# State of the Salmon: Informing the survival of Fraser Sockeye returning in 2020 through life cycle observations

Bronwyn L. MacDonald, Sue C.H. Grant, Niki Wilson, David A. Patterson, Kendra A. Robinson, Jennifer L. Boldt, Jackie King, Erika Anderson, Scott Decker, Brian Leaf, Lucas Pon, Yi Xu, Brooke Davis, and Dan T. Selbie

Fisheries and Oceans Canada
Science Branch, Pacific Region
Pacific Biological Station
3190 Hammond Bay Road
Nanaimo, British Columbia
V9T 6N7

2020

**Canadian Technical Report of Fisheries and Aquatic Sciences 3398**

Fisheries and Oceans Canada / Pêches et Océans Canada

Canada

**Canadian Technical Report of Fisheries and Aquatic Sciences**

Technical reports contain scientific and technical information that contributes to existing knowledge but which is not normally appropriate for primary literature. Technical reports are directed primarily toward a worldwide audience and have an international distribution. No restriction is placed on subject matter and the series reflects the broad interests and policies of Fisheries and Oceans Canada, namely, fisheries and aquatic sciences.

Technical reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base *Aquatic Sciences and Fisheries Abstracts*.

Technical reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page.

Numbers 1-456 in this series were issued as Technical Reports of the Fisheries Research Board of Canada. Numbers 457-714 were issued as Department of the Environment, Fisheries and Marine Service, Research and Development Directorate Technical Reports. Numbers 715-924 were issued as Department of Fisheries and Environment, Fisheries and Marine Service Technical Reports. The current series name was changed with report number 925.

**Rapport technique canadien des sciences halieutiques et aquatiques**

Les rapports techniques contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui ne sont pas normalement appropriés pour la publication dans un journal scientifique. Les rapports techniques sont destinés essentiellement à un public international et ils sont distribués à cet échelon. II n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques de Pêches et Océans Canada, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports techniques peuvent être cités comme des publications à part entière. Le titre exact figure au-dessus du résumé de chaque rapport. Les rapports techniques sont résumés dans la base de données *Résumés des sciences aquatiques et halieutiques.*

Les rapports techniques sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre.

Les numéros 1 à 456 de cette série ont été publiés à titre de Rapports techniques de l'Office des recherches sur les pêcheries du Canada. Les numéros 457 à 714 sont parus à titre de Rapports techniques de la Direction générale de la recherche et du développement, Service des pêches et de la mer, ministère de l'Environnement. Les numéros 715 à 924 ont été publiés à titre de Rapports techniques du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 925.

Canadian Technical Report of Fisheries and Aquatic Sciences 3398

2020

# STATE OF THE SALMON:

## INFORMING THE SURVIVAL OF FRASER SOCKEYE RETURNING IN 2020 THROUGH LIFE CYCLE OBSERVATIONS

Bronwyn L. MacDonald[1], Sue C.H. Grant[1], Niki Wilson[2], David A. Patterson[3], Kendra A. Robinson[3], Jennifer L. Boldt[4], Jackie King[4], Erika Anderson[4], Scott Decker[5], Brian Leaf[5], Lucas Pon[6], Yi Xu[7], Brooke Davis[7], and Daniel T. Selbie[6]

Fisheries and Oceans Canada
Science Branch, Pacific Region
Pacific Biological Station
3190 Hammond Bay Road
Nanaimo, B.C.
V9T 6N7

[1] Fisheries and Oceans Canada, Science Branch, Pacific Region, 200-401 Burrard Street, 13th floor, Vancouver, BC, V6C 3S4

[2]nikilynnwilson@gmail.com

[3] Fisheries and Oceans Canada, Science Branch, Pacific Region, Simon Fraser University, 8888 University Drive, Burnaby, BC V5A 1S6

[4] Fisheries and Oceans Canada, Science Branch, Pacific Region, Pacific Biological Station, 3190 Hammond Bay Road, Nanaimo, B.C. V9T 6N7

[5] Fisheries and Oceans Canada, Science Branch, Pacific Region, Fraser-British Columbia Interior Area, 985 McGill Place, Kamloops, B.C. V2C 6X6

[6] Fisheries and Oceans Canada, Science Branch, Pacific Region, Cultus Lake Salmon Research Laboratory, 4222 Columbia Valley Highway, Cultus Lake, B.C. V2R 5B6

[7] Fisheries and Oceans Canada, Science Branch, Pacific Region, Fraser-British Columbia Interior Area Unit 3-100 Annacis Parkway, Delta, B.C. V3M 6A2

Cat. Fs97-6/3398E-PDF ISBN 978-0-660-35889-5 ISSN 1488-5379

Correct citation for this publication:

MacDonald, B.L., Grant, S.C.H., Wilson, N., Patterson, D.A., Robinson, K.A., Boldt, J.L., King, J. Anderson, E., Decker, S., Leaf, B., Pon, L., Xu, Y., Davis, B., & Selbie, D.T. 2020. State of the Salmon: Informing the survival of Fraser Sockeye returning in 2020 through life cycle observations. Can. Tech. Rep. Fish. Aquat. Sci. 3398: v + 76 p.

# TABLE OF CONTENTS

# ABSTRACT

MacDonald, B.L., Grant, S.C.H., Wilson, N., Patterson, D.A., Robinson, K.A., Boldt, J.L., King, J. Anderson, E., Decker, S., Leaf, B., Xu, Y., Davis, B., Pon, L., & Selbie, D.T. 2020. State of the Salmon: Informing the survival of Fraser Sockeye returning in 2020 through life cycle observations. Can. Tech. Rep. Fish. Aquat. Sci. 3398: v + 76 p.

Participants of the 2020 Fraser Sockeye Science Integration workshop concluded that four year old Fraser Sockeye returning in 2020 will continue to exhibit below average survival. Specifically, four year old returns are predicted to fall below the 50% probability level of the 2020 Fraser Sockeye quantitative forecast of 638,000 four year olds, excluding Harrison. While responses differ across populations, overall survival of Fraser Sockeye will likely be below average.

Workshop participants compiled and integrated environmental and biological observations spanning the life cycle of four year old Fraser Sockeye returning in 2020. This report presents these observations, and their predicted implications for survival. Conditions observed over most of the life cycle of the four year old 2020 returns were similar to those experienced by Fraser Sockeye returns since 2017. These cohorts all exhibited below average survival, including the lowest on record, observed in 2019. The 2020 prediction of below average survival is consistent with recent salmon and associated ecosystem observations, and poor returns.

The goals of the annual Fraser Sockeye Science Integration workshop are to provide advice on survival of Fraser Sockeye populations in the upcoming return year, and improve our understanding of factors influencing survival. This is particularly important as climate change and other factors have influenced decade long declines across most of these populations. Understanding how salmon respond to current and future changes is important to the development of habitat restoration, hatchery, and science programs that are aligned to future salmon survival.

# RÉSUMÉ

MacDonald, B.L., Grant, S.C.H., Wilson, N., Patterson, D.A., Robinson, K.A., Boldt, J.L., King, J. Anderson, E., Decker, S., Leaf, B., Xu, Y., Davis, B., Pon, L., & Selbie, D.T. 2020. State of the Salmon: Informing the survival of Fraser Sockeye returning in 2020 through life cycle observations. Can. Tech. Rep. Fish. Aquat. Sci. 3398: v + 76 p.

Les participants à l'atelier d'intégration scientifique sur le saumon rouge du Fraser de 2020 ont conclu que les saumons rouges du Fraser âgés de quatre ans remontant en 2020 continueront d'afficher un taux de survie inférieur à la moyenne. Plus précisément, nous prévoyons que les montaisons de saumons de quatre ans seront sous le niveau de probabilité de 50 % de la prévision quantitative totale de 2020 pour le saumon rouge du Fraser, à l'exclusion du stock de la rivière Harrison. Cela signifie que moins de 638 000 saumons rouges du Fraser âgés de quatre ans remonteront en 2020. Bien que les réactions varient d'une population à l'autre, la survie globale du saumon rouge du Fraser sera probablement inférieure à la moyenne.

Les participants à l'atelier ont compilé et intégré les observations environnementales et biologiques couvrant le cycle vital des saumons rouges du Fraser de quatre ans remontant en 2020. Le présent rapport présente ces observations et les répercussions prévues sur la survie. Les conditions observées pendant la majeure partie du cycle vital des saumons rouges du Fraser âgés de quatre ans remontant en 2020 sont similaires à celles connues par les saumons rouges du Fraser qui sont remontés depuis 2017. Ces cohortes précédentes affichaient toutes un taux de survie inférieur à la moyenne, y compris le taux le plus bas jamais enregistré, observé en 2019. La prévision d'une survie inférieure à la moyenne pour 2020 est cohérente avec les observations récentes sur le saumon et son écosystème, ainsi qu'avec les faibles remontées.

Les objectifs de l'atelier annuel d'intégration scientifique sur le saumon rouge du Fraser sont de fournir des avis sur la survie des populations de saumon rouge du Fraser au cours de la prochaine année de montaison et de mieux comprendre les facteurs qui influent sur la survie de cette espèce. Cet atelier est particulièrement important, car les changements climatiques et d'autres facteurs ont influencé le déclin de la plupart de ces populations depuis une décennie. Il est important de comprendre comment le saumon réagit aux changements actuels et futurs pour pouvoir élaborer des programmes scientifiques, de restauration de l'habitat et d'écloseries qui soient en phase avec la survie future du saumon.

# 1 INTRODUCTION

Fraser River Sockeye salmon migrate through diverse river, lake, and ocean habitats throughout their life cycle. Most Fraser Sockeye exhibit a lake-type life history, spending their first two years of life in freshwater and their last two years in the ocean. Fraser Sockeye begin life as eggs in river or lake gravel, and subsequently rear in lakes as fry. Upon reaching the ocean, they migrate through the Strait of Georgia (SoG) to reach the Northeast (NE) Pacific Ocean before returning to their natal spawning grounds as four year olds, where they reproduce and die. This round trip covers roughly 10,000 km. There are other variations of Fraser Sockeye life history that are not covered in this report, since they generally contribute small numbers to the total Fraser Sockeye production.

The complex life-history of Fraser Sockeye makes it challenging to accurately predict the abundance that will return in a given year. There is large variability in their annual returns, which have ranged from as low as 500,000, in 2019, to 30 million, in 2010. As a result, quantitative return forecasts are highly uncertain, characterized by wide probability distributions (DFO 2011, 2012, 2013, 2014a, 2015a, 2016a, 2017, 2018, 2019, Grant et al. 2010; Grant & MacDonald 2012; MacDonald & Grant 2012). Pre-season quantitative return forecasts are produced annually for 19 Fraser Sockeye stocks and eight additional miscellaneous stock groups using a suite of forecast models, and up to 67 years of spawner-recruit data, depending on the stock. Forecasts are presented as standardized cumulative probabilities (10%, 25%, 50%, 75%, and 90%) using Bayesian statistics for biological models, or residual error for non-biological models (Grant et al. 2010). Distributions of forecasted values reflect uncertainty in returns attributed to historical variations in stock survival (recruits-per-spawner) for a given brood year escapement (or juvenile abundance): lower forecast values represent the low end of historical survivals, and high values the upper end. Probability levels indicate the chance that returns will fall at or below the associated forecasted value.

Fisheries and Oceans Canada (DFO) monitors and investigates salmon and their ecosystems with the objective of improving our understanding of factors that govern variation in salmon survival and abundances. Biological and associated ecosystem observations spanning the life cycle of Fraser Sockeye have the potential to improve the precision of return forecasts for a given year. Apart from limited smolt and fry data, and select environmental covariates, life cycle observations are not currently incorporated quantitatively into Fraser Sockeye population dynamic models (DFO 2011, 2012, 2013, 2014a, 2015a, 2016a, 2017, 2018a, 2019a, MacDonald and Grant 2012). This is attributed to the number and complexity of factors that likely contribute to salmon survival, the inter-annual variation in their relative contributions, and the limited understanding of how these factors interact.

As an interim step, the annual Fraser Sockeye Science Integration Workshop, held since 2014 (DFO 2014b, 2015b, 2016b, MacDonald et al. 2018, MacDonald et al. 2019, MacDonald et al. (in prep)), brings together Fraser Sockeye experts within DFO Science and Fisheries Management to present and discuss observations from the various ecosystems that Fraser Sockeye pass through during their life cycle. Information presented by DFO scientists in this forum includes results from formal analyses, as well as raw data, preliminary results, opportunistic observations, and expert opinion.

The purpose of this workshop is to qualitatively predict survival of the upcoming four year old Fraser Sockeye return, using expert judgement to integrate observations. Results from this science integration process can help narrow the range of possible return abundances within the wide forecast distributions produced for Fraser Sockeye, by providing qualitative assessments of potential survival, ranging from 'poor' survival to 'good' survival. Consequently, as we continue to bring these observations together and learn from previous processes, we can begin to quantitatively assess the utility of this information for informing Fraser Sockeye population dynamics and future returns.

Expanding our understanding of factors that influence salmon population dynamics will support forecasting processes, as well as fisheries management, and habitat and hatchery enhancement activities. This understanding is particularly important as ecosystems are quickly altering in response to climate change. Therefore, improved information on the drivers of salmon population dynamics will help science, hatchery, habitat, and fisheries management systems better anticipate, and respond, to future changes.

This report compiles the results of the three-day 2020 Fraser Sockeye Science Integration Workshop, integrating life cycle observations for the four year old returns of Fraser Sockeye in 2020. The workshop was held in Vancouver, B.C., from January 21-23, 2020 and included 22 participants (Appendix 1). Day one was spent in a special session, looking at the observations highlighted in the 2019 Fraser Sockeye Science Integration Workshop (MacDonald et al. 2019), compared with preliminary 2019 return data. Results from this discussion are in Section 3.1. Days two and three were broken up into four sessions that cover key stages of the Fraser Sockeye life cycle, pertaining to the four year old returns in 2020:

- Brood year spawners and egg stage (Summer/Fall 2016 - Spring 2017)
- Juvenile freshwater rearing stage (Spring 2017 - Spring 2018)
- Juvenile downstream migration (Spring 2018)
- Juvenile and sub-adult marine rearing stage (Spring 2018 – present)[1]

During each session on days 2 and 3, DFO scientists presented their relevant observations, and participants discussed and integrated these observations in the context of Fraser Sockeye survival at the corresponding life stage. Participants also identified highlights from each life stage, and associated implications for survival of the 2020 return. This report presents the contributed observations and points of discussion resulting from the 2020 workshop, organized into life cycle segments, similar to the workshop.

**After the Introduction, this paper is divided into three sections, each presenting a different level of detail to communicate to a broad range of audiences. The intent is that readers will choose to read the section that presents the level of detail of interest to them.**

**Section 2 - Highlights**: Presents highlights identified by meeting participants, along with expert opinion on the potential effects of these observations on Fraser Sockeye survival for the corresponding life stage, their confidence in those effects, the predicted significance of those effects on overall survival, and where to look in the document for more information. This section is tailored to those looking for a quick list of the key observations and their presumed effects on Fraser Sockeye survival.

**Sections 3.2-3.6 - Overview**: Provides an overview that synthesizes the observations and discussions that occurred during the workshop, in the context of the Fraser Sockeye life cycle. This section is appropriate for those looking for a summary of the main

[1] Most marine observations and data available at the time of the 2020 workshop pertain to 2018

observations discussed, with high level background on some of the survival mechanisms and their potential effects by life stage.

**Section 4 - Detailed Observations**: Catalogues detailed contributions from individual scientists and/or work teams according to the salmon life-stage, and program where appropriate. This section presents the greatest depth of information, and associated figures. Note that not all programs present at the workshop contributed sections, hence their work will only be referenced in Section 3.

# 2 HIGHLIGHTS

We predict that four year old Fraser Sockeye returning in 2020 will exhibit lower than the median forecasted survival (recruits per effective female spawner). Four year old returns are expected to fall below the 50% probability level of the total four year old forecast, corresponding to returns below 638,000 (excluding Harrison). While responses are expected to differ across populations, the overall survival response will likely fall below the median forecast. This below average survival prediction is consistent with predictions provided through this process since 2017 (MacDonald et al. 2018, MacDonald et al. 2019).

Total Fraser Sockeye survival has generally been below average (return years: 1952-2019) since the mid-1990's (Figure 1 A). Returns were particularly low between 2015 and 2017, falling near, or below, the 10% forecast probability level. Returns in 2018 were not as poor as predicted during the 2018 science integration process (MacDonald et al. 2018), falling between the 25% and 50% probability levels of the forecast. However, the 2019 returns broke records as the worst Fraser Sockeye return ever observed, with only ~500,000 Sockeye returning; falling well below the 10% probability level of the forecast. This return was further challenged by the barrier to upstream migration created by the Big Bar landslide on the Fraser mainstem (DFO 2019). This barrier affected the spawning potential of all upstream migrating populations, including the numerically dominant Chilko population.

Total survival of the dominant brood years contributing to returns between 2015 and 2017 (2011-2013 brood years) fell near or below replacement, measured as 2.0 total recruits per effective female spawner (EFS), across stocks excluding Cultus and Harrison, in each of these years (2011 brood year: 1.7 recruits/EFS; 2012 brood year: 2.1 recruits/EFS; 2013 brood year: 1.1 recruits/EFS) (Figure 1). Survival of the 2014 brood year, contributing four year olds to the 2018 return, and five year olds to the 2019 return, was slightly improved based on preliminary data (~3.6 recruits/EFS), though still well below the 1948-2014 brood year geometric average (7.2 recruits/EFS). Subsequently, four year old survival of the 2019 return was the lowest on record (0.3 age-4 recruits/EFS), though this is affected by annual variations in the age-at-return. For each stock, preliminary survival (four year old recruits/EFS) associated with the 2019 return year was exceptionally low (Figure 2).

The recent period of consistently low Fraser Sockeye survival, punctuated by some of the lowest survivals ever observed, coincided with warmer than average atmospheric and ocean temperatures, and concurrent changes in freshwater and marine ecosystems (MacDonald et al. 2018, 2019, Boldt et al. 2019). Many such observations persisted during the lifespan of the four-year olds returning in 2020.

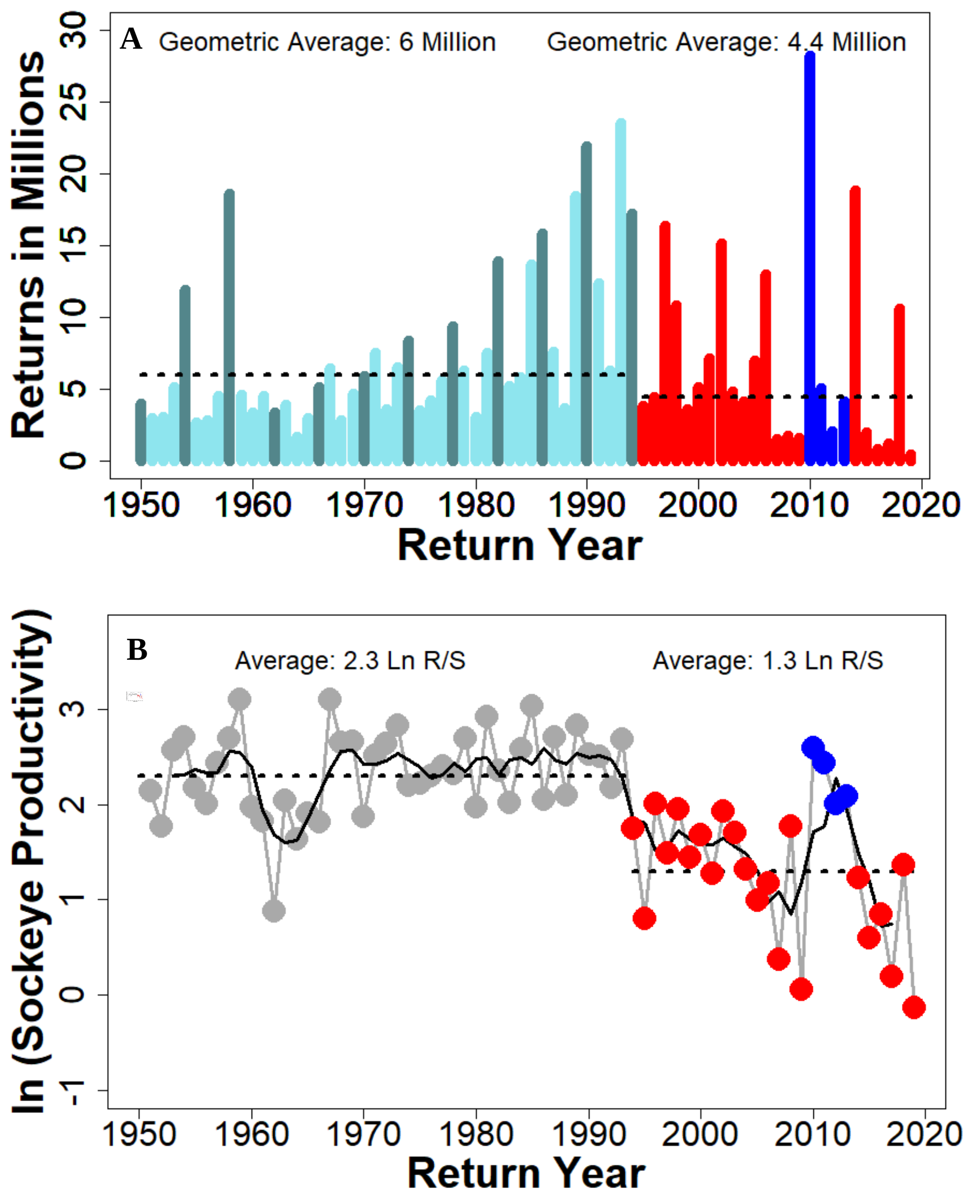



**Figure 1**. (A) Total Fraser Sockeye annual returns (dark blue vertical bars show the 2018 cycle and light blue vertical bars show the three other cycles) and (B) total Fraser Sockeye survival (grey, blue, and red dots are $\log_e$ (returns/total spawner)) are presented up to the 2019 return year. For both figures, dashed lines indicate the average values for the 1952-1994, and 1995-2019 time periods. Productivity and returns have declined in recent decades, highlighted red, with the exception of four years from 2010-2013, which were closer to average, highlighted blue.

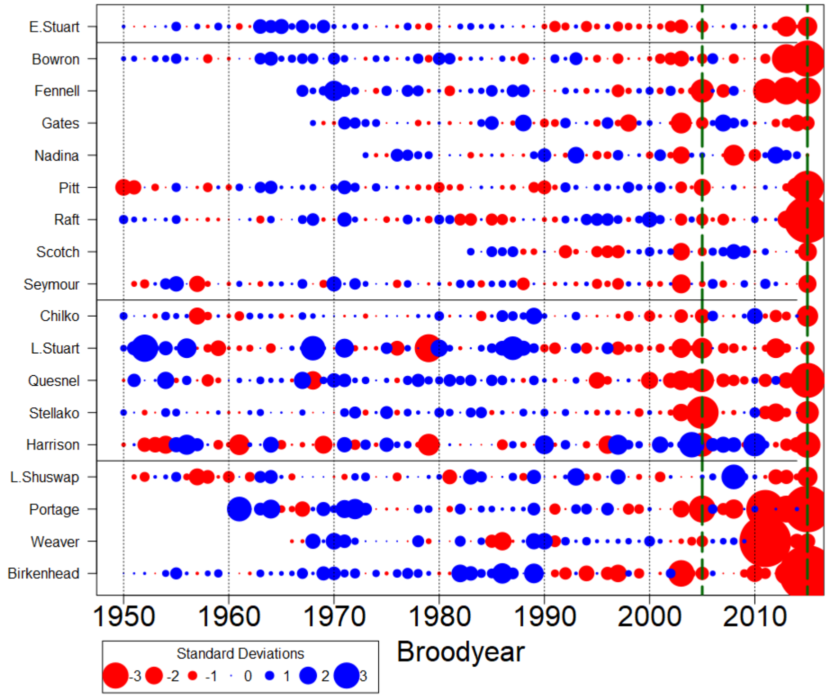



**Figure 2.** Four year old Fraser Sockeye survival (Ricker model residuals for all populations except Scotch, Seymour and Late Shuswap, which are Larkin residuals) up to the 2015 brood year (2019 return year) across 18 key populations. The 2019 data point is based on preliminary data only. Red circles indicate below average survival and blue circles indicate above average survival. Circle sizes represent the deviation from average survival for each stock; the larger the circle, the larger the deviation from average. The 2005 and 2015 brood years (2009 and 2019 return years) have been highlighted using a broken vertical green line. The 2005 brood year spurred the initiation of the Cohen Inquiry into the declines of Fraser Sockeye, and the 2015 brood year is associated with the lowest return on record.

Parental spawners of the four year old 2020 returns migrated through warmer than average river temperatures and low flow conditions to reach their spawning grounds, potentially affecting reproductive development and gamete viability, and/or having carryover effects on juveniles (Macdonald et al. 2000, Tierney et al. 2009, Sopinka et al. 2014). However, spawning ground conditions were considered normal, and spawners were reported to be in good conditions on the spawning grounds, with some exceptions. After an extremely warm November 2016, cool conditions prevailed through the remainder of the egg incubation period (Environment and Climate Change Canada (ECCC), Pacific Climate Impacts Consortium (PCIC)).

Cool temperatures continued into the spring of 2017. May 2017 was warm, leading to rapid snowmelt and high flows in early June (ECCC, PCIC). Depending on migration timing, high river flows may have helped some populations migrate downstream to their rearing lakes, and may have expanded littoral zones in some systems. Alternatively, these flows may have presented migration challenges for those populations that migrate upstream to their rearing lakes, such as Chilko and Weaver.

Summer 2017 air temperatures were above normal for the southern half of the Fraser basin, continuing into September, which likely extended the growing season in some areas, and may have positively impacted fry growth if prey were not limiting (Edmundson and Mazumder 2001). However, hot dry conditions also facilitated an extremely active wildfire season, the effects of which are unknown for salmon lake-fry development.

Air temperatures were again generally below normal overwinter in 2017, but transitioned into extremely high temperatures compared to average in May 2018 (ECCC, PCIC). The snowpack in the Fraser basin was above normal heading into spring (Ministry of Environment River Forecast Centre), and quickly melted, leading to an early Fraser River freshet, with record high day-of-year flows in May 2018. Outmigrating Fraser Sockeye smolts would have experienced variable levels of discharge depending on their migration timing. Those migrating during higher than average flows potentially benefitted from reduced predation risk (Ginetz and Larkin 1976), but may have also experienced negative effects from increased suspended sediments (Martens and Servizi 1993).

Upon reaching the marine environment in early 2018, the Northeast Pacific marine heatwave of 2013-2016, referred to as 'The Blob' had diminished (Chandler et al. 2018), though it continued to affect lower trophic levels. Timing and duration of the spring phytoplankton bloom in the SoG was normal (Costa 2019, Allen et al. 2019), as was the zooplankton biomass in the SoG (Young et al. 2019). Interestingly, species composition of the larger copepods in the SoG was shifted away from the typically spring dominant *Neocalanus plumchrus*, with *Eucalanus bungii* instead making up the majority of the large copepod biomass (Young et al. 2019).

In late 2018, conditions transitioned from a weak La Niña to a weak El Niño (Ross and Robert 2019). Additionally, new marine heatwaves were detected in the Northeast Pacific starting in fall 2018 (Hannah et al. 2019, Ross and Robert 2019). Off the West Coast of Vancouver Island (WCVI) in September 2018, the phytoplankton community composition and biomass was similar to previous years (Peña and Nemcek 2019). However, zooplankton off the WCVI was still composed of a higher than normal abundance of southern, warmer water associated copepods, and lower than normal subarctic copepods (Galbraith and Young 2019).

Fraser Sockeye run size forecast models typically take into account density-dependent survival, as represented by the historical data. This includes the high density effects of spawners competing for spawning habitat — and juveniles competing for food — on survival to the next life stage. Density-independent factors affecting survival have been challenging to incorporate effectively into most forecast models for Fraser Sockeye (MacDonald and Grant 2012; DFO 2017, 2018). These include effects of ecosystem conditions on salmon survival, independent of salmon densities.

Sea-surface temperature (SST) covariates were used to inform survival of some stocks in the 2020 forecast. However, they had little effect on the forecasts because temperature covariates are applied to the smolt outmigration time-period (spring 2018), and during this time, sea-surface temperatures in the SoG, and the PDO index, were not unusually high. These indices do not reflect the residual impacts of the 2013-2016 marine heatwave on lower trophic levels, that have an associated impact on food quality and availability for salmon..

This qualitative science integration process attempts to capture nuanced observations, to the extent currently possible, across life-stages, to reduce uncertainty in the quantitative Fraser Sockeye forecast by making predictions about potential survival. In this process, the potential impacts of each observation on survival are not summed to come to a final prediction. Instead, experts discuss observations and data, coming to their own conclusions about survival, based on their individual integration and weighting of the material, supported by published empirical relationships. Weighting of individual observations is not formalized and likely differs between participants. However, during plenary sessions, individual processes and opinions are discussed as participants come to consensus on the predicted impacts on survival for each of the four broad life stages (see below), and overall.

Participants in the 2020 science integration process predicted that Fraser Sockeye returning in 2020 will likely exhibit poor survival relative to the 1952-2019 average, given the overall warm conditions and shifted ecosystems observed in recent years. It was noted that the freshwater residence period of this cohort was generally warmer than average. Though this potentially impacted some Fraser Sockeye stocks, participants agreed that observations and current knowledge indicate low potential impacts on survival for each of the freshwater life stages, with an overall neutral effect (Table 1 & Table 2). Additionally, the dominant stocks expected in 2020, Chilko and Chilliwack (54% of the predicted return excluding Harrison), exhibited average survival to the smolt stage for Chilko, and high survival to fall fry for Chilliwack. This indicates that survival, but not necessarily fish condition, during these stages was not negatively impacted by the conditions. However, upon leaving Chilko Lake, Chilko smolts were somewhat smaller than expected based on their EFS numbers, and had lower than expected lipid levels, suggesting that growing conditions were less favourable than average. This may have impacted downstream and/or marine survival.

Participants identified that negative impacts on survival were possible during the marine phase of the 2020 Fraser Sockeye returns. This was due to the delayed effects of the 2013-2016 marine heatwave and associated ecosystem changes on the food web, potentially affecting food quality and availability for Sockeye. This was coupled with observations of additional marine heat waves beginning in fall 2018.

Ecosystems relied upon by Fraser Sockeye are changing rapidly as the effects of global climate change become more prevalent, and unusual events become more frequent. In recent years, all participants of this process have observed profound events or changes in the ecosystems and salmon life-stages they assess. It was generally agreed within the group that with climate change, conditions that salmon experience are no longer ‘normal’ in comparison to historic conditions. Meaning, as climate change proceeds, ‘baselines’ that may be considered as reference conditions will also change, and we are less likely to observe conditions that were historically common.

Such changes increase the uncertainty in our ability to predict future Fraser Sockeye survival, as all life-history stages are affected with largely unknown consequences. These changes emphasize the value of current and ongoing monitoring of salmon and their ecosystems to better understand the impacts of environmental change on salmon survival. This is critically important, as we need to improve not only short-term forecasts, but longer term predictions of the broad-scale responses of salmon populations to a changing climate. This is needed to align our fisheries management, salmon recovery, and habitat restoration activities now to future salmon production and biodiversity.

We continue to have major gaps in many of our salmon and ecosystem research and monitoring programs. These include conspicuous gaps in our freshwater lake and stream monitoring programs, non-Sockeye salmon species, and marine ecosystem monitoring. New and expanded monitoring in these areas of research will provide valuable information to help ensure sustainability of salmon stocks into the future.

Fraser Sockeye returning to the upper watershed in 2020 will be further affected by a significant landslide that occurred in French Bar canyon on the Fraser River near Big Bar, B.C. in November 2018 (Evans Ogden 2020). Impacts of this landslide have not been incorporated into this report, but negative impacts on the numbers and/or condition of spawners that reach the spawning grounds above the slide site in 2020 are expected. Specifically, populations that are likely to be impacted include the Takla-Trembleur-Early

Stuart, Bowron-ES, Nadina-ES, Taseko-ES, Chilko-S, Takla-Trembleur-Stuart-S, Quesnel-S, and Francois-Fraser-S CUs.

Highlights identified by meeting participants have been organized into two tables. Table 1 shows general highlights assumed to affect most or all Fraser Sockeye stocks. Table 2 presents highlights specific to certain stocks. Highlights are listed with associated categories of effects on survival, confidence in those effects, and potential to impact survival to the next life stage, based on expert opinion, as follows:

**Column 1: Effect:** Negative, Neutral, Positive, Variable

**Column 2: Confidence in this effect:** Possible, Likely, Very Likely

**Column 3: Potential impact on survival:** Low, Medium, High, Unknown, Incorporated (this means the consideration was included in the quantitative forecast model)

**Column 4: Page number for more information.**

Participants also came up with a summarized effect, significance, and potential impact on survival across observations for each life stage, based on plenary discussions. Details that correspond with the highlights below can be found in subsequent sections.

Table 1. General highlights for Fraser Sockeye survival pertaining to all stocks. Columns include expert opinion of potential effect of observation on survival within life stage, confidence of effect within life-stage, potential impact on survival to the subsequent life stage, and page number for more information. Participants also came up with a summarized effect, significance, and potential impact on survival across observations for each life stage, based on plenary discussions.

| **Overall** | **Effect** | **Confidence** | **Potential Impact** | **Page #** |
|---|---|---|---|---|
| **Fraser Sockeye Survival** | **Negative** | **Likely** | **NA** | NA |
| **Brood Year Spawners and Egg Stage (Summer/Fall 2016-Spring 2017)** | **Effect** | **Confidence** | **Potential impact on survival** | **Page #** |
| • Lower Fraser River temperatures were predominately above average during adult migration: Summer and Late Sockeye populations experienced conditions above 19°C during mainstem migration | Negative | Very Likely | Low | 29 |
| • Spawning ground water temperatures and stream flows for most populations were within normal ranges during spawning, with some exceptions | Neutral | Likely | Low | 30 |
| • Fraser River discharge at Hell's Gate, a migration barrier during high flows, was below average during adult migration of all run-timing groups in 2016 | Neutral | Very Likely | Low | 29 |
| • Sockeye were reported to be in good condition on spawning grounds in most areas, with some stream-specific exceptions | Neutral | Likely | Low | 29 |
| • November air temperatures were very warm, with anomalies at least 4-5°C above normal in 2016; this has the potential to influence egg incubation conditions | Negative | Possible | Low | 33 |
| **BROOD YEAR SPAWNER STAGE - summary** | **NEUTRAL** | **LIKELY** | **LOW** | |

| Juvenile Freshwater Rearing (Spring 2017-Spring 2018) | Effect | Confidence | Potential impact on survival | Page # |
|---|---|---|---|---|
| • Normal timing of Fraser River spring freshet, with above average early June flow | Neutral | Possible | Low | 35 |
| • Extensive fire season and hot summer air temperatures with unknown impacts | Unknown | Unknown | Unknown | 22 |
| • Warm fall likely lengthened the growing season in some areas | Positive | Possible | Low | 36 |
| • Overall winter 2017-2018 air temperatures below normal, transitioning to a very warm May | Neutral | Possible | Low | 41 |
| **JUVENILE FRESHWATER REARING STAGE - summary** | **NEUTRAL** | **LIKELY** | **LOW** | |

| Smolt Downstream Migration (Spring 2018) | Effect | Confidence | Potential impact on survival | Page # |
|---|---|---|---|---|
| • Early-timed peak freshet with day-of-year record flows in May; mainstem temperatures were average | Neutral | Possible | Low | 43 |
| • Populations experienced different levels of discharge based on their migration timing | Variable | Possible | Low | 43 |
| • Migration timing past Mission was slightly earlier than average, however, there may be some bias in this timing estimate | Neutral | Possible | Low | 25 |
| • Smolts at Mission varied in average length by stock | Neutral | Possible | Low | 25 |
| **SMOLT DOWNSTREAM MIGRATION - summary** | **NEUTRAL** | **POSSIBLE** | **LOW** | |

| Juvenile Marine Rearing (Spring 2018 - present) | Effect | Confidence | Potential impact on survival | Page # |
|---|---|---|---|---|
| • Northeast Pacific marine heatwave has diminished but it's effects on lower trophic levels remain (2018). | Negative | Possible | Low | 50 |
| • New marine heatwaves were observed, starting in Fall 2018, due to delayed winter cooling, and again in 2019 | Negative | Possible | Low | 49 |
| • The 2018 timing of upwelling of nutrient rich waters on the west coast of Vancouver Island was early, and magnitude was not as intense as previous years | Neutral | Possible | Low | 50 |
| • In 2018, zooplankton composition off WCVI was dominated by lipid poor, less nutritious species, consistent with reduced winter cooling; i.e. high southern copepod abundances and low subarctic copepod abundances | Negative | Likely | High | 50 |
| • Spring/Summer 2018 temperatures, salinity, and oxygen levels near normal in the SoG | Neutral | Very Likely | Low | 53 |
| • In 2018, the SoG spring phytoplankton bloom timing and duration were consistent with average | Neutral | Likely | Low | 53 |
| • SoG zooplankton biomass in 2018 was near-average | Neutral | Likely | Low | 53 |
| • In 2018, the average size of juvenile Sockeye sampled in the SoG trawl surveys was above average | Positive | Possible | Low | 26 |
| • The 2018 CPUE of juvenile Sockeye in SoG trawl surveys was above average for this cycle | Positive | Possible | Low | 26 |

| | | | | |
|---|---|---|---|---|
| • 2018 juvenile Sockeye CPUE in Queen Charlotte Strait/Southern Queen Charlotte Sound trawl surveys was above average for non-dominant cycle years | Positive | Possible | Low | 56 |
| • 2018 juvenile Sockeye condition in Queen Charlotte Strait/Southern Queen Charlotte Sound trawl surveys was average | Neutral | Possible | Low | 56 |
| • In late 2018 there was a transition from a weak La Nina to a weak El Nino | Neutral | Likely | Low | 49 |
| **MARINE RESIDENCE - summary** | **NEGATIVE** | **POSSIBLE** | **LOW** | |

Table 2. Stock-specific highlights of survival. Columns include expert opinion of potential effect of observation on survival within life stage, confidence of effect within life-stage, potential impact on survival to the subsequent life stage, and page number for more information.

**Stock-Specific Observations**

| Brood Year Spawners and Egg Stage (Summer/Fall 2016-Spring 2017) | Effect | Confidence | Impact on stock specific survival | Page # |
|---|---|---|---|---|
| • Potential for negative bias in the EFS estimation for Kamloops-ES and Shuswap-ES due to high flows | Positive | Likely | Medium | 30 |
| • Debris flow from Whitecap Creek in the Portage Creek watershed at the tail end of the spawning period possibly affected egg-to-fry survival | Negative | Likely | Medium | 30 |
| • Fertilization success evaluation of sampled Chilko spawners did not indicate anything unusual | Neutral | Likely | Low | 30 |
| • Plasma chloride and glucose values for sampled Harrison River, Gates Creek, Upper Chilliwack River and Chilko River adult Sockeye were within normal ranges expected for healthy arrivals and spawners | Neutral | Likely | Low | 30 |
| • High flow event observed in Nadina River during incubation | Negative | Possible | Low | 34 |

| Juvenile Freshwater Rearing (Spring 2017-Spring 2018) | Effect | Confidence | Impact on stock specific survival | Page # |
|---|---|---|---|---|
| • Fraser, Francois and Quesnel Lake fall fry abundances were consistent with DFO Stock Assessment reports of EFS abundances. Nothing abnormal in terms of survival | Neutral | Very Likely | High | 38, 36 |

| | | | | |
|---|---|---|---|---|
| • Chilliwack Lake: high fry/EFS, better summer-to-fall survival than the previous cycle-line survey, and fish were larger | Positive | Very Likely | High | 38 |
| • Cultus Lake: extremely poor overwinter fry survival and very low smolt numbers | Negative | Very Likely | Incorporated | 40 |
| • Nadina spawning channel had average egg-to-fry survival; Weaver channel was slightly below average | Neutral | Very Likely | High | 34 |
| • Chilko freshwater survival (smolts / EFS) was similar to the long-term average but lower than the average for the most recent 12 years | Neutral | Very Likely | High | 41 |

| Smolt Downstream Migration (Spring 2018) | Effect | Confidence | Impact on stock specific survival | Page # |
|---|---|---|---|---|
| • Chiko smolts experienced above average discharge in the Chilcotin River; temperatures were near average | Neutral | Possible | Low | 44 |
| • Chilko smolt body size was below average and slightly below expectations, based on the EFS numbers. Weight to length ratio was below expected. An unexpectedly high proportion of juveniles held over until the next spring (2019) | Negative | Possible | Medium | 47 |
| • Chilko smolts had some of the lowest lipid values observed in recent years | Negative | Possible | Medium | 48 |
| • Chilko outmigrated slightly later than average but still within the average range. Timing past Mission was similar to average | Neutral | Possible | Low | 44 |
| • Seton smolts continued to be large with high lipid values | Neutral | Possible | Low | 48 |
| • Cultus smolts migrated with similar to average timing | Neutral | Possible | Low | 44 |

# 3 OVERVIEW

## 3.1 BACKGROUND

### Fraser Sockeye Life History

Fraser Sockeye salmon spawn in rivers, streams, and along lake foreshores in the Fraser River watershed. Most Fraser Sockeye return to spawn as four year olds. They exhibit a lake-type life history, spending their first two winters in freshwater, followed by two winters in the marine environment. Approximately 20% of Fraser Sockeye return to spawn as five year olds.

Female Sockeye dig nests in the spawning ground gravel to deposit their eggs. Spawning sites vary in terms of gravel size, ranging from coarse sand to large rubble and boulders; at depths from 0.1 meters to 30 meters of water (Burgner 1991); and temperatures ranging from 7 to 14 degrees Celsius, based on data for nine Fraser Sockeye populations (Whitney et al. 2013). Eggs are then fertilized by males and incubate in the gravel through the winter. The duration of the incubation period, and timing of emergence as fry - generally mid-April to mid-May - are determined by incubation temperatures and discharge (Burgner, 1991; Macdonald et al., 1998). Following emergence, fry migrate to their rearing lakes, feeding and growing in the littoral zone then moving offshore (Morton and Williams 1990), where they rear for an additional winter.

After their second winter in freshwater, lake-type Fraser Sockeye leave their rearing lakes between April and June, and quickly migrate downstream (Clark et al. 2016). They enter the Fraser River estuary and the majority migrate north through the Strait of Georgia (SoG), Johnstone Strait, and along the continental shelf, moving offshore in the fall or winter into the Gulf of Alaska (GOA) (Welch et al. 2009, Tucker et al. 2009). The majority of Fraser Sockeye spend an additional winter distributed widely in the Northeast Pacific before returning to their spawning grounds as four year olds. Fraser Sockeye return to spawn throughout the summer and fall months, and have been aggregated into four run-timing groups based on their spawning location and migration timing through the lower Fraser River: Early Stuart (late-June to late-July); Early Summer (mid-July to mid-August); Summer (mid-July to early-September); and Late (late-August to mid-October).

A small proportion of Fraser Sockeye are river-type fish. The largest river-type population occurs in the Harrison River. These Sockeye do not rear in lakes, but instead migrate downstream in the Fraser River shortly after they emerge from their spawning gravel. They rear in the lower Fraser for 1-5 months (Birtwell et al. 1987), before spending up to six months rearing in the SoG. These salmon migrate out of the SoG through either the southern, Juan de Fuca, or northern, Johnstone Strait, route, after lake-type stocks have left this area, heading to the GOA (Tucker et al. 2009, Beamish et al. 2016). River-type Fraser Sockeye will not be covered in this report, since they generally contribute small numbers to the total Fraser Sockeye production.

## Environmental and Biological Trends 2015 - 2020

Earth is warming. The average land-ocean temperature has risen by 1°C over the last century (IPCC 2018), and the last five years were the warmest on record (NOAA 2020). Global temperatures are expected to rise 1.5°C to 3.7°C above the 1850-1900 average by the end of this century. The extent to which human society curbs our $CO_2$ and other greenhouse gas emissions will determine where in this range future temperatures fall (IPCC 2013).

Climate change impacts are already altering the freshwater and marine ecosystems upon which Canadian Pacific salmon rely. There is a growing understanding of how Pacific salmon and their habitats are being impacted by the shifting global climate, though much remains unknown (Holsman et al. 2018, IPBES 2018, Chandler et al. 2018, Boldt et al. 2019, Bush and Lemmen 2019, Grant et al. 2019). During the lifespans of the most recent returning cohorts of Fraser Sockeye, the following impacts, associated with broader climate change, have been observed in their ecosystems with subsequent effects on salmon:

- High river temperatures occurred from 2015 to 2018; summer river temperatures are increasingly exceeding upper thermal tolerances for salmon in assessed systems;
- BC snowpacks were anomalously low by early May in 2015, 2016 & 2018, and by early June in 2017; this contributed to warmer spring/summer river and lake temperatures in snow-dominated systems in those years;
- Rapid snowmelt caused early, high Fraser River freshets in 2015, 2016 & 2018;
- Record summer droughts occurred in 2015, 2017 and 2018; lower water levels can block passage to key spawning habitat, strand salmon, and increase their exposure to predators;
- Unprecedented Northeast Pacific marine heatwaves occurred in most years during late-2013 to late-2019; this has negatively affected many physical and biological ocean processes relating to salmon growth and productivity;
- Northeast Pacific Ocean zooplankton community composition exhibited characteristics consistent with a warmer ocean from 2016 to 2018, consisting of a higher than normal proportion of lower food quality species near the base of the salmon food web.

Climate change impacts such as these are predicted to continue and become more frequent and more severe moving forward. These includes warmer air temperatures (IPCC 2014a), more extreme precipitation events (IPCC 2014a), continued warming of the ocean (IPCC 2014a), rapid spring snowmelt causing higher than normal river flows, followed by below average summer and fall flows (Anslow et al. 2016), more frequent atmospheric heatwaves that are expected to be more intense and longer lasting (Meehl and Tebaldi 2004), more frequent, longer lasting, larger, and more intense marine heatwaves (IPCC 2019), and shifts in the geographic ranges of marine species (IPCC 2014a). Environmental and biological data collected over the lifecycle of returning salmon can help contribute to increasing our understanding of salmon responses to local and regional effects of climate change, to predict their future distribution, productivity, and growth.

## Review of the 2019 Workshop and Preliminary 2019 Returns

The 2019 Fraser Sockeye Science Integration Workshop predicted that density-independent survival of four year old 2019 Fraser Sockeye returns would fall below average (between forecasted return levels associated with the 25% and 50% probability levels; MacDonald et al. 2019). The prediction that survival would be poor was correct, though observed returns fell below the 25% probability level forecast. The total preliminary Sockeye run size was estimated at 485,900 (courtesy of the Pacific Salmon Commission), which is approximately 10% of the median forecast (4,795,000) and fell below the 10% probability level (1,794,000) (M. Hawkshaw DFO Stock Assessment pers. comm.).

All four Fraser Sockeye run-timing groups returned below their 25% probability level forecasts. The Early Stuart stock saw returns just below the 25% probability level (26,000 vs. 27,000 at the 25% probability level). Early Summer stocks saw returns near, but below the returns associated with the 10% probability level (93,500 vs. 111,000 at the 10% probability level). For this run-timing group, the Nadina stock contributed the largest proportion (75%) of the total run size, whereas the Early Thompson stocks (Fennell, Scotch, Seymour and Early Shuswap miscellaneous stocks) contributed only a small proportion (12%), despite being forecasted to return in similar numbers to Nadina.

Summer and Late Run stocks showed extremely low returns, both coming in at approximately 20% of the returns associated with the 10% probability level forecasts (360,000 and 22,200 vs 1,553,000 and 111,000, respectively at the 10% probability level). For the Summer run-timing group, the Chilko stock dominated (60%) the run size as expected (forecast proportion was 70.0%). For the Late run-timing group, Portage and Late Shuswap contributed the largest portion (66.7%) of the total run size, a much higher percentage than the pre-season estimate (18%). Birkenhead, on the other hand, contributed a much smaller proportion (17%) than expected (75%).

The qualitative prediction of poor survival for the 2019 four year old returns was based on notably warm conditions experienced during their freshwater residence, similar to those experienced by Fraser Sockeye returning in 2017 and 2018, which exhibited poor survival (MacDonald et al. 2019). Above average temperatures prevailed during the upstream migration of their parents (in 2015) and persisted through to their juvenile freshwater rearing stage. In the winter preceding their downstream migration as smolts, more typical conditions returned in the Northeast Pacific Ocean. Additionally, some physical and biological processes in the Northeast Pacific Ocean improved. However, southern, warm water species of zooplankton continued to dominate the nearshore food web; providing a sub-optimal food source near the base of the food web. Conditions experienced by four year old Sockeye returning in 2019 appeared to be very similar to those experienced by the majority of fish that returned in low numbers in 2017 and 2018 – which led to a fairly pessimistic outlook for 2019, though better than previous years' predictions. Returns in 2019, however, ended up being the lowest on record, lower than expected based on last year's qualitative prediction (MacDonald et al. 2019).

As part of this year's workshop, we reviewed observations presented in the 2019 science integration process (see MacDonald et al. 2019) in light of the extremely poor survival exhibited by the 2019 returns. This examination did not reveal any different conclusions regarding the survival predicted in that process. We would have still predicted survivals and associated returns that were similar to previous years based on our collective life-stage observations. Though we correctly predicted below average returns in 2019, we are clearly either missing information for a particular Fraser Sockeye life stage that represented a bottleneck, or missing the cumulative linkage of conditions observed for other life-stages of the 2019 return year. For example, it is possible that conditions in the high seas, beyond the Strait of Georgia, and Coastal Marine sampling programs, were exceptionally poor and represented a bottleneck for salmon survival.

As part of the 2019 review, we compared proportions of five lake-type Sockeye stocks sampled at various life stages pertaining to the 2019 return, to evaluate the consistency of observed relative abundances across life stages for which we have information (Figure 3). Proportions were examined for the brood year EFS in 2015, outmigrating smolts at Mission, B.C. in spring 2017, SoG trawl survey samples collected in June-July 2017, four year old 50% probability level return forecasts for 2019, and the 2019 return estimates. Stocks were selected according to their order of prevalence in the sampling programs, and include Chilko, Stellako, Quesnel, Birkenhead, and Raft/North Thompson. All other stocks were removed from the calculations of stock proportions for each sampling component.

Four-year old returns in 2019 were heavily dominated by Chilko, as expected (Figure 3). Four-year old Chilko returns made up approximately 80% of the return calculated across the five prevalent stocks. Relative four year old returns to Stellako were higher than expected based on the 2015 EFS and the official forecast at the 50% probability level, but were similar in relative proportion to the juvenile samples at Mission. Also noteworthy, four year old returns to both Birkenhead and the Raft/North Thompson were extremely low, ~200 returns in each of these systems. For Birkenhead, this was somewhat signaled in the Mission downstream program.

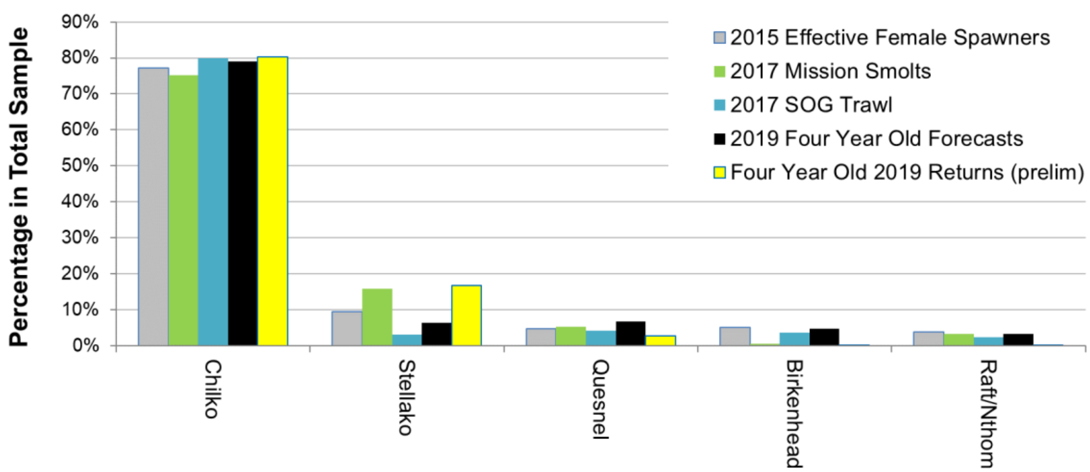



**Figure 3.** Proportions of dominant Fraser Sockeye stocks contributing to the 2019 return, measured through five sampling programs, including preliminary return estimates. Effective female spawner proportions from the 2015 brood year, smolt out-migration in the Fraser River at Mission in 2017, summer juvenile trawl sampling in the Strait of Georgia in 2017, official four-year old forecasts at the 50% probability level (M. Hawkshaw DFO Stock Assessment pers. comm.), and preliminary 2019 four-year old return estimates derived for stocks (Steve Latham, PSC).

## Fraser Sockeye Pre-season Four year Old Return Forecasts for 2020

The 2020 pre-season Fraser Sockeye salmon run size forecast generally followed the same modeling approach that has been applied since 2012 (DFO 2012, MacDonald and Grant 2012). This approach was adapted from Cass et al. (2006) and has been used for most recent years (Grant et al. 2010, Grant and MacDonald 2011, 2013, MacDonald and Grant 2012, DFO 2014a, 2015a, 2016a, 2017, 2018, M. Hawkshaw DFO Stock Assessment pers. comm.).

The total median run size forecast for 2020 is 941,000, and ranges from 274,000 to 3,945,000 at the 10% to 90% probability levels. The median run size breakdown of run-timing groups are Early Stuart (13,000), Early Summer (218,000), Summer (611,000) and Late (99,000). Chilko has as median forecast of 256,000 (80% PI: 94,000 to 722, 000) and has the largest forecast of the 27 forecasted stocks, contributing 27% of the total run size (M. Hawkshaw DFO Stock Assessment pers. comm.).

Five environmental variables have been considered in the forecast models: sea surface temperatures (SST's) at Entrance Island and Pine Island, PDO, and Fraser River discharge (mean and peak) during the ocean entry year (2018). Additional environmental variables (including more climate indices, freshwater and oceanic properties) will be implemented in future forecast models. Several alternative modeling approaches are under exploration for future forecasts, such as boosted regression trees (Y. Xu DFO Stock Assessment pers. comm.), empirical dynamic model, etc.

# 3.2 BROOD YEAR SPAWNERS AND EGG STAGE: SUMMER/FALL 2016 - SPRING 2017

Effective female spawner (EFS) numbers are used to predict returns in quantitative Fraser Sockeye forecasts, with one exception — Cultus — where smolts are used. Smolts are often also used to forecast Chilko returns, however this was not the case for 2020. Most forecasts, therefore, account for female escapements and the number of eggs released from females by stock, assessed through carcass surveys on the spawning grounds. Quantitative forecasts, however, do not account for the intergenerational effects of the parental experience on the health and survival of offspring. For example, high maternal stress can affect offspring swim performance and predator avoidance behaviour (Tierney et al. 2009, Sopinka et al. 2014). Though quantifying the effect of the parental experience is challenging, providing information on potential stresses experienced by this group may be helpful context to inform our understanding of the condition and survival of their offspring.

In general, the parental generation of the 2020 Fraser Sockeye four year old return encountered above average in-river water temperatures while migrating upstream in 2016. Temperatures were above 19°C from mid-July to late August when Sockeye from the Summer and Late run-timing groups were present (Figure 4). In the Nechako River, Early Stuart and some Early Summer and Summer populations were exposed to temperatures over 20°C during portions of their migration. Of note, exposure to water temperatures >19°C during upstream migration has been associated with impaired reproductive development and reduced gamete viability (Macdonald et al. 2000).

These overall warm in-river temperatures were associated with above normal air temperatures in June and August, though July temperatures were below normal (ECCC, PCIC). Cool July temperatures were accompanied by precipitation levels 50-125% above normal (climatology from 1971-2000) throughout most of the watershed (ECCC, PCIC). As the fall progressed, average September and October air temperatures were cooler than normal, whereas November was very warm, with air temperatures at least 4–5°C above normal (ECCC, PCIC).

All Fraser Sockeye spawners in 2016 encountered below average river flow in the lower Fraser River during their upstream migration (Figure 5). Researchers determined the effect of lower than average flows to be neutral for spawners. For comparison, higher discharge requires more energy to swim against as spawners migrate upstream to their spawning grounds. This can be particularly problematic for fish migrating through Hell's Gate, since the river is constricted at this location, and periods of high discharge create a migratory barrier there.

Spawners were generally in good condition when they arrived at spawning grounds, with little sign of migration stress. Overall spawner success was average (90%) for 2016, though results varied across populations. There were some exceptions – early arrivals at the Early Stuart and Raft River spawning areas had elevated levels of pre-spawn mortality, and there was evidence of migratory difficulties (e.g., wounds) in early arrivals at the Raft, Chilko and Stellako spawning areas. Three stocks were skewed towards female spawners: Nadina (63% females), Chilliwack (57% females), and Upper Barriere (60% females). Female spawners were skewed lower in the Weaver population (38%).

Although water temperatures and stream flows at the spawning grounds were generally favourable, high flow conditions occurred in the Harrison-Lillooet, North and South Thompson, and Quesnel systems in September. This potentially negatively biased escapement estimates for the Raft/North Thompson (Kamloops-ES CU) and South Thompson (Shuswap-ES CU) systems, therefore EFS estimates for these systems may be low. Of note, a debris flow event occurred in Portage Creek in November 2016 at the tail-end of the Sockeye spawning period. This possibly impacted egg-to-fry survival, but did not affect the escapement estimate, which was derived from a visual live count during the peak spawning period.

DFO's Environmental Watch Program collected biological samples on the spawning grounds of the Harrison River, Gates Creek, Upper Chilliwack River, and Chilko River to further investigate spawner condition. Physiological assessments of spawners from these populations did not indicate anything unusual in terms of plasma ion and metabolite values (Figure 6). Fertilization success, measured as survival to the eyed-egg stage, was sampled for Chilko spawners only, and was above expected values. Researchers caution that physiological condition and gamete viability results were based on a limited sample size and cannot be extrapolated to other populations.

As the year progressed into late fall, above normal November air temperatures had the potential to influence egg incubation degree days, and thus hatch timing and emergence, particularly in the southern portion of the Fraser basin. Early Stuart spawning tributary temperatures were unusually warm in early November during the egg incubation period. Warm water temperatures during spawning and egg incubation have direct negative effects on fertilization success and embryo survival that are population specific (Whitney et al. 2014). Incubation temperature affects swim performance (Burt et al. 2012), and phenology of hatch (Whitney et al. 2014) and gravel emergence (Macdonald et al. 1998). In-river water temperatures are site-specific and were not available for most systems apart from the Early Stuart.

Record day-of-year flows were observed in the Nadina River in mid-November. Abnormally high winter flows increase the risk of redd scouring and suspended sediments during incubation (Thorne and Ames 1987, Montgomery et al. 1996, Newcombe and Jensen 1996, DeVries 1997).

As winter took hold, overall air temperatures from December to February were approximately 3°C cooler than normal across the basin, except in the upper watershed in January (ECCC, PCIC).

## 3.3 JUVENILE FRESHWATER STAGE: SPRING 2017 - SPRING 2018

From April to June, fry emerge from their spawning gravel and migrate to their rearing lakes. Here, they feed and grow in the littoral zones — near-shore habitats with good sunlight penetration. If undisturbed, these areas typically have good planktonic plant growth supporting the invertebrates that juvenile Sockeye feed on. The level of lake productivity is generally linked to natural and human-contributed nitrogen and phosphorus nutrient levels.

In 2017, temperatures in March and April continued to be cooler than average, but were warmer in May (ECCC, PCIC). The timing of the spring freshet was normal, however discharge was well above median values in early June. Warm spring temperatures and high discharge aid fry from most populations in making the journey downstream to their rearing lakes, and can also increase littoral zone habitat in their rearing lakes. The exception to this may have been the Chilko and Weaver populations that migrate upstream to their rearing lakes. For these stocks, fry attempting to make the journey during high flows in early June may have experienced difficulty. However, data on Chilko smolts and Weaver fry did not indicate any significant issues at this life-stage.

Once the fry arrived in their rearing lakes, summer 2017 (June-August) brought above normal maximum air temperatures, especially for the southern portion of the Fraser basin. This may have had a positive effect on fry development — the optimal temperature for growth increases with increasing food availability (Brett 1971), so that warmer lake temperatures can increase growth when prey are not limiting (Edmundson and Mazumder 2001). Additionally, the warm fall may have extended the growing season. This warm, dry weather also brought with it an exceptional summer fire season; the second worst on record in BC for hectares burned (Wang and Strong 2019). The effect of smoke cover and ash on primary lake productivity was not assessed, and has unknown influences on fry development in the lake.

To help assess fry survival in rearing lakes, summer and fall hydroacoustic and trawl surveys were conducted on Fraser, Francois, Quesnel, Chilliwack, Cultus and Bowron Lakes in 2017. In Fraser and Francois Lakes, catch of age-0 fry in 2017 was a consistent with the low estimated parental abundances (Figure 7). Due to mechanical issues, no trawl surveys were conducted to verify whether these fry were Sockeye or Kokanee. However, genetic identification from the 2018 survey in Fraser Lake indicated no Kokanee in the catch, and it’s possible this was also the case in 2017. The 2017 hydroacoustic surveys in Fraser and Francois Lakes were the first assessments conducted in this system in 20 years. Both Fraser and Francois Lakes have been identified by Shortreed et al. (1996) as underutilized in terms of Sockeye production, though Francois Lake production is thought to be limited by spawning ground availability.

In Quesnel Lake, the catch of age-0 fry in 2017 was prohibitively low for distinguishing Kokanee from anadromous Sockeye. Regardless, the estimate was consistent with the extremely low EFS abundance in 2016 (Figure 8). With no reliable catch of age-0 fish for genetic testing, researchers assumed most were Kokanee.

In Chilliwack Lake, the summer to fall survival rate was 68% in 2017, as compared with a 58% survival rate recorded over the same period for the last dominant year, in 2013 (2012 brood year). The average number of fry per EFS was also higher in 2017 compared to 2013 (Figure 9), and fry were more than a gram heavier, though of similar length to 2013 fry (Figure 10).

Cultus Lake summer to fall fry survival could not be calculated, due to the addition of hatchery Sockeye into the lake for conservation purposes between surveys. However, the following spring marked the second consecutive year of extremely low outmigration, with fewer than 6,000 smolts counted migrating through the Cultus fence (spring of 2018; DFO Stock Assessment). A winter survival rate of only 1.6% was observed from fall fry to outmigrating smolts in 2018. This was the second lowest year on record (after 2017) for both total lake outmigrants and wild (unmarked) lake outmigrants.

A number of factors are contributing to poor freshwater survival in Cultus Lake (DFO 2018b, Putt et al. 2019). This includes human-caused impacts on lake nutrient loads, which are acting in combination with climate change drivers, as highlighted in a recent publication (Putt et al. 2019). Additionally, since May 2018, smallmouth bass have been reported in Cultus Lake. Though a preliminary examination of stomach contents of bass did not show evidence of predation on juvenile Sockeye, smallmouth bass are known to prey on them in other systems where they've been introduced (e.g. Fritts and Pearsons 2004; Tabor et al. 2007). This invasive predator likely represents yet another threat to the recovery of Cultus Sockeye.

Additional fry data are available for the 2016 brood year from the Nadina and Weaver spawning channels. The Nadina River spawning channel had average egg-to-fry survival, while survival in Weaver Channel was slightly below average (DFO Salmon Enhancement Program).

As the 2017 autumn gave way to winter and then to spring 2018, overall air temperatures were below normal, then transited to a very warm May where maximums were 4–5°C above normal (ECCC, PCIC). Though there is little information on the impact of overall winter air temperature on over-wintering fry survival, cooler spring temperatures in March and April of 2018 may have limited opportunities for pre-smolt growth for Shuswap and Cultus Sockeye, populations known to feed in the spring prior to outmigration.

Outmigrating smolts were enumerated at the outlets of Cultus and Chilko Lakes (Cultus presented above). The smolt outmigration (9.1M) in Chilko Lake was in the lower third of the historical range. Freshwater survival in Chilko Lake, measured as the number of outmigrating smolts per EFS, was slightly lower than expected (Figure 11), as was the length of age-1 smolts. Researchers note that the 2018 freshet began a week early at Chilko Lake, whereas timing of the smolt migration was a few days late. This may have introduced a negative bias in the estimated smolt abundance due to the premature removal of the counting weir on account of rising water levels.

## 3.4 JUVENILE DOWNSTREAM MIGRATION IN THE FRASER RIVER: SPRING 2018

The outmigrating smolts of 2018 began their downstream journey in cooler than average spring air temperatures that transitioned to a very warm May, where maximums were 4–5°C above normal (ECCC, PCIC). The Fraser River freshet was early, and high, with record high day-of-year flows in May (Figure 12) enabled by the above normal snowpack in the Fraser basin heading into spring (Ministry of Environment River Forecast Centre ).

High flow conditions, as observed in May 2018, are associated with reductions in water clarity, which can positively affect survival during outmigration through reducing predation on Sockeye smolts (Ginetz and Larkin 1976, Gregory and Levings 1998). However, high suspended sediments (Martens and Servizi 1993), and other factors associated with high discharge may negatively influence juvenile salmon.

River temperatures can affect downstream survival by influencing both the optimal smoltification window (Bassett 2015) and swim performance (Brett 1971). Overall, as most smolt populations arrived and migrated along the mainstem Fraser River, they were exposed to near-average water temperatures (ECCC; Figure 13), contributing to neutral conditions in the Fraser mainstem for most smolts in 2018.

However, outmigrating smolt populations can experience different levels of discharge and temperatures based on conditions in their individual river systems, and differences in their migration timing. The effect of river flows on smolt survival in 2018 was, therefore, considered variable, due to variability in migration timing across populations, some of which would have migrated during well above average flows. Chilko smolts experienced above average discharge in the Chilcotin River and near average water temperature during their outmigration (Figure 14 and Figure 15).

The biological condition of outmigrating salmon smolts can be used as a measure of habitat quality and overwinter survival, and as a potential predictor of future smolt-adult marine survival. A connection between juvenile size and marine survival has been previously documented in Sockeye salmon (West and Larkin 1987), though the connection has not been made consistently for other species (Bailey 1971, Henderson and Cass 1991, Freshwater et al. 2017). Previous work on smolt condition has focused on using length and weight to infer carrying capacity of lake habitats (Hume et al. 1996, Griffiths et al. 2014), and to create a mechanistic link for trophic relationships (Ballantyne et al. 2003, Ravet et al. 2010). Body lipids, however, may be a better predictor of survival, than body size (Gardiner and Geddes 1980, Post and Parkinson 2001, Simpkins et al. 2003, Biro et al. 2004). Lipid content can be used to infer early marine survival, based on the connection between energy status and time to starvation (Naesje et al. 2006), as well as more indirect associations. For example, energy status is linked to immune response (Martin et al. 2010), which can affect infection status which in turn has been connected with downstream survival (Jeffries et al. 2014) and predation risk (Miller et al. 2014) in Sockeye salmon smolts. Predator risk can also change as a function of lipid content through changes in swim performance (Litz et al. 2017; S. Wilson SFU pers. comm.).

Smolts were sampled for size and lipid content at the outlets of Chilko, Seton, and Cultus Lakes. Both Chilko and Cultus smolts had lower than expected lipids. Over 50% of sampled Chilko smolts were below the presumed 2% lipid threshold value, and had lower than expected lipids, based on the brood year EFS abundance. Chilko smolt body sizes, estimated at the outlet of Chilko Lake, were also below the 70 year average, and slightly below expectations based on brood year EFS numbers (Figure 16). The weight to length ratio of Chilko smolts was lower than expected, and an unexpectedly high proportion of juveniles remained in the lake for a second winter, delaying their seaward migration until spring 2019.

Conversely, as was the case in 2017, smolts from Seton Lake had high lipid values and large average body size compared to other populations in the Fraser. Researchers note that it is difficult to interpret the combined effect of environmental and biological conditions on population-level survival, and that sample sizes were small for some stocks.

At Mission, 2018 smolt lengths varied by stock, with Anderson-Seton being the largest and Chilko the smallest (Tadey 2020). In terms of smolt outmigration timing, fifty percent of outmigrating Chilko smolts passed Mission in the Lower Fraser River by May 7$^{th}$ (Tadey 2020). Though similar in timing to the previous year, this was later than the average recorded for the years 2012 – 2016 (since 2012, dates have ranged from April 23$^{rd}$ to May 7$^{th}$).

## 3.5 JUVENILE MARINE STAGE: SPRING 2018 – PRESENT

Most Fraser Sockeye returning in 2020 entered the ocean in spring 2018, and will remain in the Northeast Pacific Ocean until summer 2020, when they will return to their spawning grounds. The marine heatwave ("The Blob") that was present in Northeast Pacific sea surface temperatures (SST's) from 2013-2016, and moved to depth in 2017, had dissipated by the time the 2020 Fraser Sockeye cohort entered into the marine environment (Figure 17). However, the effects of this heatwave on lower trophic levels remain (Boldt et al. 2019), and new marine heatwaves were observed in fall 2018, and again in 2019 (Boldt et al. 2019, Hannah et al. 2019).

The 2020 Fraser Sockeye cohort entered the Strait of Georgia in the spring of 2018, where they reared for four to six weeks. Despite the continued global warming trend, and recent marine heatwaves in the Northeast Pacific, juveniles entered into near normal conditions in the SoG with regards to water temperatures, salinity (Figure 20), and phytoplankton abundance. Water temperatures in the SoG were cool, likely associated with a La Niña event that was in place for the first half of the year (Ross and Robert 2019). Salinity conditions were also near normal.

Winter stratification off the West Coast of Vancouver Island was stronger in 2017/18 than 2016/17, indicating a potential for weaker mixing of the water column and reduced nutrient supply from deep waters to surface waters (Ross and Robert 2019). Given the presence of a marine heatwave in the fall of 2018, it is likely that 2018/19 also had weaker than normal winter mixing (Ross and Robert 2019). The upwelling of nutrient rich water off the WCVI is an indicator of marine coastal productivity across trophic levels, from plankton to fish to birds. In 2018, the timing and magnitude of upwelling showed mixed conditions for productivity and fish growth — the intensity of the upwelling in 2018 was weak, associated with low productivity, however the timing of the transition to upwelling was early, associated with high productivity (Figure 18, Hourston and Thomson, 2019).

The timing and duration of the spring phytoplankton bloom in the Strait of Georgia was consistent with average conditions over the past 20 years (Costa 2019, Allen et al. 2019). Phytoplankton are the base of the food web in this ecosystem, and a factor in the well-being of organisms at higher trophic levels. Zooplankton feed on phytoplankton, therefore their production is linked. Zooplankton are a key component of Fraser Sockeye diets during their juvenile marine residence. SoG zooplankton biomass in 2018 was near the long-term average, with peaks in May and June for the North and Central areas, respectively (Young et al. 2019). Surveys measuring abundance anomalies were positive for some common fish foods, including hyperiid amphipods, but closer to the long-term mean for decapods and euphausiids (Figure 22, Young et al. 2019). Small copepods (such as *Pseudocalanus* spp. and cyclopoid-type copepods) were very abundant but they contributed little to the overall biomass. Large copepods are known to be lipid-rich and more favourable for fish growth. Of those sampled, *Eucalanus bungii* made up the majority of the large copepod biomass in the Strait of Georgia during the spring, representing a change from the typical spring dominant large copepod, *Neocalanus plumchrus* (Young et al. 2019).

Of note, after a three-year absence from the Strait of Georgia, harmful algal blooms occurred in early June both in the SoG and on the WCVI. The harmful algal bloom in the SoG resulted in high aquaculture fish mortality in Jervis Inlet (Esenkulova and Pearsall 2019, Haigh and Johnson 2019, Nemcek et al. 2019). This bloom was linked to the early and high Fraser River freshet and hot weather in May-June (Esenkulova and Pearsall 2019, Haigh and Johnson 2019, Nemcek et al. 2019). This can have implications for wild migrating fish, though monitoring this is a challenge.

Juvenile salmon survey catches in the SoG were average or better than average across species (Neville 2019). The catch per unit effort (CPUE) for Sockeye was average, but higher than the previous four years on this cycle. Juveniles were of average condition, and above average in length.

In Queen Charlotte Strait and Southern Queen Charlotte Sound, the CPUE for Sockeye was above the long-term average for non-dominant (excludes dominant Late Shuswap years) cycle years between 1998 and 2018 (Figure 23). Though the overall condition across all stocks was average (Figure 24), compared to within-stock averages the condition of Chilko juveniles was above average, Nadina was average and Birkenhead was below average (Figure 25).

During fall of 2018, La Niña conditions in the Northeast Pacific began to dissipate, and a weak El Niño took its place (Ross and Robert 2019). This was accompanied by delayed and reduced winter cooling, and subsequent marine heat waves were observed in the Gulf of Alaska. The magnitude of temperature anomalies in the fall of 2018 (with respect to the 1971-2000 baseline) in the Gulf of Alaska was 2-3°C above the average. As the year progressed, warmer than normal temperatures were recorded at all depths.

Phytoplankton biomass and community composition off the WCVI were generally within the range of past values. The exception was an unusual increase in biomass, and the relative abundance of diatoms, at most sampling stations along Line P, which extends from the WCVI into the Northeast Pacific (Peña and Nemcek 2019). Conversely, zooplankton distribution off the WCVI still reflected the effects of the 2014-2016 marine heat wave (Figure 19, Galbraith and Young 2019, Fisher et al. 2020). Zooplankton communities were high in southern gelatinous taxa, with high water content and low nutritional value, such as hydromedusae, salps, doliolids, and ctenophores. Conversely, they were low in northern occurring crustaceans, with high protein and lipid content, such as copepods, euphausiids, amphipods, decapods (Galbraith and Young 2019). This community composition indicates poorer feeding quality for salmon.

## 3.6 PROPORTIONS

Proportions of five key stocks returning in 2020 were compared across programs representing the life stages for which we have information on relative abundances: EFS in 2016; and migrating juveniles at Mission, the SoG, the Discovery Islands, and Queen Charlotte Strait/Southern Queen Charlotte Sound in 2018 (Figure 26). Forecasted four year old returns in 2020 are also included in this comparison, using the 50% probability forecasts provided by DFO Fraser Stock Assessment (M. Hawkshaw DFO Stock Assessment pers. comm.). Relative abundances were compared for Chilko, Chilliwack, Nadina, Stellako, and Birkenhead, as these stocks had sufficient abundances to be evaluated across programs.

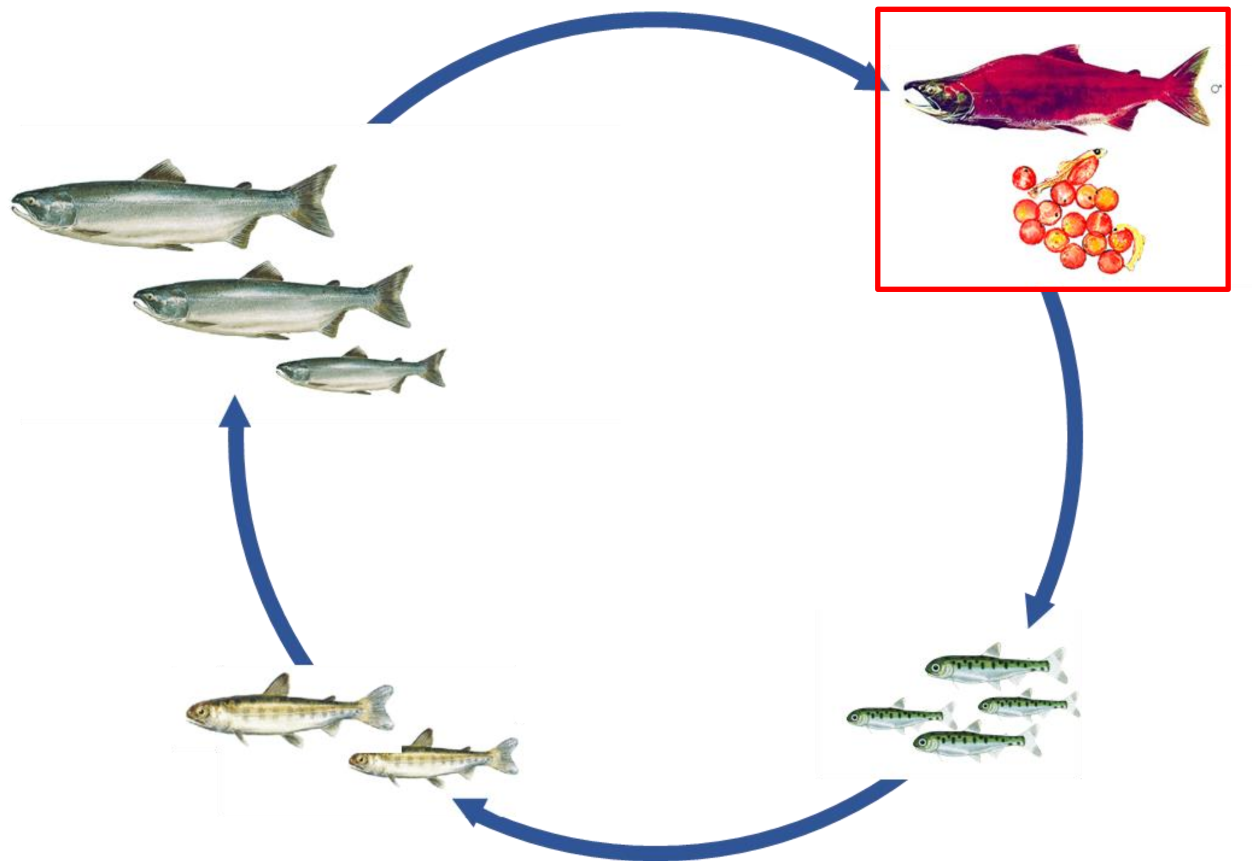
Chilko dominated the relative abundances sampled in most programs, representing ~45-60% of the five dominant stocks sampled in each (Figure 26). Chilko smolts, however, were observed in a lower proportion in the Mission juvenile survey, representing ~30% of the relative abundance. Interestingly, Chilliwack presented the opposite pattern. Chilliwack was "over-represented" in the Mission surveys, making up ~55% of the relative abundance, but only accounted for ~20% of the 2016 EFS, and ~10% of the four-year old 2020 forecast and juveniles surveyed in the SoG and Discovery Islands. Further, Chilliwack Sockeye were not captured in the Queen Charlotte Strait/Southern Queen Charlotte Sound surveys.

The pattern of over-representation of Chilliwack in the Mission surveys was encountered previously, on the same cycle line, in the 2016 Science Integration process (DFO 2016b). Juvenile samples at Mission have not been corrected for the differences in discharge that occur throughout the assessment period, and are likely biased, as discharge increases throughout the sampling period, and stocks demonstrate different outmigration timing. Notably, Chilliwack migrated earlier than Chilko in both 2014 and 2018, and Fraser River discharge peaked high and early in both of these years. Bias in the Chilliwack catch may also be caused by the location of the sampling program, which is just downstream of where Chilliwack Sockeye enter the Fraser River. Chilliwack returns in 2016 were more closely aligned with their relative proportion in the 2012 EFS than in the 2014 smolt samples at Mission, though they did return in a higher proportion than forecast, relative to the other key stocks.

Nadina showed variable proportions across the sampling programs, with a very low proportion caught at Mission (~2%) relative to EFS (10%), and a very high proportion caught in the Queen Charlotte Strait/Southern Queen Charlotte Sound program (40%) caught in two tows. Stellako and Birkenhead had somewhat more consistent proportions across programs, though Stellako was also not caught in the Queen Charlotte Strait/Southern Queen Charlotte Sound samples.

# 4 DETAILED OBSERVATIONS FROM FRASER SOCKEYE LIFE STAGES

## 4.1 BROOD YEAR SPAWNERS AND EGG STAGE



### Upstream Migration and Spawning: Summer/Fall 2016

- Overall, summer air temperatures (June-August) in the Fraser basin were above normal (climatology from 1971-2000) in 2016: maximum air temperatures were above normal in June and August and below normal in July (Environment and Climate Change Canada (ECCC), Pacific Climate Impacts Consortium (PCIC)).

- Summer precipitation was varied throughout the Fraser basin in 2016; notably, July precipitation was approximately 50-125% above normal (climatology from 1971-2000) throughout most of the watershed (ECCC, PCIC).
- Lower Fraser River water temperatures were predominately above average during adult Sockeye salmon migration, and notably above 19°C for mid-July to late-August when Sockeye from the Summer and Late run-timing groups are present (Figure 4).
- Discharge in the lower Fraser River during adult Sockeye salmon migration was below the 108-year median (Figure 5).
- Water temperatures in the Nechako River – a migratory corridor for Early Stuart and some Early Summer and Summer run-timing populations – were above 20°C during portions of the migration windows for these populations.
- Exposure to water temperatures >19°C during upstream migration has been associated with impaired reproductive development and reduced gamete viability (Macdonald et al. 2000).
- Parental experience during upstream migration can have intergenerational effects on offspring survival and phenotype. For example, high maternal stress can affect offspring swim performance and predator avoidance behaviour (Tierney et al. 2009, Sopinka et al. 2014).
- Overall, fall (September-November) air temperature anomalies in the Fraser basin varied by month: September and October were cooler than normal, whereas November was very warm, with air temperature anomalies at least 4–5°C above normal (ECCC, PCIC).

Spawner Surveys

- The number of Fraser Sockeye that returned to the spawning grounds in 2016, ~487,000, was half the cycle average of ~944,000. Escapements to the majority of the numerically dominant CUs in 2016 were below cycle line averages. Exceptions include the Pitt-ES and Nadina-Francois-ES CUs, which had escapements that were similar to cycle line averages.
- Four CUs comprised the majority (70%) of the 2016 aggregate Fraser Sockeye escapement (Chilko-S-ES, Harrison-River, Pitt-ES, and Chilliwack-ES). High precision methods were used to enumerate 78% of the aggregate Fraser escapement.
- Sex ratios were close to 50:50 for most CUs; exceptions included Nadina-Francois-ES (63% females), Chilliwack-ES (57% females), North Barriere-ES (60% females), and Harrison (U/S)-L (Weaver) (38% females).
- Spawning success for the Fraser Sockeye aggregate was average in 2016 (90%), but there was high variability across populations, and a number of CUs had below-average success.
- Timing of Sockeye arrival on the spawning grounds, and peak spawning, were well within normal ranges for most Fraser populations in 2016. Exceptions included the Takla-Trembleur-Early Stuart CU, which had a somewhat protracted spawning period, and the Lillooet-Harrison-L CU, which arrived and spawned earlier than normal.
- Sockeye were generally in good condition upon arrival on the spawning grounds with little sign of migration stress, with exceptions. Elevated levels of pre-spawn mortality were observed in early arrivals at the Takla-Trembleur-Early Stuart and Raft River (Kamloops-

ES) spawning areas, and there was evidence of migratory difficulties (e.g., wounds) in early arrivals at the Chilko-S-ES and Francois-Fraser-S spawning areas.

- Water temperatures and streamflows in the terminal spawning areas were generally within normal ranges in 2016, with some exceptions. High flow conditions occurred in the Lillooet-Harrison, North and South Thompson, and Quesnel systems in September. This may have contributed to negatively biased escapement estimates for the Kamloops-ES and Shuswap-ES CUs. Additionally, a debris flow event occurred in Portage Creek in November 2016 at the tail-end of the Sockeye spawning period. This possibly impacted egg-fry survival, but did not affect the escapement estimate, which was derived from a visual live count during the peak spawning period.

Biological Condition of Spawners and Gametes

- The physiological condition of Sockeye salmon captured from Harrison River (n=20), Gates Creek (n=20), Upper Chilliwack River (n=18) and Chilko River (n=20) spawning areas were assessed in 2016. Harrison and Gates fish were fresh arrivals to the spawning grounds, and Chilliwack and Chilko were active spawning fish. Plasma ion and metabolite values from the fresh arrival Harrison and Gates Sockeye indicated that they were in good condition, with chloride levels (mean + SD; Harrison 140 + 7 mmol/L; Gates 134 + 6 mmol/L) and glucose levels (Harrison 4.9 + 1.2 mmol/L; Gates 5.5 + 1.0 mmol/L; (Shrimpton et al. 2005) within normal ranges. Levels of ions and metabolites in active spawners from Chilko and Chilliwack were consistent with senescence and healthy active spawning (Chilko: chloride 125 + 20 mmol/L, glucose 8.8 + 4.9 mmol/L; Chilliwack: chloride 125 + 9 mmol/L, glucose 5.2 + 1.9 mmol/L; see Figure 6).
- Fertilization success to 4-cell stage was assessed in the field for 12 females and 12 males randomly caught in Chilko River; a minimum of 3 unique pairings were completed for each individual. Fertilization success was high, >89%, for all females, with the exception of a single female. Maximum fertilization success for all males was over 94%. These values are considered high in comparison to previous work (Whitney et al. 2013; Sopinka et al. 2016).
- Physiological condition and fertilization success results were based on a limited sample size and populations. This should be considered when interpreting these snapshots in time and space for population-level effects.
- Quantifying the effect and uncertainty of the parental experience on future recruitment is challenging.

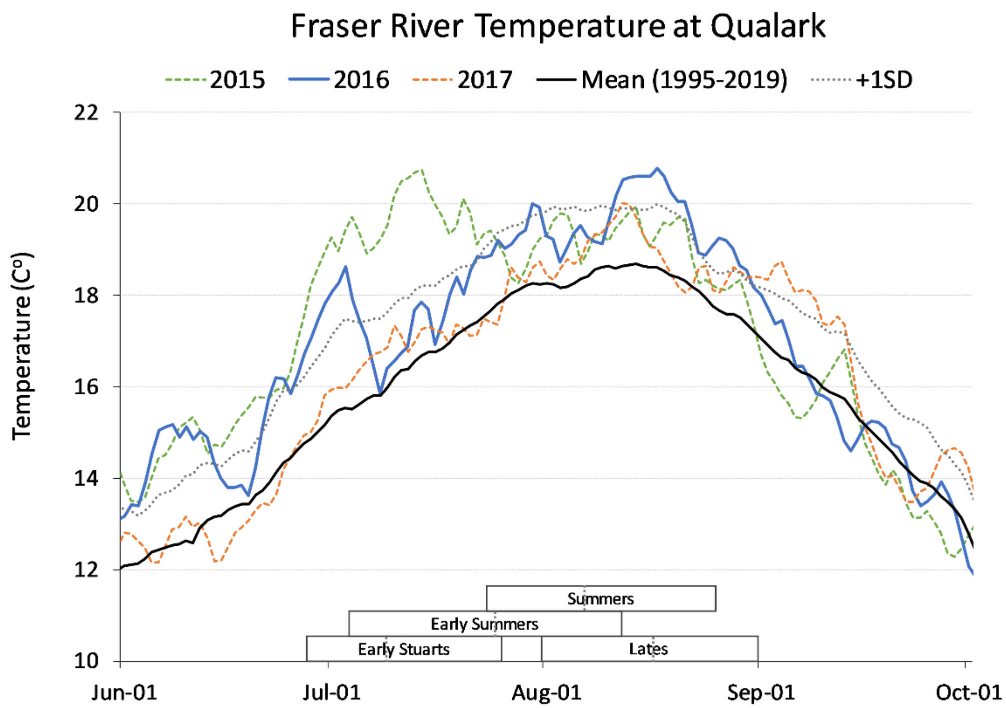



**Figure 4.** Lower Fraser River water temperature at Qualark during adult Sockeye salmon spawning migration for the 2020 returning cohort's spawning parents in 2016 (blue line), relative to 2015 (green dashed line), 2017 (orange dashed line), median (black line), and plus or minus one standard deviation (black dashed line). Each run-timing group block depicts the medial 95% of migrants estimated to have passed the Mission hydroacoustic site in 2016; the associated dotted grey lines depict the 50% migration date for each group. Data sources for this figure include the DFO Environmental Watch Program and the Pacific Salmon Commission

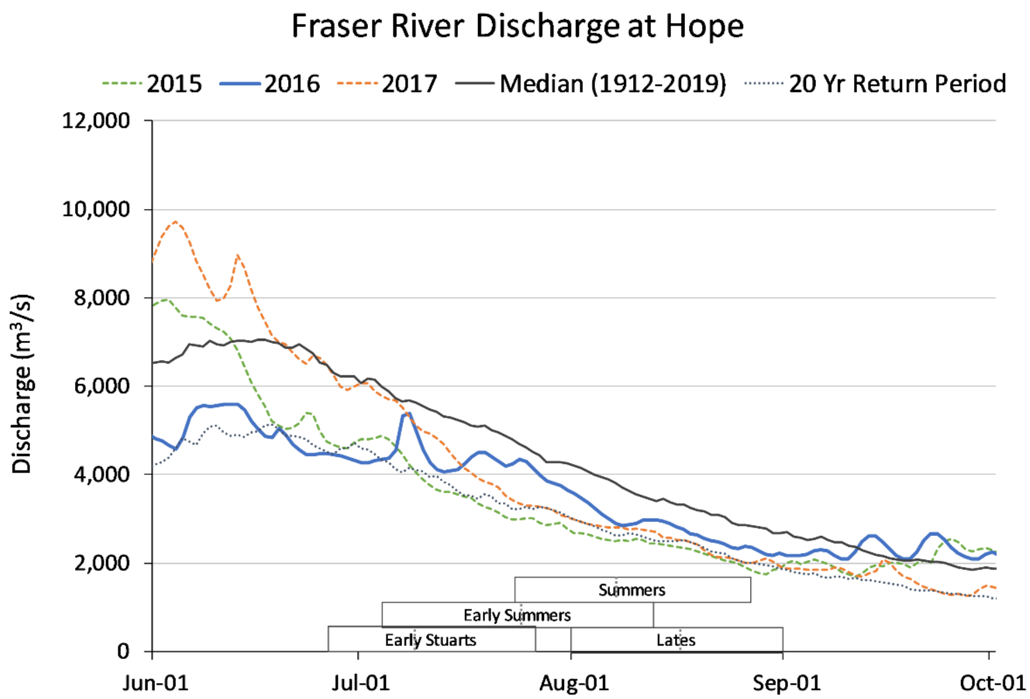



**Figure 5.** Lower Fraser River discharge at Hope during adult Sockeye salmon spawning migration for the 2020 returning cohort's spawning parents in 2016 (blue line), relative to 2015 (green dashed line), 2017 (orange dashed line), median (black line), and 20 year low return period (black dashed line). The 20-year low return period is based on day-of-the-year values, and represents a one in 20 year event. Each run-timing group block depicts the medial 95% of migrants estimated to have passed the Mission hydroacoustic site in 2016; the associated dotted grey lines depict the 50% migration date for each group. Data sources for this figure include the ECCC Water Survey of Canada and the Pacific Salmon Commission.

.

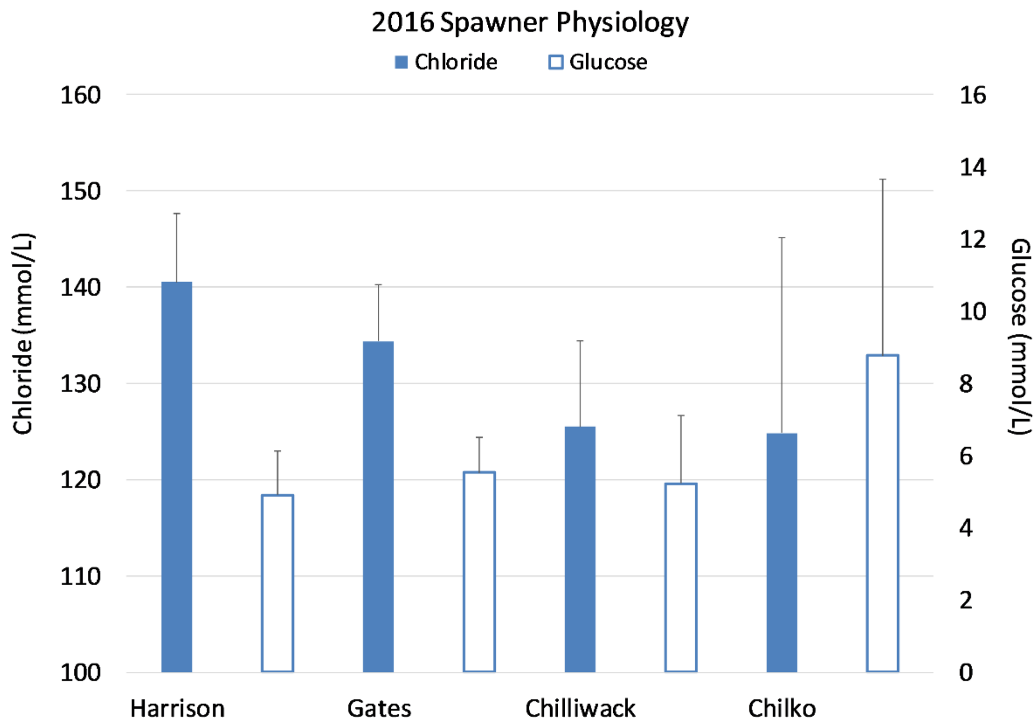



**Figure 6.** Plasma chloride (blue filled bars) and glucose (white filled bars) results for Sockeye salmon arriving at Harrison River and Gates Creek, as well as spawning Sockeye salmon from Upper Chilliwack River and Chilko River in 2016. The values are within normal ranges expected for healthy arrivals and spawners (Patterson et al. 2004, Shrimpton et al. 2005, Hruska et al. 2010, Jeffries et al. 2011). The data for this figure was provided by the DFO Environmental Watch Program.

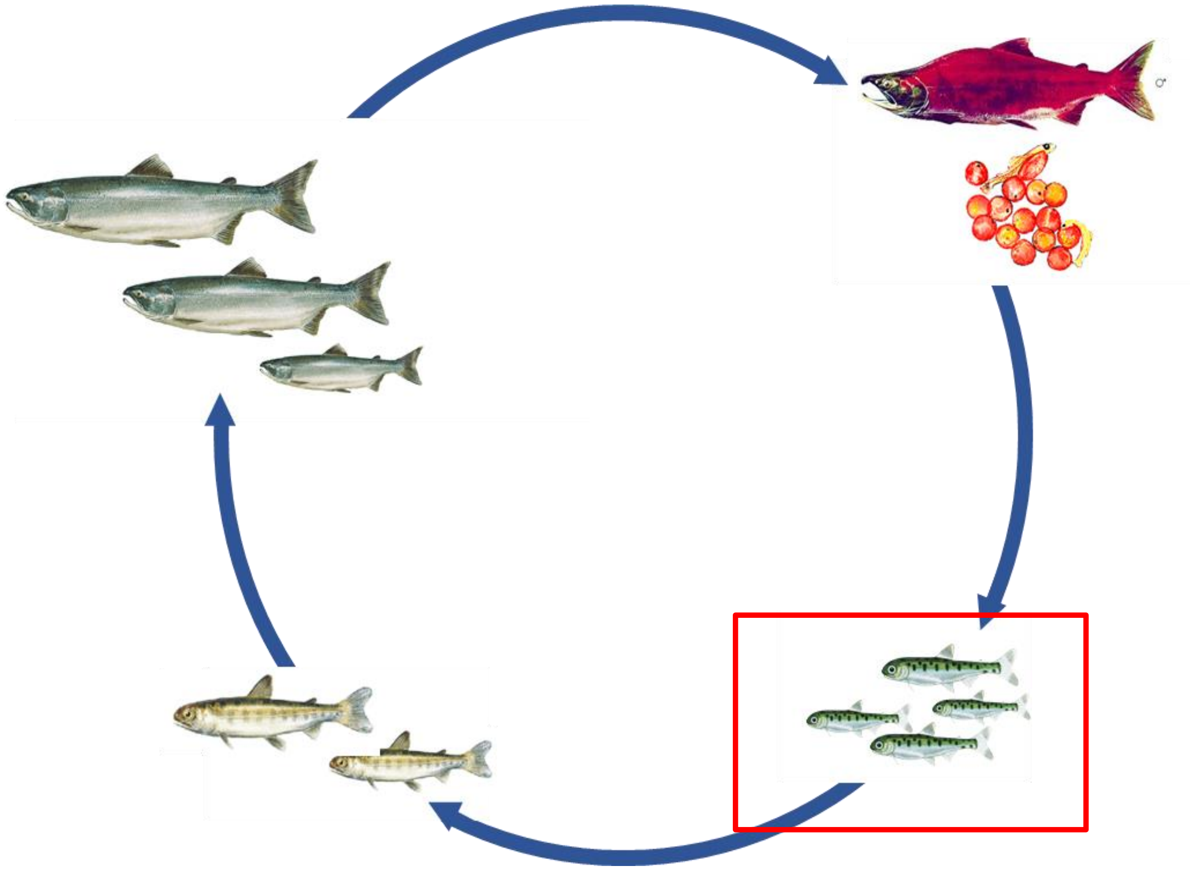
## Overwinter Incubation: Winter 2016

- As mentioned above, overall fall air temperature anomalies varied in the Fraser basin: maximum air temperatures in September and October were below normal, whereas maximum and minimum air temperatures in November were well above normal (PCIC), with the potential to influence incubation degree days and thus hatch timing and emergence, particularly in the southern portion of the basin.
- Overall winter (December-February) air temperature anomalies were approximately 3°C cooler than normal across the Fraser basin, the exception being warmer than normal anomalies observed in the upper watershed in January (ECCC, PCIC).
- Environmental conditions are not assessed by stock assessment field crews in spawning areas after the escapement enumeration projects have ended. Environmental events that occur between the end of the spawning period and the following spring that could affect egg-to-fry survival are not recorded for the majority of systems.
- High water temperatures during spawning and incubation have direct negative effects on fertilization success and embryo survival that are population specific (Whitney et al. 2014). Incubation temperature affects swim performance (Burt et al. 2012) and phenology of hatch (Whitney et al. 2014) and emergence (Macdonald et al. 1998). Low

water levels can cause dewatering and, in combination with very cold air temperatures, intergravel freezing and embryo mortality (Cope and Macdonald 1998). Conversely, high flows can scour eggs from the incubation environment and increase suspended sediment concentrations, reducing embryo survival (Thorne and Ames 1987, Montgomery et al. 1996, Newcombe and Jensen 1996, DeVries 1997).

- Day-of-year record flows were observed in the Nadina River in mid-November. Abnormally high winter flows increase the risk of redd scouring and suspended sediments during incubation.
- Early Stuart spawning tributaries were unusually warm in early November, during the incubation period. Warm temperatures can have negative effects on fertilization success and early embryo survival for temperature sensitive streams within this watershed (e.g. Frypan Creek; Braun et al. 2015), as well as influence the timing of fry outmigration (Macdonald et al. 1998).
- Nadina River spawning channel had average egg-to-fry survival (2016 brood year survival: 27%; 12-year average survival: 30%); Weaver Creek spawning channel had slightly below average egg-to-fry survival (2016 brood year survival: 38%; 12-year average survival: 47%; DFO Salmon Enhancement Program).

# 4.2 JUVENILE FRESHWATER STAGE



## Emergence and Migration to Rearing Lakes: Spring 2017

- Spring (March-May) air temperatures in the Fraser basin were varied: maximum air temperatures were cooler than normal for March and April, and warmer than normal for May (ECCC, PCIC).
- Timing of the Fraser River freshet was normal, with discharge well above the median for early June (ECCC).
- Downstream migration timing of emergent fry is dependent on incubation temperatures as well as proximate cues from water temperature and discharge (Macdonald et al. 1998). Population variation in mean fry migration timing has been associated with food availability in rearing lakes (Brannon 1987).

## Lake Rearing: Summer - Fall 2017

- Overall, summer (June-August) maximum air temperatures were above normal, especially for the southern portion of the basin. Fall (September-November) air temperature anomalies were varied: notably, September was very warm throughout the basin (ECCC, PCIC).
- Water temperature in the lower Fraser River was predominately above average throughout the summer of 2017, with temperatures 2–3°C above average for early September (DFO Environmental Watch website).
- Typically, fry transit to feed and grow from April to June in lake littoral zones, where habitat availability is related to water levels (Williams et al. 1989, Morton and Williams 1990).
- Warm spring conditions are connected to high water levels during fry migration, potentially increasing littoral zone habitat availability.
- The length of the growing season is temperature-dependent (Schindler et al. 2005), and was likely long for many Fraser Sockeye populations in 2017.
- Juvenile Sockeye growth is temperature- and ration-dependent. The optimal temperature for growth increases with increasing food availability (Brett 1971), so that warmer lake temperatures can increase growth when prey are not limiting (Edmundson and Mazumder 2001).
- The benefits of the long growing season or expanded littoral zone habitat assume that habitat is not limited by a density-dependent response. Ultimately, there are both density-dependent and density-independent relationships with survival during the fry rearing stage (Ricker 1954).

Bowron Lake

- Prior to 2017, The last, and only previous acoustic survey in Bowron Lake took place in 2004. The lake was surveyed on 18 September, 2017, and an estimate of 70,631 ± 62,480 (95% CI) juvenile Sockeye was produced. A large abundance of Kokanee was also observed (423,758 ± 240,833). The high variability in the Sockeye estimate was largely owing to the fact that we only caught juvenile *O. nerka* that were genetically identified as Sockeye in the northwest section of the lake.
- Curiously, the abundance of Sockeye fry in Bowron Lake yielded a ratio of 981 fall fry per effective female spawner, based on observations of 72 EFS in 2016. This is unusually high, and may indicate either an overestimate of juvenile Sockeye, or an underestimate of EFS. The lake was surveyed again in 2018 and in 2019, and while final numbers for 2019 have not been produced as of the time of this report, there was an abnormally high ratio observed in 2018 as well (1,863 fall fry/EFS).

Fraser Lake

- Fraser Lake was surveyed on 14 October, 2017. This was the first acoustic survey conducted on this lake since 1997. A total of 3,120,024 ± 404,166 juvenile *O. nerka* (i.e. Sockeye + Kokanee) were estimated for the lake. Due to a mechanical failure, the trawl net could not be deployed, and thus there was no species composition estimate to apply to the acoustic abundance estimate. Notably, all *O. nerka* genetically sampled from a trawl conducted on Fraser lake in 2018 were identified as Sockeye. This may suggest that there are relatively few Kokanee in Fraser Lake, and that the 2017 estimate could be fairly representative of the juvenile Sockeye population at that time. Given an estimated 15,775 EFS in 2016 (Stellako), there was up to 198 fall fry per EFS.

- Fraser Lake is a highly productive lake, that has historically been considered to be underutilized in terms of Sockeye production. Shortreed et al. (1996) found that Fraser Lake had the highest productivity in the Fraser watershed in terms of photosynthetic rate (332 mg C/m2/day), with excellent rearing habitat, that could support a maximum smolt production of 27 million. Historic acoustic surveys for this lake have typically shown much lower output, though a high fry abundance was observed for the 1988 brood year (Figure 7).

Francois Lake

- Francois Lake was surveyed from the 15th to the 16th of October, 2017. This was the first acoustic survey of the lake since 1992. As with Fraser Lake, mechanical failure prevented use of the trawl, and thus a *O. nerka* survey was conducted. A total of 5,648,608 ± 1,415,957 age-0 sized *O. nerka* was estimated for the lake. Historic surveys of Francois Lake conducted by DFO have not distinguished between Sockeye and Kokanee juveniles, and thus there is no previous data available to give an indication of Kokanee to Sockeye ratios in this lake. Densities of fish tended to be higher in the eastern half of the lake, ranging from 277 fish/ha to 284 fish/ha. Western sections of the lake saw densities ranging from 132 fish/ha to 211 fish/ha.
- Shortreed et al. (1996) also identified Francois Lake as an underutilized rearing lake, though the system was thought to be limited by spawning ground availability. The photosynthetic rate in Francois Lake (163 mg C/m2/day) was likened to that of Shuswap at the time (171 mg C/m2/day). Maximum smolt production was estimated at 72 million fish.

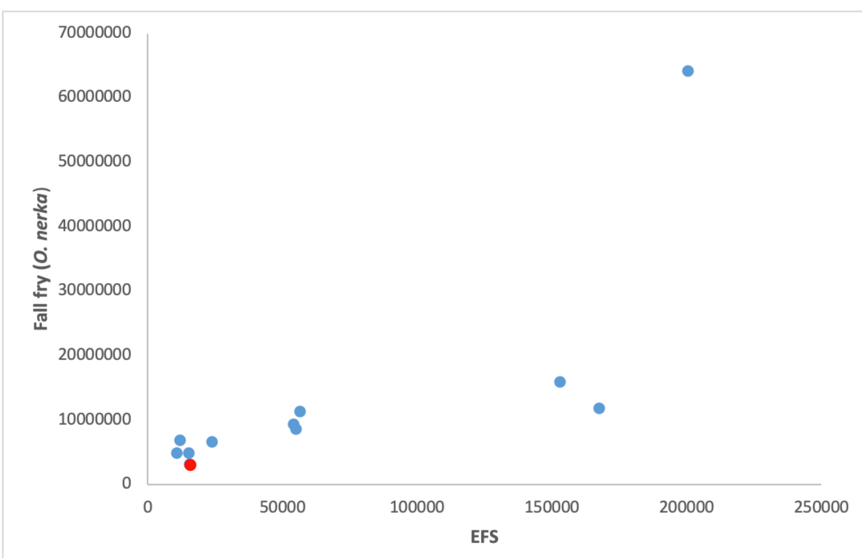



**Figure 7.** Fall fry plotted against EFS for all historic acoustic surveys of Fraser Lake. The red dot indicates data from the 2016 brood year.

<u>Quesnel Lake</u>

- EFS returns to Quesnel in 2016 were very low, with only 213 fish counted primarily in the Mitchell and Horsefly rivers (DFO Stock Assessment data). With so few spawners for the system, it was anticipated to be a challenge to collect enough juvenile *O. nerka* to develop reliable estimates of Kokanee and Sockeye. Despite the low numbers, a survey was conducted on Quesnel Lake between the 15th and 17th of September 2017, with the primary objective of collecting additional samples for metal contaminants analysis following on the 2014 Mount Polley mine tailings pond spill.
- As anticipated, the catch of age-0 *O. nerka* was prohibitively low for parsing out Kokanee, and thus an estimate of 2,774,397 ± 1,115,560 (95% CI) juvenile *O. nerka* was made for the entirety of the lake. Historic fall fry per spawner is plotted in Figure 8, though it should be noted that several of the data points corresponding to low EFS are mixed Kokanee and Sockeye fry. Densities were fairly consistent across all arms of the lake, ranging from a low of 82 fish/ha in the southern portion of the North Arm to 178 fish/ha in the eastern part of the East Arm.

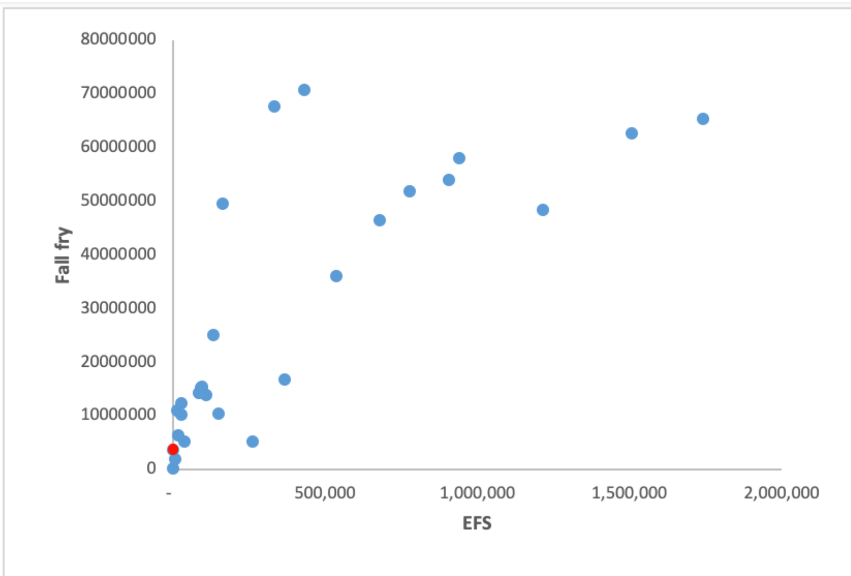



**Figure 8.** Historic acoustic fall fry estimates from most years between 1976 and 2017 are plotted against corresponding brood year EFS for Quesnel Lake. The red dot indicates data from the 2016 brood year. Although not noted here, the data points to the far left of the plot are likely to have a substantial influence by resident Kokanee juveniles.

<u>Chilliwack Lake</u>

- Summer and fall acoustic/trawl surveys were conducted on Chilliwack Lake in 2017 following on the dominant cycle line return in 2016. On August 19, an estimate of 1,697,069 ± 682,798 (95% CI) juvenile age-0 Sockeye was made, which yielded a lake-wide density of 1,429 fish/ha. The fall survey on November 1 reported a total of 1,156,882 ± 228,873 Sockeye; for a lake-wide density of 974 fish/ha. From summer to fall, a survival rate of 68% was thus observed. Using the DFO Stock Assessment EFS of 30,138 for the 2016 brood year, fry per effective female spawner estimates for summer and fall were 56.3 and 38.4 respectively. The fall fry/EFS is plotted in the context of historic survey data in Figure 9.

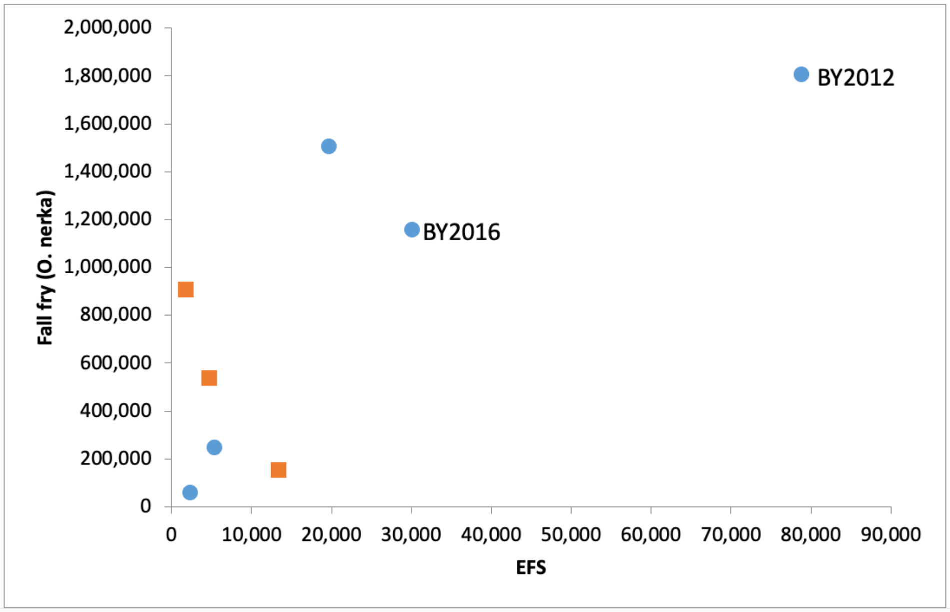



**Figure 9.** Fall fry plotted against EFS for all historic acoustic surveys of Chilliwack Lake. Blue dots represent true Sockeye estimates, while orange squares represent surveys in which Kokanee were not excluded from the estimate (i.e. *O. nerka* surveys). The 2016 brood year data point is identified (BY 2016).

- Relative to the previous dominant Chilliwack cycle line return, EFS in 2016 was 38% of the observed return in 2012, but the 2016 fall fry estimate was 64% of that from 2012, demonstrating higher fry/spawner rates. Summer to fall fry survival was also higher in 2016 than in 2012 for a similar in lake period (68% vs. 58%). As well, fry caught in the lake in 2017 were more than a gram heavier than those from the same time of year in 2013 (Figure 10). So while numbers were down from the last dominant cycle, higher in-lake survival and greater growth were observed as positive trends for the 2016 brood year Chilliwack fry.

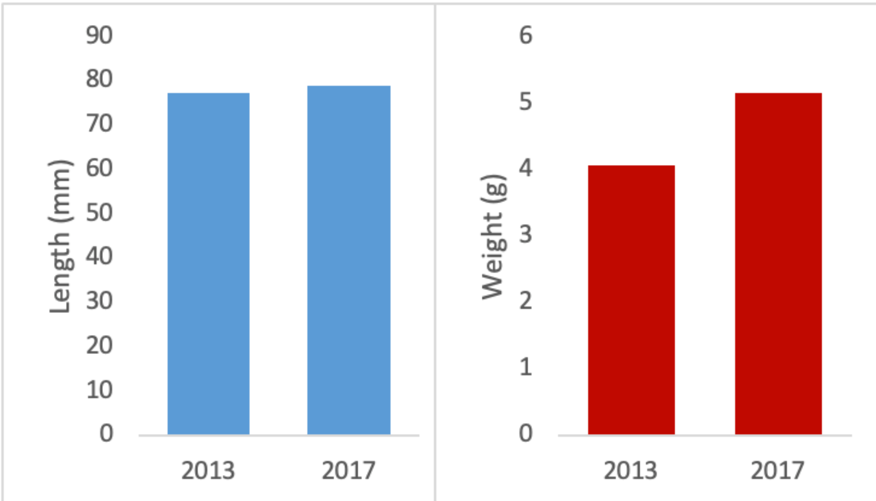



**Figure 10.** Comparison of mean length (blue bars) and weight (red bars) of Chilliwack fall fry sampled from the last two dominant cycle line years. Fry in 2013 were collected on October 22, and in 2017 on November 1. Though similar in length, fry in 2017 were a gram heavier.

Cultus Lake

- Cultus lake was surveyed in the summer (17 July) and fall (15 November) of 2017. The summer estimate was conducted prior to any hatchery reared Sockeye inputs to the lake, and an estimate of 270,870 ± 60,216 juvenile Sockeye was obtained. In fall, a population of 377,808 ± 63,804 fry was estimated following on releases of hatchery fry totaling 297,201 fish (DFO Salmonid Enhancement Program). Kokanee were also present in the catch in summer (31%) and fall (16%), though not to the same relative extent as observed in 2016 (86%).
- A recent publication highlights the high human-caused nutrient loads to the lake and increased lake temperatures caused by climate change, as contributors of poor lake survival from the egg to smolt stages (DFO 2018b; Putt et al. 2019).
- Smallmouth Bass (*Micropterus dolomieu*) were first reported in Cultus Lake in May of 2018. Since then, snorkel surveys conducted in the spring of 2019 confirmed multiple size classes and active spawning adults. Bass were primarily found near the outlet of Cultus Lake as well as Sweltzer Creek, just upstream of the smolt counting fence. While preliminary examinations of stomach contents did not show evidence of predation on juvenile Sockeye, Smallmouth Bass are known to prey on juvenile salmon in other systems in which they have been introduced (e.g. Fritts and Pearsons 2004; Tabor et al. 2007). This invasive predator likely represents yet another threat to the recovery of Cultus Sockeye.

# Overwinter in Lakes: Fall 2017 – Spring 2018

- During the fry overwintering period, winter (December-February) and spring (March-May) air temperatures were varied in the Fraser basin; notably, March and April air temperatures were below normal and May air temperatures were very warm, with maximums 4–5°C above normal (ECCC, PCIC).
- There is limited information on the impact of overall winter air temperature on overwinter fry survival.
- Below normal air temperatures in March and April of 2018 may have limited the opportunity for pre-smolt growth for Shuswap and Cultus populations – two populations known to feed in the spring prior to outmigration.

Chilko Lake

- The total smolt outmigration from Chilko Lake in 2018 was 9.1 million. This was the smallest outmigration observed since 1987. Age-1 smolts comprised 95% (8.6 million) of the 2018 smolt outmigration.
- There were 131 age-1 smolts produced in 2018 per EFS from the 2016 brood. This was slightly lower than the expected value of 135 smolts/EFS, based on the inverse loglinear relationship between freshwater productivity and brood EFS (Figure 11). Freshwater productivity for the 2018 age-1 smolt population was one of only two negative residuals in this relationship over the last 12 years (red dots).

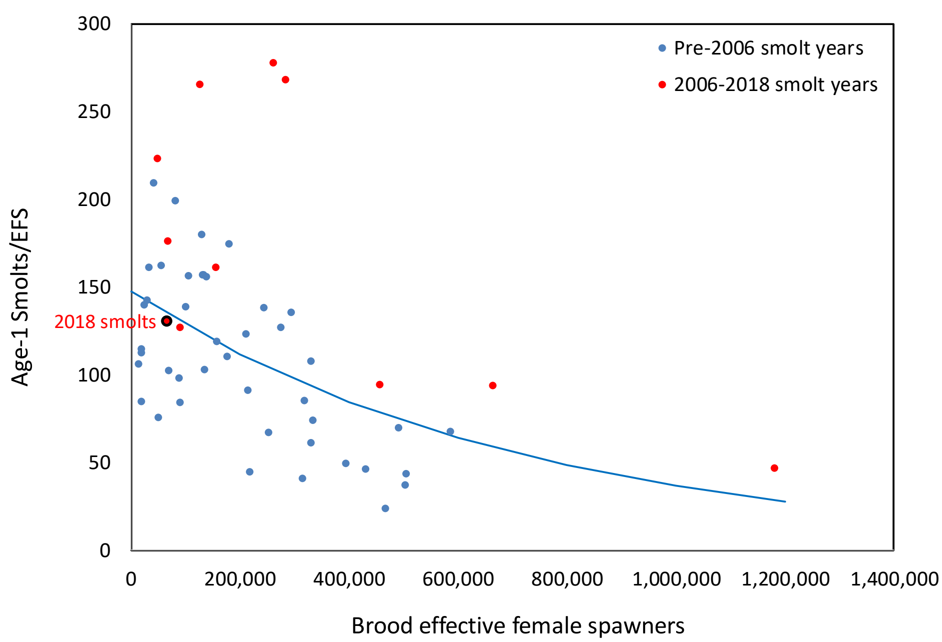
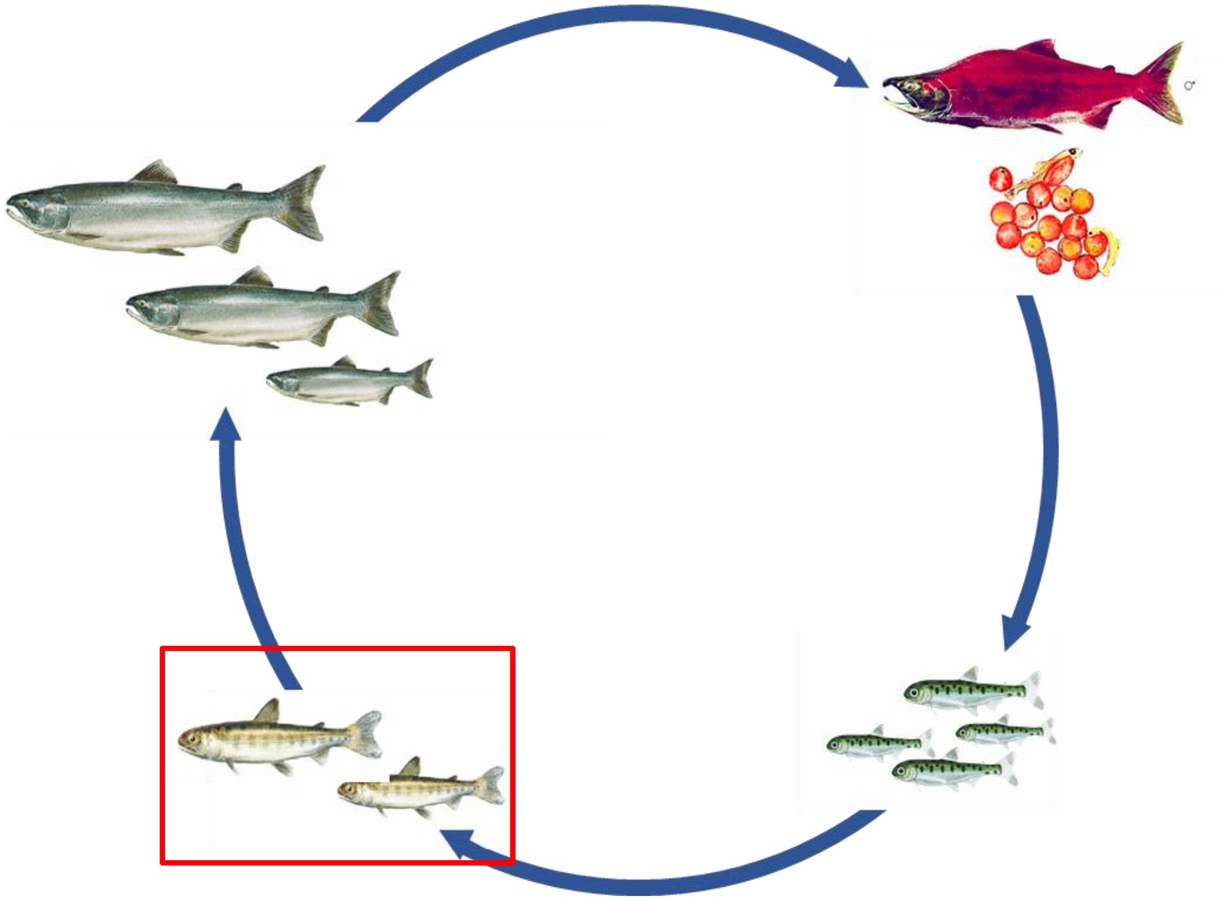



**Figure 11.** Freshwater productivity of juvenile Sockeye in Chilko Lake (number of age-1 smolts produced per EFS) by brood year abundance (EFS). The blue filled circles are pre-2006 smolt years, and the blue filled circles are the 2006 to 2018 smolt years. The blue solid line indicates predicted freshwater productivity based on the inverse log-linear regression relationship between the two variables.

Cultus Lake

- A total of 5,891 smolts naturally outmigrated from Cultus Lake in 2018, of which 3,166 were marked, indicating they were of hatchery origin and released in the lake as fry. This was the second lowest abundance on record for both total lake outmigrants and unmarked ('wild') outmigrants. An additional 53,566 hatchery smolts were released below the counting weir in Sweltzer Creek. Based on the 5,891 smolts that were counted through the fence in the spring of 2018 (5,887; DFO Stock Assessment), the overwinter survival rate from fall fry to outmigrating smolts was only 1.6%.

## 4.3 JUVENILE DOWNSTREAM MIGRATION



### Migration at Lake Outlets: Spring 2018

- Snowpack in the Fraser basin was above normal leading into spring 2018 (Ministry of Environment River Forecast Centre).
- As mentioned in previous sections, winter and early spring air temperatures in the Fraser basin were generally cooler than normal, with January and May being the exceptions. May was warm, with maximum air temperatures 4–5°C above normal (ECCC, PCIC).
- Early peak Fraser River freshet was observed: record high day-of-year flows were recorded in May 2018 (Figure 12).
- Fraser Sockeye populations experience different discharge exposure in the Fraser basin due to differences in the timing of median outmigration and flow regime.

- Water temperatures in the mainstem Fraser River were near average during outmigration (ECCC; Figure 13).
- We have assumed any large anomaly in environmental conditions has a higher risk of being negative given the potential lack of adaptation of fish to more extreme or uncommon conditions (e.g. Burgner 1991). This is in part because of limited information on population-level effects of adverse migration conditions on smolt survival.
- There can be large interannual variation in downstream smolt survival (Clark et al. 2016) and some of the potential discharge-related factors regulating this response include changes in predation risk with water clarity (Gregory and Levings 1998), decreases in predation with increases in water velocity (Ginetz and Larkin 1976), and negative influences on juvenile salmon caused by high suspended sediments associated with high discharge (Martens and Servizi 1993). Temperature can also affect downstream survival by influencing both the optimal smoltification window (Bassett 2015) and swim performance (Brett 1971).
- High flow conditions and associated reductions in water clarity during outmigration likely have a positive effect by reducing predation.
- Chilko smolts experienced above average discharge in the Chilcotin River and near average water temperature during their outmigration in 2018 (Figure 14; Figure 15).
- In 2018, the start of the spring freshet was about 1 week earlier than average (Figure 14). The smolt weir at Chilko was removed on May 12 due to high water, which is one of the earliest removal dates in the last three decades (1986-2017).
- The Chilko smolt 50% outmigration date in 2018, defined as the date when 50% of the run had moved through the counting fence at the outlet of Chilko Lake, was May 5, which was four days later than the long-term average 50% migration date (May 1). In 2018, the daily smolt passage estimate was < 1% for the last two days of weir operation, suggesting the smolt migration may have been largely complete by May 12. However, the three previous days each accounted for about 7% of the run, and the smolt migration was slightly late in 2018, so it is possible that the smolt outmigrant estimate for Chilko is biased low.
- The Cultus smolt 50% outmigration date in 2018 (April 26) was similar to the long-term average (April 24th).

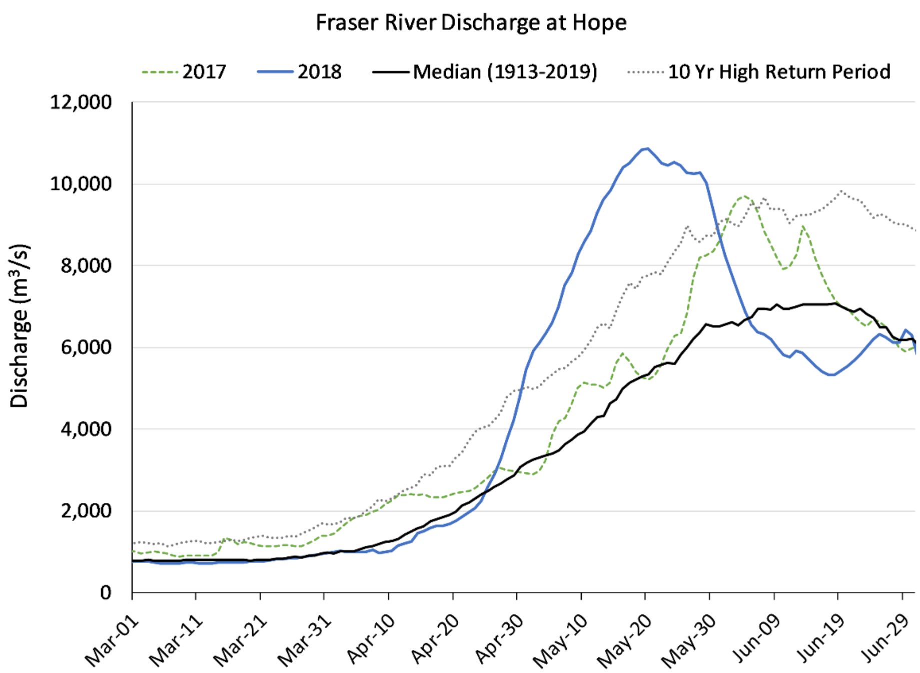



**Figure 12.** Lower Fraser River discharge at Hope during Sockeye salmon smolt outmigration in 2018 (blue line), relative to 2017 (green dashed line), the median (black line), and 10 year high return period (black dashed line). The 10-year high return period is based on day-of-year values, and represents a one in 10 year event. Data sources for this figure include the DFO Environmental Watch Program and the ECCC Water Survey of Canada.

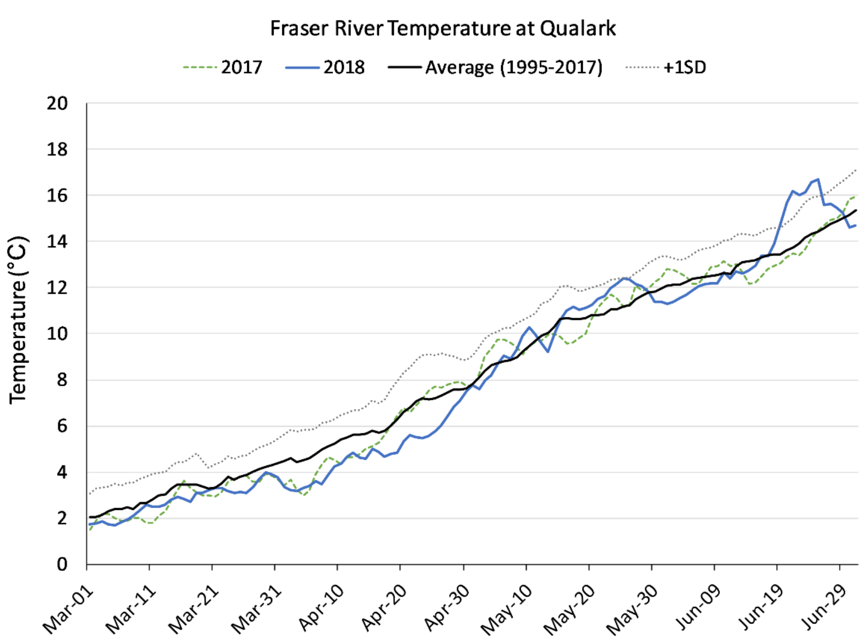



**Figure 13.** Lower Fraser River water temperature at Qualark during Sockeye salmon smolt outmigration in 2018 (blue line), relative to 2017 (green dashed line), the median (black line), and one standard deviation above the median (black dashed line). Data sources for this figure include the DFO Environmental Watch Program and the ECCC Water Survey of Canada.

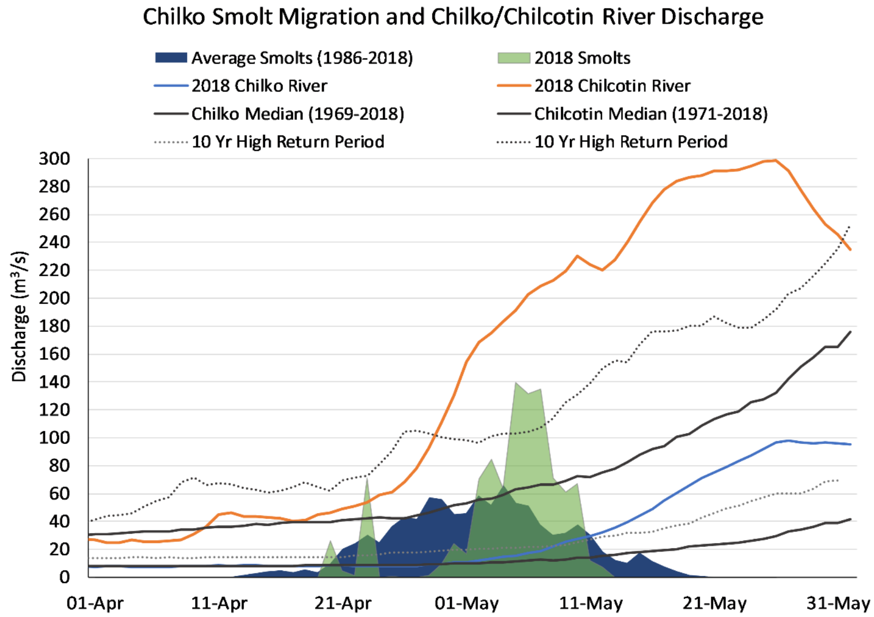



**Figure 14**. Chilko River (blue line) and Chilcotin River (orange line) discharge during the 2018 Chilko Sockeye salmon smolt outmigration (green polygon). Median Chilko and Chilcotin River discharge (black lines) and the 10-year high return period (black dashed line), based on day-of-year values, are shown for reference, as is the average smolt migration (dark blue polygon). Data sources for this figure include DFO Stock Assessment and the ECCC Water Survey of Canada.

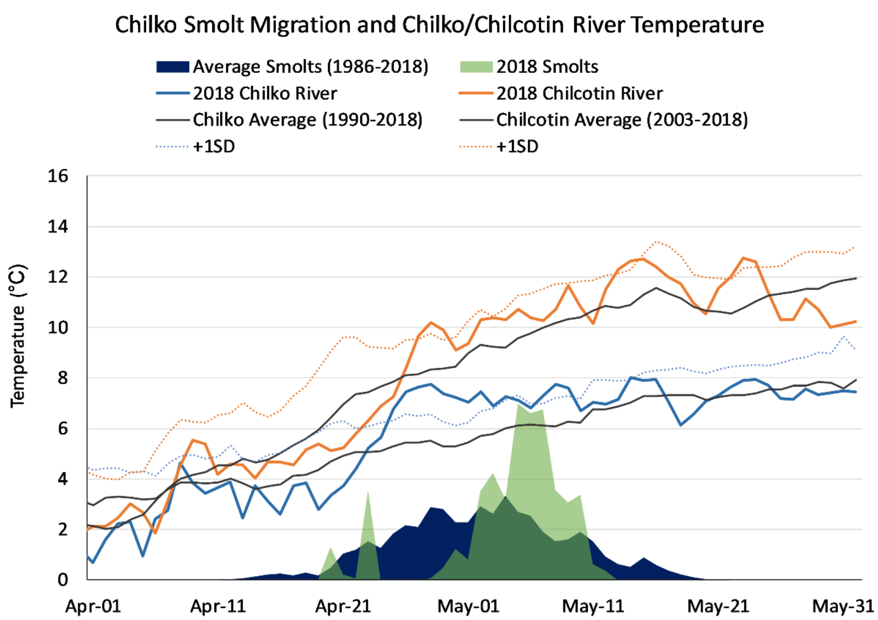



**Figure 15.** Chilko River (blue line) and Chilcotin River (orange line) temperatures during the 2018 Chilko Sockeye salmon smolt outmigration (green polygon). Chilko and Chilcotin River average temperatures (black lines) and average plus one standard deviation (blue and orange dashed lines) are presented. Average smolt migration is shown (dark blue polygon). Data sources include the DFO Environmental Watch Program, DFO Stock Assessment, and the ECCC Water Survey of Canada.

Smolt Condition

- The mean fork length of age1 smolts outmigrating from Chilko Lake in 2018 was 83 mm, which is 2 mm smaller than expected (85 mm) based on the linear relationship between annual mean smolt length and EFS abundance (Figure 16). Conversely, since 2006, the mean length of age-1 smolts has been larger than expected in the majority of years. This provides further evidence that Sockeye smolts in Chilko Lake during the winter/spring of 2017-18 experienced somewhat less favorable conditions than those generally occurring in recent years.

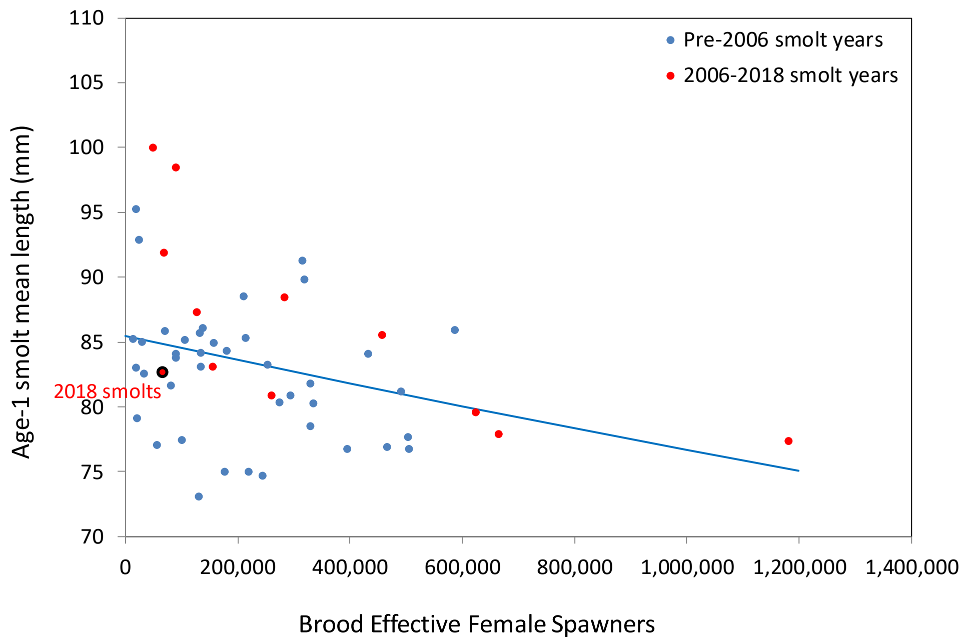
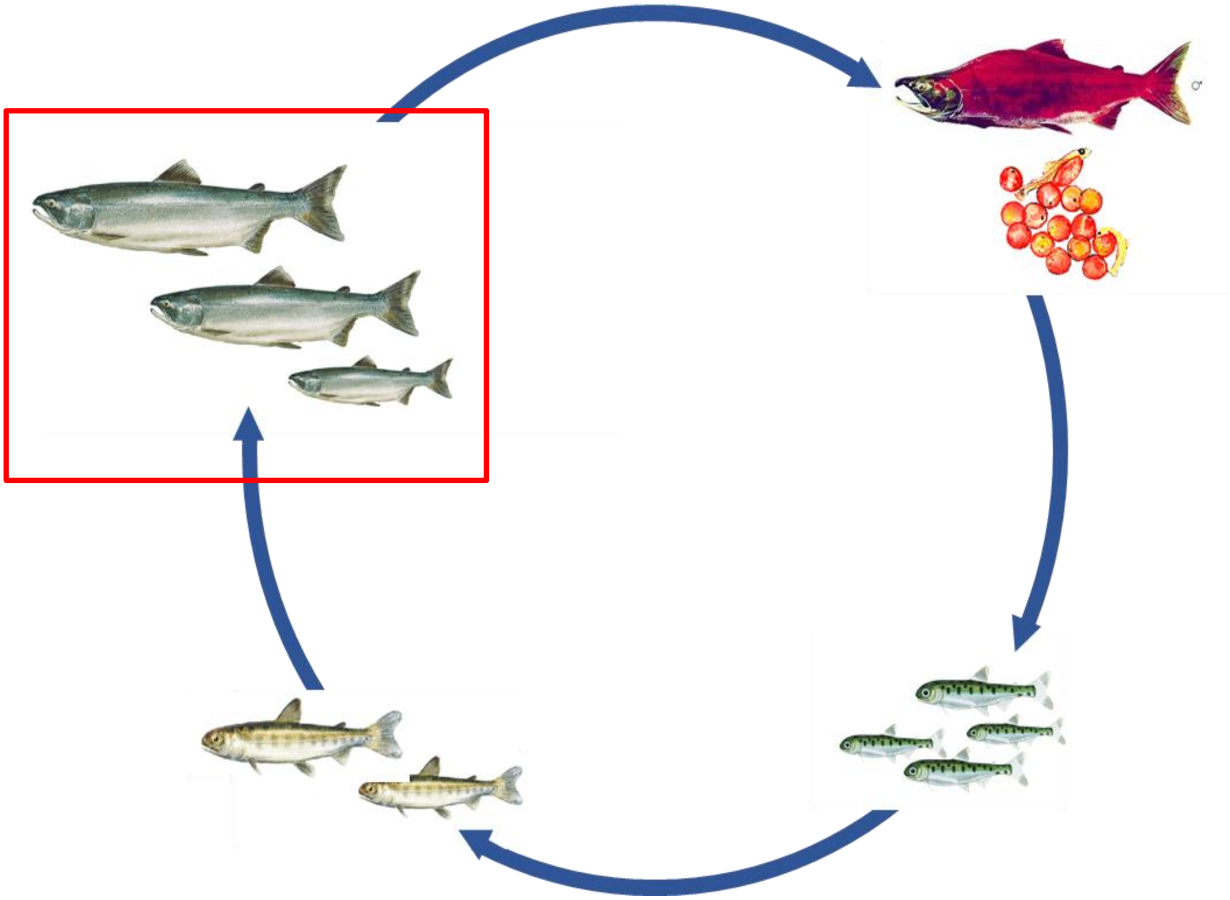



**Figure 16.** Mean fork length (mm) of age-1 smolts versus brood year abundance (EFS). The blue filled circles are pre-2006 smolt years, and the blue filled circles are the 2006 to 2018 smolt years. The blue solid line indicates predicted smolt length based on the regression relationship between EFS and average annual fork length.

- The biological condition of salmon smolts can be used as both an integrated measure of habitat quality and fry over-winter survival, as well as a potential predictor of future smolt-adult marine survival. Previous work on smolt condition has focused on using length and weight to infer carrying capacity of lake habitats (Hume et al. 1996, Griffiths et al. 2014), and to create a mechanistic link for trophic relationships (Ballantyne et al. 2003, Ravet et al. 2010). However, body lipids may be a better predictor of survival, due to starvation, than body size (Gardiner and Geddes 1980, Post and Parkinson 2001, Simpkins et al. 2003, Biro et al. 2004). Lipid content can be used to infer early marine survival, based on the connection between energy status and time to starvation (Naesje et al. 2006), as well as more indirect associations. For example, energy status is linked to immune response (Martin et al. 2010), which can affect infection status which in turn has been connected with downstream survival (Jeffries et al. 2014) and predation risk (Miller et al. 2014) in Sockeye salmon smolts. Predator risk can also change as a function of lipid content through changes in swim performance (Litz et al. 2017; S. Wilson SFU pers. comm.).

- It is nearly impossible to observe dead fish in large river systems (Patterson et al. 2007), therefore, survival is inferred from a relationship between sub-optimal fish condition and performance. The assumption is that most fish die from predation.
- Smolt energy status can also be linked to migration timing (Westley et al. 2008), which in turn will determine the environmental conditions that fish are exposed to.
- Chilko smolts had low lipid levels for the 2016 brood year, lower than expected based on brood size. Over 50% of the sampled smolts (n=68) were below the presumed 2% lipid threshold value (Gardiner and Geddes 1980).
- Cultus smolts had lower lipid values (~3%, n=20) than in recent years.
- Smolts from Seton Lake had high lipid values (~6%, n=30) and large body size compared to other populations in the Fraser.
- Note that it is difficult to interpret the combined effect of environmental and biological conditions on population-level survival. Also, sample sizes were small for some stocks.

# 4.4 JUVENILE MARINE STAGE



## Northeast Pacific Ocean Conditions and Observations: 2018-present

- Globally, 2018 was the fourth warmest year on record (Ross and Robert 2018).
- In 2018, both surface and subsurface Northeast Pacific Ocean temperatures were near normal until the fall, when marine heat waves were observed offshore and on the shelf with varying spatial and temporal scales (Hannah et al. 2019, Ross and Robert 2019) due to delayed and reduced winter cooling. This is in contrast to 2017, when subsurface temperatures remained anomalously warm in depths >100 m, after the 2014-2016 marine heat wave (Figure 17, Ross and Robert 2019).
- La Niña conditions were present for the first half of 2018, switching to weak El Niño conditions near the end of the year (Ross and Robert 2019). ENSO-neutral conditions are expected to continue through the summer of 2020

(https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/ensodisc.html).

- The winter stratification was stronger in 2017/18 than 2016/17, indicating a potential for weaker mixing of the water column and reduced nutrient supply from deep waters to surface waters (Ross and Robert 2019). Given the marine heatwave in the fall of 2018, it is likely that 2018/19 also had weaker than normal winter mixing (Ross and Robert 2019).
- In 2018, the upwelling of cool nutrient rich waters along the west coast of Vancouver Island (WCVI) started earlier than usual but was not as intense as previous years, implying mixed conditions for productivity and fish growth (Figure 18, Hourston and Thomson 2019).
- In 2018, on the west coast of B.C., phytoplankton biomass and community composition were generally within the range of past values, except there was an unusual increase in phytoplankton biomass and relative abundance of diatoms at most stations along Line P in spring (Peña and Nemcek 2019).
- In 2018 and 2019, zooplankton distribution off the WCVI still reflected the effects of the 2014-2016 marine heatwave (Galbraith and Young 2019, Fisher et al. 2020). The abundance of southern copepod species was high and subarctic copepods low; southern species were still present, consistent with reduced winter cooling (Figure 19, Galbraith and Young 2019). On-shelf and off-shelf areas in coastal BC also had higher proportions of smaller copepod species (Batten 2019).
- Pyrosomes were observed for the first time in BC waters in 2017 and 2018 but were absent in 2019.
- Steller sea lions continue to exhibit population growth, with an estimated B.C. summer breeding season population of 39,200 individuals in 2013 (Olesiuk 2018).

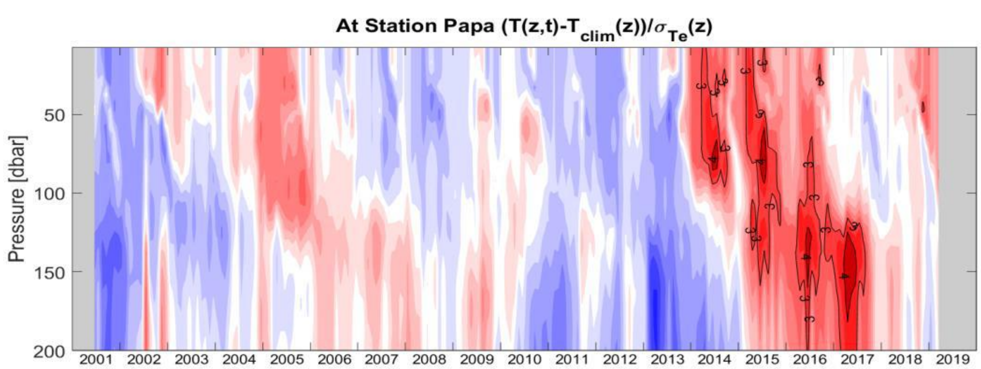



**Figure 17.** False colour plot of temperature anomalies relative to the 1956-2012 seasonally-corrected mean and standard deviation (from the Line P time series), as observed by Argo floats near Station Papa (P26: 50° N, 145° W).The cool colours indicate cooler than average temperatures and warm colours indicate warmer that average temperatures. Dark colours indicate anomalies were large compared with the 1956-2012 standard deviations. The black lines highlight regions with anomalies that were 3 and 4 standard deviations above the mean (Figure from Ross and Robert 2019).

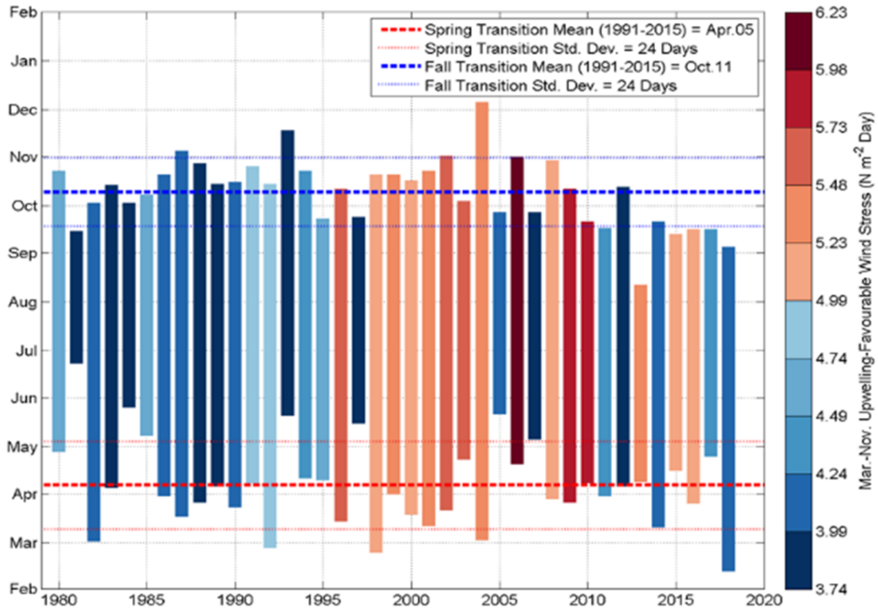



**Figure 18.** The upwelling index for the west coast of British Columbia. The length of the bar corresponds to the duration of the upwelling season, coloured by the intensity of the upwelling. The dashed red line indicates the average start to the upwelling season. Data source: NOAA/OAR/ESRL/Physical Sciences Division – University of Colorado at Boulder; https://www.esrl.noaa.gov/psd/data/. Figure from Hourston and Thomson (2019).

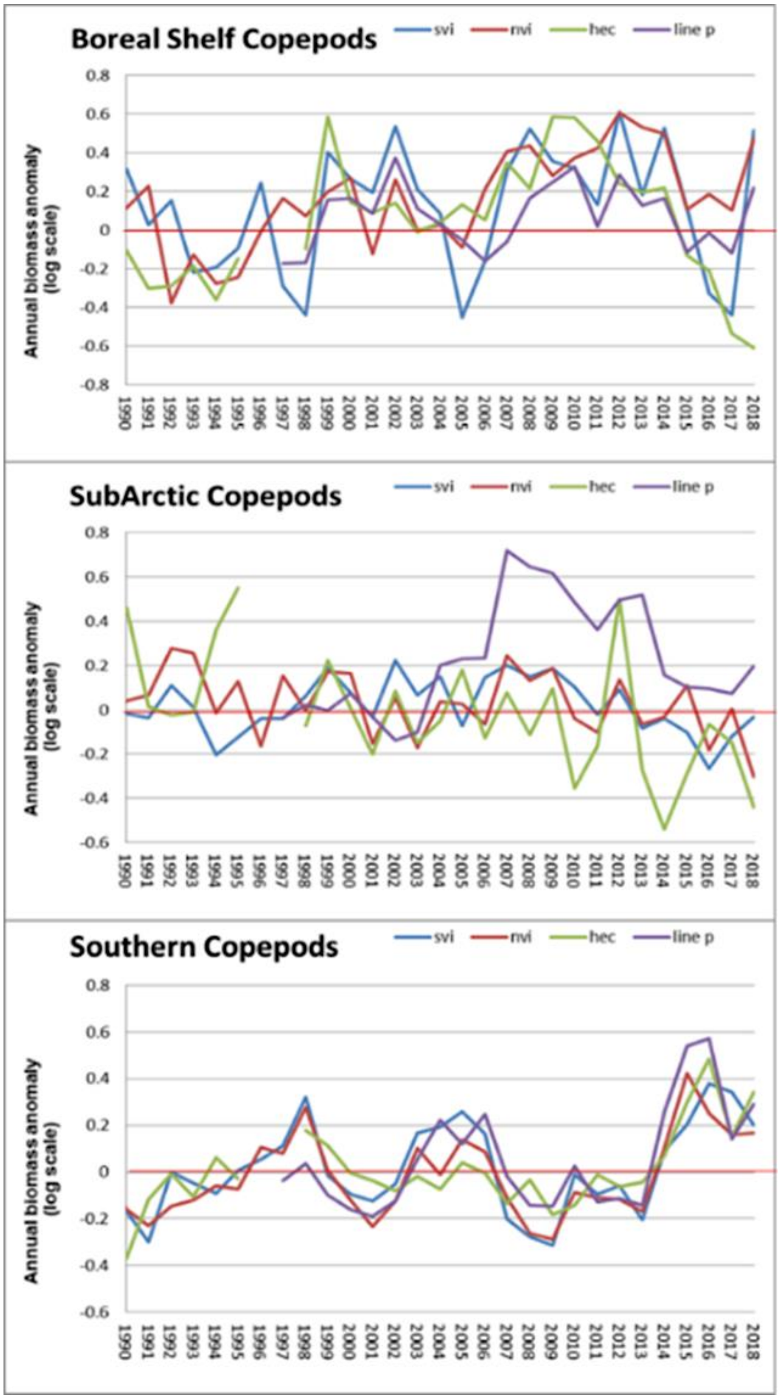



**Figure 19.** Zooplankton species-group anomaly time series for the regions in BC. Line graphs are annual log scale anomalies. Southern Vancouver Island (SVI) blue; Northern Vancouver Island (NVI) red; Hecate Strait (HEC) green; Line P – purple for all graphs. Note the y-axis changes with each taxonomic group (Figure from Galbraith and Young 2019).

## Strait of Georgia Marine Conditions and Observations: Spring/Summer 2018

- During spring and summer 2018, temperature and salinity conditions were near-normal, but as the year progressed temperatures at all depths became warmer than normal (Figure 20, Chandler 2019). The long-term freshening trend in the SoG continued, but 2018 conditions were saltier than expected by this trend.
- There was an early, rapid and high volume Fraser River freshet. The mean annual discharge was near the 100 year average, but the median annual discharge occurred 16 days earlier than the long term average (Chandler 2018).
- In the SoG, the spring bloom timing and duration was consistent with average conditions over the past 20 years (Costa 2019, Allen et al. 2019) – which implies good feeding conditions for juvenile fish.
- After a three-year absence from the SoG, a harmful algal bloom occurred in early June, resulting in high aquaculture fish mortality in Jervis Inlet (Esenkulova and Pearsall 2019, Haigh and Johnson 2019, Nemcek et al. 2019). This bloom was linked to the early and high Fraser River freshet and hot weather in May-June (Esenkulova and Pearsall 2019, Haigh and Johnson 2019, Nemcek et al. 2019).
- Pacific Herring spawning biomass was high in the SoG but not in other areas. Natural mortality for some stocks has increased (Cleary et al. 2019). The relative abundance of SoG juvenile herring was the fourth lowest in the 27-year time series and may be an indicator of diminished future recruitment strength (Figure 21, Boldt et al. 2019).
- SoG zooplankton biomass was near the long-term average in 2018 with peaks in May and June for the North and Central SoG, respectively (Young et al. 2019).
- Abundance anomalies of some common fish prey items were positive (hyperiid amphipods) or near the long term mean (decapod and euphausiids) (Figure 22, Young et al. 2019).
- Of the larger copepods, the copepod *Eucalanus bungii* made up the majority of the large copepod biomass in the Strait during the spring, representing a change from the typical spring dominant large copepod, *Neocalanus plumchrus* (Young et al. 2019).
- Northern anchovy continued to be frequently sampled in surveys (Boldt et al. 2018).
- In the SoG, juvenile salmon species survey catches were average or better than average (Neville 2019).
- The population of Harbour Seals (*Phoca vitulina*) in the Strait of Georgia appears to have remained stable since the 1990s (Majewski and Ellis, in press).
- An index of Eulachon spawning stock biomass in the Fraser River was estimated to be at a moderately high level (similar to 2015), compared to most other years from 2004-2017 (Flostrand et al. 2018).

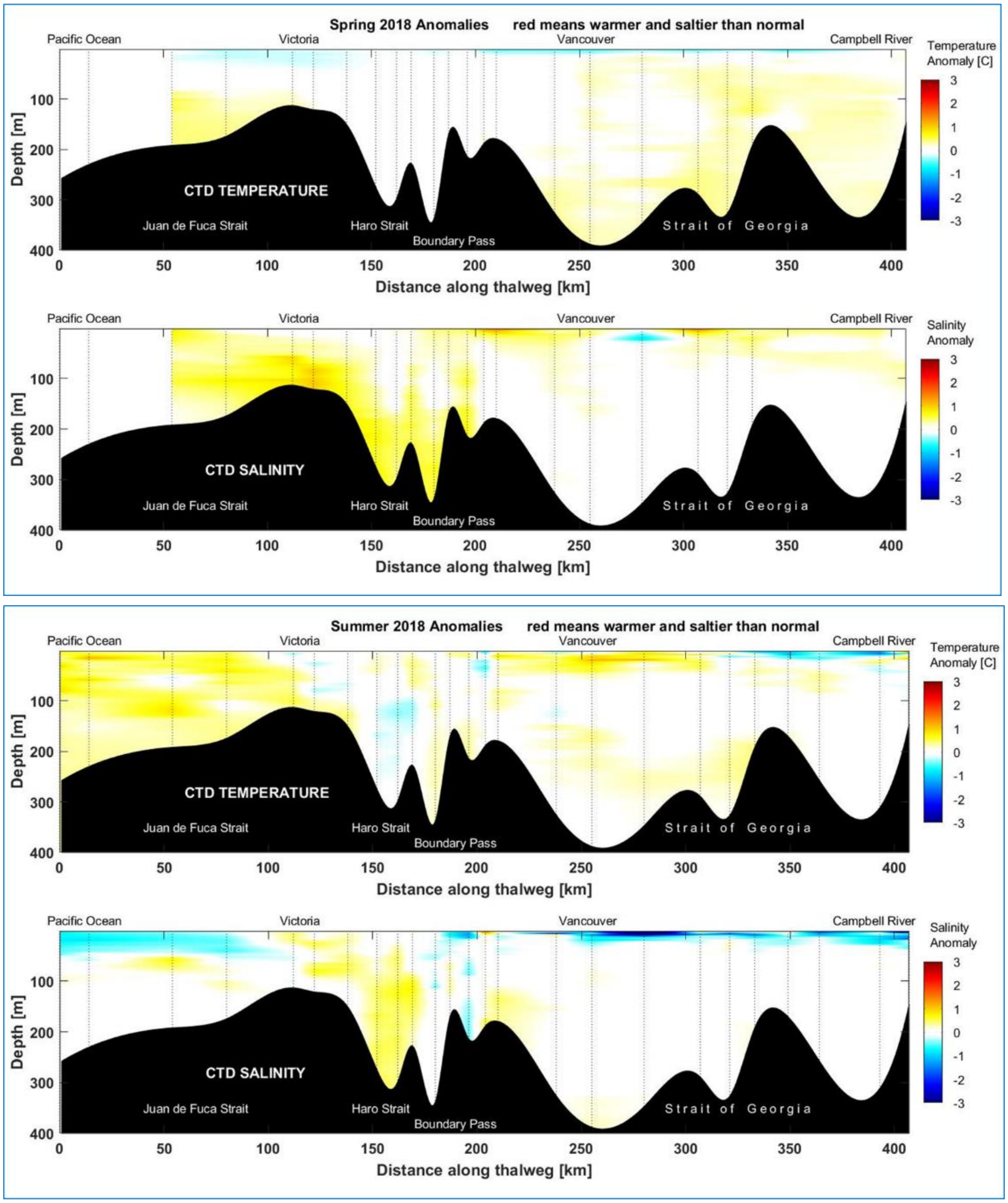



**Figure 20.** Temperature and salinity anomalies along the thalweg joining the deepest stations along the centreline of the survey in the Strait of Georgia observed in spring (upper two figures), summer (bottom two figures), in 2018. Figure adapted from Chandler (2019).

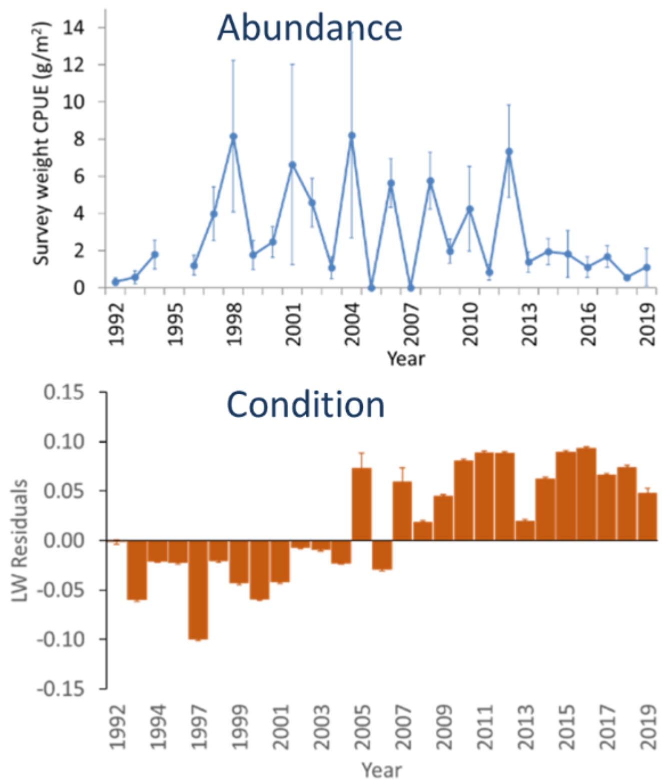



**Figure 21.** Mean catch weight per-unit-effort (CPUE; g/m$^2$; top panel) and mean condition (residuals from a double log-transformed length-weight regression; bottom panel) of age-0 herring caught in the SoG survey at core transects and stations during 1992-2018 (no survey in 1995). Standard error bars and survey CV are shown, and calculated using Thompson (1992) two-stage (transect, station) method and variance estimator. Figure adapted from Boldt et al. (2019).

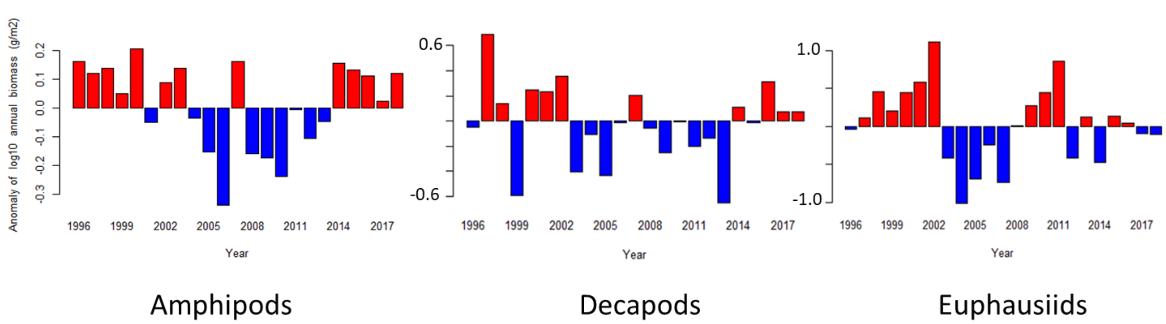



**Figure 22.** Annual biomass anomalies of 'Fish food' crustacean groups: decapods, hyperiid amphipods, and adult euphausiids. Figure from Young et al. (2019).

<u>**Queen Charlotte Strait- Southern Queen Charlotte Sound Juvenile Sockeye Surveys: Early Summer 2018**</u>

- In 2018, 15 surface trawls for juvenile salmon were conducted June 10-14 and July 6-9 in Queen Charlotte Strait and southern Queen Charlotte Sound. In total, 314 juvenile Sockeye salmon were caught in 7 tows.
- CPUE anomalies indicate that overall Fraser juvenile Sockeye salmon CPUE was above the long-term average in 2018 (Figure 23). Annual anomalies were adjusted to remove the dominant cycle from the non-dominant cycle years. Calculations for mean and standard deviation included all tows, including tows with zero catch.
- The overall condition of 28 Fraser juvenile Sockeye salmon was average in 2018 (Figure 24). Condition is estimated as the residuals from the length to weight relationship derived from samples across the whole survey time series.
- Chilko juvenile Sockeye salmon had above average condition, Nadina juvenile Sockeye salmon had average condition, and Birkenhead juvenile Sockeye salmon had below average condition in 2018 (Figure 25).

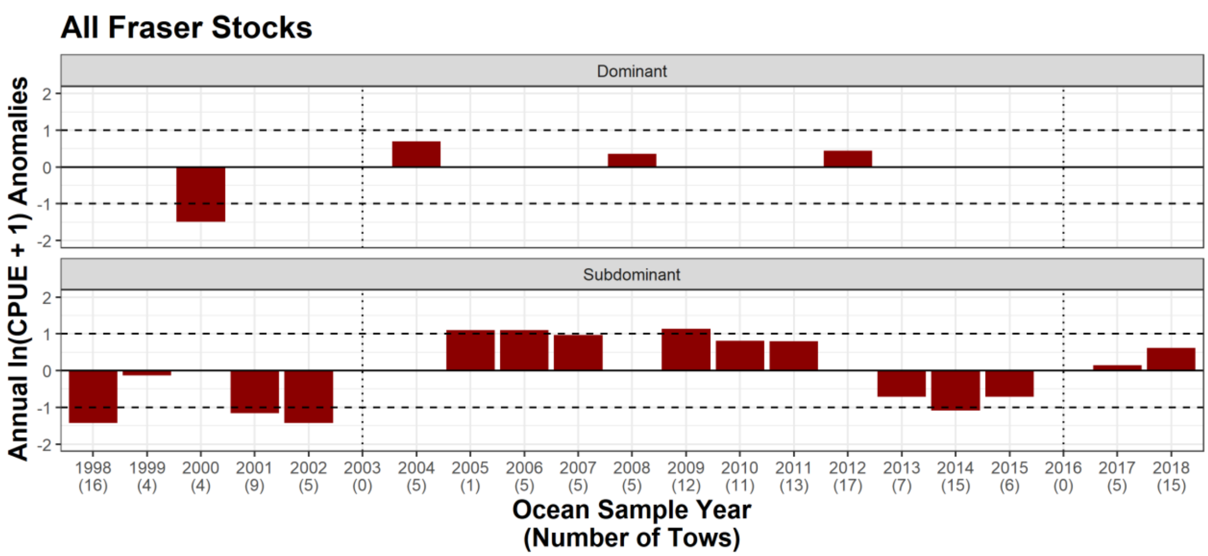



**Figure 23.** Standardized CPUE anomalies for Fraser River juvenile Sockeye salmon from early summer surface tows conducted in Queen Charlotte Strait and southern Queen Charlotte Sound. Mean anomalies are separated into dominant (2000, 2004, 2008, 2012, 2016) and subdominant ocean years. The number of tows used for each calculation are included below the years. There were no surveys in 2003 and 2016, indicated by the dotted vertical lines. The mean at zero is a solid line; ± 1 standard deviation are dashed lines.

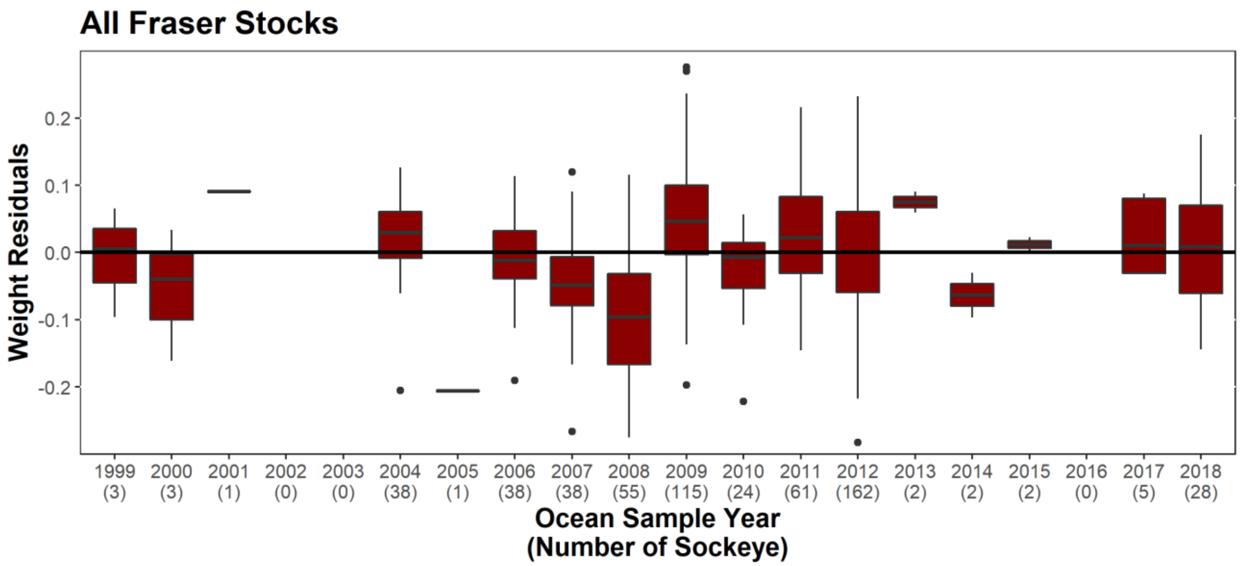



**Figure 24.** Annual weight residuals for all Fraser River juvenile Sockeye salmon sampled in early summer surface tows conducted in Queen Charlotte Strait and southern Queen Charlotte Sound. Fraser River juvenile Sockeye had average condition in 2018. Residuals were calculated from a length-weight regression over all years combined. The number of Sockeye within each year are indicated below the x- axis in brackets. Boxes are quartiles; solid lines are median values; solid circles denote outliers.

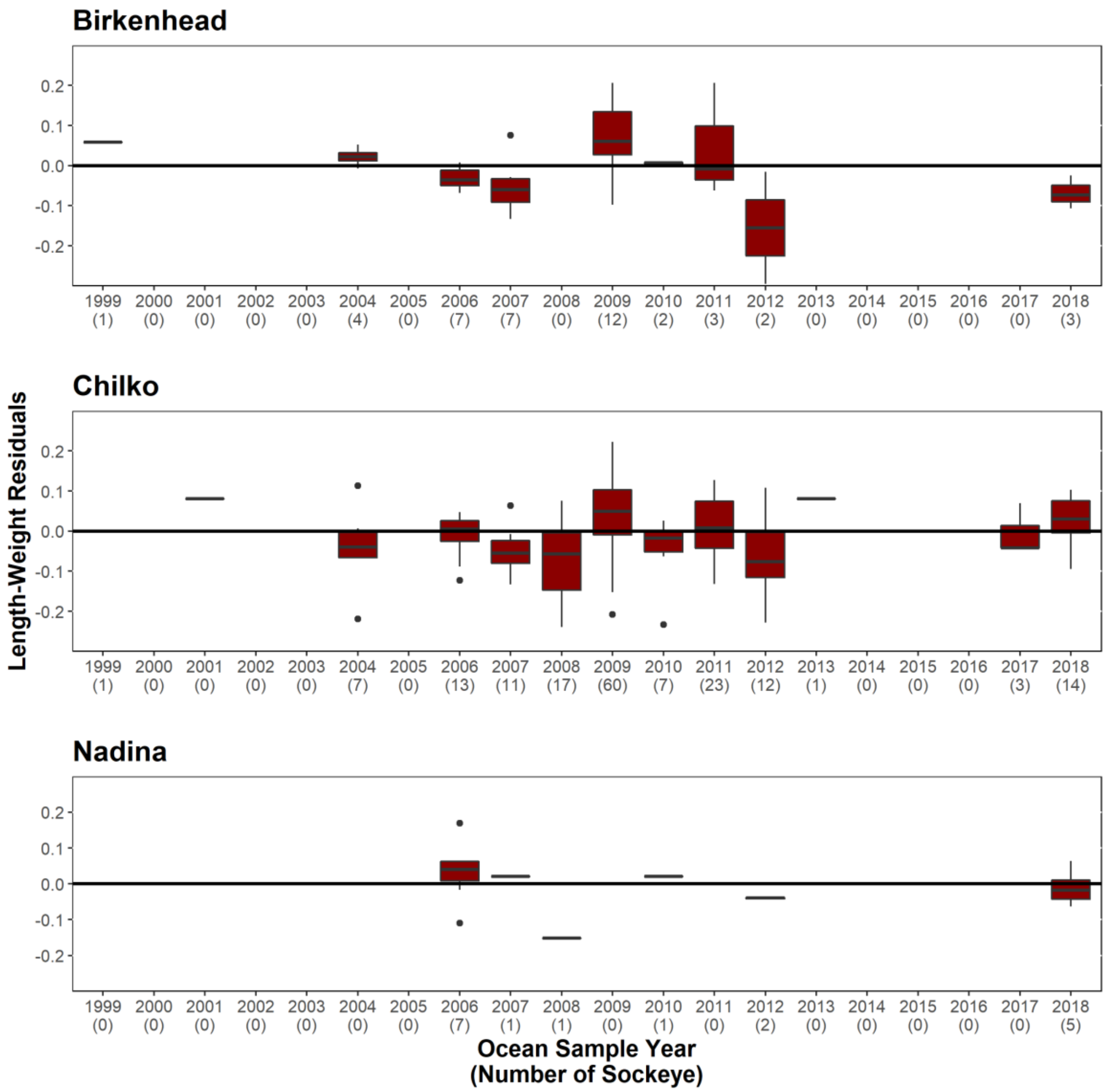



**Figure 25.** Annual weight residuals for individual juvenile Sockeye salmon stocks (Birkenhead, Chilko, and Nadina) sampled in early summer surface tows conducted in Queen Charlotte Strait and the southern Queen Charlotte Sound. Chilko had above average condition, Nadina had average condition, and Birkenhead had below average condition in 2018. Residuals were calculated from a length to weight regression with stock as a fixed effect, over all years. The number of Sockeye within each year are indicated in brackets below the year. Boxes are quartiles; solid lines are median values; solid circles denote outliers.

# 4.5 PROPORTIONS OF STOCKS OBSERVED THROUGH SAMPLING PROGRAMS

- We compared proportions of the five most populous lake-type Sockeye across sampling programs to evaluate the consistency of observed relative abundances across life stages (Figure 26). This may help identify issues if stocks are present in comparatively low abundances in samples.
- Proportions were examined for the 2016 brood year EFS, outmigrating smolts at Mission, B.C. in spring 2018, juvenile trawl survey samples collected in late June-early July 2018 in the SoG and Desolation Sound/Discovery Islands, Juvenile trawl surveys in early-June and early-July in Queen Charlotte Strait-southern Queen Charlotte Sound, and the four year old forecasts for 2020, presented at the 50% probability level (M. Hawkshaw DFO Stock Assessment pers. comm.). Stocks were selected according to their order of prevalence in the sampling programs, and include Chilko, Chilliwack, Nadina, Stellako, and Birkenhead. All other stocks were removed from calculations of stock proportions for each sampling component.
- Stock proportions at Mission are challenging to interpret given the need to maintain a consistent water velocity at the trap mouth (1.0 m/s), paired with the steady increase in discharge experienced in the Fraser River as the study progressed. Stock proportions have not been adjusted for the inverse relationship between the proportion of water volume sampled and discharge at Mission, and should be considered preliminary pending this correction. As a result, proportions of stocks that predominately migrate early in the migration season may be biased high, and proportions of stocks that predominately migrate later in the migration season may be biased low. Similarly, sampling must be corrected for locational differences in flow within the channel, which may affect proportions if stocks differ in their horizontal distribution within the water column. Mission surveys in 2018 were performed every other day, with a break in surveys between May 18$^{th}$ and May 28$^{th}$, due to the high freshet and debris in the river.
- In the Queen Charlotte Strait/Southern Queen Charlotte Sound surveys, up to 10 juvenile Sockeye per tow were sent for genetic stock identification (GSI). Stock assignments were accepted at > 0.5 probability. Apart from Chilko, Nadina, and Birkenhead, which are included in the comparisons here, North Thompson and Late Stuart were also sampled in relatively high proportions.
- Chilko dominates the key stocks observed in all sampling programs apart from one. Chilko represents ~45-60% of the four year old Fraser Sockeye abundance measured across the five dominant stocks in the 2016 brood year escapements, the SoG and Discovery Islands juvenile program, the QCStrait/Sound juvenile program, and in the 2020 four-year old forecast. The primary exception where Chilko does not dominate proportions, is the Mission juvenile program, where Chilko represents only ~30% of the relative abundance.
- Chilliwack presented the opposite pattern to Chilko. Chilliwack was “over-represented” in the Mission surveys compared to the other programs for which we currently have data. Chilliwack made up ~55% of the relative abundance at Mission, but only accounted for ~20% of the 2016 EFS, and ~10% of the four-year old 2020 forecast, and juvenile surveys in the SoG and Discovery Islands. Chilliwack Sockeye were not present in samples from the Queen Charlotte Strait/Southern Queen Charlotte Sound surveys.

- The pattern of over-representation of Chilliwack in the Mission surveys was encountered previously, on this same cycle-line, in the 2016 Science Integration process. Notably, Chilliwack migrated earlier than average, and roughly one week earlier than Chilko, in both 2014 and 2018. As mentioned, early migrants may be biased high in the Mission surveys, while late migrants may be biased low, due to the increase in discharge over the course of sampling. Notably, discharge patterns in both 2014 and 2018 peaked early and high. Bias in the Chilliwack catch at Mission may also result from the location of the sampling program, which is just downstream of where Chilliwack Sockeye enter the Fraser River. Of note, Chilliwack returns in 2016 were more closely aligned with their relative proportion of the 2012 EFS than the 2014 smolt samples at Mission, though they did return at a higher proportion than forecast, relative to the other key stocks.
- Proportions of Nadina Sockeye are variable across the sampling programs, with a very low proportion caught at Mission (~2%) relative to EFS (10%), and a high proportion caught in the Queen Charlotte Strait/Southern Queen Charlotte Sound program (40%) based on two tows.
- Stellako and Birkenhead had somewhat more consistent proportions across programs, coming in around 5-10% for each, apart from the Stellako forecast, which is 20% of the total across stocks compared. Similar to Chilliwack, Stellako Sockeye were also not caught in the Queen Charlotte Strait/Southern Queen Charlotte Sound surveys.

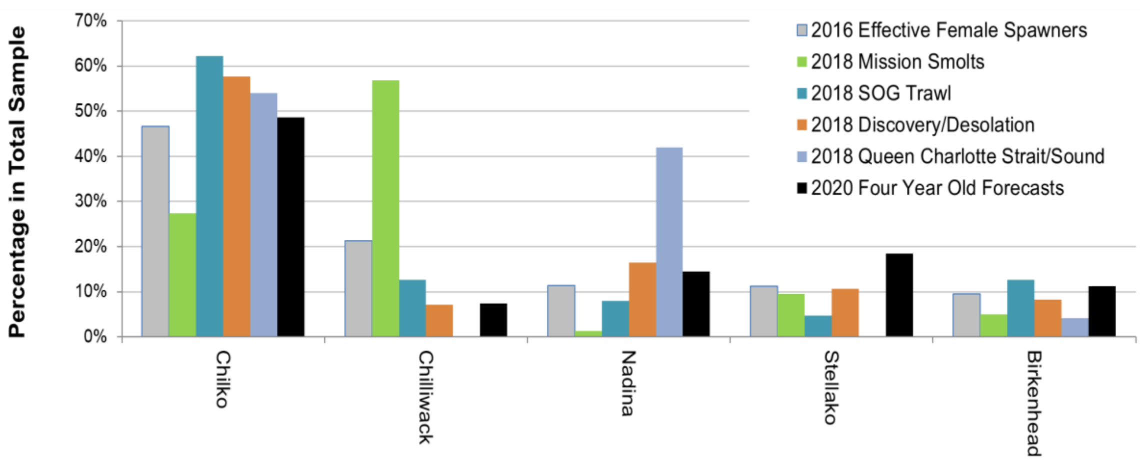



**Figure 26.** Proportions of the five dominant Fraser Sockeye stocks expected to return as four-year olds in 2020, across sampling programs. Effective female spawner proportions are from the 2016 brood year parental generation, while outmigrating juveniles were sampled through surveys at Mission in the Lower Fraser River, in the SoG and Discovery Island trawl surveys, and in the Queen Charlotte Strait/Southern Queen Charlotte Sound trawl surveys in 2018. Four year old 2020 forecasts are also included, as produced using various model forms (M. Hawkshaw DFO Stock Assessment pers.comm.).

# 5 KNOWLEDGE GAPS AND FURTHER WORK

The following are current gaps in our knowledge and research programs that limit our ability to understand Fraser Sockeye survival.

## 5.1 BROOD YEAR SPAWNERS AND EGG STAGE

- En-route loss and pre-spawn mortality are accounted for in the run size forecasts, but a better understanding of the contribution of intergenerational effects on offspring would help link brood year experience to future recruitment.
- Limited data on incubation temperatures and discharge are available. This is especially critical for spawning populations that utilize systems not dominated by the moderating influence of upstream lakes, such as Early Summer populations.
- More information on the shear stress from peak river flows events is required for bedload movement in specific systems is necessary for the assessment of redd scouring events and survival implications.
- Improvements are needed in our understanding of the impacts of adult migratory experience in the Fraser River - particularly timing, fish condition, temperatures, and flows - on survival, as reflected by en-route mortality, success of spawn, gamete quality, egg to fry survival, fry and smolt condition, and abundance.

## 5.2 JUVENILE FRESHWATER STAGE

- Currently there is limited information on the following, all of which require further research:
    - upstream fry migration challenges due to high discharge for those populations that migrate upstream (e.g. Chilko, Weaver) from spawning locations to lakes;
    - littoral zone habitat as a function of lake water levels and water temperature and their relative importance to overall juvenile freshwater survival; and
    - the impacts of overall winter air temperature on overwinter fry survival.
- Additionally, there is no standard metric for quantifying variation in length of growing season among lakes and across years
- Juvenile Sockeye experience high mortality during their freshwater residence phases from egg to fry (87%) and from fry to smolt (74%) (Quinn 2005), highlighting the importance of abundance estimates at early life stages. Currently Chilko Lake is the only wild Sockeye stock in the Fraser River watershed where survival can be partitioned into freshwater and marine components. However, Chilko Lake is a unique system that is not representative of other Sockeye nursery lakes in the Fraser River watershed. Additional juvenile monitoring (fry and smolt) for condition and abundance in other key nursery lakes in the Fraser watershed would provide information on the survival (freshwater and marine) and population and ecosystem dynamics for these systems. Additionally, our ability to assess abundances of juvenile Sockeye during the fry life stage in nursery lakes is limited by budgets and capacity, and requires the identification of priorities on an annual basis. As a result, many lakes are assessed infrequently, and some are not

assessed at all. We recommend increased assessments as permitted by capacity and budgets.

- Additional work on the effects of fry size and condition on later life-stage survival is important to understanding the dynamics of Fraser River Sockeye returns

## 5.3 JUVENILE DOWNSTREAM MIGRATION

- Conduct additional lake-outlet juvenile downstream assessments like those for the Chilko and Cultus stocks. Focus should be on assessing stocks most likely to contribute to the current year juvenile outmigration and capture at Mission. Additional health and abundance assessments of smolts as they outmigrate from nursery lakes would further our capacity to predict total Fraser Sockeye outmigration abundance and subsequent marine survival.
- It is necessary to complete the data adjustments required to account for the known parameters that bias stock composition and ocean entry estimates from Mission juvenile catch estimates. Additionally, improvements could be made to the study design by incorporating currently existing technologies to accurately measure these parameters in future studies.
- Further work on the impact of juvenile abundance entering the SoG on marine survival is another interesting but unstudied factor. If we presume the marine environment, in a given year, is the best it could be, there are two outcomes: either that strong abundance has no effect on marine survival, or the abundance saturates/overwhelms even the most favourable habitat capacity, decreasing marine survival.
- Additional knowledge gaps exist in the following areas, all of which require further research:
    - Proximate environmental or biological cues for outmigration timing of smolts, particularly temperature and discharge metrics.
    - Inter and intra-population differences in outmigration timing and therefore environmental experience
    - Critical energy condition levels in relation to starvation risk, burst swim performance, sustained swim performance, and potential interaction with disease.
    - Influences of different migratory corridors (lakes versus rivers, availability of discharge and thermal refugia, predation risk, turbidity) on migration timing and survival.
    - The potential relevance of high encounter velocities with respect to physical damage to smolts (washing machine effect).
    - Quantifiable links between outmigration conditions and survival. We have observed deviations from the norm, but are not confident in the net effect on freshwater migration survival.

## 5.4 MARINE ENTRY TO RETURNING ADULTS

- A knowledge gap exists in terms of how the recent increase in the frequency of unusual observations in the physical (e.g., marine heat wave) and biological environment (e.g., doliolids in 2016, pyrosomes in 2017) affect the survival of pelagic fish species (such as juvenile salmon and Pacific Herring) in the NE Pacific.
- Research is required to understand the trophodynamic interactions and linkages among juvenile salmon, age-0 herring, other small pelagic forage fishes, and zooplankton (timing and magnitude, and species composition) in the SoG. For example, age-0 herring could potentially be: 1) competitors for zooplankton with juvenile Sockeye, Chum, and Pink salmon, 2) prey for juvenile Chinook and Coho salmon, and/or 3) a buffer to predation. Understanding these interactions would elucidate factors that can affect fish survival in the SoG.

## 5.5 CLIMATE CHANGE VULNERABILITY ASSESSMENTS

- As global temperatures continue to increase and precipitation patterns change, conditions observed during the recent period of high temperatures will very likely become more common, and more extreme. This includes such events as higher in-river temperatures, early, high spring freshets, low river flows in summer and fall, and continued ocean warming (IPCC 2014b, Anslow et al. 2016). We must improve our ability to predict and adapt to current and expected climate conditions and their effects, through research, planning, and action.
- Recent trends in salmon abundances yield a growing, but still incomplete, view of salmon vulnerability to climate change. This vulnerability is determined by multiple factors, including salmon spawning and rearing locations, warming water temperatures, ecosystem changes, freshwater habitat alteration, salmon traits, and more. All of these factors acting alone or cumulatively increase our current uncertainty related to salmon population responses to climate change.
- Detailed assessments of salmon vulnerability to climate change are required to understand and predict future trends in salmon populations. Work was initiated on Canadian Pacific salmon vulnerability assessments in 2007 (PFRCC 1999, Nelitz et al. 2007), and reinvigorated in 2015 more broadly on a number of fish species (Hunter and Wade 2015, Hunter et al. 2015). Vulnerability assessments for Pacific salmon populations in the U.S. have recently been completed (Hare et al. 2016, Urban et al. 2016, Crozier 2017, Crozier and Siegel 2018, Crozier et al. 2019). Meanwhile, in DFO's Pacific Region, participants attending the second annual State of the Salmon meeting, held in March 2019, supported the initiation of the Pacific Salmon-Ecosystem-Climate Consortium as a mechanism to assist with integration of scientific expertise across organizations to advance assessments of Pacific salmon vulnerability to climate and habitat change. Improved integration across a wide variety of organizations that study and manage Canadian Pacific salmon, their habitats, and local climate change predictions, would advance efforts to address existing knowledge gaps in these areas. All of these efforts will assist with enabling better predictions of Fraser Sockeye survival moving forward under changing conditions.

# LITERATURE CITED

Allen, S.E., Latornell, D.J., and Olson, E. 2019. Spring phytoplankton bloom timing, interannual summer productivity in the Strait of Georgia. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2018. Edited by Boldt, J.L., Leonard, J., and P.C. Chandler. Can. Tech. Rep. Fish. Aquat. Sci. 3314. pp. 136-140. https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2018/index-eng.html.

Anslow, F., Schnorbus, M., and Campbell, D. 2016. British Columbia hydroclimatological conditions, 2015. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2015. Edited by P.C. Chandler, S.A. King, and R.I. Perry. Can. Tech. Rep. Fish. Aquat. Sci. 3179. pp. 12–21. http://waves-vagues.dfo-mpo.gc.ca/Library/365564.pdf.

Bailey, J. 1971. Osmoregulatory capability in juvenile sockeye salmon (*Oncorhynchus nerka*). Can. J. Zool. 49(6): 841–845. doi:10.1139/z71-126.

Ballantyne, A.P., Brett, M.T., and Schindler, D.E. 2003. The importance of dietary phosphorus and highly unsaturated fatty acids for sockeye (*Oncorhynchus nerka*) growth in Lake Washington — a bioenergetics approach. Can. J. Fish. Aquat. Sci. 60(1): 12–22. doi:10.1139/f02-166.

Bassett, M.C. 2015. Temporal and spatial differences in smolting among sockeye salmon (*Oncorhynchus nerka*) populations throughout fresh- and seawater migration and the effect of water temperature on the smolt window. M.Sc. Thesis, Natural Resources and Environmental Studies, University of Northern British Columbia, Prince George, B.C. https://open.library.ubc.ca/media/download/pdf/24/1.0320798/4.

Batten, S. 2019. Lower trophic levels in the Northeast Pacific. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2018. Edited by J.L. Boldt, J. Leonard, and P.C. Chandler. Can. Tech. Rep. Fish. Aquat. Sci. 3314. pp. 59–63. https://www.dfo-mpo.gc.ca/oceans/publications/soto-rceo/2018/index-eng.html.

Beamish, R.J., Neville, C.E., Sweeting, R.M., Beacham, T.D., Wade, J., and Li, L. 2016. Early ocean life history of Harrison River sockeye salmon and their contribution to the biodiversity of sockeye salmon in the Fraser River, British Columbia, Canada. Trans. Am. Fish. Soc. 145(2): 348–362. doi:10.1080/00028487.2015.1123182.

Biro, P.A., Morton, A.E., Post, J.R., and Parkinson, E.A. 2004. Over-winter lipid depletion and mortality of age-0 rainbow trout (*Oncorhynchus mykiss*). Can. J. Fish. Aquat. Sci. 61: 1513–1519. doi:10.1139/f04-083.

Birtwell, I.K., Nassichuk, M.D., and Beune, H. 1987. Underyearling sockeye salmon (*Oncorhynchus nerka*) in the estuary of the Fraser River. Can. Spec. Publ. Fish. Aquat. Sci. 96: 25–35.

Boldt, J.L., Leonard, J., and Chandler, P.C (Editors). 2019. State of the Physical, Biological and Selected Fisheries Resources of Pacific Canadian Marine Ecosystems in 2018. Can. Tech. Rep. Fish. Aquat. Sci. 3314: vii + 248. https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2018/index-eng.html.

Boldt, J.L., Thompson, M., Grinnell, M., Cleary, J., Dennis-Bohn, H., Rooper, C., Schweigert, J., Quinn II, T.J., and Hay, D. 2018. Strait of Georgia juvenile herring survey. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2017. Edited by P.C. Chandler, S.A. King, and J.L. Boldt. Can. Tech. Rep. Fish. Aquat. Sci. 3266. pp. 185–189. http://waves-vagues.dfo-mpo.gc.ca/Library/40717914.pdf.

Brannon, E.L. 1987. Mechanisms stabilizing salmonid fry emergence. Can. Spec. Publ. Fish. Aquat. Sci. 96: 120–124. doi:10.1371/journal.pone.0095853.

Braun, D.C., Reynolds, J.D., and Patterson, D.A. 2015. Using watershed characteristics to inform cost-effective stream temperature monitoring. Aquat. Ecol. 49(3): 373–388. doi:10.1007/s10452-015-9531-6.

Brett, J.R. 1971. Energetic responses of salmon to temperature. A study of some thermal relations in the physiology and freshwater ecology of sockeye salmon (*Oncorhynchus nerka*). Am. Zool. 11(1): 99–113. doi:198.103.39.129.

Burgner, R.L. 1991. Life history of sockeye salmon (*Oncorhynchus nerka*). Edited by C. Groot and L. Margolis. University of British Columbia Press, Vancouver, BC. 117 pp.

Burt, J.M., Hinch, S.G., and Patterson, D.A. 2012. Developmental temperature stress and parental identity shape offspring burst swimming performance in sockeye salmon (*Oncorhynchus nerka*). Ecol. Freshw. Fish 21(2): 176–188. doi:10.1111/j.1600-0633.2011.00535.x.

Bush, E., and Lemmen, D.S. (Editors). 2019. Canada's changing climate report. Government of Canada, Ottawa, ON. Available from www.ChangingClimate.ca/CCCR2019.

Cass, A., Folkes, M., Parken, C., and Wood, C. 2006. Pre-season run size forecasts for Fraser River sockeye in 2006. Can. Sci. Advis. Sec. Res. Doc. 2006/060: iii + 72.

Chandler, P.C. 2018. Sea surface temperature and salinity observed at lighthouses and weather buoys in British Columbia, 2017. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2017. Edited by P.C. Chandler, S.A. King, and J. Boldt. Can. Tech. Rep. Fish. Aquat. Sci. 3266. pp. 40–44. https://www.dfo-mpo.gc.ca/oceans/publications/soto-rceo/2017/index-eng.html.

Chandler, P.C. 2019. Temperature and salinity observations in the Strait of Georgia and Juan de Fuca Strait in 2018. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2018. Edited by Boldt, J.L., Leonard, J., and P.C. Chandler. Can. Tech. Rep. Fish. Aquat. Sci. 3314. pp. 113-116 https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2018/index-eng.html.

Chandler, P.C., King, S.A., and Boldt, J.L. (Editors). 2018. State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2017. Can. Tech. Rep. Fish. Aquat. Sci. 3266.: viii + 245 p. https://www.dfo-mpo.gc.ca/oceans/publications/soto-rceo/2017/index-eng.html.

Clark, T.D., Furey, N.B., Rechisky, E.L., Gale, M.K., Jeffries, K.M., Porter, A.D., Casselman, M.T., Lotto, A.G., Patterson, D.A., Cooke, S.J., Farrell, A.P., Welch, D.W., and Hinch, S.G. 2016. Tracking wild sockeye salmon smolts to the ocean reveals distinct regions of noturnal movement and high mortality. Ecol. Appl. 26(4): 959–978. doi:10.13748/j.cnki.issn1007-7693.2014.04.012.

Cleary, J., Grinnell, M., Grandin, C., Daniel, K., and Thompson, M. 2019. Pacific Herring in British Columbia, 2018. In State of the Physical, Biological and Selected Fishery

Resources of Pacific Canadian Marine Ecosystems in 2018. Edited by: Boldt, J.L., Leonard, J., and P.C. Chandler. Can. Tech. Rep. Fish. Aquat. Sci. 3314. pp. 80-84. https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2018/index-eng.html.

Cope, R.S., and Macdonald, J.S. 1998. Responses of sockeye salmon (*Oncorhynchus nerka*) embryos to intragravel incubation environments in selected streams within the Stuart-Takla watersheds. In Forest-fish Conference: Land Management Practices Affecting Aquatic Ecosystems. Edited by M.K. Brewin and D.M.A. Monita. Nat. Resour. Can. Inf. Rep. NOR-X-356, Edmonton, AB. pp. 283–294.

Costa, M. 2019. Chlorophyll phenology in the Strait of Georgia: spatial-temporal satellite observations. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2018. Edited by Boldt, J.L., Leonard, J., and P.C. Chandler. Can. Tech. Rep. Fish. Aquat. Sci. 3314. pp. 131-135. https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2018/index-eng.html.

Crozier, L. 2017. Impacts of climate change on salmon of the Pacific Northwest. A review of the scientific literature published in 2016. National Marine Fisheries Service, Seattle, WA. 26 pp. https://www.nwfsc.noaa.gov/assets/11/8905_07312017_154234_Crozier.2017-BIOP-Lit-Rev-2016.pdf.

Crozier, L., and Siegel, J. 2018. Impacts of climate change on salmon of the pacific northwest. A review of the scientific literature published in 2017. National Marine Fisheries Service, Seattle, WA. 52 pp. https://www.nwfsc.noaa.gov/assets/11/9603_02272019_153600_Crozier.and.Siegel.2018-Climate-Lit-Rev-2017.pdf.

Crozier, L.G., McClure, M.M., Beechie, T., Bograd, S.J., Boughton, D.A., Carr, M., Cooney, T.D., Dunham, J.B., Greene, C.M., Haltuch, M.A., Hazen, E.L., Holzer, D.M., Huff, D.D., Johnson, R.C., Jordan, C.E., Kaplan, I.C., Lindley, S.T., Mantua, N.J., Moyle, P.B., Myers, J.M., Nelson, M.W., Spence, B.C., Weitkamp, L.A., Williams, T.H., and Willis-Norton, E. 2019. Climate vulnerability assessment for Pacific salmon and steelhead in the California Current Large Marine Ecosystem. PLoS One 14(7): e0217711. doi:10.1371/journal.pone.0217711.

DeVries, P. 1997. Riverine salmonid egg burial depths: review of published data and implications for scour studies. Can. J. Fish. Aquat. Sci. 54(8): 1685–1698. doi:10.1139/f97-090.

DFO. 2011. Pre-season run forecasts for Fraser River sockeye and pink salmon in 2011. Can. Sci. Advis. Sec. Sci. Advis. Rep. 2011/052: 15 pp. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/SAR-AS/2011/2011_052-eng.html.

DFO. 2012. Pre-season run size forecasts for Fraser River sockeye salmon in 2012. Can. Sci. Advis. Sec. Sci. Advis. Rep. 2012/011: 10 pp. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/SAR-AS/2012/2012_011-eng.html.

DFO. 2013. Pre-season run size forecasts for Fraser River sockeye and pink salmon in 2013. Can. Sci. Advis. Sec. Sci. Advis. Rep. 2012/074: 17 pp. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/SAR-AS/2012/2012_074-eng.html.

DFO. 2014a. Pre-season run size forecasts for Fraser River sockeye (*Oncorhynchus nerka*) salmon in 2014. Can. Sci. Adv. Sec. Sci. Resp. 2014/040: 46 pp. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ScR-RS/2014/2014_040-eng.html.

DFO. 2014b. Supplement to the pre-season return forecasts for Fraser River sockeye salmon in 2014. Can. Sci. Adv. Sec. Sci. Resp. 2014/041: 57 pp. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ScR-RS/2014/2014_041-eng.html.

DFO. 2015a. Pre-season run size forecasts for Fraser River sockeye (*Oncorhynchus nerka*) and pink (*O . gorbuscha*) salmon in 2015. Can. Sci. Adv. Sec. Sci. Response 2015/014: 55 pp. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ScR-RS/2015/2015_014-eng.html.

DFO. 2015b. Supplement to the pre-season return forecasts for Fraser River sockeye salmon in 2015. Can. Sci. Adv. Sec. Sci. Resp. 2015/028: 49 pp. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ScR-RS/2015/2015_028-eng.html.

DFO. 2016a. Pre-Season run size forecasts for Fraser River sockeye (*Oncorhynchus nerka*) in 2016. Can. Sci. Adv. Sec. Sci. Resp. 2016/021: 68 pp. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ScR-RS/2016/2016_021-eng.html.

DFO. 2016b. Supplement to the pre-season return forecasts for Fraser River sockeye salmon (*Oncorhynchus nerka*) in 2016. Can. Sci. Adv. Sec. Sci. Resp. 2016/047: 61 pp. https://waves-vagues.dfo-mpo.gc.ca/Library/4062254x.pdf.

DFO. 2017. Pre-season run size forecasts for Fraser River sockeye (*Oncorhynchus nerka*) and pink (*O. gorbuscha*) salmon in 2017. Can. Sci. Advis. Sec. Sci. Resp. 2017/016: 61 pp. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ScR-RS/2017/2017_016-eng.html.

DFO. 2018a. Pre-season run size forecasts for Fraser River sockeye salmon (*Oncorhynchus nerka*) in 2018. Can. Sci. Advis. Sec. Sci. Resp. 2018/034: 70 pp. https://waves-vagues.dfo-mpo.gc.ca/Library/40715607.pdf

DFO. 2018b. Science information to support consideration of risks to Cultus Lake sockeye salmon in 2018. Can. Sci. Adv. Sec. Sci. Resp. 2018/052: 16 pp. http://waves-vagues.dfo-mpo.gc.ca/Library/40761253.pdf.

DFO. 2019, June 27. Significant rockslide in the Fraser Canyon. Media Release. Fisheries and Oceans Canada & Government of B.C. Joint Statement. https://www.canada.ca/en/fisheries-oceans/news/2019/06/significant-rock-slide-in-the-fraser-canyon.html.

Edmundson, J.A., and Mazumder, A. 2001. Linking growth of juvenile sockeye salmon to habitat temperature in Alaskan lakes. Trans. Am. Fish. Soc. 130: 644–662. doi:10.1577/1548-8659(2001)130<0644:LGOJSS>2.0.CO;2.

Esenkulova, S., Pawlowicz, R., and Pearsall, I. 2018. Nutrients, the phytoplankton community and harmful algae in the Salish Sea. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2017. Edited by P.C. Chandler, S.A. King, and J.L. Boldt. Can. Tech. Rep. Fish. Aquat. Sci. 3266. pp. 174–179. http://waves-vagues.dfo-mpo.gc.ca/Library/40717914.pdf.

Evans Ogden, L. 2020, Jan. 22. Remote landslide puts Fraser River salmon on shaky ground. *Eos. 101.* https://doi.org/10.1029/2020EO138786.

Fisher, J., Kimmel, D., Ross, T., Batten, S., Bjorkstedt, E., Galbraith, M., Jacobson, K., Keister, J., Sastri, A., Suchy, K., Zeman, S., and Perry, R.I., 2020. Copepod responses to, and recovery from, the recent marine heatwave in the Northeast Pacific. PICES Press, 28 (1): 65-71. https://meetings.pices.int/publications/pices-press/volume28/PPJan2020.pdf

Flostrand, L., MacConnachie, S., and Boldt, J. 2018. Eulachon status and trends in B.C. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian

Marine Ecosystems in 2017. Edited by P.C. Chandler, S. King, and J. Boldt. Can. Tech. Rep. Fish. Aquat. Sci. 3266. pp. 85–89. https://www.dfo-mpo.gc.ca/oceans/publications/soto-rceo/2017/index-eng.html.

Freshwater, C., Trudel, M., Beacham, T.D., Grant, S.C.H., Johnson, S.C., Neville, C.E., Tucker, S., and Juanes, F. 2017. Effects of density during freshwater and early marine rearing on juvenile sockeye salmon size, growth, and migration. Mar. Ecol. Prog. Ser. 579: 97–110. doi:10.3354/meps12279.

Fritts, A.L., and T.N. Pearsons. 2004. Smallmouth Bass predation on hatchery and wild salmonids in the Yakima River, Washington. Trans. AM. Fish. Soc. 133: 880-895. https://doi.org/10.1577/T03-003.1

Galbraith, M., and Young, K. 2019. West coast British Columbia zooplankton biomass anomalies 2018. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2018. Edited by Boldt, J.L., Leonard, J., and P.C. Chandler. Can. Tech. Rep. Fish. Aquat. Sci. 3314. pp. 64-69. https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2018/index-eng.html.

Gardiner, W.R., and Geddes, P. 1980. The influence of body composition on the survival of juvenile salmon. Hydrobiologica 69: 67–72. doi:10.1007/BF00016537.

Ginetz, R.M., and Larkin, P.A. 1976. Factors affecting rainbow trout (*Salmo gairdneri*) predation on migrant fry of sockeye salmon (*Oncorhynchus nerka).* J. Fish Res. Board Can. 33(1): 19–24. doi:10.1139/f76-003.

Grant, S.C.H., and MacDonald, B.L. 2011. Pre-season run size forecasts for Fraser River Sockeye (*Oncorhynchus nerka*) and Pink (*O. gorbuscha*) salmon in 2011. Can. Sci. Advis. Sec. Res. Doc. 2012/145: vi + 48 pp. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ResDocs-DocRech/2012/2012_145-eng.html.

Grant, S.C.H., and MacDonald, B.L. 2012. Pre-season run size forecasts for Fraser River Sockeye (*Oncorhynchus nerka*) and Pink (*O. gorbuscha*) salmon in 2013. Can. Sci. Adv. Sec. Spec. Advis. Rep. 2012/145: vi + 42 pp. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ResDocs-DocRech/2012/2012_145-eng.html.

Grant, S.C.H., MacDonald, B.L., and Winston, M.L. 2019. State of the Canadian Pacific Salmon: Responses to Changing Climate and Habitats. Can. Tech. Rep. Fish. Aquat. Sci. 3332: ix + 50 pp. http://www.dfo-mpo.gc.ca/species-especes/publications/salmon-saumon/state-etat-2019/abstract-resume/index-eng.html.

Grant, S.C.H., Michielsens, C.G.J., Porszt, E.J., and Cass, A.J. 2010. Pre-season run size forecasts for Fraser River sockeye salmon (*Oncohrynchus nerka* ) in 2010. Can. Sci. Advis. Sec. Res. Doc. 2010/042: vi + 125 pp. http://www.dfo-mpo.gc.ca/csas-sccs/publications/resdocs-docrech/2010/2010_042-eng.htm.

Gregory, R.S., and Levings, C.D. 1998. Turbidity reduces predation on migrating juvenile Pacific Salmon. Trans. Am. Fish. Soc. 127(2): 275–285. doi:10.1577/1548-8659(1998)127<0275:TRPOMJ>2.0.CO;2.

Griffiths, J.R., Schindler, D.E., Ruggerone, G.T., and Bumgarner, J.D. 2014. Climate variation is filtered differently among lakes to influence growth of juvenile sockeye salmon in an Alaskan watershed. Oikos 123(6): 687–698. doi:10.1111/j.1600-0706.2013.00801.x.

Hannah, C., Page, S., and Ross, T. 2019. Ocean surface temperatures in 2018: another marine heat wave? In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2018. Edited by J.L. Boldt, J. Leonard, and P.C. Chandler. Can. Tech. Rep. Fish. Aquat. Sci. 3314. pp. 31–36. https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2018/index-eng.html.

Hare, J.A., Morrison, W.E., Nelson, M.W., Stachura, M.M., Teeters, E.J., Griffis, R.B., Alexander, M.A., Scott, J.D., Alade, L., Bell, R.J., Chute, A.S., Curti, K.L., Curtis, T.H., Kircheis, D., Kocik, J.F., Lucey, S.M., McCandless, C.T., Milke, L.M., Richardson, D.E., Robillard, E., Walsh, H.J., McManus, M.C., Marancik, K.E., and Griswold, C.A. 2016. A vulnerability assessment of fish and invertebrates to climate change on the Northeast U.S. continental shelf. PLoS One 11(2): 30 pp. doi:10.1371/journal.pone.0146756.

Haigh, N., and Johnson, D. 2019. Harmful algal blooms around the BC coast in 2018: data from the harmful algae monitoring program. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2018. Edited by Boldt, J.L., Leonard, J., and P.C. Chandler. Can. Tech. Rep. Fish. Aquat. Sci. 3314. pp.156-162. https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2018/index-eng.html.

Henderson, M.A., and Cass, A.J. 1991. Effect of smolt size on smolt-to-adult survival for Chilko Lake Sockeye salmon (*Oncorhynchus nerka*). Can. J. Fish. Aquat. Sci. 48: 988–994. doi:10.1139/f91-115.

Holsman, K., Hollowed, A., Shin-Ichi, I., Bograd, S., Hazen, E., King, J., Mueter, F., and Perry, R.I. 2018. Climate change impacts, vulnerabilities and adaptations: North Pacific and Pacific Arctic marine fisheries. In Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options. Edited by M. Barange, T. Bahri, M.C.M. Beveridge, K.L. Cochrane, S. Funge-Smith, and F. Poulain. FAO Fisheries and Aquaculture Technical Paper, No. 627. FAO, Rome. pp. 113–138. Available from http://www.fao.org/3/i9705en/i9705en.pdf.

Hourston, R.A.S., and Thomson, R.E. 2017. Wind-driven upwelling/downwelling along the northwest coast of North America: timing and magnitude. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2016. Edited by P.C. Chandler, S.A. King, and J.L. Boldt. Can. Tech. Rep. Fish. Aquat. Sci. 3225. pp. 21–27. https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2016/index-eng.html.

Hourston, R.A.S., and Thomson, R.E. 2018. Wind-driven upwelling/downwelling along the Northwest coast of North America: timing and magnitude. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2017. Edited by P.C. Chandler, J.L. Boldt, and S.A. King. Can. Tech. Rep. Fish. Aquat. Sci. 3266. pp. 21–26. https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2017/index-eng.html.

Hourston, R.A.S, and Thomson, R.E. 2019. Wind-driven upwelling/downwelling along the northwest coast of North America: timing and magnitude. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2018. Edited by Boldt, J.L., Leonard, J., and P.C. Chandler. Can. Tech. Rep. Fish. Aquat. Sci. 3314 pp. 21-23. https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2018/index-eng.html.

Hruska, K.A., Hinch, S.G., Healey, M.C., Patterson, D.A., Larsson, S., and Farrell, A.P. 2010. Influences of sex and activity level on physiological changes in individual adult sockeye salmon during rapid senescence. Physiol. Biochem. Zool. 83(4): 663–676. doi:10.1086/652411.

Hume, J.M.B., Shortreed, K.S., and Morton, K.F. 1996. Juvenile sockeye rearing capacity of three lakes in the Fraser River system. Can. J. Fish. Aquat. Sci. 53(4): 719–733. doi:10.1139/f95-237.

Hunter, K.L., and Wade, J. 2015. Pacific large aquatic basin climate change impacts, vulnerabilities and opportunities assessment - marine species and aquaculture. Can. Man. Rep. Fish. Aquat. Sci. 3049: viii + 242 pp. https://www.dfo-mpo.gc.ca/csas-sccs/Publications/ScR-RS/2013/2013_016-eng.html.

Hunter, K.L., Wade, J., Stortini, C.H., Hyatt, K.D., Christian, J.R., Pepin, P., Pearsall, I.A., Nelson, M.W., Perry, R.I., and Shackell, N.L. 2015. Climate change vulnerability assessment methodology workshop proceedings. Can. Man. Rep. Fish. Aquat. Sci. 3086: v + 20 pp. https://cat.fsl-bsf.scitech.gc.ca/record=4055591~S6.

IPBES. 2018. The regional assessment report on biodiversity and ecosystem services for the Americas. Edited by J. Rice, C.S. Seixas, M.E. Zaccagnini, M. Bedoya-Gaitán, and N. Valderrama. Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany. 656 pp. Available from https://www.ipbes.net/system/tdf/2018_americas_full_report_book_v5_pages_0.pdf?file=1&type=node&id=29404.

IPCC. 2013. Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Edited byT.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 1535 pp. Available from https://www.ipcc.ch/report/ar5/wg1/.

IPCC. 2014a. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by R.K. Pachauri and L. Meyer. IPCC, Geneva, Switzerland, 151 pp. Available from https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf.

IPCC. 2014b. Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by C.B. Field, V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 1132 pp. Available from https://www.ipcc.ch/report/ar5/wg2/.

IPCC. 2018. Summary for policymakers. In Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change. Edited by V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield. World Meterological Organization, Geneva, Switzerland. 32 pp. Available from http://www.ipcc.ch/report/sr15/.

IPCC. 2019. Technical Summary. In IPCC special report on the ocean and cryosphere in a changing climate. Edited by H.- O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, and N.M. Weyer. pp. 35–74. Available from https://www.ipcc.ch/srocc/chapter/technical-summary/

Jeffries, K.M., Hinch, S.G., Donaldson, M.R., Gale, M.K., Burt, J.M., Thompson, L.A., Farrell, A.P., Patterson, D.A., and Miller, K.M. 2011. Temporal changes in blood variables during final maturation and senescence in male sockeye salmon *Oncorhynchus nerka*: reduced osmoregulatory ability can predict mortality. J. Fish Biol. 79(2): 449–465. doi:10.1111/j.1095-8649.2011.03042.x.

Jeffries, K.M., Hinch, S.G., Gale, M.K., Clark, T.D., Lotto, A.G., Casselman, M.T., Li, S., Rechisky, E.L., Porter, A.D., Welch, D.W., and Miller, K.M. 2014. Immune response genes and pathogen presence predict migration survival in wild salmon smolts. Mol. Ecol. 23(23): 5803–5815. doi:10.1111/mec.12980.

Litz, M.N.C., Miller, J.A., Copeman, L.A., and Hurst, T.P. 2017. Effects of dietary fatty acids on juvenile salmon growth, biochemistry, and aerobic performance: a laboratory rearing experiment. J. Exp. Mar. Bio. Ecol. 494: 20–31. doi:10.1016/j.jembe.2017.04.007.

MacDonald, B.L., and Grant, S.C.H. 2012. Pre-season run size forecasts for Fraser River Sockeye salmon (*Oncorhynchus nerka*) in 2012. Can. Sci. Advis. Sec. Res. Doc. 2012/011: v + 64 pp. http://www.dfo-mpo.gc.ca/csas-sccs/Publications/ResDocs-DocRech/2012/2012_145-eng.html.

MacDonald, B.L., Grant, S.C.H., Patterson, D.A., Robinson, K.A., Boldt, J.L., Benner, K., King, J., Pon, L., Selbie, D.., Neville, C.M., and Tadey., J.A. 2019. State of Salmon: informing the survival of Fraser Sockeye returning in 2019 through life-cycle observations. Can. Tech. Rep. Fish. Aquat. Sci. 3336: vi + 60 pp. http://waves-vagues.dfo-mpo.gc.ca/Library/40819103.pdf.

MacDonald, B.L., Grant, S.C.H., Patterson, D.A., Robinson, K.A., Boldt, J.L., Benner, K., Neville, C.M., Pon, L., Tadey, J.A., Selbie, D.T., and Winston, M.L. 2018. State of the Salmon: informing the survival of Fraser Sockeye returning in 2018 through life cycle observations. Can. Tech. Rep. Fish. Aquat. Sci. 3271.v + 53 pp. https://waves-vagues.dfo-mpo.gc.ca/Library/4072511x.pdf.

Macdonald, J.S., Foreman, M.G.G., Farrell, 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. Can. Tech. Rep. Fish. Aquat. Sci. 2326: 117 pp.

Macdonald, J.S., Scrivener, J.C., Patterson, D.A., and Dixon-Warren, A. 1998. Temperatures in aquatic habitats: the impacts of forest harvesting and the biological consequences to sockeye salmon incubation habitats in the interior of B.C. In Forest-fish conference: land management practices affecting aquatic ecosystems. Proc. Forest-Fish Conf., May 1-4, 1996, Calgary, AB. Edited by M.K. Brewin and D.M.A. Monita. Natural Resources Canada, Edmonton, AB. pp. 313–324.

Majewski, S.P., and Ellis, G.M. (in press). Abundance and distribution of harbour seals (*Phoca vitulina*) in the Strait of Georgia, British Columbia. Can. Sci. Advis. Sec. Res. Doc. XXXX/XXX: xx+ xx pp.

Martens, D.W., and Servizi, J.A. 1993. Suspended sediment particles inside gills and spleens of juvenile Pacific Salmon (*Oncorhynchus spp.).* Can. J. Fish. Aquat. Sci. 50: 586–590. doi:10.1139/f93-067.

Martin, S.A., Douglas, A., Houlihan, D.F., and Secombes, C.J. 2010. Starvation alters the liver transcriptome of the innate immune response in Atlantic salmon (*Salmo salar*).

BMC Genomics 11(1): 418. doi:10.1186/1471-2164-11-418.

Meehl, G.A., and Tebaldi, C. 2004. More intense, more frequent, and longer lasting heat waves in the 21st century. Science. 305(5686): 994–997. doi:10.1126/science.1098704.

Miller, K.M., Teffer, A., Tucker, S., Li, S., Schulze, A.D., Trudel, M., Juanes, F., Tabata, A., Kaukinen, K.H., Ginther, N.G., Ming, T.J., Cooke, S.J., Hipfner, J.M., Patterson, D.A., and Hinch, S.G. 2014. Infectious disease, shifting climates, and opportunistic predators: cumulative factors potentially impacting wild salmon declines. Evol. Appl. 7(7): 812–855. doi:10.1111/eva.12164.

Ministry of Environment River Forecast Centre. 2018. Snow Survey and Water Supply Bulletin. Available from https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/river-forecast/2018.pdf.

Montgomery, D.R., Buffington, J.M., Peterson, N.P., Schuett-Hames, D., and Quinn, T.P. 1996. Stream-bed scour, egg burial depths, and the influence of salmonid spawning on bed surface mobility and embryo survival. Can. J. Fish. Aquat. Sci. 53(5): 1061–1070. doi:10.1139/f96-028.

Morton, K.F., and Williams, I. V. 1990. Sockeye salmon (*Oncorhynchus nerka*) utilization of Quesnel Lake, British Columbia. Can. Tech. Rep. Fish. Aquat. Sci. 1756: iv + 29 pp.

Naesje, T.F., Thorstad, E.B., Forseth, T., Aursand, M., Saksga, R., and Finstad, A.G. 2006. Lipid class content as an indicator of critical periods for survival in juvenile Atlantic salmon (*Salmo salar*). Ecol. Freshw. Fish 15: 572–577. doi:10.1111/j.1600-0633.2006.00173.x.

Nelitz, M., Wieckowski, K., Pickard, D., Pawley, K., and Marmorek, D.R. 2007. Helping Pacific salmon survive the impact of climate change on freshwater habitats. Pursuing proactive and reactive adaptation strategies. Prepared for Pacific Fisheries Resource Conservation Council. Vancouver. BC. pp. 122. Available from http://skeenasalmonprogram.ca/libraryfiles/lib_193.pdf.

Nemcek, N., Hennekes, M., and Perry, I. 2019. Seasonal dynamics of the phytoplankton community in the Salish Sea from HPLC measurements 2015-2018. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2018. Edited by Boldt, J.L., Leonard, J., and P.C. Chandler. Can. Tech. Rep. Fish. Aquat. Sci. 3314. pp. 141-145. https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2018/index-eng.html.

Neville, C. 2019. Juvenile salmon in the Strait of Georgia 2018. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2018. Edited by Boldt, J.L., Leonard, J., and P.C. Chandler. Can. Tech. Rep. Fish. Aquat. Sci. 3314. pp. 210-213. https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2018/index-eng.html.

Newcombe, C.P., and Jensen, J.O. 1996. Channel suspended sediment and fisheries: a synthesis for quantitative assessment of risk and impact. N. Am. J. Fish. Manag. 16(4): 693–727. doi:10.1577/1548-8675(1996)016<0693:CSSAFA>2.3.CO;2.

NOAA. 2020. Global climate report-annual 2019. Available from https://www.ncdc.noaa.gov/sotc/global/201913 [accessed 20 February 2020]

Olesiuk, P.F. 2018. Recent trends in abundance of steller sea lions *(Eumetopias jubatus*) in British Columbia. Can. Sci. Advis. Sec. Res. Doc. 2018/006: v + 67 pp. https://waves-vagues.dfo-mpo.gc.ca/Library/40684933.pdf

Patterson, D.A., Macdonald, J.S., Hinch, S.G., Healey, M.C., and Farrell, A.P. 2004. The effect of exercise and captivity on energy partitioning, reproductive maturation and fertilization success in adult sockeye salmon. J. Fish. Biol. 64(4): 1039–1059. doi:10.1111/j.1095-8649.2004.0370.x.

Patterson, D.A., Skibo, K.M., Barnes, D.P., Hills, J.A., and Macdonald, J.S. 2007. The influence of water temperature on time to surface for adult sockeye salmon carcasses and the limitations in estimating salmon carcasses in the Fraser River, British Columbia. N. Am. J. Fish. Manag. 27(3): 878–884. doi:10.1577/M06-098.1.

Peña, A., and Nemcek, N. 2019. Phytoplankton in surface waters along Line P and off the west coast of Vancouver Island. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2018. Edited by Boldt, J.L., Leonard, J., and P.C. Chandler. Can. Tech. Rep. Fish. Aquat. Sci. 3314. pp. 54-58. https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2018/index-eng.html.

PFRCC. 1999. Proceedings-climate change and salmon stocks. Pacific Fisheries Resource Conservation Council, Vancouver, BC. Available from https://www.psf.ca/sites/default/files/lib_189.pdf.

Post, J.R., and Parkinson, E.A. 2001. Energy allocation strategy in young fish: allometry and survival. Ecology 82(4): 1040–1051. doi:10.1890/0012-9658(2001)082[1040:EASIYF]2.0.CO;2.

Putt, A.E., MacIsaac, E.A., Herunter, H.E., Cooper, A.B., and Selbie, D.T. 2019. Eutrophication forcings on a peri-urban lake ecosystem: context for integrated watershed to airshed management. PLoS One 14(7): e0219241. doi:10.1371/journal.pone.0219241.

Quinn, T.P. 2005. The behaviour and ecology of Pacific salmon and trout. American Fisheries Society. University of Washington Press, Seattle, Washington. 378 pp.

Ravet, J.L., Brett, M.T., and Arhonditsis, G.B. 2010. The effects of seston lipids on zooplankton fatty acid composition in Lake Washington, Washington, USA. Ecology 91(1): 180–190. doi:10.1890/08-2037.1.

Ricker, W.E. 1954. Stock and recruitment. J. Fish. Res. Board Can. 11: 559–623. doi:10.1139/f54-039.

Ross, T., and Robert, M. 2018. La Niña and another warm year. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2017. Edited by P.C. Chandler, S.A. King, and J.L. Boldt. Can. Tech. Rep. Fish. Aquat. Sci. 3225. pp. 27–32. https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2017/index-eng.html.

Ross, T., and Robert, M. 2019. Another warm but almost normal, year for the Northeast Pacific Ocean. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2018. Edited by Boldt, J.L., Leonard, J., and P.C. Chandler. Can. Tech. Rep. Fish. Aquat. Sci. 3314. pp. 15-20. https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2018/index-eng.html.

Schindler, D.E., Rogers, D.E., Scheuerell, M.D., and Abrey, C.A. 2005. Effect of changing climate on zooplankton and juvenile sockeye salmon growth in Southwestern Alaska. Ecology 86(1): 198–209. doi:10.1890/03-0408].

Shortreed, K.S., Hume, J.M.B., and Morton, K.F. 1996. Trophic status and rearing capacity of Francois and Fraser lakes. Can. Tech. Rep. Fish. Aquat. Sci. 2151: 58 pp.

Shrimpton, J.M., Patterson, D.A., Richards, J.G., Cooke, S.J., Schulte, P.M., Hinch, S.G., and Farrell, A.P. 2005. Ionoregulatory changes in different populations of maturing Sockeye salmon *Oncorhynchus nerka* during ocean and river migration. J. Exp. Biol. 208(21): 4069–4078. doi:10.1242/jeb.01871.

Simpkins, D.G., Hubert, W.A., del Rio, C.M., and Rule, D.C. 2003. Interacting effects of water temperature and swimming activity on body composition and mortality of fasted juvenile rainbow trout. Can. J. Zool. 81(10): 1641–1649. doi:10.1139/z03-157.

Sopinka, N.M., Hinch, S.G., Middleton, C.T., Hills, J.A., and Patterson, D.A. 2014. Mother knows best, even when stressed? Effects of maternal exposure to a stressor on offspring performance at different life stages in a wild semelparous fish. Oecologia 175(2): 493–500. doi:10.1007/s00442-014-2915-9.

Tadey, J.A. 2020. Evaluation of timing, size, abundance and stock composition of downstream migrating juvenile sockeye salmon in the lower Fraser River in 2018. Project summary presentation at the 2020 Fraser Sockeye Science Integration Workshop, Delta, BC. Jan 21-20, 2020.

Tabor, R.A., B.A. Footen, K.L. Fresh, M.T. Celedonia, F. Mejia, D.L. Low, and L. Park. 2007. Smallmouth Bass and Largemouth Bass predation on juvenile Chinook Salmon and other salmonids in the Lake Washington basin. N. Am. J. Fish. Manag. 27. 1174-1188. doi: 10.1577/M05-221.1

Thorne, R.E., and Ames, J.J. 1987. A note on variability of marine survival of Sockeye salmon (*Oncorhynchus nerka*) and effects of flooding on spawning success. Can. J. Fish. Aquat. Sci. 44(10): 1791–1795. doi:10.1139/f87-222.

Tierney, K.B., Patterson, D.A., and Kennedy, C.J. 2009. The influence of maternal condition on offspring performance in sockeye salmon *Oncorhynchus nerka*. J. Fish Biol. 75(6): 1244–1257. doi:10.1111/j.1095-8649.2009.02360.x.

Tucker, S., Trudel, M., Welch, D.W., Candy, J.R., Morris, J.F.T., Thiess, M.E., Wallace, C., Teel, D.J., Crawford, W., Farley, E. V., and Beacham, T.D. 2009. Seasonal stock-specific migrations of juvenile sockeye salmon along the west coast of North America: implications for growth. Trans. Am. Fish. Soc. 138(6): 1458–1480. doi:10.1577/T08-211.1.

Urban, M.C., Bocedi, G., Hendry, A.P., Mihoub, J.-B., Peer, G., Singer, A., Bridle, J.R., Crozier, L.G., De Meester, L., Godsoe, W., Gonzalez, A., Hellmann, J.J., Holt, R.D., Huth, A., Johst, K., Krug, C.B., Leadley, P.W., Palmer, S.C.F., Pantel, J.H., Schmitz, A., Zollner, P.A., and Travis, J.M.J. 2016. Improving the forecast for biodiversity under climate change. Science. 353(6304): aad8466-aad8466. doi:10.1126/science.aad8466.

Wang, J. and Strong, K. 2019. British Columbia's forest fires, 2018. Environment Fact Sheets. Statistics Canada. 2019002. [https://www150.statcan.gc.ca/n1/pub/16-508-x/16-508-x2019002-eng.htm](https://www150.statcan.gc.ca/n1/pub/16-508-x/16-508-x2019002-eng.htm).

Welch, D.W., Melnychuk, M.C., Rechisky, E.R., Porter, A.D., Jacobs, M.C., Ladouceur, A., McKinley, R.S., and Jackson, G.D. 2009. Freshwater and marine migration and survival of endangered Cultus Lake sockeye salmon (*Oncorhynchus nerka*) smolts using POST, a large-scale acoustic telemetry array. Can. J. Fish. Aquat. Sci. 66(5): 736–750. doi:10.1139/F09-032.

West, C.J., and Larkin, P.A. 1987. Evidence for size-selective mortality of juvenile sockeye salmon (*Oncorhynchus nerka*) in Babine Lake, British Columbia. Can. J. Fish. Aquat. Sci. 44(4): 712–721. doi:10.1139/f87-086.

Westley, P.A.H., Hilborn, R., Quinn, T.P., Ruggerone, G.T., and Schindler, D.E. 2008. Long-term changes in rearing habitat and downstream movement by juvenile sockeye salmon (*Oncorhynchus nerka*) in an interconnected Alaska lake system. Ecol. Freshw. Fish 17(3): 443–454. doi:10.1111/j.1600-0633.2008.00296.x.

Whitney, C.K., Hinch, S.G., and Patterson, D.A. 2013. Provenance matters: thermal reaction norms for embryo survival among sockeye salmon *Oncorhynchus nerka* populations. J. Fish Biol. 82(4): 1159–1176. doi:10.1111/jfb.12055.

Whitney, C.K., Hinch, S.G., and Patterson, D.A. 2014. Population origin and water temperature affect development timing in embryonic sockeye salmon. Trans. Am. Fish. Soc. 143(5): 1316–1329. doi:10.1080/00028487.2014.935481.

Williams, I. V, Gilhousen, P., Saito, W., Gjernes, T., Morton, K., Johnson, R., and Brock, D. 1989. Studies of the lacustrine biology of the sockeye salmon (*Oncorhyncus nerka*) in the Shuswap system. International Pacific Salmon Fisheries Commission Bulletin No. 24.

Young, K., Galbraith, M., and Perry, I. 2018. Zooplankton status and trends in the central Strait of Georgia, 2017. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2017. Edited by P.C. Chandler, S. King, and J. Boldt. Can. Tech. Rep. Fish. Aquat. Sci. 3225. pp. 180–184. https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2017/index-eng.html.

Young, K., Galbraith, M., and Perry, I.  2019. Zooplankton status and trends in the central and northern Strait of Georgia, 2018. In State of the Physical, Biological and Selected Fishery Resources of Pacific Canadian Marine Ecosystems in 2018. Edited by Boldt, J.L., Leonard, J., and P.C. Chandler. Can. Tech. Rep. Fish. Aquat. Sci. 3314. pp. 146-150. https://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2018/index-eng.html.

# APPENDIX 1: WORKSHOP PARTICIPANTS

| | |
|---|---|
| Keri Benner | Fisheries and Oceans Canada |
| Jennifer Boldt | Fisheries and Oceans Canada |
| Scott Decker | Fisheries and Oceans Canada |
| Cameron Freshwater | Fisheries and Oceans Canada |
| Sue Grant | Fisheries and Oceans Canada |
| Mike Hawkshaw | Fisheries and Oceans Canada |
| Stephen Healy | Fisheries and Oceans Canada |
| Ann-Marie Huang | Fisheries and Oceans Canada |
| Les Jantz | Fisheries and Oceans Canada |
| Jackie King | Fisheries and Oceans Canada |
| Jason Ladell | Fisheries and Oceans Canada |
| Steve Latham | Pacific Salmon Commission |
| Brian Leaf | Fisheries and Oceans Canada |
| Bronwyn MacDonald | Fisheries and Oceans Canada |
| Catherine Michielsens | Pacific Salmon Commission |
| Chrys Neville | Fisheries and Oceans Canada |
| David Patterson | Fisheries and Oceans Canada |
| Lucas Pon | Fisheries and Oceans Canada |
| Kendra Robinson | Fisheries and Oceans Canada |
| Daniel Selbie | Fisheries and Oceans Canada |
| Joe Tadey | Fisheries and Oceans Canada |
| Strahan Tucker | Fisheries and Oceans Canada |
| Yi Xu | Fisheries and Oceans Canada |