Cheakamus River Project Water Use Plan

Cheakamus River Chum Salmon Escapement Monitoring and Mainstem Spawning Groundwater Survey

Implementation Year 10

Reference: CMSMON1b

Evaluations of the Cheakamus River Chum Salmon Escapement Monitoring and Mainstem Spawning Groundwater Surveys from 2007-2016, and Chum Fry Production from 2001-2017

10-Year Program Review

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Prepared for:
BC Hydro
6911 Southpoint Dr, 11th floor
Burnaby, BC V3N 4X8

Prepared by:
Cynthia Fell, Collin Middleton, Josh Korman, Nich Burnett, LJ Wilson, and Caroline Melville.
InStream Fisheries Research, Inc.
1211A Enterprise Way
Squamish, BC V8B 0E8
T: +1 (604) 892-4615

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EXECUTIVE SUMMARY

This report provides a synthesis of the data, analyses, and information collected from 10 years (2007 – 2016) of monitoring juvenile and adult Chum Salmon in the Cheakamus River to address management questions (MQs) regarding the specific effects of the WUP discharge regime that asked: 1) What is the relationship between discharge, adult Chum Salmon spawning site selection, egg incubation conditions, and juvenile productivity? 2) Do the models used to calculate effective spawning area provide an accurate representation of Chum Salmon spawning site selection and the availability of spawning habitat under the WUP flow regime? and 3) Are there alternative metrics that better represent Chum Salmon spawning habitat? We used estimates of both adult and juvenile escapement combined with analyses of the relationships between discharge, groundwater, adult spawning site selection and distribution, and productivity inferred by a series of stock-recruitment analyses to address these questions.

Adult Chum Salmon escapement estimates were generated using the Pooled-Petersen mark-recapture method and varied from a low of 73,377 in 2011 to a high of 606,619 in 2016. Juvenile outmigration was estimated annually by a BTSPAS mark-recapture program and ranged from a low of 1,610,535 in 2015 to a high of 10,795,444 in 2013. The precision of both these adult and juvenile estimates varied annually.

Central to answering all management questions for this monitor was examining adult distribution and the presence of groundwater in known and potential spawning areas, and how these factors are affected by discharge. Using radio telemetry and Pooled-Petersen abundance estimates, we calculated that the majority of adults were distributed throughout spawning habitats in the lower river between RK 2.0 (Stables) and RK 7.5 (Bailey Bridge). Four mainstem reaches upstream of the Bailey Bridge were modeled as suitable habitat during the WUP consultative process; however, radio-telemetry revealed that only 12% of adults tracked over 7 years migrated into these areas, suggesting that these models incorrectly predicted effective spawning habitat in the upper river. Observations of high densities of spawning adults in habitats dominated by groundwater inflows in the lower reaches of the river near Moody's Bar (RK 3.5 – 4.5), and very little observation of spawning adults above the Bailey Bridge suggests there is a lack of groundwater attraction in upper river side-channels. With respect to discharge, in spawning sites with dominant groundwater influence, redd temperatures appeared to decrease with discharge pulses. However, there was a high degree of uncertainty associated with these analyses as groundwater data were scarce and often limited to only one year. Discharge pulses >20 m^3s^{-1} during the adult migration were linked to more side-channel habitat usage and ultimately greater juvenile productivity, likely because of more optimal incubation conditions in this habitat. Radio-telemetry data

suggested that adults that encountered more days of variable discharge >25<80 m^3s^{-1} during their upstream migration may be more likely to migrate into habitat above the Bailey Bridge. However, because the original objective and design of the radio-telemetry component of this study was unrelated to examining distribution or discharge, there was a large amount of uncertainty associated with this model. Inferences regarding adult distribution and how it is related to discharge will be strengthened by a re-designed radio-telemetry study incorporating experimental discharge pulses and finer-scale movement monitoring that was implemented in 2017; analysis of these data will begin in 2018.

The current hypothesis for the Cheakamus River discharge regime is that flows during the Chum Salmon spawning and incubation periods do not affect productivity, as measured by the number of juvenile outmigrants. However, we observed effects of discharge in both egg-to-fry and adult-to-fry stock recruitment models. In the egg-to-fry model, there were negative effects of maximum and variation in discharge, suggesting that flow pulses during the egg incubation period may reduce juvenile recruitment. Whereas in the adult-to-fry model, there was evidence that the greater number of days adult Chum Salmon experienced discharges >25 <80 m^3s^{-1} during their spawning migration from October 15 – November 7 resulted in a positive increase in juvenile recruitment. These results suggest that increasing the minimum base flow from the current 15 m^3s^{-1} to variable flows between 25 – 80 m^3s^{-1} during the adult spawning migration, and subsequently reducing these flows to near 20 m^3s^{-1} during the incubation period may result in greater juvenile productivity. We caution, however, that although these results after 10 years of monitoring offer valuable insights into the effects of WUP flows on Chum Salmon productivity in the Cheakamus River, Pacific Salmon stock-recruitment literature suggests that more than 10 years (15+) of full life-cycle monitoring (i.e. adult and juvenile) is required at minimum to confidently detect changes in a population.

We conducted no formal quantitative analyses to answer MQs 2 & 3 examining the validity of the modeled effective spawning area as an accurate representation of spawning site selection and available habitat; however, we can infer answers to these questions based on the work done on MQ1. We concluded that the models which predicted effective Chum Salmon spawning habitat in the mainstem of the Cheakamus River upstream of the Bailey Bridge (RK 7.0) during the WUP consultative were not accurate. However, results from the stock recruitment analyses suggested that variation in discharge between 25 – 80 m^3s^{-1} during the adult migration may lead to more usage of this ‘available’ habitat. To examine this more precisely, a series of discharge pulses during the adult migration period in the fall of 2017 were tested to examine their effects on adult Chum Salmon distribution. Analysis of these 2017 data are ongoing and will be reported on in late 2018. Published literature and the incubation condition monitoring results of this monitor suggest that Chum Salmon preferentially select spawning habitat characterized by groundwater upwelling. Although there were uncertainties associated with the data collected during this monitor, we found little evidence of groundwater influenced spawning habitat in upstream reaches (RK >7.0) of the mainstem river that were modelled as effective Chum Salmon spawning habitat during the WUP consultative process. Moreover, in the 10 years of this monitor, very few adult Chum have been observed or tracked into these reaches. Based on results from this study and what is known in the literature, we suspect that there are likely no other alternative metrics, apart from groundwater upwelling, that better represent effective Chum Salmon spawning habitat in the Cheakamus River.

Collectively, this synthesis presents an informed and accurate representation of Chum Salmon escapement, distribution, spawning behaviour, habitat preference, and productivity in the Cheakamus River, and how the WUP discharge regime is related to many of these factors. It also highlights many of the uncertainties still associated with the data and analyses necessary to explore these relationships. Further monitoring would significantly improve the accuracy and confidence in many of the observed relationships established in this report and ultimately more strategically guide any changes to the WUP discharge regime.

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❖

Present InStream Fisheries Research Inc. Staff

Stephanie Lingard, Cole Martin, Annika Putt, and Jennifer Buchanan

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1.0 INTRODUCTION

1.1 Project Background

The Cheakamus River watershed drains an area of 1,010 km^2 in the Coast Mountain Range of southwestern British Columbia and supports populations of Chinook (*Oncorhynchus tshawytscha*), Coho (*Oncorhynchus kisutch*), Chum (*Oncorhynchus keta*), and Pink Salmon (*Oncorhynchus gorbuscha*), resident Rainbow and Steelhead Trout (*Oncorhynchus mykiss*), Bull Trout (*Salvelinus confluentus*), and additional forage fish species. The Cheakamus is a primary tributary of the Squamish River, and is important ecologically, culturally, and recreationally to multiple stakeholder groups. Members of the Squamish First Nation harvest salmon for food, social, and ceremonial purposes, and the river also provides opportunities for commercial and recreational angling and rafting communities.

In 1957, the Cheakamus River was impounded by Daisy Lake Dam to divert a portion of water from the Daisy Lake Reservoir to the Cheakamus Generating Station for hydroelectric power production in the Squamish Valley. Following this diversion, the Cheakamus River downstream of the dam now receives only a portion of its natural discharge. There is considerable stakeholder interest in understanding how this altered flow regime affects fish populations, particularly in the lower portion of the river that is accessible to anadromous salmonids (river kilometer [RK] 0 to RK 17.5).

BC Hydro operates the Cheakamus River hydroelectric system and water release requirements from the dam have varied since the system was impounded in 1957. Prior to 1997, the water use license for the Cheakamus River specified that a minimum of 5 m^3s^{-1} of water be released to protect fish; however, the license did not specify detailed discharge regulations or targets (Mattison et al. 2014). In 1997, the Department of Fisheries and Oceans (DFO) issued an instream flow order (IFO) to BC Hydro after decades of unregulated flow releases, driven largely by power demand, were found to negatively affect fish populations. The IFO was amended in 1999 to become the instream flow agreement (IFA), which specified that greater than 5 m^3s^{-1} or 45% of the previous seven-day average inflows into Daisy Lake Reservoir must be released downstream of the dam – in effect mimicking the variability of the natural hydrograph of the river and potentially reducing negative impacts to fish. In 2006, the Cheakamus River Water Use Plan (WUP) modified the IFA and instituted a flow regime that aimed to balance minimum flows at the dam with social, economic, and environmental values of the river – one of which being sustained healthy salmon populations (BC Hydro 2005). The effect of WUP flows on fish populations in the Cheakamus River was uncertain as productivity increases were predicted using assumed rather than empirical relationships. Indeed, the productivity model upon which the WUP flows were based was found to overestimate spawning habitat availability relative to empirical measures

(Marmorek and Parnell 2002). As a result, environmental monitoring programs were instituted in conjunction with the WUP order that aimed to determine how the WUP discharge regime influenced fish populations in the Cheakamus River.

1.2 Management Questions

Chum Salmon were identified during the WUP consultative process as an important indicator of fish health in the Cheakamus River (BC Hydro 2005), and CMSMON1b in conjunction with juvenile chum data collected as part of CMSMON1a were established to explore the effects of discharge on Chum Salmon productivity (BC Hydro 2007). These monitors are not mutually exclusive, however, as data from both are used to develop stock-recruitment relationships critical for determining whether annual fluctuations in adult-to-fry and egg-to-fry survival are related to adult escapement or characteristics of the WUP discharge regime (Bradford et al. 2005). Adult monitoring was conducted for 10 years (2007 – 2016) with two primary objectives: 1) estimate the annual escapement of adult Chum Salmon in the Cheakamus River, and 2) examine the relationships between WUP discharge, groundwater upwelling, and adult Chum Salmon distribution and spawning site selection (BC Hydro 2007). These objectives were designed to address management questions developed by BC Hydro (2007) and explore the effects of WUP discharges on fish populations. Three targeted questions were addressed by the monitor:

1. What is the relationship between discharge, adult Chum Salmon spawning site selection, egg incubation conditions, and juvenile productivity?
2. Do the models used to calculate effective spawning area (based on depth, velocity, and substrate) provide an accurate representation of Chum Salmon spawning site selection and the availability of spawning habitat under the WUP flow regime?
3. Are there alternative metrics that better represent Chum Salmon spawning habitat?

For detailed descriptions of the methods, analyses, results, and discussions relevant to each year of CMSMON1a & b (2007 – 2017), please refer to technical reports available from: https://www.bchydro.com/about/sustainability/conservation/water_use_planning/lower_mainland/cheakamus.html.

2.0 METHODS

2.1 Study Area

The glacially-fed Cheakamus River is a primary tributary of the Squamish River, which flows into the Pacific Ocean via Howe Sound and the Strait of Georgia (Figure 1). Annual water temperatures in the Cheakamus River range from 0.5-15 ºC, and the typical hydrograph is characterized by low discharge

(15-20 m^3s^{-1}) in winter and late summer/early fall, and two freshet periods from spring snow-melt (April to July) and fall storm events (October – November).

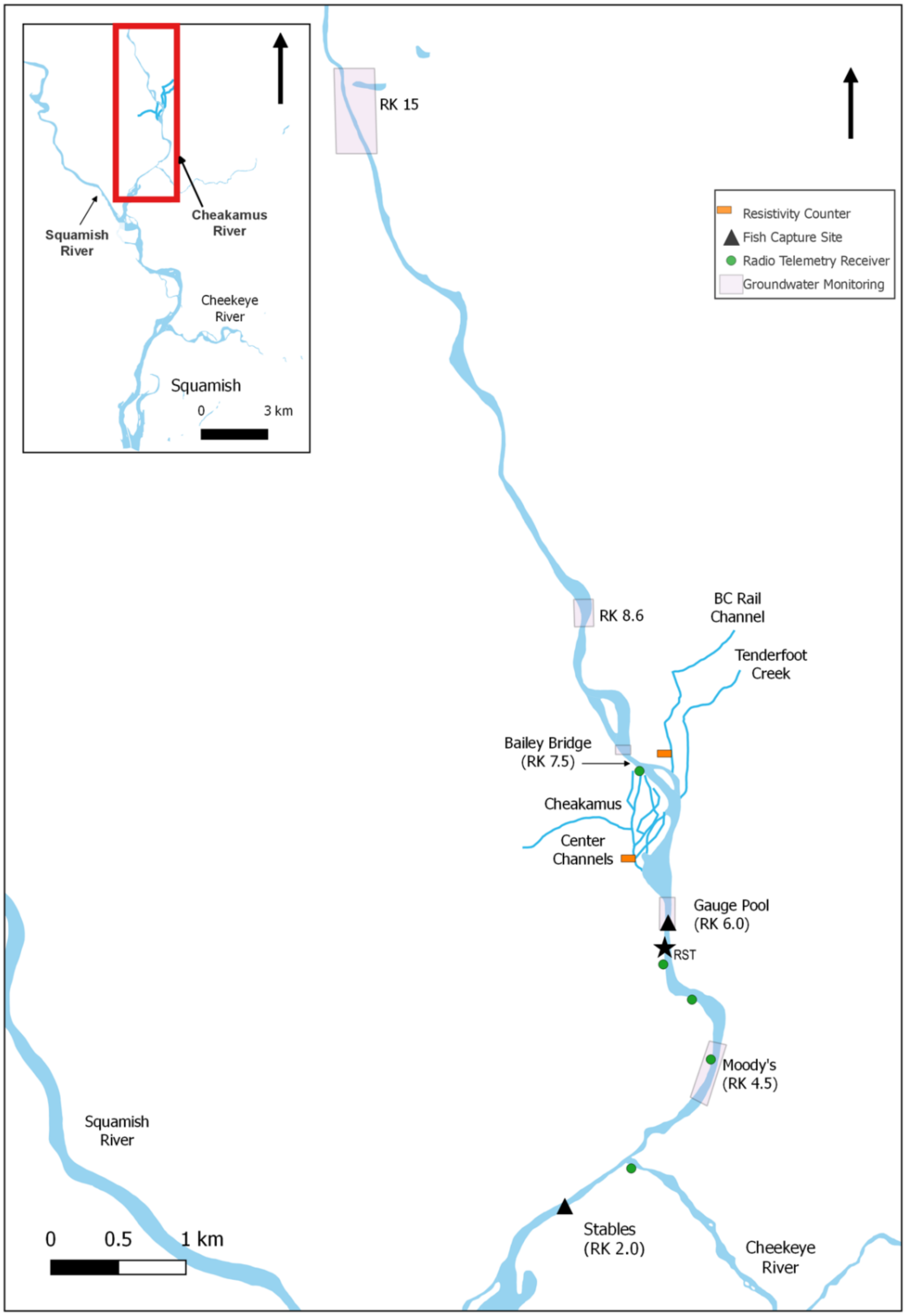

Figure 1. Cheakamus River study site showing locations of fish collection sites, radio-telemetry receivers, groundwater monitoring sites, artificial spawning channels, and rotary screw trap. Inset shows location relative to the greater Squamish River watershed.

Mainstem fish habitat in the Cheakamus River extends 17 km from the confluence with the Squamish River to a fish barrier 9 km downstream of Daisy Lake Dam. Mainstem habitat is complimented by a large network of man-made restoration channels fed either by groundwater or diverted river water (Figure 1). The original network of side channels was located at the Cheakamus Centre, formerly known as the North Vancouver Outdoor School. Additional restoration in the past decade expanded the side-channel network upstream and downstream of the Cheakamus Center to create the Mykiss Channel, BC 49 Channel, BC Rail Channel, Dave's Pond, and Moody's Channel. In addition to man-made channels, large woody debris structures were installed in the mainstem Cheakamus River to increase habitat complexity (Harper and Wilson 2008).

2.2 Chum Salmon Life History Characteristics

Adult Chum Salmon enter the Cheakamus River annually between October and December to spawn (Table 1). Peak spawning typically occurs in the first half of November and egg incubation continues through late February. Alevin hatching commences in late January, and fry begin to emerge in early February. Fry embark on their seaward migration as young-of-the-year, with peak migration occurring in April and finishing by the end of May. Chum Salmon may spend between 18 months and 5 years at sea before returning as adults to spawn in the Cheakamus River.

Table 1. Typical migration and rearing timing of Chum Salmon in the Cheakamus River.

Life History Stage	Timing
Adult migration and spawning	October 15th to December 15th
Peak adult spawning	November 1st to November 15th
Egg incubation & juvenile emergence	December 1st to March 31st
Juvenile rearing (typically 2 weeks from emergence)	February 1st to April 15th
Juvenile migration	February 1st to May 31st
Peak juvenile migration	April 1st to April 15th

2.3 Water Temperature

Mainstem river temperatures were collected hourly in each study year, proximate to rotary screw traps (RSTs) located at the Cheakamus Centre (Figure 1). Minimum, maximum, and mean temperature metrics were calculated for several time periods relating to adult migration and spawning (Table 2). These metrics were used to examine the potential effect of temperature on Chum Salmon distribution and movement patterns and were included as covariates in candidate stock-recruitment analyses.

Table 2. Summary of temperature metrics calculated annually over three distinct time periods for the Cheakamus River at the RST site.

Years	Time period	Surface Temperature Metric
2007–2016	Upstream migration (Oct 15 – Nov 7) Peak upstream migration (Oct 25 – Nov 7) Peak spawning (Nov 1 – Nov 15)	- Min. - Max. - Mean

2.3.1 Detection of Groundwater at Spawning Sites

An objective of this monitor was to determine if models used during the WUP were effective at determining the availability of Chum Salmon spawning habitat (BC Hydro, 2007). Groundwater upwelling is known to strongly influence spawning site selection (Hale et al. 1985), thus the presence of groundwater inflows in the habitat modelled as 'available' was explored and subsequently used to examine if WUP discharge influenced the effective spawning area.

Temperature loggers (Onset HOBO TidbiT v2 data loggers; UTBI-001) recorded hourly surface water and redd temperatures (i.e., at a depth of 40 cm) at confirmed and potential Chum Salmon spawning locations throughout the Cheakamus River to determine the presence of groundwater inflows. Confirmed spawning sites were identified using visual observations of Chum Salmon spawning behaviour over the course of CMSMON1b, while potential spawning sites were in areas of appropriate substrate composition and water depth/velocity from theoretical Chum Salmon preferred spawning habitat (Geist et al. 2002). Data were collected in four years (2009, 2010, 2011, 2016); however, the location of temperature loggers differed across years (Table 3). At each site, up to 15 replicate temperature loggers were installed within the substrate (40 cm deep) and distributed throughout the site to account for spatial variation in groundwater inflows. Several temperature loggers were lost in each year due to vandalism, accidental removal, and/or high discharge events (> 350 m^3s^{-1}) that caused substantial substrate mobility in the river.

Fall and winter groundwater temperatures are generally warmer and more stable than surface water temperatures in Pacific Northwest streams (Constantz 1998), and the presence of groundwater was evaluated by examining seasonal temperature differentials between surface water and temperature loggers at redd depth. Groundwater was said to be present in areas where surface water temperatures were less than those recorded at redd depths, and/or where temperature fluctuations in the water column were not observed within the substrate.

Table 3. Yearly locations of temperature loggers used for groundwater monitoring.

Years monitored	Locations	# loggers recovered
2009, 2010, 2011	Moody's Bar (RK 4.5)	11
	RST Pool (RK 5.5)	1
	Cheakamus Centre Pool (RK 5.75)	2
	Gauge Pool (RK 6.0)	2
2014, 2015, 2016	Bailey Bridge (RK 7.5)	1
	RK 8.6	4
	Road's End (RK 15)	1

We used linear modelling to assess the relationships between redd temperatures (from each recovered temperature logger) and discharge during the Chum Salmon egg incubation period (December to April). The modelling was intended to examine the effects of discharge pulses on redd temperature, thus we did not include base flow data (i.e., discharge <20 m^3s^{-1}) in the analysis. In years when discharge remained relatively stable at base flow conditions (e.g. 2015-2016) little variation in the data limited the effectiveness of modelling. The strength of relationships were assessed using R^2 values, and model residuals were examined assess for the assumptions of linearity and homogeneity of variance. In some cases, model diagnostics suggested minor correlation of residuals, possibly due to the time-series nature of the temperature data (log-transforming the data did not improve the residual diagnostics). As these models were intended to detect a relationship, rather than produce inferences, the data were not adjusted to improve model fits. A separate modelling exercise would be needed to produce predictive temperature-discharge models.

2.4 Discharge

Hourly discharge data were acquired from the Water Survey of Canada (WSC) gauge at Brackendale (08GA043; located 100 m upstream of the RST site) from 2007 to 2017. Discharge data were summarized by life-history periods (i.e., adult spawning and egg incubation) using several metrics hypothesized to affect Chum Salmon spawning and juvenile survival (Table 4; see a priori hypotheses in Lingard et al 2018). These discharge metrics were considered as covariates during stock-recruitment modelling and generalized linear modelling of adult Chum Salmon distribution and movement patterns.

Table 4. Summary of discharge metrics calculated annually in the Cheakamus River over four distinct time periods. * indicates metric was calculated for 'upstream' and 'peak' time periods only.

Year	Time period	Discharge Metric
2007 – 2016	Entire spawning season (Oct 15 – Dec 15) Upstream migration (Oct 15 – Nov 7) Peak spawning (Nov 1 – 15) Incubation period (Dec 1 – Mar 31)	- Min. - Max. - Mean - Median - Std. dev.

2.5 Adult Escapement Estimation

There are many challenges when estimating Chum escapement and spawning distribution in the Cheakamus watershed due to its large size and environmental conditions which can make traditional mark-recapture surveys difficult to implement. These challenges include restricted water visibility, considerable downstream movement of spawned-out moribund fish and access to some river/channel reaches during high river discharges (Melville and McCubbing 2000; Korman et al. 2002). As a result, traditional visual tag mark recapture approaches that are commonly employed in smaller coastal systems would be difficult and expensive to effectively implement on the Cheakamus River.

Traditional live mark-carcass recapture surveys involve tagging salmon with external tags followed by carcass surveys of all possible spawning grounds. Instead, this monitor uses a passive mark-recapture technique in place of a traditional mark-recapture carcass recovery or visual estimation study methods. This passive tag recovery approach involves the use of fixed location resistivity fish counters to enumerate all fish entering selected side channels, coupled with Passive Integrated Transponder (PIT) scanning tag readers to scan for tags on all fish at these locations. The total number of fish entering each monitored channel and the total number of tagged fish entering each channel is recorded on PIT logging equipment.

To estimate adult Chum Salmon escapement, we used a pooled Petersen mark-recapture model (Ricker 1975) combining the passive mark-recapture with PIT tag detections and counts of adult fish from resistivity counters in the Cheakamus Centre and Tenderfoot side channels. Details on model refinement can be found in the series of annual technical reports for CMSMON1b (eg. Fell et al. 2016).

2.5.1 Capture and Tagging

Two locations were selected for adult Chum Salmon capture and tagging based on ease of river access, suitability for fish capture, and proximity to resistivity counters (Figure 1). The lower river tagging site (Stables), located at RK 2.0, was fished at discharges between 15 and 30 m^3s^{-1}, while the upper river tagging site (Gauge Pool) at RK 6.0 was fished at discharges between 15 and 45 m^3s^{-1}. The maximum fishable discharge for both sites was 45 m^3s^{-1}. Daily site selection was based on real-time discharge and capture effectiveness, and both sites were often fished on the same day to maximize capture rates.

All Chum Salmon tagged during this study were captured using a tangle net deployed using an inflatable pontoon boat and secured by an on-shore crew (see details in Fell et al. 2016). Fish were removed from the net immediately following capture and placed in submerged flow-through isolation tubes to facilitate recovery prior to tagging. Once recovered, all fish were tagged with a 20 mm half-duplex PIT tag (BioMark, Boise, USA) in the dorsal musculature, and fitted with an external Petersen Disk Tag for visual identification. Sex, fork length, and condition were recorded for all individuals, with condition assessed based on criteria described in Table 5. Only condition 1 and 2 fish were PIT tagged and included in the mark-recapture model. To prevent recapture, all tagged fish were held in flow-through net pens until the end of the fishing day before being released proximate to the tagging location.

In several of the study years, a subset of Chum Salmon captured during the mark-recapture were gastric-tagged with a radio transmitter (MCFT-3A, Lotek Wireless Inc., Newmarket, Canada; or TX-PSC-I-1200-M, Sigma Eight Inc., Newmarket, Canada) programmed with a unique identification code and 5 second burst rate (Table 6). Data from radio-tagging were not used during mark-recapture modelling and were instead used to assess adult movement and distribution patterns throughout the monitoring period.

Table 5. Summary of criteria used to rate the overall condition of tagged adult Chum salmon.

Condition	Criteria
0 – 1	Appearing ‘silver’ and unspawned; appearing to have recently entered the river; sea lice present
2	Exhibits some spawning colouration, although in fresh condition and free of body decay
3	Clearly displays spawning colouration and showing early signs of body decay
4	Heavy colouration; showing signs of previous spawning activity and body deterioration / decay

Table 6. Summary of adult Chum Salmon radio-tagged during this study.

Year	Male (*n*)	Female (*n*)	Tagging location
2008	54	57	Lower river
2009	52	55	Lower river

2010	66	62	Upper and Lower river
2012	-	23	Upper river
2013	-	80	Lower river
2015	-	83	Lower river
2016	-	24	Upper and Lower river

2.5.2 Detection and Enumeration

Adult Chum Salmon recapture data were collected at three locations in the Cheakamus River annually from October 15 through to December 15 (at the entrances of the Cheakamus Centre and BC Rail side-channels, and proximate to the Tenderfoot Creek Hatchery; Figure 1). All adults were directed over or through PIT antennas located at each of the three recapture sites to determine which tagged individuals migrated into the three sites. In addition to recapturing PIT-tagged individuals, the total number of adult Chum Salmon was determined at each site for the October 15 to December 15 period. At the Cheakamus Centre and BC Rail side channels, adults were enumerated by a pass-over Logie 2100C resistivity fish counter (Aquantic Ltd.), while at the Tenderfoot Creek Hatchery, adults were enumerated by DFO observers at the hatchery entrance fence.

Adult Chum salmon entering the Cheakamus Centre and BC Rail side channels were enumerated by a pass-over resistivity counter. Fish passing over counter electrodes were detected and measured for fork length based on their resistance signal strength. Fish were classified as adults if their peak signal size (PSS) exceeded 39. PSS corresponds to the peak of a sinusoidal curve that is created when a fish passes over the counter sensor. Counter data were validated using video footage to determine true positives, error rates including false positives and false negatives, and counter accuracy. The total upstream count was determined as the number of upstream counts minus the number of downstream counts over the monitoring period. A detailed description of resistivity counter operations and enumeration techniques can be found in CMSMON1b technical reports (e.g. McCubbing et al. 2012).

2.5.3 Adult Mark-recapture Modelling

Pooled-Petersen estimates (PPEs) were used to calculate population estimates for the entire river and the area upstream of the RSTs using standard mark-recapture methods (Ricker 1975) based on the equation:

$$\widehat{N} = \frac{MC}{m}$$

Where $\widehat{N}$ is the estimated population of adult Chum Salmon in each area (entire river or upstream of RST) and its side channels, M is the total number of fish marked with PIT tags, C is the total number of fish enumerated in the side-channels, and m is the number of PIT tags detected entering the side channels (i.e., recaptures).

Pooling in the Petersen method refers to combining all mark-recapture trials into a single estimate of 'trap efficiency' (or recaptures, *m*) and generating a single population estimate for the entire study period ($\widehat{N}$). In this study, the proportion of adults detected at side channels throughout the study period is the trap efficiency, or the total percent of tagged adult Chum Salmon that migrated into the side channels. The total count of fish generated from the resistivity counters represent the total catch of the side channels (*C*). Trap efficiency, total catch of side channels, and the total number of fish marked are combined in the above equation to estimate the total population of adult Chum salmon in the Cheakamus River.

The population estimate for the Cheakamus River was divided into a whole-river estimate and an upper river estimate. The estimate for the whole river was derived from individuals marked at the Stables tagging site and recaptured at the three upstream PIT locations. The population estimate for the upper river (above the RST site, RK 5.5) was derived from fish tagged at the Gauge Pool tagging site and recaptured at the three upstream locations.

2.6 Juvenile Abundance Estimation

2.6.1 Trapping Sites and Fish Capture Methods

Juvenile Chum Salmon in the mainstem Cheakamus River were enumerated by two six-foot RSTs operated adjacent to the Cheakamus Center property at RK 5.5 (Figure 1). Traps were typically operated from February 15 – May 1 annually to enumerate Chum fry (dates varied yearly depending on environmental conditions and juvenile outmigration patterns). Fyke nets were also operated during the same period in side-channels near the adult counters at the Cheakamus Center complex, BC Rail channel, and at the Tenderfoot Creek Hatchery adult fence (Figure 1).

2.6.2 Mark-recapture Juvenile Abundance Estimation

A modified Petersen mark-recapture model was used to generate abundance estimates for juvenile Chum 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 juvenile abundance (Bonner and 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; 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 Chum 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 nets. 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).

Estimates generated from the RSTs represented the combined mainstem and side-channel estimate. Estimates 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. More detailed methods on juvenile Chum Salmon abundance estimates can be found in Lingard et al. 2017.

2.7 Egg-to-fry Survival

A primary objective of this monitor was to estimate annual egg-to-fry survival for Cheakamus River Chum Salmon to assess the effect of WUP discharge on incubation and emergence conditions as well as overall juvenile productivity. Egg-to-fry survival accounts for inter-annual variation in egg deposition per female resulting from changes in fecundity and spawning success. Egg-to-fry survival (*H'*) was estimated for the mainstem Cheakamus River upstream of the RST site, and for all monitored side-channels (i.e. Cheakamus Centre, BC Rail, Tenderfoot Creek) using the following equation:

$$H' = \left(\frac{N_t \times N_{tf} \times N_{epf} \times N_{ed}}{N_{tfry}}\right)$$

Where N_t is the adult abundance estimated by the upper river PPE for year *t*. N_{tf} is the proportion females in the population based on the sex ratio of all individuals tagged in year *t*. N_{efp} is female fecundity as evaluated by Tenderfoot Creek Hatchery in year *t* or inferred using the fork length-fecundity relationship developed for 2012-2016 ($p<0.001$, $R^2=0.34$; Fell et al. 2016). N_{ed} is the estimated proportion of eggs successfully deposited per female in year *t*, assessed by annual pre-spawn mortality surveys in the mainstem and site-channel habitats. And lastly, N_{tfry} is the BTSPAS estimate of juvenile abundance in year *t*.

2.8 Juvenile Productivity and Stock Recruitment

Stock-Recruitment analyses examine the relationship between adult escapement and subsequently density-dependent juvenile recruitment, and how this relationship can vary given the influence of additional independent factors. To explore the effects of WUP discharge on stock-recruitment for this report, a suite of annual discharge metrics were calculated to summarise the flow conditions that occurred over four distinct time periods associated with adult spawning and egg incubation during the 10 years of monitoring. These metrics were then used as covariates in a modified stock-recruitment analysis (based on *a-priori* hypotheses about discharge and juvenile salmon life history) to explore the effects of discharge on juvenile productivity (summarized in Table 6). All data used in stock-recruitment modelling were centred (subtracting the mean) and divided by the standard deviation to compare the relative effect of each covariate on the stock-recruitment relationship (Gelman 2008).

Table 7. Summary of a-priori hypotheses relating discharge variables and Chum Salmon life-history stages.

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
Days between 25 and 80	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 between 25 and 80	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
Maximum discharge	Incubation / rearing	Maximum discharge during incubation and rearing influence foraging opportunities, and scour-related mortality	Honea et al., 2016; Goode et al., 2013; Tetzlaff et al., 2005
Maximum discharge	Adult spawning period	Maximum discharge during spawning influences migration conditions and habitat availability for spawners	Tetzlaff et al., 2008; Gibbins et al., 2002
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

A Ricker model modified to include a covariate effect for discharge was fit to separate datasets for adult-to-fry and egg-to-fry stock recruitment. The form of the Ricker model used was:

$$\hat{R}_{t+1} = S_t \cdot e^{\alpha+\gamma\cdot\log(X_t)-\beta\cdot S_t}$$

where $\hat{R}_{t+1}$ is the estimated number of juveniles produced in year $t+1$; S_t is adult escapement (or the number of eggs deposited) in year t; α is the maximum survival when there are no density-dependent effects (S=0) and the value of the discharge covariate (X) is 1 (as log(1) = 0); β is a density-dependent term describing the rate of decrease in log recruits per adult (or egg) with increasing adult/egg abundance; and γ is the discharge coefficient. Maximum juvenile productivity can be related to the discharge covariate according to:

$$\alpha_t' = \alpha + \gamma \cdot \log(X_t)$$

where α_t' is log year-specific maximum productivity, and X is the standardized covariate value in year t. This model assumes that the discharge covariate affects the density-independent term (α_t') and has no effect on β. Therefore, because $e^{\alpha+\gamma\cdot\log(X)}$ represents productivity in the absence of density-dependence at a covariate value, the model can directly predict the relationship between discharge and productivity.

Posterior mean parameter estimates for α, β, and γ were obtained by hierarchical Bayesian estimation. The observation model assumed that observations of log recruits per adult (or egg) in year t were normally-distributed random variables:

$$\log\left(\frac{R_t}{S_t}\right) \sim norm\left(\log\left(\frac{\hat{R}_t}{S_t}\right), \tau\right)$$

where τ is the estimated precision, or the inverse variance (σ^{-2}).

Models were fit with single discharge covariates and compared to a base Ricker model (no discharge covariate) using Deviance Information Criteria (DIC). DIC quantifies the trade-off between fit and complexity for Bayesian models (Gelman et al. 2003), and models with lower DIC values are considered to provide a better fit to the data. Delta (Δ) DIC values represent the difference between model-specific DIC values and indicate the level of empirical support for each model. Delta levels suggested by Burnham and Anderson (2002) for Akaike Information Criteria, the maximum likelihood equivalent of DIC, were used to classify the amount of support for each model (Δ < 2 = strong; Δ < 10 = considerably less; Δ > 10 no support). The importance of each covariate was also evaluated by determining the probability that covariate coefficient (γ) was greater than zero. Because the covariates were standardized, differences in the magnitude of coefficient estimates among covariates reflect their utility for explaining variation in recruitment. All analyses were conducted using WinBUGS (Lunn et al. 2000).

Eighty-two summary discharge covariates were modeled for four habitat types (mainstem, Cheakamus Centre side channel, BC Rail side channel, and all habitat types combined) for five different distinct migration and spawning time periods in the Cheakamus River for both adult-fry and egg-fry datasets, resulting in ($82 \times 5 \times 2$) 820 different model outcomes. For this synthesis, however, only the 5 top-ranked models from the stock-recruitment analyses conducted on the data for *all habitat types combined* for both adult-to-fry and egg-to-fry datasets are presented and discussed. See Appendix 1 for tables of the full models results from each habitat type/timing combination.

2.9 Adult Chum Salmon Distribution

Evaluations of habitat use were undertaken to explore the distribution of adult Chum salmon throughout the Cheakamus River, and to examine how discharge affects movement and spawning site selection. We examined the proportion of adults in side channels relative to the mainstem river, and in the upper and lower river to infer distribution and determine the effect of discharge variation on habitat usage/spawning site selection. This also enabled us to examine the presumed usage of the predicted Chum Salmon spawning habitat in the upper river (above Bailey Bridge) that was modelled during the WUP consultative process. We determined if this assumption was true by examining proportional distributions of adults in the 'upper' and 'lower' river habitats over the 10-year monitoring period in combination with radio-telemetry derived distribution inferences.

Annual proportions of the total population of adult Chum Salmon utilizing side channel habitats relative to the mainstem Cheakamus River were also calculated annually as it has been hypothesized that discharge pulses increase side-channel usage which leads to increased egg-to-fry survival (REF), despite the assumption made during the WUP consultative process that Daisy Dam operations only affect mainstem productivity.

Lastly, data from radio tagged individuals were used to examine the distribution and movement patterns of adult Chum salmon in the mainstem river.

2.9.1 Radio Telemetry Analysis of Adult Chum Salmon Distribution

A total of 556 adult Chum Salmon (172 males, 384 females) were radio-tagged in seven of the ten years of this study with the original objective of understanding sex-specific fish behaviour and how it was related to mark-recapture population estimates (McCubbing et al. 2012). For this synthesis, however, we combined all the radio-telemetry data in an attempt to model the relationship between discharge and adult Chum Salmon distribution. Although some valuable inferences were made regarding distribution and usage of modeled habitat, the spatial and temporal resolution of the radio-telemetry data was not suitable for linking fine-scale movement patterns to variation in discharge (e.g. time-to-event analysis).

A combination of fixed stations and mobile tracking data were used in subsequent movement analyses. The number of fixed stations in operation varied among years and were located at: [1] Cheakamus-Squamish confluence (RK 0.0), [2] Cheekeye (RK 3.2), [3] Moody's Bar (RK 3.75), [4] Wood Pool (RK 5.0), [5] RST Site (RK 5.5) and [6] Bailey Bridge (RK 7.5) (Table 8). Fixed stations were operated from October 15 to December 15 of each study year.

Mobile tracking was conducted to supplement data from fixed stations and increase the temporal and spatial resolution of telemetry data. Surveys were performed on foot and by raft one to two times per week from Bailey Bridge (RK 7.5) to the Cheakamus-Squamish River confluence (RK 0.0). Periodic supplemental surveys were performed from Road's End (RK 15.0) to the Squamish River (RK 0.0) when mobile tracking data were sparse.

Table 8. Summary of the six fixed stations used to track Chum salmon in the Cheakamus River from 2008 to 2016. Grey boxes indicate years in which fixed stations were operated.

<table>
<tr><th>Year</th><th>Squamish
RK 0.0</th><th>Cheekeye
RK 3.2</th><th>Moody's
RK 3.75</th><th>Wood Pool
RK 5.0</th><th>RST
RK 5.5</th><th>Bailey B.
RK 7.5</th></tr>
<tr><td>2008</td><td></td><td style="background:#bfbfbf"></td><td></td><td></td><td style="background:#bfbfbf"></td><td style="background:#bfbfbf"></td></tr>
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<tr><td>2013</td><td></td><td style="background:#bfbfbf"></td><td></td><td></td><td style="background:#bfbfbf"></td><td style="background:#bfbfbf"></td></tr>
<tr><td>2015</td><td></td><td style="background:#bfbfbf"></td><td></td><td></td><td style="background:#bfbfbf"></td><td style="background:#bfbfbf"></td></tr>
<tr><td>2016</td><td></td><td style="background:#bfbfbf"></td><td></td><td></td><td style="background:#bfbfbf"></td><td style="background:#bfbfbf"></td></tr>
</table>

Generalized linear models (GLMs) were used to predict site selection by radio-tagged adult Chum Salmon upstream (n = 163) or downstream (n = 360) of the RST Site (Model 1) and upstream (n = 65) or downstream (n = 458) of the Bailey Bridge (Model 2). A series of *a priori* hypotheses were developed to explore the relationships between WUP discharge and eight explanatory variables in each of the models unless that variable was in fact the response (e.g. sex in Models 3 and 4) (Table 9).

Table 9. Summary of a-priori hypotheses regarding the influence of each explanatory variable used in GLMs of radio-telemetry data for adult Chum salmon.

Variable	Mechanism	References/Rationale
Maximum discharge	High flows increase the rate, frequency, and probability of upstream movement. Alternatively, high flows reduce migration rate.	Taylor and Cooke 2012 Keefer et al. 2004
Minimum discharge	Low flows decrease the rate, frequency, and probability of upstream movement.	Taylor and Cooke 2012
Variance in discharge	Variable flows promote upstream movements associated with flow increases and decreases.	Damborg et al. 2015 Trépanier at al. 1996
Discharge days	Optimal flows exist that will draw fish upstream and into side channels. More days at these flows result in broader distribution and higher survival.	Trépanier at al. 1996
Minimum temperature	Lower minimum temperatures may create a greater temperature difference between surface water (cold) and groundwater (warm) and may allow fish to more readily detect groundwater upwelling, thus affecting their site selection.	Limited literature exists on how Chum detect groundwater upwelling
Sex	Migration and spawning behaviours differ between the sexes, whereby males are more active and may spawn with multiple females.	Salo 1991 Field observations

Explanatory variables included: (1) the maximum discharge each individual experienced while tagged, (2) minimum discharge, (3) variance in discharge, (4) the number of days fish experienced discharge $\geq 25\ m^3s^{-1}$ and $\leq 80\ m^3s^{-1}$ (hereafter, discharge days), (5) minimum temperature, and (6) sex (male [1], female [0]). All variables were tested for multicollinearity using variance inflation factors (VIFs). Using data collected from PIT readers in the side channels, it was determined that 29 of the 523 radio tagged fish spawned in the Cheakamus Centre and BC Rail side channels. Due to the imbalanced sample size, a GLM was not used to predict what influenced radio tagged Chum salmon site selection between side channel (29 fish) and mainstem habitat (494 fish).

All candidate models were generated using the R package “MuMIn” (Barton 2012) and compared for parsimony using AICc. Models were further analyzed using AICc weights (wi), which describe the relative weighting of each candidate model based on the amount of information lost (Wagenmakers and Farrell 2004). Average parameter estimates were calculated using the natural average method (Grueber et al. 2011) and a 95% confidence set (Burnham and Anderson 2002). We standardized all data by centering (subtracting the mean) and dividing by two standard deviations, allowing for the direct comparison of the relative effect of explanatory variables (Gelman 2008). Model-averaged standardized coefficients for binary explanatory variables were exponentiated to create an interpretable odds ratio. Model fits were evaluated using adjusted-R^2 values. Residuals were examined for homoscedasticity, normality, and independence. Data are presented as mean ± standard deviation (SD) throughout, and statistical analyses were considered significant at $p < 0.05$.

3.0 RESULTS

3.1 River Temperature and Discharge

3.1.1 Cheakamus River Temperature

Water temperature in the mainstem Cheakamus River varied seasonally with annual minima typically reaching 0°C in December-January and maximums nearing 17°C in July-August. Average daily river temperature during the 10 years of this study ranged from 0 – 10°C (± 2.4°C SD) during the adult Chum Salmon migration period (October – December), and from 0 – 9°C (± 1.2°C SD) during the egg incubation and juvenile rearing periods (December – April) (Figure 2; Table 10). Most importantly, the range of temperatures in the Cheakamus River during both the adult migration and egg/juvenile incubation periods were within the known range of optimal temperatures for Chum Salmon (reviewed in Salo 1991).

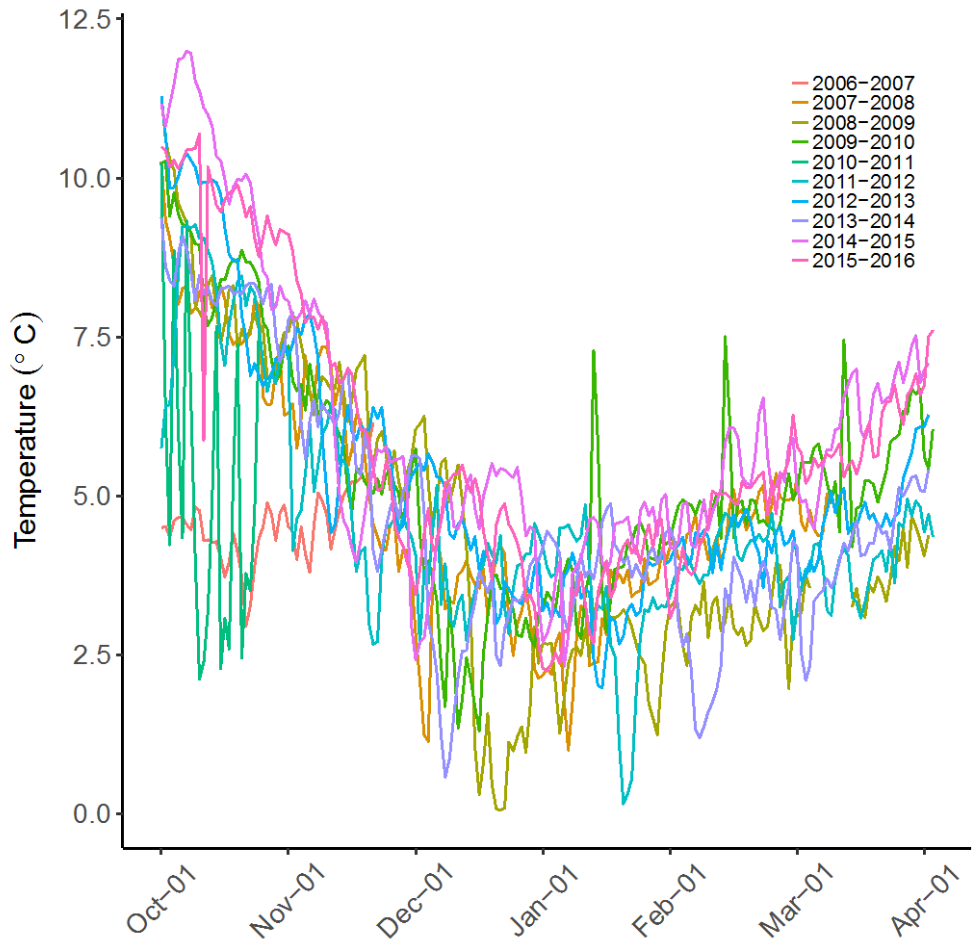

Figure 2. Mean daily temperature of the Cheakamus River at the RST site from October 1st – April 1st over 10 years of monitoring.

Table 10. Summary statistics (mean, range, standard deviation) of Cheakamus River temperatures over the adult migration, spawning, egg incubation, and juvenile rearing periods for the 10 years of this monitoring program.

Brood year	Adult migration and spawning (October 1 – December 31)			Egg incubation and juv. rearing (December 1 – March 31)		
	Mean	Range	SD	Mean	Range	SD
2006 – 2007	-	-	-	4.5	3.0 – 6.2	0.6
2007 – 2008	6.3	1.1 – 10.3	1.9	3.7	1.0 – 5.4	1.0
2008 – 2009	5.8	0.1 – 11.3	2.7	3.0	0.1 – 6.3	1.2
2009 – 2010	5.7	1.3 – 10.3	2.4	4.4	1.3 – 7.5	1.3
2010 – 2011	6.6	4.0 – 10.3	2.3	4.6	2.1 – 9.3	2.2
2011 – 2012	5.5	2.7 – 9.3	2.0	3.7	0.2 – 5.2	0.8
2012 – 2013	6.3	3.0 – 11.3	2.2	4.2	2.0 – 6.3	0.8
2013 – 2014	5.7	0.6 – 9.4	2.3	3.6	0.6 – 5.6	1.0
2014 – 2015	6.8	2.4 – 12.0	2.7	5.1	2.3 – 7.5	1.1
2015 – 2016	6.8	2.3 – 10.7	2.5	4.7	2.3 – 7.6	1.1

3.1.2 Cheakamus River Discharge

Mainstem Cheakamus River average daily discharge varied annually and seasonally during the adult migration and egg incubation/juvenile rearing periods (Table 11). During the adult migration from October 1 – December 31, average daily discharge was 33.7 m^3s^{-1} over the ten years of monitoring, although extreme values from 14.1 m^3s^{-1} – 385.0 m^3s^{-1} occurred depending on fall storm events and atypical releases from Daisy Dam (Figure 3a; Table 11). In particular, the 2014, 2015, and 2016 adult migration periods saw multiple discharge pulses >150 m^3s^{-1}, while other monitoring years had far less variable conditions and discharge rarely exceeded 130 m^3s^{-1} (Figure 3a).

Discharge during the egg incubation and juvenile rearing periods (December 1 – March 31) averaged 24.5 m^3s^{-1} (± 28.0 m^3s^{-1} SD) over the 10-year monitoring period and ranged from 13.1 m^3s^{-1} – 385.0 m^3s^{-1} depending on winter storm events and releases from Daily Lake Dam (Figure 3b; Table 11). Discharge during egg incubation and juvenile rearing was far less variable relative to the adult migration period, and only two years (2009-2010 and 2015-2016) were characterized by instances of significantly pulsed flow conditions (Figure 3b).

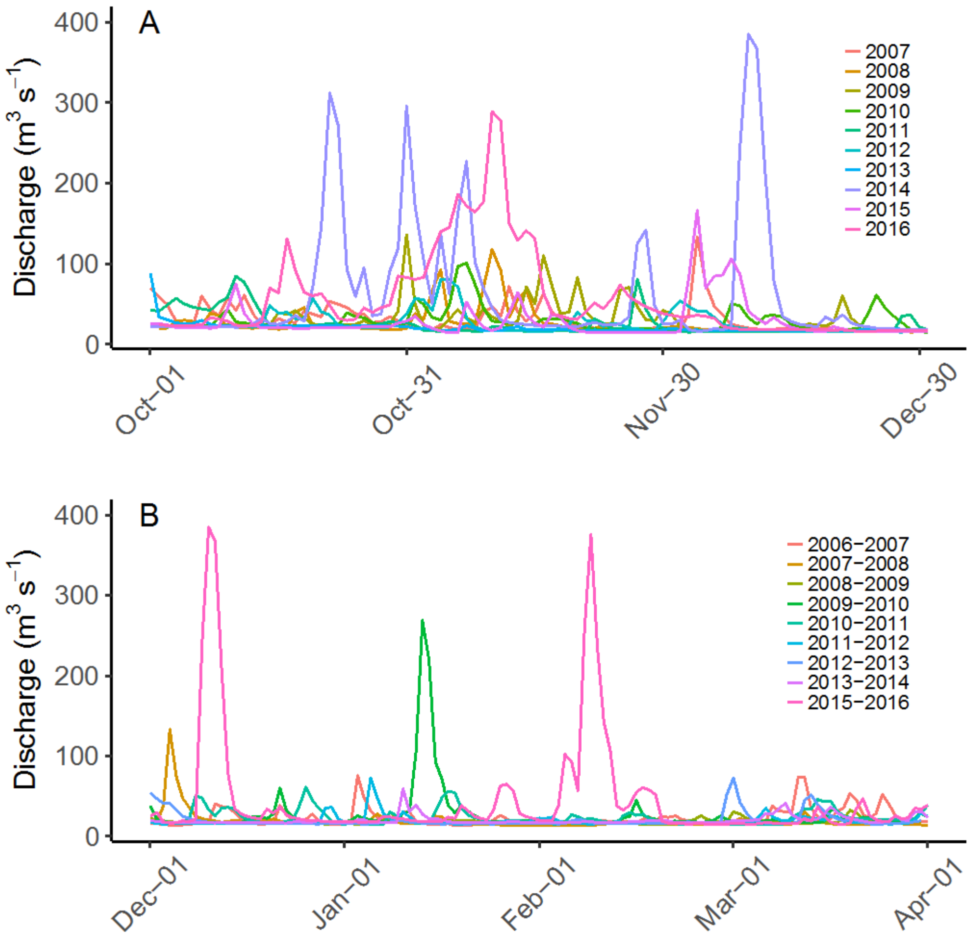

Figure 3. Mean daily discharge of the Cheakamus River during the adult spawning migration period from October 1 – December 31 (Panel A), and the egg incubation / juvenile rearing period from December 1 – April 1 (Panel B) at the WSC Brackendale gauge (08GA043) over the 10 years of monitoring.

Table 11. Summary statistics (mean, range, standard deviation) of Cheakamus River discharges over the adult migration, spawning, egg incubation, and juvenile rearing periods for the 10 years of this monitoring program.

Year	Adult migration and spawning (October 1 – December 31)			Brood year	Egg incubation and juv. rearing (December 1 – March 31)		
	Mean	Range	SD		Mean	Range	SD
2007	31.1	16.2 – 133.0	17.9	2006-2007	22.5	13.1 – 75.8	11.8
2008	25.9	15.3 – 118.0	17.7	2007-2008	18.9	13.2 – 133.0	12.6
2009	31.3	16.7 – 136.0	19.5	2008-2009	18.2	14.9 – 32.6	3.2
2010	28.8	15.1 – 101.0	15.0	2009-2010	26.8	16.5 – 269.0	31.1
2011	25.4	15.3 – 84.5	15.0	2010-2011	23.3	14.5 – 61.1	10.0
2012	26.4	15.3 – 80.9	14.2	2011-2012	19.0	15 – 72.2	7.0

2013	20.6	16.5 – 88.3	7.9	2012-2013	19.8	14.8 – 72.7	9.6
2014	63.4	16.1 – 385.0	80.2	2013-2014	20.1	16.6 – 59.2	5.9
2015	28.7	14.1 – 166.0	23.7	2014-2015	22.4	15.1 – 83.6	6.2
2016	55.6	15.6 – 289.0	55.0	2015-2016	36.5	14.5 – 385.0	51.7

3.1.3 Groundwater Analysis

Temperature loggers (n=15) were buried at 40 cm (approximate redd depth) in the river substrate to explore groundwater presence and egg incubation conditions at confirmed and potential Chum Salmon spawning sites between 2009 and 2016. In general, all sites showed evidence of groundwater upwelling due to higher water temperatures being observed within the substrate (at redd depth) relative to temperatures observed at the water surface. There was a negative linear relationship between discharge (during discharge events above base flows) and redd temperature at all sites, although fluctuations in discharge appeared to influence redd temperatures regardless of groundwater presence. The magnitude of the temperature differential (i.e., the degree of groundwater upwelling) and the strength of the linear relationship between discharge and redd temperature decreased with increasing river kilometer; however, there was variability in these findings within sites (i.e., between individuals temperature loggers), and between years.

Uncertainty in groundwater analyses was primarily related to data scarcity, both in terms of the number of loggers recovered, as well as a lack of discharge variability in some study years. In 2014, 2015, and 2016, repeated winter high water events (>350 m^3s^{-1}) removed several loggers from their locations upstream of RK 7.0, substantially reducing the amount of data recovered. Also, in 2014-2016, some of the remaining loggers may have shifted due to substrate movement, and therefore may not have remained at the exact depth and location of deployment (potentially driving within-site variability). In addition, years characterized by relatively stable discharges did not contain enough variability in discharge to be used during linear regression modelling. Despite these limitations, important trends were identified in groundwater conditions throughout the study period that can inform Chum Salmon spawning behaviour.

3.1.3.1 River Kilometer 3.5 – 4.5 (Moody's Bar)

The strongest presence of groundwater was detected between RK 3.5 and 4.5 in the area known as Moody's Bar in 2009 and 2010. Redd temperatures were consistently 3 – 5°C warmer than surface water temperatures in redds where eggs were observed (Figure 4 a & b). In 2009 there was little variation in discharge during the incubation period, therefore we could not model the redd temperature/discharge relationship; however, visual examination of the discharge and temperature patterns during this time suggest that discharge pulses can indeed lead to prominent drops in redd temperatures (Figure 4a). In 2010, there was substantial discharge variability and a negative linear relationship between discharge and redd temperatures were observed (Figure 4 b & c). In general, discharge pulses above base flows (> 20 m^3s^{-1}) led to reduced redd temperatures, although the strength of this relationship was variable between redds at this site (Figure 4c). We did not specifically examine the effect of date on the relationship between discharge and redd temperature; however, date does not appear to substantially affect the discharge-temperature relationship.

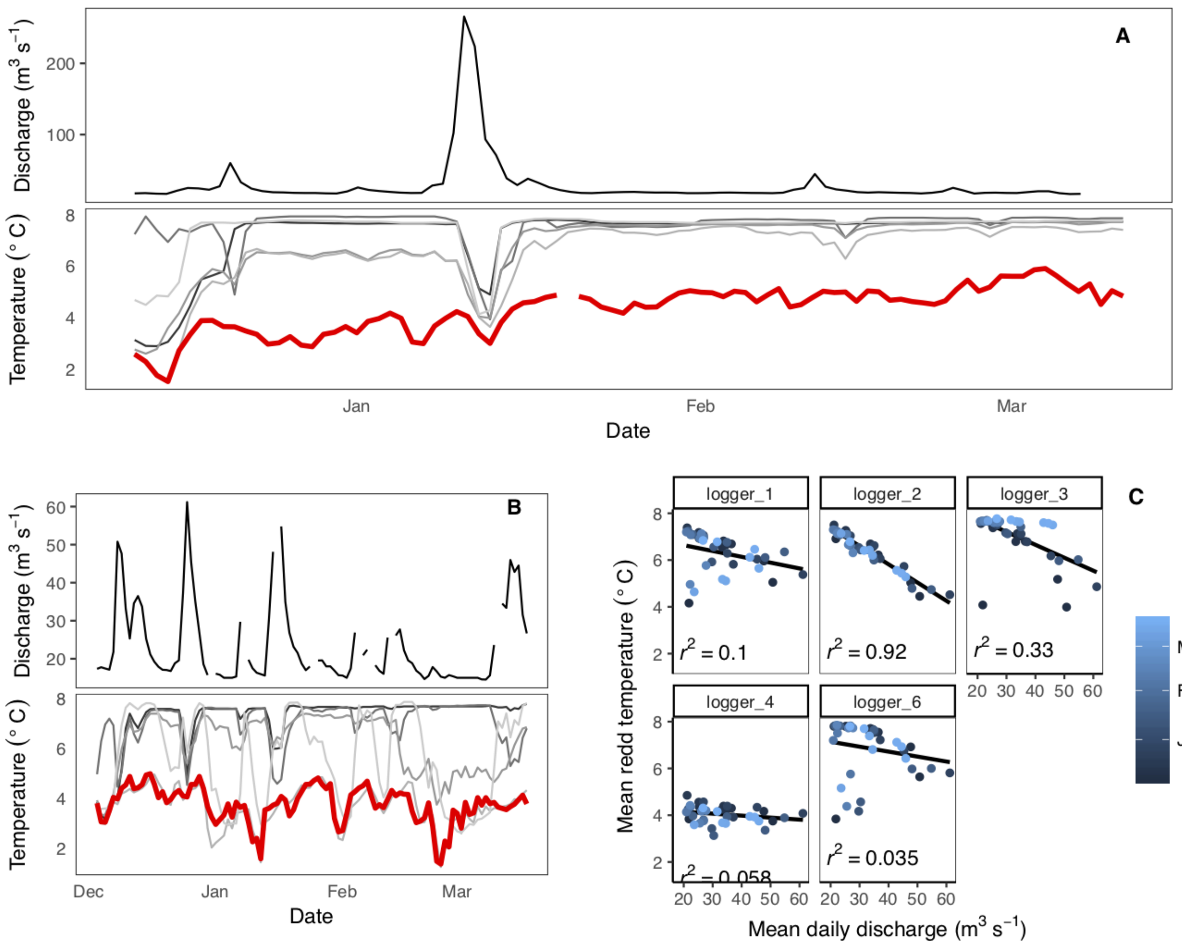

Figure 4. [Panel A] Discharge (black line, top box), redd temperatures (greyscale lines are individual loggers, bottom box), and surface water temperature (red line, bottom box); [Panels B & C] raw data and r^2 results from linear models examining the relationship between mean daily discharge and mean daily temperature for loggers buried at ~ 40cm redd depths at Moody's Bar over the 2009-2010 incubation period.

3.1.3.2 River Kilometer 5.5 – 6.0 (Gauge and Cheakamus Centre pools)

Temperature loggers were distributed throughout the Gauge and Cheakamus Centre pools from RK 5.5 – 6.0 during the 2009-2010 and 2010-2011 egg incubation periods, respectively. Temperature loggers were deployed in areas of known suitable spawning habitat indicated by the presence of eggs in redds at logger locations. Groundwater inflows were present in both these locations but were less pronounced relative to

Moody's Bar; redd temperatures were more variable (~±2°C) and more consistent with river surface water temperature at both the Gauge and Cheakamus Centre pools (Figure 5a). There was a weak negative trend between redd temperatures and discharge at the Gauge Pool, irrespective of date (Figure 5b). In the Cheakamus Centre pool in 2010-2011, only one of the two groundwater loggers recovered suggested groundwater inflows as redd temperature was consistently warmer and less variable than river surface temperature (Figure 5c). Despite variation in discharge during this period, there was no relationship between redd temperatures and discharge at this site (Figure 5d), further indicating a weak or minimal degree of groundwater inflow at this site.

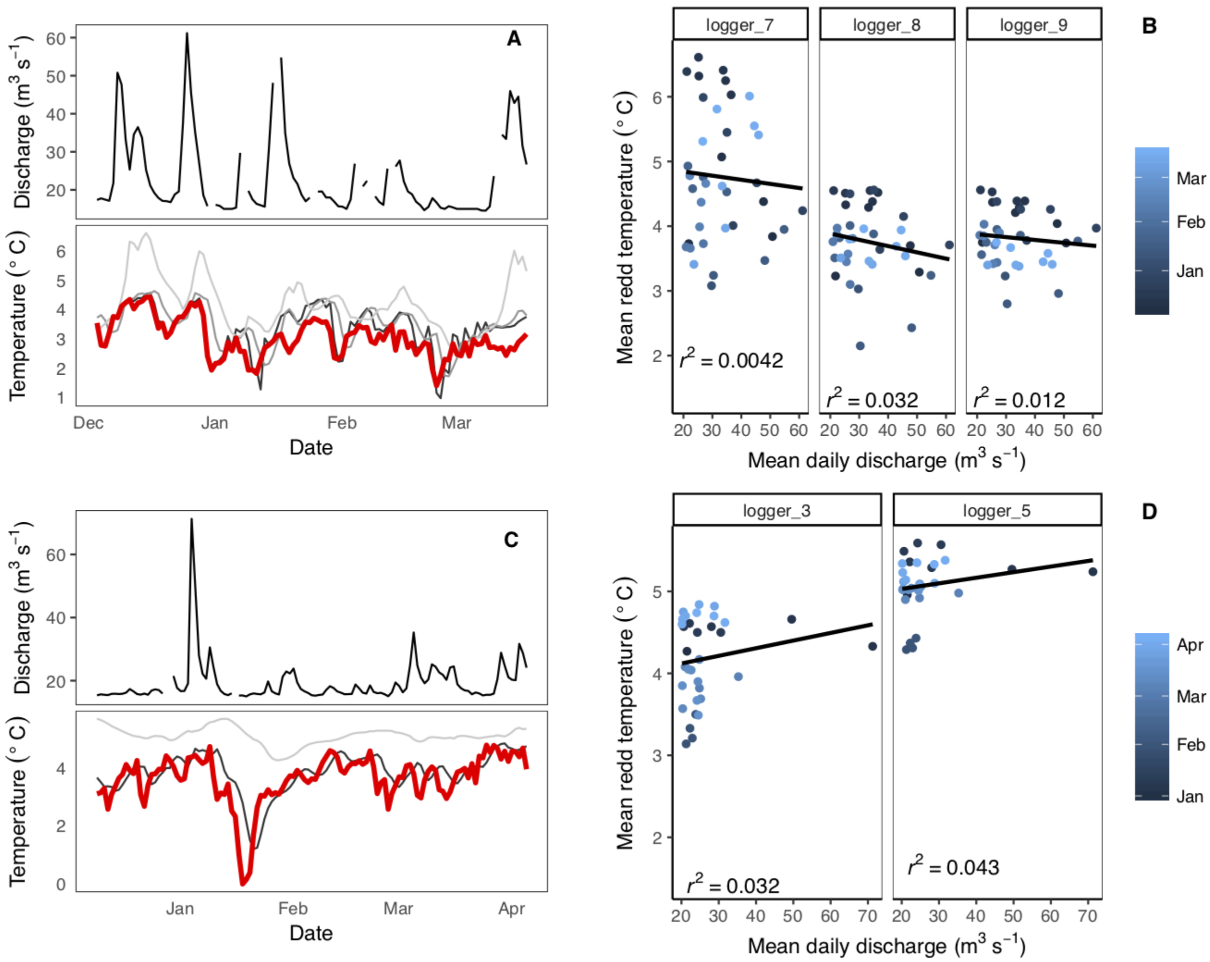

Figure 5. [Panels A (Gauge Pool; 09-10) & C (Cheakamus Centre Pool; 10-11)] Discharge (black line, top box), redd temperatures (greyscale lines are individual loggers, bottom box), and surface water temperature (red line, bottom box); [panels B (Gauge Pool; 09-10) & D (Cheakamus Centre Pool; 10-11)] raw data and r^2 results from linear models examining the relationship between mean daily discharge and mean daily temperature for loggers buried at ~ 40cm redd depths.

3.1.3.3 River Kilometer 7.0 – 16.0 (Bailey Bridge to Road's End)

Groundwater monitoring from the Bailey Bridge upstream to Road's End was only conducted during the 2016-2017 incubation period and a large flood in mid-January 2017 resulted in limited temperature data collection (6 loggers across 3 sites). In general, groundwater flows diminished progressively upstream from the Bailey Bridge to Road's End (Figure 6a). Eggs were present in the monitored sites just upstream of the Bailey Bridge and one of the two loggers recovered from this area indicated groundwater flows (redd temperatures were warmer and less variable than surface water temperatures; Figure 6a). Eggs were observed in all the monitored redds upstream at RK 8.6; redd temperatures at this site were more consistent with surface water temperatures, but substantially less variable, suggesting a much weaker groundwater influence (Figure 6b). At Road's End, the furthest upstream monitored site, eggs were present in over half the monitored redds at the time of logger deployment; however, only one logger was recovered and redd temperatures did not differ in scale or variability from river surface temperatures (Figure 6c). There was very little variability in discharge throughout the 2016-2017 incubation period (Figure 6a – c), thus no analyses were undertaken to examine the redd temperature/discharge relationship in these different habitats.

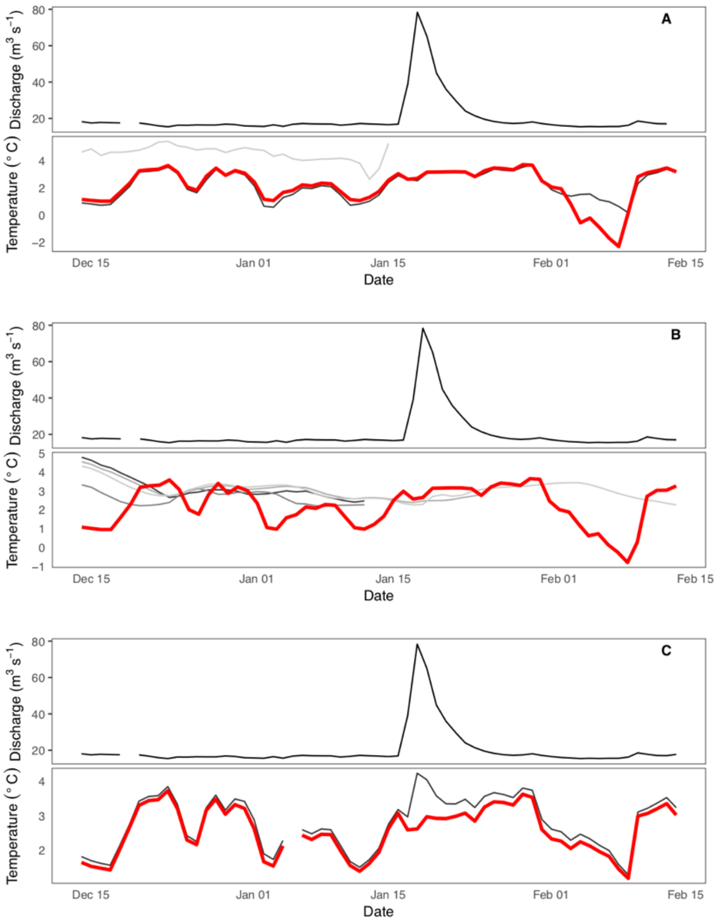

Figure 6. [Panels A & B & C] Discharge (black line, top box), redd temperatures (greyscale lines are individual loggers, bottom box), and river surface water temperature (red line, bottom box) for loggers buried at ~ 40cm redd depths at the Bailey Bridge (panel A), R.K. 8.6 (panel B), and Roads End R.K. 15.0 (panel C) over the 2016-2017 migration and egg incubation period.

3.2 Adult Escapement and Distribution

Pooled Petersen estimates of Chum Salmon adult abundance in the Cheakamus River ranged from 73,377 in 2011 to 606,619 in 2016, whereas estimates for the upper river ranged from 12,827 in 2010 to 241,048 in 2016 (Figure 7). From 2007 to 2010 (excluding 2009), radio-telemetry data indicated that the majority of adults were distributed throughout habitats in the 'lower' section of the river below the RST site. From 2011 to 2016, most adults were again estimated to be using 'lower river' habitats, although there was a notable shift toward increased 'upper river' distribution (Figure 8). Throughout the duration of this monitoring program, the proportion of adults utilizing mainstem habitat (67% - 90%) was consistently higher than the proportion of those utilizing side-channel habitat (11% - 33%; Figure 9). The proportion of adult Chum Salmon utilizing side-channel habitat at the Cheakamus Centre appeared to increase with elevated minimum discharge during the upstream migration period (Figure 10).

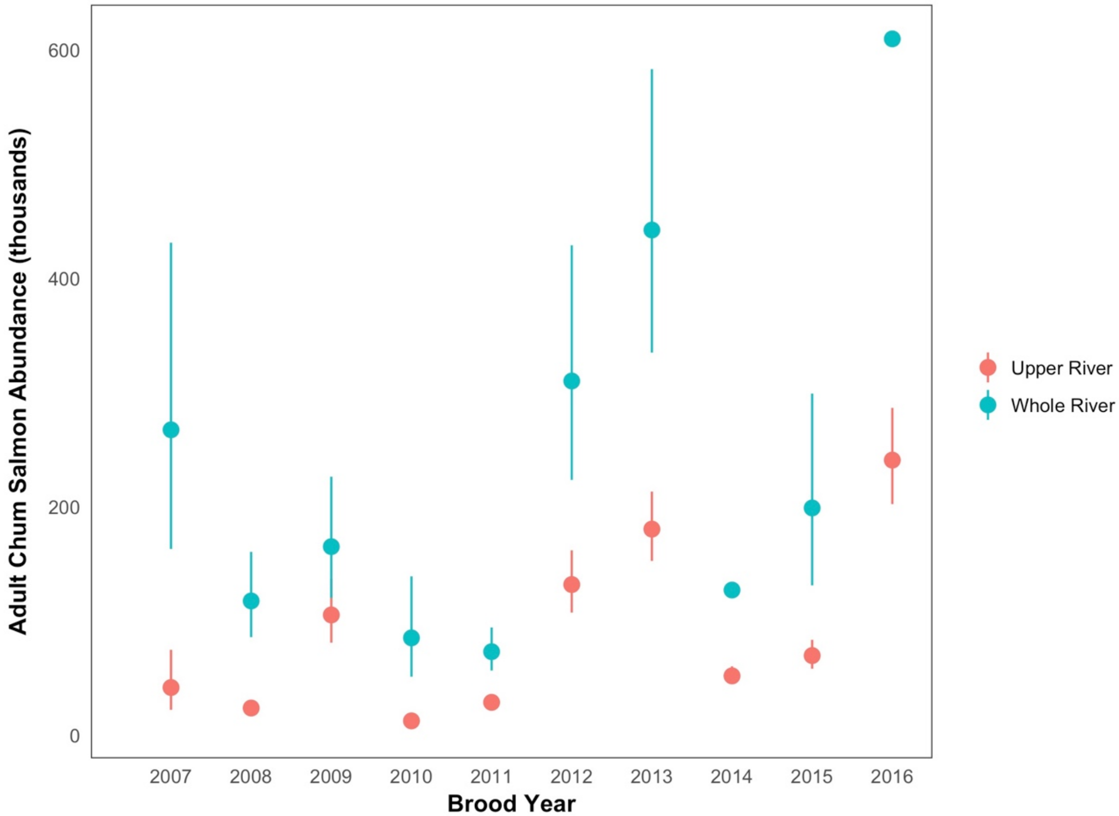

Figure 7. Annual Pooled Petersen abundance estimates of adult Chum salmon from 2007 – 2016 for the ‘upper’ (red dots) and ‘whole’ (blue dots) Cheakamus River. Error bars indicate upper and lower 95% confidence intervals.

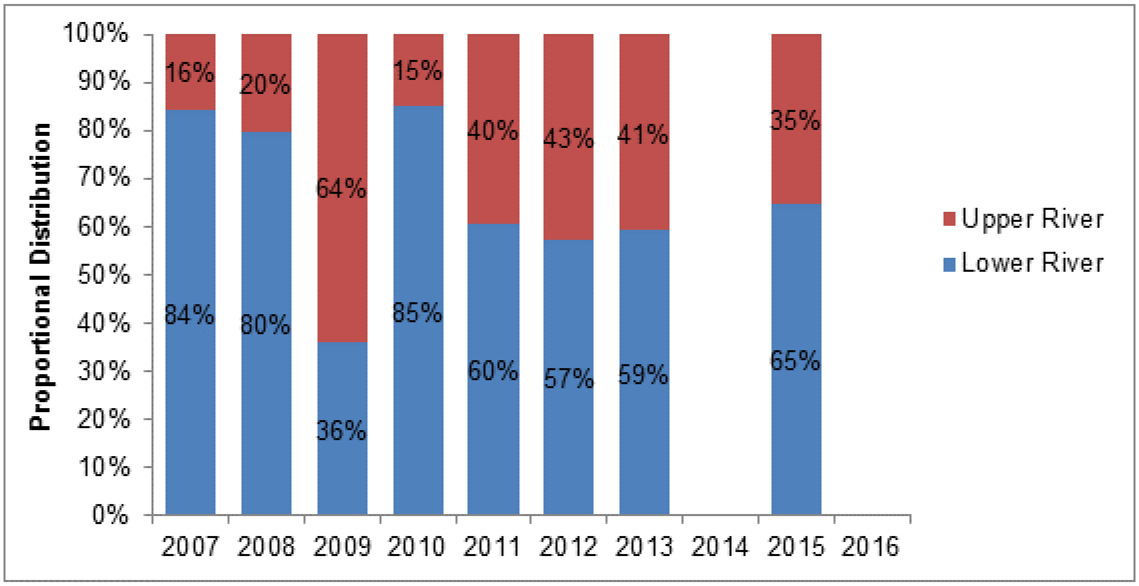

Figure 8. Estimated proportional distribution of adult Chum salmon in the Lower and Upper Cheakamus River from 2007 – 2015. Note, data for 2014 and 2016 are missing as high flow conditions only allowed for estimates of upper river distribution in these years.

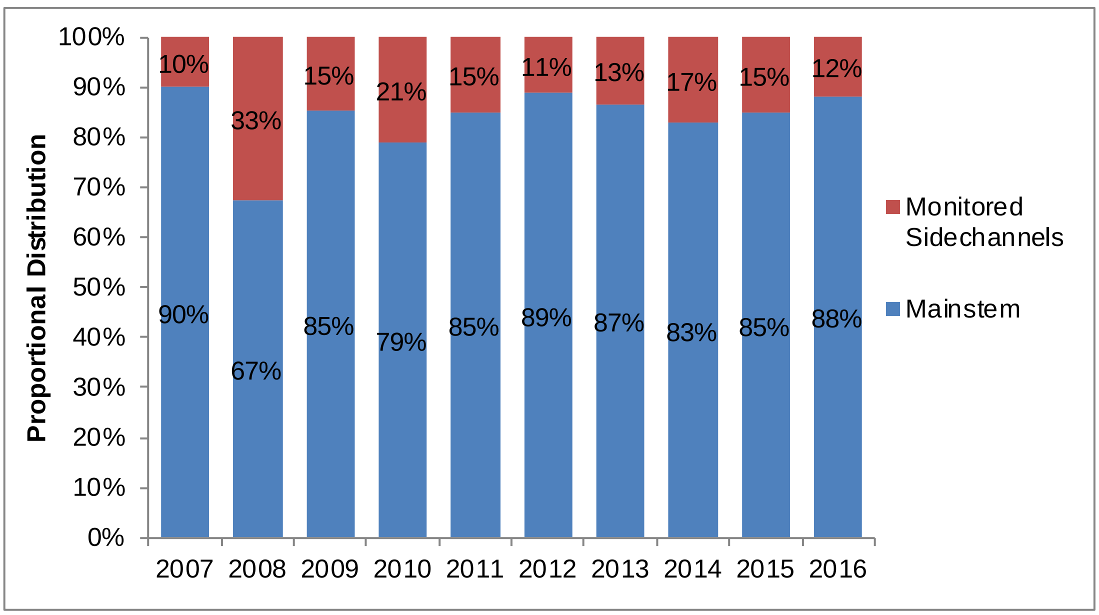

Figure 9. Estimates proportions of adult Chum salmon utilizing mainstem and side-channel habitats in the Cheakamus River from 2007 – 2016.

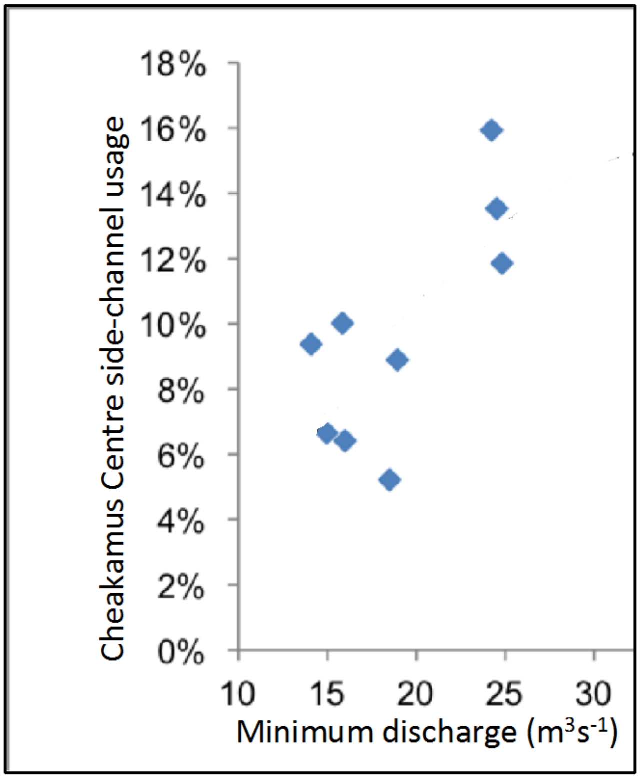

Figure 10. Relationship between discharge during the adult upstream migration period (October 15 - Dec 15) and the proportion of the total annual adult Chum Salmon population estimate utilizing side-channel habitat at the Cheakamus Centre.

3.2.1 Distribution from Radio-Tagged Adults

A series of generalized linear models (GLMs) were used to predict the final location of individuals and assess potential factors influencing movement and site selection of radio-tagged adults. In the analysis to assess factors predicting whether the final known location of radio-tagged individuals was upstream or downstream of the RST Site (RK 5.5), tagging location, tagging date minimum temperature, and minimum discharge formed the top-ranked model and explained little (19%) of the variation in the data (Table 12 & Appendix Table 2a). Most variables had similar magnitude effects (approx. -0.5 to 0.5), except for tag location (1.8) which indicated that fish tagged at the upper river tagging site were 6% ($e^{1.8}$) more likely to be detected upstream of the RSTs (Figure 11a). Tagging date had a small effect on distribution and indicated that adults tagged earlier in the migration period were more likely to spawn upstream of the RST Site (Figure 11a). Adults that experienced lower minimum mainstem river temperatures were also more likely to spawn upstream of the RST Site (Figure 11a). Maximum, minimum, discharge variance, and the number of days when discharge was ≥25 cm^3s^{-1} and ≤80 cm^3s^{-1} were not significant predictors of whether adults were detected above or below the RST Site (Figure 11a).

In the models assessing whether adults were detected at the uppermost telemetry receiver at the Bailey Bridge (RK 7.0), discharge days ≥25 m^3s^{-1} and ≤80 m^3s^{-1}, tagging date, and maximum discharge formed the top-ranked model and explained 17% of the variation in the data, with discharge days explaining 13% of the variation in the data alone (Table 12 & Appendix Table 2b). Most variables had similar size effects (approx. -0.5 to 0.5), except for discharge days (1.0), which suggested fish exposed to flows ≥25 m^3s^{-1} and ≤80 m^3s^{-1} for more days during their upstream migration were 3% ($e^{1.0}$) more likely to be detected upstream of the Bailey Bridge (Figure 11b). An additional small effect of tagging date also suggested that fish tagged earlier in the migration period were more likely to be detected upstream of the Bailey Bridge (Figure 11b). Maximum, minimum, and variance in discharge did not significantly predict whether adults were last detected above or below the Bailey Bridge (Figure 11b).

Table 12. Top 5 models from the AICc 95% confidence set for GLM analyses relating maximum discharge, minimum discharge, variance in discharge, number of days individuals experienced flows ≥ 25 m^3s^{-1} and ≤ 80 m^3s^{-1} (discharge days), minimum temperature, sex, tagging date and tagging location to the last known location of adult Chum salmon being upstream or downstream of either (1) the RST site (R.K. 5.5) or (2) the Bailey Bridge (RK 7.0). Models with *asterisks are shown to illustrate the relative effects of tagging artifacts (i.e. tagging location and date) without environmental variables.

Model	log Lik	AICc	ΔAICc	w_i	adj-R^2
(1) Upstream or downstream of RST site (R.K. 5.5)					
Tagging location + tagging date*	-290.9	589.8	5.3	0.01	0.17
Tagging location + tagging date + min temp + sex + min discharge	-286.2	584.5	0	0.10	0.19
Tagging location + tagging date + min temp + sex	-287.6	585.3	0.8	0.07	0.19
Tagging location + tagging date + min temp + sex + min discharge + discharge days	-285.6	585.3	0.8	0.06	0.19
Tagging location + tagging date + min temp + sex + discharge days	-286.6	585.4	0.9	0.06	0.19
Tagging location + tagging date + min temp + sex + max discharge + min discharge	-285.7	585.5	1.0	0.06	0.19
(2) *Upstream or downstream of Bailey bridge (RK 7.0)*					
Discharge days + tagging date + tagging location*	-141.0	290.1	2.6	0.02	0.16
Discharge days + tagging date + max discharge	-177.4	362.9	0	0.05	0.13
Discharge days + tagging date	-178.5	363.1	0.1	0.05	0.12
Discharge days + tagging date + var discharge	-177.6	363.3	0.4	0.04	0.13
Discharge days + tagging date + min temp	-177.8	363.7	0.8	0.03	0.13
Discharge days + tagging date + max discharge + min temp	-177.0	364.1	1.1	0.03	0.14

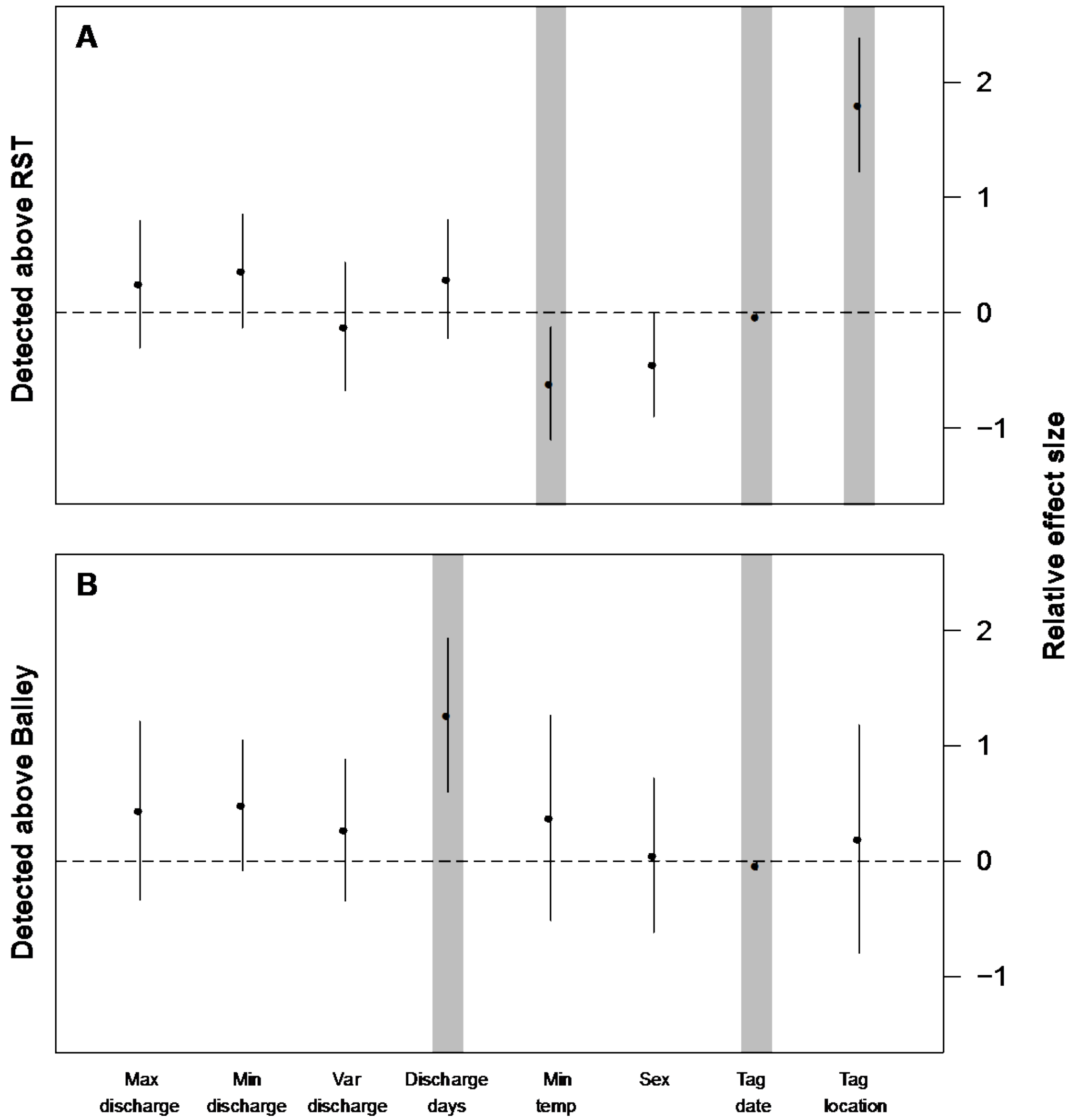

Figure 11. Model-averaged standardized coefficients for GLM models predicting detection of radio-tagged chum salmon upstream or downstream of (A) the RST Site (RK 5.5) and (B) the Bailey Bridge (RK 7.0). Coefficients have been highlighted in gray if the error bars (representing 95% confidence intervals) do not cross 0.

3.2.2 Behaviour and Discharge Relationship from Radio-Tagged Adults

Traces of adult Chum salmon movement were overlaid with hourly discharge to visually examine whether behaviour was associated with discharge fluctuations. Of the 523 Chum salmon that were detected post-release, 79 individuals (15%) exhibited distinct upstream and downstream movements directly in relation to changes in discharge (see Figure 12 for examples). Some fish displayed upstream movements as flows reduced after an increased flow event, while other fish exhibited little to no response to changes in discharge (see Appendix 3 for detections histories of all radio tagged Chum salmon).

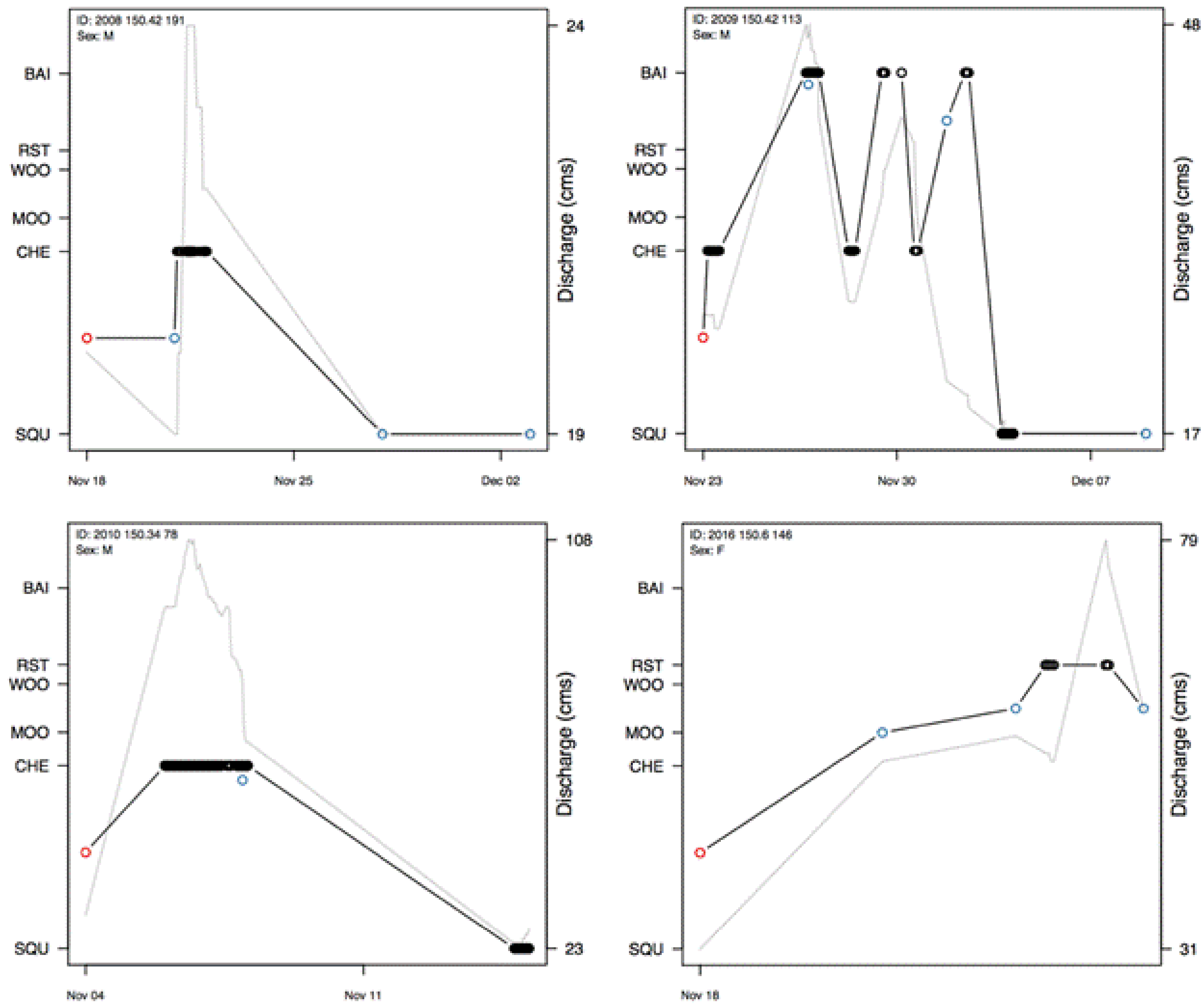

Figure 12. Example detection histories whereby fish exhibited distinct upstream and downstream movements that corresponded to changes in discharge. Black lines connect the release information (red) and data collected from fixed stations (black), and mobile tracking (blue). Grey lines correspond to the discharge in the Cheakamus River. SQU = Squamish, CHE = Cheekeye, MOO = Moody's, WOO = Wood Pool, RST = RST Site, BAI = Bailey Bridge.

3.3 Juvenile Abundance

Annual Chum salmon fry abundance was highly variable over the 10 years of monitoring, ranging from a high of 10,795,444 in 2013 to a low of 1,610,535 in 2015 to; mean abundance over the 10 years was 4,755,341 (± 3,041,526 SD) (Figure 13). Statistical confidence is these estimates is particularly high given the intensive juvenile marking effort associated with this monitor (see Lingard et al. 2017). The mean yearly contribution from side channel habitats to total yield was estimated to be 68% (range 37 –

96%), while the mean mainstem contribution was 32% (range 4 – 63%); mainstem contributions to total fry yield have been 25% or less in five out of the ten years of monitoring (Figure 14).

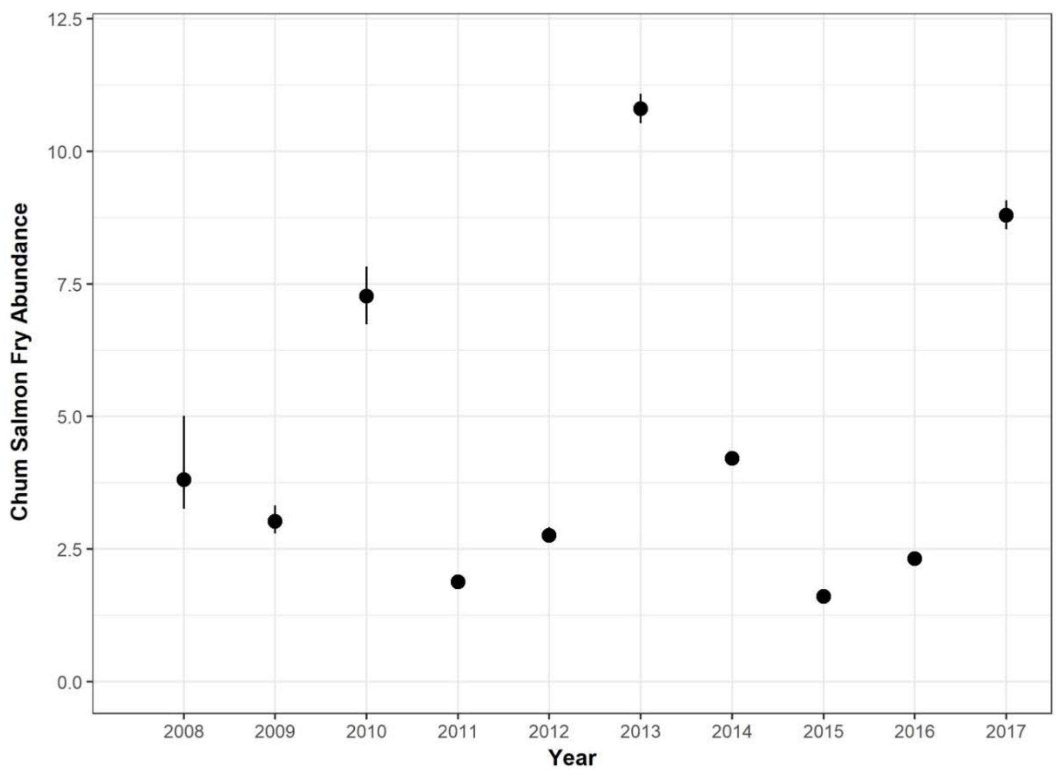

Figure 13. Annual BTSPAS abundance estimates of Chum salmon fry in the Cheakamus River from 2007 – 2017. Error bars indicate upper and lower 95% confidence intervals.

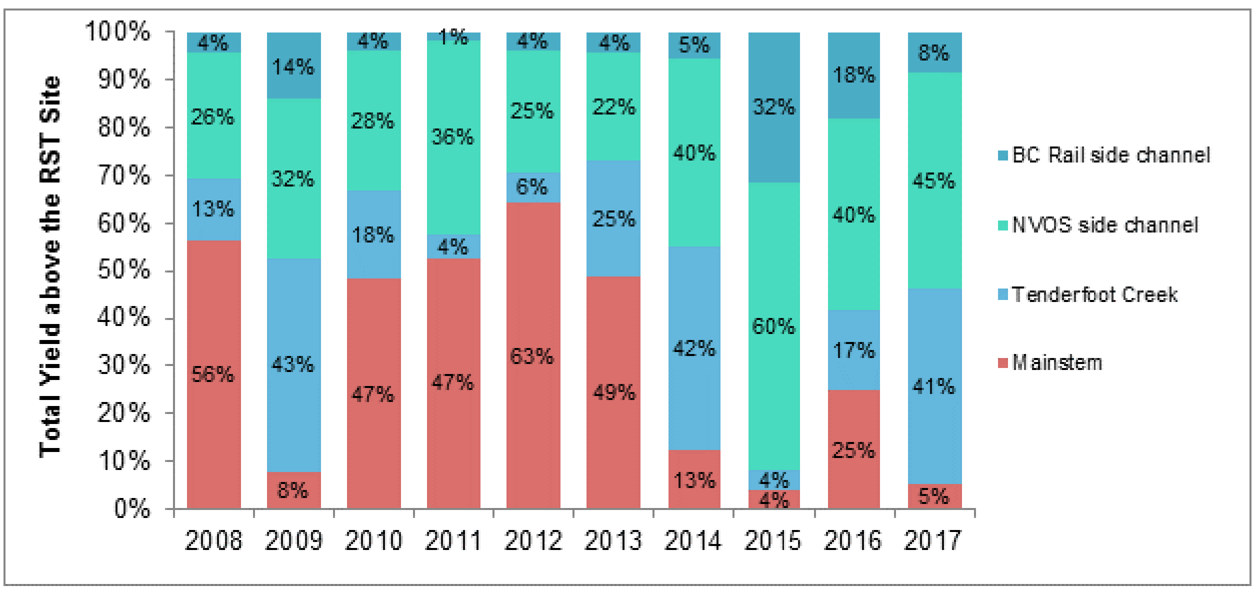

Figure 14. Annual distribution of Chum salmon fry yield from above the RST site in the mainstem Cheakamus River, Cheakamus Centre and BC Rail side channels, and Tenderfoot Creek from 2008-2017.

3.4 Egg-to-fry Survival

Cheakamus river egg to fry survival for all habitat types combined ranged from a high of 12% in 2010 to a low of 1.6% in 2013; mean egg-to-fry survival across the 10 years of monitoring was 5.4% (± 3.3% SD) (Figure 15). Egg to fry survival in the mainstem habitat alone ranged from 0.2% to 7.3% with a mean of 2.6% (± 2.4% SD) Survival in side channel habitats was consistently higher than the mainstem and combined habitats and ranged from 8.4% to 24.5% with a mean of 17.8% (± 4.8% SD) over the 10-year study period (Figure 15).

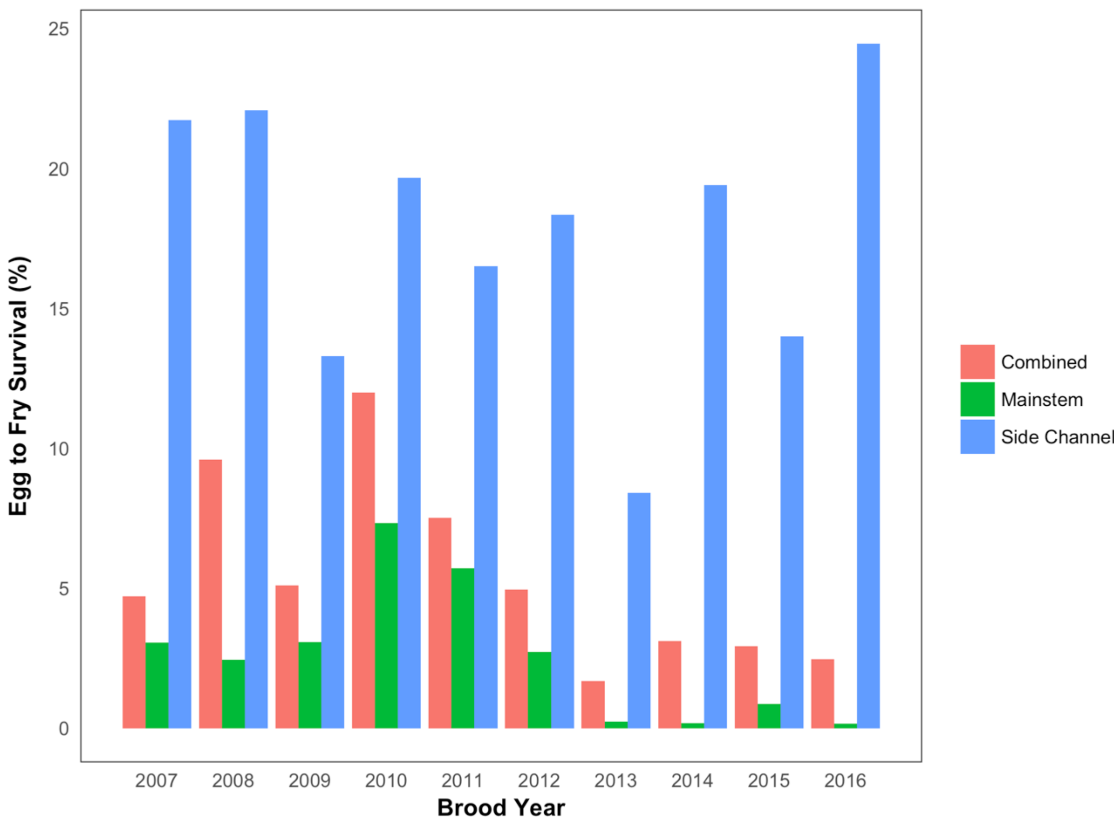

Figure 15. Estimated Chum salmon egg-to-fry survival in mainstem, side-channel, and all habitat types combined in the Cheakamus River from 2007 – 2016.

3.5 Juvenile Stock-recruitment

3.5.1 Egg-to-fry Recruitment

Effects of discharge during the egg incubation period were included in all the top-ranked models for Chum salmon egg-to-fry recruitment across all habitat types combined (11.5 km of mainstem and additional side-channel habitat; Table 13; Appendix 1). Models including covariates for maximum discharge, variance, and standard deviation had the most model support, explaining 77-80% of the variation in egg-to-fry recruitment (Table 13). ΔDIC values for these three models were between 0 – 1.5

suggesting similar levels of empirical support for each model (Table 13). Coefficient estimates for all three covariates had similar size negative effects, suggesting increased maximum and greater variability in discharge during the egg incubation period had a negative effect on juvenile productivity (Table 13; Figure 16).

Table 13. DIC model ranking statistics and coefficient estimates for Ricker models with covariate effects of discharge on Chum salmon egg-to-fry recruitment in the Cheakamus River across all habitat types (combined mainstem and side-channels). Models are compared to a base Ricker model with no covariate effect and ranked by ΔDIC – the difference between model-specific DIC values indicate the level of empirical support for each model; prob. $\gamma > 0$ is the probability that the coefficient effect is greater than 0 and used is to evaluate the importance of the covariate; R^2 is an estimate of the proportion of variance explained by each model.

Model	Coefficient estimate (γ)	Lower 95% CI	Upper 95% CI	*prob.* $\gamma > 0$	R^2	DIC	ΔDIC
Base Ricker (BR)	-	-	-	-	0.55	22.35	6.3
BR + Incubation discharge	-0.38	-0.68	-0.05	1.6	0.80	16.10	0.0
BR + Incubation discharge variance	-0.35	-0.67	0.01	2.7	0.77	17.32	1.2
BR + Incubation discharge SD	-0.35	-0.69	-0.01	2.3	0.77	17.60	1.5
BR + Incubation discharge mean	-0.35	-0.73	0.00	2.5	0.75	18.73	2.6
BR + Incubation discharge median	-0.31	-0.68	0.10	5.3	0.73	19.67	3.6

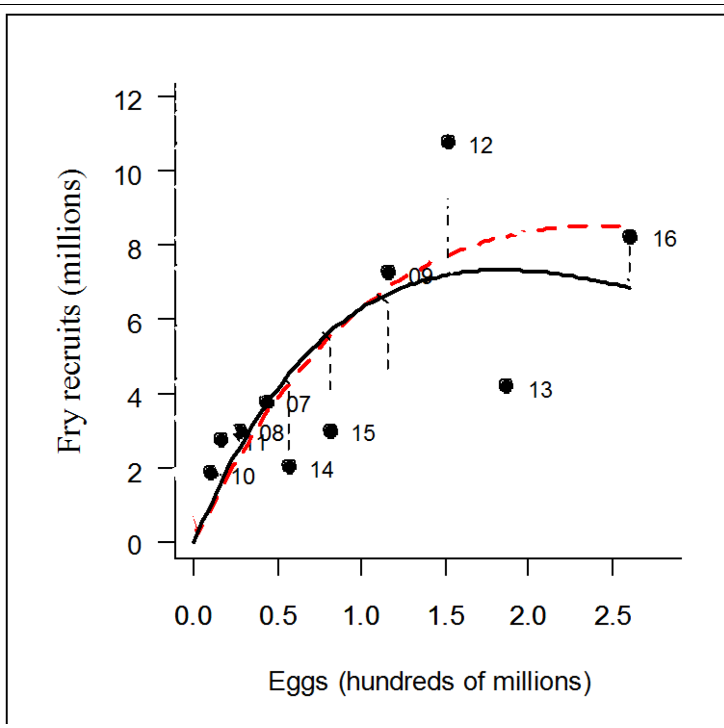

Figure 16. Stock-recruitment curve (solid black line) for the number of Chum salmon fry produced per hundreds of millions of eggs at the mean maximum discharge during egg the incubation period between Dec 1 – Mar 31 across years in the Cheakamus River for all habitat types combined. Note, the black vertical dashed lines indicate the effect of the covariate in each year; end points of these lines represent

the model predictions relative to the actual point estimate for each year (text by each point = brood year). Dashed red line is the base Ricker model without a covariate effect.

3.5.2 Adult-to-fry Recruitment

The model with a covariate for discharge days ≥ 25 m^3s^{-1} and ≤ 80 m^3s^{-1} during the upstream migration period was the top-ranked model for adult-to-fry recruitment across all habitat types (Table 14). This model explained 74% of the variation in the data (R^2 = 0.74) with 99.5% probability that the effect of discharge days (0.43) was positive. This model suggests that increases in the mean number of days during which adult Chum salmon encounter discharges ≥ 25 m^3s^{-1} and ≤ 80 m^3s^{-1} during their upstream migration will result in increased fry production (Table 14; Figure 17). The second and third ranked models with ΔDIC values from the top-ranked model of 1.2 and 2.2, respectively, also included covariate effects of maximum discharge and discharge variance during incubation (Table 3). Similar to the model for egg-to-fry recruitment, the coefficient effects of both covariates were negative, further suggesting that increased maximum and variance in discharge is associated with decreased juvenile productivity (Table 14).

Table 14. DIC model ranking statistics and coefficient estimates for Ricker models with covariate effects of discharge on Chum salmon adult-to-fry recruitment in the Cheakamus River for all habitat types. Models are compared to a base Ricker model with no covariate effect and ranked by ΔDIC – the difference between model-specific DIC values that indicate the level of empirical support for each model; prob. γ > 0 is the probability that the coefficient effect is greater than 0 and used to evaluate the importance of the covariate; R^2 is an estimate of the proportion of variance explained by each model.

Model	Coefficient estimate (γ)	Lower 95% CI	Upper 95% CI	*prob.* γ > 0	R^2	DIC	ΔDIC
Base Ricker (BR)	-	-	-	-	0.53	19.0	6.0
BR + Discharge days >25< 80 m^3s^{-1}	0.43	0.13	0.74	99.5	0.74	13.02	0.0
BR + Incubation discharge maximum	-0.30	-0.59	0.00	2.7	0.76	14.23	1.2
BR + Incubation discharge variance	-0.27	-0.58	0.06	4.6	0.74	15.25	2.2
BR + Incubation discharge SD	-0.27	-0.59	0.06	4.4	0.73	15.37	2.4
BR + Incubation discharge mean	-0.27	-0.59	0.04	4.2	0.73	15.61	2.6

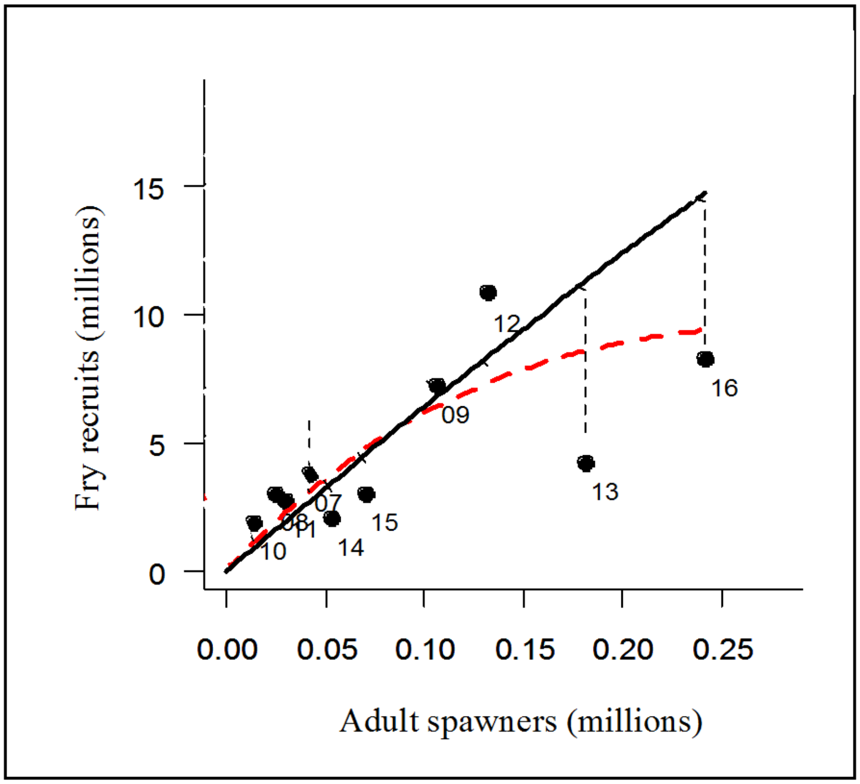

Figure 17. Stock-recruitment curve (solid black line) for the number of Chum salmon fry produced per millions of estimated spawning adults at the number of days discharge was >25<80 m^3s^{-1} during egg the upstream migration period between Oct 15 – Nov 7 across years in the Cheakamus River for all habitat types combined. Note, the black vertical dashed lines indicate the effect of the covariate in each year; end points of these lines represent the model predictions relative to the actual point estimate for each year (text by each point = brood year). Dashed red line is the base Ricker model without a covariate effect.

4.0 DISCUSSION

A large proportion of the total lifetime mortality of salmonids is accounted for during the time between adult spawning migration and juvenile emergence (Peterson and Quinn 1996), yet there is limited knowledge about the effects of discharge on these life-history periods (Malcolm et al. 2012). This is particularity true for regulated systems where discharge fluctuations can occur in un-seasonable patterns and are known to affect spawning migrations (Keefer et al. 2008), groundwater upwelling and redd site selection (Geist et al. 2002), egg incubation (Bradford 1997), and juvenile productivity (Young et al. 2011).

Below is a synthesis discussion focused on results from a series of analyses conducted on data collected over the past 10 years of monitoring to address the above three management questions and their associated null hypotheses (see BC Hydro 2007).

4.1 MQ1: discharge, adult distribution, spawning site selection, groundwater, and incubation conditions

A key aspect of MQ1 was examining the relationship between discharge, adult Chum Salmon spawning site selection, and incubation conditions; primary components of which were exploring adult distribution and groundwater upwelling (BC Hydro 2007).

We found that most adult Chum Salmon were distributed throughout spawning habitats between RK 2.0 (Stables) and RK 7.5 (Bailey Bridge), with an average of 35% of the estimated population utilizing restored side-channel habitats in this area during each year of this monitor. These findings are consistent with the literature on Chum salmon that suggest adults spawn over a wide range of habitat conditions (reviewed in Salo 1991), although in general prefer low velocity (10 – 30 cm/s) shallow streams and side-channel habitats over a wider range of substrates than do other salmon species (Geist et al. 2002). Analyses of radio-tagged adults for this synthesis confirmed the distribution derived from abundance estimates in that only 65 of the 523 (12%) adults tracked over the 7 years of radio-tagging were found to have migrated upstream of the Bailey Bridge, suggesting that most adult Chum salmon only occupy spawning habitat in the lower 7.5 km of the Cheakamus River during base discharge and likely do not utilize the ‘upper river available habitat’ modeled during the WUP consultative process. However, modelling conducted on radio-tagged fish suggested that variation in discharge above base flows where migrants encountered a greater number of days of discharge $\geq$25 cm^3s^{-1} and $\leq$80 cm^3s^{-1} during their upstream migration may increase the probability of adults moving into the habitat above the Bailey Bridge.

There are four reaches of the mainstem river above the Bailey Bridge that were modeled as suitable Chum Salmon spawning habitat during the WUP consultative process. Although we observed eggs in many confirmed redd sites here, we were unable to determine if they were in fact Chum Salmon eggs. Indeed, these upper reaches are also known to be heavily utilized by Coho and Chinook Salmon that co-migrate with Chum Salmon. Thus, interspecific competition for habitat may additionally restrict Chum Salmon spawning to the lower river. In 2017, pulsed flows during the fall adult Chum Salmon migration were tested for their effects on adult distribution given our analyses that suggested increased and more variable discharge during the adult migration could potentially lead to more utilization of this upstream habitat by adult Chum Salmon. Should these tests prove successful and operational changes be made, managers should also consider the effects such changes may have on other comigrating fish species in the river at this time, and only proceed if sufficient follow-up monitoring is in place.

Several factors may contribute to the trends in distribution and spawning site selection observed for adult Chum Salmon in this study such as elevated discharge providing upstream migration cues (Thorstad et al. 2008), or density-dependent effects on spawner distribution (Schindler et al. 2003). However, one of the most important aspects of spawning site selection, and thus distribution, of Chum Salmon throughout their geographic range is known to be the location of hyporheic exchange between groundwater and surface water in redd sites (Leman 1993; Geist et al. 2002). To explore the presence of groundwater flows at spawning sites, we monitored redd and surface water temperatures in confirmed and potential spawning locations during the egg and juvenile incubation period from December until approximately April for four years. Groundwater was consistently present in the most downstream sites between Moody’s Bar (RK 3.5 – 4.5) and the Gauge and NVOS pools (RK 5.5 – 6.0), where redd temperatures were 3°C – 5°C warmer than surface water temperatures and the majority of adult Chum Salmon were observed spawning. The limited data collected upstream from the Bailey Bridge to Road’s End (RK 16.0) suggested that redd temperatures were more consistent with surface water temperatures and that the presence of groundwater diminished in an upstream direction. This could in large part explain why few Chum salmon were observed spawning in these upper reaches and suggests that the WUP consultative models of available habitat in theses upper reaches are not effective estimates of Chum Salmon spawning habitat.

Not surprisingly, we observed higher densities of spawning adults and eggs in the lower reaches of the river where groundwater flows appear to be more constant in redd sites, which has been observed in a number of previous studies where Chum Salmon were reported to spawn in areas where relatively warm water from the hyporheic zone upwells into the river (reviewed in Hale et al. 1985 and Salo 1991; Geist et al. 2002). Groundwater upwelling into potential redd sites presumably provides the chemical (e.g. organic and inorganic constituents) and physical (e.g. flow and temperature) cues that adults use to locate spawning sites and likely increases incubation success by protecting eggs from cold temperatures and hastening incubation (Curry et al. 1995; Geist et al. 2002). Selecting groundwater sites for spawning in the Cheakamus River may provide Chum Salmon with a selective advantage if this results in earlier juvenile emergence and seaward migration, which could in turn buffer against competition from other juvenile salmonids (e.g. Chinook, Coho, and Pink fry; see Lingard et el. 2017), or high flows later in the spring (e.g. peak discharge in May – June).

We also explored how discharge was related to groundwater upwelling during the incubation period in all monitored redd sites to further address MQ1. At sites in the lower reaches of the river at Moody’s Bar where groundwater was most pronounced, there was evidence that redd temperatures decreased in response to discharge pulses above base flows during the incubation period, whereas in further upriver sites (RK 6.0 – RK 16.0) this relationship was much weaker to non-existent and redd temperatures subsequently mimicked those of the surface water. Our observations of warmer groundwater in redds that fluctuate with discharge in the lower river are consistent with those of Jordan-Knox (2003) who, in an extensive hydrogeological survey of the Lower Cheakamus Valley, found that regional groundwater upwells throughout the Cheakamus Centre floodplain (approx. RK 4.0 – 7.0) and is recharged by flows from the Cheakamus River. We suspect this phenomenon likely replaces groundwater with cool Cheakamus River water during discharge pulses, which in turn results in colder flows upwelling into redds with incubating eggs. Thus, in years when discharge pulses above base flows occur frequently during the incubation period, such decreases in redd temperatures (up to 5°C) could lead to decreased juvenile productivity via later timed emergence or redd scour during higher flows (Casas-Mulet et al. 2014). As such, managers could strive to minimize discharge pulses during the incubation period to mitigate against these adverse effects in the groundwater-influenced areas that Chum Salmon eggs and juveniles are known to occupy.

While we observed important trends and some relationships between discharge and adult distribution, spawning site selection, groundwater flows, and incubation temperatures, there are also caveats associated with the analyses and results that are important to discuss. For instance, the radio telemetry data used in the analyses for this synthesis were collected primarily for exploring questions related to female movement and spawning locations over various years (see series of annual reports for CMSMON 1b) rather than discharge effects. To that end, multiple tagging locations, the unequal distribution of males and females tagged each year, non-consecutive years of tracking, and little variation in discharge during tracking periods all contributed to the uncertainty of analyses in this report. Despite indication of discharge days ≥25 m^3s^{-1} and ≤80 m^3s^{-1} increasing the probability of migration upstream of the Bailey Bridge, and this variable having the strongest effect of any covariate in the model, such variation in flows only resulted in a 3% increase in detection probability. Moreover, results from both GLMs of the radio-telemetry data (detection above RST and Bailey Bridge) indicated that <20% of the variation in the data was accounted for by either model. To more systematically link fine-scale movement behaviour to patterns in discharge in future years, only the lower river site should be used for tagging, equal numbers of males and females should be tagged each year, and higher resolution telemetry data should be collected via re-designing the fixed station receiver network to reduce the redundancy of sites in the lower river where detection ranges overlap and include additional sites in habitats upstream of the Bailey Bridge. We should also note that a lack of variation in discharge introducing uncertainty into our analyses is consistent with the analyses of CMSMON 1a (Lingard et al. 2017). During the fall 2017 adult

Chum Salmon migration, a series of experimental discharge pulses were paired with this updated study design to address these shortcomings; analysis of this 2017 data will be reported on in late 2018.

Our analyses assessing how discharge is related to adult Chum Salmon selecting areas of groundwater flows for spawning sites and redd temperatures during the incubation period suggest that adults primarily select areas of groundwater inflows for redds and that discharge pulses may reduce redd temperatures. However, there was considerable uncertainty in the latter relationship due to data scarcity, as high discharge events in some years caused the loss of a number of loggers, and in other years no data were collected. To accurately explore and model this relationship, variation in both parameters (redd temperature and discharge) is necessary, which we did not have in many years. Although the years of monitoring were indeed useful for determining whether groundwater was present, they were inconclusive regarding the relationship between groundwater and discharge and only loosely suggested that stable discharge could help maintain consistent temperatures during the incubation period. To address this issue of data scarcity and further explore this hypothesis, we installed a >100 temperature loggers in the river substrate at confirmed and suspected spawning locations throughout the entire study site (RK 2.0 – 16.0) during the 2018 incubation period; analyses of which are slated to begin in mid-2018.

Although there are limitations and caveats associated with the data and analyses as discussed above, after 10 years of data collection and analyses, much has been learned and significant steps have been made to address and inform the adult distribution, spawning site selection, and groundwater components of MQ1. There are two null-hypotheses from the CMSMON1b terms of reference associated with MQ1 that pertain to the discussion on groundwater above (BC Hydro 2007). With respect to the null-hypothesis (H_2) that states “spawning Chum Salmon do not select areas of upwelling groundwater for spawning in the mainstem”, we reject this hypothesis given the existing literature on this subject (reviewed in Hale et al. 1985 and Salo 1991) and our observations of high densities of adults utilizing predominantly groundwater influenced spawning sites in the lower reaches of the river at Moody’s Bar, and in the groundwater fed Cheakamus Center artificial spawning channels (e.g. Fell et al. 2016). Indications that groundwater flows decrease with increasing river kilometer and a lack of adult Chum Salmon in the habitat above the Bailey Bridge further support the rejection of this hypothesis; they also indicate that the models created during the WUP process did not accurately predict effective Chum Salmon spawning habitat in the upper Cheakamus River. With respect to H_3 that states “discharge during the Chum Salmon spawning and incubation period does not affect the upwelling of groundwater in mainstem spawning areas”, we reject this hypothesis (in areas of confirmed groundwater flows in redds; e.g. Moody’s Bar and Paradise Channel) with the caveat that the degree of variability, magnitude, and the mechanisms of this relationship are still not understood. As discussed above, future years of monitoring would help further strengthen conclusions regarding this aspect MQ1 and more thoroughly explore this null hypothesis.

4.2 MQ1: discharge and juvenile productivity

The hypothesis for the current Cheakamus River discharge regime is that discharge during the Chum Salmon spawning and incubation period does not affect productivity (BC Hydro 2007). However, we observed a predominant effect of discharge on both egg-to-fry and adult-to-fry stock recruitment, suggesting that discharge does indeed effect juvenile productivity. In the egg-to-fry stock recruitment model, there were negative effects of elevated (>60 m^3s^{-1}) and more variable discharge, suggesting that flow pulses during the egg incubation period (December 1 – March 31) can have negative effects on juvenile productivity. These results are consistent with those from CMSMON 1a where regression models indicated that increased discharge during the egg incubation period negatively affected young-of-year Pink salmon abundance (Lingard et al. 2017). There are a number of adverse effects associated with discharge pulses during this particular life-history period that could lead to declines in juvenile productivity (reviewed in Young et al. 2011). For example, we have previously described how discharge pulses during the incubation period appear to be linked to decreased temperatures in redd with groundwater inflows, which could in turn lead to below optimal incubation conditions and reduce egg or juvenile survival. Discharge pulses may also directly result in the stranding deaths of juveniles or eggs along channel margins as water levels recede in shallow side-channels or river bars (Hunter 1992) or lead to mistimed seaward migrations and increased predation (Hoffarth 2004). Discharge pulses can also indirectly affect juvenile productivity by decreasing food supply, increasing sediment scour and turbidity leading to decreased feeding opportunity, or through indirect physiological stress on embryos and young fish.

Although the above factors are all known to affect egg-to-fry recruitment and do very likely contribute to a portion of the observed discharge effects in this analysis, it should be noted that there was also likely a strong effect on the observed relationship of the multiple discharge peaks of 269-385 m^3s^{-1} that occurred simultaneously with low juvenile Chum Salmon abundances during the 2009-2010 and 2015-2016 incubation periods, respectively. Interestingly, the low juvenile abundance of 2009-2010 corresponds to the year of groundwater monitoring in redds at Moody's Bar where we observed the strongest effects of discharge pulses reducing incubation temperatures, further suggesting that discharge may indeed play a critical role in juvenile productivity during the egg/juvenile incubation period. These are important observations because the storage capacity of the Daisy Lake reservoir is limited and the predicted increased frequency of extreme storm events due to climate change will likely result in increased spill from the dam and thus more frequent discharge pulses of similar or greater magnitude between December and April (Tohver et al. 2014). As Daisy Dam operations and the small reservoir have limited capacity to mitigate against the adverse effects of increased discharge during the incubation period, other precautionary measures such as increasing artificial spawning channel habitat or more frequent discharge pulses during the adult spawning migration period – which may increase upper river habitat use by adults (see discussion about distribution) – could be explored.

Maintenance of the WUP minimum flow regime is the operational standard during the adult Chum Salmon spawning migration from October to December (BC Hydro 2007). However, natural variation in discharge greater than base flows does occur during fall storm events throughout this time period, which was found to have a positive effect on juvenile productivity. In our adult-to-fry stock recruitment analysis, we determined that the greater number of days adult Chum Salmon experienced discharges ≥ 25 m^3s^{-1} and ≤ 80 m^3s^{-1} during their spawning migration from October 15 – November 7 had a positive increase in juvenile recruitment. In addition, a positive linear relationship appears to exist between increasing minimum flows (15-25 m^3/s) during peak spawning and the proportion of adult Chum Salmon utilizing side-channel habitats where egg-to-fry survival is known to be increased relative to mainstem spawning habitats because of more stable incubation conditions (Fell et al. 2016). Indeed, variability in discharge is known to influence the upstream migration behaviour, distribution, and spawning success of numerous species of salmonids, including Chum Salmon (Hunter 1959; Telzlaff et al. 2005; Taylor and Cooke 2012). Analysis of radio-tagged fish in this study also found that adults that experienced a greater number of discharge days ≥ 25 m^3s^{-1} and ≤ 80 m^3s^{-1} were more likely to move into potential spawning habitat in the 'upper river' near the Bailey Bridge. In all of these cases, greater discharge variability above base flows during the adult migration likely affects juvenile productivity by increasing adult distribution throughout suitable spawning habitat, thereby reducing density dependent mortality effects on juveniles throughout the river as a result.

In the case of both the adult-to-fry and egg-to-fry analyses, results suggest that increasing the minimum base flow in the Cheakamus River from the current 15 m^3s^{-1} to variable flows between 25 m^3s^{-1} and 80 m^3s^{-1} during the adult spawning migration, and subsequently reducing these flows to a constant 20 m^3s^{-1} during the incubation period may result in greater juvenile productivity. Such measures, however, would need to be approached with caution and continued monitoring as altering discharge patterns from October to April could have unintended consequences (stranding, forced dispersal, mistimed migration, etc.) on the migrating adult and/or the incubating and rearing juvenile Chinook, Coho, Pink salmon, and Steelhead also present in the Cheakamus River throughout this period (Lingard et al. 2017; Korman and Schick 2018). It would also be remiss to attribute these modeled juvenile productivity increases solely to the effects of discharge as there are a number of additional factors beyond the scope of this monitoring program that could influence this outcome. For example, juvenile productivity can also vary with overall watershed productivity, predation, or the physiological condition of juveniles and spawning adults. However, despite not accounting for these factors, the effects of discharge 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 different salmonid life-history stages (Arthaud et al. 2014; Zeug et al. 2014; Rebenack et al. 2015; Zimmerman et al. 2015).

As a final note on the stock recruitment analyses conducted for this monitor, we caution that the 10-year duration of CMSMON1b has been relatively short within the context of Pacific Salmon population dynamics. For longer lived species like Chum salmon with a two- to five-year life cycle and highly variable abundances, greater than 10 years of monitoring are required to detect even small to medium size changes in a population (Korman and Higgins 1997; Babcock et al. 2010). Indeed, during the design of the Cheakamus WUP monitoring program, Parnell et al. (2003) determined 12 years prior and 12 years post implementation of WUP discharges were required to detect even a 25% change in Coho smolt abundance with a statistical power of 69%. In this context, with only 10 years of complete Chum salmon population data, some years may have a greater influence on model outcomes than others (e.g. 2009 and 2015 years of low juvenile abundance effects in egg-to-fry recruitment analyses), however, we are unable to discount outliers in this low sample size situation (n = 10) because they represent true observations. As such, we suggest that monitoring for CMSMON1b (and the necessary complimentary monitoring and data from CMSMON1a) be continued for at least another full generation of Chum Salmon (~ 4 years) to improve the robustness of stock-recruitment analyses and capture more of the natural variation in population cycles that is required to determine what relationships persist and whether abnormal points are truly abnormal; doing so will improve the likelihood of any management or operation decision being successful. With respect to the null hypothesis (H_1) from the terms of reference for CMSMON1b (BC Hydro 2007) regarding the question of discharge effects on juvenile productivity in MQ1 that states: *"Discharge during the Chum salmon spawning and incubation period does not affect productivity, measured as the number of fry per spawner in the mainstem"*, we reject this hypothesis given the results and discussion above. However, we reiterate the need for continued monitoring in the coming years to more thoroughly evaluate this relationship.

4.3 MQ 2 & 3: Modelled effective spawning area as an accurate representation of spawning site selection and availability of spawning habitat

We conducted no formal quantitative analyses to address these questions, however, we can infer from the work carried out to address MQ1, particularly with respect to distribution and groundwater flows, credible answers to these questions.

The mainstem reaches of the Cheakamus River upstream of the Bailey Bridge (RK 7.0) were modelled as effective Chum Salmon spawning habitat during the WUP consultative process based on depth, velocity, and substrate, and the assumptions that more habitat would increase productivity and that discharge was the only determinant of usage (BC Hydro 2007). However, results from this study largely refute these core assumptions and highlight the limitations of the habitat suitability modelling approaches used during the WUP consultative process. During the 10 years of monitoring, adult Chum Salmon have rarely been observed in this area in marked numbers apart from one year of this monitor (2012) when overall adult abundance was high, suggesting that distribution into these upper reaches may be driven by density dependence rather than suitability of spawning habitat. Moreover, published literature and the results of this monitor suggest the primary factor in adult Chum Salmon spawning site selection is groundwater upwelling, which appears to only primarily be available in the lower river (where the majority of Chum Salmon spawning and juvenile production occurs). Although there were uncertainties associated with the data, we found little evidence of groundwater dominated spawning habitat in the upstream reaches of the mainstem river. Thus, the models developed during the WUP consultative process do not provide an accurate representation of available Chum Salmon spawning habitat, particularly in the areas upstream of the Bailey Bridge (from RK 7.0 – 16.0), and groundwater upwelling is likely the metric that best represents Chum Salmon spawning habitat. Ongoing temperature monitoring in confirmed and suspected redd sites in habitats upstream of the Bailey Bridge with respect to MQ1 (discussed in previous sections) would help further quantitatively refine answers to MQ’s 2 and 3 and inform operational decisions that could potentially increase Chum Salmon productivity in the Cheakamus River.

5.0 CONCLUSION

Monitoring of adult Chum Salmon for CMSMON1b began in 2007 following the implementation of the WUP discharge regime. Prior to 2007, no adult monitoring had been conducted, therefore, there is no treatment with which to compare adult productivity and behaviour pre- and during the WUP flows.

In the past ten years of monitoring (2007-2016), adult escapement has varied from 74,000 to 607,000 individuals. Juvenile Chum Salmon outmigration estimates have been calculated since 2001 (pre-WUP) and indicate that fry abundance has varied greatly from 1,610,535 to 10,795,444 fish annually. However, only a small average change in population size (~12%) has been detected pre- and during the WUP flows.

Our analyses from this synthesis and series of past annual reports indicate that much of the habitat downstream of the Bailey Bridge (RK 7.0) is critical to Chum Salmon productivity, particularly the artificial side-channels habitats and spawning sites with dominant groundwater inflows. We observed an average of 65% of radio-tagged adults utilizing spawning sites characterized by higher groundwater inflows (downstream of the RST site RK 5.0) each year. Discharge pulses may lead to more upstream habitat usage, although these areas are not likely as effective spawning habitat. However, discharge pulses >20 m^3s^{-1} during the adult migration can lead to increased side-channel usage, and while a lower proportion of adults utilized artificial side-channel habitats (~16%) overall, these areas contributed an average of 68% of the total fry yield each year due to much higher egg-to-fry survival rates, likely due to more stable incubation conditions.

Groundwater inflows in redd sites are an important component to determining effective spawning habitat, as our results and findings in the literature indicate that adult Chum Salmon predominantly select areas of groundwater upwelling for spawning. In the lower reaches of the Cheakamus River, we observed that discharge pulses may lead to reduce redd temperatures where groundwater is present, likely by pushing cooler surface water down into redds. However, how these changes in redd temperatures are related to discharge and their effects on spawning site selection, incubation conditions, and subsequent productivity is not yet known based on the existing data and analyses.

The Cheakamus River WUP consultative committee recommended an operating alternative and associated river flow regime change based in part on expected benefits to fish populations. A large part of which was based on a significant modeled increase (~75%) in the availability of Chum Salmon spawning habitat upstream of the Bailey Bridge (RK 7.0) (Marmorek and Parnell 2002) and the assumption that discharge was the primary factor determining usage of this habitat. However, throughout the past 10 years of monitoring, very few adult Chum Salmon have been observed utilizing these areas, suggesting the models insufficiently predicted effective Chum Salmon habitat and that the predictions used to support the move from the IFA to WUP flow regime may be incorrect. These results highlight that uncertain models are no replacement for informative monitoring that allows for direct evaluation of flow effects and underscores the need to continue with such studies until uncertainties about flow effects are resolved.

We suspect that a lack of predominant groundwater influence in this modeled effective habitat upstream of RK 7.0 is a primary factor limiting its usage by Chum Salmon. However, given that groundwater data in this habitat is limited to a single year and few loggers, further groundwater assessments and more detailed examination of egg survival would enhance our ability to more thoroughly address management questions regarding how discharge affects habitat usage, spawning site selection, incubation conditions, and productivity in this area.

We used radio telemetry data to assess how discharge is related to the distribution and spawning behaviour of adult Chum Salmon in this synthesis. Despite the original objective of the radio-telemetry component of this monitor to identify sex-specific proportional distribution for mark-recapture estimates, these data, when combined and analysed, suggested an effect of discharge pulses on increasing adult distribution into upper river habitats, although this effect was minimal (3% increase in detection probability) and there was a large amount of uncertainty associated with the analyses. Further monitoring focused on examining the effects of specific flow treatments (i.e. variable discharge pulses) throughout the adult migration period and a re-design of the radio-telemetry study would greatly increase confidence in these inferences.

We also observed that variation in discharge (i.e. pulses) likely has both positive and negative effects on juvenile productivity as examined in adult-to-fry and egg-to-fry stock-recruitment analyses, respectfully. Stock-recruitment models indicated that variation in flows >25<80 m^3s^{-1} during peak adult migration (October 15 – November 7) had a positive effect on adult to fry productivity, while increasing discharge above base flows during the egg/juvenile incubation period (December 1 – April 1) had a negative effect on egg-to-fry productivity. During the adult migration, base discharge is maintained at ~20 m^3s^{-1} and will only fluctuate if natural inflows upstream of Daisy Lake exceed the operational capacity of the generating facility and/or downstream inflows increase due to fall storm events. As such, in years when discharge is stable throughout the adult migration period, hydrological manipulation to incorporate more discharge pulses >25<80 m^3s^{-1} may improve Chum Salmon productivity. In contrast, operational manipulations to the hydrograph during the incubation period (December – April) may be less likely as discharge pulses at this time are often due to storm events that exceed the management capacity of the Cheakamus/Daisy facilities and increased spill from Daisy Dam is necessary. Although each of the stock recruitment models provide valuable operational insights and indicate dominant effects of discharge on Chum Salmon productivity, such relationships based only on ten years of data should be considered uncertain, particularly when the models include an extra parameter to examine discharge effects. Given that 10 years of monitoring is only sufficient enough to detect a moderate change in productivity in a population (Korman and Higgins 1997; Babcock et al. 2010), further monitoring paired with experimental flow treatments would greatly increase the confidence in the effects of discharge on Chum Salmon productivity in the Cheakamus River, as have been initiated in the fall of 2017.

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