seine test fisheries.

## Introduction

As part of the Pacific Salmon Treaty agreements (PST 2020, Chapter 4), the Fraser River Panel is responsible for conducting test fisheries on Fraser River sockeye salmon. Test fishery data include catch-per-unit-effort (CPUE) data, species composition and stock identification, and other biological metrics such as length, weight, and age. The CPUE data is a relative index that, when multiplied by an expansion line (inverse catchability), provides an estimate of daily abundance. There is a minimum 6-day lag before CPUE-based abundances can be aligned with reconstructed estimates derived from hydroacoustic data due to the travel time between marine test fishing locations and the lower Fraser River hydroacoustic site located near Mission, B.C. (Michielsens and Cave 2018). But while CPUE-based abundances provide more timely estimates, they are less accurate than reconstructed values due to the high degree of uncertainty in the associated expansion line. Early in-season, the expansion lines are based on historical data, but once there is sufficient overlap between CPUE-based and reconstructed timeseries, these estimates can be updated with in-season observations.

Early in-season, gillnet test fishing vessels are used to assess Early Stuart and Early Summer-run sockeye while purse seine data are traditionally used to assess Summer-run and Late-run stocks, and later-timed components of the Early Summer run (Nelitz et al. 2018). While the gillnet test fishery costs less to operate, the catchability is too low and uncertain to derive reliable abundance estimates for Summerrun and Late-run stocks. In Johnstone Strait, the Area 12 gillnet test fishery occurs at Round Island. Due to safety considerations, two gillnet vessels are used to assess abundance in the Area 20 of Juan de Fuca Strait. It is assumed to take 8 and 6 days, respectively, for sockeye observed in these gillnet test fisheries to reach the Mission hydroacoustic site. Traditionally, the primary purse seine test fishery in Johnstone Strait takes place in Area 12 ( 7 days seaward of Mission), but Area 13 ( 6 days seaward of Mission) offers an alternative test fishing location with a potentially higher catchability due to the narrower size of the Strait there. In Juan de Fuca strait, salmon encountered by the purse seine fishery in Area 20 take about 6 days to migrate to the Mission hydroacoustic site.

## Data

Expansion line analyses relied on daily CPUE data from both purse seine and gillnet test fishing vessels (Chapter B1) and daily reconstructed abundances based on Mission hydroacoustic estimates plus seaward catches (Chapter B18). Expansion line estimates were evaluated using data from 1998 to 2014. To reduce the impact of the variability in test fishing catches on the analyses, in-season expansion line estimates were based on six days of observations. A total of 524 matched Area 12 and Area 20 daily gill net CPUE estimates, 642 matched Area 12 and Area 20 purse seine CPUE estimates, and 602 matched Area 13 and Area 20 purse seine CPUE estimates were analyzed. To evaluate density dependence, total catch data for both sockeye and pink salmon were also included in the analyses. Sockeye stocks that delay their upriver migration by holding in the Strait of Georgia, such as Late run and Harrison stocks (Lapointe et al. 2003), were analyzed separately given that the variable delay and redistribution in the Gulf violates the "boxcar" migration assumptions required for run reconstructions (Cave and Gazey 1996).


Figure 1. Boxplot of 6-day gillnet and purse seine expansion line estimates across the season (1998 to 2014). Gill net estimates relate to Early Stuart, Early Summer-run and Summer-run stocks excluding Harrison while purse seine estimates relate to Summer-run excluding Harrison stocks. The high purse seine expansion lines in September are associated with low marine abundances.

## Methods

Optimizing the in-season application of expansion line (inverse catchability) estimates to daily CPUE data requires decision rules which have been obtained through retrospective analyses that evaluate the accuracy of different marine expansion line strategies to predict abundances at Mission 6 to 8 days later (Table 1). Due to time-varying trends (Figure 1) and density-dependent effects on catchability, simply applying the lagged observed expansion line values may not provide the best estimates. In addition, because in-season daily catchabilities cannot be calculated for delaying stocks, the validity of catchability estimates derived from other stock components must be assessed.

Using the data from 1998 to 2014, retrospective analyses for different expansion line strategies (Table 1) were performed by predicting the total annual abundances for a given stock group ( $\widehat{N_{y}}$ ) and comparing this to the observed total abundances ( $N_{y}$ ). The bias (i.e. mean percent error, MPE), and precision (i.e. mean absolute percent error, MAPE) of the predicted annual abundances were calculated using:
(1) $\quad$ MPE $=\frac{100}{\mathrm{n}} \cdot \sum \frac{\widehat{N}_{y}-N_{y}}{N_{y}}$
(2) $\quad \mathrm{MAPE}=\frac{100}{\mathrm{n}} \cdot \sum\left|\frac{\widehat{N}_{y}-N_{y}}{N_{y}}\right|$
where $\widehat{N_{y}}$ is the predicted total annual abundance, derived from the daily Johnstone Strait (A12 or 13) and Juan de Fuca Strait (A20) CPUE data and the expansion line (1/catchability, q):

$$
\begin{equation*}
\widehat{N_{y}}=\sum_{d}\left(\frac{C P U E_{y, d, A 20}}{q_{y, d, A 20}}+\frac{C P U E_{y, d, A 12}}{q_{y, d, A 12}}\right) . \tag{3}
\end{equation*}
$$

When using Area 13 purse seine data, catches seaward of the Area 13 purse seine test fishery ( $C_{y, d, S e a A 13}$ ) are added to predict the abundance in Area 12.

$$
\begin{equation*}
\widehat{N_{y}}=\sum_{d}\left(\frac{C P U E_{y, d, A 20}}{q_{y, d, A 20}}+\frac{C P U E_{y, d, A 13}}{q_{y, d, A 13}}+C_{y, d, S e a A 13}\right) \tag{4}
\end{equation*}
$$

For gillnet (GN) test fisheries, it was assumed that the sockeye catchability is the same in both test fisheries:
(5) $\quad q_{G N, A 20}=q_{G N, A 12}$.

The relative catchability of the different purse seine test fisheries was assumed to be related to the relative width of the area swept or sampled, i.e., the width of the migratory channel at the test fishing site in relation to the size of the fishing net. Because the relative width of the area swept in Johnstone Straight is 2.2 times larger than in Juan de Fuca Strait, it is assumed that the sockeye catchability of the purse seine test fishery in Area 12 is 2.2 times greater than in Area 20:
(6) $\quad q_{P S, A 12}=2.2 \cdot q_{P S, A 20}$.

Similarly, the catchability in Area 13 is assumed to be 1.5 times greater than the in Area 12 :
(7) $\quad q_{P S, A 13}=1.5 \cdot q_{P S, A 12}$.

Because the catchabilities of the different fisheries are assumed to be related, often only Area 20 expansion lines are reported ( $1 / q_{y, d, A 20}$ ).

Table 1 provides an overview of the main in-season expansion line strategies for the different stock groups and test fisheries that have been evaluated to determine the optimal approach for estimating $q_{y, d, A 20}$. Performance of the strategies was evaluated for different subsets of years: (1) all years, (2) recent 8 years since 2007, (3) high and low abundance years, (4) pink salmon (odd) years, and (5) by cycle line. In addition to the main strategies, additional strategies evaluated the length of days on which to base the in-season expansion line ( 6 days versus 1 days, 3 days, all dates to date) and the size of the adjustment to the expansion line. An expansion line strategy that relied on 6 days of in-season data for example would rely on daily reconstructed abundances and CPUE data observed 7 to 12 days prior because it takes an additional 6 days to travel from the marine test fishing locations to the lower Fraser River hydroacoustic site. The resulting Area 20 in-season expansion line is calculated as follows:

$$
\begin{equation*}
\frac{1}{\mathrm{q}_{\mathrm{d}_{1}, A 20}}=\sum_{d_{2}=d_{1}-7}^{d_{1}-12} N_{d_{2}, A 20} / \sum_{d_{2}=d_{1}-7}^{d_{1}-12} C P U E_{d_{2}, A 20} \tag{8}
\end{equation*}
$$

Adjustments to in-season expansion lines allowed to account for time-varying trends across the season and density-dependent effects. Adjustments had been implemented either by multiplying the in-season expansion line for Area $20\left(1 / q_{y, d, A 20}\right)$ with the adjustment or by adding or subtracting the adjustment.

Comparing performance using total abundance instead of daily estimates reduced the susceptibility of the analyses to violations in migration speed assumptions and reduced the weight of low abundance days while also increasing the importance of high abundance days. In addition, comparing total estimates allowed the same performance measures to be used to assess the expansion lines for delaying Late-run and Harrison stocks.

Table 1. Overview of the main expansion line strategies evaluated for different test fisheries and stock groups by comparing the MAPE and MPE. Additional strategies evaluated the length of days on which to base the in-season expansion line ( 6 days versus 1 day, 3 days, all days to date) and size of the adjustments to the expansion lines.

| Expansion line strategy | Gillnet data |  | Purse seine data |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  |  |  |  |  |
| Constant historical expansion line |  |  | X | X | X | X |
| Increasing historical expansion line depending on date | x | X |  |  |  |  |
| In-season expansion line based on observed 7-12 days prior | X |  | X | X |  |  |
| In-season observed expansion line for other groups |  | X |  |  | X | X |
| In-season expansion line adjusted | X |  | X | X |  |  |
| In-season observed expansion line for other groups adjusted |  | X |  |  | X | X |
| In-season observed expansion line, set-specific adjusted |  |  |  |  | X |  |
| In-season expansion line adjusted based on CPUE | x |  | X | x |  |  |
| In-season expansion line adjusted based on total catch | X |  | X | X |  |  |
| In-season expansion line adjusted, set-specific adjusted |  |  | X | X |  |  |

## Results

Using gillnet test fishery data, if the gradual increase in the historical expansion line is accounted for, the resulting run size estimates for Early Stuart, Early Summer and Summer run excluding Harrison are unbiased (Figure 2, a1, strategy 1) but the estimates will not be very precise (Figure 2, b1). Using an inseason expansion line increases the precision, but due to the lag in updating the observations, the resulting abundance estimates are biased low (Figure 2, a1 and b1, strategy 2 ). The bias can be corrected on average by multiplying the observed expansion line with a factor of 1.25 to account for the increasing trend (Figure 2, a1 and b1, strategy 3). Further improvements can be made by adjusting the expansion line depending on total daily catch, with smaller catch days requiring larger adjustments compared to larger catch days (Figure 2, a1 and b1, strategy 4, Table 2). When restricting the data to recent years, results are similar but slightly more pronounced (Figure 2, a2 and b2). Applying the same gill net expansion lines from non-Harrison stocks to estimate daily abundances for Harrison results in abundances that are too low, even if in-season adjusted expansion line estimates are used (Figure 1, a3). Assuming the expansion line for Harrison is double the expansion line for other stocks removes the bias and improves the precision of the daily estimates (Figure 2, a3, b3).

For purse seine test fishery data (Figure 3), in-season expansion lines are more precise than historical expansion estimates but, in the case of Summer run excluding Harrison, may slightly overestimate abundance unless the in-season expansion line is reduced (Figure 3, a1 and b1). Abundance estimates can be improved by adjusting the expansion line depending on total catch, with larger catch days requiring bigger downward adjustments (Table 2). Adjusting expansion lines of individual fishing sets does not seem to further improve abundance estimates. For Harrison sockeye, the best expansion line strategy relies on the in-season expansion line for Summer run excluding Harrison without adjustments (Figure 3, a2 and b2). For Late-run sockeye, the best strategy is also to rely on in-season expansion lines for Summer run but to adjust them based on total catch (Figure 3, a3 and b3). Using an historical expansion line of 230 for Late run results in unbiased but imprecise total run size estimates. A full overview of the recommended expansion line strategies is provided in Table 2.


Figure 2. Overview of the performance in terms of bias (MPE, a) and precision (MAPE, b) of different expansion line strategies evaluated for marine gillnet test fisheries targeting Early Stuart, Early Summer-run and Summer-run sockeye excluding Harrison across all years (a1 and b1), in recent years (a2 and b2) and Harrison sockeye across all years (a3 and b3). Expansion line strategies include: 1) increasing historical expansion line depending on date, 2) in-season expansion line, 3) adjusted in-season expansion line, 4) in-season expansion line adjusted based on catch, and 5) in-season expansion line with Harrison specific adjustment.


Figure 3. Overview of the performance in terms of bias (MPE, a) and precision (MAPE, b) of different expansion line strategies evaluated for marine purse seine test fisheries targeting Summer run excluding Harrison (a1 and b1), Harrison (a2 and b2) and Late-run sockeye (a3 and b3). Expansion line strategies include: 1) historical Summer run excluding Harrison expansion line, 2) in-season expansion line based on Summer run excluding Harrison, 3) adjusted in-season Summer run excluding Harrison expansion line depending on total catch, 4) set-specific adjustment of in-season Summer run excluding Harrison expansion line depending on total catch, and 5) historical Late run expansion line.

Table 2. Overview of the top performing expansion line strategies evaluated for different test fisheries and different stock groups through retrospective analysis of data covering 1998 to 2014.

| Gillnet catchability |  |
| :---: | :---: |
| Early Stuart, Early Summers, and Summers excl. Harrison | In-season expansion line $\times 1.25$ to account for time-varying expansion line trends. <br> Further improvement can be made depending on total catch: <br> - If total catch < 500, in-season expansion line x1.5 <br> - If $500<$ total catch < 1000, in-season expansion line x1 <br> - If total catch > 1000, in-season expansion line $\mathbf{x 0 . 9}$ <br> Prior to in-season estimates being available, rely on historical expansion line depending on date. |
| Harrison | In-season observed expansion line for Summer run excl. Harrison x 2 . Prior to in-season observed estimates being available, rely on historical Summer run excl. Harrison expansion line depending on date x 2 . |
| Late run | Insufficient data available to assess gillnet catchability. When needed, apply the same expansion line as other non-Harrison stocks. |
| Purse seine catchability |  |
| Early Summer, Summer run excl. Harrison | In-season expansion line -20 to account for slightly decreasing expansion line. Further improvement can be made depending on total catch: <br> - If total catch < 500, in-season expansion line <br> - If 500 < total catch < 10,000, in-season expansion line - 20 <br> - If total catch $>10,000$, in-season expansion line -40 <br> Prior to in-season estimates being available, rely on 180 historical expansion line. |
| Harrison | In-season observed expansion line for Summer run. <br> Prior to in-season estimates being available, rely on historical Summer run expansion line - 20. |
| Late run | In-season observed expansion line for Summer run. <br> Further improvement can be made depending on total catch: <br> - If total catch < 500, in-season expansion line Summer run +10 <br> - If 500 < total catch $<10,000$, in-season expansion line Summer run - 10 <br> - If total catch > 10,000, in-season expansion line Summer run - 50 Prior to in-season observed Summer run estimates being available, rely on historical Late run expansion line of 230. |

## Planned Changes and Potential Areas for Improvement

The above analyses include data up to 2014 and could be updated with more recent data. This is even more important in case of trends in catchability over time.

## References

Cave, J.D. and Gazey, W.J. 1994. A preseason simulation model for fisheries on Fraser River sockeye salmon (Oncorhynchus nerka). Can. J. Fish. Aquat. Sci. 51 :1535-1549.

Lapointe, M.F., Cooke, S.J., Hinch, S.G., Farrell, A.P., Jones, S., MacDonald, S., Patterson, D., Healey, M.C., and Van Der Kraak, G. 2003. Late-run sockeye salmon in the Fraser River, British Columbia are experiencing early upstream migration and unusually high rates of mortality: what is going on? In Proceedings of the 2003 Georgia Basin/Puget Sound Research Conference, Vancouver, B.C.

Nelitz, M., Hall, A., Michielsens, C.G.J., Connors, B., Lapointe, M., Forrest, K. and Jenkins, E. 2018. Summary of a review of Fraser River test fisheries. PSC Technical Report: 40.

PST. 2020. Treaty between the government of Canada and the government of the United States of America concerning Pacific salmon as modified through January 2020.

Michielsens, C.G.J. and Cave, J.D. 2019. In-season assessment and management of salmon stocks using a Bayesian time-density model. Can. J. Fish. Aquat. Sci. 76: 1073-1085.

# B5. Sampling Protocol 

A.M. Phung and D. Brkic


#### Abstract

Summary This report reviews the sampling protocol relevant to in-season assessments of sockeye salmon. DNA and scale samples are collected regularly from test fisheries, and opportunistically from commercial fisheries as fisheries occur. This sampling design is intended to provide up-to-date stock identification data for in-season Fraser River Panel (FRP) meetings which occur twice a week. Depending on the test fishery, it typically takes between 2 and 5 days from when a fish is caught and sampled to when the data are available at FRP meetings. The delay is affected by the geographic location of the fishery, the availability of shipping services, and how samples for various fisheries are prioritized depending on changing management needs. Commercial samples are obtained at fish plants. When sampling, one scale sample and one DNA sample are collected per fish and stored respectively in a scale book and on Whatman filter sheets. Scale samples are shipped to the Pacific Salmon Commission (PSC) Secretariat office where they are read, and the metadata is stored in a database. The DNA is shipped to the Pacific Biological Station for analysis. Once the DNA has been analyzed, the data are further processed by the stock identification biologists at the PSC Secretariat office.


## Introduction

During the in-season period, the Pacific Salmon Commission (PSC) operates a suite of test fisheries along the northern (Johnstone Strait) and southern (Juan de Fuca Strait) approaches and in the lower Fraser River (Chapter B1) to obtain an index of sockeye and pink abundance throughout their migration towards Mission (Chapter B18). DNA (Chapter B9) and scale (Chapter B7) samples collected from catches in marine test fisheries give an early indication of the ages and stock composition of salmon that are returning to the Fraser River. In addition to age of fish, scale samples provide information on growth rate and can potentially be used to determine the stock of origin. Lengths and weights of fish are also often recorded in test fishery and commercial fishery sampling (Chapter B6).

In addition to sampling of test fishing catches, commercial catches are also sampled in-season. The main objective of the commercial catch sampling program is to gather information from DNA samples, scale samples, and biological data in order to estimate stock composition of the total commercial catch. In comparison to test fisheries, which generally collect information on sockeye migration (i.e., all of the sockeye in an area at a given time), commercial fisheries are sampled with a focus on estimating catches. The number and magnitude of commercial fishery openings vary from year to year depending on sockeye run size. When run sizes are high, the large number of samples obtained from commercial fisheries may provide better representation of the sockeye catch than test fisheries. The information from commercial catch samples is used to help determine the relative exploitation of each of the Fraser River sockeye management groups within a commercial fishery opening. This information can also contribute to run-size assessments, especially when used complementary to data from the test fisheries.

During Canadian commercial fisheries openings, processing plants in the vicinities of Nanaimo and Vancouver are targeted for sampling landings. For commercial openings in northwest Washington State, processing plants in Bellingham are primarily targeted to sample landed catches.

## SAMPLING DESIGN

## Test Fisheries

The goal of sampling test fishery catches is to provide the most up-to-date stock composition information during in-season Fraser River Panel (FRP) meetings which occur on Tuesdays and Fridays. The geographic location of test fisheries coupled with limitations in air carrier services can lead to delays in data flow in-season. When fish are caught in Area 12 test fisheries, samples can take three (in the case of purse seine catch) to five (for gillnet catch) days until the stock composition data are available to be presented at the Friday FRP meetings. For the Tuesday FRP meeting, it can take three to four days after fish are caught to obtain Area 12 gillnet data and Area 12 purse seine data, respectively. When fish are caught in Area 20 test fisheries, samples can take two (purse seine) to three (gillnet) days until the data are available to be presented at the Tuesday or Friday Panel meeting. Purse seine samples are generally prioritized over gillnet samples as purse seine samples are considered to be more representative of the true population. This is because gill nets are believed to be selective towards certain stocks and fish that swim closer to the surface (Šmejkal et al. 2015), and because of sizeselectivity imposed by the mesh size. The sampling schedule for collecting biological information varies depending on the test fishery. Table 1 shows the sampling schedule for 2018 and lists the target daily sample sizes for each test fishery. A sample consists of one DNA tissue "punch" (obtained using a onehole punch on the adipose fin), one scale, and biological data including length, weight, and sex (Chapter B6). The schedule and sample sizes may vary between years depending on shipping logistics and size of the catch.

Table 1. Sockeye DNA and scale samples collected per day for each PSC test fishery.

| PSC test fishery | Number of boats | Schedule | DNA samples per day | Scale samples per day |
| :---: | :---: | :---: | :---: | :---: |
| Cottonwood | 1 | DAILY | 50 | 50 |
| Whonnock | 1 | DAILY | 50 | 50 |
| Area 20 Gill Net | 2 | Sun, Tues, Thurs, Sat | 100 | 115 |
|  |  | Mon, Wed, Fri | None | 115 |
| Area 20 Purse Seine | 1 | Sun, Mon, Wed, Fri | 100 | 115 |
|  |  | Tues, Thurs, Sat | None | 115 |
| Round Island Area 12 Gill Net | 1 | Sun, Tues, Fri | 100 | 115 |
|  |  | Mon, Wed, Thurs, Sat | None | 100 |
| Blinkhorn Area 12 Purse Seine | 1 | Sun, Tues, Thurs, Sat | 100 | 115 |
|  |  | Mon, Wed, Fri | None | 100 |
| Area 13 Purse Seine | 1 | Tues, Thurs, Sat | 100 | 115 |
|  |  | Sun, Mon, Wed, Fri | None | 100 |
| Naka Creek Area 12 Gill Net | 1 | Every 3-4 days | 100 | 100 |
| U.S. Area 4B,5 GN | 1 | DAILY | 100 | 100 |
| Qualark GN | 1 | DAILY | 50 | 50 |
| Gulf Troll | 2 | DAILY | (per boat) 100 | (per boat) 115 |
| U.S. Area 7 Reefnet | 3 | Twice a week | 100 | 115 |

## Commercial Fisheries

Commercial fishery samples are collected opportunistically as fisheries occur. Generally, the target for a sampling trip is to collect 100 samples from each commercial fishery opening by gear type and key statistical area if fish are caught. This usually results in about 200-300 samples per sampling trip. Some commercial fisheries are sampled more intensively than others depending on catch numbers, logistics, and utility of the collected information at the time to the FRP meeting. When sampling purse seine commercial fishery catches, ideally more than 100 samples would be collected per area as catches tend to be higher than for other gear types. Unlike test fisheries which follow a strict sample collection schedule outlined pre-season, samples for commercial fisheries are more challenging to plan for due to uncertainty around where and when catches are going to be landed. Table 2 provides a summary of guidelines for sampling frequency during a year with ample available TAC such as 2018. Canadian commercial catches from Areas B, D, E and H are sampled at fish plants in Vancouver while catches from Areas B, D, G and H are sampled at fish plants in Nanaimo. US commercial catches in Areas 7 and 7A are sampled at fish plants in Bellingham. In-season communication with fish plant representatives is crucial to planning sampling trips to maximize the amount of information that can be obtained.

When catches are large, commercial sampling may include ratio counts. Ratio counts involve estimating the proportion of rare, visually identifiable fish types (e.g., adipose-clipped fish and/or jacks) to other fish within the catch and includes additional targeted sampling of those fish. Jacks may be an indicator of abundance for the following years, while sampling adipose-clipped fish is used to assess stocks of interest more precisely such as the Cultus Lake sockeye stock.

Table 2. Sampling frequency guidelines for commercial fisheries by key statistical area in a high TAC year. Sampling frequency describes the number of sampling trips, not the total number of samples collected. Most sampling trips involve the collection of two or three sample sets of 100 fish from multiple statistical areas.

| Fishery User | Gear Type | Key statistical areas | Sampling frequency |
| :--- | :--- | :--- | :--- |
| Area B | PS | Area 12, 13, 29 | 3 times per week |
| Area D | GN | Area 12, 13 | 2 times per week |
| Area E | GN | Area 29 | After every opening |
| Area H | TR | Area 12, 13 and 29 | 1 time per week |
| Area G | TR | Area 125,126,127 | Infrequent |
| US-AC | PS, GN, RN | Area 7,7a | 2 times per week |
| US-TI | PS, GN, RN | Area 7, 7a | 2 times per week |

## Methods

The protocol for collecting DNA and scale samples and biological information is the same for both test fishery and commercial fisheries. Samplers distinguish sockeye from other salmon species by following guidelines outlined in the Sampling Manuals for test fishing observers and port samplers. Scale samples, DNA samples, and/or biological data, such as fish length, weight, and sex are collected on the boat, after landing, or at a processing plant. DNA, scales and biological data are primarily collected as "matched samples", meaning each piece of information can be traced back to the same fish. This permits comparisons of age, size, sex, and growth between and within stocks. In some instances, there are scale samples taken without associated DNA or biological information (Table 1). This "scale-only" sampling is performed because there are limitations in how many DNA samples can be analyzed due to costs and efforts needed to collect, analyze and process these samples. For commercial sampling, time is a limiting factor and sampling information is triaged. DNA has the highest priority, followed by scales, lengths, sexes, and finally weights. If time is a limiting factor due to scheduled fish plant operations, samplers may opt to exclude lower-priority information from the collection.

Scale samples are placed in a scale book along with all the biological data from that individual salmon and the DNA sample number. The "preferred scale" is selected from each salmon unless it is missing or damaged and is located on the left side of the salmon, on the second scale row above the lateral line in a diagonal line from the posterior of the dorsal fin to the anterior of the anal fin (Figure 2). If the preferred scale is missing, the next closest scale is taken as long as it is at least two scale rows above the lateral line and behind the front of the dorsal fin. Scales higher than four scale rows above the lateral line may be sampled in rare cases if all scales near the preferred scale location are missing. This is because the characteristics of the scales on a sockeye vary dorso-ventrally (top to bottom). In this case, the sampler notes that a non-preferred scale was used. If there are no usable scales on the left side of the fish, a right-side scale may be used, but the sampler must take note of this because it can affect how the scale is read. If neither side of the fish has appropriate scales to sample, the sampler should pick another fish if there is an adequate number of fish to sample.


Figure 2. The preferred location of the scale to sample. Scales higher than four scale rows above the lateral line are non-preferred.

DNA samples are collected by using a one-hole punch and punching one small, thin disk from the margin of the adipose fin of the salmon. If the adipose fin is missing, a caudal fin clip is taken instead. While the sample is still wet, the DNA is placed on a Whatman sheet. The alternative storage of DNA in ethanol vials is less desirable but is used in cases where Whatman paper is not available or if heavy wind and/or rain make using Whatman sheets difficult. To prevent contamination, sampling equipment is rinsed after each sample is taken.

The procedures to gather biological data such as length, weight, and sex, are described in Chapter B6. Ratio counts are determined by dividing the total number of jacks or adipose-clipped fish encountered by the total number of fish counted. To conduct ratio counts in a fish plant, the number of fish without an adipose fin is counted as fish pass by on a conveyor belt as they are being off-loaded. DNA and scale samples as well as biological information are collected for jacks and fish missing their adipose fin (adipose-clipped or adipose-damaged).

Scale samples are analyzed at the Scale Lab within the PSC Secretariat office in Downtown Vancouver. DNA samples are analyzed by the Molecular Genetics Lab at the Pacific Biological Station (PBS) in Nanaimo. For the Johnstone Strait test fisheries, test fishing observers drop off biological samples at an air carrier service to be shipped as soon as possible to Vancouver. For the Area 20 Juan de Fuca test fisheries, the test-fishing observer delivers biological samples to a contractor in Port Renfrew who drives the samples to AC Taxi in Nanaimo in the evening. In the morning, AC Taxi delivers the DNA samples to PBS and the scale samples to an air carrier service. The samples are picked up from the air carrier service in Vancouver by PSC staff. In-river DNA samples from Cottonwood and Whonnock are also flown to PBS for analysis.

## References

Šmejkal, M., Ricard, D., Prchalová, M., Říha, M., Muška, M., Blabolil, P., and Kubečka, J. 2015. Biomass and abundance biases in European standard gillnet sampling. PloS one, 10(3), e0122437.

# B6. Length, Weight, and Sex 

D. Brkic and A.M. Phung


#### Abstract

Summary Biological information of salmon collected by the Pacific Salmon Commission (PSC) includes length, weight, and sex information. Length measurements are used to supplement stock identification information (Chapter B9) and as inputs into models that differentiate fish species based on hydroacoustic lengths, i.e., length-based mixture models (Chapter B16). Weights in combination with lengths are important for understanding fish condition but also provide the fishing industry with information on the potential value of expected catches. Sex information is equally important as analyses of lengths and weights often requires separation of the sexes. Lengths are measured and recorded in terms of fork length, postorbital fork length (POF), and postorbital hypural length ( POH ). Length measurements are taken using a "POF stick" while weights are measured using industrial scales. Sex is determined by making an incision in the abdomen and inspecting the gonads by touch.


## Introduction

The Pacific Salmon Commission (PSC) collects and stores biological information - including length, weight, and sex - from salmon sampled from commercial and test fishery catches. Differences in average historical length between fish stocks may be used during stock identification to help resolve uncertain stock assignment (Chapter B9). Fish lengths also help distinguish different species within a mixture of different length estimates obtained from hydroacoustic data (Chapter B16). Multi-year records of length and weight may reveal deviations from average, which could be important in fisheries planning as larger fish are more valuable both in terms of catch and in terms of brood stock.
Determining the sex of sampled fish is important as morphological differences between the sexes may lead to differential catchability in fishing gears as well as varying offload weights when fish are sold. Analyses done on length and weight data also generally require separation of the sexes.

## LENGTH DEFINITIONS

The Pacific Salmon Commission collects three different types of length measurements: fork length, postorbital fork length (POF), and postorbital hypural length (POH). Figure 1 shows the difference between fork length, POF, and POH.


Figure 1. Illustration of the different salmon length measures recorded by the PSC.
Fork length is the length from the anterior-most part of the fish to the posterior end of the middle caudal rays. Fork length is best used to determine the overall size of a fish when it has deeply forked tails and difficult-to-distinguish hypural plates as is the case for salmon. The PSC uses fork lengths in the hydroacoustic length-based mixture models.

The postorbital fork (POF) length measures the length from the posterior of the orbit (the back of the eye) to the posterior end of the middle caudal rays. Excluding the snout of the fish in the measurement helps circumvent the impact of highly variable snout lengths, as male salmon tend to develop distinct hooked snouts during maturation. The PSC sometimes uses POF to supplement stock identification information based on scales and DNA. POF is also used to track changes in length-at-age across return years.

The postorbital hypural ( POH ) length is the length from the posterior of the orbit to the hypural notch. This length measure is especially used during sampling on the spawning ground when the caudal fins tend to degrade, especially among females, causing the POF to become highly variable. Both the orbit and hypural north, used to determine the POH , can be identified on even highly degraded carcases. The PSC uses POH during sampling on spawning grounds as well as during in-river test fishery sampling. This allows comparing the POH of the test fishery samples against spawning ground samples.

Other types of fish lengths include mid-eye fork length (MEF) and standard length. These lengths are generally not taken by the PSC but are entered into the PSC's scale database when samples are received from other organizations. MEF is the length from the middle of the orbit to the fork in the tail. MEF length is generally taken in fishery samples by the Alaska Department of Fish and Game. Standard length is the length from the tip of the snout to the hypural notch and is generally taken for spawning ground samples by Fisheries and Oceans Canada.

## SAMPLING DESIGN

There are five main types of biological data collected in the field by the PSC: fork length, POF, POH, weight, and sex. Tables 1 to 3 show which lengths are taken at each fishery, whether weights are taken, and the sample sizes for lengths and weights.

Fork lengths are generally only measured at the Whonnock gillnet test fishery and the Cottonwood gillnet test fishery. Fork lengths are measured for sockeye, pink, chum, Chinook, and unreleased (dead) coho salmon. Fork lengths are not measured for steelhead and released (live) coho. Forks lengths from Whonnock and Cottonwood are typically used within hydroacoustic length-based mixture models. If there are insufficient fork length samples available from Whonnock and Cottonwood, additional fork lengths data may be required from other test fisheries or commercial fisheries.

Postorbital fork (POF) lengths are measured at all PSC test fisheries and when commercial fisheries are sampled. POF is only measured for sockeye and pink salmon. For commercial fisheries and reef net test fisheries, sample sizes for length are determined by catch sizes and DNA sample requirements. Every fish sampled for DNA has an associated POF measurement unless the samplers are facing extreme time limitations at fish plants.

Postorbital hypural ( POH ) lengths are the primary length measurements for spawning grounds samples. At the Cottonwood and Whonnock test fisheries, POH is measured for all sampled sockeye, adiposeclipped Chinook, and coho salmon. At Whonnock, POH lengths are also measured for pink salmon.

Weights of individual fish are measured only for sockeye and pink salmon and only at the Cottonwood, Whonnock, Area 20 GN, Area 20 PS, Area 4B/5 GN, Qualark GN, and Area 7 RN test fisheries. Individual weights are also measured for commercial fishery samples. Weights are not measured for individuals that are incomplete such as fish that are damaged by seals or dressed. For commercial samples, individual weights may not be measured if time is a limiting factor. Bulk weights, which is the net weight of a tote, may also be recorded and are used to calculate the average weight. For Chinook, chum, and coho caught at test fisheries, only bulk weights are recorded when the fish are sold.

Sexes are recorded for all sampled sockeye and pink salmon whenever possible. For commercial samples, sexes may not be determined if time is limiting.

Table 1. Sockeye sampling summary by fishery. The types of lengths taken at each fishery are shown as well as whether weights are taken and the sample size of each.

| Fishery | Length type | Weight | Sample Size (up to) |
| :--- | :--- | :--- | :--- |
| Cottonwood GN | FL/POF/POH | Yes | $50 /$ day |
| Whonnock GN | FL/POF/POH | Yes | 50/day |
| Area 20 GN | POF | 2 days/week | 115/day |
| Area 20 PS | POF | 2 days/week | 115/day |
| Area 12 GN | POF | No | $115 /$ day |
| Area 12 PS | POF | No | $115 /$ day |
| Area 13 PS | POF | No | $115 /$ day |
| Area 4B/5 GN | POF | Yes | $100 /$ day |
| Qualark GN | POF | Yes | $50 /$ day |
| Gulf Troll | POF | No | 115/boat/day |
| Area 7 RN | POF | Yes | Variable |
| Albion GN | POF | No | All fish |
| Commercial | POF | Yes | Variable |
| Spawning Grounds | POH | No | Variable |

Table 2. Pink sampling summary by fishery on odd years only.

| Fishery | Length type | Weight | Sample Size (up to) |
| :--- | :--- | :--- | :--- |
| Cottonwood GN | FL | No | $100 /$ week |
| Whonnock GN | FL/POF/POH | Yes | $100 /$ week |
| Area 20 PS | POF | No | $100 /$ week |
| Area 12 PS | POF | No | $100 /$ week |
| Area 13 PS | POF | No | $100 /$ week |
| Qualark GN | POF | Yes | $200 /$ year |
| Gulf Troll | POF | No | $100 /$ week |
| Area 7 RN | POF | Yes | Variable |
| Commercial | POF | Yes | Variable |
| Spawning Grounds | POH | No | Variable |

Table 3. Chinook, coho and chum sampling summary by fishery.

| Fishery | Species | Length type | Weight | Sample Size |
| :--- | :--- | :--- | :--- | :--- |
| Cottonwood GN | Chinook | FL/POH* | No | All fish |
| Cottonwood GN | Coho | FL/POH | No | All fish |
| Cottonwood GN | Chum | FL | No | All fish |
| Whonnock GN | Chinook | FL/POH* | No | All fish |
| Whonnock GN | Coho | FL/POH | No | All fish |
| Whonnock GN | Chum | FL | No | All fish |

*adipose-clipped fish only

## Methods

All lengths are measured using a "POF Stick": a custom-made 1-meter aluminum ruler with one fixed post at the zero marker and one sliding post. The posts are $6-7 \mathrm{~cm}$ long and generally have a fine-pointed tip. The accuracy of POF sticks is tested by setting the POF stick measurement to 50 cm , then measuring from the inner edge of the fixed post to the point of the sliding post using measuring tape or another ruler (Figure 2). Lengths are recorded in centimeters or millimeters and are rounded to the nearest millimeter.


Figure 2. A POF stick and how it can be used to measure lengths. Lengths are measured from the front of the fixed post to the point of the sliding post

Fork lengths are measured by placing the inner end of the fixed post of the POF stick in front of the fish snout and moving the point of the sliding post to the fork in the tail. Fork length is not measured if damage to the snout or tail prevents an accurate reading.

Postorbital fork (POF) lengths are measured by placing the fixed post of the POF stick into one of the eye sockets of the fish. The point of the sliding post is then moved to the fork in the tail. POF lengths are not taken if damage to the eye sockets or tail prevents an accurate reading.
Postorbital hypural ( POH ) lengths can be measured in three different ways. For the first method, the flesh covering the hypural plate is cut away with a knife to reveal the hypural notch. The fixed post of the POF stick is then inserted into the eye socket and the sliding post is pointed at the hypural notch. This is the preferred method for spawning grounds sampling as it is the most accurate. For the second method, the sampler feels the tail of the fish to estimate the location of the hypural notch. The hypural plate is distinctly elevated at the base of the caudal fin rays. The measurement is taken from the eye socket to the estimated position of the hypural notch. This method is preferred for test fishery sampling as it is the most time-efficient and does not damage the fish and reduce retail value. The third method involves folding over the rays of the caudal fin until it can no longer be bent. The measurement can then be taken from the eye socket to the position of the final bend. This method is another time-efficient alternative to the first method but is less accurate.
Weights are measured using a Kilotech industrial dial scale or an AND SK-WP digital scale. Scales are calibrated using two known weights: 1.390 kg and 3.915 kg . Weights are recorded either in pounds or kilograms and are always rounded to one decimal place. Average weight is calculated by dividing the total weight of fish in a sample by the sample size. If bulk weight was recorded, the average is calculated by dividing the net weight of a tote by the number of fish in it.

To determine the sex of a fish, a cut is made in the belly approximately two inches long from between where the pectoral fins originate and along the midline of the stomach. The sampler inserts their finger into the cut until the spine is reached, feeling along the outside of the internal organs. If the fish is female, the lumpy texture of the egg-filled ovaries can be felt. If the fish is male, the smooth testes can be felt. If the sampler is inexperienced or if the sex is indistinguishable by feel, the cut in the belly can be extended further to the posterior and the body cavity opened for a visual examination. For spawning grounds samples, the sex can be determined by visual examination of exterior morphology, but the body cavities of females are still examined to evaluate egg deposition or success of spawn.

## Planned Changes and Potential Areas for Improvement

Erroneous or anomalous length and weight measurements can enter the database unnoticed despite some existing preventative measures. An error-checking tool is under development to detect outliers in length-weight data so errors can be caught and rectified earlier. If the source of an error cannot be identified or if it can't be fixed, anomalous data can be flagged and subsequently excluded from analysis if desired. Obvious errors can be removed, such as when fork lengths are shorter than POF lengths. The tool can also track data accuracy by fishery, allowing fishery-specific sources of errors to be addressed.

# B7. In-Season Scale and Age Reading Methods 

J.E. Sellars and M.R. Forrest


#### Abstract

Summary Fraser sockeye salmon stocks are managed by four management groups: Early Stuart, Early Summer run, Summer run and Late run. This stipulation within the Pacific Salmon Treaty requires salmon run size, catches and escapement estimates to be split into these four groups using stock composition estimates. In-season, stock composition estimates are derived from catch samples through scale reading i.e., by analysing scale characteristics and growth patterns and comparing the resulting patterns against the patterns of salmon with known stock origin. While DNA-based stock identification (Chapter B9) replaced scale-based methods as the primary method in 2002, scale-based methods still have an important role in the assessment for Fraser River sockeye salmon: they provide stock-ID information earlier and when DNA estimates are not available and they provide additional information to refine DNA-based stock proportions. In addition to providing stock-ID data, scales are the primary method to assess fish age. Since the majority of Fraser sockeye return as four-year olds, the portion of age four compared to age five sockeye is an important indicator to evaluate the strength of the sockeye run in relation to the strength of the run in the previous year. High age five proportions inseason may indicate that returns are less favorable than the previous year.


## Introduction

It was Dr. C.H. Gilbert, who in the early 1900s, first recognized that the freshwater scale patterns of Fraser River sockeye salmon stocks differ (Henry 1961) as they reflect unique variations in growth patterns that develop while stocks are spatially isolated, such as during juvenile residence in lakes or streams, or during certain phases of marine residence (Gable and Cox-Rogers 1993). In addition, it is also possible that genetic differences between stocks play a role in observed scale pattern differences (Gable and Cox-Rogers 1993).

Sockeye salmon scales contain a permanent record of the life history of a fish beginning with the early fry stage. As the fish grow in body size, corresponding radial scale growth takes place. New basal plates are formed under existing plates and hyalodentine ridges (circuli) are deposited on the margins between adjoining plates. The circuli appear under magnification as partially concentric rings which radiate outward from the scale focus (Figure 1, Gable and Cox-Rogers 1993). Widely spaced bands of circuli reflect rapid growth in the summer, and compactly spaced bands of circuli growth reflect growth in the winter (Bilton and Ludwig 1966). Scales contain two distinct zones of scale growth: the freshwater zone, consisting of thin, narrowly spaced circuli, and an outer marine zone, consisting of thick, widely spaced circuli (Figure 1). A third zone lies between the freshwater and marine scale zone. This is the "spring growth" or "plus-growth" zone. Circuli in this zone are of intermediate size and form just prior to, or soon after, ocean entry. Circuli counts in the freshwater and spring growth zones as well as distance measures within these zones are used by the PSC for stock identification and to evaluate the rate of growth in freshwater in a given year.


Figure 1. Scale image with labels and radial line along which circuli counts are made.

## Data

In-season scale samples are collected regularly from test fisheries, and opportunistically from commercial fisheries as fisheries occur. For each sockeye sampled, one scale is collected, stored in a scale book and shipped to the Pacific Salmon Commission (PSC) Secretariat office. The PSC scale lab reads the scales and archives the associated information in a database together with other relevant information collected during the sampling process. The associated metadata can be used to match scale information of individual fish with DNA results as well as biological and fisheries information collected in the field. The PSC scale database contains records dating back to 1912. Initially only spawning ground scale samples were represented but since 1977 commercial and test fishing scale samples have also been collected and stored in the database. In addition to the adult scale information, the database also contains smolt scale information from 1948 to present. Since 1991, the lab analyses between 15,00051,000 sockeye scales annually, both for freshwater growth patterns as well as age.

## Methods

Scales are forwarded to the PSC scale lab from multiple temporal and spatial locations in scale books. Each scale is removed from the scale book and cleaned before mounting onto a gummi card. Heat and pressure using a hydraulic press are used to make an impression of the scales on to a clear sheet of acetate. It is the microscopic image of the scale impression on the acetate that is used for scale aging and analysis. Using a microscope connected to a camera and computer, the image of the scale is captured, stored and analyzed using Image-pro premier software and the resulting scale measurements are stored in an Excel spreadsheet (Batchelor 2016).

Using expertise and experience, in combination with the image software, the scale analyst will examine and document the condition of the scale using condition codes (Table 1) and documents the circuli count of the freshwater growth zone, the spring growth count, the diameter of the focus, the distance from the focus to the fifth circuli, the distance from the focus to the annulus and the age. Circuli counts are made along a specific radial line for consistency of results (Figure 1), chosen to be the ventral $20^{\circ}$ radial line (Clutter and Whitesel 1956). This line extends ventro-anteriorly from the focus of the scale,
forming an angle of $20^{\circ}$ with the horizontal or longitudinal axis of the scale and is disclosed by overlaying the transmitted scale image with a grid onto which a longitudinal axis and two $20^{\circ}$ radial lines have been etched. The circulus count is then made along the ventral $20^{\circ}$ radial line.

Table 1. Condition codes used to describe scale condition and available information.

| CONDITION CODES (CC) |  |  |  |  |
| :--- | :---: | :--- | :--- | :---: |
|  | CC | Scale info available | Scale Condition |  |
| READABLE | $\mathbf{1}$ | AGE \& CC | READABLE |  |
|  | $\mathbf{2}$ | AGE \& CC | RESORBED SCALE - Age questionable |  |
|  | $\mathbf{3}$ | AGE BUT NO CC | AGEABLE BUT CC UNREADABLE |  |
|  | $\mathbf{4}$ | AGE \& CC | AGE BASED ON SCALE NOT OTOLITH |  |
| UNREADABLE | $\mathbf{5}$ | NO AGE OR CC | LATERAL LINE |  |
|  | $\mathbf{6}$ | NO AGE OR CC | NON-SOCKEYE |  |
|  | $\mathbf{7}$ | NO AGE OR CC | UNREADABLE |  |
|  | $\mathbf{8}$ | NO AGE OR CC | MISSING |  |
|  | $\mathbf{9}$ | NO AGE OR CC | REGENERATED |  |
|  | $\mathbf{1 0}$ | FW AGE | SOCKEYE THAT HAS MATURED IN FRESHWATER |  |
| READABLE | $\mathbf{1 2}$ | AGE \& CC | $1 / 3$ is good and the rest is resorbed 2-3 circuli |  |
|  |  |  |  |  |
| READABLE | $\mathbf{1 3}$ | AGE \& CC | OR |  |
|  |  |  | Growth to 1st Marine is small in comparison to the growth |  |
|  |  |  | to the 2nd Marine - ie. The spacing is not the same from the |  |
| READABLE | $\mathbf{1 4}$ | AGE \& CC | focus to the 1st as it is to the 2nd marine. |  |
| READABLE | $\mathbf{1 5}$ | AGE \& CC | Scale too big to be digitized |  |
| READABLE | $\mathbf{1 6}$ | AGE \& CC | Special note |  |
| READABLE | $\mathbf{1 7}$ | AGE \& CC | Growth to 1st marine is extremely large. |  |

Sockeye have multiple age classes (Table 2) and the PSC uses the Gilbert and Rich nomenclature for age classification (Clutter and Whitesel 1956). The first number denotes the age at spawning and a subscript or second number denotes the age at which the sockeye migrated to sea. For example, a $4_{2}$ aged sockeye returns to its natal stream to spawn and die at four years of age. It has spent one year in the lake, migrated to sea in its second year of life and returned to its natal stream after 2 years at sea. The scales of the sockeye are aged by examining the number of annuli in the freshwater zone and the number of annuli in the marine zone For Fraser sockeye, the majority of the adult salmon will be $4_{2}$ and $5_{2}$ fish.

Table 2. Common age classes of adult Fraser River sockeye salmon. Ocean or sea type sockeye only spend one year in freshwater while for sockeye maturing in freshwater, the age of spawning equals the number of years in freshwater.

| Age of | Number of years in freshwater |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
| spawning | 1 year | 2 years | 3 years | 4 years |
| 2 years | $2_{1}$ | $2_{2}$ |  |  |
| 3 years | $3_{1}$ | $3_{2}$ | $3_{3}$ |  |
| 4 years | $4_{1}$ | $4_{2}$ | $4_{3}$ | $4_{4}$ |
| 5 years | $5_{1}$ | $5_{2}$ | $5_{3}$ | $5_{4}$ |
| 6 years |  | $6_{2}$ | $6_{3}$ | $6_{4}$ |
| 7 years |  | $7_{2}$ | $7_{3}$ | $7_{4}$ |

When all scales of a samples have been aged, each of the scales is re-aged by the same analyst. The scale data is then merged with the field and sample data within an Excel application that allows for data entry, data merging, error checking and summarising data. As an error checking tool, it highlights missing data, outliers, data that does not fall within specific boundaries and unusual data. Once the data have been merged and error checked, a second scale analyst will re-age and check a large proportion of the scales. This is another step to ensure aging accuracy, but also to ensure scale interpretation remains consistent between analysts. Analysts must be experienced and well-trained in aging to differentiate true annuli from stresses and false checks. The data are then summarized and uploaded into the scale database for use by the stock identification biologists (Chapter B8).

## References

Batchelor, M.M. 2016. Scale Analysis Application V1-2016-08-15-132043, Alces Imaging and Automation.

Bilton, H.T and Ludwig, S.A.M. 1966. Times of annulus formation on scales of sockeye, pink, and chum salmon in the Gulf of Alaska. Journal Fisheries Research Board of Canada, 23, 1403-1410.

Clutter, R.L. and Whitesel, L.E. 1956. Collection and Interpretation of Sockeye Salmon Scales, International Pacific Salmon Fisheries Commission, Bulletin IX.

Gable, J. and Cox-Rogers, S. 1993. Stock Identification of Fraser River Sockeye Salmon: Methodology and Management Application, Pacific Salmon Commission Technical Report No. 5.

Henry, K.A. 1961. Racial identification of Fraser River sockeye salmon by means of scales and its application to salmon management, International Pacific Salmon Fisheries Commission, Bulletin XII.

# B8. Stock Composition Estimates Based on Scale Pattern Analyses 

P. Samarasin and S. Latham


#### Abstract

Summary Returning Fraser River sockeye stocks differ in timing and are aggregated into "management groups" to facilitate their management. Assessments in support of management therefore require stock composition information. The stock composition of mixed stock fishery samples can be estimated by comparing the scales from these samples against scale patterns from fish with known stock origin (i.e., scales collected at spawning grounds). Until 2002, scale-based methods were the primary mode of stock identification for Fraser River sockeye salmon. Within the current assessment framework, stock composition estimates derived through scale pattern analyses provide additional information to refine DNA-based stock proportions (Chapter B9) or provide estimates when DNA-based stock identification is not available. Although scale pattern analyses have been used for the last 50 years, the statistical approach has changed over time. This report provides a summary of historical and current (2018) approaches for scale pattern analysis for identification of Fraser River sockeye salmon stocks. The current scale pattern analysis method is a combination of two multivariate statistical methods - linear discriminant analysis (LDA) with principal components analysis (PCA). Scale pattern data from spawning ground samples are used to develop discriminant functions for separating Fraser River sockeye stocks, and the derived functions are applied to in-season scale samples from mixed-stock fisheries to estimate sample stock proportions. The model output provides stock proportions for the sample and stock assignment probabilities for individual sockeye salmon.


## Introduction

The recognition of differences in scale characteristics among different sockeye salmon stocks is attributed to Gilbert (1914-1925). However, use of scales to identify Fraser River sockeye stocks was first examined in the mid-1900s by Hamilton (1947) and Clutter and Whitesel (1956). At that time, the analysis used number of circuli in the freshwater zone of the scale to distinguish between stocks within the Fraser River watershed. Fraser River sockeye typically spend their first year in freshwater where they can differ considerably in their growth rates. Growth rates depend on freshwater conditions, and rearing lakes differ in temperature, food availability, and other factors that affect growth. Fish growth is closely related to scale growth (Clutter and Whitesel 1956), and growth is recorded in the scales which can be used to infer the origin of returning adult fish. There is variation in growth rate from year to year, however, resulting in differences in scale characteristics for any given stock among years. The stock composition of a mixed-stock fishery can be estimated by comparing growth patterns in a sample of scales from caught fish to growth patterns of fish with known stock origin (scales collected at spawning grounds). Here, the sample refers to a collection of scales removed by fisheries observers for determining the stock composition of the catch.

## Data

Sockeye salmon scales (one per fish) collected from fisheries and spawning grounds are read by PSC scale analysts who determine each salmon's age and measure scale characteristics (see Chapter B7). The
following scale variables are directly measured or calculated by scale analysts and are used in the statistical model to estimate stock composition: first count (count of circuli to the $1^{\text {st }}$ freshwater annulus), plus or "spring" growth (circulus count between the freshwater annulus and marine growth), measured distances from the center to annulus, from the center to the $5^{\text {th }}$ circulus, from the $1^{\text {st }}$ circulus to the annulus, from the $1^{\text {st }}$ to $5^{\text {th }}$ circulus, and the adjusted center width. For generating discriminant functions: spawning ground scales with readable freshwater zones and known ages (from otoliths) are used. Only readable scales are included in mixtures for scale pattern analysis, and these may include or exclude individuals with resorption of their scales that would tend to underestimate the true age.

## Methods

Scale pattern analysis methods have changed over time as statistical methods and implementation have evolved with increasing computation power. Two Pacific Salmon Commission (PSC) technical reports outline the use of scale pattern analysis for identification of Fraser River sockeye salmon stocks. First, Henry (1961) documented the univariate scale pattern analysis procedure for the identification of Fraser River sockeye stocks. This method used the number of freshwater circuli to estimate stock composition of the sample. Historical timing differences among major stock groups and the presence of plus growth were used to refine estimates but were not formally incorporated in the method. However, this method was not adequate when there were more than four stocks in the sample and only performed well in very simple situations. From the late 1970s onwards, PSC staff investigated multivariate methods to distinguish Fraser River sockeye stocks. In 1987, Henry's univariate method was replaced by a multivariate discriminant analysis method. Gable and Cox-Rogers (1993) documented this multivariate discriminant analysis, which used first count, plus growth, and distance from $1^{\text {st }}$ circulus to the freshwater annulus to discriminate among stocks. Stocks expected to be present more than $5 \%$ in a given statistical area during a given catch were included in the discriminant function analysis model and the expected presence was predicted based on in-season timing abundance curves, historical timing data, and forecasted run sizes. From 1987-2001, this multivariate scale pattern analysis was the primary in-season method of stock identification for Fraser River sockeye salmon. DNA-based stock composition estimation (Chapter B9) became the main method of stock identification in 2002 but scale-based estimates were still frequently used. From 2009 to 2017, scale-based stock compositions were infrequently incorporated into accounting files except when suitable DNA-based results were not available. For each stock, the discriminant function was based on scale standards obtained from spawning ground samples of the same cohort that returned a year earlier (i.e., age $3_{2}$ samples were used for the age $4_{2}$ model and age $4_{2}$ samples were used for the age $5_{2}$ model) and the samples from the previous year on the cycle (e.g., 2014 age $4_{2}$ spawning ground samples for 2018 age $4_{2}$ model). The resulting stock composition estimates from the discriminant analysis were further revised using a classification matrix correction procedure (Cook and Lord 1978) which employed misclassification rates of the spawning ground scales as determined during the development of discriminant function models. The current statistical approach for scale analysis (2018 onwards) generates stock assignment probabilities for individual scales (salmon) in the sample (see Table 1), and these probabilities are used to revise DNA-based stock composition estimates in a total weight of evidence approach (Chapter B9).

The current method is a combination of principal component analysis (PCA) and discriminant analysis (mainly linear discriminant analysis), where discriminant analysis is performed on principal component scores instead of scale variables directly. Principal component analysis allows information from all measured scale variables to be used in the discriminant analysis by creating synthetic variables (called principal components) that are linear combinations of the original variables. Discriminant analysis is a classification method that allows assignment of stock membership based on a set of independent variables extracted from non-independent trait measurements (the measured scale variables can be strongly correlated, so this procedure is necessary). As in the past, scale pattern analyses are conducted
separately for age $4_{2}$ and age $5_{2}$ sockeye salmon. For the age $4_{2}$ model, spawning ground scales from age $4_{2}$ individuals from 4 years prior and spawning ground scales from age $3_{2}$ individuals from the previous year are used as scale standards (i.e., training data). For the age $5_{2}$ model, spawning ground scales from age $4_{2}$ individuals from the previous year are used as scale standards. Principal component analysis is performed first on scale variables and the principal component scores for the top five principal components are retained. A discriminant analysis is performed on principal component scores to generate discriminant functions from the training data (without incorporating the stock-specific sample sizes of the training data). Figure 1 illustrates the discriminant function space of 2018 age $4_{2}$ summerrun Fraser River sockeye salmon spawning ground samples, which are training data for the 2022 age 42 scale model.

Once the discriminant function has been developed, it can be used to estimate stock assignment probabilities of in-season scale samples from various fisheries. Scale samples from in-season fisheries are read and a principal component analysis is performed first on the quantified scale variables. Principal component scores are retained and rotated similar to the training data. Next, discriminant analysis is performed to apply the previously developed discriminant functions to the in-season sample to generate stock assignment probabilities for individual scales in the sample (Table 1), and sample stock composition estimates (Table 2). Here, prior probabilities are obtained from the relative daily abundance forecast from the Fisheries Planning Model (Chapter A6). A stock composition estimate for age $4_{2}$ and age $5_{2}$ sockeye in the sample is estimated by assigning each scale to its highest probability stock (i.e., stock 1) and then applying the bias-correction procedure (Cook and Lord 1978, Table 2) to the results for each of these ages. A total estimate is obtained through a weighted sum of the stock composition across ages (including some ages for which no formal statistical model is run, e.g., Harrison age $3_{1}$ and $4_{1}$ scales).


Figure 1. Discriminant function space of 2018 age 42 Summer-run Fraser sockeye salmon from spawning ground scales.

Table 1. Example scale model output showing assignment probabilities for each scale in the sample.

| Fish Code | Stock 1 | Probability <br> 1 | Stock 2 | Probability <br> 2 | Stock 3 | Probability <br> 3 | Stock 4 | Probability <br> 4 | Stock 5 | Probability <br> 5 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 2018122717 | Stel | 0.59 | Weaver | 0.18 | LStu | 0.08 | LShP | 0.04 | Hfly | 0.04 |
| 2018122718 | LShP | 0.78 | ESTh | 0.13 | Chil | 0.08 | Mtch | 0 | Hfly | 0 |
| 2018122719 | LShP | 0.77 | Chil | 0.12 | ESTh | 0.11 | Mtch | 0 | Nahatlatch | 0 |
| 2018122747 | Hfly | 0.42 | Mtch | 0.17 | RaNT | 0.13 | Birkenhead | 0.13 | LShP | 0.06 |
| 2018122748 | LShP | 0.83 | ESTh | 0.15 | Chil | 0.02 | Mtch | 0 | Hfly | 0 |
| 2018122749 | Stel | 0.57 | LStu | 0.12 | RaNT | 0.11 | Birkenhead | 0.05 | Weaver | 0.05 |
| 2018122750 | LShP | 0.81 | ESTh | 0.13 | Chil | 0.04 | Mtch | 0.01 | Hfly | 0 |
| 2018122752 | Weaver | 0.48 | Big.Silver | 0.4 | Stel | 0.08 | LStu | 0.02 | Nadina | 0.01 |
| 2018122753 | LShP | 0.86 | ESTh | 0.07 | Chil | 0.06 | Mtch | 0 | Hfly | 0 |
| 2018122754 | LShP | 0.88 | ESTh | 0.11 | Chil | 0.01 | Mtch | 0 | Hfly | 0 |
| 2018122755 | LShP | 0.77 | Chil | 0.16 | ESTh | 0.07 | Mtch | 0 | Hfly | 0 |

Table 2. Example scale model output showing stock composition estimates for the sample with and without bias correction

| Stock | Scale probability (uncorrected) | Scale probability (bias-corrected) |
| :--- | ---: | ---: |
| Big Silver | 0 | 0.01 |
| Birkenhead | 0.01 | 0 |
| Bowron | 0 | 0 |
| Chil | 0.03 | 0 |
| Chwk | 0 | 0 |
| Cultus | 0 | 0 |
| ESTh | 0 | 0 |
| EStu | 0 | 0 |
| Gates | 0 | 0.04 |
| Hfly | 0.06 | 0.05 |
| LShP | 0.82 | 0.61 |
| LStu | 0 | 0.03 |
| Mtch | 0 | 0.05 |
| NBar | 0 | 0 |
| Nadina | 0 | 0 |
| Nahatlatch | 0 | 0 |
| PiAC | 0 | 0 |
| RaNT | 0 | 0.18 |
| Stel | 0.07 | 0 |
| Tsko | 0 | 0.01 |
| Weaver | 0.01 | 0 |
| Widg | 0 | 0.01 |

## Planned Changes and Potential Areas for Improvement

1. Potentially non-Fraser stocks will be included in the scale model (e.g., Lake Washington, Baker Lake, Nimpkish, etc.).
2. For in-season purposes, spawning ground scale data from previous years will be supplemented with in-season scale data that have a high confidence stock-of-origin (through DNA analysis) for developing discriminant functions.
3. The improvement afforded by updating discriminant functions in the post-season with new spawning ground samples and new relative abundance priors will be evaluated.
4. The bias-correction method will be reviewed and improved or replaced.

## References

Clutter, R.I. and Whitesel, L.E. 1956. Collection and interpretation of sockeye salmon scales. Int. Pac. Salmon Fish. Comm. Bull. IX: 159 p.

Cook, R.C. and Lord, G.E. 1978. Identification of stocks of Bristol Bay sockeye salmon (Oncorhynchus nerka) by evaluating scale patterns with a polynomial discriminant method. Fish. Bull., U.S. 76: 415-423.

Gable, J. and Cox-Rogers, S. 1993. Stock identification of Fraser River sockeye salmon: methodology and management application. PSC Tech. Rep. No. 5.

Gilbert, C.H. 1914-1925. Contributions to the life-history of the salmon, Nos. 1-10. Rept. Comm. Fish. B.C. 1913-1915, 1917-1919, 1921-1924.

Hamilton, J.A.R. 1947. Significance of certain scale characters in the recognition of Fraser River sockeye races. M.A. thesis. Univ. of British Columbia, Vancouver, B.C. 154 p.

Henry, K.A. 1961. Racial identification of Fraser River sockeye salmon by means of scales and its application to salmon management. Int. Pac. Salmon Fish. Comm. Bull. XII: 97 p.

# B9. DNA-based Stock ID Method 

P. Samarasin and S. Latham


#### Abstract

Summary Fraser River sockeye fisheries are regulated at the level of stock aggregates (Early Stuart, Early Summer, Summer, and Late run) called management groups, making the identification of Fraser River sockeye salmon stocks a fundamental requirement for their assessment and management. Sockeye salmon is an excellent candidate for performing DNA-based stock identification because of strong natal fidelity, which has led to strong genetic differentiation over time. DNA-based stock identification has been regularly used by the Pacific Salmon Commission (PSC) since 2002. Prior to 2002, scale-based stock identification methods were the primary means of stock identification. Genetic stock identification (GSI) involves extraction of DNA from tissue samples collected following fisheries and generation of a multi-locus genetic profile. Genetic profiles from fishery catches of unknown stock composition are subsequently compared against a genetic baseline with known stock origin using, in our case, the Bayesian framework as implemented by the CBayes stock identification program. CBayes generates stock assignment probabilities for individual fish in a sample and summarizes the overall stock composition for the sample. In-season, stock identification results are used to determine stockspecific catch estimates as well as stock-specific estimates of upstream migration (Chapter B17). As such, genetic stock identification results are essential for stock-specific reconstructions to assess the total run size and timing by management group (Chapter B18).


## Introduction

In accordance with the Pacific Salmon Treaty (PST 2020, Chapter 4, section 3), Fraser River sockeye salmon are managed as four management groups, with each management group consisting of one or more stocks (Table 1). The membership of stocks among management groups is determined by their relative migration timing, and not based on spawning ground location (Figure 1). For example, the Early Summer-run management group contains stocks such as Pitt River sockeye and Nadina River sockeye with spawning grounds that are about 1000 km apart, whereas other stocks that are spatially closer to these stocks belong to different management groups, e.g., the Stellako stock which is spatially proximal to Nadina is part of Summer-run management group. Consequently, stocks within a management group may experience very different migration difficulties and spawning conditions as adults and freshwater rearing conditions as juveniles. This may result in very different survival and productivity estimates for individual stocks within a management group, requiring assessments at finer stock resolutions in addition to assessment at the management group level. Therefore, high resolution stock identification is a key component of in-season Fraser River sockeye salmon assessments.

Until 2002, scale-based analyses of mixed-stock fisheries samples (Chapter B8) was the primary means of Fraser River sockeye stock identification. Even though the PSC's use of DNA to identify stocks is relatively new, underlying population genetic principles for conducting genetic stock identification (GSI) have been well established for decades. DNA-based GSI of other fish and wildlife, using the same principles, have been conducted since the early 1990s (e.g., van de Ven et al. 1990).

Sockeye salmon populations are excellent candidates for application of DNA-based GSI methods because of the strong degree of natal fidelity and local adaptation exhibited by the species, leading to genetic differentiation among populations over time (Taylor 1991, Quinn 2005, Keefer and Caudill 2014).

The level of genetic differentiation among stocks of interest is the most important determinant of the success of DNA-based stock identification methods. If genetic differentiation among stocks of interest is high, GSI methods can easily determine the origin of each fish in a mixed-stock fishery sample (Araujo et al. 2014). Levels of genetic differentiation between sockeye salmon stocks in the Fraser River and nearby areas have been studied and shown to be significant among most stocks of interest (Beacham et al. 2004, Beacham et al. 2010). Thus, GSI for estimating Fraser River sockeye salmon stocks in marine and in-river fisheries gained prominence over time as the scientific basis, accuracy, and reliability of these methods was demonstrated.


Figure 1. Spatial location of 27 Fraser River sockeye salmon stocks, which are aggregated into four management groups, i.e., Early Stuart, Early Summer, Summer, and Late run).

Table 1. Relationship of DNA baseline samples to Fraser River sockeye stock groups and management groups.

| DNA Baseline Sample | Stock (aggregated to 19 Fraser River stocks) | Management Group |
| :---: | :---: | :---: |
| Driftwood-Narrows <br> Dust-Sinta <br> Bivouac-Rossette <br> Paula-Felix | Early Stuart | Early Stuart |
| Chilliwack_Kok <br> Chilliw_lake <br> DollyVarden_Cr <br> Pitt_River <br> Coquitlam_Kok <br> Alouette_Kok <br> Bowron <br> Nadina <br> Gates_Creek <br> Nahatlatch <br> Taseko <br> Upper_Barriere <br> Scotch <br> Seymour <br> Eagle <br> Upper_Adams <br> Cayenne | Chilliwack <br> Pitt / Alouette / Coquitlam <br> Nadina / Bowron <br> Gates / Nahatlatch <br> Taseko <br> North Barriere <br> Early South Thompson | Early Summer |
| Harrison <br> WidgeonSlough <br> Middle_River <br> Pinchi_Creek <br> Tachie <br> Kuzkwa_Creek <br> Stellako <br> Chilko_south <br> Chilko_north <br> Chilko <br> Lower_Horsefly <br> McKinley <br> Mid_Horsefly <br> Upper_Horsefly <br> Mitchell <br> Wasko-Roaring <br> Blue_Lead_Ck <br> Raft <br> NorthThompson | Harrison Late Stuart Stellako Chilko Horsefly Mitchell and other non- Horsefly Quesnel | Summer |
| Birkenhead <br> Big_Silver <br> Eagle_late <br> LittleRiver-LittleShu <br> Lower_Adams <br> Lower_Shuswap <br> MiddleShuswap <br> Portage_Creek <br> Weaver <br> Cultus_Lake | Birkenhead / Big Silver Late Shuswap / Portage Weaver / Cultus | Late |

## Data

Sockeye salmon DNA is obtained from a small amount of tissue, in the case of Fraser River sockeye salmon usually collected from the adipose fin of the fish. The baseline or reference samples comprise
tissues collected from salmon of known stock origin on the spawning grounds; samples of unknown origin, which get compared to the baseline, are collected from various fisheries. Further details of the DNA sampling procedure can be found in Chapter B5. Collected tissue samples are sent to the Molecular Genetics Laboratory at the Pacific Biological Station (Fisheries and Oceans Canada, Nanaimo, BC) where DNA is extracted, loci of interest are amplified through polymerase chain reaction (PCR), and genotypes are estimated at 14 microsatellite loci (Beacham 2004) and five single nucleotide polymorphism (SNP) loci (Beacham 2010). The resulting multi-locus genotypes constitute the genetic profiles of individual sockeye salmon that are used for further GSI analyses.

## Methods

At a conceptual level, GSI analyses are similar to scale-based stock composition analyses. Both methods compare some characteristics of sockeye of unknown origin against characteristics of salmon with known origin to estimate the stock composition of the unknown sample. In scale pattern analyses, scale characteristics are compared, whereas GSI compares allelic frequencies to infer stocks of origin. Genotypes of fish from spawning ground locations have been collected over years and serve as reference data or genetic baseline to assign individuals of unknown origin to a stock by determining how similar their observed genetic profiles are to different baseline samples. The genetic baseline for Fraser River Panel sockeye analyses includes 50 Fraser River stocks, organized into 19 reported stock groups (Table 1), and 37 non-Fraser stocks. First, individuals in a mixed-stock fishery sample are assigned to their stocks of origin by calculating the probability of the individuals originating from different spawning ground locations (Table 2). Once all individuals are assigned to stocks of origin with corresponding probabilities, these assignment probabilities are summed to calculate the stock composition of the entire sample (Table 3). Up to 100 individuals are usually analyzed simultaneously to estimate the stock composition of a sample. Individuals with eight or more missing loci are excluded from the analysis.

Table 2. Example CBayes output showing stock assignment probabilities for individual fish in the sample. Only the top two stocks are shown here but the actual output will show the top three.

| Fish ID | Stock 1 | Region 1 | Probability 1 | Stock 2 | Region 2 | Probability 2 |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Area20PS_PSC(17) seine 43501 | Chilko_south | 13 | 0.96 | Chilko_north | 13 | 0.02 |
| Area20PS_PSC(17) seine 43502 | Tachie | 11 | 0.93 | Stellako__ | 12 | 0.07 |
| Area20PS_PSC(17) seine 43503 | Chilko_south | 13 | 0.58 | Chilko_north | 13 | 0.42 |
| Area20PS_PSC(17) seine 43504 | Tachie___ | 11 | 0.70 | Stellako__ | 12 | 0.30 |
| Area20PS_PSC(17) seine 43505 | Tachie | 11 | 0.90 | Nadina | 4 | 0.08 |
| Area20PS_PSC(17) seine 43506 | Pitt_River | 3 | 1.00 |  |  |  |
| Area20PS_PSC(17) seine 43507 | Birkenhead_ | 17 | 0.99 | Harrison__ | 9 | 0.01 |
| Area20PS_PSC(17) seine 43508 | Stellako__ | 12 | 0.97 | Tachie___ | 11 | 0.04 |
| Area20PS_PSC(17) seine 43509 | Harrison_ | 9 | 0.96 | Tachie___ | 11 | 0.03 |

Table 3. Example Cbayes output of stock composition estimates for a sample.

| Stock <br> code | Stock name | Stock <br> composition | Standard <br> deviation |
| :---: | :--- | :---: | :---: |
| 1 | Early Stuart | 3.4 | $(2.1)$ |
| 2 | Chilliwack | 0.0 | $(0.2)$ |
| 3 | Pitt / Alouette / Coquitlam | 19.8 | $(3.9)$ |
| 4 | Nadina / Bowron | 2.4 | $(1.8)$ |
| 5 | Gates / Nahatlatch | 3.0 | $(1.7)$ |
| 6 | Taseko | 0.0 | $(0.1)$ |
| 7 | North Barriere | 0.0 | $(0.2)$ |
| 8 | Early South Thompson | 3.0 | $(1.8)$ |
| 9 | Harrison | 7.3 | $(2.6)$ |
| 10 | Widgeon Slough | 0.0 | $(0.1)$ |
| 11 | Late Stuart | 17.8 | $(4.6)$ |
| 12 | Stellako | 7.7 | $(3.2)$ |
| 13 | Chilko | 0.5 | $(4.6)$ |
| 14 | Horsefly |  | $(0.6)$ |
|  | Mitchell and non-Horsefly | 0.0 | $(0.2)$ |
| 15 | Quesnel | 0.0 | $(0.2)$ |
| 16 | Raft / North Thompson | 1.0 | $(1.0)$ |
| 17 | Birkenhead / Big Silver | 0.0 | $(0.4)$ |
| 18 | Late Shuswap / Portage | 0.0 | $(0.1)$ |
| 19 | Weaver / Cultus |  |  |

Assignment of individuals to their stocks of origin is implemented in the Cbayes software program (Neaves et al. 2005). This program analyzes stock mixtures by implementing a Bayesian model described in detail by Pella \& Masuda (2001). Compared to maximum likelihood methods of estimating stock composition such as SPAM (Debevec et al. 2000), this Bayesian mixture model has more relaxed model assumptions and more flexibility to deal with incomplete genotypes when some loci are not successfully amplified by PCR and cannot be scored. Pella and Masuda's (2001) Bayesian mixture model r treats baseline genotypes as a sample, rather than a population parameter that is known precisely, relaxing the need to have very large baseline sample sizes that are truly representative of the population of interest. Genotypes found in the mixture can also be used to update allele frequency estimates in the baseline sample. Furthermore, this method better addresses the problem of underestimating more abundant stocks and overestimating rare stocks (Pella \& Masuda 2001). The Fraser River Panel transitioned from using SPAM estimates to using Cbayes estimates between 2008 and 2011, during which all previous years' sockeye DNA samples were re-analyzed with Cbayes.

When running Cbayes, the Gelman-Rubin diagnostic is used to assess convergence of ten independent Markov chain Monte Carlo (MCMC) chains. This diagnostic helps determine if the probability space is explored adequately by the search algorithm and if sufficient MCMC samples are utilised when summarizing results. The raw stock composition results from the Cbayes program are corrected for small stock bias by reassigning stock estimates below a threshold determined by the sample size. This removes very small stock estimates that are based on fractions of an individual and reassigns that proportion estimate to the most frequent stock in the mixture. Next, for each individual, GSI results are
aligned with the scale-based information and size data. If there is sufficient evidence from these additional pieces of information to indicate that the GSI result for an individual is inaccurate, the stock identification biologist adjusts the results based on expert integration of the combined evidence.

## Evaluation

Research by Beacham and colleagues characterized the population genetic structure of Fraser River sockeye salmon (Withler et al. 2000, Beacham et al. 2004) and established the scientific basis for using DNA-based stock identification (Beacham et al. 2004, Beacham et al. 2006, Beacham et al. 2010). Beacham et al. (2004) examined inter and intra- population genetic variation for Fraser River sockeye populations, population genetic differentiation, power of individual loci used for analyses, and accuracy of stock composition estimates. Most Fraser River sockeye salmon populations of interest exhibit strong genetic differentiation from each other, and this facilitates successful GSI. The performance of various GSI methods has been evaluated in the scientific literature (e.g., Araujo et al. 2014, Brenden et al. 2015). At levels of genetic differentiation typical among Fraser River sockeye stocks, Araujo et al. (2014) found no significant difference in performance between CBayes and ONCOR (Kalinowski et al. 2007), a popular alternative GSI software program.

## Planned Changes and Potential Areas for Improvement

Additional work planned to be undertaken includes:

1. Explore improving stock identification at the stock level for stocks that are relatively difficult to distinguish, such as Late Stuart and Stellako.
2. Explore the potential for distinguishing sub-stocks at the DNA baseline sample level (Table 1).
3. Establish methods for comparing the efficacy of GSI across sampling areas or conditions, e.g., evaluate likelihoods of stocks of origin of individuals unaffected by stock compositions of other individuals in the same sample mixtures versus the most probable stock of origin identified by Cbayes.

## References

Araujo, H.A., Candy, J.R., Beacham, T.D., White, B. and Wallace, C. 2014. Advantages and challenges of genetic stock identification in fish stocks with low genetic resolution, Trans. Am. Fish Soc., 143:2, 479488.

Beacham, T.D., Lapointe, M., Candy, J.R., McIntosh, B., MacConnachie, C., Tabata, A., Kaukinen, K., Deng, L., Miller, K.M. and Withler, R.E. (2004) Stock identification of Fraser River sockeye salmon using microsatellites and major histocompatibility complex variation, Trans. Am. Fish Soc., 133:5, 1117-1137.

Beacham, T.D., McIntosh, B., MacConnachie, C., Miller, K.M., Withler, R.E. and Varnavskaya, N. 2006. Pacific Rim population structure of sockeye salmon as determined from microsatellite analysis, Trans. Am. Fish Soc., 135:1, 174-187.

Beacham, T.D., McIntosh, B., and Wallace, C. 2010. A comparison of stock and individual identification for sockeye salmon (Oncorhynchus nerka) in British Columbia provided by microsatellites and single nucleotide polymorphisms. Can. J. Fish. Aquat. Sci., 67, 1274-1290.

Brenden, T.O., Bence, J.R., Weihai, L., Tsehaye, I., and Scribner, K.T. 2015. Comparison of the accuracy and consistency of likelihood-based estimation routines for genetic stock identification. Meth. Ecol. Evol., 6, 817-827.

Debevec, E.M., Gates, R.B., Masuda, M., Pella, J., Reynolds, J., and Seeb, L.W. 2000. SPAM (Version 3.2): Statistics Program for Analyzing Mixtures. Journal of Heredity, 91:6, 509-510.

Kalinowski, S.T., Manlove, K.R., and Taper, M.L. 2007. ONCOR: A computer program for genetic stock identification. Bozeman, MT: Montana State University.

Keefer, M.L. and Caudill, C.C. 2014. Homing and straying by anadromous salmonids: a review of mechanisms and rates. Rev. Fish. Biol. Fisheries, 24, 333-368.

Neaves, P.I., Wallace, C.G., Candy, J.R., and Beacham, T.D. 2005. Cbayes: Computer program for mixed stock analysis of allelic data. Version v3.0 [online]. Free program distributed by the authors over the internet. Available form http://www.pac.dfo-mpo.gc.ca/sci/mgl/Cbayes e.htm

PST. 2020. Treaty between the government of Canada and the government of the United States of America concerning Pacific salmon as modified through January 2020.

Pella, J. and Masuda, M. 2001. Bayesian methods for analysis of stock mixtures from genetic characters. Fish. Bull., 99, 151-167.

Quinn, T.P. 2005. The behavior and ecology of Pacific salmon and trout. Seattle, Wash: Univ Washington Press.

Taylor, E.B. 1991. A review of local adaptation in Salmonidae, with particular reference to Pacific and Atlantic salmon. Aquaculture, 98, 185-207.

Van de Ven, M., Powell, W., Ramsay, G., and Waugh, R. 1990. Restriction fragment length polymorphisms as genetic markers in Vicia. Heredity, 65, 329-342.

Withler, R.E., Le, K.D., Nelson, R.J., Miller, K.M. and Beacham, T.D. 2000. Intact genetic structure and high levels of genetic diversity in bottlenecked sockeye salmon (Oncorhynchus nerka) populations of the Fraser River, British Columbia, Canada. Can. J. Fish. Aquat. Sci., 57, 1985-1998.

# B10. Daily Estimation of Salmon Passage at the Mission Site 

C.R. Lagasse and Y. Xie

## Summary

The PSC operates a hydroacoustic site near Mission, $B C$, that provides daily estimates of salmon passage in the Fraser River throughout the summer. When used in combination with daily species composition estimates (Chapter B16), these estimates contribute to in-season assessments by providing daily sockeye and pink salmon abundance information for run reconstructions (Chapter B18), adjustment of test fishery expansion lines (Chapter B4), prediction of en-route mortality to spawning grounds (Chapter B22), and estimates of Fraser pink salmon escapement. To sample the entire width of the river at the site, a configuration of multiple sonar systems is operated at the site, including two shore-based ARIS imaging sonars (Chapter B13), a side-looking split-beam (Chapter B11), and a mobile, downward looking splitbeam system (Chapter B14). The cross-river location of each sonar and its observed fish targets are determined based on GPS coordinates and then input into a flux estimation model to determine the total daily salmon passage.

## Introduction

Accurate estimates of daily migration abundance are an integral component of in-season assessments of Fraser sockeye management groups. Hydroacoustic monitoring provides a non-invasive, continuous means of monitoring fish migration that is widely used by fisheries agencies for assessing salmon populations. The PSC (and its predecessor the IPFSC) have operated a hydroacoustics monitoring facility on the lower Fraser River every summer since 1977 to assess upstream passage of sockeye and pink salmon. By providing accurate and timely estimates of passage, information from the PSC hydroacoustics site contributes to in-season run reconstructions (Chapter B18) of Fraser sockeye and pink salmon runs, adjustments of test fishery expansion lines (Chapter B4), prediction of en route mortality using management adjustments (Chapter B22) and estimates of Fraser pink salmon escapement.

The PSC hydroacoustics site is located two kilometers upstream of the Mission Railway Bridge and approximately 80 kilometers from the mouth of the Fraser River (Figure 1). This location was originally selected because it is just above the commercial fishing boundary and almost all sockeye populations migrate past it on their upstream migration (with the exception of Pitt River and Widgeon sockeye). The river is approximately 400 meters wide at the site and influenced by tidal changes in water height.


Figure 1. Map of the Lower Fraser River indicating the Mission hydroacoustics monitoring site.
Due to the large channel width, a combination of three or more hydroacoustic systems are deployed to adequately monitor the salmon migration areas (Figure 2). The nearshore left bank area is monitored by a stationary split-beam system (Chapter B11) and an ARIS imaging sonar (Chapter B13) deployed at the end of a fish deflection weir. The ARIS system covers up to the first 30 meters while the split-beam system extends coverage by an additional 30-60meters. The left bank area is where most of the upstream migration typically occurs and is a key focus for monitoring efforts. The left bank ARIS system increases the accuracy of the left bank, especially during periods of high abundance when the split-beam system has been known to underestimate abundances. The nearshore right bank area is monitored using another ARIS imaging sonar and typically observes less than $20 \%$ of the daily upstream salmon migration. In addition to abundance information, the ARIS systems on both the left and right bank provide estimates of salmon species composition using a mixture model based on acoustically observed fish lengths (Chapter B16). The remaining offshore region is monitored by a mobile, downward-looking split-beam system deployed from a sampling vessel that transects the river (Chapter B14).

To produce a daily estimate of salmon passage, the data collected by each hydroacoustic system is processed, analyzed and input into a flux estimation model. This report describes the flux estimation model for estimating daily salmon passage from a configuration of multiple sonars at the site.


Figure 8. Cross-river view of the sampling geometry of the sonar systems operated at the Mission hydroacoustics site. The four systems shown are the left bank ARIS (A1, covering 0 to 30 m ), the left bank split-beam (S1, covering 0 to 50 m ), the mobile split-beam ( $M$ ), and the right bank ARIS (A2, covering final 30 m ). The beam geometries of left bank ARIS (A1) are represented by the hollow triangles and overlap with the S1 beam geometries which are represented by the filled coloured triangles. The blue filled offshore area represents the cross-river region sampled by the mobile split-beam. The gray filled area represents the river bottom. Note that the cross-river range scale on the $x$-axis is compressed relative to the vertical depth scale on the $y$-axis.

## Methods

To determine salmon passage across the entire river channel at the Mission hydroacoustics site, the passage estimates from the four monitoring systems (left bank ARIS, A1; left bank split-beam, S1; mobile split-beam, $M$; and right bank ARIS, A2) must be combined. To accomplish this, the cross-river width is divided into 5 meter range bins, then for each range bin, the salmon passage from a single monitoring system is applied. The range bins sampled by each system are determined from their GPS location along with their sampling range and compass bearing. These sampling areas are updated throughout the field season as the river levels drop and the systems are moved further offshore. The analysis of the positioning, selection, and addition of sonar system configurations for the daily estimate are completed using the Flux Estimator software developed by the PSC (Lagasse 2019).

If a range bin is sampled by multiple systems, only the most accurate system is used for the salmon passage estimate, while other estimates are excluded to avoid double-counting. Estimates from shorebased systems are preferentially used over mobile estimates whenever possible due to their higher sampling intensity and more accurate ability to track fish locations and behavior. Where multiple shorebased systems overlap in sampling area, as is the case with the left bank split-beam and ARIS, the splitbeam is used for the daily estimate in most cases due to its ability to sample a greater portion of the water column and extrapolate into unsampled areas (Chapter B11). However, during periods of very high-density fish passage, such as the peak of the Fraser pink migration in 2019, the split-beam cannot accurately distinguish among fish tracks and may underestimate fish passage, so the left bank ARIS would be used instead to estimate nearshore salmon passage.

The distribution of salmon passage across the river channel tends to change throughout a season depending on river flows, species composition, tidal fluxes, and other factors. River flows and turbidity are higher in July than August or September, and a greater proportion of the migration occurs in the offshore areas observed by the mobile system. As flows decrease, the tidal influence on water heights increases and fish passage becomes more concentrated along the shorelines. During odd-numbered years when pink salmon return to the Fraser River, migration past the Mission hydroacoustics site is highly concentrated in near-shore areas, with less than $10 \%$ of daily passage observed in offshore regions.

All of the systems operated at the Mission hydroacoustics site sample throughout the day and night with the shore-based systems operating continuously for 24 hours a day. Therefore, assuming there are no gaps in data collection, each estimate of daily salmon passage is based on 24 hours of monitoring data. To group each day and night period into the same assessment interval, the daily estimates do not coincide with calendar days, but instead begin at 05:00 each day. For example, the estimate of daily salmon passage at Mission for July 4 would include data beginning at 05:00a.m. on July 4 and continuing to 04:59a.m. on July 5.

Data collected by each of the systems is reviewed and processed by 8:30a.m. every morning by PSC staff throughout the field season to generate the estimate of salmon passage for the previous day. Summary statistics are calculated for the daily estimate of salmon passage including the ratio of fish travelling downstream (S1 Ratio downstream, Rd), the proportion of daily passage observed by each sonar system, the percentage of passage extrapolated in unsampled areas (\% Extrapolated), and the number of transects performed by the mobile sampling vessel and the number of daily targets observed by the mobile vessel (Table 1). The summary statistics also include total salmon estimates based on alternative system configurations (e.g., $S 1+M, A 1+M+A 2, S 1+M+A 2$ and $A 1+S 1+M+A 2$ ). Once the daily estimate of total salmon passage is published, the species composition of salmon (Chapter B16) is estimated to determine the daily passage of sockeye salmon past Mission.

Table 1. Summary statistics for the estimate of daily salmon passage using August 20, 2019 as an example. JD is the Julian calendar date. Rd is the ratio of total fish travelling downstream.

| Mission Date | JD | S1 Flux Proportion | Mobile Flux Proportion | A2 Flux Proportion | Total Salmon Official | ```Systems For Estimate``` |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| 8/20/2019 | 232 | 75.2\% | 9.2\% | 15.6\% | 49,553 | S1+M+A2 |
| 8/20/2019 232 |  | Estimates by sonar configuration:  <br> TotalSalmon TotalSalmon <br> (S1+M) (S1+M+A2) |  | TotalSalmon $(A 1+M+A 2)$ | TotalSalmon $(\mathrm{A} 1+\mathrm{S} 1+\mathrm{M}+\mathrm{A} 2)$ |  |
|  |  | 41,823 | 49,553 | 49,363 | - |  |
|  |  | Other statistics: S1 Rd | \%S1 Extrapolated | \%Extrapolated | Mobile Targets Daily |  |
|  |  | 1.8\% | 18.8\% | 14.1\% | 15 |  |
|  |  | S1 Hours Data | A2 Hours Counts | Mobile Transects Daily |  |  |
|  |  | 22 | 24 | 184 |  |  |

## Planned Changes and Potential Areas for Improvement

An ARIS sonar has been in use on the left bank since 2017 (Chapter B13) and research is currently ongoing to compare the fish passage estimates between the ARIS and split-beam systems and to eventually phase out the split-beam system.

## References

Lagasse, C. 2019. Estimation Procedures Using PSC Fish Flux Estimator V3.3. Pacific Salmon Comm. Special Tech Manual. January 2019.

# B11. Left Bank Salmon Passage Based on Shorebased Split-beam Sonar 

C.R. Lagasse and Y. Xie

## Summary

A shore-based split-beam sonar deployed near the left bank of the Mission hydroacoustics site is a key component of the estimation system for salmon passage. Split-beam technology was first adopted for the Mission site in 2004 and has been operated continuously throughout the salmon monitoring period in all years since then. An hourly stratified sampling design is used for data collection, consisting of systematic spatial sampling of ten non-overlapping vertical areas up to a range of 60 metres offshore. The echo data is filtered, tracked, and classified to distinguish fish tracks from debris, bubbles and other noise. All data is then manually verified by PSC staff prior to estimating associated abundance by analysing a daily summary of fish tracks within the flux model (Chapter B12). The left-bank estimate typically accounts for more than half of the daily salmon passage at the Mission site.

## Introduction

Split-beam sonar is widely used for fisheries acoustics in riverine and marine applications around the world. By collecting information on the position within the sound-beam and signal strength of echoes, the technology allows fish to be tracked in 3-dimensional space, thereby providing a method for estimating fish passage in both upstream and downstream directions. Within the Fraser River, splitbeam monitoring at the Mission site was first implemented in 2004 following recommendations from a hydroacoustics working group in 1994 and feasibility studies from 1995 to 2002 (Xie et al. 2005). Since 2004, a shore-based split-beam sonar has been operated from the left bank of the Mission site to continuously monitor fish migration in the river and contribute to daily estimates of salmon passage. This system is generally the most important component of the daily passage estimate because the majority of salmon migrate closer to the left bank of the site where water flows are weakest.

To estimate fish passage observed by the split-beam, the raw signal of echoes must be filtered, processed and verified to distinguish between fish and non-fish targets so that detected fish can be counted using a target-tracking method. Once the left bank split-beam data has been verified, key statistics of tracked fish, including their abundance and direction of travel, are imported into a flux model to determine the daily fish passage (Chapter B12). The PSC has developed and refined these procedures over time and performs them on a daily basis throughout the migration of sockeye and pink salmon within the Fraser River to provide real-time estimates of daily salmon passage for in-season management.

## Methods

## EQUIPMENT AND DEPLOYMENT

At the beginning of each field season, the PSC installs a sectional fish deflection weir (Enzenhofer et al. 2005) on the left bank of the river to allow deployment of its split-beam and imaging sonars (Figure 1), and to direct the movement of salmon past the sonar systems. The deflection weir is deployed up to a depth of approximately 4 meters and sections are added to extend the weir throughout the summer as
river levels drop. The split-beam system is attached to the weir using a U-bracket that allows its depth to be adjusted in the water column. Conduit poles installed along the entire length of the weir prevent fish from swimming behind or too close to the transducer.

The split-beam currently used by the PSC is manufactured by Hydroacoustics Technology Incorporated (HTI) and operates at a frequency of 200 kHz with an elliptical beam geometry of $2^{\circ} \times 10^{\circ}$ effective beam height and width. The beam is oriented with its longer axis parallel to river flow to optimize fish detection. The transducer is powered by an HTI Model 243 echosounder that is stored in a trailer on shore. Once deployed, the split-beam system is operated continuously to collect data 24 hours a day throughout the field season.


Figure 1. The fish deflection weir and deployed split-beam and ARIS imaging sonar on the left bank of the Mission site. The underwater position and orientation of the split-beam are indicated by the red square and arrow. A close-up view of the split-beam transducer are shown in the inset photo.

The elliptical beam geometry of the split-beam can only sample a small portion of the water column, therefore a stratified sampling design with multiple vertical aims is used for greater sampling coverage. The stratified sampling design consists of ten aims of non-overlapping, $2^{\circ}$ vertical apertures with each aim sampling for 6 minutes each hour up to a range of 60 metres offshore (Figure 2). The vertical tilt and bearing of the transducer is controlled by a SIDUS SS250 rotator and monitored using an Impact Subsea ISD4000 motion reference unit, which also records the water height at the site where tidal influences can be very pronounced.

## DATA COLLECTION AND PROCESSING

To identify individual targets among the acoustic pings transmitted by the split-beam, the received echoes are first processed using a single-echo detection (SED) threshold that removes any targets below an acoustic target strength threshold of approximately -45 dB (Ehrenberg and Torkelson 1996). The target strength of adult salmon is normally greater than - 40 dB , therefore the SED filters out most signals that are too weak and/or too narrow (relative to the projected pulse width) to have originated from a salmon. The SED filtered single-target data are analyzed using an alpha-beta tracker (Blackman
and Popoli 1999) to form tracks of detected targets, following the targets over time in a threedimensional space. An automated discriminant function analysis (DFA) is then applied to the target tracks to distinguish fish tracks from debris or other noise (Xie at al. 2012). In some cases, particularly during the peak migration of pink salmon, a DFA is not applied because it cannot distinguish dense schools of fish from noise.

Following the automated fish track identification, the tracks are manually verified by trained staff that review the echogram data using the Split-beam Fishtrack graphic user interface editing software developed by the PSC (Figure 3). Targets are verified by examining the summary statistics of target track features such as speed, direction of travel, and target strength, as well as looking for broader patterns in the distribution of echoes in the water column. For example, bottom echoes can be visually identified and removed based on their very low speeds, clumped distributions and consistent sampling ranges. This processing and editing procedure is performed daily for every hour of split-beam data.

The verified fish tracks are then exported into a spreadsheet containing statistics on the target strength, number of pings, direction of travel, and the 3-dimensional location and speed for each of the individual verified fish tracks. These data are then imported into the PSC Flux Estimator software for further summary and analysis (Chapter B12). The flow chart in Figure 4 describes the steps of left bank splitbeam data processing.


Figure 2. Hourly sampling design of the left bank split-beam system (red square) with the ten vertical aims represented by coloured wedges. Each of the aims has a vertical height of $2^{\circ}$, resulting in a total coverage of $20^{\circ}$ of the water column. The maximum sampling range is 60 meters, though many of the aims near the river boundaries use reduced ranges to avoid interference from the water surface or river bottom. The gray filled area represents the river bottom as profiled in July 2018.


Figure 3. Echogram or visual display of left bank split-beam data for a 6-minute sampling interval generated by the PSC Fish Track software. Each of the coloured traces represents an individual fish track. Black dots represent noise such as surface bubbles or debris. These data represent a period of low fish passage on August 16, 2019.


Figure 4. Flow chart describing the procedure for left bank split-beam data processing.

## Planned Changes and Potential Areas for Improvement

Over the last decade, the split-beam system on the left bank has relied on an $\mathrm{HTI} 2^{\circ} \times 10^{\circ}$ transducer and Model 243 echosounder for data collection. In the near future, this equipment will need to be replaced. HTI has discontinued support for its echosounders requiring alternative suppliers to be explored. An ARIS sonar has been in use on the left bank since 2017 (Chapter B13) and research is currently on-going
to compare the fish passage estimates between the ARIS and split-beam systems and to eventually phase out the split-beam system.

## References

Blackman, S.S., and Popoli, R. 1999. Design and Analysis of Modern Tracking Systems. Artech House, Norwood, MA.

Ehrenberg, J.E., and Torkelson, T. C. 1996. Application of dual-beam and split-beam target tracking in fisheries acoustics. ICES Journal of Marine Science, 53: 329-334

Enzenhofer, H.J., Cronkite, G.M.W., and Holmes, J.A. 2005. A sectional fish deflection weir and installation boom for riverine applications. Can. Tech. Rep. Fish. Aquat. Sci. 2605: iv+ 14 p.

Xie, Y., Gray, A.P., Martens, F.J., Boffey, J.L., and Cave, J.D. 2005. Use of Dual-Frequency Identification Sonar to Verify Salmon Flux and to Examine Fish Behaviour in the Fraser River. Pacific Salmon Comm. Tech. Rep. No. 16: 58 p.

Xie, Y., Michielsens, C.G.J., and Martens, F.J. 2012. Classification of fish and non-fish acoustic tracks using discriminant function analysis. ICES Journal of Marine Science, doi:10.1093/icesjms/fsr198.

## B12. Flux Model for Fish Passage Based on Splitbeam System

Y. Xie and PSC Hydroacoustics Staff

## Summary

Fish passage in the Fraser River in the left-bank nearshore area at Mission is monitored with a multi-aimed split-beam sonar (Chapter B11). Sounding ranges at steeper (either upper or lower) aims are significantly shortened to avoid echoes from the river bottom and water's surface. While fish passage in the ensonified zone can be directly estimated, passage in the acoustic blind zones is projected from observed passage values using a nearest-neighbour extrapolation algorithm.

## Introduction

Fish passage in nearshore areas, up to 60 m from either bank, is monitored by shore-based side-looking sonar systems. On the right bank, the bottom of the nearshore area is generally concave. This allows an ARIS with a single vertical aim with a beam-width of $15^{\circ}$, to effectively sample the entire water column for the nearshore area on the right bank (Figure 1).


Figure 1. Sampling ranges for the left and right banks nearshore areas. The left-bank split-beam system (LB.S1) uses 10-aim stratified unequal ranges to sample the nearshore water column. The right-bank ARIS system (RB.A2) uses a single-aim to sample the nearshore water column (out to 40 m ).

On the left-bank, the bottom of the nearshore area is convex. This area therefore requires stratified sampling of fish passage in the left-bank nearshore area with a split-beam system on a rotator allowing for stratified sampling at 10 aims. The multiple aims allow flexibility in sampling different portions of the water column with optimal sounding ranges. Sounding ranges at upper or lower aims are significantly shortened to avoid echoes from river boundaries (i.e. the river bottom and water's surface). However, the differential sounding ranges for different aims can result in acoustic blind zones near the river surface and bottom. While fish passage in the ensonified zone can be directly estimated (Chapter B11), passage in the blind zone is projected from observed flux values using a nearest-neighbour extrapolation algorithm (Bowman and Azzalini 1997).

## Methods

## DATA COLLECTION

The left-bank split-beam system is deployed at the end of a fish deflection fence as shown in Figure 2. The $2^{\circ} \times 10^{\circ}$ split-beam transducer uses an hourly systematic sampling scheme to sample the nearshore water column at 10 non-overlapping aims with a sampling time of 6 minutes per aim (see Chapter B11 for details). After a 24-hour sampling period, the system obtains a cumulative distribution for the nearshore fish passage as shown in Figure 3.


Figure 2. The fish deflection weir and deployed split-beam system on the left bank of the Mission site. The underwater position and orientation of the split-beam sonar are indicated by the red square and arrow.


Figure 3. Cumulative fish distribution (black dots) over a 24 -hour sampling period by the left-bank split-beam system. For the monitored nearshore area (within the 2 vertical black lines), there are areas not ensonified by the sound-beam. Fish passage through these blind zones is estimated by the nearest-neighbour method.

## REPRESENTATION OF LEFT-BANK NEARSHORE CROSS-SECTION WITH FINITE CELLS

To estimate the total abundance of fish in the left-bank nearshore cross-section, the area is represented by 2 dimensional cells, each 5 m wide and 1 m high (Xie 2002), as shown in Figure 4. Note that in these cross-section plots the river bottom is the vertical reference $(y=0)$ so that the flat surface of the mean waterline is transformed to a curvy line (the red line) which mirrors the river bottom. Based on the proportion of the cell ensonified and the proportion of the cell under water, cells are classified into 5 classes:

1. Fully ensonified and fully submerged cells (e.g. cells indicated by the black arrows in Fig. 4);
2. Partially ensonified and fully submerged cells with coverage $>50 \%$ (e.g. cells indicated by the green arrows in Fig. 4);
3. Partially ensonified and fully submerged cells with coverage $<50 \%$ (e.g. cells indicated by the blue arrows in Fig. 4);
4. Partially submerged cells (e.g. cells indicated by the pink arrows in Fig. 4);
5. Cells completely above the waterline (e.g. cells indicated by the purple arrows in Fig. 4).


Figure 4. Classifications of 2 dimensional cells by the proportions ensonified and submerged. A total of 5 classes are identified, examples of which are shown by arrows of different colors (see text for details). Values in individual cells are estimates of hourly fish flux through the cells (see next section for details).

## CALCULATIONS OF HOURLY FISH FLUX THROUGH INDIVIDUAL CELLS

The hourly fish flux, i.e. the number of fish per hour, is calculated using different methods for the 5 classes of cells, as outlined below.

For fully ensonified cells that are fully submerged in the water (type 1), the hourly fish flux ( $f$ ) is calculated by a linear expansion of the number of fish observed daily in the cell ( $N$ ) divided by the total daily sampling minutes ( $T$ ):

$$
\begin{equation*}
f_{1}=\frac{N}{T} \times 60 . \tag{1}
\end{equation*}
$$

For cells that are fully submerged and ensonified for more than $50 \%$ (type 2), the hourly flux f is calculated the same way, except that an area expansion factor ( $1 / \alpha$ with $\alpha$ being the ensonified proportion of the cell area) is applied to equation 1 to expand the observed flux to the entire area of the cell:
(2) $f_{2}=\left(\frac{N}{T} \times 60\right) / \alpha$.

For instance, if the sound-beam ensonifies $75 \%$ of the cell area, then the expansion factor would be $1 / 0.75=1.33$.

For cells that are fully submerged and ensonified for less than $50 \%$ (type 3), we consider the observed area to be too small to expand the observed flux to the entire cell area. Instead, the flux in the area that is not ensonified is based on the flux in the nearest-neighbour cell, by taking the mean of the estimated flux in the horizontally $\left(f_{h}\right)$, vertically $\left(f_{v}\right)$ and diagonally $\left(f_{d}\right)$ neighbouring cells. The total flux for this class of cells is then:

$$
\text { (3) } \quad f_{3}=f_{1}+(1-\alpha) \cdot\left(\frac{f_{h}+f_{v}+f_{d}}{3}\right)
$$

with $\alpha$ indicating the ensonified proportion of the cell area and (1- $\alpha$ ) indicating the area for which the nearest-neighbour method is used to derive the hourly flux. Taking the cell with the flux value of 542.72 (fish/hour) in Figure 4 as an example, we demonstrate the application of Equation 3 to this partially ensonified cell. In this example, the ensonified proportion for the area of this cell is $33 \%$ and the flux in this area is 237 fish/hour. The nearest neighbour method projects a flux of $456.3=(569.17+343.37+$ 360.83 )/3 (fish/hour). Therefore, the flux for this cell is, according to Equation 3: $f_{3}=237+$ $(1-0.33) \times 456.3=542.7$ fish/hour.

For cells not fully submerged in the water (type 4), the estimated flux for a entire cell produced by the above calculations must be reduced by a factor of $\beta$, the submerged portion of the cell:

$$
\text { (4) } \quad f_{4}=\beta \cdot f
$$

Taking the cell with the flux value of 402.89 fish/hour in Figure 3 as an example, we estimate the flux for this cell based on the nearest-neighbour method to be $469.3=(295.9+542.72+569.17) / 3$ fish/hour, assuming the cell is fully submerged. However, this cell is only $85.8 \%$ submerged; therefore, the flux for this cell according to Equation 4 is: $f_{4}=0.858 \times 469.3=403$ fish/hour. The fish flux for cells entirely above the waterline (type 5 ) is zero.

## FLUX ESTIMATOR SOFTWARE

The representation of the left-bank cross section by $5 \mathrm{~m} \times 1 \mathrm{~m}$ cells and the above calculations of ensonified and submerged proportions of individual cells are implemented by the Visual C++ based software program, FluxEstimator. The software includes a graphical user interface (GUI) system to allow the user to visually examine the outputs of flux values for individual cells. Users can use the GUI to overrule extrapolated flux for individual cells if the flux values appear either too high or too low relative to the neighbouring cells' values. However, in most data scenarios, the flux outputs are not altered.

The FluxEstimator graphs are presented in Figure 5. The top graph shows the upstream fish targets while the bottom graph show targets that move downstream. In this example, the net upstream flux (upstream flux - downstream flux) in the ensonified area is 4039.6 fish/hour. The fish flux in the blind zones is calculated using the methods described in the previous section (Xie et al. 2005). In this example, the net upstream hourly flux through the entire left-bank monitoring area is 5297.33 fish/hour. In this scenario, the extrapolated flux accounts for $23.7 \%$ of the total estimated flux.


Figure 5. Plots of hourly fish flux for the entire left-bank monitoring area. (a) upstream flux; (b) downstream flux. Dots represent locations of ensonified fish targets. The area inside the curvy lines is the ensonified area.

## References

Bowman, A. W., and Azzalini, A. 1997. Applied smoothing techniques for data analysis. The kernel approach with S-Plus illustrations. Oxford Science Publications, Clarendon Press. Oxford.

Xie, Y. 2002. Estimation of Migratory Fish Abundance Using River-Transect Sampling by a Split-beam Transducer. Presented at ICES Symposium on Acoustics in Fisheries and Aquatic Ecology. Montpellier, France, 10-14, June 2002.

Xie, Y., Gray, A.P., Martens, F.J., Boffey, J.L., and Cave, J.D. 2005. Use of dual-frequency identification sonar to verify salmon flux and to examine fish behaviour in the Fraser River. Pacific Salmon Comm. Tech. Rep. No. 16: 58 p.

# B13. Shore-based Imaging Sonar Systems 

M. Bartel Sawatzky

Summary
Imaging sonar technology such as DIDSON and ARIS systems provides visually intuitive data that are currently used by fisheries biologists to estimate salmon escapement and species composition in the Fraser River. This technology has been utilized officially at the Pacific Salmon Commission's Mission hydroacoustics monitoring site since 2009. This document outlines the deployment, sampling design, and fish counting methods for the imaging data generated by the Sound Metrics ARIS 1800 system as it is currently used in the hydroacoustics program.

## Introduction

The Pacific Salmon Commission (PSC) hydroacoustics program has been enumerating upstream salmon passage through the lower Fraser River at Mission since 1977. Over the years, various new technologies have been tested and adopted to improve the accuracy of salmon passage estimates. The program started with a single-beam sonar system and a split-beam system was added to the program in 2004. These systems however did not allow to visually identify the objects passing the monitoring site, which can cause problems when there is a lot of debris in the river or during periods of very dense upstream migration. In 2001, acousticians and sonar engineers from the University of Washington developed a high-resolution image sonar system that allow users to visually identify detailed shapes of underwater objects. The sharp resolution and the ease of use and interpretation of the image information make imaging sonar one of the best tools for observing fish behaviour in a turbid riverine environment such as the lower Fraser River at Mission, B.C.

Imaging sonar technology has been utilized in the PSC hydroacoustics program since 2004, beginning with trials of the DIDSON system (Dual-Frequency Identification Sonar, Belcher et al. 2002) to assess its ability to estimate fish flux in areas ensonified by the left bank split-beam system (Chapter B11). These trials also assessed the DIDSON system for the purposes of estimating fish flux in blind zones of the left bank split-beam system, identifying non-salmonid fish targets and obtaining statistics on fish behaviour (Xie et al. 2005). After the successful completion of these trials, the DIDSON system was officially integrated into the PSC hydroacoustics program in the summer of 2009 to monitor upstream salmon passage (Lagasse et al. 2017).
Initial experiments with an ARIS 1800 system were conducted during the 2015 field season to compare its data to the data collected by the DIDSON and $2^{\circ} \times 10^{\circ}$ split-beam transducer deployed from the left bank of the Mission hydroacoustic site. This comparison revealed that the ARIS, with its increased resolution, produced similar counts to the DIDSON at close range on the left bank (Lagasse et al. 2016). Similar comparisons of the ARIS and DIDSON imaging sonar systems continued for the 2016 field season, this time with the two units sampling the same portion of the water column. This further testing showed that the ARIS and DISON systems produced statistically identical results of fish passage (Lagasse et al. 2017).

Currently, the ARIS imaging sonar systems are deployed on both the right and left banks, capturing approximately $60-80 \%$ of the total daily salmon passage at the Mission site (Conrad et al. 2019). While testing is underway to also employ the ARIS on the vessel transecting the mid-section of the river, the current document focuses on the ARIS data collection and counting methodology used to produce nearshore estimates.

## Methods

## SYSTEM DEPLOYMENT AND DATA COLLECTION

The PSC Mission hydroacoustic site is located 80km upstream from the mouth of the Fraser River where the maximum width of the river is approximately 450 metres and the maximum depth varies from 13 to 17 metres depending on discharge levels. The site is operational during the sockeye and pink salmon migration periods, generally from early July to September or October each year. The hydroacoustics site is comprised of the left bank field site, which houses the majority of the field site equipment, and the right bank field site, directly across the river from the left bank site.

## Right bank

The right bank field site is an off-grid location directly across the Fraser River from the main work trailer of the Mission program. It is powered by a battery bank which is charged by solar and gas-generator power. The ARIS system is mounted with a pole-mount to an aluminum cross arm attached to the end of a telescopic fish weir (Enzenhofer and Cronkite 2005). Fully deployed, the fish weir extends 20 m from the river bank. The river profile on the right bank has a gradual downward slope which is ensonified by an ARIS 1800 unit using one vertical aim, varying between $-3^{\circ}$ to $-8^{\circ}$ depending on water levels, to a maximum range of 40 m . The aim is split into 4 range bins (Figure 1) and the ARIS system is programed to record each range bin for 10 minutes per hour. The resulting files are transferred wirelessly to the left bank trailer for on-site processing by staff.


Figure 1. Diagram of the right bank ARIS sampling scheme.

## Left bank

The left bank field site houses the main passage estimation systems. As much as $80 \%$ of salmon passage occurs on the left bank and it is monitored using both an HTI split-beam system and an ARIS 1800 imaging sonar. Both systems are mounted to the end of a large fish weir that also acts as a dock and walkway for two vessels that are used at the site. The HTI split-beam system normally samples to a range of 50 to 60 metres, and the ARIS system overlaps the HTI split-beam system to a maximum range of 45 metres. This overlap in sampling area allows the ARIS system to be used as a data verification tool during low to medium abundance scenarios. As left bank passage increases, the split-beam system may become saturated and its individual target recognition capabilities are diminished. The ARIS system does a much better job of tracking individual targets when abundances are high and is relied upon for near shore $(0-30 \mathrm{~m})$ passage during peak migration events. Further information on the left-bank splitbeam system can be found in Chapter B11.

Due to the semi-convex shape of the nearshore river bottom on the left bank and the limited vertical beam-width of the imaging sonar, the ARIS system requires multiple vertical aims to sample the entire water column in the first range bin of 0-10m (Figure 2). Two vertical aims (approximately $-14^{\circ}, 0^{\circ}$ depending on system deployment and water height) are used for the first range bin. The two nearshore aims are configured to minimise "blind areas" near the river bottom and upper water column which can accommodate high salmon passage due to tidal influences. The three farther range bins ( $10-40 \mathrm{~m}$ ) are sampled using a single aim $\left(-3^{\circ}\right)$ as the vertical beam width of the ARIS system can adequately cover the water column at those ranges. Each aim and range bin are sampled individually on a systematic hourly sampling schedule. Fish passage in each of the stratified spaces is recorded for 10 minutes per hour.


Figure 2. The non-overlapping stratified hourly sampling spaces by the left bank ARIS system. The left-bank ARIS system is mainly relied upon for passage up to 30 metres nearshore while the splitbeam system extends the sampling range up to 60 metres.

## DATA PROCESSING

## Counting Procedures

The ARIS data are collected hourly and each aim/bin is sampled for 10 minutes per hour (Figure 2). The files are uploaded to the central processing computer where they are counted by hydroacoustics staff using the ARISFish software specifically designed by Sound Metrics for post-processing of ARIS data. The staff members count all upstream and downstream fish targets with tally counters, regardless of size, for the first 5 minutes of each file. The coefficient of variation (CV) associated with the resulting hourly fish count estimates is $6.5 \%$ (Xie and Martens 2014). It is possible to count the entire 10 minutes of each recording, but the gain in precision is minor (CV of 5.5\%). During low abundance scenarios, the playback framerate of the sonar files can be increased to complete the counts faster. When passage rates
increase, it becomes challenging to count the files in real time, so the framerate is decreased to ensure the counts are accurate.

## Generating an Imaging Sonar Passage Estimate.

Once the Imaging sonar counts associated with a 24 hour period are complete, a total daily fish passage estimate is calculated. In order to generate a passage estimate for salmon, non-salmon species must be removed from the total fish counts. This is achieved by taking length measurements of a subset of fish images from the same imaging sonar files used for fish counting and running them through a mixture model to calculate the proportion of salmon sized targets (Chapter B15). Those proportions are then applied to the corresponding counts to derive the daily salmon passage estimates for both the right and left bank ARIS systems. The ARIS data are then ready to be included in the daily total salmon estimate which also includes passage estimates from the left bank and mobile split-beam systems (Chapter B10).

## References

Belcher, E., Hanot, W., and Burch, J. Dual-Frequency Identification Sonar, (Proceedings of the 2002 International Symposium on Underwater Technology, Tokyo, Japan, April 16-19, pp. 187-192, 2002).

Conrad, B., Dufault, A., Hawkshaw, M., Huang, A., Jenkins, E., Lagasse, C., Lapointe, M., Litz, M., Martens, F.J., Michielsens, C.G.J., Scroggie, J., Staley, M., Whitehouse, T., Wor, C., and Xie, Y. 2019. Hydroacoustics Review Technical Summary. Pacific Salmon Comm. Tech. Rep. No. 41: 369 p.

Enzenhofer and Cronkite. 2005. A simple adjustable pole mount for deploying DIDSON and split-beam transducers. Canadian Technical Report of Fisheries and Aquatic Sciences 2570.

Lagasse, C.R., Martens, F.J., Nelitz, J.L., Bartel-Sawatzky, M., and Xie, Y. Assessment of Adaptive Resolution Imaging Sonar (ARIS) for fish counting and measurements of fish length and swim speed in the Lower Fraser River: A final project report to the southern boundary endowment restoration and enhancement fund. Pacific Salmon Commission, June 2016.

Lagasse, C.R., Bartel-Sawatzky, M., Nelitz, J.L., and Xie, Y. 2017. Assessment of Adaptive Resolution Imaging Sonar (ARIS) for fish counting and measurements of fish length and swim speed in the lower Fraser River, year two: A final project report to the Southern Boundary Restoration and Enhancement Fund. Pacific Salmon Commission. June 2017.

Xie, Y., Gray, A.P., Martens, F.J., Boffey, J.L., and Cave, J.D. 2005. Use of Dual-Frequency Identification Sonar to Verify Salmon Flux and to Examine Fish Behaviour in the Fraser River. Pacific Salmon Comm. Tech. Rep. No. 16: 58 p.

Xie, Y., and Martens, F.J. 2014. An empirical approach for estimating the precision of hydroacoustic fish counts by systematic hourly sampling. North American Journal of Fisheries Management, 34:3, 535-545.

# B14. Offshore Salmon Passage Based on Mobile Transecting Split-beam System 

Y. Xie and PSC Hydroacoustics Staff


#### Abstract

Summary At the PSC hydroacoustic site at Mission, salmon are known to utilize the entire 400 m river width of the Fraser River as they migrate upstream. While nearshore areas up to 50 m from either bank are well monitored by the shore-based sonar systems (Chapter B11 and B13), fish migrating beyond this range are monitored by a downward looking mobile split-beam sonar system deployed from a vessel continuously transecting the river. The transect sampling of the river by the mobile split-beam system acquires information on fish density in the offshore area. This density information is combined with fish speed and direction of travel statistics through a mobile fish flux model to produce a daily estimate of offshore fish passage.


## Introduction

During the summer monitoring season, the width of the Fraser River at the PSC Hydroacoustic monitoring site is, on average, 400 m . Due to the reduced strength of underwater sound over longer distances, side-looking sonar systems are unable to effectively detect salmon targets across the entire river. According to Medwin and Clay (1998), in $15^{\circ} \mathrm{C}$ fresh water, a 200 kHz sound loses approximately 1 decibel of its magnitude per 100 m of propagation, or in a linear scale, the sound loses $20 \%$ of its intensity per 100 m due to attenuation.

At the Mission site, salmon are however known to utilize the entire river width for their upstream migration. Fish migrating in nearshore areas (up to 50 m from either bank) are well monitored by the shore-based sonar systems; fish beyond this nearshore range are monitored by a downward looking mobile split-beam sonar system deployed from a vessel that continuously transects the river at the site. For more information regarding the configuration of the Hydroacoustics site, please see Chapter B10.

The mobile split-beam system acquires data used to estimate fish density in the offshore area. This density information is combined with behavioural statistics, such as fish speed and direction of travel, using a mobile fish flux model, which results in a daily estimate of offshore fish passage. Since the mobile system cannot reliably measure the swimming behaviour of fish while transecting the river, parameters such as speed and direction of travel are based on the fish behaviour in the left-bank nearshore area measured by the left-bank split-beam system (Chapter B11).

## Data

The mobile split-beam data are collected using a downward looking split-beam transducer towed by a vessel that continuously transects the Fraser River. The vessel is a 6.7 m long aluminum hull motorboat (Figure 1a) and its beam (width) is 2.6 m with a 0.9 m draft in fresh water. The moderately V-shaped hull is designed specifically for surveying fish in shallow waters. The vessel is powered by a stern-drive Volvo Penta 3.0-liter gasoline engine which drives a 3-bladed propeller. During normal transecting, the propeller is kept at a rotational speed ranging from 1200 to 2000 rpm depending upon the discharge level and tidal currents. A GPS receiver is installed onboard to record the transecting trajectory and speed during mobile surveys. On average, it takes about five minutes for the vessel to complete a crossriver transect at the site at a mean cruising speed of $1.4 \mathrm{~m} / \mathrm{sec}$ (or 2.7 knots). Excluding time spent on
stationary sampling and shift changes and refueling, the vessel completes on average a total of 170 transects per day. The vessel has little impact on the natural behavior of migrating fish at water depths greater than 4m (Xie et al 2008).

To survey fish in the offshore areas of the river, which are at most 18 m deep, a Biosonics $6^{\circ}$ circular nominal split-beam transducer powered by a DT-X echosounder (http://www.biosonicsinc.com) is deployed from the vessel. The transducer is mounted on a towed body on the port side of the vessel (Figure 1b) and is kept in a downward-looking orientation while being towed. The transducer emits 0.2 ms long $210-\mathrm{kHz}$ acoustic pulses at a ping rate of 20 pings per second. The sounder's source level is set at 220 dB . Echoes with echo levels exceeding -130 dB are logged into the hard drives of the sounder. This raw echo data is suitable for single-echo-detection (SED) processing (Ehrenberg and Torkelson 1996). The SED processing removes any echo signals with acoustic target strength (TS) below -45 dB (adult salmon normally possess TS > -40dB).

Because the downward looking split-beam system cannot be used to derive behavioral data, these data are obtained from the stationary left-bank split-beam system instead (Chapter B11).


Figure 1. (a) The transecting vessel for the mobile survey; (b) The tow-body housing the downward looking split-beam transducer.

## Methods

## OFFSHORE FISH DENSITY

The raw echo data are analyzed using an alpha-beta tracker (Blackman and Popoli 1999) by forming tracks of detected targets, that allow to follow the targets over time in a three-dimensional Cartesian space ( $X, Y, Z$ ). The identified fish tracks are verified by trained staff that review the echogram data with interactive editing software to remove non-fish targets (Figure 2). The tracks are identified by examining the summary statistics of tracks such as their target strength, detection probability, continuity in the space-time domain (echogram) of track trajectories, as well as their echogram patterns prior to SED processing (the raw echo patterns). This visual critiquing and editing procedure is performed each day for all the split-beam data using the Split-beam Fishtrack software developed by the PSC (Xie 2004). The fish track data produced by the mobile split-beam system provides daily estimates of the average number of fish detected per transect across the river. With associated GPS location data, we can obtain the spatial distributions of the detected fish for a cross-section of the river at Mission (Figure 3).


Figure 2. Echogram display of mobile split-beam data comprising 5 complete transects (generated by the PSC Fish Track software). Each of the coloured traces represents an individual fish track, totaling in this case 11 fish. Black dots represent echoes that are noise such as bubbles, debris or the river bottom. These data were collected on September 18, 2018 during the Late-run sockeye dominant migration period.


Figure 3. Scatter plot of 24-hour cumulative cross-river fish distribution acquired by the mobile split-beam system at the PSC Mission Hydroacoustics site on September 18, 2018. Dots represent locations of detected fish by the mobile system.

## OFFSHORE FISH PASSAGE

With the fish density information acquired from the mobile split-beam system using the alpha-beta tracker as well as the Fishtrack software and fish behavior statistics estimated from the left-bank system, a fish flux model is used to combine these two types of information to calculate fish flux: the daily number of fish migrating upstream in the offshore area surveyed by the mobile sounding vessel.

Detailed descriptions of the model can be found in Xie et al. $(2002,2005)$. The key derivations and resulting model estimator are listed below.

To derive the total daily abundance in the offshore area, the offshore fish density data are summarized by individual cells (Figure 4).

It has been shown (Xie et al 2002, 2005) that the net upstream fish flux for each cell can be obtained through the following formula:

$$
\begin{equation*}
f=\frac{m_{T} v_{u}}{L}\left[1-\left(1-\frac{v_{d}}{v_{u}}\right) \cdot \frac{n_{d}}{n_{d}+n_{u} \cdot v_{d} / v_{u}}\right] \cdot\left[1-2 \frac{n_{d}}{n_{d}+n_{u}}\right] \tag{1}
\end{equation*}
$$

where $L$ is the full beam-width of the sound-beam at mean depth of the cell, $m_{T}$ is the mean number of fish detected per transect at the cell over a 24 -hour sampling period by the mobile split-beam system, $v_{u}$ and $v_{d}$ are the mean speeds of the up- and down-stream fish detected by the left-bank split-beam system over the 24 -hour sampling period, and $n_{u}$ and $n_{d}$ are the totals of up-and down-stream fish detected by the left-bank split-beam system over the 24-hour sampling period.

This above equation combines information obtained from the mobile system (transect measurements of $m_{T}$ ) and the left-bank systems (shore-based stationary measurements of mean speed and up- versus down-stream fish) to produce a measure of offshore fish flux through individual cells. Summation of the offshore flux over all the offshore cells provides us with the estimate of total offshore fish flux. The key underlying assumption of this equation is that fish behaviour is statistically similar between nearshore and offshore areas. Xie et al (2007) however showed differential behaviour between fish migrating in the inshore areas of left and right banks. Therefore, a direct measurement of offshore fish behaviour would provide more accurate behavioural parameter estimates than the current method and would improve the overall estimate of mobile flux.


Figure 4. Plot of September 18, 2018 hourly cross-river fish flux: number of fish migrating upstream through individual cells (5m horizontal by $1 m$ vertical) per hour with red colored cells representing a higher number of fish migrating upstream. The total flux estimated by the mobile system for this day is 2819.89 fish/hour. Note: the flux data is displayed in the plot using the river bottom as the vertical reference so that the flat surface waterline is transformed to a curvy line (the blue line) which mirrors the river bottom.

## References

Blackman, S.S., and Popoli, R. 1999. Design and analysis of modern tracking systems. Artech House, Norwood, MA.

Ehrenberg, J.E., and Torkelson, T.C. 1996. Application of dual-beam and split-beam target tracking in fisheries acoustics. ICES Journal of Marine Science, 53: 329-334.

Medwin, H., and Clay, C.S. 1998. Fundamentals of acoustical oceanography. Academic Press.
Xie, Y. 2002. Estimation of Migratory Fish Abundance Using River-Transect Sampling by a Split-beam Transducer. Presented at ICES Symposium on Acoustics in Fisheries and Aquatic Ecology. Montpellier, France, 10-14, June 2002.

Xie, Y. 2004. PSC Split-beam Fish Tracker User’s Guide: 2004 Version. Pacific Salmon Comm. Special Tech Manual. June, 2004.

Xie, Y., Gray, A.P., Martens, F.J., Boffey, J.L., and Cave, J.D. 2005. Use of dual-frequency identification sonar to verify salmon flux and to examine fish behaviour in the Fraser River. Pacific Salmon Comm. Tech. Rep. No. 16: 58 p.

Xie, Y, Gray, A.P., Martens, F.J., and Cave, J.D. 2007. Development of a shore-based hydroacoustics system on the right bank of the Lower Fraser River to monitor salmon passages: A project report to Southern boundary restoration and enhancement fund. Pacific Salmon Commission, Vancouver, British Columbia. April, 2007.

Xie, Y., Michielsens, C.G.J., Gray, A.P., Martens, F.J., and Boffey, J.L. 2008. Observations of avoidance reactions of migrating salmon to a mobile survey vessel in a riverine environment. Can. J. Fish. Aquat. Sci. 65: 2178-2190.

# B15. Length-based Mixture Model for Imaging Sonars 

J.L. Nelitz, C. Lagasse and Y. Xie

## Summary

At the PSC Hydroacoustics Site in Mission, BC, information collected from imaging sonars (DIDSON and ARIS) has been used since 2011 to estimate fish passage in nearshore areas off both the left and right banks (Chapter B13). To accurately determine the proportion of fish passage that is comprised of salmon, a length-based mixture model is used to estimate the relative proportions of salmon-sized targets versus small, resident-fish-sized targets. The mixture model is also used to estimate proportions among salmon species, including pink, sockeye, and Chinook, during periods when two or more salmon species are co-migrating past the PSC Hydroacoustics site. Fish length data used by the model are measured from subsamples of the acoustic images collected by the imaging sonars. The mixture-model-based estimates of salmon proportions are applied to fish passage estimates in nearshore areas on both the left and right banks and are used to produce imaging-sonar-based estimates of daily nearshore upstream salmon passage.

## Introduction

A variety of fish species, either migrating past or residing in the proximity of the PSC Hydroacoustics Site, are detected and imaged by the imaging sonar at the monitoring site. However, the mandate of the PSC Hydroacoustics program is to enumerate salmon passage past the site, specifically sockeye and pink salmon. Therefore, salmon passage must be distinguished from passages of non-salmon species. Salmon species in the Fraser River include Chinook, chum, coho, pink, and sockeye, while resident fish include Peamouth Chub, White Sturgeon, Red-sided Shiners, and a variety of other species (Figure 1).

Imaging sonar acquires acoustic images of fish while they migrate in the river, which allows for the counting of fish as they migrate past the site and the measurement of lengths of individual fish. See Chapter B13 for more information on imaging sonar at the Hydroacoustics site. To differentiate salmonsized targets from small resident fish, fork lengths (FL), the length from the fish's nose to its tail, are measured from a subset of the imaging sonar data. Since 2011, a length-based mixture model has been applied to imaging-sonar-based length data at the PSC hydroacoustics site to estimate species proportions. The mixture model statistically distinguishes small resident fish from migrating salmon to generate accurate salmon passage in nearshore areas. Length data are collected and compiled daily and analyzed using the mixture model. The estimated proportions of both small resident fish (around 20 cm in mean FL) and salmon-sized fish (> 40 cm in FL) are applied to the total fish counts produced by the imaging sonar to derive the daily nearshore salmon passage estimates off both banks. The mixture-model-based species proportions can also be used to estimate relative abundances among salmon species. This is used during the Chinook and sockeye comigration period (July to early August) or the initial pink and sockeye comigration period (mid-August to early September) to estimate the abundance of each species. There are other estimation methods for salmon species composition, for more information, see Chapter B16. This document describes the key procedures for measuring lengths from sonar images, and how these lengths are used by the mixture model to estimate species proportions.


Figure 1. Examples of common salmon and resident fish species encountered in the Fraser River, $B C$. Chinook salmon (A), chum salmon (B), coho salmon (C), pink salmon (D), sockeye salmon $(E)$, Peamouth Chub (F), White Sturgeon (G) and Red-sided Shiners (H).

## Data

A subset of ARIS fish images are measured to determine their fork lengths (FL) using the vendor provided software, ARISFish. The fork length refers to the length from the fish's nose to the fork of its tail. Because the resolution of the images produced by the imaging sonar often does not allow for the exact identification of the true 'fork' of the fish tails, the locations of the fork are subject to random error. A comparison study between biological FL and acoustically measured FL for sockeye indicates however that acoustically measured FL by imaging sonar is unbiased (Xie et al. 2013).

Over a 24 -hour period, a total of 8 hours (per range bin) of imaging data are subsampled with 20 fish images selected for length measurements. This produces a total of 160 FL measurements for each of the range bins. For the left bank, the image data from all 4 range bins are used for length measurements. This gives a daily total of $20 \times 4 \times 8=640$ length measurements per day for the left bank. For the right bank, due to the degrading imaging quality in the furthest bin, the species composition information for Bin3 is used for Bin4. This gives a daily total of 480 length measurements for the right bank per day.

Corresponding fish passage is counted for 5 minutes per hour in each of the range bins from both the left and right-bank acoustic sites. All fish, except Sturgeon, are counted, including small, presumably resident fish. In addition to the length measurements of fish for which the species is unknown, the mixture model also relies on species-specific length information obtained from test fishing catches in the current as well as previous years. These historical FL data are used as mean length priors in the mixture model.

## Methods

Once all the length measurements for a range bin are available, a mixture model is fitted to the resulting distribution of length data to estimate the proportion of different species within the mixture (Figure 2). Three different estimation methods can be used: maximum likelihood estimation (MLE), discriminant function analysis (DFA) and single-value-threshold (SVT) method. The mixture model requires initial values for the means and standard deviations for the distributions of lengths for the different fish species that make up the mixture, i.e. the mean fork length and associated standard deviations for each species. The mean fork lengths of each salmon species is based on the average lengths observed in nearby test fisheries. Early in the season, when test fishing catches are still limited, marine FL data or previous' year means can be relied upon until more relevant data become available. While the acoustically measured FL is unbiased, the measured lengths are subject to random, unbiased errors due to various factors such as the aspect angle and the range of ensonified fish. This results in a sigma or a coefficient of variation (CV) of acoustically measured length for sockeye salmon that is larger than that
of the true length distribution: $13 \%$ vs. $6 \%$ (see Figure 3). The mixture model assumed a CV of $13 \%$ for both sockeye and Chinook's measured lengths. The assumption of Chinook's measured lengths having the same CV as sockeye needs to be verified in the future. In addition to prior information on the mean length and the coefficient of variation, the model also requires prior information on the number of species to be classified. The most used prior for the number of groups is a 3 : small resident fish, sockeye, and chinook salmon. This 3 -group mixture model is used during the early part of the sockeye migration when the river is dominated by these 3 groups and throughout the season during non-pink years. A 4 - or 5 -group mixture model is used when pink salmon are co-migrating and/or when the lower river testfishing programs indicate a noticeable presence of jack Chinook in the river.


Figure 2. Fitting of the length-based mixture model to length data from 3392 fish images acquired by ARIS on the left bank from July 9 to July 28, 2019. Based on these data, the mixture analysis estimates $69 \%$ small resident fish, $22 \%$ sockeye, and $9 \%$ Chinook salmon.


Figure 3. Fork Length data from Whonnock and Mission, Aug 17-20, 2011 (Xie et al 2013). (a) histogram of fork-length from 206 sockeye salmon caught at Whonnock. (b) histogram of lateral length measurements of 394 fish images acquired by DIDSON at Mission during the sockeye dominant migration period. The mean of the biological FL is 62.4 cm and the mean acoustically measured length is 62.3 cm . The standard deviations of the 2 data sets are 3.6 cm and 8 cm , resulting in coefficients of variation of $6 \%$ and $13 \%$, respectively.

Due to the temporal variation of salmon influx in a 24 -hour monitoring period, the unweighted sampling of hydroacoustic length data could result in biased species composition estimates, especially when
differentiating salmon from resident, non-salmon species. To reduce the bias, the length-based mixture model is also applied to the hourly data. The resulting abundance-weighted model uses a spline-fit algorithm to reconstruct a full time series of hourly salmon proportions from the subsampled length data (Figure 4). Multiplying this hourly proportion time series with the hourly abundance time series leads to an abundance-weighted daily salmon proportion. The details of the mixture model can be reviewed on pages 44-51 of Xie et al. (2013). The model is implemented using the statistical software package $R$ and can be readily run under the platform of R-Studio (https://rstudio.com/).


Figure 4. Reconstructed hourly salmon proportion time series for September 24, 2018, indicating both the 8 hours of observed proportions (black circles) as well as projected proportions (red circles). The daily salmon proportion was estimated to be $74 \%$.

One of the advantages of the length-based mixture model is that it allows to provide species composition information on days when test fishing catches are absent or small. In addition, model results tend to be robust when distinguishing small resident fish from sockeye and adult Chinook. However, when using a 4 or 5-group mixture model during the periods of comigration with pink salmon and/or relatively large proportions of jack Chinooks, resulting species composition estimates can be subject to large uncertainties given the limited differences in average lengths between the species.

## References

Martens, F.J., Michielsens, C.G.J., and Xie, Y. 2011. Estimation of species composition from DIDSON fish lengths using mixture analysis. Poster.

Michielsens, C.G.J., Martens, F.J., Nelitz, J.L., and Xie, Y. 2009. Species composition estimation using hydro-acoustic fish length within a Bayesian mixture model. Poster.

Xie, Y., Gray, A.P., Martens, F.J., Boffey, J.L., and Cave, J.D. 2005. Use of Dual-Frequency Identification Sonar to Verify Salmon Flux and to Examine Fish Behaviour in the Fraser River. Pacific Salmon Comm. Tech. Rep. No. 16: 58 p.

Xie, Y., Martens, F.J., Michielsens, C.G.J., and Cave, J.D. 2013. Implementation of stationary hydroacoustic sampling systems to estimate salmon passage in the Lower Fraser River: A final project report to the southern boundary restoration and enhancement fund. Pacific Salmon Commission. May 2013.

Xie, Y. 2019. Estimation of sockeye abundance using length-based species proportions during sockeye and chinook comigration periods. PSC Memo on July 30, 2019.

# B16. Species Information: Overview 

C.G.J. Michielsens


#### Abstract

Summary Species composition estimates are essential for translating daily fish passage estimates at the hydroacoustic site at Mission, BC, into daily sockeye abundance estimates. Since 2009, fish passage at the hydroacoustic site has been estimated using a combination of split-beam and imaging sonars (DIDSON and ARIS, Chapter B13). A mixture model is applied to histograms of fish length data measured from the imaging files to estimate the relative proportions of salmon-sized targets versus small, resident-fish-sized targets and to derive daily salmon abundance estimates (Chapter B15). The abundance estimates can be further separated by salmon species using a variety of different data sources and methods. The different methods each have their own shortcomings which may be more pronounced depending on sample sizes and the relative and/or absolute abundance of the different species. The selection of the method to estimate species specific abundances is dependent on the concurrence between estimates, known biases under different conditions, and sample sizes. The following reports provide an overview of the different methods and describes some of these biases.


## Introduction

As part of the Treaty agreements (Diplomatic Note of August 13, 1985), the Fraser River Panel is responsible for the collection of hydroacoustic data at Mission, $B C$, and to enumerate salmon passage past the site, specifically sockeye and pink salmon. The process to estimate the number of sockeye and pink salmon is a two staged process. First, salmon passage must be distinguished from passage of nonsalmon resident fish species, which include Peamouth Chub, White Sturgeon, Redside Shiner, and a variety of other species. This is done by measuring the acoustic lengths of individual fish and fitting a mixture model to the resulting distribution of length data to estimate the proportion of salmon versus resident fish (Chapter B15). In a second stage, the proportion of sockeye and/or pink salmon will need to be determined. Within the Fraser River, salmon species also include Chinook, chum, and coho salmon. The proportion of Chinook salmon can be substantial when sockeye abundances are low early in the season or during years of low sockeye abundance. There are a multitude of different methods that can be used to determine species composition and the different methods will be described here as well as their known biases.

## Methods

## SALMON VERSUS NON-SALMON SPECIES PROPORTIONS

The distinction of salmon versus non-salmon species is made using fish length measurements of individual fish acquired using the acoustic image of the fish obtained through imaging sonar. More specifically, the fork lengths (FL), the length from the fish's nose to the fork of its tail, are measured from imaging sonar data using vendor-provided, user-driven software (ARISFish by Sound Metrics Corp). Over a 24 -hour period, a total of 8 hours of imaging data are subsampled with 20 fish images randomly selected for length measurements. This produces a total of 160 fork length measurements for each of the hydroacoustic sampling areas. A mixture model is fitted to the resulting distribution of length data to estimate the proportion of different species within the mixture (Figure 1). Three different estimation
methods can be used: maximum likelihood estimation (MLE), discriminant function analysis (DFA) and single-value-threshold (SVT) method. The maximum likelihood method will require initial values for the means and standard deviations for the individual distributions that make up the mixture. The resulting model might fit the data but the individual distributions might not always make biological sense, e.g. results may eliminate certain species such as jack Chinook even though there is evidence from the test fishery that this age group of Chinook salmon should be present. The MLE method is especially prone to errors when the sample size is small. The strength of the DFA method lies in the fact that the method relies on Bayesian priors for the individual distributions, i.e. mean lengths and standard deviations. This model therefore can produce results even when sample sizes are small but the resulting mixture model might not fit the data very well. The SVT method uses length thresholds for the different species. It works well when there is no overlap in the length distributions of the different species or when the overlap is symmetrical. The larger the asymmetry in the overlap, the larger the bias in the SVT proportion estimates. This method is least preferred but allows for verification of the other estimates.


Figure 1. Fit of the mixture model to length data from 3392 fish images acquired by ARIS from July 9 to July 28, 2019 on the left bank over a range bin of 10 to 30 meter. The resulting mixture model estimates $69 \%$ of the fish to be small resident fish, $22 \%$ are sockeye and $9 \%$ are Chinook salmon.

## SALMON SPECIES PROPORTIONS

A multitude of different species methods are used to derive daily sockeye and pink salmon abundance estimates from the total daily salmon passage estimates (Table 1, Martens et al., 2019, Michielsens and Cave, 2013). Traditionally, salmon species composition are derived from catch data collected by the Whonnock test fishery with the proportions based on gilled and girthed catch. In case of low daily salmon catch numbers (<15), catches also include tangled salmon. When catches are low, these estimates are however very uncertain and highly variable. In addition, this method has some known biases as pink salmon, who migrate primarily near-shore, tend to be less vulnerable to this test fishery, resulting in an underestimate of pink salmon abundance. Chinook salmon on the other hand tend to have a higher catchability, resulting in an overestimation of Chinook abundances. Similar analyses can be done with the catch data from the Qualark test fishery. The resulting daily sockeye abundance
estimates can be considered minimum estimates of the abundance that passed the Mission site given the fact that several sockeye stocks migrate past Mission but do not pass Qualark, i.e. Chilliwack (Early Summers); Harrison (Summers); and Birkenhead, Big Silver, Weaver, and Cultus (Late run). For Chinook, the daily abundance estimates at Qualark early in the season can be considered estimates of the Chinook abundance at Mission given that the Chinook stocks that do not migrate past Qualark, i.e. Chilliwack and Harrison, are later timed fall Chinook. The same concerns about assuming equal catchability applies for this method. The catchability correction model aims to reduce the potential biases due to differences in catchability by estimating a different catchability for the different salmon species. In recent years, the correction to the resulting sockeye abundances have been limited to the low sockeye catches.

An alternative estimate of daily sockeye abundance at Mission can be obtained by using sockeye CPUE data from the Whonnock test fishery in combination with a historical expansion line estimate (1/catchability). This method is regularly relied upon early in the season when no hydroacoustic data are yet available, or in pink salmon years when daily salmon abundances are dominated by pink salmon stocks. While the daily sockeye abundance estimates derived from CPUE data may differ substantially from the hydroacoustic based sockeye abundance estimates when available, averaged over three days, the CPUE based method produces similar abundance estimates unless catchability in a given year deviates substantially from average. The Chinook CPUE data from the Albion test fishery can be similarly used in combination with a historical expansion line estimate to derive daily Chinook abundance estimates at Mission (Hawkshaw, 2018). In cases when salmon species are limited to sockeye and Chinook salmon, the daily sockeye abundance can be estimated by subtracting the daily Chinook abundance estimates from the total daily salmon estimates. Similar concerns remain about the representativeness of the historical catchability estimates in the current year.

In the past, there has been clear evidence that the differences in catchability estimates can lead to overestimated Chinook abundance estimates, whereby the sum of the daily reconstructed Chinook abundance greatly exceeded the total post-season run size of Fraser River Chinook. To ensure daily estimates are in-line with realistic total run size estimates for Chinook salmon, the preseason Chinook run size forecasts of 6 different Chinook groups (Spring 1.2, Spring 1.3, Summer, 1.3, Summer 0.3, Chilliwack and Harrison) are used in combination with the timing and spread of each stock group to forecast daily Chinook abundances across the season and the associated uncertainty around those daily estimates i.e. the $95 \%$ probability interval (Figure 2). In case no alternative species composition data are available due to a lack of test fishing catches or if the resulting estimates are considered unreliable, the median forecast of the daily Chinook abundance can be used to derive daily sockeye abundance estimates. Alternatively, the upper $97.5 \%$ confidence limit can be used to cap the daily Chinook abundance estimates derived from test fishing catch data. While it is possible to exceed the upper confidence limit on a given day or several days, consistently exceeding this limit would require that Chinook returns exceed the $97.5^{\text {th }}$ percentile of the forecast.


Figure 2. Boxplot of daily Fraser River Chinook abundance forecasts, based on 2020 run size forecasts for Spring 1.2, Spring 1.3, Summer, 1.3, Summer 0.3, Chilliwack and Harrison Chinook, used in combination with migration timing and spread estimates.

In recent years, returns of Fraser River sockeye have been extremely low. As a result, the relative sockeye abundance has decreased, and the importance of accurate species composition estimates increased. The majority of the species composition methods discussed thus far rely on in-river test fisheries whose catches decrease with decreasing abundances. In recent years, it has been especially challenging to obtain catch data early in the season when abundances are lowest or for catches to be sufficiently large to obtain desired sample sizes from which to derive species composition estimates. Hydroacoustic length information has not experienced similar sample size challenges and the stratified species composition method has been used to derive salmon species composition estimates. The method is stratified as it relies on the hydroacoustic length information and the mixture model for the species composition of the salmon abundance along the left and right bank and the Whonnock test fishing catch data for the species composition in the midsection of the river. The mixture model however performs best when the different species differ substantially in mean lengths which is the case when distinguishing sockeye from resident fish. Pink and sockeye salmon are however more similar in length and especially in years with larger pink salmon and smaller sockeye, the limited difference in average lengths may result in increasingly uncertain species composition estimates. Alternatively, fish wheel information can be used for the species composition along the shore.

Other methods exist to estimate in-river species composition and these are tracked but not used very often given the large associated uncertainty. One of those methods relies on marine CPUE data of Fraser River sockeye used in combination with an expansion line (Chapter B4). The resulting daily marine abundance estimates can be used in a forward reconstruction to predict the number of sockeye within the river. When using this method for species composition, only historical expansion lines can be used, resulting in the larger uncertainty as using the in-season expansion line requires knowing the sockeye abundance at Mission.

Table 1. Overview of different data sets and methods used to estimate daily abundances of different salmon species at Mission, their in-season use and concerns regarding their application.

| Data and method | In-season use and concerns |  |
| :--- | :--- | :--- |
| Whonnock catch | - | Traditional species composition method |
| proportions | - | Sample sizes may be insufficient to derive (reliable) estimates |
|  | - Catchability differs across species |  |
| Qualark catch | - | Resulting Chinook and sockeye estimates can be used as minimum estimates at |
| proportions | - | Mission |
|  | - Cample sizes may be insufficient to derive (reliable) estimates |  |
| Catchability | - | Reduces potential biases due to differences in catchability |
| correction model | - | Corrections may be insufficient to remove substantial biases |

While there exist many different methods to estimate species composition, they all have some shortcomings that may substantially bias species composition estimates under certain conditions. Inseason, the different methods are run jointly, and the resulting sockeye, Chinook and pink salmon abundances are compared. Concurrence in abundance estimates when relying on multiple different methods will provide increased confidence in the use of species composition estimates derived from those methods while deviation from other estimates will decrease an estimate's credibility.

## Planned Changes and Potential Areas for Improvement

Improvement to the estimation of the species composition has been one of the recommendations identified during the Hydroacoustic Review (Conrad et al., 2019). That review resulted in the development of the catchability correction model. Currently, there are plans in place to further expand the species composition methods by including a non-linear CPUE model and an integrated multi-species model that would incorporate the various data sources. Species composition estimation can also be improved by evaluating the performance of the different models. Thus far, the lack of known postseason abundance estimates for the different species has prevented the use of retrospective analyses to
evaluate model performance. Alternatively, the bias and precision of the different methods could be evaluated through simulations. Such a simulation study has been undertaken for the mixture model, but this work has not yet been expanded to include the stratified version of the mixture model.

## References

Conrad, B., Dufault, A., Hawkshaw, M., Huang, A., Jenkins, E., Lagasse, C., Lapointe, M., Litz, M., Martens, F.J., Michielsens, C., Scroggie, J., Staley, M., Whitehouse, T., Wor, C., and Xie, Y. 2019. Hydroacoustics Review Technical Summary. Pacific Salmon Comm. Tech. Rep.: 41, 369 p.

Hawkshaw, M. 2018. Additional methods for estimating Chinook passage at Mission. Fraser River Panel presentation, April 2018, Vancouver.

Martens, F.J., Jenkins, E. and Michielsens, C.G.J. 2019. Review of methods to assess species composition. Fraser River Panel presentation, June 2019, Suquamish.

Michielsens, C.G.J. and Cave, J. 2013. In-season estimation of species composition at Mission. Fraser River Panel presentation, April 2018, Squamish.

PST. 2020. Treaty between the government of Canada and the government of the United States of America concerning Pacific salmon as modified through January 2020.

# B17. In-season Application of Stock ID Information 

E.S. Jenkins, F.J. Martens and C.G.J. Michielsens

## Summary

Fraser River sockeye are managed by management group, as per the Pacific Salmon Treaty. Therefore, stock proportion estimates must be applied to catches, in-season abundance indices, and escapement estimates in order to split the data into the four current management groups. Sockeye catch samples are taken from test fisheries (Chapter B5), as well as other fisheries when available, and the mix of stocks within that sample is determined through scale and genetic analyses (Chapter B8 and B9). The resulting stock proportion estimates are not only used to determine the stock proportions of the total catch from which the sample was taken, but are also assumed to represent the stock proportions of the sockeye that escaped the fishery and continued their upstream migration. If no samples are taken to represent a particular catch, then stock proportion estimates based on another catch (that best represents that group of fish) are applied. The resulting stock-specific estimates of catch and escapement past Mission are then used in further reconstructions to assess, for each management group, the total run size in marine areas (Chapter B18), as well as the potential escapement to the spawning grounds.

## Introduction

According to the Pacific Salmon Treaty (PST 2020, Chapter 4, section 3), Fraser sockeye salmon stocks are managed as part of four stock management groups: Early Stuart, Early Summer run, Summer run and Late run. This stipulation within the treaty requires salmon catches and escapement abundance estimates to be split into the four different stock aggregates corresponding with each of the four different management groups.

PSC staff conduct sampling programs designed to identify stock proportions of Fraser River sockeye salmon in marine areas as well as in the river. This is done by sampling the catches from test fisheries; these samples are assumed to represent the stock composition of the available fish. The resulting stock composition estimates are used in combination with daily abundance estimates obtained from in-river hydroacoustic data (Chapter B10) and from marine catch-per-unit effort (CPUE) data (Chapter B2) to derive daily abundance estimates by management group, both in marine areas as well as in the river. Stock proportions are also applied to assign catches by the different fisheries (commercial, test, Ceremonial \& Subsistence (C\&S), First Nations, and recreational fisheries) to different management groups.

Stock proportion estimates are essential for reconstructions. For backwards reconstructions (Chapter B18), the stock-specific daily escapement estimates past Mission are added to the stock-specific catch abundances seaward of Mission, resulting in stock-specific daily marine abundance estimates. These marine daily abundance estimates allow for assessment of the associated run size, either using time density models (Chapter B19) when only part of the run has been observed in-season, or using the total marine abundance when the entire run has been observed. Similarly, forward reconstructions using stock-specific daily escapement estimates past Mission, in combination with stock-specific daily catch abundance estimates upstream of Mission, allow for the prediction of the number of spawners expected to reach the spawning grounds or other locations within the watershed (Qualark, for example).

## Data

The data required for daily reconstructed abundance estimates include catch, escapement, and stock ID (as well as the stock ID sample size). To derive time-series' of stock-specific daily abundance estimates, the daily estimate of total sockeye escapement past the hydroacoustic site at Mission is multiplied with stock proportion estimates derived from catch samples. Stock-specific catch data are included for backward reconstructions of the marine abundance estimates, as well as the forward reconstructions of the potential spawning escapement. Further information on the derivation of daily abundance estimates at Mission, daily catch information, and daily stock proportion estimates from catch samples can be found in Chapters B10, B18, and B8, B9, respectively.

Currently, 20 different sockeye stocks are accounted for in the stock proportion estimates: 19 Fraser River sockeye stocks and the remaining non-Fraser stocks, which are combined into one group (Chapter B9). The majority of the samples analyzed using scale reading and DNA methods are obtained from test fishing catches (Chapter B1). As a result, for each of the test fishing locations, there exist 20 time-series of stock proportions covering the entire duration of a fishery. Additional catch samples from commercial, C\&S, First Nations, and recreational fisheries are also analyzed. However, the logistics of collecting, transporting and analyzing samples from these additional fisheries in a timely fashion for inseason assessments is complex, and the resulting time series of stock proportion estimates may not cover all fisheries in all areas for their full duration. In addition, limited abundances and / or low salmon catchability may result in sample sizes below the recommended 100 fish in marine area test fisheries and 50 fish for in-river test fisheries. Therefore, the size of the sample from which the stock proportion estimate has been derived is important for the successful application of stock proportion estimates. The sample size helps to determine the uncertainty associated with an estimate; it can also indicate the need to combine stock proportion estimates across multiple days.

## Methods

Stock proportion estimates are applied to both abundance and catch estimates. It is important that the stock proportion estimates are applied to all days and areas associated with the abundance time series, not only the days on which the catch was taken or for the fisheries from which the catch was taken. There are several options to estimate stock proportions when no sample was taken or analyzed on a given day or for a particular area. Stock proportions can be borrowed from a previous or following day, interpolated between days before and after, or borrowed from a nearby fishery. In cases where information from other fisheries is used, the date of the information is offset to reflect the time required for the sockeye to migrate between the two fishing areas, therefore ensuring that the stock proportion information from the other fishing area reflects the same block or group of fish. In cases where a sample size is much smaller than the recommended amount, the samples for several days may be combined and the resulting stock proportions applied to the catches on all of the days included in the sample. Especially in the river, limited sample sizes can be a serious issue, and requiring more complex methods to combine stock proportion information from various samples.

Once stock proportion time series' have been completed and cover all days, areas, and fisheries for which abundance estimates or catch data are available, they can be multiplied to generate stock-specific daily abundances and catch estimates (Figure 1). These stock-specific estimates can be summed by management group and across days to generate management-group-specific estimates of abundance and catch to date. In addition, the stock-specific daily estimates can also be used within backward reconstructions to generate stock-specific daily marine abundance estimates, or within forward reconstructions to calculate stock-specific daily abundance estimates expected to reach the spawning grounds (Chapter B18).


Figure 1. Data flow for the collection and application of stock proportion estimates to escapement estimates and catch data. Used within reconstruction models, it allows the generation of stock-specific daily abundance estimates in marine areas (to be used for run-size assessment purposes) and at the spawning grounds (to be compared against spawning escapement targets). Processes are represented by blue rectangles and resulting estimates by green rectangles with rounded corners.

## Planned Changes and Potential Areas for Improvement

Currently, 20 different sockeye stock groups are accounted for by the stock proportion estimates and the files associated with the assignment of stock proportion estimates to catch and escapement data are therefore called the CR20 files (Catch and Racial files for 20 groups). Based on DNA stock ID methods, the number of groups can be expanded to close to 90 , and a new set of CR files has been created to account for this expansion: CR100 files. While it is not advisable to use the estimates in the CR100 files at their finest resolution, storing the data at this level ensures increased flexibility in terms of grouping the different stocks and 'rolling-up' the estimates according to the different groupings. In addition, the CR100 files include several non-Fraser stock groups rather than combining them into one group. Currently, a database is being created that would store the data from the CR100 files. Once completed
this database will allow flexible, multi-year queries to be performed on the catch and escapement data by stock and management group, and estimates to be rolled up in a variety of ways, including temporally, geographically, etc. In the future, we might also switch to using the CR100 files in-season.

## References

PST. 2020. Treaty between the government of Canada and the government of the United States of America concerning Pacific salmon as modified through January 2020.

# B18. In-season Marine Reconstructions 

M.J. Hague and C.G.J. Michielsens


#### Abstract

Summary Run reconstructions are a key tool for fisheries stock assessment and allow biologists to combine catch and escapement data to estimate daily abundances and annual run size. The Pacific Salmon Commission (PSC) is responsible for developing and applying run reconstruction models for Fraser River sockeye salmon as well as disseminating and archiving the resulting estimates. In-season reconstructions are applied both forward and backwards. Forward reconstructions predict stock-specific escapement into the river based on marine daily abundances derived from stock-specific catch-per-unit-effort (CPUE) data from marine test fisheries (Chapter B2) combined with assumptions about migration speed and delay behaviour. Backward reconstructions add stock-specific daily estimates of marine and lower river catches to stock-specific daily escapement estimates (Chapter B10) to reconstruct the total daily abundance in marine areas. The estimates are used to derive time series of marine timing, migration spread and diversion rate. Backward reconstructions also allow to update in-season test fishing catchability estimates (Chapter B4). The following report describes the basic structure and underlying assumptions of the reconstruction model, and the time series it generates.


## Introduction

Management of Fraser River sockeye salmon fundamentally relies on accurate estimates of run size (for deriving the amount of total allowable catch (TAC)), and migration behavior (to determine how to access the TAC). As part of the Pacific Salmon Treaty (PST) agreements (PST 2020, Chapter 4, paragraph 13(a)), Commission staff are responsible for providing in-season updates to Fraser River sockeye salmon run size, timing, and diversion rate.

Run reconstructions have been a key tool for salmon fisheries management for over 80 years; their application first thoroughly described by Starr and Hilborn (1988). PSC Secretariat Staff are responsible for developing and applying run reconstruction models for Fraser River sockeye (Cave and Gazey 1994) and archiving their results. Within these reconstruction models, stock-specific daily marine and lower river catches are added to stock-specific daily escapement estimates obtained by the PSC hydroacoustic facility (Conrad et al. 2019) to reconstruct daily abundances as the salmon run as it approaches the marine areas around Vancouver Island. In-season, daily reconstructed abundances are used to provide the best in-season estimate of run-size, timing, and diversion for Fraser River sockeye populations, either directly from the reconstructed abundance or when used within in-season assessment models (Michielsens and Cave 2018), project abundances of fish expected to be available to different fisheries, and update test fishery catchability estimates (Chapter B4).

After the fishing season concludes, reconstructions are used to update several time series of sockeye migration behaviour, including marine timing (date when $50 \%$ of a run has passed through marine areas), northern diversion (percent of a run migrating through Johnstone Strait), spread (number of days comprising $95 \%$ of the marine migration), and delay (days holding off the mouth of the Fraser River in the Straight of Georgia). In addition, Canada relies on historical time series of run size, timing, and diversion to generate pre-season forecasts (Chapters A1 and A2) which are critical inputs for pre-season planning and simulations (Cave and Gazey 1994, Chapter A6 and A7) and are also used as informative
priors in Bayesian in-season run size models (Michielsens and Cave 2018, Chapter B19). In addition, historical run reconstructions are used in retrospective evaluations of fishery harvest rates (PSC 1995) and to develop decision rules for updating in-season test fishery catchability coefficients (Chapter B4).

## Data

The key data used to reconstruct daily marine abundances along the Johnstone Strait and Juan de Fuca route are: test fishery catch-per-unit-effort (CPUE) data (Chapter B2), test fishery catchability (Chapter B4), landed catches, Mission daily abundances (Chapter B10) and stock identification (Chapter B9). To populate the reconstruction model, information is also required regarding migration distances between fishery areas and the river, as well as assumed migration rates (Hague et al. 2019). Summer run sockeye are assumed to migrate a distance of 257 km in 6-days, corresponding to an average daily migration rate of $43 \mathrm{~km} /$ day between the Area 20 purse seine test fishing location and the Mission hydroacoustic site. Late-timed sockeye are assumed to take an average of 8 -days, covering $32 \mathrm{~km} /$ day, to make the same journey.

## Methods

The box-car run reconstruction model assumes salmon move in groups, i.e., box-cars, from the marine areas to the Fraser River through a series of fisheries that will impact the number of salmon in a group (Cave and Gazey 1996). The assessment of Fraser River sockeye relies on two different reconstruction approaches: backward reconstruction and forward reconstruction, and both are used to assess Fraser River sockeye salmon (Figure 1).


Figure 1. Schematic illustration of a basic box-car run reconstruction model. The colored bars represent different statistical fishing areas, with the left most square representing the most seaward location. Each "fish/hook" represents one day of fishing. Each fish represents one daily block of fish. Black fish in each panel are not exposed to a fishery opening on a given day, while grey fish are. Each panel represents a daily time-step. The top panel represents the shape of the unfished run prior to entering marine approach fisheries. The bottom panel represents the shape of the run at Mission, with certain days of abundance reduced due to catch removals.

The backwards box-car reconstruction is used to estimate total daily marine abundances by adding seaward catches $(C)$ onto daily abundance estimates $(N)$ at Mission. To simplify the reconstruction, dates $(d)$ associated with the daily catch report (the catch date) from each fishery $(f)$ in each statistical area ( $A$ ) and the daily abundance data at Mission (the upstream migration date) are adjusted to the date associated with a geographical reference point. For the reconstruction and assessment of Fraser River sockeye salmon the reference point used is the site of the Area 20 purse seine test fishery located at the seaward entrance of Juan de Fuca Strait. The dates associated with the data from other areas are adjusted based on the amount of time (rounded to the day) it takes for sockeye to migrate to these areas from the reference point. Assuming it takes 6 days for Summer run sockeye to migrate between Area $20\left(A_{20}\right)$ and Mission ( $A_{\text {Mission }}$ ) implies a 6 day offset ( $O_{A 20, ~ M i s s i o n ~}$ ) that would result in the Area 20 date ( $d_{A 20}$ ) associated with abundance estimates at Mission ( $N_{\text {Mission }}$ ) to be 6 days earlier than the actual date:

$$
\begin{equation*}
N_{d_{A 20}, A_{M i s s i o n}}=N_{\left(d-o_{A 20, M i s s i o n}\right), A_{M i s s i o n}}=N_{(d-6), A_{M i s s i o n}} \tag{1}
\end{equation*}
$$

The same assumptions about migration speeds and associated offsets are also made for the sockeye migrating through Johnstone Strait. For example, it takes about 7 days to migrate from the Area 12 purse seine test fishing site to Mission, resulting in an offset of -1 , making the corresponding Area 20 date for catches caught by purse seine test fishery $\left(f_{P S, T F}\right)$ in the Area $12\left(A_{12}\right)$ one day later than the actual date:

$$
\begin{equation*}
C_{d_{A 20}, f_{P S, T F}, A_{12}}=C_{\left(d-o_{A 20, A 12}\right), f_{P S, T F, A_{12}}=C_{(d+1), f_{P S, T F}, A_{12}} .} . \tag{2}
\end{equation*}
$$

The following description assumes that all the dates associated with the data have already been adjusted to the correspond to the Area 20 reference date. Also, the reconstruction is implemented for individual stocks ( $s$ ) but this has been omitted from the descriptions to simplify the equations. Information on the application of stock ID within the reconstructions can be found in Chapter B17.

In addition to adjusting all dates to a common reference date, reported catch data that may include catches across several 'blocks' of fish (due to the large size of the statistical area for which they are reported) are spread across $n$ migration days depending on the fishery and the statistical area so that the sum of the catch proportions $\left(p_{n}\right)$ equals the total catch reported:

$$
\begin{equation*}
C_{d_{20}, f, A}=\sum_{1}^{n} p_{n} \cdot C_{d_{20}-n+1, f, A} \tag{3}
\end{equation*}
$$

For the actual backward reconstruction, all the daily seaward catches along both approach routes are added to the daily Mission passage estimates to reconstruct the total daily abundance $\left(N_{d_{A 20}}\right)$ at the entry of the marine fishing areas:

$$
\begin{equation*}
N_{d_{A 20}}=N_{d_{A 20}, A_{M i s s i o n}}+\sum C_{d_{A 20}, f, A} \tag{4}
\end{equation*}
$$

In-season, forward reconstructions are used that remove the daily catches between the marine area and Mission from the daily marine abundance estimates to predict daily abundances at Mission.

$$
\begin{equation*}
N_{d_{A 20, A_{M i s s i o n}}}=N_{d_{A 20}}-\sum C_{d_{A 20}, f, A} \tag{5}
\end{equation*}
$$

In this case, the daily marine reconstruction estimates are based on test fishery CPUE data (Chapter B2), used in combination with catchability estimates (Chapter B4). CPUE-based marine abundances and the derived Mission abundances are important in-season as they provide an early indication of abundances prior to fish arriving at Mission. Both gillnet and purse seine CPUE data are relied upon in-season. Each day, the marine reconstruction model allows stock assessment biologists to select which test fisheries to rely upon as well as to average estimates when data from more than one test fishery are available for a particular area. Within the reconstruction files, marine test fishery CPUE data are also combined with reconstructed abundances from Mission to provide in-season updated catchability estimates (Chapter B4). This further allows the selection of catchability estimates for the different test fisheries in the
reconstruction, i.e. rely on historical pre-season expansion lines or a variety of different in-season and adjusted in-season expansion lines depending on the available test fishery data.

## DERIVED TIME SERIES

Both forward and backward reconstructions are essential to derive additional time series of diversion through Johnstone Strait, the proportion of Late run delaying its upstream migration, the timing of the run and the spread.

The daily (northern) diversion rate estimates, i.e. the proportion of the total daily estimate migrating through Johnstone Strait, are based on CPUE data from test fisheries operating in Juan de Fuca and Johnstone Straits (Putman et al. 2014).

The reconstruction is also used to derive daily estimates of delaying Late run and Harrison stocks (Lapointe et al. 2003). Delaying Fraser River sockeye stocks are defined as holding in the Strait of Georgia for an extended number of days (or weeks) prior to redistributing and migrating upstream, resulting in a roughly bi-model distribution. Instead of using Mission passage to update test fishing catchability estimates for delaying stocks, the difference between marine abundances and upstream escapement is used to estimate the number of salmon delaying their upstream migration. The quality of these predictions will depend on the quality of the CPUE-based daily abundance estimates. Post-season, the estimates of delay can be improved by rescaling the CPUE-based abundances so that the total of CPUE-based daily abundances equals the total post-season run size, i.e. the sum of the total reconstructed daily abundance estimates at Mission plus seaward catch. It should be noted that in the case of delaying stocks, it is not possible to run the backward reconstruction as the box-car movement assumption is broken and the Mission escapement and catches cannot be aligned with seaward abundances.

The reconstructed daily abundance time series are also used to derive estimates of timing and spread. The marine migration date, also referred to as the Area 20 date or marine $50 \%$ date, indicate the date when half (50\%) of the run would have passed through Area 20 assuming all fish migrated via that route. The spread is defined as the number of days of migration comprising $95 \%$ of the run.

These historical time series are used in forecasting models (Chapter A2) that set pre-season expectations, allow for the prediction of fisheries impacts (Chapter A6 and A9) and serve as informative prior probability distribution inputs into the in-season stock assessment models (Michielsens and Cave 2019, Chapter B19).

## Planned Changes and Potential Areas for Improvement

More complex post-season reconstruction files are already in development, with increased stock resolution, improved flexibility and transparency in migration assumptions, and the ability to reconstruct abundance time series to multiple locations of interest (Hague et al. 2019). The post-season files also incorporate additional information and a more complex series of decision rules to derive marine abundances used in forward reconstructions and for delaying stock groups. While several of these improvements are only possible post-season, the ability to reconstruct time series to key index locations would improve the capacity for evaluating route-specific catches and abundances as well as generate projections of species and stock-specific encounter rates in-season.

## References

Cave, J.D. and Gazey, W.J. 1994. A preseason simulation model for fisheries on Fraser River sockeye salmon (Oncorhynchus nerka). Can. J. Fish. Aquat. Sci. 51 :1535-1549.

Conrad, B., Dufault, A., Hawkshaw, M., Huang, A., Jenkins, E., Lagasse, C., Lapointe, M., Litz, M., Martens, F.J., Michielsens, C.G.J., Scroggie, J., Staley, M., Whitehouse, T., Wor, C., and Xie, Y. 2019. Hydroacoustics Review Technical Summary. Pacific Salmon Comm. Tech. Rep. No. 41: 369 p.

Hague, M.J, Phung, A., McMillan, M., and Michielsens, C.G.J. 2019. S1-FRP02 Improving pre-season planning and in-season estimates of Fraser River sockeye stocks through stock- and cycle line-specific estimates. SEF Final Report.

Lapointe, M.F., Cooke, S.J., Hinch, S.G., Farrell, A.P., Jones, S., MacDonald, S., Patterson, D., Healey, M.C., and Van Der Kraak, G. 2003. Late-run sockeye salmon in the Fraser River, British Columbia are experiencing early upstream migration and unusually high rates of mortality: what is going on? In Proceedings of the 2003 Georgia Basin/Puget Sound Research Conference, Vancouver, B.C.

Michielsens, C.G.J. and Cave, J.D. 2019. In-season assessment and management of salmon stocks using a Bayesian time-density model. Can. J. Fish. Aquat. Sci. 76: 1073-1085.

Pacific Salmon Commission. 1995. Pacific Salmon Commission run-size estimation procedures: An analysis of the 1994 shortfall in escapement of late-run Fraser River sockeye salmon. PSC Tech. Rep.: 6

PST. 2020. Treaty between the government of Canada and the government of the United States of America concerning Pacific salmon as modified through January 2020.

Putman, N.F., Jenkins, E.S., Michielsens, C.G.J. and Noakes, D.L.G. 2014. Geomagnetic imprinting predicts spatio-temporal variation in homing migration of pink and sockeye salmon. J. R. Soc. Interface 11: 20140542.

Starr, P., and Hilborn, B. 1988. Reconstruction of harvest rates and stock contribution in gauntlet salmon fisheries: application to British Columbia and Washington sockeye Oncorynchus nerka). CJFAS 45: 22162229.

# B19. In-season Time-density Model 

C.G.J. Michielsens

## Summary

The in-season assessment of Fraser River sockeye salmon relies on the Bayesian implementation of a time-density model to estimate run size and associated run timing. This model is fit to available catch-per-unit-effort (CPUE) data from gill net test fisheries in statistical fishing Areas 12 and 20, purse seine data in Areas 12, 13 and 20 (Chapter B2), and reconstructed daily abundance estimates derived from hydroacoustic data collected at Mission (Chapter B10) and seaward catches. The model relies on prior probability distributions of run size, timing, standard deviation (or spread), diversion rate, and test fishery catchability based on pre-season forecasts or historical observations (Chapters A1 and A2). Updated posterior distributions are produced by the model for timing, abundance, diversion, and sometimes spread, but the catchability priors are not updated. Instead, the daily catchabilities are assumed to be fixed but uncertain inputs, based initially on historical estimates, and later on in-season observations as they become available (Chapter B4). Early in-season, the model tends to underestimate the number of days for the salmon to pass through marine areas, and therefore the standard deviation of the migration (spread) is also considered a fixed but uncertain parameter. If necessary, this assumption can be relaxed after the peak of the run has been observed. The model is applied to stock aggregates which share similar migration timing and fall within the same management groups. For stocks that delay their upstream migration, only marine CPUE are used to assess the run, resulting in larger run size uncertainty in comparison to stocks that also rely on marine reconstructed data.

## Introduction

The Fraser River Panel is responsible for the in-season management of Fraser River sockeye stocks, as stipulated by the Pacific Salmon Treaty between Canada and the United States (PSC in-season). Under the terms of the Treaty, Commission staff are responsible for providing the Panel and Technical Committee with in-season updates of run size. Historically, two different methods had been relied upon for the in-season assessment of salmon stocks: regression models relating indicators of abundance (or cumulative abundance) on a given date with total run-size estimates obtained post-season (Fried and Hilborn 1988, Ryall 1998) and time-density (or cumulative time-density) models that estimate the proportion of the migration on a given date (Walters and Buckingham 1975, PSC 1995, Springborn et al. 1998). These time-density models rely on the date of peak abundance as well as the shape of the daily abundance profile over time. They can be fit to abundance indices such as catch-per-unit-effort (CPUE) data from commercial or test fisheries, as well as absolute estimates of abundance reconstructed from catch and real-time escapement data.

While time-density models have the advantage that the timing of the migration is an estimated model parameter compared to a fixed input as is the case for alternative in-season assessment models that rely on regression analyses using catch or CPUE (PSC 1995, Ryall 1998), the simultaneous estimation of timing and run size can also pose some challenges. The peak of the run can only be confirmed once more than $50 \%$ of the migration has been observed. Consequently, prior to the peak, runs that are small and early or late and large may be indistinguishable (Adkison and Cunningham 2015). The integration of all available sources of data and information within the assessments is therefore important to ensure
timely in-season management decisions. Bayesian methods offer an ideal platform for such analyses while also accounting for the uncertainty in the resulting estimates (Fried and Hilborn 1988, Hyun et al. 2005). This document describes a general time-density model developed in a Bayesian framework for the in-season assessment of run size and timing for Fraser River sockeye salmon.

## Data

The in-season assessment of Fraser River sockeye stocks relies on four types of data: Lower Fraser River daily abundance estimates from the hydroacoustic program at Mission, catches seaward of the hydroacoustics program, test fishing catch and effort, and stock identification data (Woodey 1987). The reduced allowable exploitation of Fraser River sockeye in recent years has increased the reliance on test fishing CPUE information rather than commercial data as an index of abundance. The main marine test fisheries for in-season assessments are the gill net and purse seine test fisheries in DFO statistical Areas 12 and 13 (Johnstone Strait), and Area 20 (Juan de Fuca Strait). The combined CPUE data from these two Straits provide time series of relative daily abundance. Reconstructed estimates of daily absolute abundance in the same areas are derived through backward reconstruction methods (Starr and Hilborn 1988) using upstream daily passage estimates by the Mission hydroacoustics program in combination with seaward catches (Chapter B18). Both the CPUE and the reconstructed data are multiplied by stock proportion estimates (Chapter B17) to produce multiple timeseries resolved at finer stock resolutions. Separate models are then parameterized for stock aggregates within each management group that have distinctly different migration timing, catchability, or migration behaviour (e.g. delay or non-delay). To simplify the model description within this report, stock indices have been omitted from the model equations.

In-season, the marine CPUE data are considered early indicators of the expected daily abundance at Mission 6-days later, as it takes Fraser sockeye approximately 6-days to travel from the marine test fishery locations to the hydroacoustic site at Mission. Therefore, in-season, there is a 6 -day lag between CPUE and reconstructed timeseries. In addition, reconstructed marine abundance estimates are only available for stocks that do not delay their upstream migration into the Fraser River due to the violation of basic reconstruction assumptions (Chapter B18). For stocks like Harrison and delaying Late run stocks, only marine CPUE data can be used to assess these stocks, resulting in larger run size uncertainty.

## Methods

The following model description assumes that all timeseries have been offset in order to align with a single geographical reference location associated with the Area 20 purse seine test fishing site (Chapter B18). Date indices corresponding to data from all other locations are adjusted accordingly based on the relative difference in assumed fish migration time between Area 20 and Mission, and the migration time between the location of interest and Mission. For example, it takes approximately 7-days for sockeye to migrate from the Area 12 purse seine test fishing site to Mission, making the corresponding Area 20 date for the CPUE data of the purse seine test fishery in Area 12 one day later than the actual date. All dates mentioned in the description of the time-density model below refer to Area 20 dates.

## IN-SEASON TIME-DENSITY MODEL

The in-season time-density model to assess the run size and timing of different Fraser River sockeye groups relies on a time-density function to represent the daily salmon migration past the marine test fishing locations (Mundy 1979, Cave and Gazey 1994, Springborn et al. 1998). Two different versions of the time-density model are used depending on the available test fishing data and the associated quality. The marine gill net data are of lower quality as a relative index of abundance compared to the purse seine data given the substantially lower catchability of sockeye salmon by gill nets versus purse seines,
i.e., they catch a much smaller proportion of the run. The marine gill net data are however essential for the assessment of early-timed, low abundance stocks for which the cost of running expensive purse seine test fisheries would be prohibitive. Given the high variability in the individual gill net CPUE timeseries for the Area 12 and 20, the two time-series are combined into a total CPUE time-series to assess the combined abundance migrating through marine areas. In cases where purse seine CPUE data are available, a more detailed version of the model assesses the abundance in both approaches separately. The following paragraphs will first describe the model using marine gill net data, followed by a description of a more complex model version incorporating data from both gear types.

The daily abundance of salmon $\left(N_{d}\right)$ passing the marine reference locations on a given day $d$ can be represented as:

$$
\text { (1) } \quad N_{d}=N \cdot f(d)
$$

where $f(d)$ is the time-density function of migrating salmon, i.e., the daily proportion of the total run size and $N$ is the total run size or the total recruitment of salmon, available to coastal fisheries. For Fraser sockeye, we assume a normal distribution of migrating salmon over time (Gilhousen 1960, Cave and Gazey 1994):
(2) $\quad f(d \mid T, S)=\frac{1}{S \sqrt{2 \pi}} e^{-\frac{1}{2}\left(\frac{d-T}{S}\right)}$
where $T$ is the mean timing of the salmon migration and $S$ is the standard deviation. Reconstructed daily marine abundances ( $N_{t}^{o b s}$ ) deviate from the daily abundances predicted by the time-density model ( $N_{d}$ ):
(3) $\quad N_{d}^{o b s}=N_{d}+v_{d}$
with $v_{d} \sim N\left(0, \sigma_{v}^{2}\right)$ reflecting the deviation. Based on the salmon abundance available on a given day $\left(N_{d}\right)$, the associated CPUE by the gill net $(G N)$ test fishery on that day $\left(l_{d, G N}\right)$ is given by:
(4) $\quad I_{d, G N}=q_{d, G N} \cdot N_{d}$
where $q$ represents the catchability coefficient, i.e., the proportion of the daily abundance taken as catch by one unit of effort. The observed CPUE data differ from the model predictions assuming lognormal residual errors:

$$
\begin{equation*}
I_{d, G N}^{o b s}=I_{d, G N} \cdot \exp \left(w_{d, G N}\right) \tag{5}
\end{equation*}
$$

with $w_{d, G N} \sim N\left(0, \sigma_{w, G N}^{2}\right)$.
In cases when purse seine test fishery data are available in addition to gill net data, the time-density model is expanded to include daily abundance estimates in Johnstone as well as Juan de Fuca Strait:

$$
\text { (6) } \quad N_{d, A 12}=N \cdot D \cdot f(d) \text { and } N_{d, A 20}=N \cdot(1-D) \cdot f(d)
$$

where $N_{d, a}$ is the daily abundance on a given day $d$ in area $a$ (A12 or A20), and $D$ is the (northern) diversion rate, i.e. the proportion of the run migrating through Johnstone Strait (A12) (Chapter A2). For gill net test fisheries, it is assumed that the sockeye catchability is the same in Johnstone Strait versus Juan de Fuca Strait. Therefore the Gill net CPUE on a given day ( $l_{d, G N}$ ) is:

$$
\begin{equation*}
I_{d, G N}=q_{d, G N} \cdot\left(N_{d, A 12}+N_{d, A 20}\right) \tag{7}
\end{equation*}
$$

For purse seine test fisheries, it is assumed that the catchability depends on the relative width of the area swept or sampled, i.e., the width of the migratory channel at the test fishing site in relation to the size of the fishing net. Because the relative width of the area swept in Juan de Fuca Strait is 2.2 times larger than in Johnstone Strait, it is assumed that the sockeye catchability of the purse seine test fishery in Area 12 is 2.2 times greater than in Area 20. Similarly, the catchability in Area 13 is assumed to be 1.5
times greater than in Area 12, or 3.3 times greater than in Area 20. The purse seine CPUE on a given day in the Area 12, 20 and $13\left(I_{d, P S, a}\right)$ is therefore respectively:
(8) $\quad I_{d, P S, A 20}=q_{d, P S, A 20} \cdot N_{d, A 20}$,

$$
\begin{align*}
& I_{d, P S, A 12}=2.2 \cdot q_{d, P S, A 20} \cdot N_{d, A 12}, \text { and }  \tag{9}\\
& I_{d, P S, A 13}=3.3 \cdot q_{d, P S, A 20} \cdot\left(N_{d, A 12}-C_{d, A 12}\right) \tag{10}
\end{align*}
$$

where $C_{d, A 12}$ is the total catch taken between Area 12 and 13 on a given day. The observed CPUE data for the different test fisheries $(f)$ differ from the model predictions assuming lognormal residual errors:
(11) $I_{d, f}^{o b s}=I_{d, f} \cdot \exp \left(w_{d, f}\right)$
with $w_{d, f} \sim N\left(0, \sigma_{w, f}^{2}\right)$. Reconstructed daily marine abundances ( $N_{d}^{o b s}$ ) deviate from the daily abundances $\left(N_{d}\right)$ predicted by the time-density model:

$$
\begin{equation*}
N_{d}^{o b s}=N_{d, A 12}+N_{d, A 20}+v_{d} \tag{12}
\end{equation*}
$$

with $v_{d} \sim N\left(0, \sigma_{v}^{2}\right)$ reflecting the deviation. For stocks that delay their upstream migration, reconstructed daily abundance estimates will not be available.

## BAYESIAN IMPLEMENTATION INCORPORATING PRIOR KNOWLEDGE

The time-density model described above requires the simultaneous estimation of total run size ( $N$ ), timing of the migration $(T)$, the diversion rate ( $D$ ), and the variances of the residual error terms ( $\sigma_{v}^{2}$ and $\left.\sigma_{w}^{2}\right)$. For several of the model parameters, additional information is available to formulate informative prior probability distributions which can be incorporated using a Bayesian estimation approach (Gelman et al. 1995). The prior probability distributions for run size, timing and diversion rate are based on the pre-season forecasts (Chapters A1 and A2). The assumed distributions for run size, timing and diversion rates are respectively a lognormal, normal and beta distribution (Table 1). The normal prior probability distribution for the standard deviation of the migration $(S)$ is based on historical data. Because early inseason, the model tends to underestimate the spread of the migration (i.e. the number of days it takes for the $95 \%$ of the run to pass through the marine test fishing areas), this model parameter is considered fixed but uncertain by default. However, this model parameter can be estimated if in-season data clearly indicates a strong deviation from historical standard deviations.

For the catchability coefficient ( $q$ ) , a normal prior probability distribution is assumed for the inverse of the catchability coefficient $\left(q^{-1}\right)$, i.e., the expansion line. At the start of the season, the prior probability distributions for the gill net and purse seine expansion lines are based on historical data, but later in the season, these distributions are based on in-season observations (Chapter B4). Unlike other prior probability distributions, these distributions for expansion lines are not further updated by the model. Uninformative gamma distributions are used as priors for the residual error terms ( $\sigma_{v}^{2}$ and $\sigma_{w}^{2}$ ).
Figure 1 provides a graphical overview of the Bayesian time-density model as described above. This model was developed and is run in WinBUGS 1.4 (Spiegelhalter et al. 2003) and called from the statistical software package $R$ ( $R$ Core Team 2013). All the model results undergo diagnostics to remove the impact of initial MCMC samples, to eliminate the negative impact of autocorrelation within the MCMC chains and to ensure convergence (Best et al. 1995). We assume the reported statistics of the posterior probability distributions represent the true underlying distributions.

## A. MODEL PARAMETERS



B. TIME-DENSITY MODEL


## C. DATA




## D. MODEL FIT



Figure 1. Graphical overview of the Bayesian time-density model when applied for the in-season assessment of Fraser River sockeye. Prior probability distributions (A) based on preseason forecasts of run size, migration timing and standard deviation of the migration allow the prediction of the daily abundance of salmon assuming a normal distribution of migrating salmon over time (B). Reconstructed daily marine abundance estimates and marine test fishery CPUE data are collected and updated continuously throughout the salmon migration (C) and the model predicted daily abundance estimates are fitted to these data. Relative abundance estimates such as CPUE data however require an additional model parameter, in this case a catchability estimate. The uncertainty in daily abundance estimates derived from CPUE data is therefore represented using boxplots. Comparing the model predictions against the data allows the model to derive the posterior probability distributions of the model parameters (A). To simplify this figure, the probability distribution for the diversion rate and the variance parameters have been omitted.

Table 1. Probability density functions (pdfs) of the Bayesian time-density model and the parameter values of the prior pdfs used to assess Fraser River sockeye salmon.

| Prior probability density function | Parameter values for Fraser River sockeye |
| :--- | :--- |
| $\mathrm{R} \sim \operatorname{Lognormal}\left(\ln (\mathrm{m}), 1 / \ln \left(1+\mathrm{CV}^{2}\right)\right)$ | Median and CV derived from the run size forecast |
| $\mathrm{T} \sim \operatorname{Normal}\left(\mu, 1 /\left(\mu^{*} \mathrm{CV}\right)^{2}\right)$ | Mean and CV derived from the timing forecast |
| $\mathrm{S} \sim \operatorname{Normal}\left(\mu, 1 /\left(\mu^{*} \mathrm{CV}\right)^{2}\right)$ | Mean and CV derived from historical data |
| $\mathrm{D} \sim \operatorname{Beta}\left(\mu^{*} \eta,(1-\mu)^{*} \eta\right)$ | Mean derived from the diversion rate forecast, $\eta=20$ |
| $\mathrm{q}^{-1} \sim \operatorname{Normal}\left(\mu, 1 /\left(\mu^{*} \mathrm{CV}\right)^{2}\right)$ | Mean and CV based on historical data, later on in-season data |
| $1 / \sigma_{v}^{2}=\tau_{N} \sim \operatorname{Gamma}(0.001,0.001)$ | Mean $=1$, variance $=1000$ |
| $1 / \sigma_{w}^{2}=\tau_{1} \sim \operatorname{Gamma}(0.001,0.001)$ | Mean $=1$, variance $=1000$ |

## References

Adkison, M.D. and Cunningham, C.J. 2015. The effects of salmon abundance and run timing on the performance of management by emergency order. Can. J. Fish. Aquat. Sci. 72: 1518-1526.

Best, N., Cowles, M.K. and Vines, K. 1995. CODA manual. Version 0.30. MRC Biostatistics Unit, Cambridge, UK.

Cave, J.D. and Gazey, W.J. 1994. A preseason simulation model for fisheries on Fraser River sockeye salmon (Oncorhynchus nerka). Can. J. Fish. Aquat. Sci. 51 :1535-1549.

Fried, S.M., and Hilborn, R. 1988. In-season forecasting of Bristol Bay, Alaska, sockeye salmon (Oncorhynchus nerka) abundance using Bayesian probability theory. Can. J. Fish. Aquat. Sci. 45: 850-855.

Gelman, A., Carlin, J.B., Stern, H.S. and Rubin, R.B. 1995. Bayesian data analysis. Chapman and Hall, London, UK.

Gilhousen, P. 1960. Migratory behaviour of adult Fraser River sockeye. Int. Pac. Salmon Fish. Comm., Prog. Rep. 78 p.

Hyun, S-Y, Hilborn, R., Anderson, J.J., and Ernst, B. 2005. A statistical model for in-season forecasts of sockeye salmon (Oncorhynchus nerka) returns to the Bristol Bay districts of Alaska. Can. J. Fish. Aquat. Sci. 62: 1665-1680.

Michielsens, C.G.J. and Cave, J.D. 2019. In-season assessment and management of salmon stocks using a Bayesian time-density model. Can. J. Fish. Aquat. Sci. 76: 1073-1085.

Mundy, P.R. 1979. A quantitative measure of migratory timing illustrated by application to the management of commercial salmon fisheries. Ph.D. Dissertation. Univ. of Washington, Seattle, 85 p.

PSC. 1995. Pacific Salmon Commission run-size estimation procedures: An analysis of the 1994 shortfall in escapement of late-run Fraser River sockeye salmon. Pacific Salmon Commission Tech. Rep. 6: 179 p.

PST. 2020. Treaty between the government of Canada and the government of the United States of America concerning Pacific salmon as modified through January 2020.

R Core Team (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Ryall, P. 1998. Evaluation of the reliability of in-season run-size estimation techniques used for Southern British Columbia Chum salmon (Oncorhynchus keta) runs. N. Pac. Anadr. Fish Comm. Bull. 1: 380-387.

Spiegelhalter, D., Thomas, A., Best, N. and Lunn, D. 2003. WinBUGS. Version 1.4 user manual. MRC Biostatistics Unit, Cambridge, UK.

Springborn, R.R., Lampsakis, N.D. and Gallucci, V.F. 1998. A time-density model to estimate run-size and entry timing in a salmon fishery. N. Am. J. Fish. Man., 18: 391-405.

Starr, P., and Hilborn, R. 1988. Reconstruction of harvest rates and stock contribution in gauntlet salmon fisheries: application to British Columbia and Washington sockeye (Oncorhynchus nerka). Can. J. Fish Aquat Sci 45: 2216-2229.

Walters, C.J. and Buckingham, S. 1975. A control system for intraseason salmon management. IIASA working paper. IIASA, Laxenburg, Austria, 19 p.

Woodey, J.C. 1987. In-season management of Fraser River sockeye salmon (Oncorhynchus nerka): meeting multiple objectives, p. 367-374. In H.D. Smith, L. Margolis, and C.C. Wood [ed.] Sockeye salmon (Oncorhynchus nerka) population biology and future management. Can. Spec. Publ. Fish. Aquat. Sci. 96.

# B20. In-season SMURF Model 

## S. Latham and C.G.J. Michielsens

## Summary

The in-season assessment of run size and associated run timing of Fraser River sockeye salmon consists primarily of the Bayesian implementation of a time-density model (Chapter B19). This model relies on reconstructed daily abundance estimates (Chapter B18), which are initially based on marine test fishery data until, six days later, these preliminary estimates can be replaced by daily hydroacoustic estimates of migration past Mission (plus seaward catch). For Late-run stocks, which delay and redistribute prior to migration into the Fraser River, it is not possible to replace the daily estimates from test fishing with daily hydroacoustic-based estimates, and this leads to larger in-season run size uncertainty. To ameliorate impacts of this uncertainty when assessing Late-run stocks and fill the Late-run information gap when making in-season management decisions, an alternative abundance-prediction method (SMURFing, i.e., Smolt Method of Updating Run Forecasts) was developed. This method relies on in-season estimates of early-returning stocks to predict abundances of later-returning stocks, assuming equal post-smolt marine survival among stocks. This method takes advantage of juvenile sampling programs and stock compositions of seaward-migrating juveniles produced by those programs. To the degree that relative abundances are the same in returning adults as in the outmigrating juveniles, the estimated returns of earlier stocks are predictive of the returns of later stocks. During dominant Shuswap return years, this method is applied to predict the abundance of Late Shuswap/Portage from in-season run-size estimates of Early Thompson in combination with estimates of relative abundance from the juvenile outmigration. Uncertainty in juvenile stock compositions and in-season run size estimates for Early Thompson stocks contribute to uncertainty in the predicted run size for Late Shuswap/Portage, as do potential violations of assumptions.

## Introduction

Due to extreme interannual variability in marine survival, return strengths of Fraser River sockeye have been highly unpredictable in recent years. For example, recruits per effective female spawner varied from less than 1 in the 2005 brood year to more than 12 in the 2006 brood year (DFO 2018), resulting in returns below the 10th percentile and above the $90^{\text {th }}$ percentile in pre-season forecasts in 2009 and 2010, respectively. Due to such variability, the prediction intervals of forecasts have broadened, reducing their utility for effective fishery planning, and intensifying demand for accurate and timely inseason assessments of abundance. For example, in 2018, the $80 \%$ probability interval for the total return of Fraser River sockeye was 5-37 million (see Chapter A1).

The challenge of forecasting Fraser sockeye abundance in the pre-season has necessitated an intense inseason assessment program, and run sizes are typically estimated with time-density models. These models rely on the date of peak abundance and the shape of the daily abundance profile over time (Chapter B19). The daily marine abundance estimates are derived through reconstructions (Chapter B18) and are initially based on test fishery data. Once the salmon migrate into the Fraser River and pass the hydroacoustic site at Mission, these initial estimates are replaced with hydroacoustic-based estimates for most stocks. Unfortunately, some Late run stocks delay and redistribute prior to migration into the river, making it impossible to replace the uncertain test fishing-based estimates. In addition, in-
season run-size estimation using the time-density model is only possible when $50 \%$ of the run has been observed. Prior to the peak, runs that are small and early or late and large may be indistinguishable (Adkison and Cunningham 2015). As a result, management is under-informed about Late-run sockeye when making fisheries management decisions. Other information, however, may be available to help bridge this gap.

Stock proportions are important for planning fisheries in their own right, with respect to impacts on non-target stocks. In addition, the relative abundances they represent are somewhat less difficult to predict than absolute abundances (run sizes), reflecting positive correlation in productivity amongst stocks (Latham and Michielsens 2022). Broad regional correspondence in productivity trends emphasize the important role of factors impacting survival in coastal areas where the stocks share similar environments early in their marine lives (Mueter et al. 2002). To take advantage of correlated marine survival, a 'Smolt Method of Updating Run Forecasts' (SMURF) was developed that uses the in-season run size estimates of an earlier-returning 'Reference Stock' and the ratio among stocks in out-migrant juveniles to provide an in-season run-size estimate of the later-returning 'Predicted Stock'. This estimate is both independent of the pre-season forecast and available before traditional in-season run-size updates for the Predicted Stock. As described below, this method helps to fill the information gap between the pre-season forecast and the in-season time-density model results that become available after the peak of the run has been observed.

## Data

The model for SMURFing requires at least two highly processed data inputs: (i) relative stock composition estimates among outmigrant juveniles (smolts or post-smolts) captured two years prior to the year of return, and (ii) in-season estimates of the run size of 2-ocean sockeye from a Reference Stock in the year of return. Stock compositions are estimated for outmigrating juveniles with DNA as in Beacham et al. (2004). Run size for a Reference Stock is generally estimated using a time-density model (Chapter B19) or reconstruction-based (Chapter B18), but also alternate estimates of run size can be used, e.g., terminal hydroacoustics for Chilliwack sockeye on the 2020 cycle line. If stock composition estimates (Chapter B9) used in generating daily abundances and run-size estimates for the Reference Stock use the same method as for the juvenile stock composition, biases inherent in the method may be at least partially offset.

Stock compositions of returning adults are estimated mostly from catches in Statistical Areas 12, 13, 20, and 29 (Chapter B5). Samples of outmigrating juveniles can be collected from multiple locations, including lake outlets, river main stems, or marine locations where a high proportion of the outmigration passes during a short period of time (e.g., the Discovery Islands in Areas 12 and 13, Neville et al. 2016). The latter may be preferable (Latham and Michielsens 2022), but more replicates across years should be obtained to test that idea. For returns in 2018, juvenile samples were collected in 2016 from (i) the Mission downstream trap operated by DFO (Mahoney et al. 2013), (ii) salmon trawl and seine programs operated by DFO in Areas 12-16 (Neville et al. 2016), and (iii) hand-operated seine sampling conducted in Areas 12 and 13 by Hakai Institute (Johnson et al. 2019). Resulting genotypes were graciously shared with the PSC Secretariat by these organizations.

SMURFing could theoretically be used in many circumstances but could be most beneficial in predicting in-season run size of later-timed stocks that (i) are important for fisheries management considerations, and (ii) are difficult to estimate in a timely manner using traditional time-density methods or other methods. The Late run on Shuswap dominant years is a prime example, due to the effects of their migration delay and redistribution as described above (Chapter B18). It is important for fisheries management to obtain early in-season run-size estimates for these Late-run stocks, and even more so given the overlap in migration between management groups. Therefore, in-season run-size estimates of

Early Thompson are used in combination with relative juvenile abundance estimates of Early Thompson in comparison to Late Shuswap/Portage to produce early in-season Late-run run size estimates.

In-season age composition estimates are additional data inputs required for some applications of this method. As most Fraser River sockeye are 2-ocean fish upon their return, stock proportions of smolts and post-smolts two years earlier are most like stock proportions among returning adults. For Early Thompson and Late Shuswap/Portage on Shuswap dominant cycle years, the proportion of other ages is negligible. With other years or other stocks, however, the proportion of 2-ocean individuals in both the Reference Stock and the Predicted Stock must be estimated from scale samples from sockeye identified to those stocks using DNA in-season. The abundance of 2-ocean sockeye in the Reference Stock predicts the abundance of 2-ocean sockeye in the Predicted Stock, with the latter scaled-up to represent the return of all ages. In-season age estimates are derived from scales collected and analyzed at the PSC Secretariat Office (Chapter B7).

## Methods

Depending upon several critical assumptions, in-season estimation of earlier-returning stocks can, in combination with the ratio between earlier stocks and later stocks among out-migrating juveniles, be used to produce a quantitative prediction regarding the abundance of later-returning stocks. Of the various assumptions made when using this method, the most critical are the assumptions of equal catchability of juveniles among stocks and equal survivability among stocks between the juvenile sampling period and recruitment to adulthood. That is, SMURFing requires unbiased, representative samples of the post-smolt stock proportions, and it requires that those proportions are the same when the sockeye return to the Fraser River. The method makes other assumptions, but violations of those other assumptions (e.g., equivalent maturity schedules in the Reference Stock and Predicted Stock) are more amenable to study and estimated to have a relatively minor impact. A more complete list and evaluation of assumptions can be found in Latham and Michielsens (2022). Violations of most assumptions are expected to be reduced among stocks with juveniles that smolt at similar sizes and follow similar migration routes on similar dates.

The following paragraphs provide a detailed description of the model as it was applied to assess the run size of Late Shuswap/Portage in 2018. The model assumed that the abundance ( $N$ ) of Late Shuswap/Portage (LShP) stocks versus Early Thompson (ETho) stocks was the same, in a relative sense, for post-smolt juveniles $(J)$ as for returning adult recruits $(R)$ :

$$
\begin{equation*}
\frac{N_{J, E T h o}}{N_{J, L S h P}}=\frac{N_{R, E T h o}}{N_{R, L S h P}} . \tag{13}
\end{equation*}
$$

The ratio of post-smolt abundances could be rewritten as:

$$
\begin{equation*}
\frac{N_{J, E T h o}}{N_{J, L S h P}}=\frac{N_{J, E T h o} /\left(N_{J, E T h o}+N_{J, L S h P}\right)}{N_{J, L S h P} /\left(N_{J, E T h o}+N_{J, L S h P}\right)}=\frac{p_{E T h o}}{p_{L S h P}}=\frac{p_{E T h o}}{\left(1-p_{E T h o}\right)} \tag{14}
\end{equation*}
$$

with $p_{\text {ETho }}$ representing the proportion of Early Thompson post-smolts from the combined sample of post-smolts from Early Thompson, Late Shuswap/Portage. Equation 1 could then be re-written as

$$
\text { (15) } \quad N_{R, L S h P}=N_{R, E T h o} \cdot\left(\left(1-p_{\text {ETho }}\right) / p_{\text {ETho }}\right)
$$

with $N_{R, E T h o}$ being the in-season run size for Early Thompson, and $N_{R, L S h P}$ the in-season run size for Late Shuswap/Portage.

Early during the in-season management period, the run size of Early Thompson was derived through the application of a time-density model fitted to daily reconstructed marine abundance estimates as well as catch-per-unit effort (CPUE) data collected by gillnet and purse test fishing vessels in Statistical Areas 12 and 20 (Michielsens and Cave 2019, Chapter B19). As the season progressed, the Early Thompson run
size was derived by combining: 1) daily reconstructed marine abundance estimates on days for which abundances had been estimated at the Mission hydroacoustic site, 2) six-day projections of marine abundances based on marine CPUE data in combination with marine catchability estimates, and 3) predictions of the abundance seaward of marine test fisheries based on the time-density model. The resulting run size estimate for Early Thompson, including the associated uncertainty, was used as an uncertain input into the model to predict the run size of Late Shuswap/Portage. For this model, we assumed a lognormal distribution for the Early Thompson run size:

$$
\begin{equation*}
N_{R, E T h o} \sim \operatorname{Lognormal}\left(\ln (m), 1 / \ln \left(1+C V^{2}\right)\right) \tag{16}
\end{equation*}
$$

With $m$ and CV being the median and coefficient of variation of the in-season run size distribution for Early Thompson.

The proportion of Early Thompson post-smolts ( $p_{E T h o}$ ) among out-migrating smolts of both Early Thompson and Late Shuswap/Portage was estimated assuming the observed Early Thompson smolt proportions $p_{E T h o}^{o b s}$ from various juvenile sample collection programs in different areas ( $A$ ) followed a binomial distribution:

$$
\begin{equation*}
p_{E T h o, A}^{o b s} \sim \operatorname{Binomial}\left(p_{E T h o}, n_{A}\right) \tag{17}
\end{equation*}
$$

where $n_{A}$ was the total sample size of Early Thompson and Late Shuswap/Portage post-smolts in area $A$. Bayesian application of this model required a prior probability distribution for the Early Thompson postsmolt proportion, which was assumed to be an uninformative, uniform distribution between 0 and 1:

$$
\text { (18) } \quad p_{\text {ETho }} \sim \operatorname{Uniform}(0,1) .
$$

The model described above was developed and run in WinBUGS 1.4 (Spiegelhalter et al. 2003). Model results underwent diagnostics to remove the impact of initial MCMC samples, to eliminate the negative impact of autocorrelation within the MCMC chains, and to ensure convergence (Best et al. 1995). We assumed that the reported statistics of the posterior probability distributions represented the true underlying distributions. Results were reported in terms of the median and the $80 \%$ probability interval (PI).

## Results

In 2018, the median pre-season forecast for the return of Late Shuswap/Portage sockeye was 7.0 million ( $80 \%$ PI: $3.3-15.1$ million), comprising 99.5\% 2-ocean sockeye. At the median forecast, this group was forecast to contribute $95 \%$ of the total return of the Late-run management group. Two years prior, in 2016, the ratios of Late Shuswap/Portage to Early Thompson out-migrating juveniles did not differ significantly across juvenile programs ( $p=0.31$ ), and the average was 4.4 to 1 ( $80 \% \mathrm{PI}: 4.1-4.8$ ). This ratio was applied to the in-season run size estimate of Early Thompson to generate an estimate of the Late Shuswap/Portage run. On August 10, the first in-season Late Shuswap/Portage SMURFing estimate was presented to the Fraser Panel, 3.6 million ( $80 \%$ PI: 2.6-5.0 million), based on an Early Thompson estimate of 0.81 million ( $80 \%$ PI: $0.63-1.07$ million). Two weeks later (August 24), when the Early Thompson estimate was 1.26 million ( $80 \% \mathrm{PI}$ : 1.23 - 1.32 million), the corresponding SMURFing estimate for Late Shuswap/Portage was 5.6 million ( $80 \% \mathrm{PI}: 5.2-5.9$ million).

The resulting uncertainty in the run-size estimate for Late Shuswap/Portage was a function of the uncertainty in the ratio of Late Shuswap/Portage to Early Thompson in the juvenile sample and the uncertainty in the in-season run size estimate of Early Thompson. The former estimate (the ratio and its uncertainty) was a fixed property of the juvenile sample, whereas the latter estimate fluctuated as dictated by in-season data, trending toward lower uncertainty as more of the Early Thompson run size
was accounted for by high-precision hydroacoustic and catch accounting methods. SMURFing estimates change with every update to the estimated abundance of the Predicted Stock.

The results from SMURFing can be compared against other in-season and post-season estimates. In 2018, the first time-density model estimate of Late Shuswap/Portage was reported to the Panel on August 21 ( 6.3 million; $80 \%$ PI: 4.3 - 19.0 million). On August 24 , a more precise estimate ( 6.3 million; $80 \% \mathrm{PI}$ : 3.7-9.4 million) was presented. From August 28 through mid-September precision of this estimate varied little; the median estimate fluctuated between 5.7 and 6.5 million, while the $80 \%$ PI was stable near $3.7-7.2$ million. The estimated return of Late Shuswap/Portage at the end of the season was 4.5 million, which was $97.5 \%$ of the accounted Late run. The final in-season ratio of Late Shuswap/Portage to Early Thompson stocks was 3.4, significantly lower than the ratio of 4.4 estimated from post-smolt samples. In 2014, this ratio was more similar between post-smolt samples and eventual estimates in the 2014 return year (Latham and Michielsens 2022).

## Planned Changes and Potential Areas for Improvement

Because SMURFing to assess Late Shuswap/Portage is only done on 2018 cycle years, and historical juvenile data are limited, evaluations of the performance of this model in comparison to other in-season run-size models has been restricted to 2014 and 2018 and is somewhat anecdotal. It is therefore important to better understand the underlying assumptions: the degree to which these assumptions are violated, factors that minimize or exacerbate those violations, and the impact of those violations on assessments. Future analyses will include a greater number of potential pairs of Reference Stocks and Predicted Stocks to better understand these uncertainties and possibly expand the applicability of SMURFing in Fraser Panel assessment and management.

## References

Adkison, M.D. and Cunningham, C.J. 2015. The effects of salmon abundance and run timing on the performance of management by emergency order. Can. J. Fish. Aquat. Sci. 72: 1518-1526.

Beacham, T.D., Lapointe, M., Candy, J.R., McIntosh, B., MacConnachie, C., Tabata, A., Kaukinen, K., Deng, L., Miller, K.M., and Withler, R.E. 2004. Stock identification of Fraser River sockeye salmon using microsatellites and major histocompatibility complex variation. Trans. Am. Fish. Soc. 133: 1117-1137.

Best, N., Cowles, M.K., and Vines, K. 1995. CODA manual. Version 0.30. MRC Biostatistics Unit, Cambridge, UK.

DFO. 2018. Pre-season run size forecasts for Fraser River sockeye (Oncorhynchus nerka) salmon in 2018. DFO Can. Sci. Advis. Sec. Sci. Resp. 2018/034, 70 p.

Johnson, B.T., Gan, J.C.L., Godwin, S.C., Krkosek, M., and Hunt, B.P.V. 2019. Juvenile salmon migration observations in the Discovery Islands and Johnstone Strait in British Columbia, Canada in 2018. NPAFC Doc. 1838. 25 p.

Latham, S., and Michielsens, C.G.J. 2022. What can Discovery Island post-smolts tell us about returning Fraser river sockeye? Final report to the Pacific Salmon Commission, Vancouver, BC. 35 p.

Mahoney, J.E., Tadey, J.A., Whitehouse, T.R., Neville, C., and Kalyn, S.M. 2013. Evaluation of timing, size, abundance and stock composition of downstream migrating juvenile sockeye salmon in the lower Fraser River - a report to the Pacific Salmon Commission. Fisheries and Oceans Canada, Delta, BC. 27 p.

Michielsens, C.G.J. and Cave, J.D. 2019. In-season assessment and management of salmon stocks using a Bayesian time-density model. Can. J. Fish. Aquat. Sci. 76: 1073-1085.

Mueter, F.J., Ware, D.M., and Peterman, R.M. 2002. Spatial correlation patterns in coastal environmental variables and survival rates of salmon in the north-east Pacific Ocean. Fish. Oceanogr. 11: 205-218.

Neville, C.M., Johnson, S.C., Beacham, T.D., Whitehouse, T., Tadey, J., and Trudel, M. 2016. Initial estimates from an integrated study examining the residence period and migration timing of juvenile sockeye salmon from the Fraser River through coastal waters of British Columbia. North Pacific Anadromous Fish Commission, Bulletin 6: 45-60. doi:10.23849/npafcb6/45.60.

Spiegelhalter, D., Thomas, A., Best, N., and Lunn, D. 2003. WinBUGS. Version 1.4 user manual. MRC Biostatistics Unit, Cambridge, UK.

# B21. Gulf Troll-based Run Size 

M.J. Hague and C.G.J. Michielsens


#### Abstract

Summary Early in-season indications of Fraser River sockeye abundance are provided by marine test fishery data. While these abundance estimates are uncertain given both the daily and interannual variability in catchability, once fish reach the hydroacoustic site in the Fraser River, these initial estimates are updated with more precise reconstructed estimates calculated from abundance at Mission plus seaward catches. However, some populations may delay their upstream migration for days, or even weeks. When they do migrate upstream, the fish are often redistributed, making it impossible to replace the initial test fishing-based daily marine abundance estimates with more accurate hydroacoustic-based estimates. Delay in upstream migration mainly occurs among Harrison and Late-run stocks excluding Birkenhead/Big Silver, and has the biggest impact on fisheries management on years with large Late Shuswap abundance (i.e., 2018 cycle line years). On those years, an additional Strait of Georgia troll test fishery is operated in August and September to provide additional information regarding the presence and magnitude of delaying fish. More specifically, the CPUE data from the Gulf troll test fishery is used to predict the abundance of Late-run fish holding in the Strait of Georgia. The resulting estimate can be combined with estimates of upstream fish passage, catch, and abundance seaward of the Gulf troll sampling areas to provide updated estimates of Late-run run size.


## Introduction

As part of the Pacific Salmon Treaty (PST) agreements (PST 2020, Chapter 4, paragraph 13(a)), PSC staff are responsible for providing in-season updates of Fraser River sockeye salmon run size, timing, and diversion rate. For most of the sockeye stocks, preliminary daily abundance estimates derived from marine test fishery catch-per-unit-effort (CPUE) data are later replaced with more precise reconstructed daily abundance estimates based on hydroacoustic data collected at Mission and seaward catches (Chapter B18). However, some sockeye stocks delay their upstream migration and hold in the Strait of Georgia for days, or even weeks (Lapointe et al. 2003). This behavior is most apparent for Harrison, LateShuswap and Weaver-Cultus stock components (Lapointe et al. 2003). Due to both the redistribution of the run as well as the large amount of time it may take to reach the river, Mission-based abundance estimates cannot be used for these stocks to update the initial daily abundance estimates from marine test fisheries. The highly variable and unpredictable nature of the extent of the delay further complicates their in-season assessment.

To improve in-season assessment information for delaying stocks, a troll test fishery was established in 1987 in the Strait of Georgia, i.e., the Gulf troll test fishery (Chapter B1, Nelitz et al. 2018). While the initial purpose of this fishery was to confirm the presence or absence of a significant number of delaying fish in the Gulf, as well as estimate their abundance, over time these estimates were incorporated formally into the run size assessment procedures for Late-run stocks.

## Data

The Gulf Troll test-fishery in the Strait of Georgia is usually initiated in mid-August and runs through September. The actual end-date of this fishery depends on the timing of the upstream migration of the
run. During this time, two vessels survey six defined areas, or quadrants, on a weekly basis (Figure 1). Each vessel spends approximately 8 hours covering one quadrant a day (Lagasse et al. 2020), thereby completing the survey of all six quadrants after 3 days. This fishery is typically only in operation on dominant and sub-dominant cycle line years when Late run abundance is expected to be high, and a substantial percentage of Late-run stocks are expected to exhibit delay behavior.


Figure 1. Location of the six quadrants ( $Q-1$ to $Q-6 A$ ) surveyed by the Gulf Troll test fishery. All six areas are surveyed by two vessels over the course of 3 days and CPUE of the individual quadrants is weighted by the relative area of each quadrant to derive a combined CPUE estimate.

The Gulf Troll catch-per-unit-effort (CPUE) is defined as catch-per-1000 hook minutes, where hookminutes are calculated as the total daily fishing time multiplied by the average number of hooks per line on each vessel (Cave 1997, Chapter B2). To account for density dependent effects on the catchability of the troll test fishery (once a hook has caught a fish, it is no longer fishing), the total CPUE data of all fish species combined is corrected to derive the sockeye-specific CPUE using the following equation:
(8) $\quad$ CPUE $\left._{S}=\frac{C_{S}}{C_{T}} e^{(0.123+1.012 \cdot \ln C P U E}{ }_{T}+0.0746 \cdot\left(\ln C P U E_{T}\right)^{2}\right)$
where $C_{S} / C_{T}$ is the proportion sockeye $(s)$ in the total catch $\left(C_{T}\right)$ and $C P U E_{T}$ is the unadjusted all-species catch-per-unit-effort. The latter is based on the catch of all target and non-target species including
shakers (under-sized juvenile salmonids). These calculations are done for each of the six individual quadrants.


Figure 2. Relationship between corrected (Equation 1) and uncorrected sockeye CPUE in the Gulf troll test fishery. The solid line is the 1:1 relationship. Outliers are rare occurrences where effort was low, catch of other salmon species was high, and catch of sockeye was low.

Once all 6 quadrants have been surveyed, the sockeye CPUE of a survey period is then estimated by weighing the sockeye CPUE of the individual quadrants by the proportion each quadrant represents in the total area surveyed ( $p_{q}$, Table 1):

$$
\begin{equation*}
C P U E=\sum_{q=1}^{6}\left(p_{q} \cdot C P U E_{q}\right) . \tag{9}
\end{equation*}
$$

All quadrants carry similar weight except quadrant four (largest area) and quadrant 6 (smallest area). Prior to using the CPUE data in the model to predict the abundance of delaying Late run sockeye, the CPUE data are multiplied with the proportion of Late run stocks within the DNA samples taken from Gulf Troll catches.

Table 1. Relative proportion of the total Gulf Troll survey area represented by each quadrant (Cave 1997).

| Quadrant | Relative size of the <br> survey area $\left(p_{q}\right)$ |
| :---: | :---: |
| Q-1 | 0.148 |
| Q-2 | 0.171 |
| Q-3 | 0.176 |
| Q-4 | 0.262 |
| Q-5 | 0.178 |
| Q-6 | 0.065 |

Migration into the Strait of Georgia is estimated using a forward reconstruction of daily abundance estimates based on seaward test fisheries (Chapter B18). In the post-season, these daily marine abundances are rescaled so that the total marine estimate is equivalent to the final in-season run size estimate based on Mission abundance plus seaward catch. In the forward reconstruction, a fixed 4-day migration time is assumed between the Area 20 reference location and the entrance to the Strait of

Georgia. Once fish resume their spawning migration, it is assumed they need an additional 4-days to migrate from the Strait of Georgia to the Mission hydroacoustic site.

The historical abundance estimates of Late-run salmon resident in the Strait of Georgia on a given day ( $N_{d, S O G}$ ) are calculated by removing catches $(C)$ and estimates of daily migration into the Fraser River ( $N_{d, \text { Mission }}$ ) from the cumulative abundance of fish entering the Strait of Georgia:

$$
\begin{equation*}
N_{d, A_{i}}=\left(\sum_{d=1}^{n} N_{d}-\sum_{A=A_{1}}^{A_{i-1}} C_{d, A}\right)-\left(\sum_{d=1}^{n} N_{d, M i s s i o n}+\sum_{A=A_{i}}^{A_{j}} C_{d, A}\right) \tag{10}
\end{equation*}
$$

where $A_{i}$ indicates the Strait of Georgia area, $A_{1}$ to $A_{i-1}$ indicate all the areas seaward of the Strait of Georgia and $A_{i}$ to $A_{j}$ include all the areas seaward of Mission until and including the Strait of Georgia. Equation 3 assumes the dates associated with all catch and abundance estimates are adjusted to reflect reference location dates based on the amount of time (rounded to the day) it takes for sockeye to migrate from the area to the reference location (Chapter B18).

## Methods

To estimate the total abundance in the Strait of Georgia, a log-linear regression model is used that relates historical estimates of CPUE to total abundances in the Gulf on a given day ( $N_{d}$ ):

$$
\begin{equation*}
\ln \left(N_{d}\right)=a+b \cdot \ln \left(C P U E_{d}\right) \tag{11}
\end{equation*}
$$

Structural uncertainty and observation error are incorporated into the model through the use of a Bayesian framework. While uncertainty in catchability is accounted for, the model assumes that catchability remains stationary. However, experts (both biologist and fishermen alike) suspect that catchability declines as the season progresses as fish (a) redistribute closer to the river mouth and become inaccessible to fishing gear, and (b) rates of gear attraction decline as salmon stop feeding closer to their spawning time. For these reasons, and also supported by statistical evidence, the historical dataset is divided into two time periods: August and September, and separate models are used in each month to estimate total Late run abundances. Analyses also suggest a statistical difference in model fit between dominant/sub-dominant years and off cycle years. Therefore, various model combinations using different data subsets were explored, including different cycle-line combinations and separation or pooling of August and September timeseries. Due to data limitations, care should be taken when running the model for dominant years only using only September or August data.

## Results

The model produces estimate of the number of delaying Late run sockeye in the Gulf of Georgia, both in terms of the median and the $80 \%$ probability interval (Figure 3). The resulting estimates can be combined with estimates of observed catch, escapement estimates and seaward projections to derive total run size estimates (Table 2). The seaward projections are obtained from a combination of reconstructed abundance estimates based on more seaward marine test fishing data (Chapter B18) and predictions of the tail of the run seaward of the marine test fishery using the time-density model (Chapter B19).


Figure 3. Example model estimates of total Late-run abundance in the Strait of Georgia on September 19, 2018 using September data only and dominant/sub-dominant data only. Median estimates ranged from 939,000 to 1,075,000 depending on model selection but there is substantial uncertainty associated with these estimates based on the reported $80 \%$ probability intervals (PIs).

Table 2. Total run size estimates (thousands) for Late run stocks including Birkenhead/Big Silver based on catch plus escapement, estimates of delay using the Gulf Troll model based on different historical data sets and projections of abundance seaward of the Gulf Troll test fishery.

| Gulf Troll model based on historical data used | Catch + Escape. | Delay |  |  | Projection | Run size |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | median | 80\% Pl |  |  | median |  |  |
| September data, all years | 3,472 | 1,075 | 633 | 1,825 | 12 | 4,559 | 4,117 | 5,309 |
| Aug/Sept data, dom/subdom years | 3,472 | 939 | 508 | 1,730 | 12 | 4,423 | 3,992 | 5,214 |

## Planned Changes and Potential Areas for Improvement

Prior to the 2022 season, additional analyses will be done to better understand the raw Gulf troll data, including an evaluation of the sampling approach and the quadrant weighting scheme. The performance of the different alternative models in terms of their ability to predict the abundance in the Strait of Georgia will be evaluated as well as the methods to combine Gulf troll estimates with estimates of catch and escapement and seaward projections to predict total run size estimates.

## References

Cave, J. 1997. Review of Area 29 Troll Test Fishing. PSC Memo. 17 p.

Lagasse, C.R., Xie, Y., Nelitz, J.L., Bartel-Sawatzky, M. 2020. A pilot study on the application of hydroacoustic surveys to assess the abundance of delaying sockeye in Georgia Strait: A Final Project Report to the Southern Boundary Restoration and Enhancement Fund. Pacific Salmon Commission. October 2020.

Lapointe, M., Cooke, S.J., Hinch, S.G., Farrell, A.P., Jones, S., McDonald, S., Patterson, D., Healey, M.C., and Van Der Kraak, G. 2003. Late-run sockeye salmon in the Fraser River, British Columbia, are experiencing early upstream migration and unusually high rates of mortality - what is going on? Proceedings of the 2003 Georgia Basin/Puget Sound Research Conference.

Nelitz, M., Hall, A., Michielsens, C.G.J., Connors, B., Lapointe, M., Forrest, K., and Jenkins, E. 2018. Summary of a Review of Fraser River Test Fisheries. Pacific Salmon Comm. Tech. Rep. No. 40: 155p.

PST. 2020. Treaty between the government of Canada and the government of the United States of America concerning Pacific salmon as modified through January 2020.

# B22. Management Adjustments 

M.R. Forrest and M.J. Hague


#### Abstract

Summary Management Adjustments (MAs) are the additional fish allocated to escape fisheries for the purpose of increasing the likelihood of achieving the spawning escapement target (SET). The selection of an appropriate MA is within the purview of the Fraser River Panel who take into account en-route losses due to adverse migration condition but also other factors that cause differences between predicted and observed spawning ground estimates (DBEs, Differences Between Estimates). Historical DBE estimates are based on differences between the actual number of spawners on the spawning grounds (spawning escapement SE) and the predicted spawning ground estimates based on the number of salmon migrating past the hydroacoustic site at Mission minus the total catch above Mission (potential spawning escapement PSE, DBE=SE-PSE). Sources for DBEs include en-route mortality as well as errors (bias and imprecision) introduced through the estimates of Mission escapement, spawning ground escapement, First Nations and recreational catches above Mission, and stock composition. Preseason and in-season, DBE predictions can be obtained through a variety of different methods: based on historical discrepancies or based on observed or forecasted environmental conditions or migration timing. The Fraser River Panel uses these DBE predictions and other tools and information to agree upon MAs for pre-season planning and in-season management.


## Introduction

In-season, PSC staff incorporate Fraser River Panel agreed upon MAs into TAC calculations in accordance with the Pacific Salmon Treaty Chapter IV, section 13b. The Panel relies on a variety of different pieces of information to derive the MA: historical estimates of difference between post-season observations and in-season projections of spawner numbers, i.e., the difference between estimates (DBEs), in-season environmental observations, and in-season model predictions of the DBE. The latter are based on statistical models using observed and in-season forecasts of river conditions and in-river migration timing. The models consider the historical differences between post-season spawning ground estimates (spawning escapement SE) and in-season projections of spawning escapement, i.e., Mission escapement minus catch above Mission (potential spawning escapement PSE, DBE= SE-PSE). For Early Stuart, Early Summer-run and Summer-run stocks, the models relate historical DBE estimates to river conditions measured near Hope, B.C. in the Fraser River (Chapter B24). When discharge levels or temperatures are above average, DBEs also tend to be high. In addition, for Early Stuart and Early Summer runs, in-season estimates are consistently higher than spawning ground estimates even when migration conditions are within normal ranges, and this tendency is also captured by the models. For Late-run sockeye, historical DBEs are related to the date when half the run has migrated past Mission (i.e., Mission $50 \%$ date), which captures the impact of the early migration behaviour observed since the mid-1990s on the migration success of these stocks (Lapointe et al. 2003, Chapter B25).

## Data

The historical escapement differences, $50 \%$ migration dates at Hells Gate and Mission and the associated 19 -day mean and 31-day mean temperature and discharge estimates are the primary biological data used in the statistical models. The historical DBE estimates and the $50 \%$ migration dates
are summarised primarily by management group, except for some stocks like Pitt, Chilliwack, Harrison/Widgeon and Birkenhead/Big Silver, whose location closer to the mouth of the Fraser River decreases expected en-route losses associated with adverse migration conditions. The resulting DBE data therefore relates to the following groups: Early Stuart, Early Summer run without the Pitt and Chilliwack River components, Pitt River, Chilliwack River, Summer run without the Harrison/Widgeon component, Harrison/Widgeon, Late run group without the Birkenhead/Big Silver component and Birkenhead/Big Silver. Data for other groupings are also maintained, however, currently not used. The historical data ranges from 1977 to present. Some years are excluded for a management group or component to avoid potential biases in escapement estimates: if the year is not representative, if the data collection is not comparable to current practice or if the circumstances resulting in the estimates are unlikely to happen again. A list of the excluded years for each of management group or component can be found on the PSC SharePoint site for the Fraser River Panel among the data set files and is updated regularly.

The 50\% Hells Gate date for a management group is determined from its Area 20 date (Chapter B18). The travel time from Area 20 to Mission is assumed to be 6 days for the Early Stuart, Early Summer and Summer run sockeye. The subsequent travel time from Mission to Hells Gate is assumed to be 5 days for the Early Stuart and Summer run sockeye and only 4 days for the Early Summer run sockeye. The Late run travel time from Area 20 to Hells Gate depends on their delay before up-stream migration and varies substantially across years.

The Fisheries and Oceans (DFO) Environmental Watch Program provides both historical as well as inseason observed and forecasted Fraser River temperatures and flows (Chapter B23). In-season the observations and forecasts of daily temperature and discharge are provided twice weekly, are presented in graphs to Fraser River Panel (Figure 1), and are used within mathematical models to predict the discrepancy between the SE and PSE, i.e., to predict the DBE. The forecasts allow the Fraser River Panel to make informed in-season fisheries decisions 3-4 days after the 50\% date in Area 20 but prior to all 19 days of temperature and discharge data are available. This facilitates a more informed decision-making process and allows the Fraser Panel to proactively update in-season management adjustments to improve the probability of achieving spawning escapement goals.

In addition to the data used within the models predicting the DBE, the Fraser River Panel also incorporates additional information in their decision-making process. To that aim, the DFO Environmental Watch group also provides temperature data from the Fraser River mainstem and tributaries and how they compare to historical estimates (Table 1). Additional observations such as migration challenges, observed mortalities, pooling fish and observations on the spawning grounds are collected by DFO (DFO Stock Assessment, DFO Resource Management and other research groups) and communicated to the Fraser Panel. This includes the migration challenges encountered following the Big Bar rockslide and subsequent remediation work.


Figure 1. Example of in-season Fraser River temperature at Qualark, B.C. and Fraser River discharge at Hope, B.C. graph.

Table 1. Example of in-season Fraser River mainstem and tributary temperatures.

| Upriver of Slide | Map \# | Current Temperatures 14-Jul | Daily Mean | Historic Median | $\begin{gathered} \text { Deviation } \\ \text { from } \\ \text { Historical } \\ \text { Median } \\ \hline \end{gathered}$ | Historic Year Range |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Fraser River Mainstem |  |  |  |  |  |  |
|  |  | Fraser River @ Qualałk | 17.8 | 16.2 | 1.6 | 1981-2010 |
|  | 2 | Fraser River @ Texas Creek | 17.2 | 16.6 | 0.6 | 2006-2016 |
| - | 3 | Fraser @ Marguerite | NA | NA | NA |  |
| - | 4 | Upper Fraser @ Shelley | 13.6 | 13.8 | -0.2 | 1994-2016 |
| Fraser River Tributaries |  |  |  |  |  |  |
|  | 5 | Thompson R. @ Ashcroft | 17.4 | 15.7 | 1.7 | 1995-2016 |
|  | 6 | South Thompson @ Chase | 18.2 | 16.6 | 1.6 | 1994-2016 |
|  | 7 | North Thompson @ McLure | 14.8 | 12.5 | 2.3 | 2008-2016 |
| $\checkmark$ | 8 | Quesnel R. @ Quesnel | 16.5 | 14.6 | 1.9 | 2000-2016 |
| - | 9 | Nechako R. @ Isle Pierre | 20.1 | 18.4 | 1.7 | 2006-2016 |
| - | 10 | Stuart R. @ Ft. St. James | 18.7 | 17.5 | 1.2 | 2000-2016 |

## Methods

In-season DBE predictions provided by PSC Secretariat staff are based on temperature and discharge models and run-timing models. For Early Stuart, Early Summer and Summer run, there exist significant relationships between temperature, discharge and historical DBEs (Chapter B24). For Late-run sockeye the mathematical model is a regression model that relates extended freshwater residence to DBE estimates (Chapter B25).

Some components of a management group are excluded from the models and alternative methods to predict the DBEs for those components are used: Pitt River and Chilliwack for the Early Summer run group, Harrison/Widgeon for the Summer run group, and Birkenhead/Big Silver for the Late run group.
Among Early Summer run stocks, Pitt River sockeye do not pass Mission and their passage is therefore not well estimated. In addition, their upstream migration distance within the Fraser River is short and thus they have minimal exposure to adverse river conditions. Given the data issues, a fixed DBE is used for Pitt River based on the median of all years with suitable data. The upstream migration distance to Chilliwack is similarly short, resulting in minimal exposure to adverse river conditions. The timing of this stock is substantially earlier than the timing of other Early Summer run stocks and this would impact the $50 \%$ migration date when combined with other Early Summer run stocks. In addition, the abundance of Chilliwack sockeye has not been estimated well prior to the use of DNA to identify stocks. Given the low abundance of Chilliwack on certain years, the DBE for Chilliwack is based on the median of all suitable years of data that have more than 30 sockeye identified as Chilliwack fish within the river. And on dominant and subdominant years, when Chilliwack abundances are higher and the quality of the DBE estimates is therefore greater, only the dominant and subdominant years of data are used to derive the median.

For Summer run sockeye, Harrison/Widgeon sockeye data are excluded from environmental DBE models because of their shorter migration distance within the Fraser River and because the relationship between Harrison/Widgeon DBEs and environmental conditions is poor. The DBE for Harrison/Widgeon
sockeye can also be significant while the DBEs for other Summer run sockeye is much smaller. The DBE for Harrison/Widgeon sockeye is based on the median of all suitable years since the start of the DNA collection.

For Late-run sockeye, Birkenhead/Big Silver sockeye are excluded from the DBE models because, unlike other late run stocks, these sockeye don't delay their upstream migration in Georgia Strait. The DBE for Birkenhead/BigSilver sockeye is based on the median across all suitable years.

The Fraser River Panel however manages Fraser River sockeye by management group. To accommodate the different DBEs for each component of a management group, a weighted proportion DBE (pDBE) approach is used. The MA models predict the pDBE for each management group excluding the components that rely on historical medians. Subsequently, a weighted average pDBE is calculated to combine the estimates of the different components. This is done by weighting the pDBE of each component by the associated relative abundance. Because the management group pDBEs depend on the relative abundance of the components, in-season DBEs can change with changes in run-size, regardless of changes in DBE predictions. When the abundances of the components are small relative to the total management group, weighting the pDBE by the components has almost no impact on the aggregate pDBE. The weighted approach is most beneficial for Late run stocks with high proportions of Birkenhead/Big Silver (PSC 2019). Following the results of additional retrospective analyses, the Panel has foregone the weighted approach when the abundance of the components is small relative to the total management group.

For in-season Fraser River Panel meetings, the Panel is provided with graphs of Fraser River temperature at Qualark, B.C. and Fraser River discharge at Hope, B.C. (Figure 1), a table of Fraser River mainstem and tributary temperatures (Table 1) and the predictions of the DBE models (Chapters B24 and B25) as well as in river observations such as carcass counts, fish holding behavior and fish condition and reports from the spawning grounds or from other areas with potential migration challenges such as Big Bar.

The Panel may choose to adopt (if either party accepts) or not adopt (if both parties reject) the MA estimate corresponding to the pDBE prediction for a management group or may choose a different value as they see fit (by bilateral agreement).

## Planned Changes and Potential Areas for Improvement

There is a cost to underestimating or overestimating in-river loss. When the DBE is underestimated managers do not meet spawning objectives. If the DBE is overestimated harvest opportunities are lost. The DFO Environmental group and PSC staff continue to work at improving the models and tools used to estimate en-route loss.

Currently models and other tools are focused on the environmental impact on in-river migration to the spawning grounds. There is currently no way to forecast bias and imprecision in Mission escapement estimates, in-river catch estimates, spawning escapement estimates and stock composition.

In addition to the statistical MA models, the Fraser River Panel uses other tools to supplement their decision-making process. They can also use "the Supplemental Approach" which relies on temperature and discharge thresholds identified by the historical data. This method is currently being evaluated through retrospective analyses. The MA models and the additional MA tools aid the Panel in their directive to achieve spawning escapement targets and maximize harvest opportunities for Fraser sockeye.

## Appendix

Table A1. Derivation of historical DBE estimates and subsequent transformations (DBE = Difference Between Estimates, SE = Spawning Escapement, PSE = Potential Spawning Escapement, pDBE = Proportional Difference Between Estimates, pMA = Proportional Management Adjustment, MA = Management Adjustment).

1. $D B E=S E-P S E$
2. $p D B E=\frac{(S E-P S E)}{P S E}$
3. $p M A=\left(\frac{P S E}{S E}\right)-1$
4. $p D B E=\frac{1}{1+p M A}-1$
5. $p M A=\frac{1}{1+p D B E}-1$
6. $M A=S E T \cdot p M A$

## References

Cummings, J.W., Hague, M.J., Patterson, D.A. and Peterman, R.M. 2011. The Impact of Different Performance Measures on Model Selection for Fraser River Sockeye Salmon. North American Journal of Fisheries Management, 31:323-334.

Hague, M.J. and Patterson, D.A. 2014. Evaluation of Statistical River Temperature Forecast Models for Fisheries Management, North American Journal of Fisheries Management, 34:1, 132-146

Lapointe, M.F., Cooke, S.J., Hinch, S.G., Farrell, A.P., Jones, S., Macdonald, S., Patterson, D., Healey, M.C., and Van Der Kraak, G. 2003. Late-run sockeye salmon in the Fraser River, British Columbia are experiencing early upstream migration and unusually high rates of mortality: what is going on? In Proceedings of the 2003 Georgia Basin/Puget Sound Research Conference. pp. 1-14.

Morrison, J. 2005. Fraser River Temperature and Discharge Forecasting: 2004 Review. Canadian Technical Report of Fisheries and Aquatic Science 2594.

Morrison, J. and Foreman, M.G.G. 2005. Forecasting Fraser River flows and temperatures during upstream salmon migration. Journal of Environmental Engineering and Science, 4: 101-111.

PSC. 2019. Evaluation of the weighted pDBE approach. Fraser River Panel meeting: 25 April 2019, Richmond, BC.

# B23. EWatch Temperature and Discharge Forecasts 

M.R. Forrest, M.J. Hague and D. Patterson


#### Abstract

Summary The DFO Environmental Watch (EWatch) Program provides PSC managers with scientific advice and environmental data to assess the impact of different environmental factors on the migration success of Pacific salmon in fresh water (https://www.pac.dfo-mpo.gc.ca/science/habitat/frw-rfo/index-eng.html\#info). In-season EWatch generates Fraser River forecasts of water temperature at Qualark, B.C. and discharge at Hope, B.C. and provides this information to the Fraser River Panel in bi-weekly reports from July to September. They also provide real time temperature data from key EWatch temperature monitoring stations within the Fraser River watershed and real time Fraser River discharge data from a Water Survey of Canada (https://wateroffice.ec.gc.ca) site in the lower river. The temperature and discharge forecasts are used along with observed daily temperature and discharge in environmental models (Chapter B24) to provide the Fraser River Panel with early indications of adverse environmental conditions and potential en-route losses, that may impact their Management Adjustment (MA) decisions (Chapter B22).


## Introduction

For the management of Fraser River sockeye salmon, the Fraser River Panel relies on Management Adjustments (MAs), which are the additional fish allowed to escape fisheries to increase the likelihood of achieving the spawning escapement target (SET) (Chapter B22). To select appropriate values for the MAs, the Panel relies on a wide range of different pieces of information that allow to evaluate in-river migration conditions and potential en-route losses. Among the information are the results of the models that relate temperature and discharge within the Fraser River to differences between predicted and observed spawning ground estimates, i.e., to Differences Between Estimates (DBEs) (Chapter B24). These models use 19-day average Fraser River temperature at Qualark, B.C. and discharge at Hope, B.C., associated with the $50 \%$ migration date of the management group, as model inputs. Of the 19 days, 15 days of data proceed the Hells Gate migration date. The DFO Environmental Watch group is responsible for providing both observed and forecasted Fraser River temperature and flows twice weekly throughout the migration season (Patterson et al. 2008). The 10-day forecasts (Morrison 2005, Morrison et al. 2005, Hague et al. 2014) provide managers with an early indication of the expected DBE and allow the Fraser River Panel to make informed fisheries decisions 3-4 days after the 50\% date in Area 20. This facilitates a more informed decision-making process and allows the Fraser Panel to proactively adjust management actions to improve the probability of achieving spawning escapement goals.

Water temperature and discharge are forecasted by different methods. In the past, a complex hydrological model (Morrison 2005) that required intensive meteorological inputs was used to make the 10-day forecasts of Fraser River temperature at Qualark. Currently the Hope Statistical Model (HSM) (Hague et al. 2014) and a generalized additive mixed effects model (GAMM) (Gardner 2016) are used to forecast Fraser River temperature at Qualark, B.C. The evaluations of the HSM (Hague et al. 2014) and the GAMM (Gardner 2016) models confirmed the benefit of using these less data intensive models to inform fisheries decisions. These models using air temperature and discharge covariates explained a significant proportion of the variability in daily summer water temperatures in the Fraser River. To produce the 10 -day forecast of Fraser River discharge at Hope, the first 3 days are forecasted using a
routing model based on upstream flows and the next 7 days are forecasted using an historic decay model that tracks the shape of historic hydrograph.

## Data

The EWatch program has an environmental monitoring program which consists of a comprehensive network of temperature logger stations along key salmon migration routes throughout the Fraser Watershed (https://www.pac.dfo-mpo.gc.ca/science/habitat/frw-rfo/index-eng.html\#info) (Figure 1). The EWatch program provides the PSC with observed Fraser River water temperature data from this network of real-time data loggers and from others that are operated by Water Survey of Canada. The EWatch group also provides the PSC with observed discharge data from Water Survey of Canada (https://www.canada.ca/en/environment-climate-change/services/wateroverview/quantity/monitoring/survey.html).


Figure 1. Locations of key EWatch and WSC temperature monitoring stations and major Fraser River sockeye salmon spawning grounds (https://www.pac.dfo-mpo.gc.ca/science/habitat/frw-rfo/index-eng.html)

Because Hells Gate forms a well-known impediment to salmon migration (Roos 1991, Macdonald et al. 2000) and because there exist long time-series of historical environmental conditions associated with the monitoring stations located at Hope and Qualark (Patterson et al. 2007, Macdonald et al. 2010), these two sites are used as the main geographic reference points to describe Fraser River environmental conditions.

The following list provides a detailed overview of the various data sets used to derive the observed and forecasted water temperature and discharge time series:

- Historical daily mean Fraser River water temperatures recorded near Qualark, B.C.: data prior to 2007 (Patterson et al. 2007), data from 2007 to current (DFO, EWatch Program).
- Observed daily Fraser River upstream temperatures measured by Water Survey of Canada (https://wateroffice.ec.gc.ca/login e.html). Verified and collated by the EWatch program.
- Observed and Historical daily discharge recorded near Hope, B.C.: Wateroffice, Government of Canada - Real-Time Hydrometric Data (https://wateroffice.ec.gc.ca/login e.html). Due to the inverse relationship between discharge and thermal capacity (Web et al. 2003), discharge explains a significant proportion of the variability in water temperature (Neumann et al. 2003, van Vliet et al. 2011). Daily mean river discharge near Hope, B.C. was identified as providing the best fit to Qualark water temperatures (Hague et al. 2014).
- Air temperature - Environment and Climate Change Canada (https://weather.gc.ca/). Water temperature has a high correlation with air temperature (Cluis 1972, Kothandaram and Evans 1972, Stefan and Preud'homme 1993) because they are influenced by the same heat transfer processes (Mohseni and Steffan 1999). Air temperatures from Kamloops, B.C. were shown to provide the best fit to Qualark water temperatures relative to that from other locations further upstream or downstream in the watershed (Hague et. al 2014).
- Air temperature forecast - Forecasts of air temperature come from both Environment and Climate Change Canada (https://weather.gc.ca/) and Weather Network (https://www.theweathernetwork.com/ca).
- Hope discharge forecast - Since 2020, forecasted flows have been supplemented by the BC River forecast center, using the CLEVER model (http://bcrfc.env.gov.bc.ca/freshet/map clever.html).


## Methods

The EWatch group uses a combination of the Hope Statistical Model (HSM, Hague et al. 2014) and a generalized additive mixed effects model (GAMM) (Gardner 2016) to produce 10-day forecasts of Fraser River temperature at Qualark.

The statistical model to produce 10-day daily forecasts of river temperature (Hague et al. 2014) is a stochastic model in which daily water temperature $(T)$ is predicted using a combination of seasonal and non-seasonal components, similar to Caissie et al. (2001):
(1) $\quad T=S+R+r$
whereby $S$ is the seasonal (harmonic) variability in water temperature, $R$ is the non-seasonal variability driven by exogenous environmental variables and $r$ is the non-seasonal variability driven by serial autocorrelation. A range of different statistical models following equation 1 are used to forecast the daily temperature. While $S$ and $r$ are common to all these models, the non-seasonal variation in water temperature $R$ is distinct for each model by using seasonal residuals of air temperature, discharge, or air temperature and discharge. A harmonic method (Hague et al. 2014, Cluis 1972, Caissie et al. 2001) to model seasonal trends for the water temperature, air temperature and discharge is applied. The advantage of using statistical models is the relative simplicity and minimal data requirements (Benyahya et al. 2007, Hague et al. 2014). They require less physical input data and typically use readily available measurements of air temperature, river flow, and water temperature along with historical seasonal trends to generate short-term river temperature forecasts (Gardner 2016).

The GAMM model is the second model used for short-term forecasting of river temperature and provides broader spatial coverage with more flexible and cost-effective implementation of river temperature forecasting (Gardner 2016). This approach models in-season temperatures by combining a linear regression model for daily water temperature with a sinusoidal smoothing spline of seasonal trends (Gardner 2016):

$$
\begin{align*}
& \quad T_{i . j}=\left(\alpha+\mu_{j}\right)+\beta_{1} A_{i-1, j}+\beta_{2} Q_{i-1, j}+\beta_{3} T_{i-1, j}+\beta_{4} A_{i-1, j} \cdot L+  \tag{2}\\
& \beta_{5} Q_{i-1, j} \cdot L+f\left(\text { day }_{i}\right)+\varepsilon_{i, j} \\
& \text { With } \varepsilon_{i, j} \sim N\left(0, \sigma_{e}^{2}\right) \text { and } \mu_{j} \sim N\left(0, \sigma_{u}^{2}\right) .
\end{align*}
$$

In equation $2, T_{i, j}$ is the predicted river temperature on day $i$ in year $j, A_{i-1}, Q_{i-1}, T_{i-1}$ are respectively the air temperature, the discharge and the water temperature of the previous day, $A_{i-1} x L$ is the interaction of air temperature and location and $f$ represents a cubic regression spline smoothing function of Julian day, which allows the model to fit the seasonal trend. The residual error ( $\varepsilon$ ), and year-specific variation of intercept $\left(\mu_{j}\right)$ are normally distributed with a mean of zero. In this model, discharge, air temperature, water temperature, and location are all fixed effects. Discharge ( $Q, \mathrm{~m}^{3} / \mathrm{s}$ ) is used as a predictor variable to account for the inverse relationship between discharge and river temperature (Webb et al. 2003). Air temperature $\left(A,{ }^{\circ} \mathrm{C}\right)$ is included due to the high correlation between air and water temperature (Kothandaraman 1972, Stefan and Preud'homme 1993) from heat exchange processes (Mohseeni and Stefan 1999). Current water temperature ( $T{ }^{\circ}{ }^{\circ} \mathrm{C}$ ) is a predictor of water temperature in the near future (Caissie et al. 1998). Location ( $L$ ) is included as a fixed effect due to the differences in mean temperature at different locations, as well as the location-specific effects of air and discharge on river temperature.
The model choice (HSM versus GAMM) and forecast inputs are a function of past model performance and the available data. Both the HSM and the GAMM model are evaluated annually by the EWatch group using three main performance metrics (root mean square error, mean raw error and mean absolute error) which compare forecasted and observed water temperature values. Errors in forecasted discharge and temperature are also evaluated. In addition, the model's performance is evaluated using type I (false-positive) and type II (false-negative) error rates which are associated with critical temperature thresholds related to salmon migration performance and mortality ( $18-21^{\circ} \mathrm{C}$ ). In future, type I and type II error rates which are associated with critical discharge thresholds will be evaluated as well.

Discharge is forecasted by two different models. For the first 3-days of the forecast, a routing model based on upstream flows is used (pers. comm. D. Patterson). For the last 7-days of the forecast a historic decay model is used (pers. comm. D. Patterson). This model uses the historic slope for a given day of the year applied to the previous days forecast. Reports describing the methods and comparative analyses to methods used by the B.C. River Forecast Centre are still in progress.

## Planned Changes and Potential Ireas for improvement

As indicated above, the temperature and discharge forecasts are used in-season along with observed temperature and discharge in statistical models to provide managers with an early indication of the expected discrepancy between the predicted and observed spawning ground estimates, i.e. the difference between estimates (DBEs). These DBE models incorporate uncertainty through Bayesian estimates. The Fraser Panel is provided with a confidence level on the likelihood of obtaining different values of a parameter when particular data have been observed (Ellison 1996). However, the Fraser Panel would also like to see the uncertainty in the temperature and discharge forecasts being incorporated. This is something to consider in the future.

## References

Benyahya, L., Caissie, D., St-Hilaire, A., Ouarda, T.B.M.J., and Bobee, B. 2007a. A review of statistical water temperature models. Canadian Water Resources Journal 32:179-192.

Benyahya, L., St-Hilaire, A., Ouarda, T.B.M.J., Bobee, B., and Ahmadi-Nedushan, B. 2007b. Modeling of water temperatures based on stochastic approaches: case study of the Deschutes River. Journal of Environmental Engineering and Science 6:437-448.

Caissie, D., El-Jabi, N., and Satish, M.G. 2001. Modelling of maximum daily water temperatures in a small stream using air temperatures. Journal of Hydrology 251:14-28.

Caissie, D., El-Jabi, N., and St-Hilaire, A. 1998. Stochastic modelling of water temperatures in a small stream using air to water relations. Canadian Journal of Civil Engineering 25:250-260.

Cluis, D.A. 1972. Relationship between stream water temperature and ambient air temperature. Nordic Hydrology 3:65-71.

Ellison, A.M. 1996. An introduction to Bayesian inference for ecological research and environmental decision-making. Ecological Applications 6(4): 1036-1046.

Gardner, L.N. 2016. A Generalized Additive Mixture Effects Modelling (GAMM) approach to short-term river temperature forecasting for the Fraser River, British Columbia: model evaluation and implications for salmon fishery management. Simon Fraser University, Burnaby, BC.

Hague, M.J. and Patterson, D.A. 2014. Evaluation of Statistical River Temperature Forecast Models for Fisheries Management. North American Journal of Fisheries Management 34(1): 132-146.

Kothandaraman, V., and Evans, R.L. 1972. Use of air-water relationships for predicting water temperature. Illinois State Water Survey, Report of Investigation 69, Urbana.

MacDonald, J.S., Foremean, M.G.G., Farrel, T., Williams, I.V., Grout, J., Cass, A., Woodey, J.C., Enzenhofer, H., Clarke, W.C., Houtman, R., Donaldson, E.M., and Barnes, D. 2000. The influence of extreme water temperatures on migrating Fraser River sockeye salmon (Oncorhynchus nerka) during the 1998 spawning season. Canadian Technical Report of Fisheries and Aquatic Sciences: 2326.

MacDonald, J.S., Patterson, D.A., Hague, M.J. and Guthrie, I.C. 2010. Modeling the Influence of Environmental Factors on Spawning Migration Mortality for Sockeye Salmon Fisheries Management in the Fraser River, British Columbia. Transactions of the American Fisheries Society 139:768-782.

Mohseni, O., and Stefan, H.G. 1999. Stream temperature/air temperature relationship: a physical interpretation. Journal of Hydrology 218:128-141.

Morrison, J. 2005. Fraser River temperature and discharge forecasting: 2004 review. Canadian Technical Report of Fisheries and Aquatic Sciences 2594.

Morrison, J. and Foreman, M.G.C. 2005. Forecasting Fraser River discharges and temperatures during upstream salmon migration. Journal of Environmental Engineering and Science 4:101-111.

Neumann, D.W., Rajagopalan, B. and Zagona, E.A. 2003. Regression model for daily maximum stream temperature. Journal of Environmental Engineering 129:667-674.

Patterson, D.A., MacDonald, J.S., Skibo, K.M., Barnes, D., Guthrie, I., and Hills, J.A. 2007. Reconstructing the summer thermal history for the lower Fraser River, 1941 to 2006, and implications for adult sockeye
salmon (Oncorhynchus nerka) spawning migration. Canadian Technical Report of Fisheries and Aquatic Sciences 2724.

Patterson, D.A., Morrison, J., and Hague, M.J. 2008. Updates to the Fraser River Environmental Watch Program Monitoring and Forecasting Protocol

Roos, J.F. 1991. Restoring Fraser River salmon: a history of the International Pacific Fisheries Commission, 1937-1985. Pacific Salmon Commission, Vancouver.

Stefan, H.G., and Preud'homme, E.B. 1993. Stream temperature estimation from air temperature. Water Resources Bulletin 29:27-45.
van Vliet, M.T.H., Ludwig, F., Zwolsman, J.J.G., Weedon, G.P., and Kabat, P. 2011. Global river temperatures and sensitivity to atmospheric warming and changes in river flow. Water Resources Research 47: W02544.

Webb, B.W., Clack, P.D., and Walling, D.E. 2003. Water-air temperature relationships in a Devon River system and the role of flow. Hydrological Processes 17:3069-3084.

# B24. DBE Temperature and Discharge Model 

M.R. Forrest and M.J. Hague

## Summary

Since 2002, the Pacific Salmon Commission has used environmental conditions in the lower Fraser River to predict differences between potential spawning escapement based on Mission estimates minus upstream catch and escapement on the spawning grounds (Macdonald et al. 2010). Reliably predicting the discrepancy between estimates (DBEs) increases the probability of achieving spawning escapement targets. Temperature and discharge models are used by the PSC to provide the Panel with likely spawning escapement outcomes and the Panel uses this information to determine how many extra fish are needed to meet spawning objectives, i.e. the size of the Management Adjustment (MA, Chapter B22). In these models, mean Fraser River temperature at Qualark, B.C. and mean Fraser River discharge at Hope, B.C. (Morrison 2005, Morrison et al. 2005, Hague et al. 2014) are related to historical timeseries of escapement discrepancies to generate either pre-season or in-season DBE predictions for Fraser River sockeye salmon (O. nerka) management (or run timing) groups.

## Introduction

Under the Pacific Salmon Treaty, the Fraser River Panel has the discretion to add additional fish to the spawning escapement target (SET) set by Canada for Fraser River sockeye salmon (O. nerka) to ensure spawning requirements are met (PST, Article IV, Chapter 4, Paragraph 3b). These additional fish are called the Management Adjustment (MA) and are meant to increase the likelihood of achieving the SET (Chapter B22). Post-season, MAs are defined by the differences between estimates (DBEs), i.e., the difference between the predicted spawning ground estimates (Potential Spawning Escapement, PSE, i.e. the number of salmon migrating past the hydroacoustic site at Mission minus the total catch above Mission), and the actual postseason estimates of the total number of spawners at the spawning grounds (Spawning Escapement, PE), with DBE=SE-PSE. Pre-season and in-season, DBE predictions can be derived through a variety of different methods: based on historical discrepancies, based on observed or forecasted environmental conditions or based on migration timing. This Chapter focuses on the temperature and discharge models developed jointly between the PSC and DFO to predict the DBE for Early Stuart, Early Summer-run and Summer-run sockeye (Macdonald et al. 2010). Each run timing group experiences distinct river conditions, with a greater likelihood of extreme discharge during the early runs and extreme temperature during the summer runs. Environmental extremes are known to create migratory challenges and contribute to increased levels of mortality during the return spawning migration. Historically, when discharge levels or temperatures within the Fraser River are above average, DBEs tend to be high. In addition, for Early Stuart and Early Summer runs, in-season Potential Spawning Escapement estimates are consistently higher than spawning ground estimates even when migration conditions are within normal ranges, and this tendency is also captured by the DBE models.

## Data

The historical escapement differences (DBEs), Hells Gate $50 \%$ dates and associated 19-day mean and 31day mean temperature and discharge data are the primary data used in the environmentally-based DBE models (Chapter B22). The DBEs are calculated as the difference between the spawning escapement (spawning ground estimate) and the potential spawning escapement (Mission passage minus catch
upstream of Mission). Each management group has its own DBE dataset because each group experiences different environmental conditions depending on when they migrate up the Fraser River.

The Hells Gate $50 \%$ date is the date on which $50 \%$ of the management group will pass Hells Gate in the Fraser River. The Hells Gate date is calculated based on marine migration dates indexed to statistical Area 20 in Juan de Fuca Strait (Chapter B18). The travel time from Area 20 to Mission (the location of the PSC hydroacoustic monitoring program) is assumed to be 6 -days for the Early Stuart, Early Summer and Summer run sockeye. The travel time from Mission to Hells Gate is assumed to be 5-days for the Early Stuart and Summer run sockeye and 4-days for the Early Summer run sockeye. In-season, the Area 20 dates for the different management groups derived through the run size assessment models are converted into Hells Gate Migration dates. This date in return is essential to derive the mean temperature and discharge information for the different management groups as the 19-day mean water temperature and discharge estimates used in-season rely on data 15 days before and 3 days after the Hells Gate date. Post-season, 31 day means are used to summarise the environmental conditions in the Fraser River, based on 15 days of observations before and 15 days after the Hells Gate date.

The DFO Environmental Watch Program provides updates of observed and forecasted Fraser River water temperature at Qualark, B.C. and discharge at Hope, B.C. twice weekly throughout the migration season (Chapter B23). Daily observed discharge values are accessed from the Environment Canada Water Office online database (https://wateroffice.ec.gc.ca/login e.html) and daily observed Fraser River water temperature at Qualark is provided by the DFO Environmental Watch group (Patterson et al. 2007) who also provides the 10 day forecasts of temperature and discharge. The temperature forecast is predicted by a statistical model that uses water temperature, air temperature, river discharge and seasonal trends (Hague et al. 2014) while the discharge forecast is derived by a routing model based on upstream flows and a historic decay model (pers. comm. D. Patterson).

## Methods

The temperature and discharge models use environmental conditions in the Fraser River as predictive variables to predict the DBE. There are significant relationships between lower river environmental conditions and historical DBEs for Early Stuart, Early Summer-run and Summer-run management groups (Macdonald et al. 2010, Cummings et al. 2011, Figure 1).


Figure 1. Relationship between the average 19-day temperature at Qualark and the \%DBE (Difference between estimates) and between the average 19-day discharge at Hope and the \%DBE for Early Stuart, Early Summer-run and Summer-run sockeye.

The resulting DBE temperature and discharge model is expressed as:
(1) $\quad \ln \left(\frac{P S E}{S E}\right)=a+b_{1} \cdot \mu_{T}+b_{2} \cdot \mu_{T}^{2}+b_{3} \cdot \mu_{Q}+b_{4} \cdot \mu_{Q}^{2}$

With $\mu$ representing the 19-day (in-season) or 31-day (post-season) mean of the Fraser River temperature ( $T$ ) or discharge ( D ) around the Hells Gate migration date. The dependent variable is expressed as the ratio of the Potential Spawning Escapement (PSE) over the Spawning Escapement (SE). The log transformation of the dependent variable is required to meet the assumptions of homoscedasticity (Zar 1996) and to constrain predictions in the range 0 or higher. The predictive variables are the 19-day or 31-day mean Fraser River temperature ( $T$ ) and discharge $(Q)$. The quadratic term for both discharge and temperature is included ( $T+T^{2}, Q+Q^{2}$ ) in the regression equation.

In-season the 19-day means are based on 9 or more days of observed data and 10 or less days of forecasted data, given predictions are only made 10 days out because of constraints in forecasting daily environmental data (Hague and Patterson 2014). The 19-day model provides managers an early inseason indication of the expected DBE in order to be more proactive in their management process as it allows a \%DBE prediction to be made between 3 to 4 days after the Area $2050 \%$ date and 1 to 2 days prior to the Mission 50\% date. Post-season, once 31 days of observed T \& Q data are available for a management group, the MA models are fit to a 31 -day mean $T$ and $Q$ centered around the $50 \%$ date at Hells Gate. The 31-day model captures $90 \%$ or more of a run's exposure to environmental conditions at Hells Gate and provides a better fit to the historical DBE data than environmental data averaged over a shorter time-period (Hague et al. 2007).
The model is run in WinBUGS (Spiegelhalter et al. 2003) with an R (R Core Team 2013) interface. This program allows the application of Bayesian methods to calculate the probability of the value of a parameter given the observed data (Wade 2000) and to provide an explicit expression of the amount of
uncertainty in these parameter estimates (Ellison 1996). As a result, it is also possible to quantify the uncertainty of the forecasted DBE and provide a probability interval (Ellison 1996) in addition to the point estimate for the forecasted DBE.

Each management group has its own historical dataset and MA models are run separately for each group. This is because each management group experiences different conditions depending on when they migrate up the Fraser River. Early Stuart sockeye salmon often experience higher discharges due to freshet that might continue into early July. Early Summer-run sockeye salmon can experience both high discharges and high temperatures, as they start their migration while discharge might still be high due to late freshet, and they may migrate through the peak of high summer water temperatures in the Fraser River. Summer-run sockeye often experience high temperatures as they also migrate during the peak of summer; however, depending on their timing they might migrate when days are getting shorter and night cooling begins.

The current temperature and discharge models predict a DBE for each management group but do not incorporate stock specific information despite known differences in tolerances to adverse environmental conditions (Eliason et al. 2011). Stock-specific differences are addressed by reducing the number of years in the historical dataset used for predicting DBEs. For example, in Dominant or Subdominant Early South Thompson years, the Early Summer-run dataset might be reduced to only Dominant or Dominant and Subdominant years. Early South Thompson sockeye generally dominate the Early Summer run management group in Dominant and Subdominant years and it is believed that their response to environmental conditions would be better reflected by years in which they make up larger proportions of the Early Summer run. The datasets can also be reduced to odd years in pink salmon years and cycle line years. However, this generally reduces the data points and influences the fit of the model. Another method used to address stock-specific differences is the weighted pDBE approach described in Chapter B22.

## Results

The temperature and discharge models produce prediction of the DBEs, including the $80 \%$ probability interval (PI), for Early Stuart, Early Summer and Summer run stocks for different Area 20 dates indicating the timing of the run (Table 1). In-season, the Area 20 date or marine migration date will be obtained from the run size assessment models (Chapter B19). Depending on the Area 20 migration date, the Hells Gate $50 \%$ date will differ and this in turn will impact the 19-days of temperature and discharge data used within the DBE model. For example, on August 21, the mean temperature and discharge when assuming the Area 20 timing is August 7, will be based on 19 days of observed data, 15 days observed prior to the Hells Gate date of August 17 and 3 days after. Because all of the 19 days of temperature and discharge data for this example are based on observations, no forecasts are needed to calculate the 19day means. However, if the Hells Gate migration date is August 18, the 19-day mean used as input in the DBE model will be based on 18 days of observed data and one forecasted day (August 21). Thanks to the 10-day forecasts of temperature and discharge, DBE predictions can be made 3 to 4 days after the $50 \%$ migration date in Area 20. This allows the Fraser Panel to proactively adjust management actions to improve the probability of achieving spawning escapement goals and facilitates a more informed decision-making process.

Table 1. In-season table produced on 21 August 2018 containing the model predictions of expected percent Differences Between Estimates (\%DBEs) and the implied proportional Management Adjustment (pMA). Depending on the assumed migration timing (Area 20 Date) of the management group, the 19 day mean temperature and discharge values will differ, resulting in different DBE predictions.

| Area 20 | Hells Gate | Average Temperate ${ }^{\circ} \mathrm{C}$ | Average <br> Discharge $\mathrm{m}^{3} / \mathrm{s}$ | Number of obs. | Number of forec. |  | $\begin{aligned} & \text { edicte } \\ & \text { \% DBE } \end{aligned}$ |  |  | mplie <br> onal M | A) |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
| Date | Date | (19 days) | (19 days) | days | days | median | 10\% | 90\% | median | 10\% | 90\% |
| Pre-Season Values |  |  |  |  |  |  |  |  |  |  |  |
| 8-Aug | 18-Aug |  |  |  |  | -19\% |  |  | 0.23 |  |  |
| Current model pres | dictions |  |  |  |  |  |  |  |  |  |  |
| 04-Aug | 14-Aug | 20.0 | 3016 | 19 | 0 | -48 | -2 | -73 | 0.92 | 0.02 | 2.70 |
| 05-Aug | 15-Aug | 20.0 | 2977 | 19 | 0 | -46 | 3 | -72 | 0.85 | -0.03 | 2.57 |
| 06-Aug | 16-Aug | 19.8 | 2933 | 19 | 0 | -42 | 13 | -70 | 0.72 | -0.12 | 2.33 |
| 07-Aug | 17-Aug | 19.7 | 2887 | 19 | 0 | -36 | 28 | -67 | 0.56 | -0.22 | 2.03 |
| 08-Aug | 18-Aug | 19.5 | 2838 | 18 | 1 | -29 | 44 | -65 | 0.41 | -0.31 | 1.86 |
| 09-Aug | 19-Aug | 19.3 | 2788 | 17 | 2 | -24 | 58 | -64 | 0.32 | -0.37 | 1.78 |
| 10-Aug | 20-Aug | 19.2 | 2734 | 16 | 3 | -19 | 76 | -62 | 0.23 | -0.43 | 1.63 |

## Model evaluation

DBE models and the derived Management Adjustment are used by managers to achieve spawning escapement targets while maximizing harvest. Underestimates of the DBE can lead to conservation concerns if excess catch causes too few fish to reach spawning grounds, whereas overestimates of DBE can result in foregone catch (Cummings et al. 2011). Various studies have evaluated the performance of the various DBE models (Cummings et al. 2011, Dionne et al. 2018) used to predict in-river loss. Cummings et al. (2011) found that although the best DBE models varied depending on the management group and performance measures, there was strong evidence that DBE forecasts and derived MA estimates based on some combination of environmental or biological data outperformed the approach of applying no MA at all.

A study by Hague et al. (2008) examined whether data from lower Fraser River temperature and discharge stations are appropriate environmental indices for the basin as a whole. Adult salmon encounter a range of temperatures and discharges along their up-river migration route and these values may not be consistently well-correlated to lower river conditions, particularly for populations with natal spawning grounds $>500 \mathrm{~km}$ from the ocean or for populations entering the river after mid-August. Results suggested that, in general, lower Fraser River environmental conditions were well correlated to conditions upriver; however, correlation strength decreased as a function of increasing distance and/or slower migration rates.

## Planned Changes and Potential Areas for Improvement

Given the cost to underestimating or overestimating DBEs, DFOs EWatch group and PSC staff continuously work to improve the models and tools used to estimate en-route loss (Patterson et al. 2019, Dionne et al. 2018).

Currently models and other tools are focused on the environmental impact on successful in-river migration to the spawning grounds. There is currently no way to forecast bias and imprecision in Mission escapement estimates, in-river catch estimates, spawning escapement estimates and stock composition.

## References

Cummings, J.W., Hague, M.J., Patterson, D.A., and Peterman, R.M. 2011. The Impact of Different Performance Measures on Model Selection for Fraser River Sockeye Salmon. North American Journal of Fisheries Management, 31:323-334.

Dionne, K.A. and Patterson, D.A. 2018. Improvements to predicting en-route loss estimates for Fraser sockeye salmon. PSC SEF Final Report.

Eliason, E. J., Clark, T.D., Hague, M.J., Hanson, L.M., Gallagher, Z.S., Jeffries, K.M., Gale, M.K., Patterson, D.A., Hinch, S.G. and Farrell, A.P. 2011. Differences in thermal tolerance among Sockeye Salmon populations. Science 332:109-112.

Hague, M.J. and Patterson, D.A. 2007. Quantifying the Sensitivity of Fraser River Sockeye Salmon (Oncorhynchus nerka) Management Adjustment Models to Uncertainties in Run Timing, Run Shape and Run Profile. Canadian technical Report of Fisheries and Aquatic Sciences 2776.

Hague, M.J. and Patterson, D.A. 2014 Evaluation of Statistical River Temperature Forecast Models for Fisheries Management. North American Journal of Fisheries Management, 34:1, 132-146.

Hague, M.J., Patterson, D.A. \& Macdonald, J.S. 2008. Exploratory Correlation Analysis of Multi-site Summer Temperature and Flow Data in the Fraser River Basin. Canadian technical Report of Fisheries and Aquatic Sciences 2797: viii +60p.

Ellison, A.M. 1996. An Introduction to Bayesian Inference for Ecological Research and Environmental Decision-Making. Ecological Applications. 6(4), pp. 1036-1046.

MacDonald, J.S., Foremean, M.G.G., Farrel T., Williams, I.V., Grout, J., Cass, A, Woodey, J.C., Enzenhofer, H., Clarke, W.C., Houtman, R., Donaldson, E.M., and Barnes, D. 2000. The influence of extreme water temperatures on migrating Fraser River sockeye salmon (Oncorhynchus nerka) during the 1998 spawning season. Canadian Technical Report of Fisheries and Aquatic Sciences 2326.

MacDonald, J.S., Patterson, D.A., Hague, M.J. and Guthrie, I.C. 2010. Modeling the Influence of Environmental Factors on Spawning Migration Mortality for Sockeye Salmon Fisheries Management in the Fraser River, British Columbia. Transactions of the American Fisheries Society 139:768-782.

Morrison, J. 2005. Fraser River temperature and discharge forecasting: 2004 review. Canadian Technical Report of Fisheries and Aquatic Sciences 2594.

Morrison, J. and Foreman, M.G.C. 2005. Forecasting Fraser River discharges and temperatures during upstream salmon migration. Journal of Environmental Engineering and Science 4:101-111.

Spiegelhalter, D., Thomas A., Best N. and Lunn, D. 2003. WinBUGS. Version 1.4 user manual. MRC Biostatistics Unit, Cambridge, UK.

R Core Team 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Wade, P.R. 2000. Bayesian Methods in Conservation Biology. Conservation Biology 14(5): 1308-1316.

Zar, J.H. 1996. Biostatistical analysis, $3^{\text {rd }}$ edition. Prentice Hall, upper Saddle River, New Jersey.

# B25. DBE Run Timing Model and Upstream Migration Timing Model 

M.R. Forrest and M.J. Hague


#### Abstract

Summary Late run sockeye stocks excluding Birkenhead/Big Silver traditionally delay their migration to the Fraser River in the Strait of Georgia. Since 1995, these stocks have however entered the Fraser River earlier, resulting in extended freshwater residence times, exposure to higher river temperature and discharge; and increased mortality (Lapointe et al. 2003, Cooke et al. 2004). The $50 \%$ migration date at Mission captures the early migration behaviour and is used as a predictive tool in the DBE run timing model that relates the upstream migration timing to the migration success of these stocks, i.e. the difference between the predicted and the observed spawning escapement (difference between estimates, DBEs). DBE predictions based on the upstream migration should be available prior to observing all the late run sockeye upstream to be useful for marine fisheries management. Therefore, the upstream migration timing model uses the historic relationship between the proportion upstream migration to-date and upstream timing to predict the $50 \%$ migration date at Mission for Late run sockeye excluding Birkenhead/Big Silver.


## Introduction

Late run stocks excluding Birkenhead/Big Silver do not migrate immediately upstream. Instead, they hold in the Strait of Georgia close to the mouth of the river before initiating up-river migration. Since 1995, Late run sockeye arrive in the Strait of Georgia at the normal time but migrate up the river earlier than normal. There is a high mortality associated with this diverging behaviour resulting in a higher observed DBE (difference between estimates) between potential spawning escapement based on Mission estimates minus upstream catch and escapement on the spawning grounds (Macdonald et al. 2010). In order to mediate these en-route losses, additional fish are allowed to escape upriver of Mission to account for anticipated DBEs, i.e., differences between in-season versus post-season estimates of spawning escapement. The addition of fish to an escapement target for the purpose of increasing the likelihood of achieving the spawning escapement target (SET) is called the Management Adjustment (MA, Chapter B22). The Fraser River Panel relies on both in-season observations as well as DBE predictions to derive appropriate MA estimates. For Late-run sockeye excluding Birkenhead/Big Silver, the DBE run timing model in combination with the upstream migration timing model are used to predict the DBE. The DBE run timing model uses the relationship between the historical $50 \%$ migration date at Mission and the historical DBEs to make in-season DBE prediction. The in-season estimate of the upstream migration date in turn is derived through the upstream migration timing model for Late run sockeye excluding Birkenhead/Big Silver which relies on the historical relationship between the percentage of upstream migration to date and the $50 \%$ migration date at Mission. The percentage upstream migration to date indicates the proportion of the sockeye that continued their upstream migration into the Fraser River and the sockeye that made it to the Strait of Georgia (Area 29).

## Data

The historical differences between estimates (DBEs) and Mission $50 \%$ migration dates for Late run sockeye are the primary data used in the DBE run timing model. Birkenhead/Big Silver stocks are excluded from the Late run DBE and $50 \%$ migration data because they do not delay their upstream migration. The Mission $50 \%$ migration timing relates to the date when $50 \%$ of the run will have passed Mission. Additional data used to predict the upstream migration timing for Late-run excluding Birkenhead/Big Silver are the reconstructed abundance estimates of these stocks in the Strait of Georgia. Forward reconstructions predict abundances into the Strait of Georgia based on marine daily abundances derived from stock-specific catch-per-unit-effort (CPUE) data and historical catchability estimates of marine test fisheries combined with assumptions about migration speed (Chapter B18). Dividing the total upstream migration to date by the total reconstructed abundance in the Strait of Georgia to date gives an estimate of the proportion of upstream migration to date.

## Methods

The DBE run timing model uses Mission timing as a predictive variable to predict the DBE. The DBE is expressed as $\operatorname{In}(\mathrm{PSE} / \mathrm{SE})$, whereby PSE is the potential spawning escapement and SE is the actual spawning escapement. The log transformation is required to meet the assumptions of homoscedasticity (Zar 1996) and to restrict predictions to positive numbers. Upstream timing is described by the Mission $50 \%$ migration date. Higher (more negative) DBEs are associated with early upstream migration (Figure 1).


Figure 1. Relationship between \%DBE and the Mission 50\% migration date for Late Run sockeye excluding Birkenhead/Big Silver.

In-season, the Mission 50\% migration date is predicted by the upstream timing model. This model looks at the historical relationship between the proportion of upstream migration to date and the post-season $50 \%$ migration date for Late-run excluding Birkenhead/Big Silver (Figure 2). The dependent value for the upstream timing model is the $50 \%$ date at Mission. The predictive variable is the percentage of resident fish reconstructed into the Strait of Georgia which have migrated past Mission on a given date. Earlier in the season, predictions of upstream migration timing are more uncertain (lower $\mathrm{R}^{2}$ ) compared to later in the season. The higher the proportion of upstream migration to date, the more precise the timing estimate. Uncertainty around the upstream timing will impact the uncertainty around the resulting DBE predictions.


Figure 2. Example of the relationship between the $50 \%$ date at Mission and the percentage of resident fish reconstructed into the Gulf which have migrated past Mission on a given date.

The DBE run timing and upstream migration timing models incorporate uncertainty through the application Bayesian estimation methods. Rather than providing the Fraser River Panel with a fixed DBE prediction or $50 \%$ migration date at Mission through frequentist statistics, the use of Bayesian methods allows the quantification of the uncertainty associated with the predictions (Ellison 1996). The Bayesian regression models are run in Winbugs (Spiegelhalter et al. 2003) with an R-code interface ( $R$ Core Team 2013).

## MODEL EVALUATION

DBE models and the derived Management Adjustment are used by managers to achieve spawning escapement targets while maximizing harvest. Underestimates of in-river loss can lead to conservation concerns if excess catch causes too few fish to reach spawning grounds, whereas overestimates of inriver loss can result in foregone catch (Cummings et al. 2011). Various studies have evaluated the performance of the DBE model (Cummings et al. 2011, Dionne et al. 2018) used to predict in-river loss for Late run sockeye excluding Birkenhead/Big Silver. Cummings et al. (2011) found that MA forecast based on the DBE model outperformed applying no MA at all.

Cummings et al. (2011) ranked the DBE run timing model for Late run sockeye as the best in terms of hind cast criteria. This model performed better than models relying on temperature and discharge. But the in-season uncertainty associated with the Mission migration date reduces the reliability of the resulting DBE predictions. When the Late-run run-size is small, estimating delay can be even more difficult.

## Planned Changes and Potential Areas for Improvement

The DFO EWatch group and PSC staff continue to work at improving the models and tools used to estimate en-route loss given the cost to underestimate or overestimate in-river losses.

## References

Cooke, S.J., Hinch, S.G., Farrell, A.P., Lapointe, M.F., Jones, S.R.M., Macdonald, J.S., Patterson, D.A. Healey, M.C., and Van Der Kraak, G. 2004. Abnormal migration timing and high en-route mortality of sockeye salmon in the Fraser River, British Columbia. Fisheries, 29(2): 22-33.

Cummings, J.W., Hague, M.J., Patterson, D.A., and Peterman, R.M. 2011. The Impact of Different Performance Measures on Model Selection for Fraser River Sockeye Salmon. North American Journal of Fisheries Management, 31:323-334.

Dione, K.A. and Patterson, D.A. 2018. Improvements to predicting en-route loss estimates for Fraser sockeye salmon. PSC SEF Final Report.

Ellison, A.M. 1996. An Introduction to Bayesian Inference for Ecological Research and Environmental Decision-Making. Ecological Applications. 6(4), pp. 1036-1046.

Lapointe, M.F., Cooke, S.J., Hinch, S.G., Farrell, A.P., Jones, S., Macdonald, S., Patterson, D., Healey, M.C., and Van Der Kraak, G. 2003. Late-run sockeye salmon in the Fraser River, British Columbia are experiencing early upstream migration and unusually high rates of mortality: what is going on? In Proceedings of the 2003 Georgia Basin/Puget Sound Research Conference. pp. 1-14.

MacDonald, J.S., Patterson, D.A., Hague, M.J. and Guthrie, I.C. 2010. Modeling the Influence of Environmental Factors on Spawning Migration Mortality for Sockeye Salmon Fisheries Management in the Fraser River, British Columbia. Transactions of the American Fisheries Society 139:768-782.

Spiegelhalter, D., Thomas, A., Best, N. and Lunn, D. 2003. WinBUGS. Version 1.4 user manual. MRC Biostatistics Unit, Cambridge, UK.

R Core Team 2013. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Zar, J.H. 1996. Biostatistical analysis, $3^{\text {rd }}$ edition. Prentice Hall, upper Saddle River, New Jersey.

# B26. Total Allowable Catch (TAC) 

## F.J. Martens

## Summary

Available Total Allowable Catch (TAC) is an important pre-requisite for in-season fisheries. The Pacific Salmon Treaty (PST), Chapter 4, describes the calculations for TAC for Fraser River sockeye and pink salmon. TAC is calculated as the remaining portion of the annual aggregated Fraser River sockeye and pink salmon abundance available after the spawning escapement target, the Management Adjustment (sockeye only), the agreed Fraser River Aboriginal Fisheries Exemption (AFE, sockeye only) and the expected catch in Panel-authorized test fisheries are deducted. If there is a remaining portion of sockeye or pink salmon run size available for harvest in Fraser Panel Area waters, the United States (U.S.) share shall not exceed 16.5 percent of the TAC for sockeye salmon and not exceed 25.7 percent of the TAC for pink salmon. This calculation is subject to adjustments for harvest overages or underages from previous years based on post-season catch estimates (see Chapter 4 Para 8(a to d) for details). The remaining TAC in addition to AFE catches are assigned to Canada. This report also describes the TAC-related decisions involving sockeye directed fisheries.

## Introduction

While the Fraser River Panel's primary objective is to reach Spawning Escapement Targets (SET) for individual sockeye and pink salmon management units (MUs), its second objective is to achieve international allocation of the Total Allowable Catch (TAC) for both species (PST, Chapter 4). The Treaty states that the U.S. share of the annual Fraser River sockeye and pink salmon Total Allowable Catch (TAC) will not exceed 16.5 and 25.7 percent of the sockeye and pink salmon TAC, respectively. The remaining available catch is deemed Canada's share. The following document describes in detail the TAC calculation as well as further adjustments and other considerations.

## TAC CALCULATIONS

The four main deductions for calculating the TAC include the Spawning Escapement Target (Chapter A4), the Management Adjustments (sockeye only) (Chapter B22), the Aboriginal Fisheries Exemption (sockeye only) and the Panel approved test fishing catch (Chapter A5) (Table 1). Annually, Fisheries and Oceans Canada (DFO) provides escapement targets and a sockeye spawning escapement plan for each management group (MU) as per Chapter 4, paragraph 3 of the PST. For each MU, the TAM (Total Allowable Mortality) rules that account for both fishing and natural mortality due to adverse environmental conditions are incorporated to ensure sufficient fish reach the spawning grounds. Although the TAM rule defines the target levels, these levels can be further increased if the Panel decides there are other competing factors that would preclude the SETs from being reached. These factors are natural, environmental or stock assessment factors and for the purposes of the TAC calculation are referred to as Management Adjustments (MAs, MacDonald et al. 2010). MAs are additional fish added to the SET for the purpose of increasing the likelihood of achieving the SET. When the SET is increased by the MA, the resulting target is referred to as the adjusted SET (Table 1). In case the sum of the SET and MA exceeds the forecasted or in-season estimated run size, the adjusted SET is capped to match that run size estimate (e.g. in the case of Early Stuart in 2018). For pink salmon the escapement plan provided by DFO does not change based on in-season migration conditions.

Table 1. An example of a detailed calculation of total allowable catch (TAC) and achievement of international catch shares for Fraser sockeye salmon by management group in 2018.

|  | Fraser Sockeye |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: |
|  | Early <br> Stuart | Early Summer | Summer | Late | Total |
| RUN STATUS, ESCAPEMENT NEEDS \& AVAILABLE SURPLUS |  |  |  |  |  |
| In-season Abundance Estimate | 125,000 | 1,800,000 | 4,100,000 | 4,700,000 | 10,725,000 |
| Adjusted Spawning Escapement Target * | 125,000 | 885,600 | 1,804,000 | 1,955,200 | 4,769,800 |
| Spawning Escapement Target (SET) | 108,000 | 720,000 | 1,640,000 | 1,880,000 | 4,348,000 |
| \%SET from TAM rules | 86\% | 40\% | 40\% | 40\% |  |
| Management Adjustment (MA) | 74,500 | 165,600 | 164,000 | 75,200 | 479,300 |
| Proportional MA (pMA) | 0.23 | 0.23 | 0.10 | 0.04 |  |
| Test Fishing Catch (TF, post-seas. est.) | 1,100 | 24,200 | 51,600 | 36,200 | 113,000 |
| Surplus above Adjusted SET \& TF * | 0 | 890,200 | 2,244,400 | 2,708,600 | 5,843,300 |
| DEDUCTIONS \& TAC FOR INTERNATIONAL SHARING |  |  |  |  |  |
| Aboriginal Fishery Exemption (AFE) | 6,900 | 75,100 | 153,400 | 164,600 | 400,000 |
| Total Deductions (Adj.SET + TF + AFE) | 132,900 | 984,800 | 2,009,000 | 2,156,000 | 5,282,800 |
| Available TAC (Abundance - Deductions) | 0 | 815,200 | 2,091,000 | 2,544,000 | 5,450,100 |
| UNITED STATES (Washington) TAC |  |  |  |  |  |
| Propor. distrib. TAC - Payback | 0 | 134,100 | 344,100 | 418,600 | 896,900 |
| Proportionally distributed TAC ** | 0 | 134,500 | 345,000 | 419,800 | 899,300 16.5\% |
| U.S. Payback | 0 | -400 | -900 | -1,100 | -2,400 |
| Washington Catch | 600 | 191,500 | 490,600 | 310,800 | 993,500 |
| Deviation from TAC - Payback | -600 | -57,400 | -146,500 | 107,800 | -96,700 |
| CANADIAN TAC |  |  |  |  |  |
| Propor. distrib. TAC + Payback + AFE | 6,900 | 756,100 | 1,900,300 | 2,290,000 | 4,953,300 |
| Propor. distrib. TAC + U.S. Payback | 0 | 681,000 | 1,746,900 | 2,125,400 | 4,553,300 83.5\% |
| AFE | 6,900 | 75,100 | 153,400 | 164,600 | 400,000 |
| Canadian Catch excluding ESSR Catch | 6,900 | 578,300 | 1,807,800 | 2,338,400 | 4,731,500 |
| Deviation from TAC + Payback + AFE | -100 | 177,700 | 92,500 | -48,400 | 221,800 |
| TOTAL |  |  |  |  |  |
| Available TAC + U.S. Payback + AFE | 6,900 | 890,600 | 2,245,400 | 2,709,700 | 5,852,500 |
| Total Catch excluding ESSR Catch | 7,500 | 769,900 | 2,298,400 | 2,649,200 | 5,725,000 |
| Deviation from TAC + U.S. Payback + AFE | -600 | 120,700 | -53,100 | 60,600 | 127,500 |

* The surplus cannot exceed the estimated abundance.
** Washington sockeye and pink shares according to Annex IV, Chapter 4 of the Pacific Salmon Treaty.

In addition to the adjusted SET, the Treaty also defines an Aboriginal Fisheries Exemption (AFE) of up to 400,000 sockeye, set aside for Canadian in-river and marine area Aboriginal fisheries (i.e. for First Nations opportunities to harvest salmon for Food, Social and Ceremonial (FSC) purposes). The AFE is also deducted from the total run size prior to determining the TAC for international sharing. As the TAC is
calculated by stock management group (Early Stuart, Early Summer, Summer and Late run), the AFE needs to be allocated across these four groups. For Early Stuart the exemption is up to $20 \%$ of the AFE, and the AFE for the remaining management groups is based on the average proportional distribution of First Nations harvests for the most recent three cycles, modified annually as required. If pre-season or in-season there is insufficient harvestable surplus in any management group to allow achieving the AFE allocation for that management group, then the AFE distribution is adjusted so that AFE for that management group is the greater of the catch, the projected catch by Aboriginal fisheries or the available harvestable surplus. Lastly, any test fishing catch from Panel approved test fisheries is also removed from the total run size when calculating the available TAC for international sharing. There are no MAs or AFEs for pink salmon.

Once the TAC is defined for each of the four MUs, the U.S. share is based on the aggregate TAC, i.e., across the four MUs. To the extent practicable, the Panel shall develop and implement a fishing plan that provides the U.S. fishery with the opportunity to harvest its 16.5 percent aggregate share of the TAC of Fraser River sockeye and its 25.7 percent share of the Fraser River pink salmon TAC. To accomplish this, the Panel shall take into consideration the availability of both the sockeye salmon TAC and pink salmon TAC, through the entire fishing season, while to the extent practical, minimizing the impacts on overlapping of sockeye management groups with little or no TAC. To do this the Panel strives to develop and implement fishing plans that concentrate U.S. fisheries on the most abundant MU(s), i.e., the ones that provide the largest percentage of the available TAC. To the extent practicable the harvest should be distributed evenly across the available TAC for each MU however, given that the proportion of migration of different MUs through U.S. waters on any given year may be variable, this may result in more than 16.5 percent of the TAC for one or more of the less abundant MUs (see Chapter 4 Para 3e for details). In addition, some of the less abundant management groups may even have no TAC. To allow access to the TAC of the more abundant management group, some incidental harvest may occur on the overlapping MUs that may have little or no TAC. Bycatch on a MU with little or no TAC is defined by the low abundance exploitation rate (LAER) which limits the exploitation rate of that group to a small amount (\%) as defined by Canada's preseason spawning escapement plan. Managing to a LAER situation typically occurs for one of the following reasons: when the run size is below the lower fisheries reference point (Pestal et al. 2008), when the adjusted SET (SET + MA) is greater than the run size or when the adjusted SET is less than the run size, but the resulting TAC is small enough for the exploitation rate to be less than the LAER. For example, in 2018 there was no international TAC for Early Stuart sockeye, but fisheries on Early Summer run resulted in a small catch of Early Stuart fish in U.S. fisheries (Table 1). This by-catch was still below the defined LAER of $10 \%$ for the Early Stuart management group in 2018.

## ADJUSTMENTS TO TAC CALCULATIONS

Adjustments are made to the U.S. share of the TAC in the case of previous-year(s) harvest overages (more fish caught than allocated share) or underages (less fish caught than allocated share from the previous year(s) (see Chapter 4 Para 8(a to b) for details). Currently, there are no adjustments for overages that are a result of TAC reductions after the scheduling of the last Panel approved U.S. fishery of the season or for any harvest of Fraser River sockeye that occurs in Alaska (see Chapter 4 Para 8(c to d) for details). Adjustments for underages are made if Canada directly impedes the US from obtaining its share of the TAC, but not because the U.S. failed to deploy sufficient effort or fish were not accessible to U.S. fisheries due to northern migration patterns or harvesting constraints. Adjustments, for previous year overages or underages, are limited so that the resulting TAC is not reduced by more than 5\% or increased by more than $15 \%$ unless the Panel deems otherwise. If in a given year there is an overage or underage, from a previous season, to be carried forward but no available TAC, by Panel agreement, the overage or underage is carried forward to the subsequent year(s). Any residual overage or underage on
the last year of the Chapter (i.e., 2028) will be carried forward to the next Chapter Period. Reasons for adjustments include the following: (1) management imprecision in U.S. fisheries (2) Canada impeding the U.S. from pursuing its in-season share.

## OTHER TAC CONSIDERATIONS

Currently, the Panel considers four different sockeye management groups (Early Stuart, Early Summer, Summer and Late run) to derive SETs and the aggregated TAC. The Panel can however assign additional management groups by mutual decision (Chapter 4 para $2 f$ of PST). For example, prior to 2010, the Birkenhead group formed a fifth management group. Should additional management groups be assigned, then the TAC calculation applies in a similar fashion as for the four management groups.

As agreed to by the Parties in Chapter 4 of the Treaty, Alaska District 104 catches are excluded from the TAC calculation. Fraser River sockeye incidentally caught in District 104 fisheries directed at pink salmon comprise a small portion of the catch in that fishery and are not considered to be the target species/stock. As a result, this catch is not included in the TAC calculation but is included in the postseason estimate of total run size.

ESSR catch (escapement surplus to spawning requirement) is also excluded from the TAC table. This is catch from a Canadian fishery that occurs in terminal areas (e.g., Weaver Creek sockeye). As these fish are 'in excess' of the spawning requirement (Garner and Parfitt 2006), they are not included in the exploitation rate as this would unnecessarily inflate the exploitation rate and indicate an inaccurate portrayal of in-season management of harvest. As a result, this catch is not included in the Canadian catch in the TAC table (DFO 1999).

In addition to the Alaska and ESSR catch not included in the TAC calculation, Fisheries Induced Mortalities (FIMs) are also not included (Michielsens et al. 2019). FIMs are a component of the catch that is released (non-retention), and some of these released fish are expected to die due to the stress of capture and handling. Although the mortality associated with this catch is not included in the TAC calculation it is included for the calculation of the exploitation rate which may limit access to TAC.

## FISHERIES EVALUATIONS IN RELATION TO SOCKEYE TAC

Available TAC is an important pre-requisite for in-season fisheries. Once the panel adopts in-season run size and MA estimates for the different management groups, the TAC table (Figure 1) is adjusted to take into account the newly adjusted SETs. In addition, updated catch numbers in the TAC table will include both catches of fisheries that have concluded as well as preliminary catch estimates for ongoing fisheries. The remaining available TAC for sockeye will determine if additional sockeye directed fisheries will be allowed to take place. When there is TAC available for all fisheries management groups impacted by the proposed fishery, TAC is the main consideration. In case there is no TAC for one of the overlapping management groups, this group will be managed under a LAER, and for a U.S. fishery under this scenario to be approved, the resulting catches of the U.S fisheries proposal should be deemed small but acceptable by the parties.

## References

DFO 1999. An allocation policy for Pacific Salmon. A new direction: The fourth in a series of papers from Fisheries and Oceans Canada. 40p.

DFO 2018. Integrated Fisheries Management Plan. Salmon, Southern BC: June 1, 2018 - May 31, 2019.

DFO 2021. Integrated Fisheries Management Plan. Salmon, Southern BC: June 1, 2018 - May 31, 2022.

Garner, K., and Parfitt, B. 2006. First Nations, Salmon Fisheries and the Rising Importance of Conservation. Vancouver, BC: Prepared for the Pacific Fisheries Resource Conservation Council.

MacDonald, J.S., Patterson, D.A., Hague, M.J. and Guthrie, I.C. (2010). Modeling the Influence of Environmental Factors on Spawning Migration Mortality for sockeye salmon fisheries management in the Fraser River, British Columbia. Transactions of the American Fisheries Society. 139:768-782

Michielsens, C.G.J., Taylor, E. and Hague, M.J. 2019. Fishing-induced mortality of sockeye in pink directed fisheries. Presentation to the Fraser River Panel, Richmond, April 2019.

Pestal, G., Ryall, P., and Cass, A. 2008. Collaborative Development of Escapement Strategies for Fraser River Sockeye: Summary Report 2003-2008. Can. Man. Rep. Fish. Aquat. Sci. 2855: viii + 84 p.

PST. 2020. Treaty between the government of Canada and the government of the United States of America concerning Pacific salmon as modified through January 2020.

## Glossary of Terms

Aboriginal Fishery Exemption (AFE): A number of sockeye that for the purposes of management and calculating the Total Allowable Catch (TAC) are reserved for First Nations fisheries.

Abundance: The number of fish or the size of a stock.
Acoustically measured fish length: Fork length measurements from the fish's nose to the fork of its tail using ARIS fish images.

Acoustic blind zone: Area from which the return echoes are excluded from the recording by an echo sounder system.

Acoustic ensonified zone: Areas from which the return echoes are recorded by an echo sounder system.
Acoustic ping: Transmission of a single or a group of acoustic pulse(s).
Adipose-clipped (ADC): A salmon that is missing an adipose fin without notable scarring. Hatcheries mark released smolts by removing their adipose fin.

Adipose-damaged (ADD): A salmon that is missing its adipose fin with notable scarring and may or may not be a hatchery clipped fish.
Adipose fin: A small fleshy fin without rays found on the back behind the dorsal fin of some teleost fishes such as salmon.

All Citizen fishery: Refers to a type of fishery in the U.S., as opposed to U.S. Tribal fisheries.
Allele: Alternative forms of a gene inherited from each parent.
Anal fin: The median, unpaired, ventrally located fin that lies behind the anus.
Annulus: Zones of thin circuli indicating a sudden decrease in growth rates, interpreted as a period of winter growth.
Area $\mathbf{2 0}$ date: An index of marine migration timing, assuming the entire run migrated through Canadian fishery management Area 20 in Juan de Fuca Strait.

ARIS: Adaptive Resolution Imaging Sonar hydroacoustic equipment used to count passing fish.
Bayesian: Statistical method based on Bayes' theorem which specifies how prior probability distributions and data interact in the generation of estimates.

Brood year (BY): The year in which an individual fish was spawned.
C\&S: Ceremonial and Subsistence. This is a type of fishing conducted by Tribes in the U.S.
Catch per unit of effort (CPUE): A relative measure of the abundance of the target species.
Caudal fin: Often called the tail fin. It provides the main power for forward movement of the fish.
Circuli: Circular bony ridges, concentric around the focus; the rings that are laid down on scales during the growth of the fish.

Coefficient of variation (CV): Statistical measure of the dispersion of data points around the mean.
Conservation Unit (CU): Group of wild salmon sufficiently isolated from other groups that is very unlikely to recolonize naturally within an acceptable time frame if extirpated.

Cycle line: A series of years associated with a cohort of Fraser sockeye assuming spawners are 4 years old. A cycle line of a particular year includes every 4th year. For example, the 2020 cycle line includes 2008, 2012, 2016 and 2020.

Cyclic dominance: Pattern of persistent large abundance every four years, followed by a slightly smaller subdominant year, with extremely low abundances in two off-cycle years.

Delay: Number of days sockeye will delay in the Strait of Georgia during their migration to the Fraser River. Stocks typically delaying their upstream migration include Harrison and Late run sockeye excluding Birkenhead/Big Silver.

Demonstration fishery: A Canadian commercial fishery designed to test particular gear configurations or explore the feasibility of harvests either in non-traditional areas or by non-traditional gear. A limited number of licenses are typically issued to permit these fisheries.

Density dependence: Stock-recruit dynamics whereby a large number of spawners are thought to have a negative effect on productivity such that subsequent recruit numbers are reduced.

Difference between estimates (DBEs): Difference between spawning escapement (SE) and potential spawning escapement (PSE) (DBE=SE-PSE).
Discharge: Volumetric flow rate of water.
Discriminant function analysis: A statistical procedure that classifies unknown individuals into a certain group and indicates the probability of the classification.

Diversion rate (Northern diversion rate): Proportion of the salmon run that migrates through Johnstone Strait (northern approach) as opposed to Juan de Fuca Strait (southern approach).

Dorsal Fin: A median fin along the back of the fish which is supported by rays.
Dorsal hump: Distinct hump often developed by male salmon prior to spawning.
Early Stuart run: Earliest of the four Fraser River sockeye management groups. This group spawns in the Takla-Trembleur Lake system.

Early Summer run: Sockeye management group that returns to the Fraser River after the Early Stuart run timing group and prior to the Summer run.

Economic Opportunity (EO) fishery: Commercial Fraser River First Nations fishery in the Lower Fraser River.

Echosounder: The topside, land-based component of the hydroacoustics system that provides power, data transfer, and signal processing to the submerged transducer.

Effective Female Spawners (EFS): The total number of female spawners multiplied by a measure of spawning success that relates to the fraction of females subsampled in a population that either died with all of their eggs ( $0 \%$ spawning), none of their eggs ( $100 \%$ spawning success) or with an intermediate fraction of their eggs ( $50 \%$ spawning success).

El Niño Southern Oscillation: Inter-annual climate variability event in the Pacific Ocean that occurs every two to seven years and persists for less than 2 years, characterized by coupled variations in sea surface temperature and sea level pressure.

En route loss (en route mortality): Estimate of the number of salmon migrating up the river that die en route to the spawning grounds.

Escapement (SE): Spawning escapement of adult male and female spawners and jack spawners (precocious age 3 males) as estimated through assessment programs conducted on the spawning grounds or projected from other data when such programs are not conducted.

Excess Salmon to Spawning Requirements (ESSR): Term associated with fish that are surplus to those needed to completely seed an artificial spawning channel and available to be harvested in terminal areas. In the Fraser River, ESSR harvest is most frequently associated with sockeye and the spawning channel at Weaver Creek.

Expansion line (EL): Inverse of the catchability coefficient, which indicates the extent to which a stock is susceptible to fishing.

Exploitation rate (ER): The proportion of a fish stock or population removed by fishing.
Fish density: Number of fish per unit volume (fish $\mathrm{m}^{-3}$ ).
Fishery-induced Mortality (FIM): Mortality associated with the release of caught fish due to stress of capture or handling. Fishery-induced mortality is also referred to as release mortality.

Fishery Planning Model: A pre-season simulation model that allows the Fraser River Panel to evaluate the impacts of various fishery options on the achievement of management objectives, given pre-season expectations such as abundance, stock composition, migration timing, diversion rate, spawning escapement targets, management adjustments and catch objectives.

Fish flux: Number of fish passing through a unit area per unit time (fish $\mathrm{sec}^{-1} \mathrm{~m}^{-2}$ ).
Focus: The circular area on the scale that is formed when the yolk sac of the salmon fry has been absorbed and scales start being formed and grow.

Fork length: Length from the fish's nose to the fork of its tail.
Food, Social and Ceremonial (FSC) fishery: Non-commercial First Nations fishery.
Fraser River Panel (FRP): Responsible for the in-season regulation of fisheries in Southern BC and Northern Puget Sound targeting Fraser River sockeye and pink salmon.

Fraser River Sockeye Spawning Initiative (FRSSI): A multi-year collaborative planning process by DFO to develop a long-term escapement strategy using a simulation model that allows for the evaluation of the performance of different escapement strategies through the application of different harvest control rules. In addition, it explores the robustness of these strategies to different key sources of uncertainty such as possible alternative population dynamics and future patterns of productivity.

Fraser River Technical Committee (FRTC): Technical Committee that supports the work of the PSC Fraser River Panel.

Freshwater zone: The area on the salmon scale that represents the time the fish spent in freshwater.
Fry: Juvenile freshwater life history stage when salmon have emerged from the gravel, completed yolk absorption, and are less than a few months old.

Gear: Equipment used to fish.
Genetic differentiation: A measure of how different two populations are genetically based on what alleles they share.

Genetic profile (or multilocus genotype): A composite of genotypes from different locations of the genome. Current Fraser sockeye salmon genetic profile contains 19 locations of the genome.

Genotype: Genetic make-up at a particular location of the genome that is composed of alleles inherited from the two parents.

Gilbert-Rich age notation: Method to describe the age of a salmon, $N_{a}$, where $N$ is the total age of the fish and $a$ is the fresh-water age, also known as the age of ocean entrance.

Gillnet (GN): A fishing net which is hung vertically such that fish attempting to swim through the net are entangled by their gills.

Harvest Control Rule (HCR): Operational component of a harvest strategy that conveys the pre-agreed rules that determine how much fishing can take place.

Hydroacoustics: Technology involving sonars to detect fish in the water.
Hypural plate: A wide, fan-like plate onto which the caudal fin rays are attached.
Individual transferable quota (ITQ): Fisheries management tool to allocate proportions of the total available catch to individual fishers or companies who have long-term right to the quota and can trade it with others.

In-season assessments: Assessments to inform fisheries management in real time throughout the fishing season.

Integrated Fisheries Management Plan (IFMP): DFO document to communicate on the planning of fisheries and their management to DFO staff, co-management boards and other stakeholders.

International Pacific Salmon Fisheries Commission (IPSFC): International Commission formed in 1937 between governments of Canada and the United States for the protection, preservation and extension of the sockeye and pink salmon fishery of the Fraser River. The IPSFC was dissolved in 1985 following the signing of the Pacific Salmon Treaty.
Jack: A male salmon that spawns after spending a year or two less in the sea than most individuals of its species. Jack sockeye are distinguished by having a fork length of 45 cm or less.

Kalman filter model: Model describing the population dynamics between the number of spawners and recruits, taking into account non-stationary, most common in terms of productivity.

La Niña: Inter-annual climate variability event characterized by anomalous cool sea surface temperature and low sea level pressure.

Larkin model: Model describing the population dynamics between the number of spawners and recruits, taking into account delayed density-dependent interactions across successive brood years, resulting from food depletion or buildup of pathogens or predators in response to large abundances of spawners.

Lateral Line: A sensory organ of fishes which consists of a canal running along the side of the body and allows perception of low frequency vibrations and pressure differences.

Late run: One of the four sockeye management groups, returning last to the Fraser River.
Local adaptation: A population that has evolved characteristics to survive and reproduce in specific local environmental conditions.

Locus (plural Loci): A location in the genome.
Low Abundance Exploitation Rate (LAER): The purpose of managing a sockeye management group in a LAER situation is to permit by-catch of that stock group in fisheries directed at other management
groups or species with available surpluses. The application of a LAER for a management group has the effect of limiting the exploitation rate (ER) of that group to a small amount, e.g., $10 \%$ or $20 \%$.

Management Adjustment (MA): Additional fish added to an escapement target to account for en route losses due to adverse environmental conditions for the purpose of increasing the likelihood of achieving that target.

Management Unit (MU) or group: Aggregates of sockeye salmon stocks that are used by the Fraser River Panel for the management of Fraser River sockeye: Early Stuart, Early Summer, Summer, and Late run sockeye.

Management Strategy Evaluation (MSE): A simulation model to test different potential harvest control rules to achieve the management objectives.

Marine growth: Growth of the fish during their time in saltwater.
Marine growth circuli: Rings or circuli formed on the scale during the time the fish was in saltwater.
Markov chain Monte Carlo (MCMC): Algorithm used in Bayesian analyses to approximate the posterior probability distribution by random sampling.

Maximum likelihood estimation (MLE): Statistical method to estimate model parameters, given the observed data.

Maximum sustainable yield (MSY): The largest average catch that can be removed from a stock over an indefinite period under existing environmental conditions.

Median: $50^{\text {th }}$ percentile of the distribution
Microsatellite: A genetic marker characterized by repeating sequences of DNA where number of repeats are used to characterize alleles.

Migration date or $\mathbf{5 0 \%}$ date: Dates when half (50\%) of the total run would have passed a location.
Miscellaneous stock: A stock forecasted by DFO without a spawner-recruit relationship, given a lack of recruit data of sufficient length.

Multivariate method: A statistical method that uses more than one independent variable in the analysis.

Natal fidelity: Tendency of organisms to return to their birthplace to reproduce.
Nearest-neighbor method: A spatial statistical approach to predict missing values based on observations in neighboring areas.

NEPSTAR: Northeast Pacific Salmon Tracking and Research ocean model which provides near real-time estimates of current velocity in the North Pacific.

Non-directed/targeted: Fish caught incidentally by fisheries targeting other species.
Non-retention: In fisheries where one species is targeted but by-catch of a second species is expected, regulations may specify that the fish of the second species be released, not retained. Non-target species that are released are assigned gear-specific fishing induced mortality rates (see FIMs), that are accounted for along with landed catches in estimates of total exploitation rates.

Northern Diversion rate: Proportion of the salmon run that migrates through Johnstone Strait (northern approach) as opposed to Juan de Fuca Strait (southern approach).

Otolith: Bony structure found in the inner ear of salmon, used to age fish.

Pacific Decadal Oscillation (PDO): Atmospheric and oceanic index used to describe the inter-decadal variability in the climate of the North Pacific Ocean.

Pacific Salmon Commission: Regional Fisheries Management Organization (RFMO) overseeing the Pacific Salmon Treaty (PST) between Canada and the United States.

Pacific Salmon Treaty: Bilateral agreement between Canada and the United States addressing the conservation and allocation of Pacific salmon.

Panel Area Waters: Geographical area defined under the Pacific Salmon Treaty in which Fraser River sockeye and pink salmon management is subject to provisions of the Treaty.

Plus growth: Area on the scale where lake (lacustrine) growth ends and sea growth begins, composed of circuli which are intermediate in width. An area of freshwater circuli that indicates growth after the last freshwater annulus has been formed. Highly variable between stocks

Polymerase chain reaction (PCR): a molecular biology method to create many copies of targeted parts of the genome to allow further genetic analyses

Potential Spawning Escapement (PSE): Mission escapement estimate minus in-river catch upstream of Mission.

Pre-spawn mortality: Females that reach the spawning grounds but die without releasing their eggs.
Principal component analysis: A statistical method to summarize a set of variables that are correlated (e.g., scale data) by creating synthetic variables called principal components that are linear combinations of the original variables. Principal components are not correlated with each other and satisfy the independence assumption in many statistical methods.

Principal component scores: Transformed variable values after principal component analysis.
Prior (prior probability distribution): A probability distribution that express the information about a parameter before any observed data. Priors may be based on historical observations, theoretical expectations, etc.

Productivity: The ability of a salmon population to sustain itself, often defined as the number of adult fish produced per spawner.

Purse Seine (PS): A net that can be drawn into the shape of a bag using the line along the bottom of the net like the drawstring of a purse.

Reconstruction: Forward reconstructions predict daily escapement into the river based on marine daily abundance estimates while backward reconstructions add marine and lower river daily catches to daily escapement estimates to reconstruct daily abundances in marine areas.

Recreational fishing (sport fishing): Non-commercial fishing as a leisure activity or to provide food for personal consumption.

Recruit: A salmon that survives to maturity is considered a "recruit" from its parent generation, or brood year.

Recruits per spawner (R/S, RS): A measure of productivity of a population or stock. The number of salmon surviving to maturity per each adult salmon that successfully spawned in the freshwater spawning grounds.

Reef net (RN): A net suspended between two boats. The net is anchored for stability.

Resorption: The physical wearing down of the scales from the environmental stress of moving from marine waters to freshwater waters. It makes the scale difficult to age as the perimeter of the scale is worn away.

Return year: The year in which an individual salmon returns to freshwater with intent to spawn.
Ricker model: Model describing the density-dependent population dynamics between the number of spawners and recruits.

Run size: The total number of returning adult salmon prior to being impacted by fisheries en-route to the spawning grounds.

Run timing group: One of four Fraser River sockeye management group characterized by different timing of their migration to the Fraser River: Early Stuart, Early Summer, Summer and Late run.

Scale: Thin plate of keratinized protein that grows continuously on the skin of a fish
Scale pattern analysis: Using the circuli to determine patterns in scale growth used for aging and determining origin of salmon

Set net: Gillnet anchored in position rather than drifted.
Single nuclear polymorphism (SNP): a genetic marker with alleles that differ at a single nucleotide base
Smolt: Life history stage where the young salmon are typically rearing in lakes or rivers (1-2 years). Time when the freshwater zone circuli are laid down. In late winter, the fish begin the change which will adapt them to marine life (smolting or smoltifying). Spring sees the smolts move towards marine waters.

Spawner: Adult salmon that successfully migrate from marine environments to freshwater spawning grounds and have the opportunity to reproduce, after avoiding natural mortality and harvest.

Spawning Escapement (SE): Spawning escapement of adult male and female spawners and jack spawners (precocious age 3 males) as estimated through assessment programs conducted on the spawning grounds or projected from other data when such programs are not conducted.

Spawning Escapement Plan: The sockeye escapement plan specifies escapement requirements that vary with run size for each management group and includes an abundance below which there are very limited directed harvests allowed and a total mortality cap.

Spawning escapement target (SET): Target for total adult spawning escapement for each spawning population as defined each year by Canada's Spawning Escapement Plan.

Split-beam: Quarterly separation of received echoes by 4 quadrants of the transducer plate.
Spread: Number of days encompassing $95 \%$ of a stock's migration.
Spring growth: Area on the scale where lake (lacustrine) growth ends and sea growth begins, composed of circuli which are intermediate in width. An area of freshwater circuli that indicates growth after the last freshwater annulus has been formed. Highly variable between stocks.

Stock: A genetically distinct population of salmon, spawning at similar times and location.
Stock assessment: Use of statistical and mathematical calculations to estimate fish abundance as well as the impact of fisheries management decisions on fish abundance.

Summer run: One of the four sockeye management groups returning to the Fraser River after the Early Summer run and prior to the Late run.

Target strength (TS): A decibel measure of the backscattering cross section of a target (relative to $1 \mathrm{~m}^{2}$ ) that can be used to measure the acoustic size of a target.

Time-density model: In-season run size assessment model that estimates allows to estimate run size and migration timing based on the proportion of the migration on a given date.

Transducer: A piezoelectric device usually built from certain types of ceramics that transforms electrical energy to mechanical energy and vice versa. In other words, an acoustic transducer converts electric signal into an acoustic signal via vibrations of a ceramic element, and then receives the incoming sound wave and converts it back into an electric signal.

Transect sampling: Sampling from a mobile platform along pre-set routes.
Troll (TR): Fishing by trailing a baited line along behind a boat.
Total Allowable Catch (TAC): The abundance of sockeye available to be caught after spawning and other requirements have been subtracted from the run size.

Total Allowable Mortality (TAM): For each Fraser sockeye management group at different run sizes, Canada's Spawning Escapement Plan specifies the Total Allowable Mortality from all sources, including catches through fishery removals and en route mortality, represented by the Management Adjustment.

Total Allowable Mortality (TAM) cap: Maximum amount of Total Allowable Mortality.
Univariate method: A statistical method that use only a single independent variable in the analysis.
Whatman Sheet: Filter paper used from drying and preserving DNA samples.

## Acronyms and Abbreviations

| AC | All Citizens |
| :---: | :---: |
| ADFG | Alaska Department of Fish and Game |
| AFE | Aboriginal Fishery Exemption |
| ARIS | Adaptive Resolution Imaging Sonar |
| BEST | Bivariate ENSO Timeseries |
| BY | Brood year |
| Cl | Confidence Interval |
| COSEWIC | Committee on the Status of Endangered Wildlife in Canada |
| CPUE | Catch per unit effort |
| CU | Conservation Unit |
| CV | Coefficient of variation |
| cyc | Cycle line |
| DBE | Difference between estimates |
| DFA | Discriminant Function Analysis |
| DFO | Fisheries and Oceans Canada |
| DIDSON | Dual-frequency Identification SONar |
| EFS | Effective Female Spawners |
| Ei | Entrance Island |
| EL | Expansion Line |
| EO | Economic Opportunity |
| ER | Exploitation rate |
| ESSR | Excess salmon to spawning requirements |
| EWatch | DFO Environmental Watch |
| F | Fishing mortality |
| FIM | Fishing-induced mortality |
| FN | First Nations |
| FPM | Fishery Planning Model |
| FRP | Fraser River Panel |
| FRSSI | Fraser River Sockeye Spawning Initiative |
| FRTC | Fraser River Technical Committee |
| FSC | Food, Social and Ceremonial |
| GAM | General Additive Model |


| GAMM | Generalized Additive Mixed-effects Model |
| :---: | :---: |
| GLM | Generalised linear model |
| GN | Gill net |
| GSI | Genetic Stock Identification |
| GUI | Graphic user interface |
| HCR | Harvest control rule |
| HR | Harvest rate |
| HSM | Hope Statistical Model |
| IFMP | Integrated Fisheries Management Plan |
| IPSFC | International Pacific Salmon Fisheries Commission |
| ITQ | Individual transferable quota |
| JD | Julian date |
| JS | Johnstone Strait |
| LAER | Low abundance exploitation rate |
| LDA | Linear discriminant analysis |
| LRP | Limit Reference Point |
| M | Natural mortality |
| MA | Management Adjustment |
| MAE | Mean Absolute Error |
| MCMC | Markov chain Monte Carlo |
| MEF | Mid-eye fork length |
| MRE | Mean Raw Error |
| MSE | Management Strategy Evaluation |
| MSY | Maximum Sustainable Yield |
| MU | Management Unit |
| NEPSTAR | North East Pacific Salmon Tracking and Research |
| ONI | Oceanic Niño Index |
| OSCAR | Ocean Surface Current Analysis Real-time |
| p50 | $50^{\text {th }}$ percentile (similar for $\mathrm{p} 10, \mathrm{p} 25, \mathrm{p} 75, \mathrm{p} 90$ ) |
| PBS | Pacific Biological Station |
| PCA | Principal components analysis |
| PCR | Polymerase chain reaction |
| pDBE | Proportional Difference between estimates |
| PDO | Pacific Decadal Oscillation |


| PED | Passage estimate difference |
| :---: | :---: |
| PI | Probability Interval |
| Pi | Pine Island |
| pMA | Proportional Management Adjustment |
| POF | Postorbital fork length |
| POH | Postorbital hypural length |
| POM | Princeton Ocean Model |
| PS | Purse seine |
| PSC | Pacific Salmon Commission. |
| PSE | Potential Spawning Escapement |
| PST | Pacific Salmon Treaty |
| R | Recruits |
| REF | Retrospective Evaluation Framework |
| RMSE | Root mean square error |
| RN | Reef net |
| RS | Recruits per spawner |
| RSA | Run size adjustment |
| SARA | Species at Risk Act |
| SCAM | Shape constrained additive models |
| SE | Spawning escapement |
| SET | Spawning escapement target |
| SID | Stock Identification |
| SNP | Single nucleotide polymorphism |
| SOG | Strait of Georgia |
| SOI | Southern Oscillation Index |
| SSS | Sea surface salinity |
| SST | Sea surface temperature |
| TAC | Total Allowable Catch |
| TAM | Total Allowable Mortality |
| TF | Test Fishery |
| Tr | Tribal |
| TR | Troll fishing |
| TS | Target Strength |
| WDFW | Washington Department of Fish and Wildlife |


[^0]:    ${ }^{1}$ Stocks are designated miscellaneous stocks by DFO until sufficient length of spawner-recruit time series are available.
    ${ }^{2}$ For Chilliwack, spawner-recruitment data are starting to be of sufficient length to consider stock-recruit models in addition to using R/EFS from a proxy stock.

[^1]:    Note: Model descriptions can be found in Table 2.
    *Stocks are designated miscellaneous stocks by DFO until sufficient length of spawner-recruit time series are available
    ${ }^{+}$Covariate Description

[^2]:    *Qualark test fishery only provides information for stocks that migrate past Qualark

