Cheakamus River Project Water Use Plan

Cheakamus River Juvenile Salmon Outmigration Enumeration

Final Data Report: 2001-2017

Reference: CMSMON1a

Implementation Year 10

Cheakamus River Juvenile Salmonid Outmigration Enumeration Assessment

Final Data Report 2017

Study Period: 2001-2017

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Executive Summary

Cheakamus River juvenile salmon abundance was estimated from 2001 to 2017 under CMSMON1a of the Cheakamus River Water Use Plan (WUP). To answer the management questions:

MQ1. What is the relationship between discharge and juvenile salmonid production, productivity, and habitat capacity of the mainstem and major side-channels of the Cheakamus River?

MQ2. Did juvenile salmonid production, productivity, or habitat capacity change following implementation of the WUP flow regime?

From 2001 to 2017, juvenile salmon (Pink, Chinook and Coho salmon) were trapped on the mainstem Cheakamus River using Rotary Screw Traps (RSTs). Juvenile salmon were also trapped in side channels using fyke nets and weir- style fish fences. Mark-recapture methods were used to estimate weekly abundance for both side channels and mainstem habitats.

Two flow treatments were tested over the monitoring program. The Interim Flow Agreement (IFA), in place from 2000 to 2006, was characterised as a more natural hydrograph with 45% of the previous days inflows being released into the Cheakamus River. The WUP flow treatment, in place from 2007 to 2017, is characterised as a set of minimum flows to be maintained throughout the year.

Juvenile salmon abundance was highly variable over the monitoring period. Pink Salmon abundance ranged from 82,000 to 29,000,000 between 2002 and 2016. Pink Salmon juveniles are not present in odd-years in the Cheakamus River; therefore, a total of 8 abundnance estimates were generated for this species over the WUP monitoring period. Chinook Salmon abundance was also highly variable ranging from 17,000 to 870,000. A total of 15 Chinook Salmon abundance estimates were generated in this monitoring program. Coho salmon abundance ranged from 69,000 to 150,000 and a total of 17 abundance estimates were generated. The majority (> 60%) of all juvenile salmonids reported on in this monitor appeared to originate in the mainstem Cheakamus River.

To answer MQ1, a suite of discharge and temperature variables were calculated for the Cheakamus River for use in linear regression modeling with juvenile salmon abundance. Discharge and temperature variables were summarized for the spawning, incubating/rearing, and migrating periods for each species. Variables calculated from discharge and temperature data for each life history period included minimum, variance and cumulative.

Signficant relationships were found between Cheakamus River environmental variables and juvenile salmon abundance. However, relationships were variable among species. For instance, Chinook Salmon appeared to respond positively when discharge was held higher during the adult spawning window in August (i.e., discharge maintaned at 40 m^3/s^{-1} or slightly higher through August 31st) (R^2=0.51, p= <0.001). Minimum water temperature in August had a strong negative influence on Chinook abundance the following spring (R^2= 0.88, p= <0.001). High discharge events in the egg incubation and juvenile rearing periods (October through January) was negatively related to Pink Salmon abundance (R^2= 0.29, p= 0.03). Coho Salmon abundance was also negatively affected by high winter discharge events, specifically events in December (R^2= 0.29, p= 0.03).

The relationships found in this regression analysis indicated that extreme temperatures and discharge events forecasted to increase with climate change are likely to have signficant effects on salmon populations in the Cheakamus River. Daisy Lake Resevoir is small and has limited storage capacity to buffer the Cheakamus River from large storms and late summer droughts. Most noteably Chinook Salmon appear to require more water and cooler temperatures during their August spawning window.

T-tests were used to compare the difference in Chinook and Coho salmon abundance between IFA and WUP flow treatments to answer MQ2. T-tests were not performed on Pink Salmon abundance data as too few data points were collected under each treatment. No significant differences were found in the mean abundance of each species between flow treatments (Chinook: p= 1.0, Coho: p=0.70). However, the statistical power of these tests was low due to the small sample size under each flow treatment (n < 10 *per* treatment); therefore the likelihood of failing to detect a true difference in abundance is signficant.

Significant limitations and uncertainties were identified with the chosen study design of CMSMON1a and caution should be taken in interpreting the results of this analysis of the effects of Daisy Dam operations on salmonids in the Cheakamus River. First, because the scope of the project was limited to monitoring to a single life stage for Pink, Chinook and Coho salmon the relationships found in the regression modeling may be confounded by other factors not accounted for, most signficantly adult spawner abundance. In other words, annual variability in juvenile abundance may reflect changes in adult spawner abundance rather than a true effect of discharge or temperature. Second the limited time period of the monitoring program reduced the statistical power to detect even small changes (25%) in abundance between IFA and WUP flow treatments to an unacceptably low level (< 60%). Thirdly, the limited period of monitoring and dicharge variability increases the leverage events like the 2003 flood or 2005 chemical spill had on regression relationships. In some cases relationships were driven by one or two events that were not repeated over the course of the study. Further years of monitoring, and likely a widening of monitoring scope, for species such as Chinook, are required to adequately determine the effects of dam operations on salmon in the Cheakamus River.

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Glossary of Terms

AUC	Area-Under-The-Curve
BTSPAS	Bayesian Time-Stratified Spline Model
DFO	Fisheries and Oceans Canada
IFA	Instream Flow Agreement
IFO	Interim Flow Order
NVOS	North Vancouver Outdoor School
RST	Rotary Screw Trap
SD	Standard Deviation
TH	Tenderfoot Hatchery
VIE	Visual Implant Elastomer
WSC	Water Survey of Canada
WUP	Water Use Plan
YOY	Young-Of-The-Year

1.0 INTRODUCTION

1.1 *Background*

The Cheakamus River is a salmon bearing river in the south coast of British Columbia and is important ecologically, culturally and recreationally to multiple stakeholder groups. The Squamish Nation harvest salmon in the Cheakamus River for food, social and ceremonial purposes. The watershed also provides opportunities for commercial anglers, raft guiding outfitters and recreational users (i.e., anglers and water sports).

The Cheakamus River was dammed for power generation and flood control in 1957. The Cheakamus Generation Project consists of a 28 m high, 680 m long dam that impounds the Cheakamus River and creates Daisy Lake Reservoir. Daisy Lake Reservoir has a storage capacity of 55,000,000 m^3 of water. Water is diverted from Daisy Lake through an 11 km tunnel through Cloudburst Mountain to a powerhouse on the Squamish River (Figure 1). The maximum capacity of the diversion through Cloudburst to the Squamish River is 60 $m^3 s^{-1}$. No fish passage structures were constructed in Daisy Dam due to the anadromous migration barrier at river km 17.5, which is below the dam.

Prior to 1997, the water licence for the Cheakamus Generation Project on the Cheakamus River specified that water must be released for fish. Post construction, minimum flows of 320 cubic feet per second (~9.5 m^3s^{-1}) between April and December and 200 cubic feet per second (~5.6 m^3s^{-1}) were recommended by Fisheries and Oceans Canada (DFO). However, there was no legal requirement for BC Hydro to meet these recommended minimum flows (Mattison et al. 2014). In 1997, Fisheries and Oceans Canada issued an Interim Flow Order (IFO) with specific minimum flows for the Cheakamus River. An Instream Flow Agreement (IFA) resulting from the order was implemented in 1999. The IFA specified that the greatest of either 5 $m^3 s^{-1}$ or 45% of the previous days' inflows to the lake be released from Daisy Dam (within a daily range of 37% to 52% and within 45% of the previous 7 days' average) (BC Hydro, 2005).

Uncertainties regarding the effects of the IFA on salmonid populations were identified in 1999 during the water use planning process (BC Hydro, 2005) and monitoring studies were initiated in the spring of 2000 to address the key uncertainties. In 2005, a matrix of minimum discharges was presented to the Water Comptroller in the Cheakamus River Water Use Plan (WUP) (BC Hydro, 2005). The WUP describes discharge rules for the Cheakamus River designed to balance environmental, social and economic values. An objective of the Cheakamus River WUP is to maximize the productivity of wild fish populations. The changes made to the IFA during the creation of the WUP flow structure were based on expected benefits to wild fish populations resulting from increases in available fish habitat (BC Hydro 2005). The new flow order (hereafter, WUP) for the Cheakamus River was approved by the Water Comptroller and implemented on February 26, 2006.

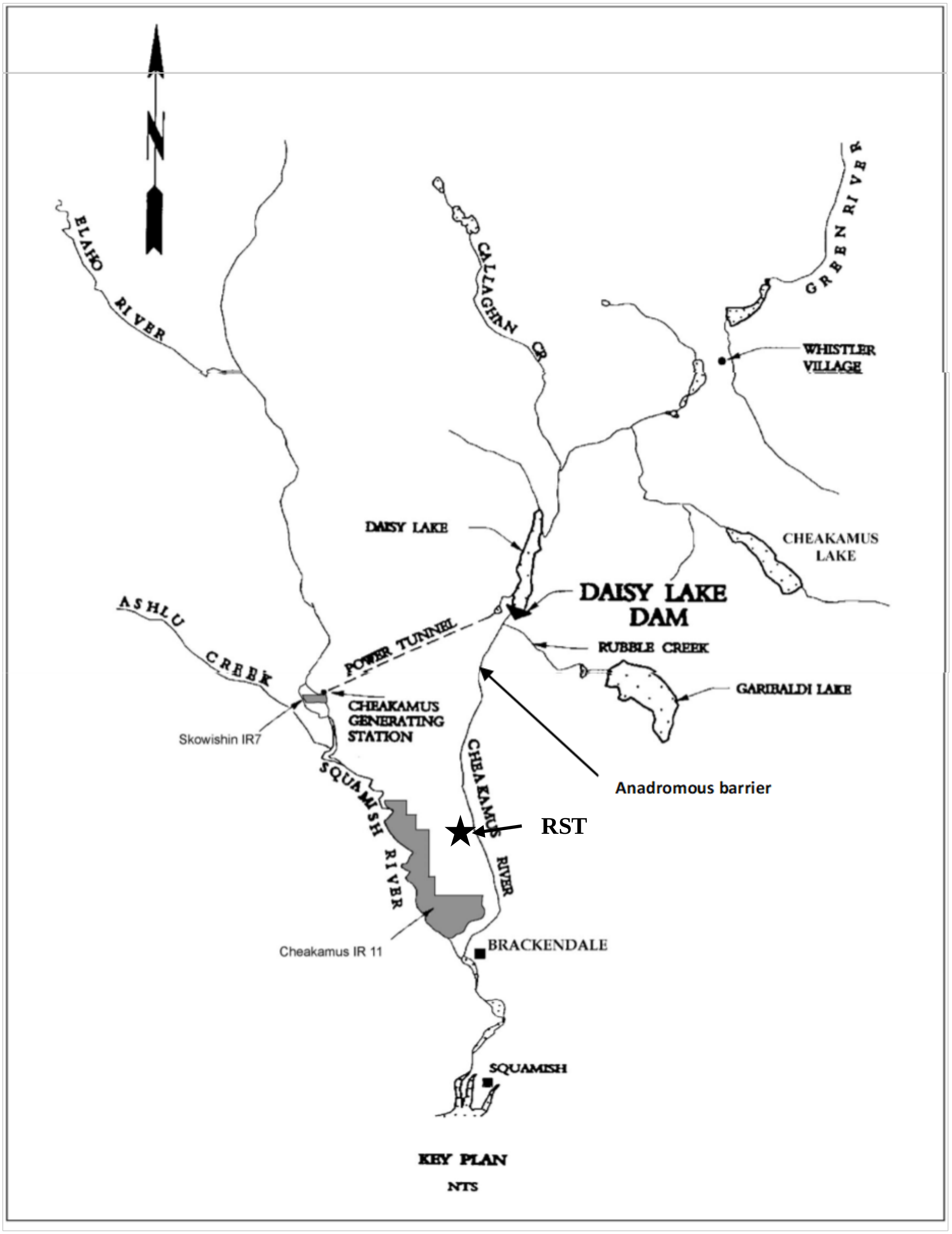


Figure 1. Map of the Cheakamus River and Daisy Generation Project in southwestern British Columbia.

Discharge requirements for operations under the implemented WUP were altered from the IFA to a required minimum flow at the following two locations:

1) Minimum flow required downstream of Daisy Lake Dam:

i) 3 $m^3 s^{-1}$ from Nov 1 to Dec 31

ii) 5 $m^3 s^{-1}$ from Jan 1 to Mar 31

iii) 7 $m^3 s^{-1}$ from Apr 1 to Oct 31

2) Minimum flow required at the Brackendale Water Survey of Canada (WSC) Gauge:

i) 15 $m^3 s^{-1}$ from Nov 1 to Mar 31

ii) 20 $m^3 s^{-1}$ from Apr 1 to Jun 30

iii) 38 $m^3 s^{-1}$ from Jul 1 to Aug 15

iv) 20 $m^3 s^{-1}$ from Aug 16 to Aug 31[1]

v) 20 $m^3 s^{-1}$ from Sep 1 to Oct 31

At the time of implementation, the effects of the WUP flow regime on fish populations were uncertain. Using relationships between fish habitat and fish production, Marmorek and Parnell (2002) outlined the expected benefits from the WUP flow regime. To assess the relationship between fish habitat and fish production, a study using rotary screw traps (RSTs) and mark-recapture methods to monitor juvenile salmonid production began in the spring of 2000 (Melville & McCubbing 2001) and has continued annually to 2017 following the terms of reference for Monitor 1a (hereafter, CMSMON1a). The objectives of this report are to synthesize the 17 years of juvenile fish abundance data towards answering the CMSMON1a management questions listed below.

1.2 *Management Questions*

CMSMON1a aims to assess the effects of the Water Use Plan prescribed flows below Daisy Dam on juvenile salmonid production and productivity in the Cheakamus River. The two management questions for CMSMON1a are:

[1]Unless directed to maintain 38 $m^3 s^{-1}$ for recreational purposes.

MQ1. What is the relationship between discharge and juvenile salmonid production, productivity, and habitat capacity of the mainstem and major side-channels of the Cheakamus River?

MQ2. Did juvenile salmonid production, productivity, or habitat capacity change following implementation of the WUP flow regime?

Juvenile Chum Salmon (*Oncorhynchus keta*) abundance data collected under CMSMON1a are also used in the Chum Salmon Adult Escapement Monitor (CMSMON1b) to address the question that is part of

MQ1. How does fry yield correlate to chum adult escapement, distribution, and density and is this affected by variance in discharge?

Juvenile Chum Salmon data were also used in CMSMON6 (Groundwater Side-Channels Monitor) to address the following management question:

MQ4. To what extent does salmonid production vary in North Vancouver Outdoor School (NVOS) and Tenderfoot Hatchery (TH) side-channels in relation to groundwater flow interaction with the Cheakamus River when discharge is $\leq$ 40 $m^3 s^{-1}$, and to what extent has the implementation of the WUP affected salmonid production in the NVOS and TH side-channel habitats compared to the pre-WUP state.

The focus of this report is to answer MQ1 and MQ2 for Pink (*O. gorbuscha*), Coho (*O. kisutch*) and Chinook (*O. tshawytscha*) salmon juveniles. Chum Salmon and Steelhead Trout (*O. mykiss*) are discussed in detail in CMSMON1b (Fell et al., in progress) and CMSMON3 (Korman and Schick, in progress), respectively. Productivity – as defined in the terms of reference for CMSMON1a – refers to the number of juveniles produced per spawner (BC Hydro 2006). Habitat capacity is defined as the asymptote of the spawner recruit curve. Because spawner abundance was not collected for the three species in CMSMON1a, juvenile fish abundance was the only metric that could be related to the management questions for Pink, Coho and Chinook salmon.

1.3 *Flood of 2003 and 2005 Caustic Soda Spill*

Two noteworthy events occurred in the Cheakamus River during the monitoring period that should be mentioned due to their impacts on fish populations. First, a rain-on-snow event in October 2003 resulted in a 100-year flood event. During this flood, discharge in the Cheakamus River exceeded the rating curve for the WSC Gauge at Brackendale (08GA043), reaching a maximum of 709 $m^3 s^{-1}$ on October 19, 2003.

Second, on August 5, 2005, a CN train de-railed at river kilometer (rkm) 19 and spilled 41,000 liters of caustic soda (NaOH) into the Cheakamus River. This event had significant impacts on fish populations and are documented in detail in McCubbing et al., (2006). Effects of these impacts are considered in the context of the results of this monitoring program.

2.0 METHODS

Here we provide a synthesis of juvenile fish abundance data to answer the management questions defined in Section 1.2 of this report. Detailed methods of annual data collection and results can be found in Lingard et al. (2016), or in previous annual reports at: (https://www.bchydro.com/about/sustainability/conservation/water_use_planning/lower_mainland/cheakamus.html).

2.1 *Site Description*

2.1.1 Study Area

The Cheakamus River is a major tributary of the Squamish Watershed and enters the Squamish River approximately 20 km north of Howe Sound (Figure 1). The Cheakamus Watershed covers an area of 1,010 km^2 in the coastal mountain range of southwestern British Columbia and is glacially fed. Annual water temperatures range from 0.5 to 15 ºC in the anadromous reach of the watershed. The Cheakamus River typically includes low flow periods (15-20 $m^3 s^{-1}$) in both winter and late summer/early fall, and two high flow periods resulting from spring snow melt (April to July) and fall storm events (October to November).

Daisy Dam is located on the Cheakamus River approximately 26 km upstream of the confluence with the Squamish River and impounds Daisy Lake Reservoir. A natural barrier to anadromous fish migration exists 9 km downstream of Daisy Dam at river km 17. The 17km of the Cheakamus River below the natural barrier supports populations of anadromous salmon and trout. Ten species of salmonids are present in the Cheakamus Watershed: Pink, Coho, Chum, Chinook, Sockeye (*O. nerka*) and Kokanee (*O. nerka*) salmon as well as Rainbow and Steelhead Trout, Cutthroat Trout (*O. clarkii*), Bull Trout (*Salvelinus confluen*tus), and Dolly Varden (*S. malma*).

The mainstem habitat in the Cheakamus River is complimented by a large area of man-made restoration channels which are fed either by groundwater or surface water diverted from the mainstem river (Figure 2). The first restoration channel in the Cheakamus River was built in 1982 at the property now known as the Cheakamus Center. In the 1990s and early 2000s, a network of restoration channels was expanded as part of the Dave Marshall Salmon Reserve. Additional channels have been built upstream and downstream of the Cheakamus Center and include Mykiss Channel, BC 49 Channel, BC Rail Channel, Dave's Pond and Moody's Channel. In addition to the constructed channels, large woody debris structures were placed in the mainstem Cheakamus River to increase habitat complexity (Harper and Wilson 2007).

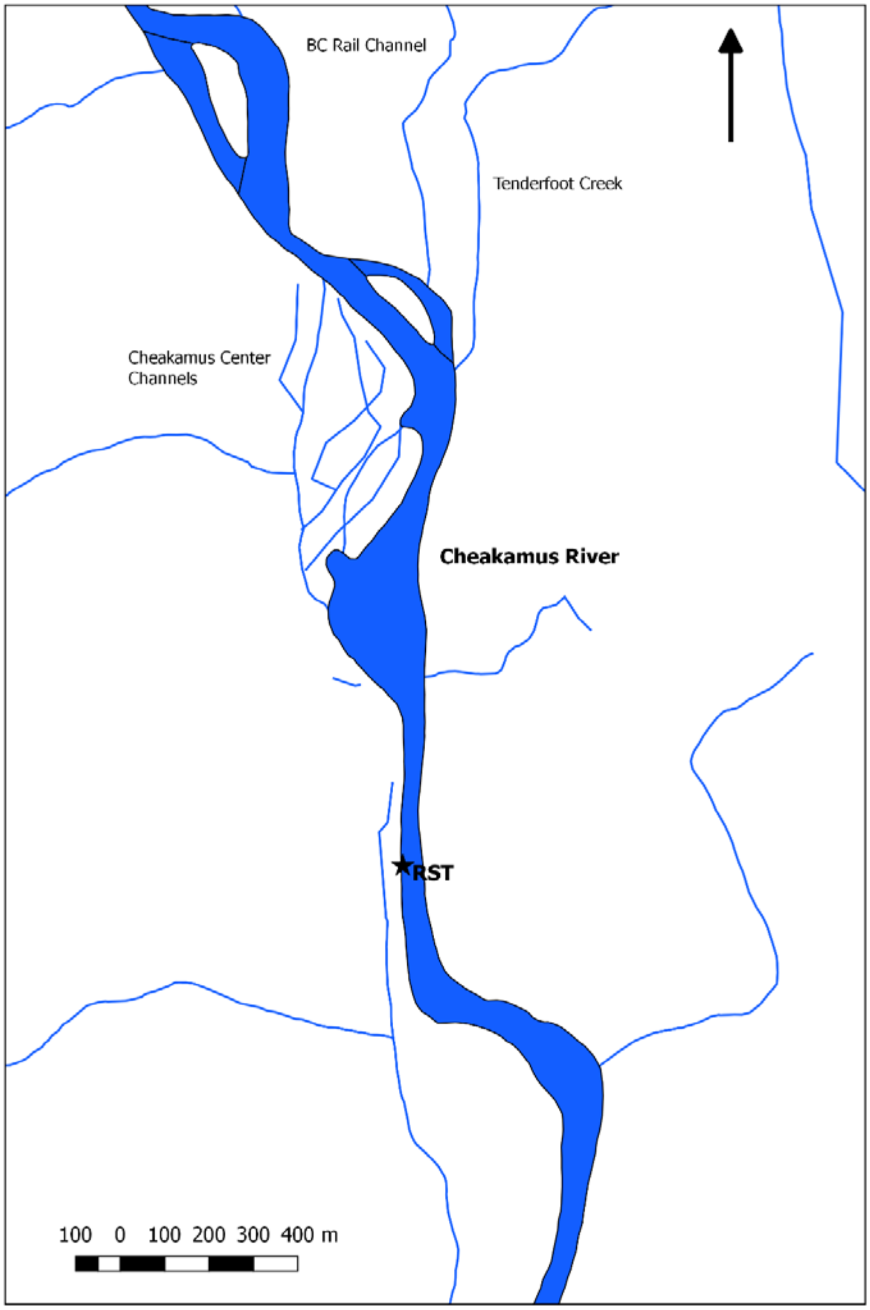


Figure 2. Map of the study area including the Cheakamus River and major side-channels.

2.1.2 Salmon Life-History Characteristics in the Cheakamus River

Salmonids are present in the Cheakamus River year-round. Pink Salmon are odd-year dominant (i.e., 2013, 2015, 2017, etc.) and adults are present between July and September. Pink Salmon juveniles begin emerging in January and migrate downstream between February and May as young-of-the-year (YOY).

Both summer and fall spawning Chinook Salmon populations are present in the watershed. Adult Chinook Salmon enter the Cheakamus River beginning in June. Spawning occurs in August for the summer population and between late September and mid-October for the fall population. Chinook Salmon juveniles express a diversity of life histories resulting from complex trade-offs between genetic and environmental factors (Volk et al., 2010; Bourret et al., 2016). YOY Chinook Salmon start to emerge in January. Between February and May, a substantial portion of the population emigrate shortly after emerging as YOY fry (35 to 50 mm). A smaller portion of juvenile Chinook Salmon remain for several months and emigrate as large (60 to 80 mm) YOY between May and September (sub-yearling or 'ocean-type'), while others overwinter in the Cheakamus River and migrate the following spring as yearling (or 'stream-type') smolts.

Adult Coho Salmon return to spawn between October and January. Coho Salmon spawning occurs between December and February. Juvenile Coho Salmon start to emerge in March and typically remain in the freshwater environment for a year before migration to marine environments as yearling smolts (Sandercock, 1991). An unknown proportion of the population migrate as YOY to rear in estuarine and marine environments (Lingard, 2015). Recent research in Washington, Oregon and Alaska indicates that YOY Coho Salmon emigrants contribute significantly to adult returns (Bennett et al., 2015; Koski, 2009).

Wild salmon populations in the Cheakamus River are supplemented by hatchery production from the Tenderfoot Creek Hatchery (operated by DFO). Over the duration of CMSMON1a, the Tenderfoot Creek Hatchery has enhanced Pink, Chum, Coho, and Chinook salmon and Steelhead trout populations in the Cheakamus River. Hatchery production methods and release totals have varied among years. See Lingard et al., (2016) for more detailed information on hatchery releases.

Table 1. Start and end dates for freshwater life history periods by species.

Species	Age class	Life history period	Time period
Chinook and Pink	Adult	Adult spawning	Aug 1 to Oct 31
Chinook and Pink	YOY (0+)	Incubation and juvenile rearing	Oct 1 to Jan 31
Chinook and Pink	YOY (0+)	Juvenile outmigration	Feb 1 to May 1
Coho	Yearling (1+)	Adult spawning	Nov 1 to Jan 1
Coho	Yearling (1+)	Juvenile rearing	Feb 1(smolt year-1) to Feb 1
Coho	Yearling (1+)	Juvenile outmigration	Feb 1 to Jun 30

2.2 *Juvenile Abundance Estimation*

2.2.1 Trapping Sites and Fish Capture Methods

Juvenile fish in the mainstem were enumerated by two six-foot RSTs operated adjacent to the Cheakamus Center (formerly NVOS) property (10U 0489141:5518035, Figure 2) at rkm 5.5. Traps were typically operated between February 15 and June 15 annually[2]. Fyke nets were operated in both groundwater and river-augmented (flow through) side-channels in the Cheakamus Center complex, the BC Rail Channel and Tenderfoot Creek (Figure 2). Fence traps, spanning the entire channel, were installed on the Cheakamus Center and BC Rail side-channels to capture yearling Coho Salmon (1+) and Steelhead trout (2+ & 3+) smolts from April 1 to June 15 each year (Figure 2).

2.2.2 Mark-Recapture Abundance Estimation

A modified Petersen mark-recapture model was used to generate abundance estimates for juvenile salmon in the Cheakamus River. In traditional Petersen methods, data pooling between sampling events (or strata) is often required in the event of sparse data. Pooling strata assumes homogeneity in capture probabilities, which is often violated due to varying river discharge and capture effort throughout the run. When heterogeneity is present, pooled Petersen estimators can substantially underestimate uncertainty in abundance estimates. A Bayesian Time-Stratified Spline Model (BTSPAS) was used to estimate annual fish abundance (Bonner & Schwarz, 2011). The BTSPAS model is a modified Petersen mark-recapture model that estimates weekly abundance using splines to model the general shape of the run. The Bayesian hierarchical method shares information on catchability among strata when data are sparse (Bonner and

[2]Trapping dates varied across years due to environmental factors (discharge events) and, to some extent, increased understanding of juvenile salmon outmigration patterns. For details on annual trapping dates, see annual reports at: https://www.bchydro.com/about/sustainability/conservation/water_use_planning/lower_mainland/cheakamus.html

Schwarz 2011). See Bonner and Schwarz (2011) for a detailed explanation of the model and its development.

Abundance estimates were generated for weekly strata for both the RSTs and fyke nets in side-channels. Weekly strata for YOY Chinook, Chum and Pink Salmon ran from Tuesday to Monday. Fish captured between Monday and Thursday were marked with a biological stain and released upstream of the RSTs or fyke net. Fish were not marked between Friday and Sunday to allow the mark group to move past the trap before the next strata began (Lingard et al., 2016). Note that Chum Salmon data collected under this project are discussed in CMSMON1b (Fell et al., in progress).

Weekly strata for Coho Salmon and Steelhead trout smolts ran from Monday to Sunday. Fish captured at the Cheakamus Center fence were used as the mark group for the RSTs. Fish were marked daily using Visual Implant Elastomer (VIE) tags and caudal fin clips. Each stratum was assigned a unique mark. Smolts were held in a holding box until dusk. Coho and Steelhead captured at the Cheakamus Center and the BC Rail fence were considered the entire catch for each channel and were counted daily.

Estimates generated from the RSTs represented the combined mainstem and side-channel estimate. Estimates generated from side-channel traps were subtracted from the RST estimate to determine comparative production from side-channel and mainstem habitat. Hatchery production totals were not included in the population estimates generated from this study.

2.3 IFA-WUP Comparisons of Mean Juvenile Salmon Abundance

We used t-tests to test for a significant difference in mean juvenile salmon abundance during the IFA (2000 to 2006, N=6) and WUP (2007 to 2017, N=10) flow treatments. The type of t-test (Student's or Welch's) selected for each species was dependent on whether the assumptions of equal variance (Brown-Forsythe Test $\alpha \geq 0.05$) and normality (Shapiro-Wilk $\alpha \geq 0.05$) were met.

Note that the power of the t-tests used to compare IFA and WUP time periods was low given the small number of abundance estimates under each flow treatment. The power of the t-test is further reduced by the high variability of juvenile fish abundance estimates (Ham & Pearsons, 2000; Melville & McCubbing, 2012). T-tests were not performed for Pink Salmon abundance due to a low sample size (IFA N=3, WUP N=5) resulting from their presence in only odd years.

2.4 Linear Regression Modeling

Many factors in both freshwater and marine environments have the potential to affect juvenile salmonid abundance (e.g., river discharge [Zimmerman et al., 2001; Connor and Pflug 2004; Zeug et al., 2014; Rebenack et al., 2015], temperature [Beer et al., 2001, Murray and McPhail 1988], marine productivity

[Hinch et al., 1995; Beamish et al., 2004]). As part of the data synthesis, we reviewed published relationships between environmental factors and juvenile fish abundance to compile a list of regression variables that may affect juvenile abundance in the Cheakamus River. Whenever possible, time series data were assembled for all environmental variables in the Cheakamus River or proxy data were obtained from other rivers and salmonid populations in the south coast region of British Columbia.

2.4.1 Spawner Abundance and Marine Survival

Spawner abundance data are required to evaluate where differences in annual juvenile production are attributable to changes in freshwater survival. Spawner abundance data were not collected for Coho, Chinook and Pink salmon in the Cheakamus River during the WUP monitoring program. To compensate for the lack of adult abundance data and inform whether trends in juvenile abundance may have been related to regional (marine) conditions and/or conditions within the Cheakamus River, spawner abundance and marine survival data were compiled for adjacent populations in the south coast of British Columbia (Table 2). From 2001 to 2015, spawner abundance and marine survival has been highly variable among salmon populations in the south coast of British Columbia (Figures A1, A2 and A3). Due to the lack of consistent regional trends, we did not include spawner data or marine survival for neighbouring salmon populations in this synthesis analysis.

Table 2. Marine survival and adult escapement data collected from south coast British Columbia streams for comparison to Cheakamus River juvenile salmon abundance.

Species	Variable	Brood Years Available	Data Source
Coho Salmon	St. of Georgia Marine Survival	1999 to 2012	DFO unpublished data
Coho Salmon	Squamish Nation Cheakamus River Adult Counts	2000 to 2016	Squamish Nation unpublished data
Chinook Salmon	St. of Georgia Marine Survival	2000-2012	DFO unpublished data
Chinook Salmon	Squamish Nation Cheakamus River Adult Counts	2000-2016	Squamish Nation unpublished data
Chinook Salmon	Fraser Ocean Type Age 3 Adult Chinook Escapement	2000 -2015	Pacific Salmon Commission Joint Chinook Technical Committee (2016)
Chinook Salmon	Lower St. of Georgia Ocean Type Age 3 Adult Chinook Escapement	2000-2015	Pacific Salmon Commission Joint Chinook Technical Committee (2016)
Pink Salmon	Squamish Nation Cheakamus River Adult Counts	2000-2016	Squamish Nation unpublished data
Pink Salmon	Fraser River Adult Pink Production	2001-2015	Fraser River Panel (2016)

2.4.2 Environmental Variables

Environmental data were compiled for the Cheakamus River to determine if variations in juvenile abundance were associated with changes in physical conditions and/or dam operations. Discharge and temperature were selected based on their potential to affect biological processes at distinct stages in the freshwater life history of each species or published relationships to juvenile salmon abundance (Table 2, Table 3). Discharge metrics (minimum discharge or days over minimum discharge) were also included in the linear models for their informative value to BC Hydro for future water management decisions.

Discharge was measured hourly throughout the duration of the monitoring period by the WSC Gauge at Brackendale (10U 0489186:5518291), located 100 m upstream of the RST site (**Figure 2**). Hourly water temperature was collected using an Onset TidbiT v2 data logger (UTBI-001) installed at the RST site. Temperature data were collected from February 15 to June 15 from 2001 to 2006. Beginning in 2007, water temperature was collected year-round.

Daily temperature and discharge were summarized in the following ways: minimum, cumulative, variance, and days over WUP-specified minimum flows (e.g., days over 40 $m^3 s^{-1}$ in August or days over 15 $m^3 s^{-1}$ in December). We also calculated the number of days between 25 and 80 $m^3 s^{-1}$ for November. We included this variable due to its significance for Chum Salmon spawning under CMSMON1b (Fell et al., in progress) to evaluate if there were similar relationships between this discharge metric and other salmonids in the watershed. Cumulative discharge was calculated by summing the average daily discharge over the specified period. Selected time periods represent the known spawning, egg incubation, juvenile rearing or juvenile outmigration period for each species (Table 1). Variables were calculated for each life history period (e.g., variance in discharge between August and October) as well as by individual month within a life history period (e.g., variance in discharge in August).

Due to the allowance in the WUP for flows to be decreased from 38 to 20 $m^3 s^{-1}$ on August 15 during the Chinook and Pink salmon spawning period, discharge metrics were also calculated from August 1 to 14 and August 15 to 31 to test whether this discretionary decrease influences juvenile fish abundance.

Table 3. A priori hypotheses developed for variable selection in linear modelling of Cheakamus River environmental variables and juvenile salmon abundance

Variable	Salmon Life history period	Hypothesis	References
minimum discharge	adult spawning period	Minimum discharge during adult spawning influences adult migration conditions and habitat availability for spawners	Webb et al., 2001 Cheakamus 2D Model
minimum discharge	incubation / rearing / migration	Minimum discharge during juvenile incubation, rearing and migration influences available habitat area	Cheakamus 2D model
discharge variance	adult spawning period	Variability in discharge affects migration timing and behavior in adult salmon	Tetzlaff et al., 2005, 2008; Smith, et al., 1994
discharge variance	incubation / rearing	Variability in discharge during incubation and rearing affects juvenile abundance through stranding related mortality, reduced habitat stability, and early emigration.	Bradford et al., 1997; Freeman et al., 2001; Rebenack et al., 2015; Irvine 1986
discharge variance	migration	Variability in discharge during migration affects migration conditions and influences migration date and age	Zeug et al., 2014
days over minimum discharge	incubation / rearing/ migration	Pulses over minimum discharge during juvenile incubation, rearing and migration cause stranding induced mortality and reduced habitat stability	Bradford et al., 1997; Freeman, et al., 2001; Zimmerman et al., 2015; Bradford et al., 1995
days over minimum discharge	adult spawning period	Pulses of discharge during adult spawning affect influences adult migration conditions and behavior	Smith et al., 1994; Web et al., 2001; Tetzlaff et al., 2005
cumulative discharge	incubation / rearing	Increased cumulative discharge during incubation and rearing influence foraging opportunities, and scour related mortality	Honea et al., 2016; Goode et al., 2013; Tetzlaff et al., 2005
cumulative discharge	adult spawning period	Cumulative discharge during spawning influences migration conditions and habitat availability for spawners	Tetzlaff et al., 2008; Gibbins et al., 2002
cumulative discharge	migration	Cumulative discharge during migration affects survival of rearing migrating juveniles and migration conditions	Zeug et al., 2014
minimum temperature	spawning and incubating	Minimum water temperature influences maturation rate of embryos, date of emergence, and adult spawner success	Beer and Anderson 2001; Murray and McPhail 1988; Geist et al., 2006; Hodgson and Quinn 2002; Goniea et al., 2006
minimum temperature	rearing/ migration	Minimum temperature during juvenile migration period influences juvenile growth and migration timing	Beakes et al., 2014; Jonsson and Ruud-Hansen 1985; Marine and Cech 2004
cumulative temperature	all	Cumulative temperature influences rate of: embryo maturation, juvenile growth and adult spawning behavior, and physiological stress of adult salmon	Murray and McPhail 1988; Marine and Cech 2004; Sykes et al., 2009; Wagner et al., 2005

2.6.2 Linear Regression Modeling

Mixed effect (ME) and multiple linear regression (MLR) are commonly used to assess the effects of environmental variables on salmon productivity (Arthaud et al., 2010, Zeug et al., 2014). Both ME and MLR analyses are used to examine correlations between two or more independent variables and a single dependent variable. Due to limited freshwater life history and biological data for Coho, Chinook and Pink salmon, it was not feasible to use either ME or MLR analyses for the CMSMON1a synthesis.

Individual linear regressions were used to determine whether changes in juvenile abundance were associated with changes in environmental variables (Figure 3). For each environmental variable selected for modeling, we tested for assumptions of normality using a Shapiro-Wilk test ($p<0.05$). Variables that failed to meet the criteria for normality were log-transformed and normality was re-assessed. Transformed variables that failed to meet the assumption of normality were omitted from this analysis. Due to the limited data and weakness of the Shapiro-Wilk test to detect non-normality in small samples ($N<30$) (Razali & Wah, 2011), additional post-regression model diagnostics were performed. We assessed model residuals for linearity, normality, and homoscedasticity, and evaluated the effect of potential influential observations on modelled relationships.

Linear regression variables were closely related due to overlapping measurement units and time periods (e.g., monthly and seasonal discharge variables), and collinearity between significant predictor variables was assessed using Pearson's correlation matrices. If two or more regression variables were significantly correlated ($p<0.05$), we presented the variable explaining the greatest amount of variability in juvenile abundance (i.e., the highest regression R^2).

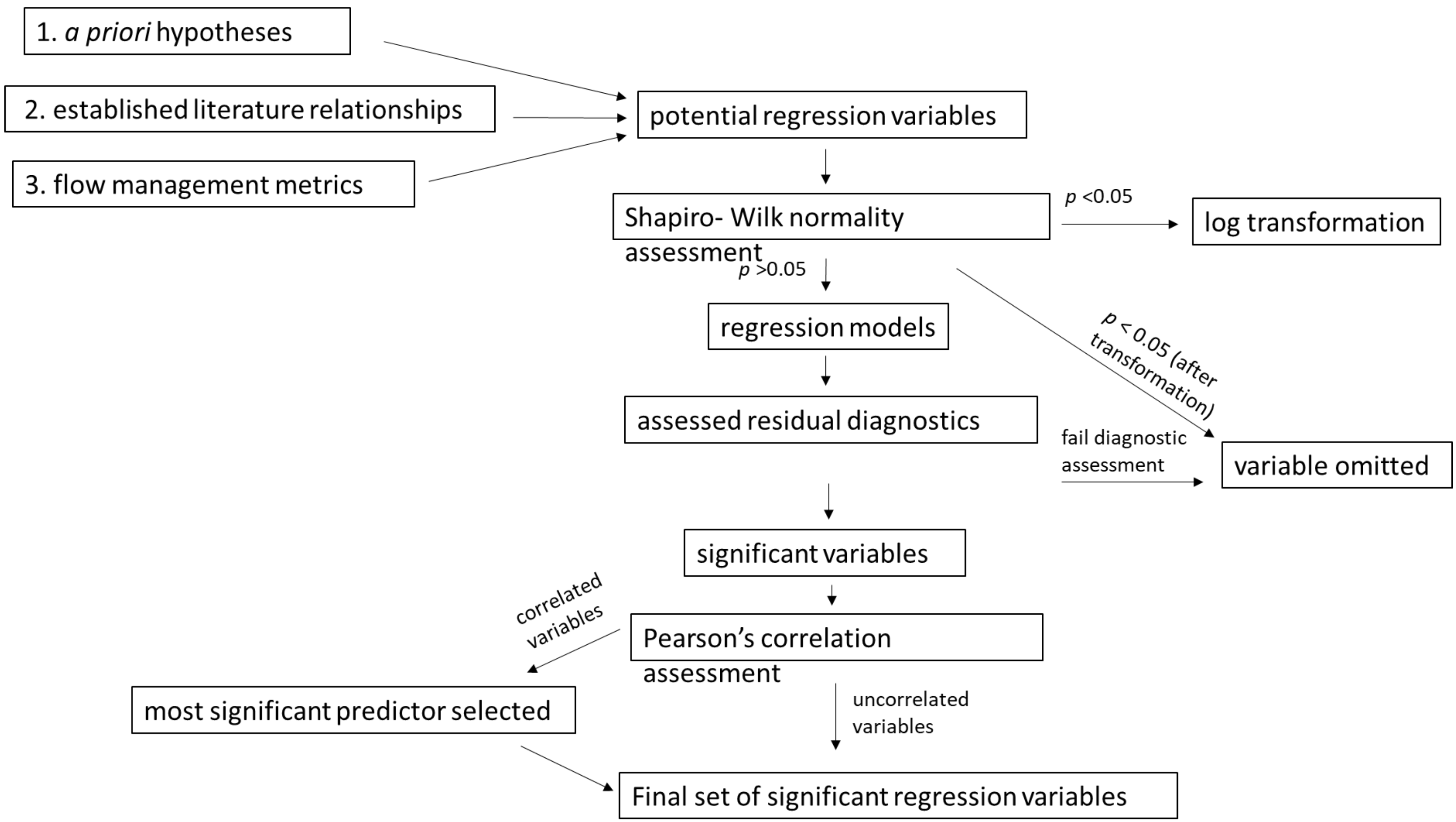


Figure 3 Schematic of analysis methods used for CMSMON1a data synthesis.

3.0 RESULTS

3.1 *Pink Salmon*

3.1.1 Pink Salmon Juvenile Abundance Estimates

Abundance of YOY Pink Salmon was highly variable over the study period. Between 2001 and 2017, annual Pink Salmon abundance ranged from 82,834 to 29,314,436 with a mean abundance of 8,808,936 (SD 11,700,397) (Table 4, Figure 4). Annual abundance estimates for YOY Pink Salmon generated from the BTSPAS model had high precision with coefficients of variation (*cv*) ranging from 0.01 to 0.17 (Table 4). Annual catch of Pink Salmon from RSTs ranged from 27,038 to 1,900,820 fish (Table 4). Between 10% and 57% of Pink Salmon were found to migrate out of side-channels (Table 4). Average side-channel production was 22% of total YOY Pink Salmon abundance (Table 4).

Table 4. Annual abundance estimates for YOY Pink Salmon leaving the Cheakamus River between February 15 and May 1 from 2002 to 2016. Capture of YOY Pink Salmon in odd years were near zero in the Cheakamus River.

Year	Mean abundance	SD	97.5% Lower	97.5% Upper	*cv*	Annual catch	Percent counted in side-channels
2002	1,671,625	286,619	1,274,882	2,303,970	0.17	27,038	Not assessed
2004	82,834	13,474	60,785	113,686	0.16	2,742	Not assessed
2006	303,488	9,817	285,605	323,715	0.03	41,336	Not assessed
2008	2,060,948	89,979	1,898,856	2,247,535	0.04	41,873	57%
2010	6,157,377	606,896	5,191,698	7,547,475	0.10	238,730	10%
2012	29,314,436	630,824	28,145,838	30,583,733	0.02	1,447,749	11%
2014	25,387,473	31,4061	24,782,837	26,014,983	0.01	1,900,820	14%
2016	5,491,140	260,514	5,032,642	6,046,211	0.05	258,353	19%

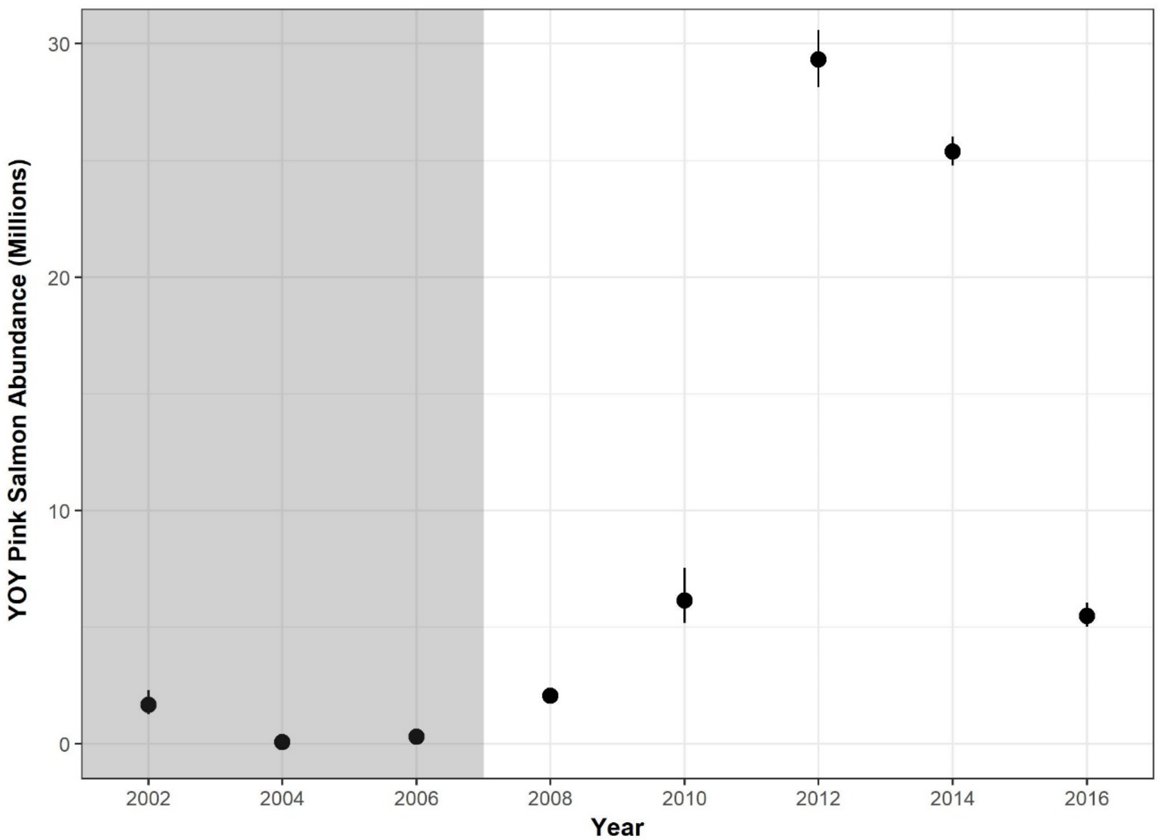


Figure 4. Annual abundance estimates of YOY Pink Salmon in the Cheakamus River. Error bars represent 97.5% confidence intervals. Grey shaded area represents abundance estimates under IFA flow conditions. Non-shaded area represents abundance estimates under WUP flow conditions.

3.1.2 IFA and WUP Flow Treatment Comparisons

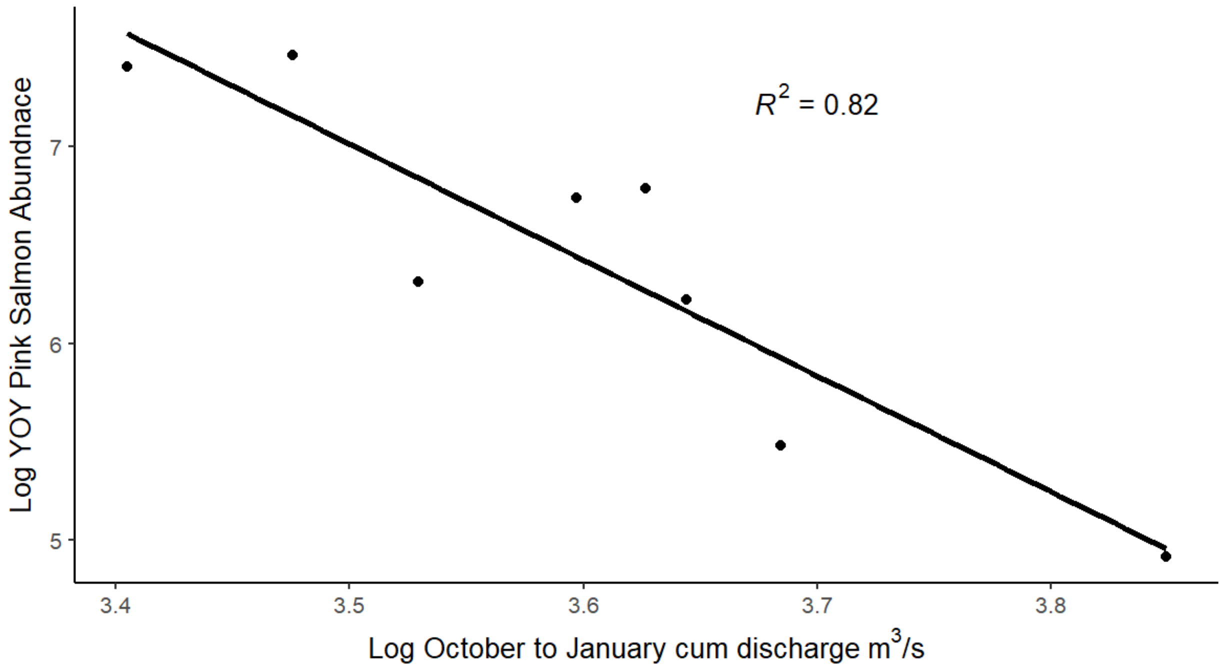
YOY Pink Salmon abundance increased between IFA and WUP time periods. Mean YOY Pink Salmon abundance during IFA (2002-2006) and WUP (2008-2016) time periods were 686,706 (SD 861,934) and 13,682,275 (SD 12,650,594), respectively. Annual abundance estimates during IFA and WUP time periods did not overlap (IFA = 82,680 - 1,671,625; WUP = 2,060,948 - 29,314,436). We did not statistically test for differences in YOY Pink Salmon abundance between flow treatments due to a low sample size (*N*=3 IFA, *N*=5 WUP).

3.1.3 Linear Model Results

Linear regressions were performed between YOY Pink Salmon abundance and the environmental variables listed in Table A1. Environmental variables for which the slope of the relationship with YOY Pink Salmon abundance was significantly different than zero included multiple discharge metrics between October and January, and minimum discharge between February and April (Table 5). All significant variables in the Pink Salmon incubation period (log_{10} October to January cumulative discharge, log_{10} cumulative October discharge, November days over 20 $m^3 s^{-1}$, and days between 25 and 80 $m^3 s^{-1}$) were significantly correlated (Table A3). Of the correlated variables in the incubation period, the logarithm of October to January cumulative discharge was negatively related to YOY Pink Salmon abundance and explained the greatest amount of variation ($R^2 = 0.82$, p-value <0.001) (Table 5, Figure 5). The only variable for which the relationship was positive and significant was February to April minimum discharge ($R^2=0.79$, p-value <0.001) (Figure 5).

Table 5. Summary of significant regression results between Log YOY Pink Salmon abundance and Cheakamus River environmental variables.

Variable	Life stage	*df*	*p*-value	R^2
Log_{10} October to January cumulative discharge	Incubation	6	<0.001	0.82
February to April min discharge	Juvenile outmigration	6	<0.001	0.79
Log_{10} Cumulative October discharge	Incubation	6	0.04	0.53
November days over 20 $m^3 s^{-1}$	Incubation	6	0.04	0.55
November days between 25 and 80 $m^3 s^{-1}$	Incubation	6	0.01	0.68



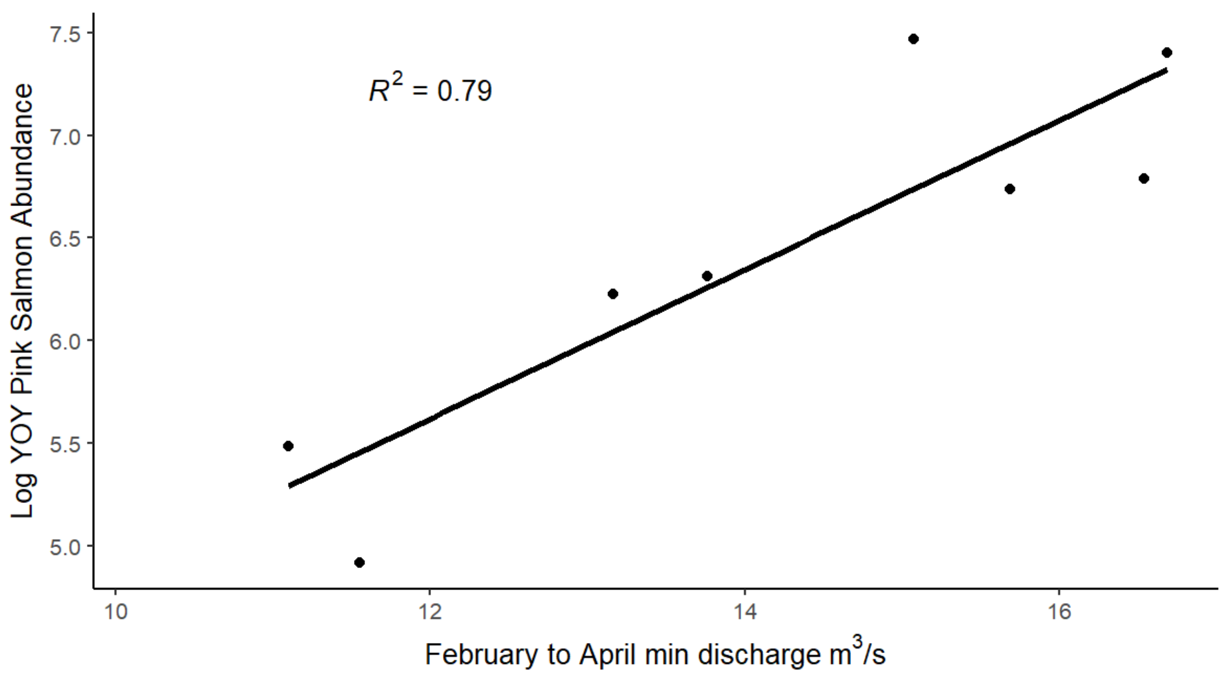


Figure 5. Plots of the two most significant log-linear relationships between YOY Pink Salmon abundance and Cheakamus River environmental variables.

3.2 Coho Salmon

3.2.1 Coho Salmon Juvenile Abundance Estimates

Between 2001 and 2017, annual Coho Salmon abundance ranged from 28,712 to 119,815 (Table 6, Figure 6). Mean Coho Salmon abundance between 2001 and 2017 was 76,908 (SD 25,202). The coefficient of variation for Coho smolt abundance estimates ranged from 0.04 to 0.27. The percentage of smolts migrating out of side-channels ranged between 9% and 36% of total annual abundance.

Table 6. Annual estimates of Coho Salmon smolt abundance generated by the BTSPAS model.

Year	Mean abundance	SD	97.5% Lower	97.5% Upper	*cv*	Annual catch	Percent counted in side-channels
2001	74,537	12,713	68,534	94,444	0.17	3,696	36%
2002	100,653	26,972	74,291	160,517	0.27	2,549	Not assessed
2003	118,161	9,833	104,299	141,550	0.08	5,823	Not assessed
2004	71,481	15,437	53,504	108,386	0.22	1,048	Not assessed
2005	61,472	8,316	48,448	80,513	0.14	1,609	Not assessed
2006	35,444	3,744	29,416	44,350	0.11	1,165	Not assessed
2007	97,832	5,882	87,798	110,736	0.06	7,237	Not assessed
2008	81,624	11,367	63,999	108,508	0.14	3,036	Not assessed
2009	60,686	8,238	50,802	80,920	0.14	6,614	22%
2010	101,271	3,687	95,281	109,805	0.04	10,681	24%
2011	62,593	4,359	55,276	72,393	0.07	5,238	14%
2012	66,944	5,599	58,222	79,329	0.08	6,194	19%
2013	83,707	3,321	77,765	90,817	0.04	7,244	18%
2014	119,815	15,425	99,185	157,584	0.13	15,060	19%
2015	28,712	1,541	26,014	32,108	0.05	2,748	17%
2016	69,120	8,539	57,206	90,552	0.12	6,250	Not assessed
2017	73,390	14,148	61,775	98,141	0.19	13,431	9%

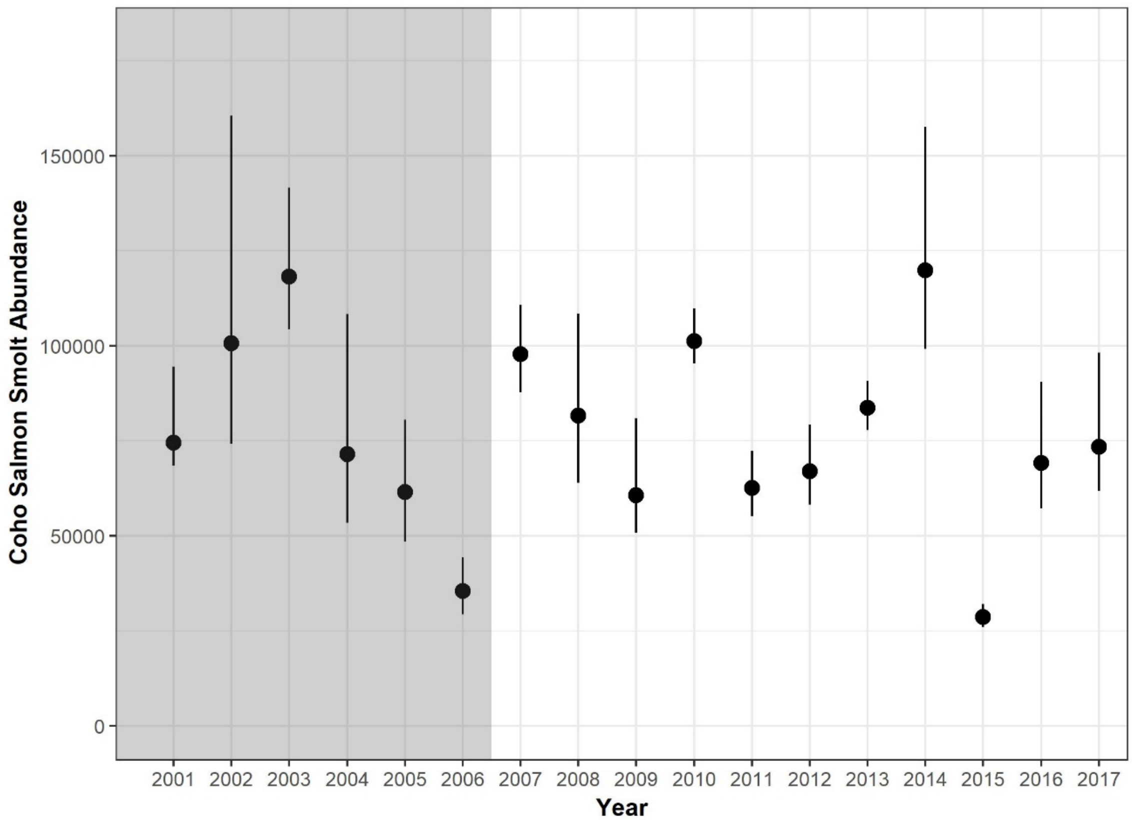


Figure 6. Annual abundance estimates of Coho Salmon yearling smolts leaving the Cheakamus River. Error bars represent 97.5% confidence intervals. Grey shaded area represents abundance estimates under IFA flow conditions. Non-shaded area represents abundance estimates under WUP flow conditions.

3.2.2 IFA and WUP Flow Treatment Comparison

Mean Coho Salmon smolt abundance was similar between IFA and WUP time periods. Mean abundances during IFA and WUP time periods were 76,958 (SD 29,183) and 76,881 (SD 24,298), respectively. Annual smolt abundance overlapped during the IFA and WUP time periods (IFA = 35,444 - 118,161; WUP =28,712 - 119,815).

Coho Salmon smolt abundances met the assumption of normality and equal variance (Shapiro-Wilk: W=0.96, p-value=0.06; Brown-Forsythe: F(1,11.96)=0.16, p-value=0.70). Differences in mean smolt abundance between the IFA and WUP flow treatments were not significant (Student's t-test: t(15)=0.40, p-value=0.70).

3.2.3 Linear Model Results

Linear regressions were performed between Coho Salmon smolt abundance and the environmental variables listed in Tables A1 and A2. Variables for which the slope of the relationship was significantly different than zero included: $\log_{10}$ cumulative December discharge, $\log_{10}$ variance in December discharge, and $\log_{10}$ cumulative October discharge (Table 7, Figure 7).

Two of the three significant linear relationships to Coho Salmon smolt abundance returned an R^2 of 0.29 and p-value of 0.03: $\log_{10}$ December cumulative discharge, $\log_{10}$ December discharge variance. Note that these two metrics were highly correlated (Pearson correlation r= 0.88, p-value <0.001) (Table A4). Log_{10} cumulative October discharge was also significantly related to smolt abundance but explained less variability in Coho Salmon smolt abundance (R^2=0.26). Significant discharge metrics were negatively related to smolt abundance (Figure 7).

The relationships between smolt abundance and significant December discharge metrics were heavily influenced by two points representing the winters of 2005/2006 and 2014/2015. These two winters were characterised by multiple sub-tropical storm events in December. With these points removed, the linear relationship was substantially weaker for both $\log_{10}$ December cumulative discharge (R^2 reduced from 0.29 to 0.01) and $\log_{10}$ December discharge variance (R^2 reduced from 0.29 to 0.04). In the model of $\log_{10}$ October cumulative discharge and smolt abundance, one year (representing the 2003 flood year) was also highly influential. With 2003 removed from the model the model R^2 increased from 0.29 to 0.45.

Table 7. Summary of significant regression results between Coho Salmon smolt abundance and selected variables.

Variable	Life stage	*df*	*p*-value	R^2
Log_{10} December cumulative discharge	Incubation	15	0.03	0.29
Log_{10} December discharge variance	Incubation	15	0.03	0.29
Log_{10} Cumulative October discharge	Adult migration, juvenile rearing	14	0.04	0.26

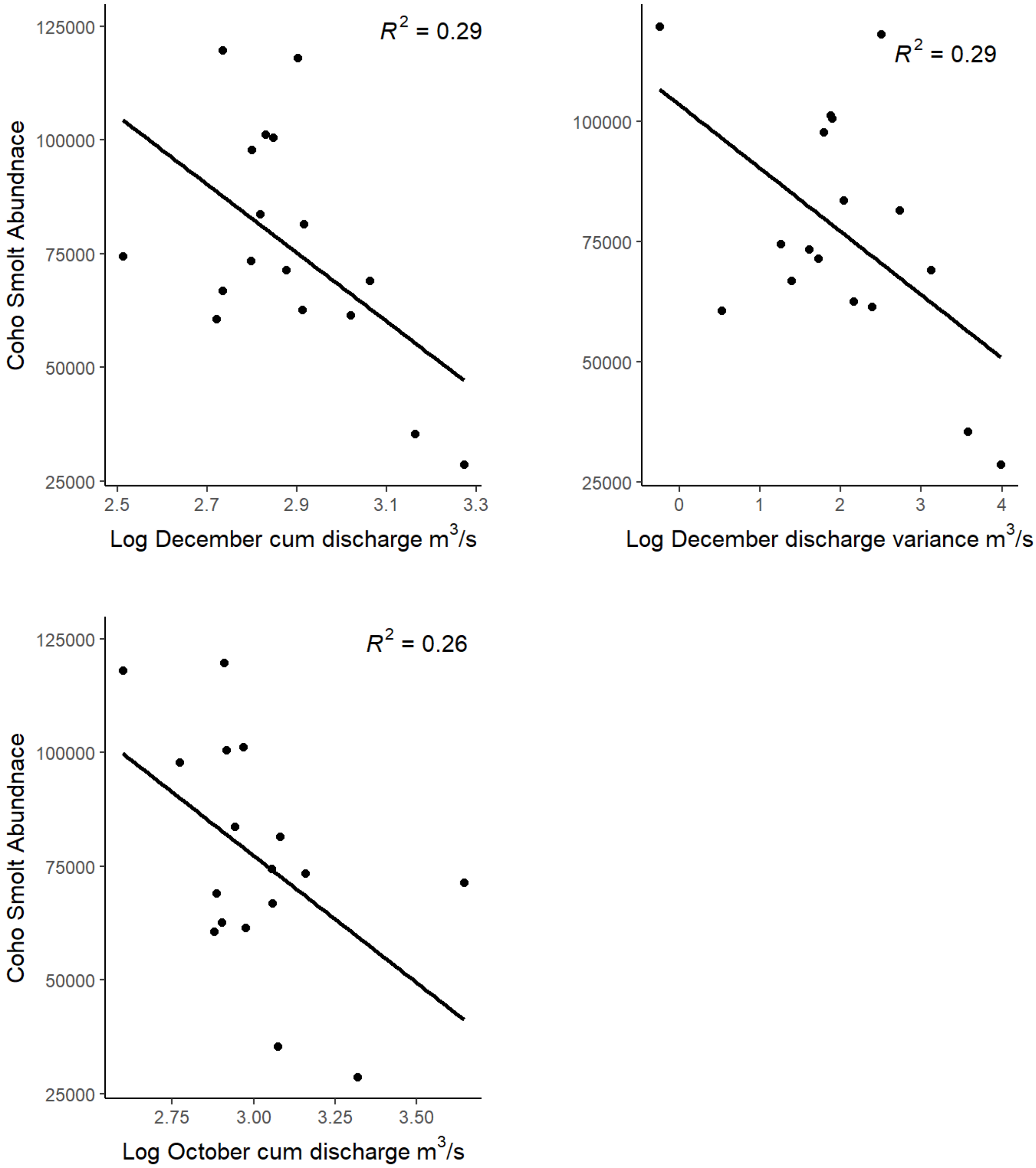


Figure 7. Plots of the three most significant log-linear relationships between Coho Salmon smolt abundance and selected variables.

3.3 Chinook Salmon

3.3.1 Chinook Salmon Juvenile Abundance

Annual YOY Chinook Salmon abundance estimates were highly variable throughout the monitoring period. Between 2001 and 2017, YOY Chinook Salmon abundance ranged from 16,484 to 874,946 (Table 8, Figure 8). Mean Chinook Salmon abundance between 2001 and 2017 was 253,173 (SD 222,225). An abundance estimate was not generated in 2006 (the year following the 2005 caustic soda spill) due to insufficient catch of Chinook Salmon (*N*=499).

Precision of annual YOY Chinook Salmon abundance estimates was the lowest of the three-species reported in CMSMON1a (*cv* range: 0.04 to 0.67, Table 8). Annual catch of YOY Chinook Salmon from RSTs was also lower than for Pink or Coho salmon. In 13 of the 15 years for which YOY Chinook Salmon abundance estimates were generated, annual catch was less than 10,000 fish (Table 8). Very few (<10 per year) YOY Chinook Salmon were captured in side-channel traps; therefore, abundance estimates were not generated for side-channels.

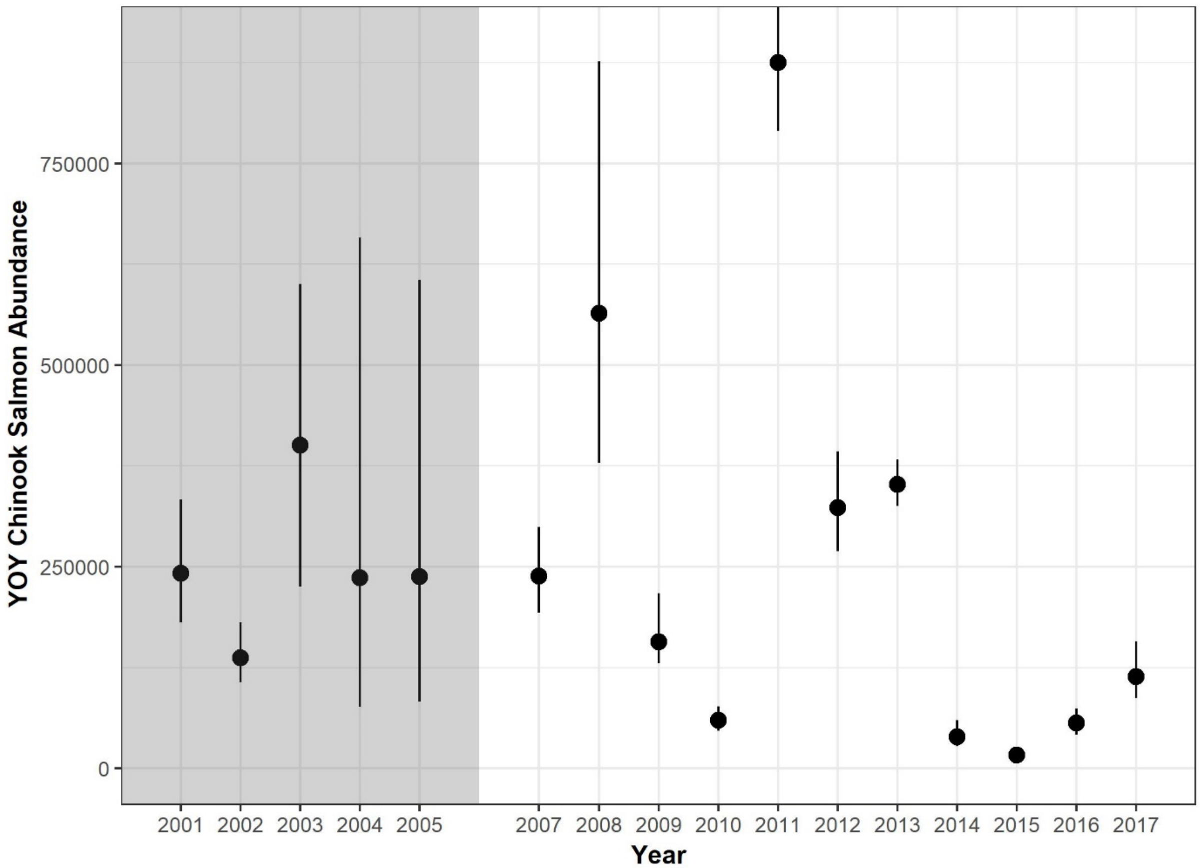


Figure 8. Annual abundance estimates for YOY Chinook Salmon in the Cheakamus. Error bars represent 97.5% confidence intervals. Grey shaded area represents abundance estimates under IFA flow conditions. Non-shaded area represents abundance estimates under WUP flow conditions.

Table 8. Annual estimates of YOY Chinook Salmon abundance generated by the BTSPAS model. No abundance estimate was generated in 2006 due to insufficient catch.

Year	Mean abundance	SD	97.5% Lower	97.5% Upper	*cv*	Annual catch
2001	167,946	39,688	180,674	333,839	0.16	8,578
2002	131,623	18,966	107,404	181,068	0.14	7,567
2003	385,534	98,652	225,488	600,794	0.25	5,859
2004	204,896	159,17	76,061	657,876	0.67	1,232
2005	211,909	154,69	83,365	605,230	0.65	1,107
2006	NA	NA	NA	NA	NA	499
2007	198,588	27,475	193,121	299,055	0.12	8,737
2008	564,313	132,30	378,680	876,185	0.23	5,127
2009	157,151	21,335	130,562	217,512	0.14	8,039
2010	60,040	7,799	47,132	77,166	0.13	3,649
2011	874,946	46,220	790,305	970,473	0.05	31,933
2012	323,375	32,315	269,226	392,903	0.10	8,787
2013	352,356	14,881	325,128	382,873	0.04	22,248
2014	39,001	9,413	27,941	59,812	0.24	3,154
2015	16,484	3,100	12,062	24,014	0.19	1,111
2016	56,470	8,474	41,910	74,511	0.15	1,922
2017	114,146	20,781	87,365	157,560	0.18	6,477

3.3.2 IFA and WUP Flow Treatment Comparison

Mean abundance of YOY Chinook Salmon between IFA and WUP time periods were similar. Mean abundance during the IFA and WUP time periods was 250,860 (SD 94,732) and 254,224 (SD 265,485), respectively.

Annual YOY Chinook Salmon abundance estimates were not-normally distributed (Shapiro-Wilk: W=0.86, p-value=0.02). Although Chinook Salmon abundance did not meet the criteria for normality, we used untransformed data in the t-test and linear regressions. The power of the Shapiro-Wilk test for small samples sizes (N <30) is low (Razali and Wah 2011) and the Shapiro-Wilk p-value was close to our chosen alpha level. Variance in mean IFA and WUP abundance estimates was equal (Brown-Forsythe Test: F(1,11.49)=0.01, p-value=0.94). Differences in mean abundance between the IFA and WUP time periods was not statistically significant (Student's t-test: t(14)=0.06, p-value=1.0).

3.3.3 Linear Model Results

Linear regressions were performed between YOY Chinook Salmon abundance and the environmental variables listed in Table A1. Environmental variables for which the slope of the relationship was significantly different than zero included: minimum discharge in August and cumulative water temperature during the Chinook Salmon egg incubation period (October to January) (Table 9). Log_{10} minimum discharge in both the first and second half of August was significantly and positively related to Chinook Salmon abundance; however, increased minimum discharge between August 15 and 31 explained a greater amount of variation in YOY Chinook Salmon abundance (R^2=0.51, *p*-value <0.001) (Table 9, Figure 9).

Minimum water temperature in August was also significantly and negatively related to YOY Chinook Salmon abundance and explained the greatest amount of variation in abundance (R^2=0.88, *p*-value <0.001) (Figure 8). Cumulative October temperature explained the second greatest amount of variability in YOY Chinook Salmon abundance (R^2=0.74, *p*-value <0.001) (Figure 9). Relationships between YOY Chinook Salmon abundance and cumulative water temperature in December and October to January were weaker (R^2=0.46, *p*-value=0.03 and R^2=0.44, *p*-value=0.04, respectively) (Table 9).

Many variables found to be significantly related to YOY Chinook Salmon abundance were correlated (Table A5). Log_{10} minimum discharge in both the first and second half of August were both highly correlated to minimum water temperature in August (first half *r*= -0.84, *p*-value <0.001; second half *r*=-0.85, *p*-value <0.001) (Table A5). Log_{10} minimum discharge in the second half of August was also correlated to cumulative water temperature in October (*r*= -0.62, *p*-value=0.04) and October to January (*r*= -0.81, *p*-value <0.001). Minimum August water temperature was significantly correlated to cumulative water temperature in October (*r*=0.70, *p*-value=0.03). October and December cumulative water temperatures were correlated (*r*=0.73, *p*-value=0.01).

Table 9. Summary of significant regression results between YOY Chinook Salmon abundance and Cheakamus River environmental variables.

Variable	Life stage	*df*	*p*-value	R^2
Log_{10} Aug 1 to 14 min Discharge	Adult spawning	14	0.02	0.31
Log_{10} Aug 15 to 31 min Discharge	Adult spawning	14	<0.001	0.51
October to January cumulative temperature	Juvenile incubation	8	0.04	0.44
October cumulative temperature	End adult spawning/ begin incubation	8	<0.001	0.74
December cumulative temperature	Juvenile incubation	8	0.03	0.46
August minimum temperature	Adult spawning	8	<0.001	0.88

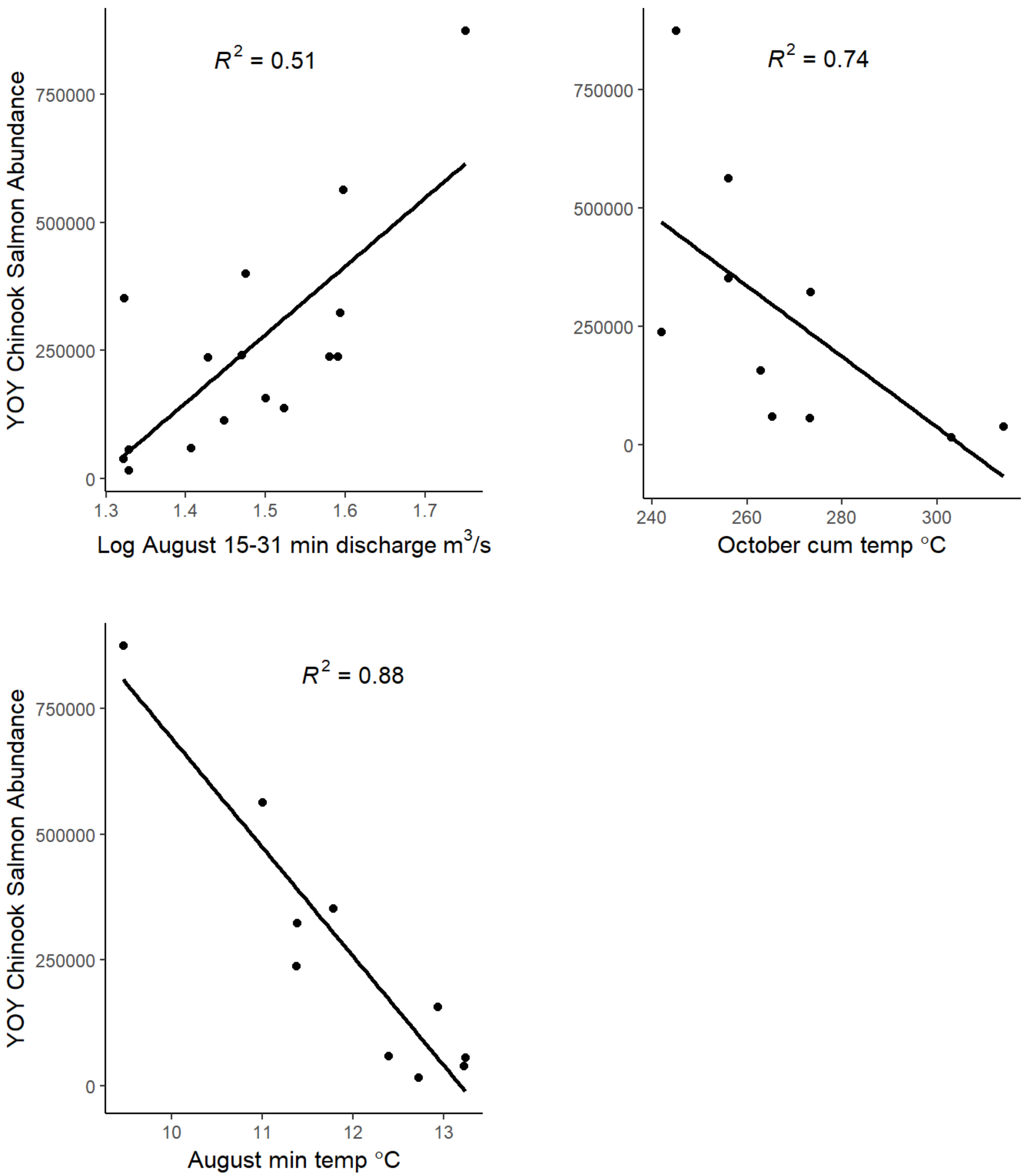


Figure 9. Plots of three most significant linear and log-linear relationships between YOY Chinook Salmon abundance and Cheakamus River environmental variables.

4.0 DISCUSSION

Fluctuations in river discharge can have substantial effects on Pacific salmon, and the degree to which discharge fluctuations affect salmon depends on the timing and magnitude, frequency and rate of change in flows (Harnish et al., 2013). Discharge in un-regulated rivers in the south coast of British Columbia generally follow a predictable pattern with large discharge increases occurring in the spring and fall. Small discharge fluctuations also occur through out the year in south coast watersheds due to rain events. Fluctuations (or absences of fluctuations) in discharge downstream of hydroelectric facilities may occur in patterns atypical of the season, and have been documented to negatively affect spawning, incubation and juvenile rearing in Pacific salmon (Malcolm et al., 2012; Young et al., 2011; Zeug et al., 2014).

The Cheakamus River WUP process identified key uncertainties regarding how anadromous salmonids respond to changes in discharge resulting from operations at Daisy Dam. To address these uncertainties, specific management questions were outlined in a terms of reference for each monitor (BC Hydro 2007). CMSMON1a has two management questions:

> MQ1. What is the relation between discharge and juvenile salmonid production, productivity, and habitat capacity of the mainstem and major side-channels of the Cheakamus River?
>
> MQ2. Does juvenile salmonid production, productivity, or habitat capacity change following implementation of the WUP flow regime?

CMSMON1a was initiated to provide juvenile Chum Salmon and Steelhead Trout abundance data to CMSMON1b and CMSMON3 that collect adult abundance data for each respective species. Data for the remaining species reported in CMSMON1a (Pink, Coho and Chinook salmon) are limited to annual juvenile abundance. Without adult abundance data, productivity, or the relationship between recruits and spawning adults, cannot be calculated. Environmental variables that affect adult spawner returns, such as marine productivity and fishing pressure, are accounted for in productivity, but not juvenile abundance. Changes in juvenile abundance may be incorrectly attributed to freshwater variables such as discharge, when in fact the true effect is related to decreased spawner abundance (MacKenzie et al., 2013). A major limitation with using juvenile salmon abundance to answer the management questions is the wide array of factors that could influence annual abundance. Additional variables that may affect juvenile abundance include discharge (Zeug et al., 2014; Arthaud et al., 2010), water temperature (Fuhrman et al., 2018), predator abundance (Walsworth & Schindler, 2016), watershed productivity (Wipfli et al., 2003), density dependent survival among juvenile salmonids (Einum and Nislow 2005), marine productivity (Beamish et al., 2004), and fishing pressure in both ocean and freshwater environments (Hard et al., 2008).

Accounting for all potential environmental variables is beyond the scope of CMSMON1a, and the significant relationships identified between juvenile abundance and discharge and temperature metrics may be confounded by additional variables. Despite this limitation, the significant variables identified in this analysis have been identified by other researchers as predictors of juvenile abundance and salmonid productivity in the Pacific Northwest and are biologically related to mechanisms known to affect salmon at different life stages (Arthaud et al., 2014; Rebenack et al., 2015, Zeug et al., 2014; Zimmerman et al., 2015).

The time required to detect population level effects depends on the life cycle and life history of the species (Babcock et al., 2010; Peterman 1990;); with longer time periods required for longer lived species with highly variable annual abundances. In the context of salmon population dynamics, the study duration of CMSMON1a was relatively short and not well suited to the length of a salmon life cycle. Pink Salmon life cycles are two years in duration. A three-year life history dominates in south coast Coho Salmon populations (Beamish et al., 2004), while Chinook Salmon return to spawn between ages 3 and 6. Taking this into consideration, one to three generations were monitored under the IFA flow treatment and two to five generations were monitored under the WUP flow treatment.

A power analysis was completed for the Cheakamus River during the design of the Cheakamus WUP monitoring program. In this analysis Parnell et al. (2003) determined 12 years prior and 12 years post implementation of the WUP were required to detect a 25% change in Coho smolt abundance with statistical power of 69%. For Coho Salmon, which has the most robust data set of all three species, only 6 data points were collected under the IFA and 10 under the WUP. For Pink Salmon, only 3 data points pre and 5 data points post WUP were collected. For Chinook Salmon 6 and 9 data points were collected under pre and post WUP conditions, respectively.

Having few observations results in some years (such as the 2003 flood) having a high leverage effect on regression relationships. For example, without the effects of the 2003 flood or the extremely wet winter of 2014-2015 the relationships between juvenile abundance and discharge would have been significantly different than presented in this analysis. In some cases, influential points may make a non-significant relationship appear significant, while in other cases they represent the upper and/or lower limits of the true relationship, but it takes a longer time series than we possess to obtain the natural variation required to determine whether abnormal points are truly abnormal. However, outliers represent true observed events and cannot be discounted in the analysis.

Despite the limitations of the CMSMON1a dataset, relationships were developed between juvenile fish abundance and discharge that can be used to answer MQ1. MQ2 was more difficult to address and we do not consider it answerable within the study design of CMSMON1a. Detailed discussion of the management questions follows in the sections below.

4.1 *MQ1: What is the relationship between discharge and juvenile salmonid production, productivity, and habitat capacity of the mainstem and major side-channels of the Cheakamus River?*

We developed relationships between discharge and temperature and juvenile fish abundance in the Cheakamus River. The relationships between discharge and temperature and juvenile fish abundance were not consistent among species. For example, Chinook Salmon were more sensitive to water temperature than Pink and Coho salmon. Discharge during the fall and winter was a significant predictor of juvenile Pink and Coho salmon abundance, but not of Chinook Salmon abundance.

Pink salmon

Regression models indicated that increased discharge during the egg incubation period (October to January) negatively affected YOY Pink Salmon abundance. Pink Salmon juveniles likely begin to hatch in late November or early December in the Cheakamus River and YOY Pink Salmon have been observed as early as the first week of January (InStream Fisheries Research; unpublished data.). Alevin and emergent juvenile salmon are sensitive to stranding from sudden changes in discharge (Puffer et al., 2017). Incubating eggs and juvenile salmonids are also sensitive to discharges at which small substrate becomes mobile (DeVries, 1997). The frequency of extreme storm events that result in high discharges between November and January in the Pacific Northwest is predicted to increase with climate change (Tohver et al., 2014). Given the storage capacity of Daisy Lake, it is unlikely that Daisy Dam operations can be modified to mitigate the effects of increased winter storm events resulting in high discharges during the incubation period for Pink Salmon.

Pink Salmon abundance was also positively related to increased discharge during the juvenile outmigration period (February to April). Increased discharge has been shown to affect the migration timing and survival of juvenile Chinook Salmon (Zeug et al., 2014) as well as multiple species of Pacific salmon in the Columbia River Basin (Čada et al., 1997). Increases in discharge during the spring are common in the Cheakamus River due to snow melt and spring storm events and likely offer beneficial migration conditions for juvenile salmonids.

Coho Salmon

Fewer relationships were significant between Coho Salmon and environmental variables; however, linear modeling results indicate discharge in December may negatively influence smolt abundance the following spring. High winter discharges in other systems have been documented to influence the timing of smolt migrations to marine environments (Rebenack et al., 2015). High winter discharge in the Cheakamus River results from storm events and are generally representative of natural hydrological events. It is unlikely that Daisy Dam operations could be changed due to the small storage capacity of the reservoir, to mitigate the effects of high winter discharge on the spring Coho migration abundance or migration timing. Additionally, it may be beneficial for some smolts to leave in the fall or winter due to the high discharges to provide better foraging opportunities for juveniles remaining in the river over winter (Chapman, 1962).

Recent research suggests Coho Salmon juvenile life history is not as static as once thought. Spring and fall emigrant YOY and yearling smolts are increasingly being found to contribute to adult returns across the extent of their North American range (Bennett et al., 2015; Koski, 2009). Given the improved understanding of variable juvenile life histories in Coho Salmon, further research would be required to examine freshwater survival in the Cheakamus River to fully understand the relationship between winter discharge and Coho Salmon abundance and productivity.

The limited number of significant relationships between Coho Salmon and environmental variables was likely influenced by their time spent in the freshwater environment. Coho Salmon juveniles spend approximately 18 months in freshwater from egg to smolt. Therefore, signals from individual seasons that affect rearing Coho Salmon may be diminished by summarizing data over a long-time period. Similarly, because there are multiple life history stages for Coho Salmon (incubating eggs, YOY, smolt) in freshwater relationships to environmental variables in one life stage may be confounded or masked by interactions between multiple factors over other life history stages. It is likely that if survival between fresh water life stages was assessed for Coho Salmon as in CMSMON-3, for steelhead, more relationships between Cheakamus River environmental variables and Coho Salmon survival would be discovered.

Chinook Salmon

In Chinook salmon, increased discharge during the summer population's spawning period had a positive effect on juvenile abundance. Between the first and second half of August, increased minimum discharge between August 15 and 31 explained a greater amount of variability in YOY Chinook Salmon abundance. Based on brood stock collection performed by the Tenderfoot Hatchery, August is the peak spawning period for summer Chinook Salmon in the Squamish River watershed, including the Cheakamus River. The WUP allows for a discretionary decrease from 38 to 20 $m^3 s^{-1}$ on August 15, unless directed by the Water Comptroller to maintain 38 $m^3 s^{-1}$ for recreational purposes. For large-bodied fish like Chinook Salmon, higher discharges (38 $m^3 s^{-1}$) during the adult spawning period may provide better migration conditions and opportunities for spawning in habitat that is too shallow at 20 $m^3 s^{-1}$. Moderate peaks in discharge during the spawning period have been documented to influence the timing of pre-spawning river entry by adult Atlantic Salmon (Tetzlaff et al., 2008) as well as the presence of large adults in shallow water spawning habitats (Malcolm et al., 2012).

Water temperature during the Chinook Salmon spawning period and the start of the egg incubation period had a greater significant effect than discharge on YOY Chinook Salmon abundance. August minimum water temperature was the most significant variable related to YOY Chinook Salmon abundance in the Chinook Salmon spawning window. Increasing water temperature during the summer spawning period is projected to be a significant limiting factor for Chinook Salmon populations as climate change progresses (Honea et al., 2016). While beyond the scope of this study and unlikely to be possible given the storage capacity of the Daisy Lake Resevoir, future considerations in water use planning process should include exploring the possibility of mitigating the effects of climate change on August water temperature with dam operations.

Increased cumulative water temperature in October also had a significant and negative effect on YOY Chinook Salmon. The majority of both fall and summer spawning Chinook Salmon eggs are likely deposited by the end of October. Embryo development rates in salmonids are influenced by water temperature with faster development occurring at higher water temperature (Fuhrman et al., 2018). In the Cheakamus River, most of the thermal units required for embryo development are likely obtained in September and October before water temperatures drop 1 to 2°C over the winter. Increased water temperature during the first weeks of October likely affects emergence and migration timing of YOY Chinook Salmon the following spring. Murray and McPhail (1988) found Chinook Salmon juveniles would emerge 115 days (4 months) after spawning if reared at 8°C but juveniles reared at 14°C would emerge at 63 days (2 months). A difference of a few degrees in daily water temperature in August and October likely influences when juvenile Chinook Salmon emerge and begin their downstream migration.

Water temperature in August, during summer Chinook Salmon spawning period, was significantly and negatively correlated with minimum discharge in August. A previous WUP monitor found that water temperatures downstream of Daisy Dam are influenced by dam operations, however the authors concluded that the effects of dam operations on water temperature are mitigated in the anadromous reach by inflows from tributaries (Rubble and Culliton Creeks) (McAdam 2001). In other words, the mitigating effects of the tributaries indicate that the water temperature in the anadromous reach is not influenced by water being spilled out of Daisy Lake. However, the temperature study did not explore how dam releases might be used to mitigate the effects of solar radiation and air temperature on water temperature. The negative correlation between August minimum water temperature and August minimum discharge suggests that higher discharges may result in lower water temperatures. This relationship is complex and is influenced by several factors including late melt of snow pillows and rain events associated with cooler temperatures. Taken together, the relationship between discharge, temperature and emergence timing is a critical area for further research on Cheakamus River Chinook Salmon.

4.2 *MQ2 Did juvenile salmonid production, productivity, or habitat capacity change following implementation of the WUP flow regime?*

MQ2 was difficult to address due to the lack of comparable pre-WUP data and thus we consider it to be unanswerable. Pacific salmon have complex life histories spanning freshwater and marine environments with highly variable annual abundances among and within populations. The ability to detect trends in salmon abundance using data from a single life history stage within the time frame of most monitoring programs (< 20 years) is often constrained by high variability in abundance and the multitude of potential environmental factors influencing survival (Korman and Higgins 1997; Ham and Pearsons 2000; Parnell et al., 2003; Wagner et al., 2013). The power of the t-tests used in this analysis to detect changes in salmon abundance within the time frame of this monitoring program is low and there is a high likelihood of a type 2 error (i.e., failure to detect a difference in means) (Melville & McCubbing 2012; Parnell et al., 2003).

Assessing trends in Pink Salmon abundance was particularly challenging due to their alternate year presence in watersheds. Compared to other species, the absence of Pink Salmon in some years extends the time required to detect a change in abundance (Melville & McCubbing 2012). Although it was not possible to test a difference in mean abundance between IFA and WUP flow treatments due to low sample size, mean Pink salmon abundance under the WUP flow treatment was 20-fold greater than the mean abundance under the IFA flow treatment. It is unlikely that this increase was in response to WUP flows as the trend has been observed in multiple odd-year Pink Salmon populations on both sides of the Pacific Ocean (Irvine et al., 2014). The increasing trend of odd-year Pink Salmon observed during the WUP flow treatment likely resulted from favourable climate conditions in the Pacific Ocean (Irvine et al., 2014).

We did not find a significant difference in mean abundance of Coho Salmon smolts between flow treatments. The Coho dataset was more robust than the datasets for the other species in that the annual study period captured the entire run of Coho Salmon (Lingard et al., 2016) and abundance estimates were generated for all years between 2001 and 2017. Although it is difficult to tease out the effects of the 2003 flood and 2005 spill from other confounding factors, these two events likely had significant impacts on Coho abundance during the IFA flow period (Melville & McCubbing 2006). It is possible that the difference in abundance between IFA and WUP flow treatments would have been greater had these two events not occurred during the IFA flow treatment.

The range of YOY Chinook Salmon abundances between IFA and WUP flow treatments was similar and mean abundances did not differ significantly. However, there were notable limitations in the Chinook Salmon abundance data. The precision of the estimates was low due to low catches in all years. The migration of YOY Chinook consistently started prior to the trapping period, resulting in incomplete estimates of annual abundance (Lingard et al., 2016). Chinook Salmon also display a range of juvenile rearing and emigration strategies not enumerated by the RST trapping program which further limit the ability to detect changes in juvenile Chinook Salmon abundance in relation to the WUP flow treatment.

5.0 REMAINING UNCERTAINTIES

A substantial uncertainty regarding the effects of juvenile salmon to the WUP flow treatment surrounds Chinook Salmon. Chinook Salmon are documented to exhibit a wide range of juvenile life history strategies (Miller et al., 2010). Juvenile Chinook Salmon in the Cheakamus River will emigrate as newly emergent YOY (30-50 mm), in the fall as larger (< 60 mm) YOY, or the following spring as yearling smolts (> 80 mm). Discharge has been shown to affect the age at migration in juvenile Chinook Salmon in other rivers in North America (Zeug et al., 2014). Determining whether the WUP flow treatment affects the productivity of Chinook Salmon juveniles in the Cheakamus River would require a study of multiple life history strategies and survival rates between life history stages, as well as further understanding habitat usage. Such an approach has been employed for Chum salmon and Steelhead trout in CMSMON1b and CMSMON3, respectively..

Low abundance of Chinook Salmon from 2014 to 2017 is a trend of concern and is likely related to regional trends of poor ocean survival in the Strait of Georgia (Preikshot et al., 2013). However, Chinook Salmon populations have considerable heterogeneity in abundance and marine survival trends among Strait of Georgia populations and life history types (Ruff et al., 2017). The lack of adult abundance data and variability among populations within the south coast region confound our ability to determine whether Cheakamus River conditions are contributing to the recent low abundance of Chinook Salmon, or whether these effects are due to ocean conditions. Consequently, there is a need to determine if freshwater survival is contributing to the low abundance of Chinook Salmon in the Cheakamus River.

A notable uncertainty is how climate change will affect all species in the watershed and whether the WUP can be modified to help mitigate some of these potential effects. Storm events in the fall and winter months are projected to increase in frequency and magnitude with climate change (Tohver et al., 2017). Additionally, stream water temperatures are forecasted to increase with climate change (Van Vliet et al., 2013) and salmon populations are at risk of extirpation from some watersheds (Crozier 2015). The relationships presented in this report indicate a sensitivity of juvenile salmon to high winter discharges and high water temperatures during the summer and fall. Although the Cheakamus River has over 3 kilometers of side-channel habitat to protect from high discharge events in the mainstem, the majority of Pink, Chinook, and Coho salmon juveniles were found to originate out of mainstem habitats in the Cheakamus River. The reliance of Pink, Chinook and Coho salmon on mainstem habitat for rearing and spawning in the Cheakamus River indicates a need to further understanding of habitat use and freshwater survival in these species to support the development of water management solutions to buffer these populations from the potential cumulative effects of climate change and Daisy Dam operations.

Conflicting relationships between discharge and individual species may exist within the Cheakamus Watershed. For example, from this analysis, it appears that increased discharge in August may benefit Chinook Salmon. However, this timing overlaps with the emergence and early rearing of steelhead trout, a highly sensitive life stage for juvenile stranding and displacement (Tetzlaff et al., 2005; Korman et al., 2011). Because of the complex array of species and timing of life history stages in the watershed, an assessment of conservation priorities will be required before decisions can be made regarding flow release practices from Daisy Dam.

6.0 CONCLUSION

We monitored juvenile salmon abundance of Pink, Chinook and Coho salmon in the Cheakamus River for seventeen years between 2001 and 2017. Six years of data were collected prior to implementation of the Cheakamus WUP flow regime. The monitoring program was implemented to reduce uncertainties surrounding the relationship between juvenile salmon abundance and discharge in the Cheakamus River below Daisy Dam, as outlined in the Cheakamus Water Use Plan 2007.

We were successful in developing relationships between juvenile salmon abundance and discharge in the Cheakamus River to answer MQ1. The relationships developed in this analysis will be informative for how future BC Hydro operations of the Cheakamus River will be determined and indicate stable WUP flows may not be beneficial for all species, such as Chinook Salmon, depending on the time of year. In other species, such as Coho and Pink Salmon, stable WUP flows over winter appear to be beneficial. Although these findings are significant for management of the Cheakamus, we caution managers to consider the short time duration, and limited scope of the monitoring program to a single life stage.

We were not able to determine whether there was a change between pre and post WUP flows due to the short monitoring duration for each regime to answer MQ2. Continued monitoring with specific scope changes (i.e. adult abundance estimates, tests of specific treatments, etc.) for Pink, Coho and Chinook Salmon would be required to increase confidence in population responses to BC Hydro operations. Further research to better understand the mechanisms by which discharge affects specific life stages of individual species may also be required to support decision makers in setting priorities at a watershed scale.

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8.0 APPENDICES

Table A1. Variables selected for regression modeling with Cheakamus River juvenile Pink, Coho and Chinook salmon abundances for BC Hydro CMSMON1a

Variable	Name	Species
	August to October minimum discharge	Chinook and Pink
Log10	August to October discharge variance	Chinook and Pink
Log10	August to October cumulative discharge	Chinook and Pink
	August to October days over 40	Chinook and Pink
Log10	August 1_14 minimum discharge	Chinook and Pink
Log10	August 15_31 minimum discharge	Chinook and Pink
Log10	August 15_31 days over 40	Chinook and Pink
Log10	October to January minimum discharge	Chinook and Pink
Log10	October to January discharge variance	Chinook and Pink
Log10	October to January cumulative discharge	Chinook and Pink
Log10	February to April cumulative discharge	Chinook and Pink
Log10	February to April discharge variance	Chinook and Pink
	February to April minimum discharge	Chinook and Pink
	February to April cumulative temperature	Chinook and Pink
Log10	February to April variance temperature	Chinook and Pink
	February to April minimum temperature	Chinook and Pink
Log10	February to April max temperature	Chinook and Pink
	August to October cumulative temperature	Chinook and Pink
	August to October variance temperature	Chinook and Pink
Log10	August to October minimum temperature	Chinook and Pink

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Variable	**Name**	**Species**
	October to January cumulative temperature	Chinook and Pink
	October to January variance temperature	Chinook and Pink
	October to January minimum temperature	Chinook and Pink
	August cumulative temperature	Chinook and Pink
	August days over 40 $m^3 s^{-1}$	Chinook and Pink
	September cumulative temperature	Chinook and Pink
Log10	September cumulative discharge	Chinook and Pink
Log10	September discharge variance	Chinook and Pink
Log10	August minimum discharge	Chinook and Pink
	September minimum discharge	Chinook and Pink
Log10	August variance discharge	Chinook and Pink
Log10	August cumulative discharge	Chinook and Pink
Log10	September cumulative discharge	Chinook and Pink
	October days over 22 $m^3 s^{-1}$	Chinook, Pink, Coho
	October cumulative temperature	Chinook, Pink, Coho
Log10	October cumulative discharge	Chinook, Pink, Coho
Log10	October discharge variance	Chinook, Pink, Coho
	November days over 20 $m^3 s^{-1}$	Chinook, Pink, Coho
	November days between 25 and 80 $m^3 s^{-1}$	Chinook, Pink, Coho

Table A2 Variables selected for regression modeling with Cheakamus River Coho Salmon smolt abundance

Variable	Name	Species
	November to January minimum discharge	Coho
Log10	November to January discharge variance	Coho
	November to January cumulative discharge	Coho
	February to June discharge variance	Coho
	February to June minimum discharge	Coho
	February to June cumulative discharge	Coho
Log10	February to June variance temperature	Coho
	February to June cumulative temperature	Coho
	February to June minimum temperature	Coho
	November to January cumulative temperature	Coho
	November to January variance temperature	Coho
	November to January minimum temperature	Coho
	Smolt Rearing cumulative temperature	Coho
	Smolt Rearing variance temperature	Coho
	Smolt Rearing minimum temperature	Coho
	Smolt Rearing cumulative discharge	Coho
Log10	Smolt Rearing discharge variance	Coho
	Smolt Rearing minimum discharge	Coho
Log10	Cheakamus Coho Adult Count	Coho
Log10	Cheakamus YOY Pink Salmon abundance	Coho

Table A3. Pearson's correlation *p*-values of variables found to have significant linear or log-linear relationships to Cheakamus River YOY Pink Salmon abundance.

	Log_{10} October to January cumulative discharge	February to April min discharge	Log_{10} Cumulative October discharge	November days over 20 $m^3 s^{-1}$	November days between 25 and 80 $m^3 s^{-1}$
Log_{10} October to January cumulative discharge	0.000	0.353	0.002	0.000	0.001
February to April min discharge	0.353	0.000	0.627	0.268	0.082
Log_{10} Cumulative October discharge	0.002	0.627	0.000	0.122	0.167
November days over 20 $m^3 s^{-1}$	<0.001	0.268	0.122	0.000	<0.001
November days between 25 and 80 m^3 s	0.001	0.082	0.167	0.000	0.000

Table A4. Pearson's correlation *p*-values of variables found to have significant log-linear relationships to Cheakamus River Coho Salmon smolt abundance.

	$\mathbf{Log_{10}}$ December cumulative discharge	$\mathbf{Log_{10}}$ December discharge variance	$\mathbf{Log_{10}}$ Cumulative October discharge
$\mathbf{Log_{10}}$ December cumulative discharge	0.000	0.316	0.185
$\mathbf{Log_{10}}$ December discharge variance	0.316	0.000	<0.001
$\mathbf{Log_{10}}$ Cumulative October discharge	0.186	<0.001	0.000

Table A5. Pearson's correlation *p*-values of variables with significant linear or log-linear relationships to YOY Chinook Salmon abundance in the Cheakamus River.

	Log_{10} Aug 1 to 14 min Discharge	Log_{10} Aug 15 to 31 min Discharge	October to January cumulative temperature	October cumulative temperature	December cumulative temperature	August minimum temperature
Log_{10} Aug 1 to 14 min Discharge	0.000	0.117	0.166	0.499	0.765	0.003
Log_{10} Aug 15 to 31 min Discharge	0.117	0.000	0.005	0.040	0.410	0.002
October to January cumulative temperature	0.166	0.005	0.000	0.126	0.337	0.051
October cumulative temperature	0.499	0.040	0.126	0.000	0.013	0.033
December cumulative temperature	0.765	0.410	0.337	0.013	0.000	0.540
August minimum temperature	0.003	0.002	0.051	0.033	0.540	0.000

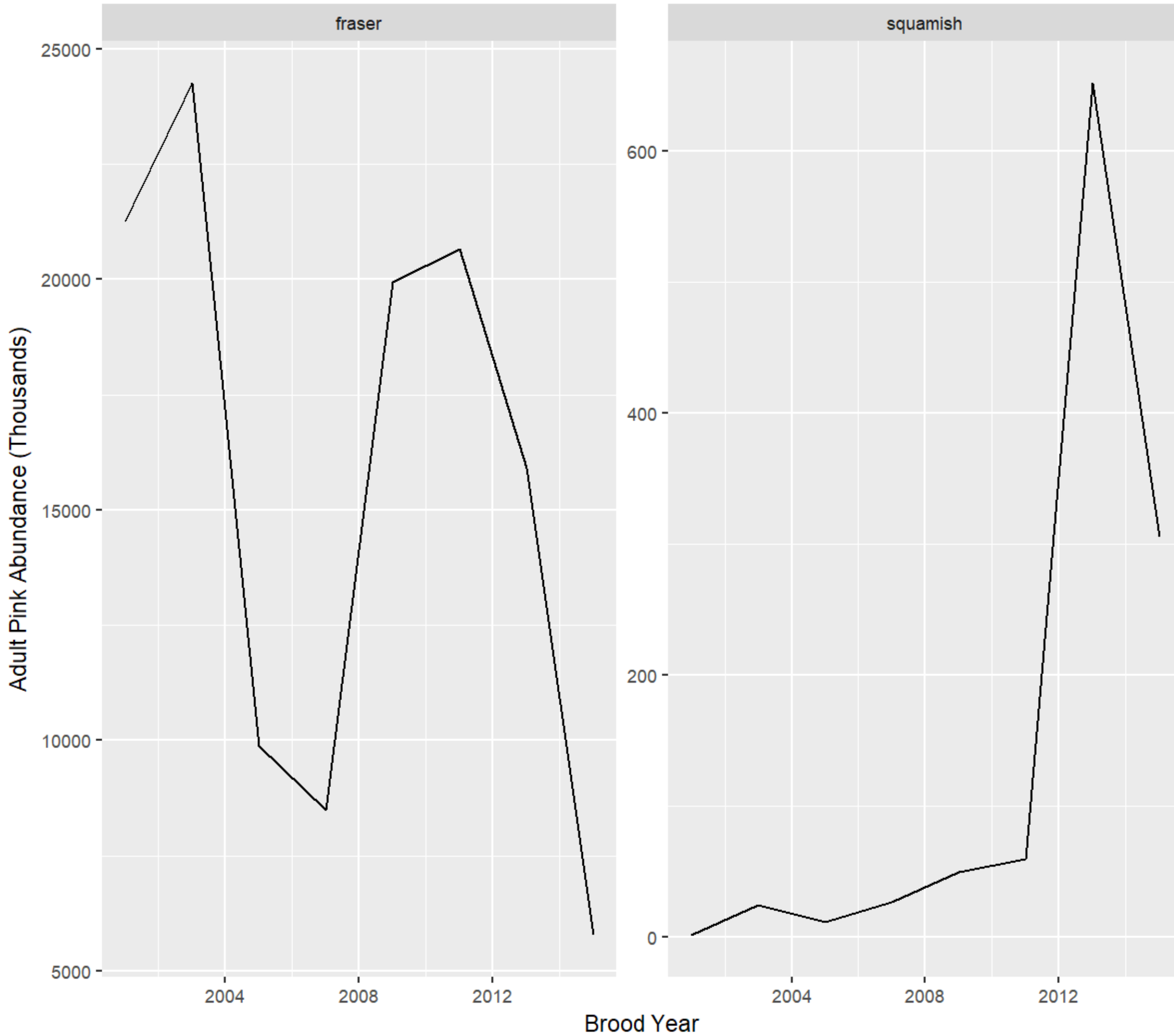

Figure A1 Plot of Fraser River and Squamish River Adult Pink Salmon abundance estimates 2001-2015.

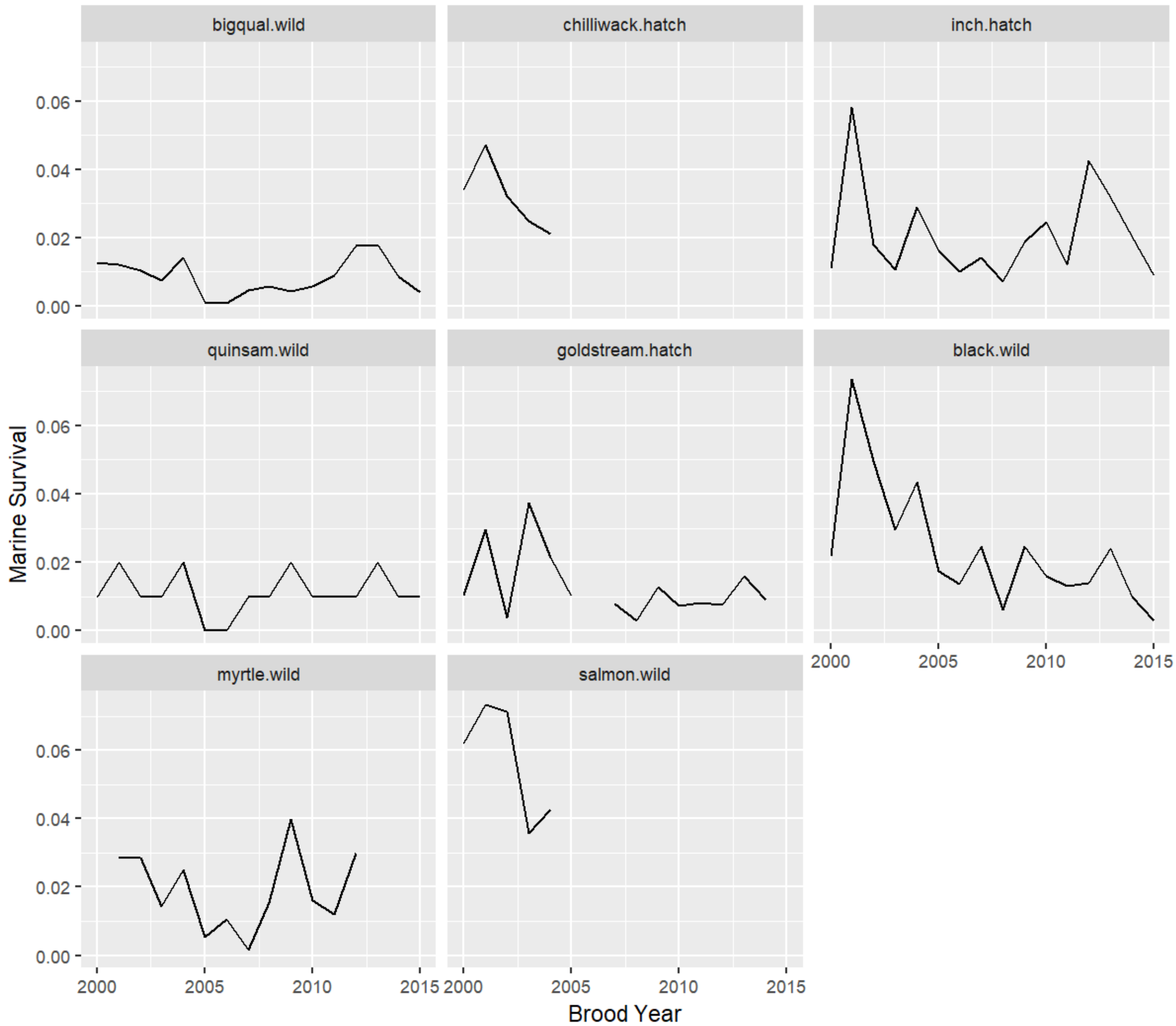

Figure A2 Marine Survival for Coho Salmon for multiple populations in the Straight of Georgia (DFO unpublished data).

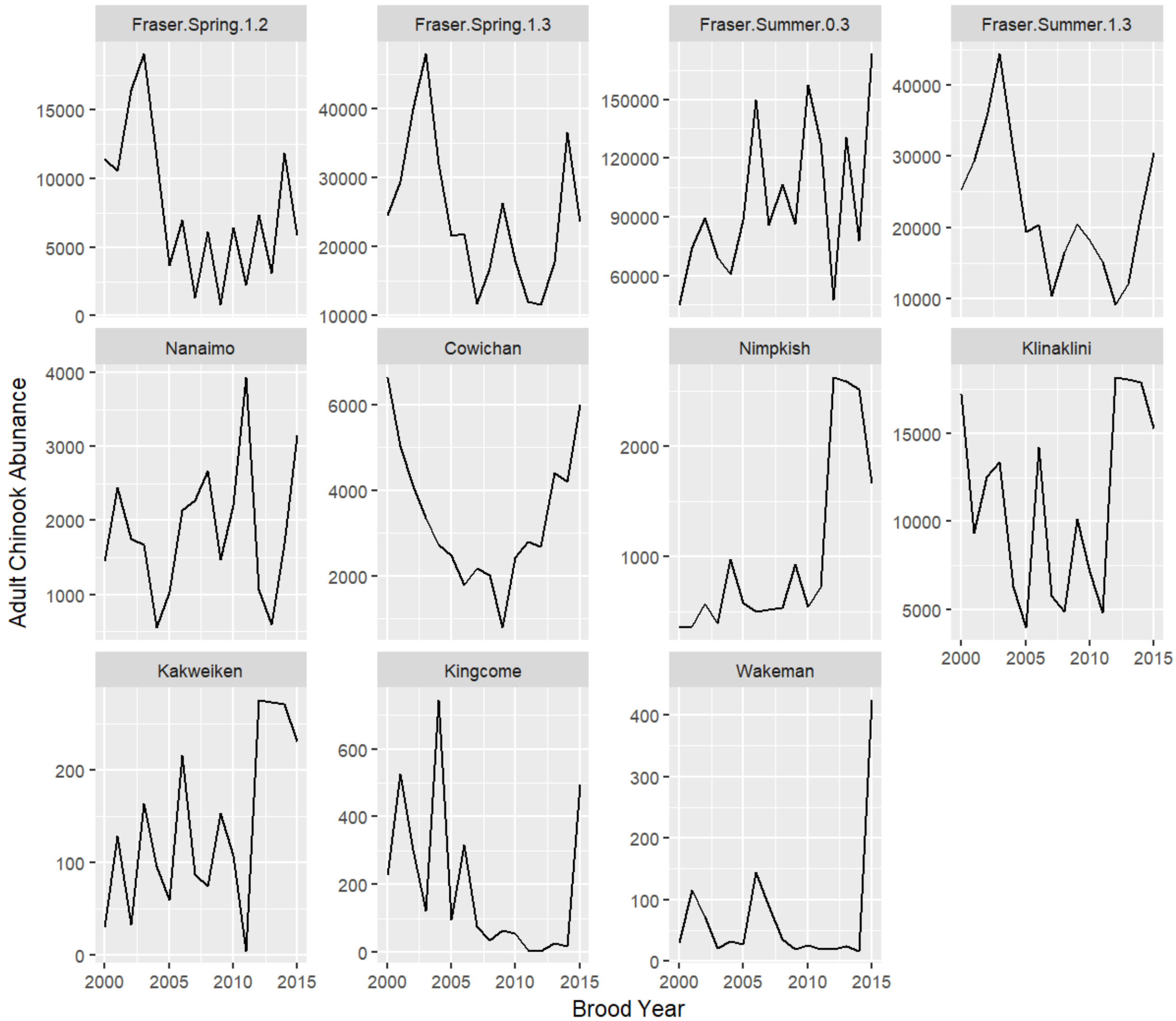

Figure A3 Chinook Salmon adult abundance data from other south coast British Columbia watersheds. Data sourced from Pacific Salmon Commission Join Chinook Technical Committee (2016).