Cheakamus River Project Water Use Plan

Cheakamus River Chum Salmon Escapement Monitoring and Mainstem Spawning Groundwater Survey

Implementation Year 12

Reference: CMSMON1b

Cheakamus River adult Chum Salmon Monitoring

Study Period: October 2018 – May 2019

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EXECUTIVE SUMMARY

The previous 11 years (2007 – 2017) of monitoring for CMSMON1b aimed to determine effects of the WUP discharge regime on groundwater upwelling, adult Chum Salmon spawning site selection, distribution, and overall productivity. Stock-recruitment analyses have suggested that 'pulse flows' – or periods of increased discharge variability in the Cheakamus River between 25 and 80 m^3s^{-1} during the Fall adult migration – likely increases juvenile productivity. However, notable uncertainties have remained with respect to the accuracy of this stock-recruitment relationship and with the groundwater/discharge relationship in areas above the Bailey Bridge. BC Hydro extended monitoring through the 2018-2019 adult migration and juvenile incubation/rearing periods to further investigate the relationships between groundwater and spawning site selection and strengthen support for the hypothesis that greater discharge variability is associated with increased productivity of juvenile Chum Salmon. In this additional year of monitoring, experimental pulse flows were continued during the Fall adult migration such that discharge was manipulated between 25 and 80 m^3s^{-1}. Improved groundwater monitoring also occurred throughout the spawning and incubation periods. This report discusses results from this 12th year of monitoring and how they address these uncertainties and help answer management questions for CMSMON1b.

Fall 2018 saw the lowest estimated adult Chum Salmon escapement (34,333 adults) and corresponding juvenile recruitment (1,442,931) in the history of CMSMON1b. The majority of adults were distributed throughout spawning habitats in the lower reaches of the Cheakamus River between river kilometer (RK) 2.0 (Stables) and below RK 7.5 (Bailey Bridge), with 18% of the estimated population utilizing lower river side-channel habitats and 16% of radio tagged individuals tracked above the Bailey Bridge. Despite more discharge variability during the Fall migration from pulsed flows, there was no empirical relationship between discharge and maximum migration distance achieved by radio-tagged fish. We did, however, make multiple observations of adults spawning in confirmed groundwater influenced habitat proximate to RK 15.0 (Road's End) in the days following flow pulses. These observations suggest variation in Fall discharge above base WUP flows may affect groundwater availability and provide access to additional spawning habitat in the upper reaches of river, however additional monitoring would be required to test this hypothesis.

In contrast to previous years, we observed only one peak of entry timing into side-channels that occurred near November 7th. Despite the lack of empirical evidence, the pattern of daily side-channel entries was similar to that of previous years where models suggested daily entries could be increased by pulsing discharge above the daily mean during the adult migration. Increasing entry into side channels

could potentially increase Chum Salmon productivity, as egg-to-fry survival is consistently higher in side channels relative to the mainstem river.

Improved groundwater monitoring in 2018/2019 confirmed evidence of upwelling throughout the study site. Sites with evidence of the strongest upwelling were located downstream of the Bailey Bridge, where the majority of adult Chum Salmon are observed spawning year to year. However, there was also strong evidence of groundwater upwelling upstream of the Bailey Bridge proximate to Road's End, where adult Chum Salmon were also observed spawning. The degree of groundwater upwelling varied substantially both within and between sites and with variation in discharge, limiting the development of predictive models but suggesting groundwater and discharge are likely related.

Experimental pulse flows during the 2018 Fall adult migration resulted in the most variable hydrograph in the history of the monitor relative to standard WUP flows. Yet despite the above average discharge conditions, record low adult escapement and juvenile recruitment in 2018/2019 reduced the magnitude of pulse flow effects and model fit in both the egg-to-fry and adult-to-fry stock- recruitment models. These models continued to support the hypothesis that more variability in flows during the adult migration period increases juvenile productivity, although with less certainty in predictions following the addition of these new data. Stock-recruitment models fit with an interaction to examine whether juvenile productivity was related to varying combinations of yearly adult escapement and pulse flows produced inconclusive results. However, general trends from these models suggested that greater pulse flow days during the fall migration may be more effective at increasing productivity during years of higher adult abundance, when density dependent effects may be stronger. Overall, these results continue to suggest that discharge is indeed related to productivity, and that regulating discharge during adult migration and juvenile incubation could be used as a management tool to increase Chum Salmon productivity in the Cheakamus River. We caution, however, that because Chum Salmon are a long-lived species with highly variable abundances that can be influenced by numerous other physiological and environmental factors, inferences drawn from these stock-recruitment relationships with relatively small sample sizes (i.e. years of monitoring) could be biased or inaccurate. Indeed, continued monitoring of adult and juvenile Chum Salmon productivity would improve the robustness of stock-recruitment analyses and predictions of pulse flow effects on productivity. Going forward, however, it would be prudent to consider the development of additional study components that examine productivity and a power analysis exercise to help guide the scope of future stock-recruitment monitoring.

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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 ecologically, culturally, and recreationally important 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.

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 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. From 1957 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, Fisheries and Oceans Canada (DFO) issued an instream flow order (IFO) to BC Hydro after decades of unregulated flow releases (driven largely by power demand) were expected 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 an effort to mimic the natural variability of the river hydrograph and potentially reduce 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 to sustain healthy salmon populations (BC Hydro 2007). 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 (including

CMSMON1b) 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 2007). CMSMON1b (monitoring adult Chum Salmon) and CMSMON1a (monitoring juvenile Chum Salmon) 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 required 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 has been conducted for the past 12 years (2007 – 2018) 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?

A 10-year synthesis of CMSMON1b (Fell et al. 2018) concluded there were remaining uncertainties regarding the effect of the WUP flow regime on Chum Salmon productivity. In particular, with how discharge affects groundwater-influenced egg/juvenile incubation conditions and adult distribution, and how 'pulse flows' (periodical discharge manipulations between 25 and 80 m^3s^{-1}) during the Fall adult migration may affect juvenile productivity. To address these uncertainties, BC Hydro initiated an additional two years of monitoring for the 2017-2018 and 2018-2019 adult migration and juvenile incubation/rearing periods. In this time, monitoring has focused exclusively on examining the relationships between discharge, adult distribution, and groundwater-influenced spawning sites, and evaluating the effect of continued experimental pulse flows on Chum Salmon productivity using stock-recruitment relationships.

Results from the 2017-2018 monitor continued to support that regulating discharge during adult migration and juvenile incubation could be used as a management tool to affect distribution and increase Chum Salmon productivity. However, inferences drawn from relationships with relatively small sample sizes (i.e. limited tracking data, groundwater data, years of monitoring, etc.) could be biased or inaccurate. This report discusses methods and results from the 2018-2019 monitoring season and how they build on previous years to more accurately address the CMSMON1b management questions and assess hypotheses about groundwater, distribution, and productivity. For detailed descriptions of the methods, analyses, results, and discussions relevant to previous years of CMSMON1a & b (2007 – 2017), 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 (December - March) and late summer/early Fall (August - September), and two freshet periods from spring snow-melt (April - July) and Fall storm events (October – November). Mainstem fish habitat in the Cheakamus River extends 17 km from its confluence with the Squamish River to a natural 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).

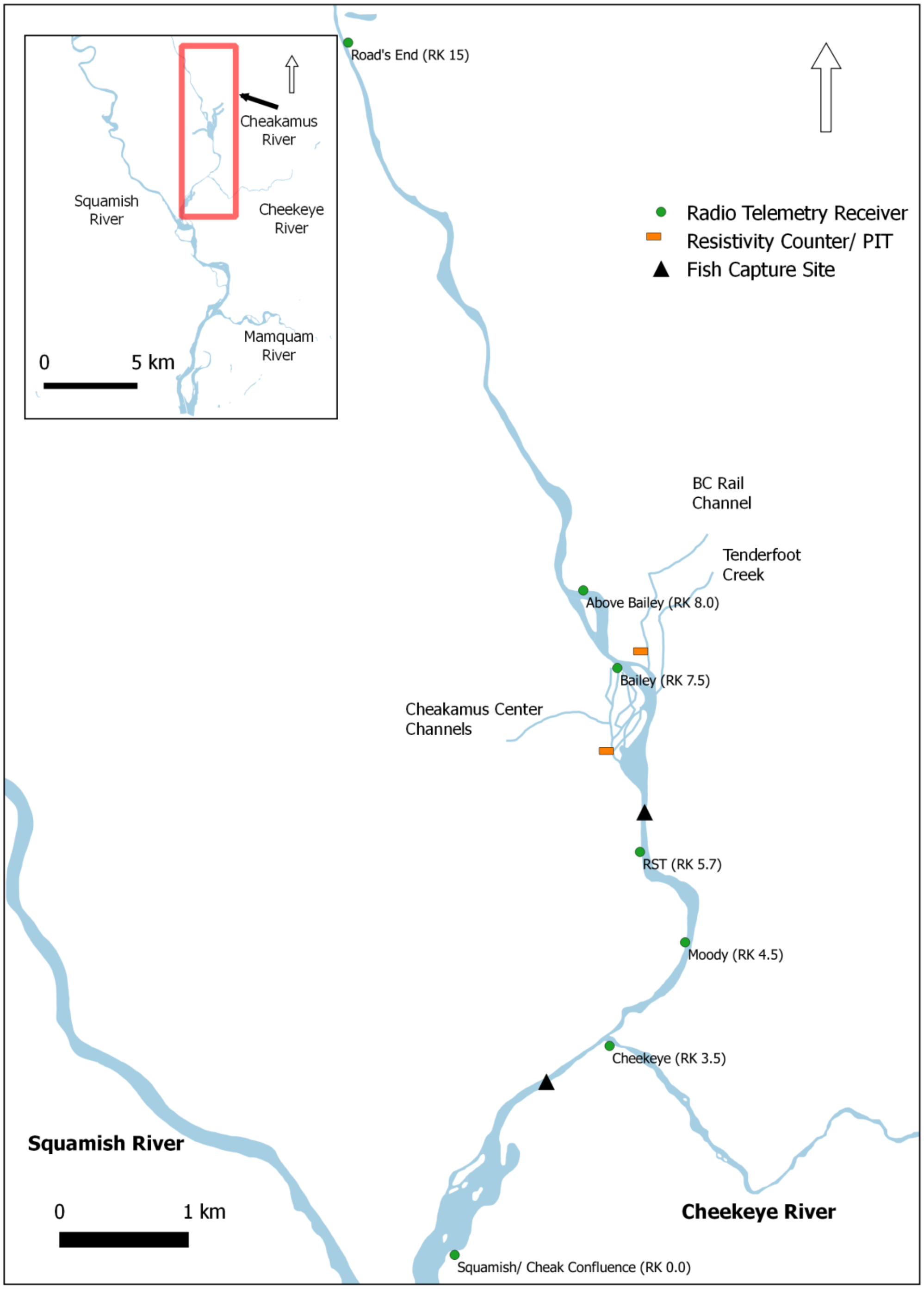

Figure 1. Cheakamus River study site showing locations of fish collection sites, radio-telemetry receivers, artificial spawning channels, resistivity counters, and rotary screw trap. Inset shows location relative to the greater Squamish River watershed. A Water Survey of Canada (WSC) gauge (08GA043) is located at the 'Gauge Pool' site. Adult Chum Salmon escapement was determined through mark-recapture efforts, PIT tag detections and adult counts from resistivity counters.

2.2 Cheakamus River Discharge

Experimental pulse flow conditions during the Fall salmon migration were designed to mimic a more natural hydrograph that would have existed prior to the WUP. This was accomplished by timing manipulations of outflows at BC Hydro's Daisy Lake Dam with natural river inflows to achieve the maximum number of days above the previous 11-year mean (5.4 days) when daily average discharge in the Cheakamus River was between 25 – 80 m^3s^{-1} from October 15 – December 15, 2018.

Hourly discharge data used in all subsequent analyses were acquired from the Water Survey of Canada (WSC) gauge at Brackendale (08GA043) located 100 m upstream of the rotary screw trap (RST) site. Discharge data were summarized across four Chum Salmon life-history periods: the entire spawning season (Oct 15-Dec 15), the upstream migration (Oct 15-Nov 7), the peak spawning period (Nov 1-Nov 15), and the egg incubation period (Dec 1 – Mar 31). Discharge metrics included minimum, maximum, mean, and median discharge, as well as the standard deviation and variance in discharge, and the number of days between 25 and 80 m^3s^{-1} (see Fell et al. 2018). These discharge metrics were considered as covariates during stock-recruitment modelling and models of adult Chum Salmon distribution.

2.3 Groundwater Monitoring at Spawning Sites

It is well established that adult Chum Salmon select areas of groundwater upwelling for spawning in the lower Cheakamus River (Fell et al. 2018; Middleton et al. 2018) and throughout their range (Hale et al. 1985). As such, we have concluded that the models used to predict Chum Salmon spawning habitat during the WUP consultative process were not accurate because they did not incorporate groundwater flows into their predictions (Management Question 2 and H_2 in BC Hydro 2007; Fell et al. 2018; Middleton et al. 2018). However, there is still uncertainty regarding the presence of suitable groundwater-influenced spawning sites in the upper reaches of the river above the Bailey Bridge (RK 7.5), if these sites are utilized by Chum Salmon, and whether discharge affects upwelling of groundwater in spawning sites in general (Middleton et al. 2018). Given these uncertainties, an alternative hypothesis was proposed for CMSMON1b (BC Hydro 2007):

> H_3: Discharge during the Chum Salmon spawning and incubation period does not affect the upwelling of groundwater in mainstem spawning areas.

We improved on the groundwater and spawning site monitoring methods used in previous years (described in Fell et al. 2018; Middleton et al. 2018) to address the knowledge gaps highlighted above. Redd temperature monitoring was extended to occur throughout the entire duration of the spawning/incubation period from November 15, 2018 to March 15, 2019. Temperature loggers were distributed at 9 sites between Moody's Bar (RK 4.5) and Road's End (RK 15), and more densely concentrated in areas upstream of the Bailey Bridge to test for groundwater in upper reaches of the river (Figure 1 & 3). Monitoring sites were selected based on their suitability for Chum Salmon spawning (i.e., appropriate depth, velocity, and substrate composition) and/or previous observations of confirmed spawning behaviour. Loggers (n = 35; iButton, Maxim Integrated, San Jose, USA) recording hourly temperature were buried ~30 cm below the substrate surface (approximate redd depth) using a pounding-rod technique to ensure they were not dislodged or scoured throughout the season. Replicate loggers were installed at each site to account for spatial variability in groundwater upwelling; the number of replicates ranged from 2 to 6 depending on the size of the site and the variability of site characteristics. Temperature loggers located at the suspension bridge and RST sites recorded hourly surface water temperature.

Areas of groundwater upwelling were identified using differentials between redd temperatures and surface water temperatures (see details in Fell et al. 2018). Fall and winter groundwater temperatures are generally warmer and more stable than surface water temperatures in Pacific Northwest streams (Constantz 1998), thus we considered groundwater upwelling to be present at sites where surface water temperatures were lower than redd temperatures, and/or where temperature fluctuations in the water column were not observed within the redds. We further designated the presence of groundwater as either strong (i.e., evidence was consistent amongst years and replicate temperature loggers, and/or there was a large temperature differential) or none (i.e., evidence was inconsistent, and/or the temperature differential was minimal i.e. <1°C). To confirm selection for groundwater among Chum Salmon, we qualitatively compared adult spawning locations (assessed during mobile telemetry floats; See Section 2.4.2) and observations of fry during Spring 2019 stranding surveys with study sites demonstrating strong groundwater upwelling.

We used time series' of redd temperature and Cheakamus River discharge to qualitatively test hypotheses H_3 and determine whether discharge pulses interact with groundwater upwelling. We did not quantitatively relate discharge and redd temperature due to the complex nature of groundwater upwelling (i.e., the difficulty in fitting predictive models), the variability in the location of groundwater upwelling, and the variability in the magnitude and direction of differentials between redd temperatures and surface water temperatures.

2.4 Adult Escapement Estimation

We estimated adult Chum Salmon escapement in Fall 2018 (and in all previous monitoring years) using a Pooled-Petersen mark-recapture model (Ricker 1975; Fell et al. 2018). This method combines a passive mark-recapture model with PIT tag detections and adult counts from resistivity counters in the

Cheakamus Centre and Tenderfoot Creek side channels. Additional details on model specification and refinement as well as the capture and recapture methods described below can be found in previous CMSMON1b annual reports (e.g. Fell et al. 2016).

2.4.1 Capture and Tagging

All Chum Salmon tagged during this study were captured using a tangle net deployed from an inflatable pontoon boat and secured by an on-shore crew (see details in Fell et al. 2016). Two locations were used based on ease of river access, suitability for fish capture, and proximity to resistivity counters (Figure 1). The lower river site (Stables, RK 2.0) was fished at discharges between 15 and 30 m^3s^{-1} and the upper river site (Gauge Pool, RK 6.0) 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 captured fish were tagged with a 24 mm half-duplex PIT tag (Oregon RFID, Portland, USA) in the dorsal musculature and fitted with an external Petersen Disk Tag for visual identification. A subset were also 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. Radio telemetry data was used to assess movement and distribution patterns. Sex, fork length, and condition were recorded for all individuals.

2.4.2 Telemetry Monitoring and Enumeration

The radio-telemetry receiver array was expanded in 2018 with 5 additional stations to improve the resolution of adult migration monitoring (Table 1). In total, 7 ‘Orion’ radio receivers (Sigma Eight Inc., Newmarket, Canada) each fitted with a 3-element Yagi antenna were located from the Cheakamus-Squamish River confluence (RK 0.0) to Road’s End (RK 15) and ran continuously throughout the monitoring period (October 15 – December 20, 2018; Figure 1). Detection efficiencies for all fixed-station receivers was >85%. In-river mobile radio-telemetry tracks using a Lotek SRX-600 receiver (Lotek Wireless Inc., Newmarket, Canada) and visual surveys for spawning adults were also conducted once per week to supplement fixed-station data. All radio-telemetry data was managed and cleaned following the methods described in Fell et al. 2018.

Table 1. Names and locations of fixed station radio-telemetry receivers used to monitor adult Chum Salmon migration in the Cheakamus River from October 15 – December 20, 2018.

Radio Receiver Station (*indicates new in 2018)	River Kilometer Location (RK)
Squamish-Cheakamus River confluence*	0.0
Cheekeye-Cheakamus River confluence	3.5
Moody’s Bar*	4.5
RST pool*	5.7
Bailey Bridge	7.5

Wellness Centre*	8.0
Road's End*	15

To enumerate adult Chum Salmon with mark-recapture modeling, recapture data were collected at three locations in the Cheakamus River from October 15, 2018 to December 12, 2018: at the entrances of the Cheakamus Centre and BC Rail side-channels, and proximate to the Tenderfoot Creek Hatchery (Figure 1). At these three sites, all adult migrants passed PIT antennas to determine which tagged individuals migrated into which site; all migrants (tagged and untagged) were enumerated by either a pass-over Logie 2100C resistivity fish counter (Aquantic Ltd.) at the Cheakamus Centre and BC Rail side channels or by DFO observers at the Tenderfoot Creek hatchery entrance fence. It is important to note that the passive counting methods (i.e. resistivity counters and PIT antennas) employed in this study do not function at discharges >80 m^3s^{-1}.

2.4.3 Adult Mark-recapture Modelling

Pooled-Petersen mark-recapture estimates were used to calculate adult escapement for the entire river and the area upstream of the RSTs (including side channels). The estimate for the whole river was derived from individuals marked at the Stables and Gauge Pool tagging sites 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. Escapement was estimated using the equation:

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

Where $\widehat{N}$ is the estimated escapement in each area (entire river or upstream of RST), M is the total number of fish marked with PIT tags, C is the total number of fish entering the side-channels (i.e., captured/enumerated by the resistivity counter), and r is the number of PIT tagged fish entering the side channels (i.e., recaptures; Ricker 1975).

Pooling in the Petersen method refers to combining all mark-recapture trials into a single estimate of 'trap efficiency' (or recaptures, r) and generating a single escapement estimate for the entire study period ($\widehat{N}$).

2.5 Juvenile Abundance Estimation

A Bayesian Time-Stratified Spline model (BTSPAS) was used to estimate annual juvenile Chum Salmon abundance in the Cheakamus River as a part of CMSMON1a (see Lingard et al. 2017 for more details). The BTSPAS model is a modified Petersen mark-recapture model that estimates weekly abundance using splines to model the general shape of the migration. 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 mainstem Cheakamus River and the side channels. Juvenile Chum Salmon in the mainstem Cheakamus River were enumerated by two six-foot rotary screw traps (RSTs) operated adjacent to the Cheakamus Center property at RK 5.5 from February 18 – April 25, 2019 (Figure 1). Fyke nets were used during the same period to enumerate juveniles in side-channels at the Cheakamus Center complex, BC Rail channel, and at the Tenderfoot Creek Hatchery adult fence (Figure 1). 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. Estimates generated from the RSTs represent 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.

2.6 Egg-to-fry Survival

Egg-to-fry survival accounts for inter-annual variation in egg deposition per female resulting from changes in fecundity and spawning success and is an important indicator of incubation and emergence conditions and overall juvenile productivity. 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 Pooled-Petersen estimate for year *t*. N_{tf} is the proportion of 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*. See Fell et al. 2018 for further details of calculations.

2.7 Juvenile Productivity and Stock-recruitment

Stock-recruitment analyses examine the relationship between adult escapement and subsequently density-dependent juvenile productivity and how this relationship can vary given the influence of additional independent factors. In this report, we continued to build on stock-recruitment relationships developed for CMSMON1b that explore the effect of the WUP discharge regime and experimental pulse flows on productivity described in Fell et al. (2018) and Middleton et al. (2018). We re-examined the suite of annual discharge metrics that summarised flow conditions occurring over four distinct time periods throughout the adult spawning and egg incubation periods across all habitat types (mainstem and side channels combined). These metrics were used as covariates in modified Ricker stock-recruitment analyses to explore the effects of discharge during peak adult migration (October 25 – November 7) on juvenile productivity (Table 7 in Fell et al. 2018).

Following review of previous years' stock-recruitment analyses with BC Hydro biologists, we also modeled stock-recruitment relationships with an interaction effect to explore whether productivity varied with changes in yearly adult escapement and discharge combinations. It must be noted, however, that because non-parametric stock-recruitment methods are dependent on asymptotic relationships, their reliability when applied to small sample sizes may be unknown (Subbey et al. 2014). Furthermore, Gelman (2018) has suggested that a model needs 16 times the sample size to effectively estimate an interaction than to estimate a main effect. Therefore, given small sample sizes in the presented analyses (n = 12), it is likely that results are spurious and/or non-informative.

We fit stock-recruitment relationships with both single-discharge and interaction covariates and compared them to a base Ricker model (i.e. model with no discharge covariate) using Deviance Information Criteria (DIC). We also compared models with and without interaction terms to each other using DIC. DIC quantifies the trade-off between fit and complexity for Bayesian models (Gelman 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. All covariates used in stock-recruitment modelling were standardized (i.e., re-scaled to have a mean of one and standard deviation of zero) to compare the relative effect of each covariate on the stock-recruitment relationship (Gelman 2008). Because the covariates were standardized, differences in the magnitude of coefficient estimates among covariates reflect their utility for explaining variation in recruitment. A detailed description and equations for the modified-Ricker model used in these analyses is described in Fell et al. 2018; all modeling was performed in JAGS and R (R Core Team 2017) using package 'jagsUI'.

2.8 Adult Chum Salmon Distribution

Discharge pulses have been hypothesized to affect adult Chum Salmon distribution by increasing side-channel usage and encouraging migration into habitats upstream of the Bailey Bridge (RK 7.5), which may lead to less density-dependent effects on egg/juvenile survival and improved productivity (Fell et al. 2018). We used the same methods described in Middleton et al. (2018) to examine the relationship between side-channel usage and pulse flows. Briefly, we modelled daily entry counts (of PIT and resistivity counter counts separately) of adults into side channels as a function of daily average discharge and day of year (to control for migration timing) using negative binomial generalized linear models to account for over-dispersion in count data. Both models only included count and discharge data that occurred when flows were <80 m^3s^{-1}, as both PIT and resistivity counting operations cease to function above this threshold. Model fits were assessed by over-dispersion and Chi-square tests.

We examined how discharge affects adult Chum Salmon distribution in the mainstem Cheakamus River using radio telemetry data from Fall 2018. Data from fixed radio-receiver stations were combined with weekly mobile tracking data to determine individual migration histories and maximum RK achieved. We used a linear model to examine the maximum RK achieved by radio-tagged fish in 2018 as a function of sex, tagging date to account for migration timing, the maximum discharge an individual encountered while in the Cheakamus River, and a categorical variable describing the number of days during the migration characterized by pulse flows (i.e. discharge >25<80 m^3s^{-1}; low = 0-4 days, medium = 5-7; high = 8-11). All covariates were standardized to allow for the direct comparison of the relative effect of each explanatory variable (Gelman 2008) and model residuals were examined for linearity and homogeneity.

3.0 RESULTS

3.1 Cheakamus River Discharge

Mainstem Cheakamus River daily average discharge during the Fall adult Chum Salmon migration from October 15 – December 15, 2018 ranged from 15.7 – 240.17 m^3s^{-1} (47.1 ± 1.2[1]), with 47% (29 of 62) of days falling within the 25 – 80 m^3s^{-1} pulse flow conditions (Figure 2A). Fifty-two percent (12 of 23) of days were characterized by pulse flow conditions during 'peak' adult migration (October 15 – November 7), which is more than double the previous 11-year mean (5.3 days) for this period. Discharge during the egg incubation and juvenile rearing period ranged from 14.9 – 109.3 m^3s^{-1} (23.3 ± 0.25) (Figure 2B).

[1] Data throughout the results are presented as mean ± standard error.

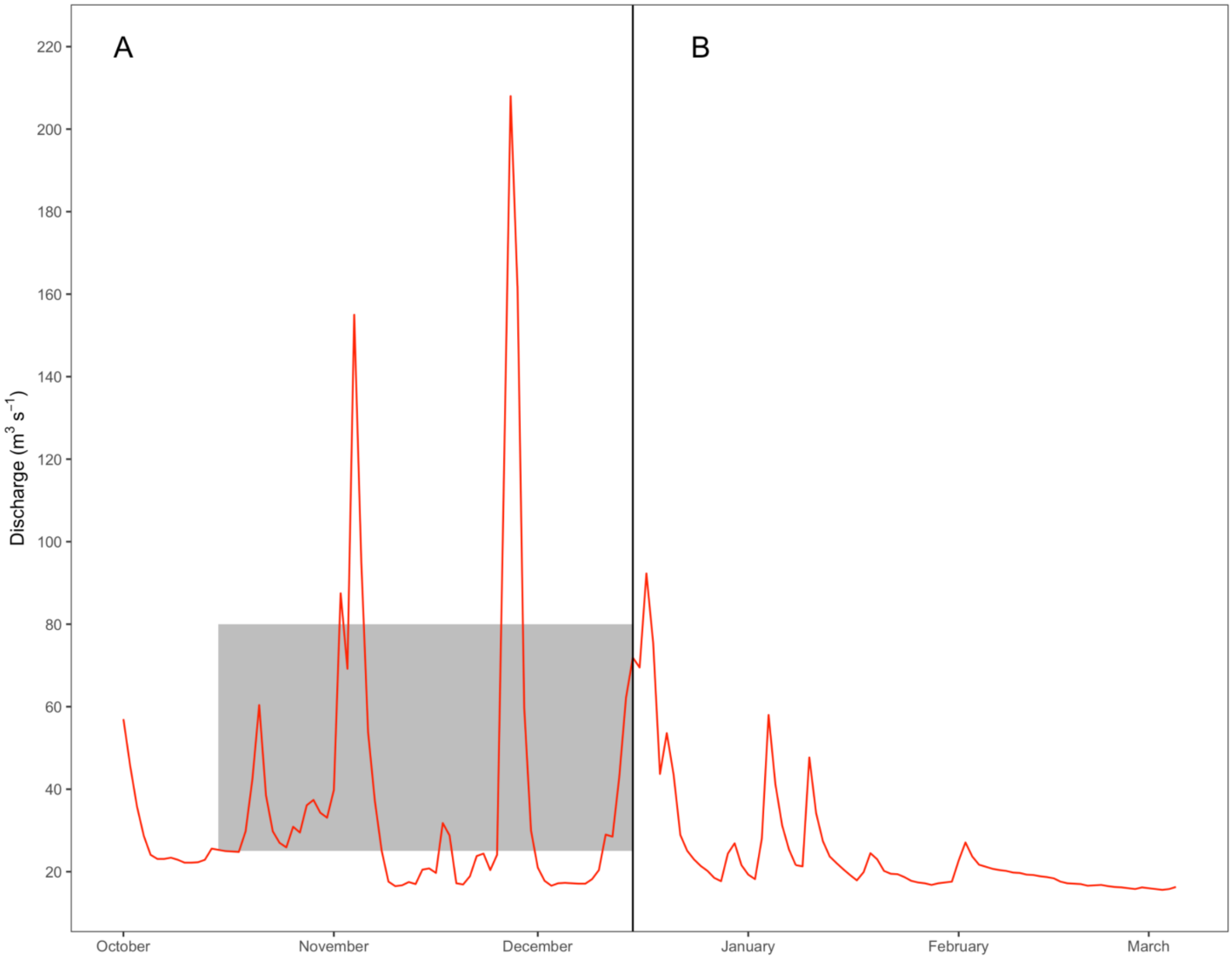

Figure 2. Mean daily discharge of the Cheakamus River during the adult spawning migration period from October 1 – December 15, 2018 (Panel A), and the egg incubation / juvenile rearing period from December 15, 2018 – April 1, 2019 (Panel B) at the WSC Brackendale gauge (08GA043). The grey shaded box highlights period during the adult migration when discharge was between 25 – 80 m^{3}s^{-1}.

3.2 Groundwater Analysis

A total of 21 sub-surface temperature loggers were recovered from the Cheakamus River on March 17, 2019, of which, 19 loggers yielded complete sub-surface temperature time series. The remaining 14 loggers (i.e., of the 35 deployed) were not recovered or were displaced during the monitoring period (Figure 3).

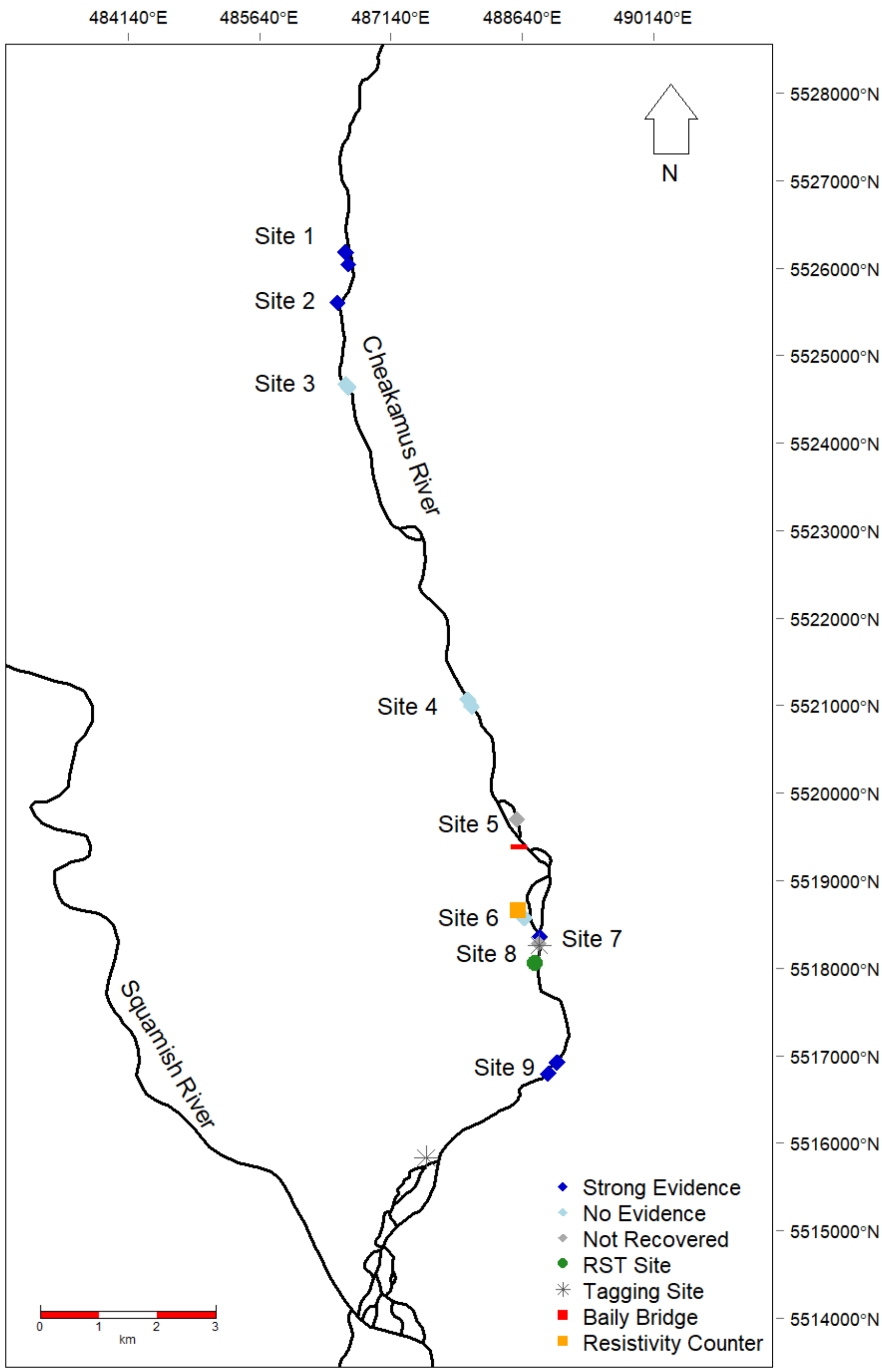

Figure 3. Map of the Cheakamus River study area showing points of interest and sub-surface temperature logger sites exhibiting strong (dark blue diamonds) or no evidence (light blue diamonds) of groundwater upwelling.

We examined the temperature differential between redd temperature and surface temperature to identify sites with evidence of groundwater upwelling. Two areas showed evidence of strong groundwater upwelling including Sites 1 and 2, proximate to the end of the Paradise Valley road, and Sites 7 and 9 at Gauge Pool and Moody's Bar, respectively (Figure 3; Figure 4). Sites 3 – 6 between Road's End and Gauge Pool (i.e. mid-river) showed no evidence of groundwater upwelling (Figure 3; Figure 5). Groundwater evidence was consistent among replicate loggers deployed at each site.

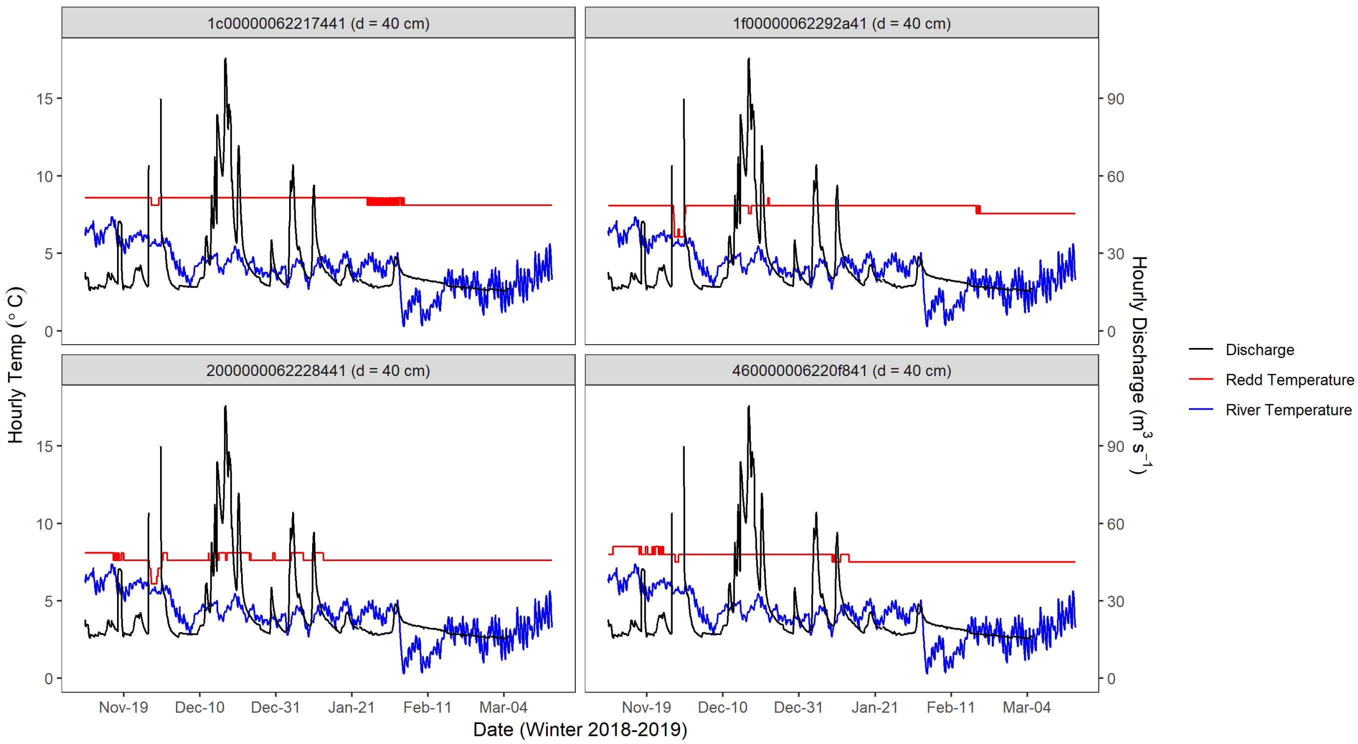

Figure 4. Redd temperature (red line) recorded by four loggers deployed at Moody's Bar (Site 9) in the Cheakamus River, surface river temperature (blue line), and discharge (black line) .

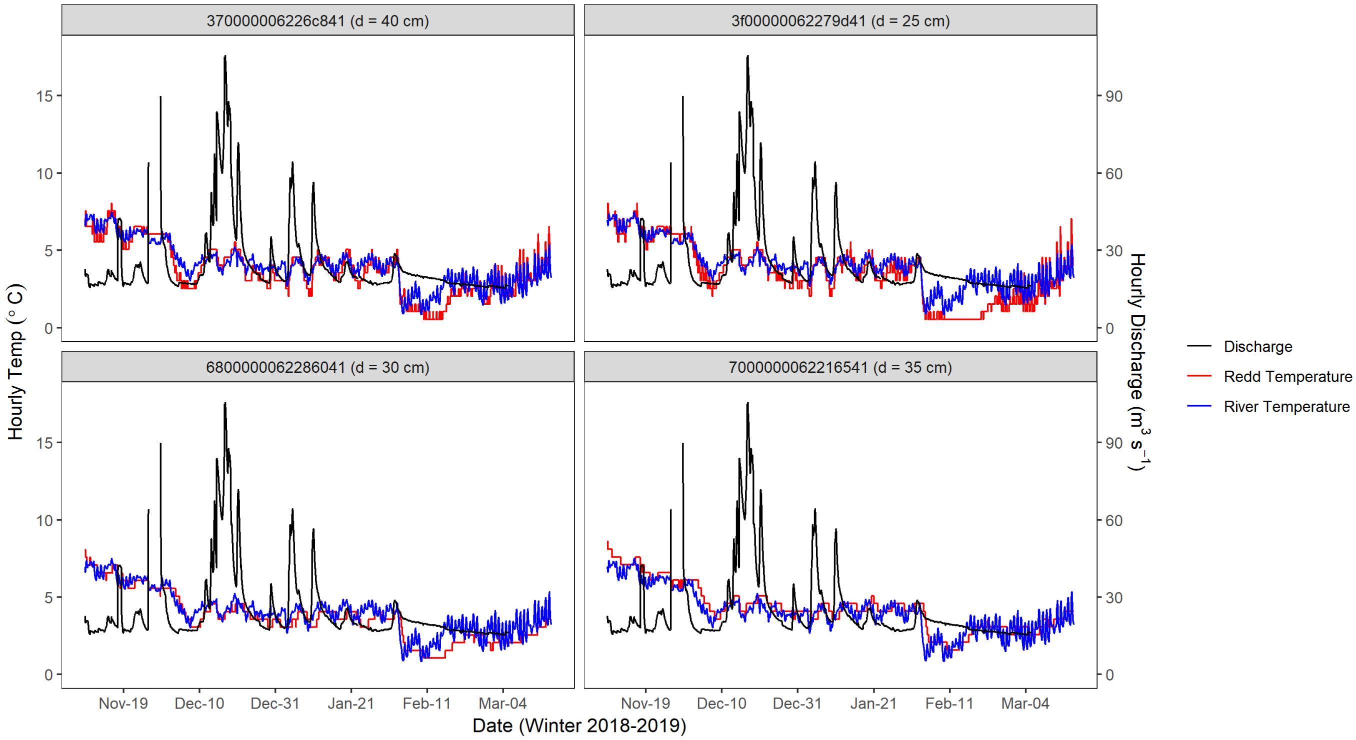

Figure 5. Redd temperature (red line) recorded by four loggers deployed at Site 3 in the middle Cheakamus River, surface river temperature (blue line), and discharge (black line).

We overlaid strong groundwater upwelling sites with confirmed locations of adult Chum Salmon spawning and Chum Salmon fry observed during spring 2019 stranding surveys (Jody Schick; personal communication, June 2019) to determine whether adults select areas of groundwater upwelling for spawning in the Cheakamus mainstem (H_2). Chum Salmon consistently spawn in high abundances at all sites downstream of the Bailey Bridge, which include sites with strong groundwater upwelling (Sites 7 and 9), as well as sites with no evidence of groundwater (Site 6). Adult spawning and Chum Salmon fry were also observed at Sites 1 and 2 near Road's End, which were characterized by strong upwelling. No spawning adults or fry were observed between sites 3 through 5 in the middle-river where there was no evidence of groundwater.

Several large discharge pulses occurred over the 2018 – 2019 incubation period that affected groundwater upwelling as described by redd temperature. At sites with evidence of strong groundwater upwelling, large discharge pulses generally resulted in a short-term decline in redd temperature. Redd temperature returned to pre-pulse values gradually following the end of the discharge pulse. At Site 9, characterized by very strong groundwater evidence, discharge pulses did not affect groundwater temperature as strongly, likely due to the strength of groundwater influence. The magnitude of the effect of discharge on groundwater temperature varied among sites and within the same site, highlighting the site-specific nature of groundwater upwelling in the Cheakamus River.

3.3 Adult Chum Salmon Escapement

The Pooled-Petersen adult Chum Salmon abundance estimate for the Cheakamus River in 2018 was 34,333 (range: 28,923 – 39,742) for the whole river and 26,370 (range: 21,450 – 31,291) for the upper river (i.e., upstream of the rotary screw trap at RK 5.5, Figure 1). These estimates have ranged from 50,588 to 602,619 for the whole river from 2007 – 2017; notably, the 2018 whole river estimate consists of 16,255 fewer returning adults than the previous lowest recorded estimate (2017: 50,588) since the monitor began in 2007 (Figure 6).

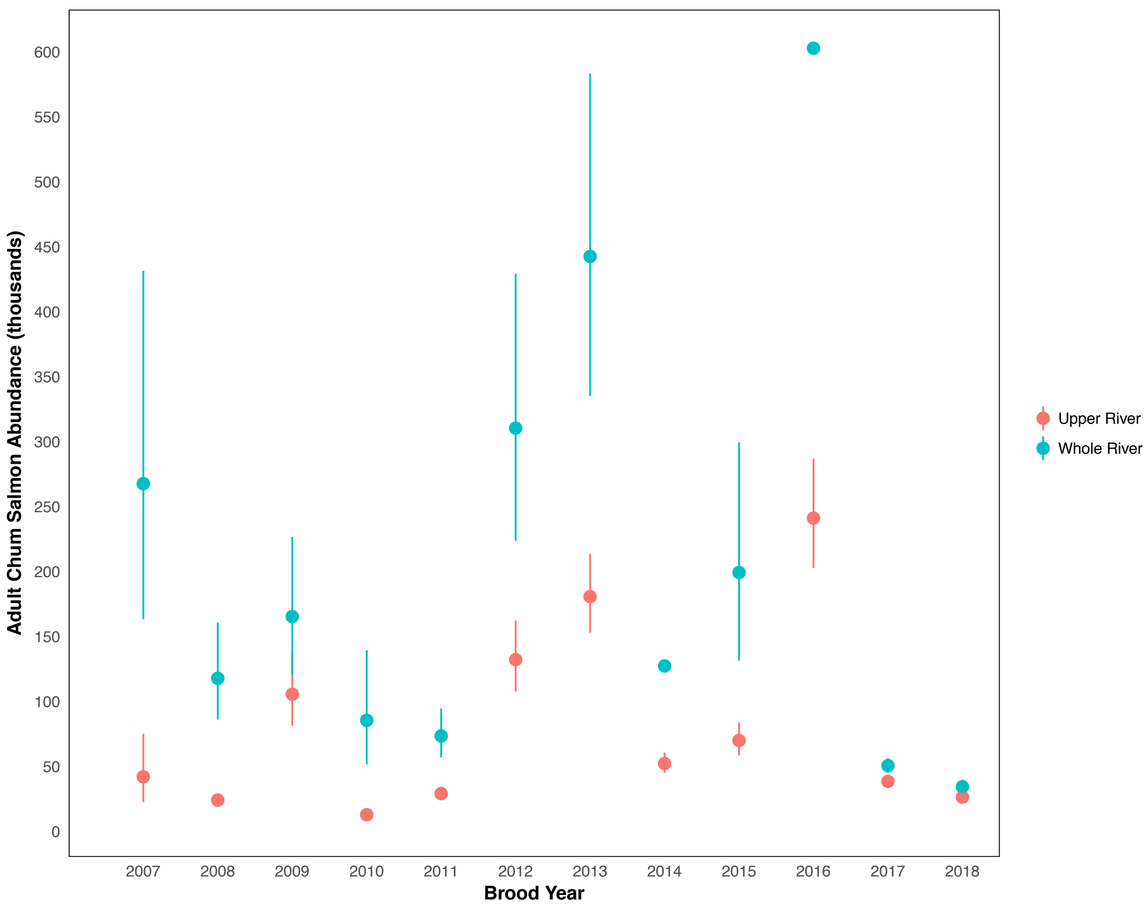

Figure 6. Annual Pooled-Petersen abundance estimates of adult Chum Salmon from 2007 – 2018 for the upper (red dots) and whole (blue dots) Cheakamus River. Error bars indicate upper and lower 95% confidence intervals. Points with no visible error bars exhibit confidence intervals smaller than the scale of the figure.

Resistivity counter data indicated that 82% of estimated adults utilized mainstem habitat, while the remaining 18% were distributed throughout side-channel habitats; this is consistent with previous year's estimates of proportional distribution (Table 2).

Table 2. Estimated proportional distribution of adult Chum Salmon among mainstem and side-channel habitats in the Cheakamus River from 2007 – 2018.

Year	Mainstem	Side Channels
2007	0.9	0.1
2008	0.67	0.33
2009	0.85	0.15
2010	0.79	0.21
2011	0.85	0.15
2012	0.89	0.11
2013	0.87	0.13
2014	0.83	0.17
2015	0.85	0.15
2016	0.88	0.12
2017	0.79	0.21
2018	0.82	0.18

3.4 Discharge-related Chum Salmon Distribution

Observations of combined daily entries into the Cheakamus Centre, BC Rail, and Tenderfoot side-channels from both resistivity-counter and PIT datasets indicated a single peak of entry timing that occurred during the second week of November following an increase in discharge from 38 m^3s^{-1} to 160 m^3s^{-1} (Figures 7 & 8). Negative-binomial generalized linear models were used to assess the relationship between daily entries (counter and PIT) into side-channels and mean daily discharge. In contrast to results from this model for the 2017 migration season (Middleton et al. 2018), neither the counter nor PIT models detected any statistical effect of discharge or migration timing on entries into side-channels in 2018 (Table 3); however, patterns in the data were similar to those of 2017 and suggest a continuation in the trend of increased side-channel entry with pulse flows (Middleton et al. 2018, Figures 8 & 9).

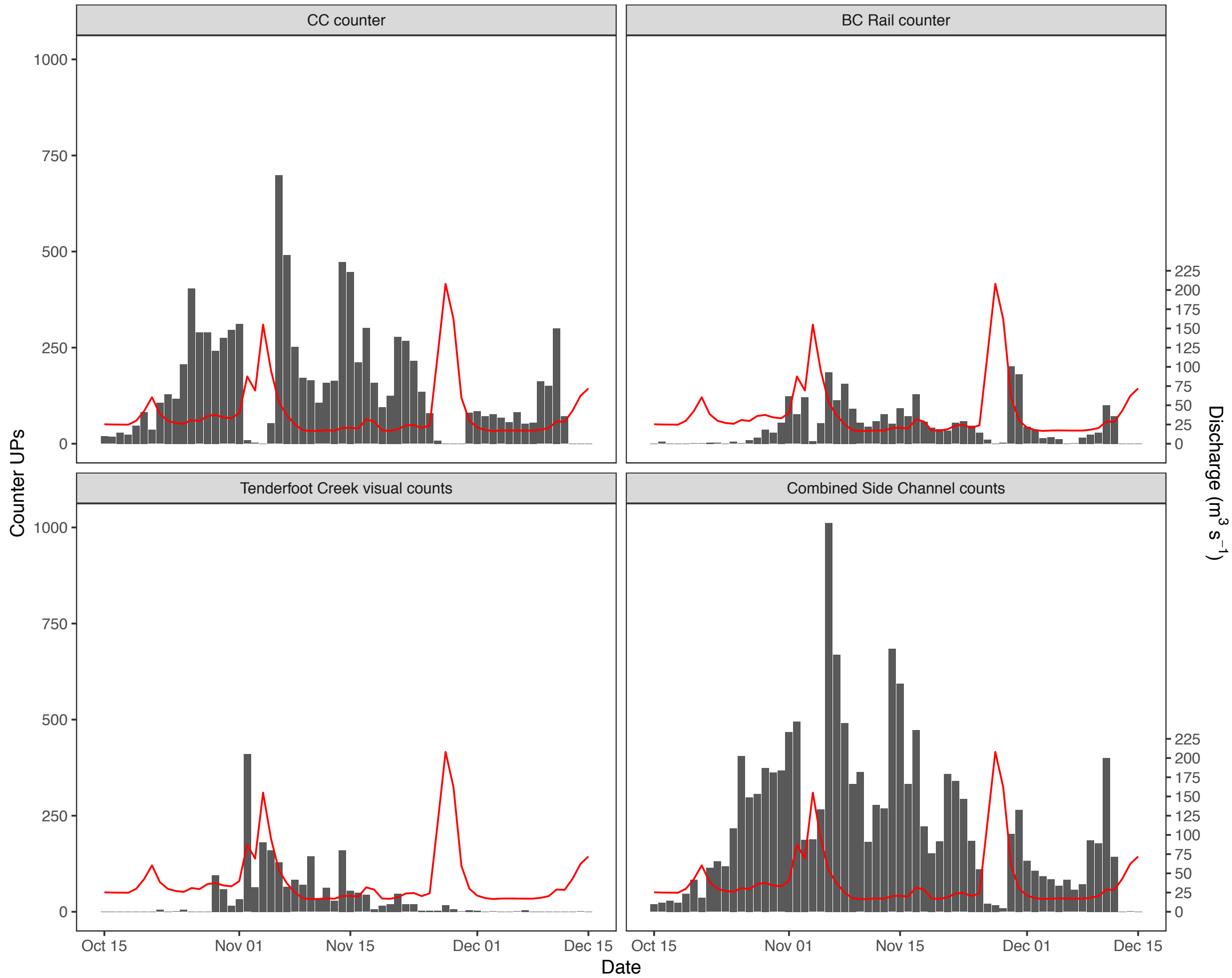

Figure 7. Daily UP (entry) counts from resistivity counters and visual counts at Cheakamus Centre, BC Rail, and Tenderfoot Creek side-channels (black bars) relative to the Cheakamus River daily average discharge (red line) from October 15 – December 15, 2018.

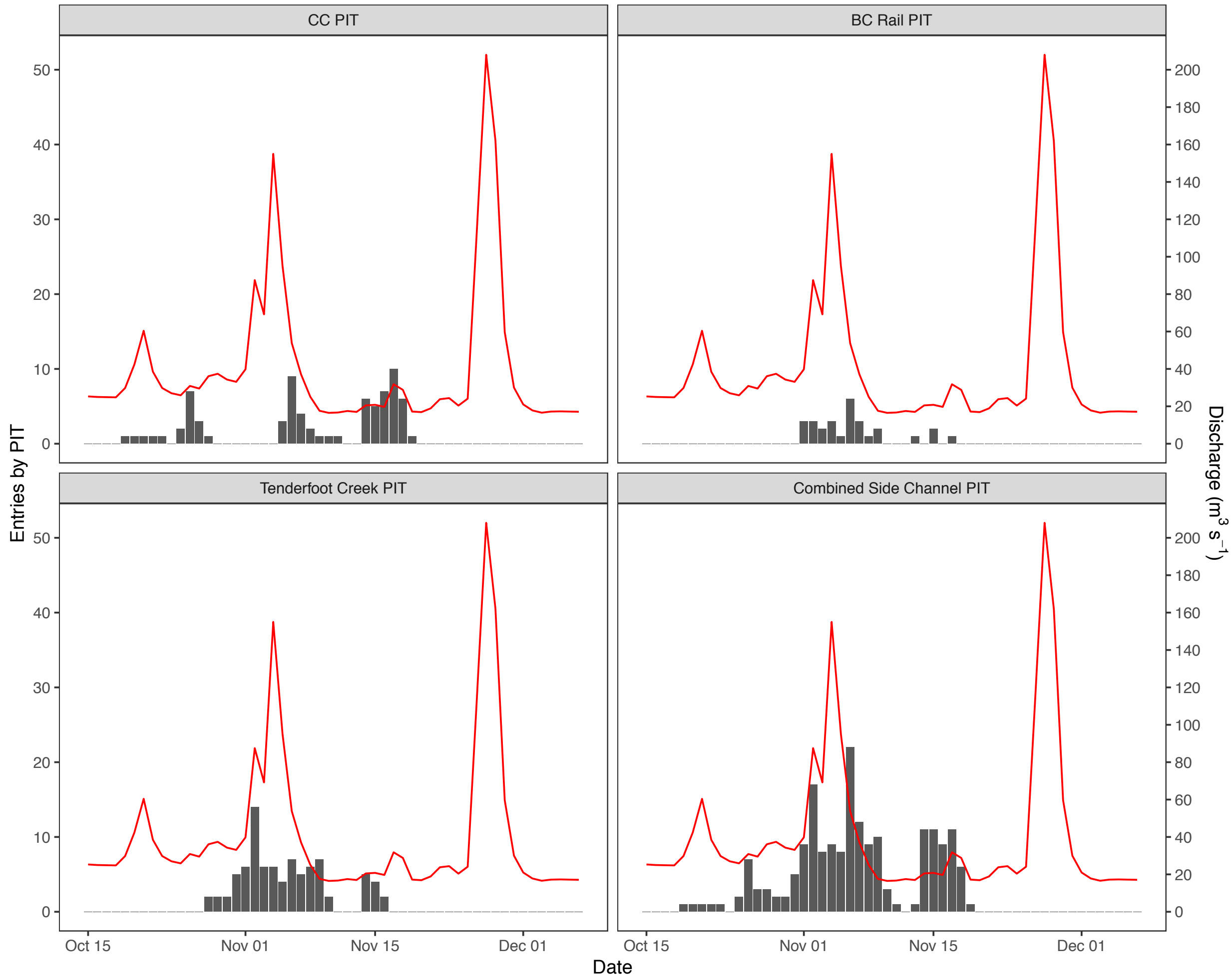

Figure 8. Daily unique PIT tag entry detections from the Cheakamus Centre, BC Rail, and Tenderfoot Creek side-channels (black bars) relative to the Cheakamus River daily average discharge (red line) from October 15 – December 15, 2018.

Table 3. Model statistics from negative-binomial GLMs of the relationship between daily average discharge and the daily number of 'Counter' and 'PIT' entries into all monitored side channels in the Cheakamus River between October 15 – December 15, 2018.

	Coefficient estimate	SE	*p*	Lower 95% CI	Upper 95% CI
Counter model					
Intercept	5.52	0.11	2.00 e^{-16}	5.52	5.76
Tagging date	0.15	0.13	0.24	-0.20	0.50
Mean daily discharge	0.21	0.12	0.10	-0.06	0.50
PIT model					
Intercept	1.06	0.24	1.15e^{-5}	0.61	1.56
Tagging date	-0.23	0.26	0.39	-1.18	0.68
Mean daily discharge	0.38	0.26	0.14	-0.13	1.00

Radio-tagged fish achieved maximum river kilometer migration distances that ranged from 0.0 (Cheakamus – Squamish River confluence) to 14.6 (Road's End) RKs; the mean maximum distance achieved was 3.7 RKs, near Moody's Bar. Contrary to previous years, 9 of the 56 individuals tracked in 2018 were detected above the Bailey Bridge (RK 7.5). Only 2 of these fish were detected near Road's End, while the remaining 7 individuals were only detected within 100 m upstream of the Bailey Bridge. Twenty-three of the tracked individuals did not migrate upstream of the tagging location (RK 2.0) and were only subsequently detected at the Cheakamus – Squamish River confluence (RK 0.0). The 23 fish that did not migrate upstream experienced a higher mean-maximum discharge of 159.5 m^3s^{-1} (range: 16.0 – 240.2 m^3s^{-1}) during their individual detection periods relative to those 33 individuals that were tracked upstream following tagging who encountered a mean-maximum discharge of 52.2 m^3s^{-1} (range: 17.2 – 177.9 m^3s^{-1}).

In the linear model examining the relationship between the maximum river kilometer achieved by tagged individuals as a function of sex, migration timing, maximum discharge, and migration days encountering pulse flows, there were significant negative associations between maximum river kilometer and maximum discharge ($p < 0.01$), and low numbers of pulse flow days ($p < 0.01$) (Table 4). These results suggest that the maximum migration distance achieved by individual adult Chum Salmon is increased by reductions in maximum discharge, and by increasing days of pulse flow conditions. Adjusted R^2 for this model is 0.59, indicating good model fit (Table 4).

Table 4. Statistics for the linear model of maximum river kilometer achieved by radio-tagged Chum Salmon in the Cheakamus River between October 15 – December 15, 2018 as a function of sex, migration timing, maximum discharge and pulse flow days; Q in this table represents discharge.

	Coefficient estimate	SE	*p*	Lower 95% CI	Upper 95% CI
Intercept	6.93	1.36	$5.06e^{-6}$	4.20	9.65
Sex (m)	0.61	0.71	0.39	-0.81	2.02
Tag Date	-0.20	0.40	0.64	-0.99	0.61
Max Q.	-2.22	0.32	$7.39e^{-9}$	-2.86	-1.57
Low Q. Days >25<80	-4.85	1.32	$5.58e^{-4}$	-7.49	-2.21
Med Q. Days >25<80	-1.70	1.24	0.177	-4.19	0.79
F	16.9				
Adj. R^2	0.59				
p-value	$1.05e^{-9}$				

3.5 Juvenile Abundance

Chum Salmon fry abundance in Spring 2019 was estimated to be 1,442,931 (± 76,726), which is the lowest estimate on record since the beginning of CMSMON1b (Figure 9). In general, estimates of juvenile Chum Salmon abundance have been highly variable over the 12 years of monitoring, ranging from 10,795,444 (± 2,313,237.2) in 2013 to 1,442,931 (± 76,726) in 2019 (Figure 9). Statistical confidence is these estimates is particularly high given the intensive juvenile marking effort associated with this monitor (see Lingard et al. 2017).

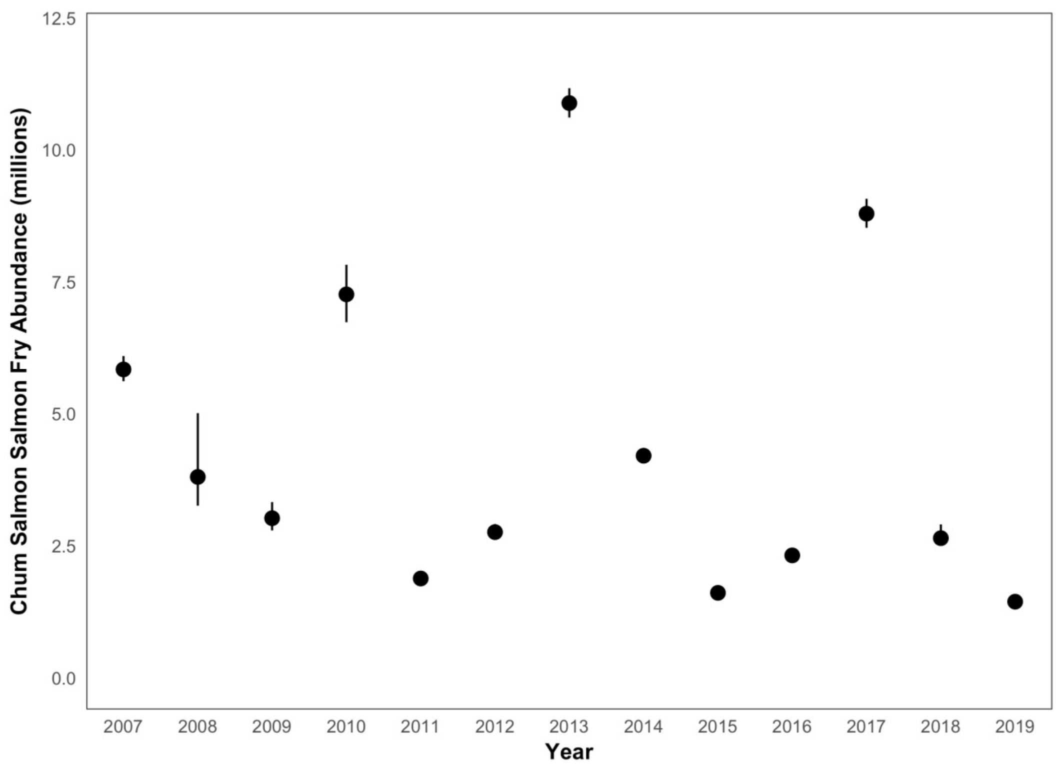

Figure 9. Annual abundance estimates of Chum Salmon fry in the Cheakamus River from 2007 – 2019 as determined by a BTSPAS model. Error bars indicate upper and lower 95% confidence intervals.

3.6 Egg-to-fry Survival

Estimates of Cheakamus River egg-to-fry survival in 2018 for side-channel, mainstem habitat, and both habitats combined were 12%, 1.0%, and 2.5%, respectively (Figure 10). The estimate of combined survival rates fell within the range of the previous 11-year estimate (1.6 - 12%); mean egg-to-fry survival across the 12 years of monitoring was 5.2% (± 3.1% SD) (Figure 10).

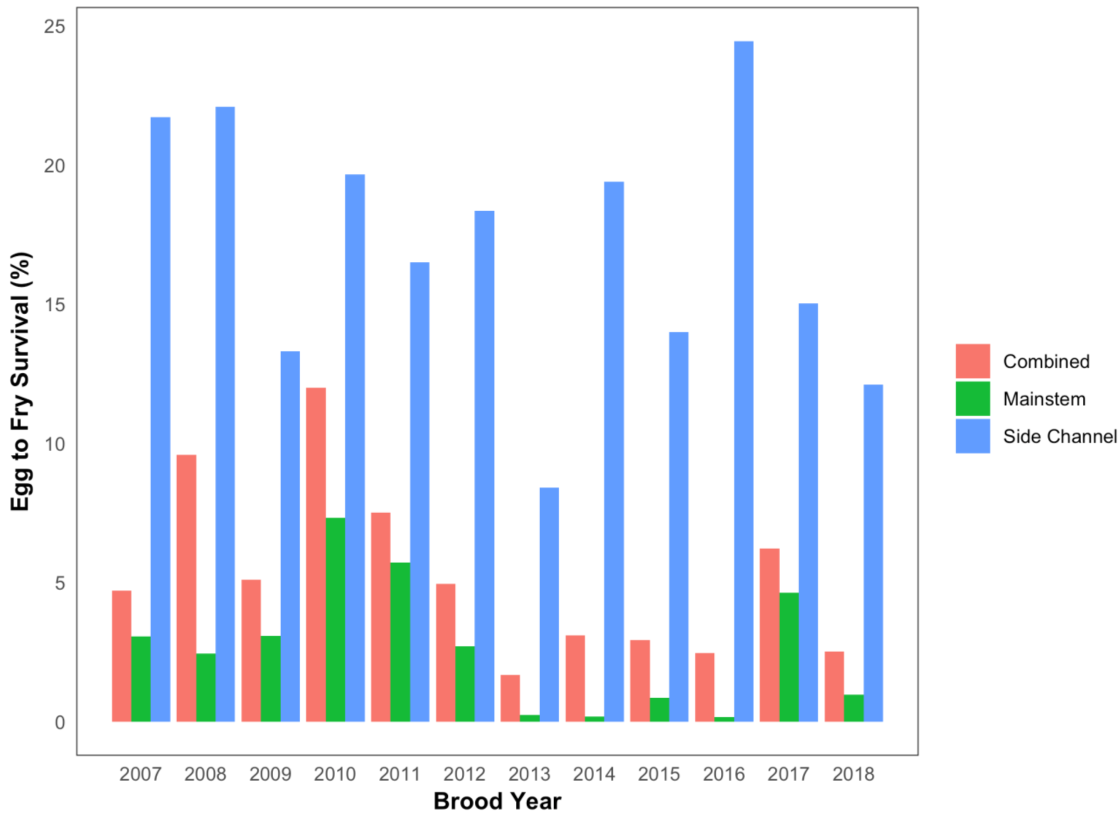

Figure 10. Estimated Chum Salmon egg-to-fry survival in mainstem, side-channel, and all habitat types combined in the Cheakamus River from 2007 – 2018.

3.7 Juvenile Stock-Recruitment

Building on analyses from previous years, we continued to model the effects of discharge on egg-to-fry and adult-to-fry Chum Salmon recruitment across all habitat types (side-channels and mainstem combined; for more details on model construction see Fell et al. 2018 and Middleton et al. 2018). We also modeled stock-recruitment relationships with interactions to examine whether productivity varied with changes in yearly adult escapement and discharge combinations. Below we illustrate the combinations of escapement and pulse flow conditions from the past 12 years of monitoring along with results from the 5 top-ranked main-effect stock-recruitment models and their interaction equivalents.

3.7.1 Combinations of Adult Escapement and Pulse Flow Conditions

To illustrate the different combinations of adult escapement and Fall pulse flow conditions encountered in this monitor and their utility as data in stock-recruitment analyses, we assigned each parameter to one of three categories (low, medium, high) in the matrix presented below (Table 5). The replication and clustering of escapement/pulse flow conditions within some combinations and absence of data in others demonstrates how sample size in these stock-recruitment analyses limits statistical power in main-effects models. The accuracy of estimates of the effects of discharge on egg-to-fry and adult-to-fry productivity could only be improved by increasing *n* (i.e. monitoring years) to yield additional combinations of conditions. This data structure also clearly lacks replication up to 16 times *n* of the main effect needed to accurately estimate interactive effects (Gelman 2018), and highlights how interaction testing in these stock-recruitment models with low *n* and missing data is likely to produce uninformative results.

Table 5. Illustrative matrix of estimated yearly adult Chum Salmon escapement and days of pulse flow conditions during peak Fall migration from 2007 – 2018 for CMSMON1b. Each year of escapement-pulse flow combination in this matrix represents a data point used in stock-recruitment analyses of discharge effects on egg-to-fry and adult-to-fry recruitment. Escapement and Pulse flow data were treated as a continuous variable in all stock-recruitment analyses.

		Pulse flow days during peak migration (> 25 < 80 m^3s^{-1})		
		Low (0 – 4)	Medium (5 – 7)	High (8 – 11)
Yearly adult escapement	Low (12, 827 – 28,373)		2008	2010, 2018
	Medium (28,374 – 112,187)	2011, 2015	2007, 2009, 2014, 2017	
	High (112,188 – 241,048)	2013, 2016		2012

3.7.2 Egg-to-fry Recruitment

Consistent with egg-to-fry stock-recruitment results from previous years (Fell et al. 2018; Middleton et al. 2018), main effects of discharge during the adult migration and 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 6). The two top-ranked models included covariate effects for pulse flow days >25 and < 80 m^3s^{-1} during the peak adult migration and maximum discharge during the egg incubation period (Table 6). These models explained 34% and 52% of the variation in egg-to-fry recruitment variance, respectfully, and had ΔDIC values that indicated similar levels of empirical support for each model (Table 6).

Coefficient estimates for pulse flow days >25 and < 80 m^3s^{-1} and maximum discharge during the egg incubation period were 0.26 and -0.30, respectfully. These results suggest an increase in egg-to-fry recruitment when the number of days during peak adult migration in which discharge was >25 and < 80 m^3s^{-1} increased from the 12-year mean (5.8 days; Figure 11), and a decrease in recruitment when maximum discharge increased during the egg incubation period (Table 6).

We also examined the effect of interactions between yearly adult escapement and pulse flows (days >25<80 m^3s^{-1}) on this stock-recruitment relationship. DIC ranking of interaction models differed slightly from that of the main-effect models (see Appendix 1), but ΔWAIC values, a measure of the change in fit between the main-effect and interaction models, indicated little difference between the two (Table 6). For example, the top-ranked egg-to-fry model included the pulse flow parameter, and although the R^2 for its interaction equivalent was slightly higher (0.34 vs. 0.37), ΔWAIC between the two models was minimal, suggesting very little empirical difference (Table 6). Despite this difference, general predictions from the interaction model suggest that increased fall pulse flow days may have a stronger effect on recruitment in years when adult escapement is higher (Figure 12c) – likely via greater distribution of adults throughout spawning habitats and reduced density-dependent effects on juveniles. However, there is a high degree of uncertainty associated with this interaction and caution must be taken with this interpretation. For example, the current model also suggests that recruitment would continually increase with pulse flow days and yearly adult escapement and fail to asymptote, which is contrary to standard density-dependent theory and likely an artifact of the limited data currently available to test for such an interaction (Figure 12b & c).

Table 6. 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). Statistics from equivalent models including interactions are shown in italicized parentheses. 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; R^2 is an estimate of the proportion of variance explained by each model. ΔWAIC is a measure of the change in fit between the main-effect and interaction models.

Model	Coefficient estimate	Lower 95% CI	Upper 95% CI	R^2	DIC	ΔDIC *(ΔWAIC)*
Base Ricker (BR)	-	-	-	0.32 *(0.32)*	25.4 *(25.8)*	0.37 *(-0.001)*
BR + Discharge days >25< 80 m^3s^{-1}	0.26 *(0.08)*	-0.12 *(-0.56)*	0.65 *(0.73)*	0.34 *(0.37)*	25.1 *(26.9)*	0 *(1.03)*
BR + Incubation discharge max	-0.30 *(-0.77)*	-0.63 *(-1.33)*	0.03 *(-0.17)*	0.52 *(0.29)*	25.2 *(21.9)*	0.22 *(-1.51)*

BR + Incubation discharge mean	-0.30 *(-0.71)*	-0.62 *(-1.42)*	0.03 *(-0.03)*	0.52 *(0.27)*	25.8 *(25.1)*	0.74 (0.88)
BR + Spawning discharge mean	-0.19 *(-0.47)*	-0.58 *(-1.01)*	0.17 *(0.08)*	0.35 *(0.28)*	26.2 *(30.9)*	1.24 *(-0.13)*
BR + Spawning discharge SD	-0.21 *(-0.44)*	-0.58 *(-1.02)*	0.17 *(0.14)*	0.28 (0.30)	26.3 *(30.2)*	1.30 *(0.59)*

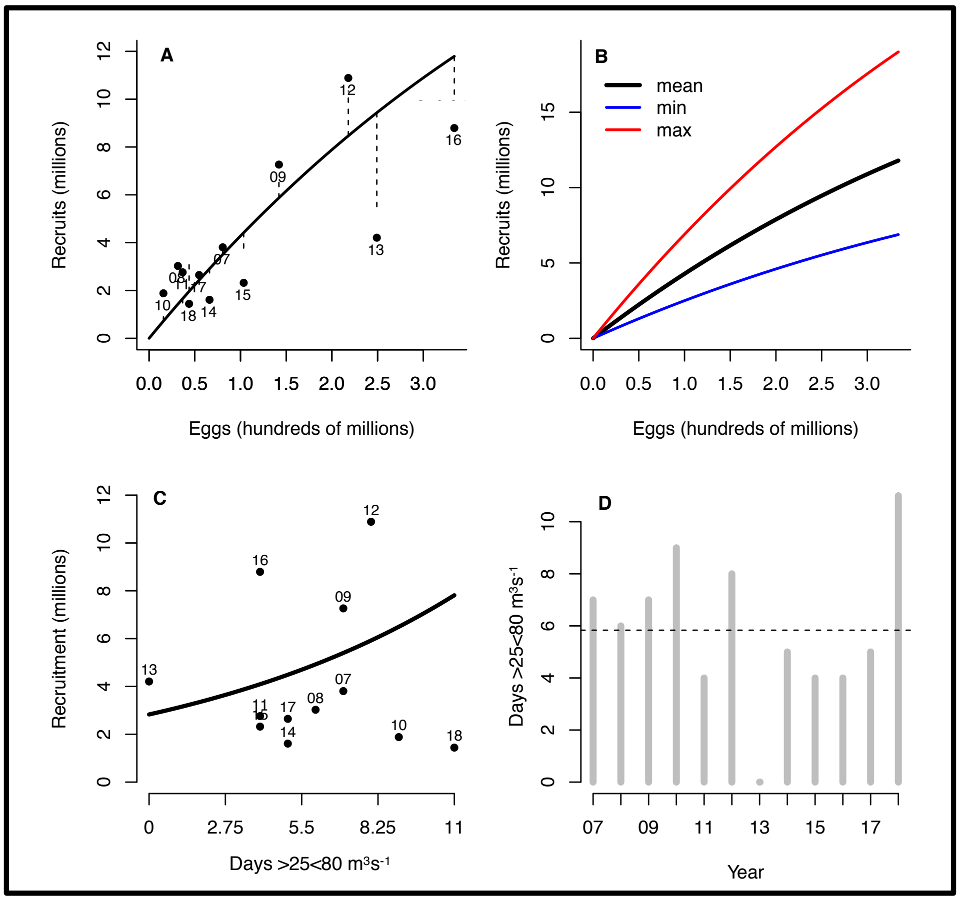

Figure 11. Stock-recruitment curve for the number of Chum Salmon fry produced per hundreds of millions of eggs; individual points are data from each of the 12 years of monitoring (panel A). Estimated numbers of recruits per hundred million eggs at the mean, minimum, and maximum values of pulse flow days >25<80 m^3s^{-1} during the adult migration period (panel B). Estimated juvenile recruitment by pulse flow days >25<80 m^3s^{-1} over the 12 years of monitoring (panel C). Average number of days per year from 2007 – 2018 when discharge was >25<80 m^3s^{-1} (panel D).

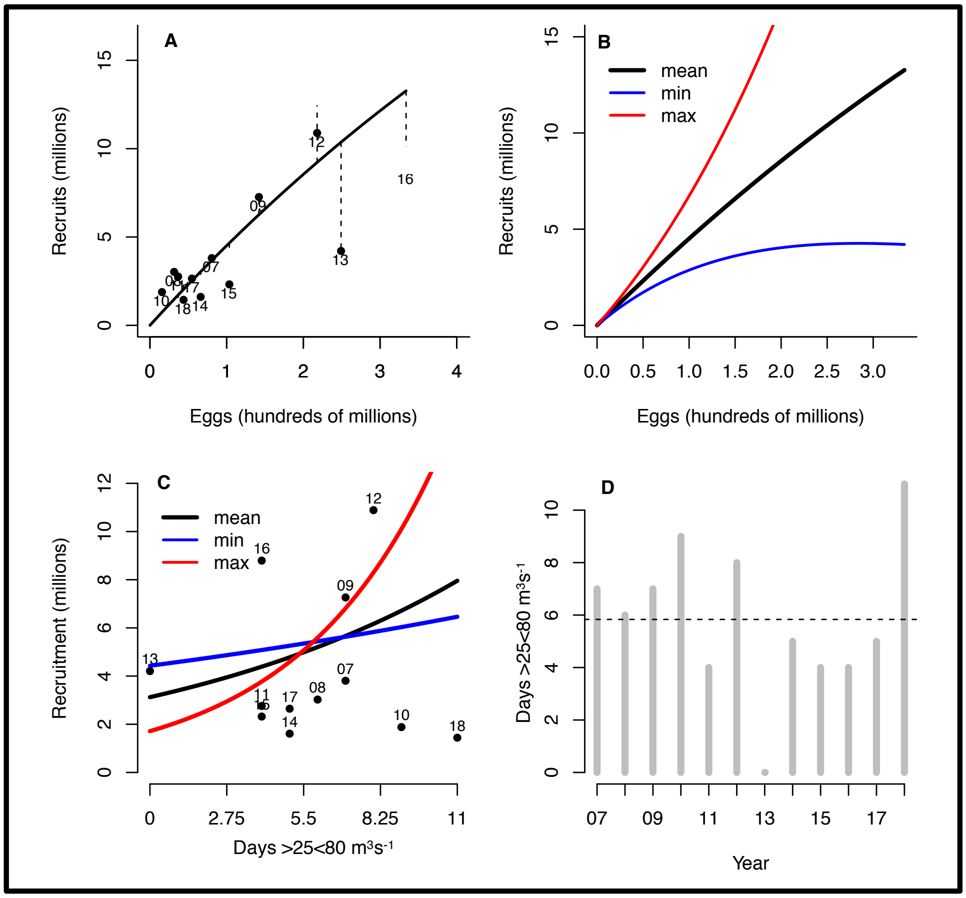

Figure 12. Stock-recruitment curve for the number of Chum Salmon fry produced per hundreds of millions of eggs; individual points are data from each of the 12 years of monitoring (panel A). Interaction effect on the estimated number of recruits per hundred million eggs at the mean, minimum, and maximum values of pulse flow days >25<80 m^3s^{-1} as a function of adult abundance during the adult migration period (panel B). Interaction effect on estimated juvenile recruitment by pulse flow days >25<80 m^3s^{-1} as a function of adult abundance over the 12 years of monitoring (panel C). Average number of days per year from 2007 – 2018 when discharge was >25<80 m^3s^{-1} (panel D).

3.7.3 Adult-to-fry Recruitment

The estimated number of juvenile Chum Salmon recruits per adult spawner was the lowest recorded in the 12 years of monitoring, but model results were similar to that of previous year's estimated adult-to-fry stock-recruitment relationships (Figure 13). The top-ranked model included positive pulse flow effects across all habitat types, which continues to support the leading CMSMON1b hypothesis that more days of variable flows between 25 and 80 m^3s^{-1} during peak Fall adult migration may increase fry production (Table 7). However, both the magnitude of this effect (coefficient estimate = 0.32) and model fit (R^2 = 0.4) were reduced in 2018 relative to previous years (2017 coefficient estimate = 0.40; R^2 = 0.74; Middleton et al. 2018). In addition, the second and third top-ranked models in 2018 included effects indicating increases in maximum and mean discharge, respectfully, during the egg incubation period may negatively affect adult-to-fry recruitment (Table 7). Both these models had ΔDIC values < 2 suggesting similar levels of empirical support for their effects relative to the top-ranked model (Table 7).

As with egg-to-fry recruitment, ranking of adult-to-fry interaction models differed from main-effect equivalents (see Appendix 1), but ΔWAIC values indicated little difference in fit between the two model types. R^2 values of main-effect models were all greater than their interaction equivalents (Table 7). Again, consistent with the general predictions from the egg-to-fry interaction model, the interaction adult-to-fry model indicated that increased pulse flows may be more effective at increasing juvenile productivity during years of higher adult escapement (Figure 14c). However, the model again also made illogical predictions of continually increasing recruitment at mean and max values of pulse flow days and yearly adult escapement that was associated with a high degree of uncertainty (Figure 14 b & c).

Table 7. 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 across all habitat types (combined mainstem and side-channels). Statistics from equivalent interaction models are shown in italicized parentheses. 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; R^2 is an estimate of the proportion of variance explained by each model. ΔWAIC is a measure of the change in fit between the main-effect and interaction models.

Model	**Coefficient estimate (γ)**	**Lower 95% CI**	**Upper 95% CI**	R^2	**DIC**	**ΔDIC *(ΔWAIC)***
Base Ricker (BR)	-	-	-	0.34 *(0.32)*	25.2 *(4.9)*	2.7 *(-0.01)*
BR + Discharge days >25< 80 m^3s^{-1}	0.32 *(0.08)*	-0.02 *(-0.56)*	0.671 *(0.73)*	0.40 *(0.39)*	22.6 *(26.9)*	0 *(1.03)*
BR + Incubation discharge max	-0.32 *(-0.77)*	-0.62 *(-1.33)*	0 *(-0.17)*	0.57 *(0.30)*	24.0 *(21.9)*	1.5 *(-1.51)*
BR + Incubation discharge mean	-0.32 *(-0.71)*	-0.62 *(-1.41)*	-0.03 *(-0.03)*	0.61 *(0.27)*	24.1 *(25.1)*	1.5 *(0.88)*
BR + Incubation discharge median	-0.31 *(-0.35)*	-0.60 *(-1.14)*	-0.01 *(0.44)*	0.63 *(0.46)*	24.5 *(30.6)*	2.0 *(2.5)*
BR + Spawning discharge variance	-0.26 *(-0.48)*	-0.60 *(-1.01)*	0.06 *(0.08)*	0.47 *(0.37)*	25.0 *(29.5)*	2.4 *(0.51)*

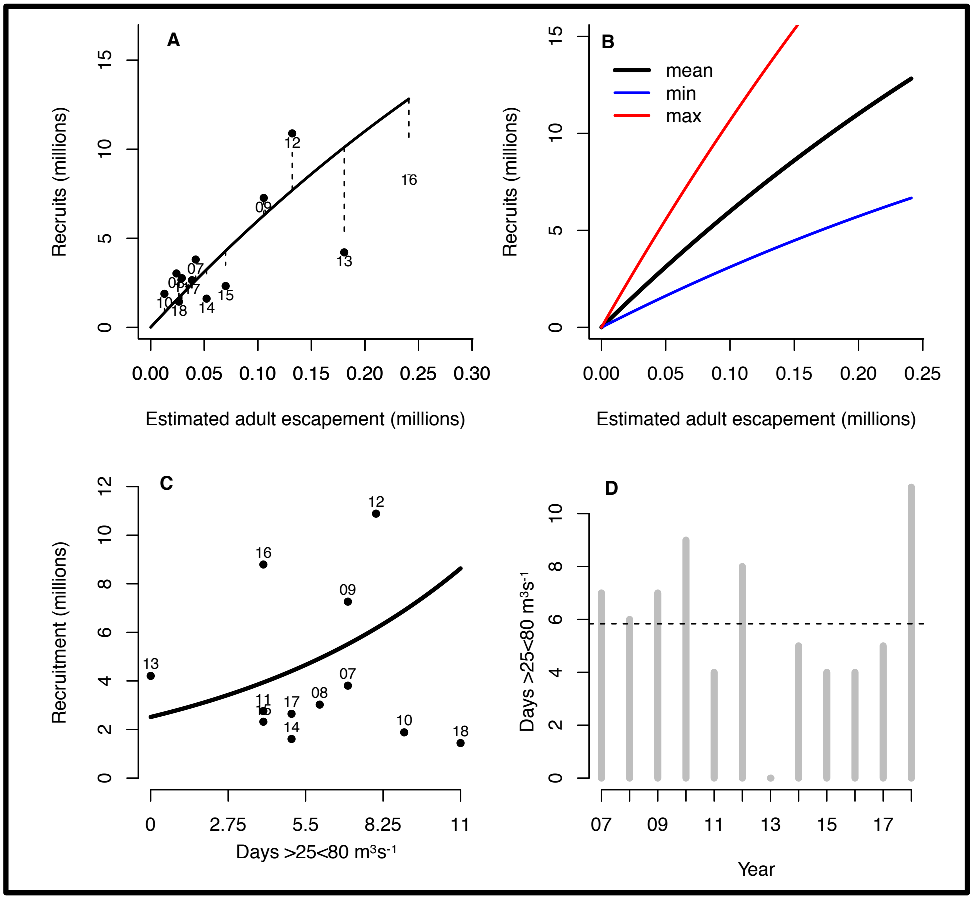

Figure 13. Stock-recruitment curve for the number of Chum Salmon fry produced per millions of adult spawners; individual points are data from each of the 12 years of monitoring (panel A). Estimated numbers of recruits per estimated spawner abundance at the mean, minimum, and maximum values of pulse flow days >25<80 m^3s^{-1} during the adult migration period (panel B). Estimated juvenile recruitment by pulse flow days >25<80 m^3s^{-1} over the 11 years of monitoring (panel C). Average number of days per year from 2007 – 2018 when discharge was >25<80 m^3s^{-1} (panel D).

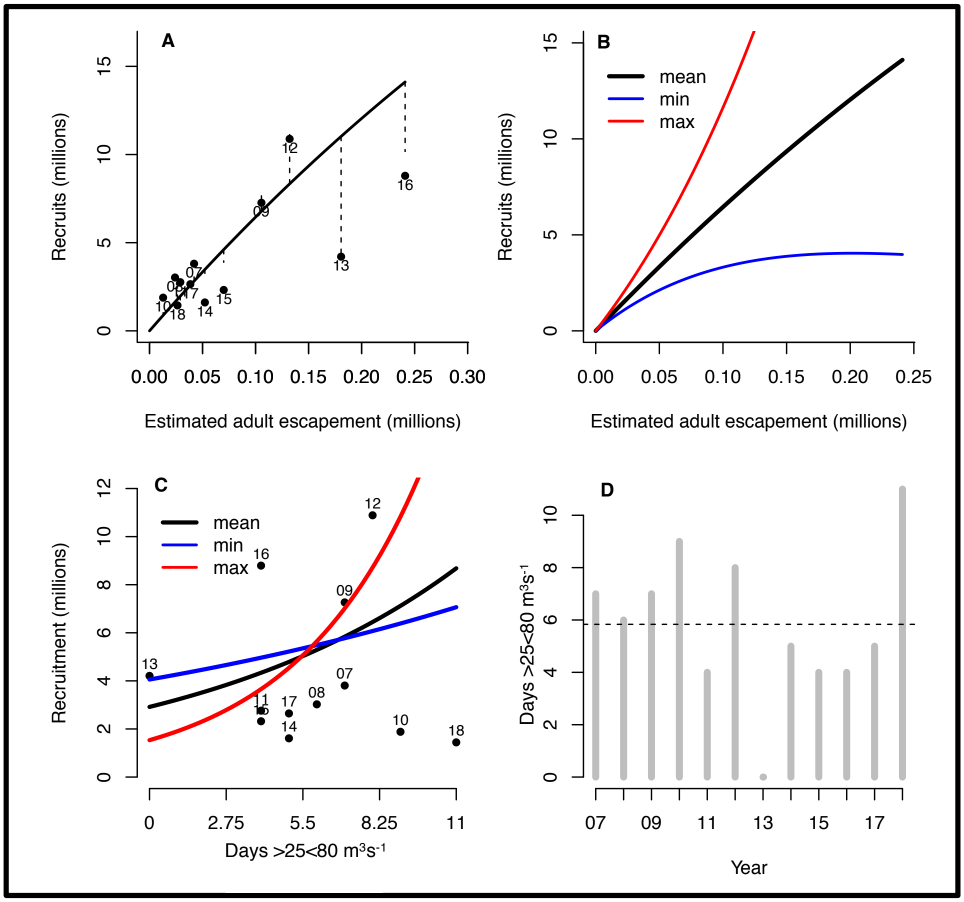

Figure 14. Stock-recruitment curve for the estimated number of Chum Salmon fry produced per estimated millions of adult spawners; individual points are data from each of the 12 years of monitoring (panel A). Interaction effect on the estimated number of recruits per estimated spawner abundance at the mean, minimum, and maximum values of pulse flow days >25<80 m^3s^{-1} as a function of adult abundance during the adult migration period (panel B). Interaction effect on the estimated juvenile recruitment by pulse flow days >25<80 m^3s^{-1} as a function of adult abundance over the 12 years of monitoring (panel C). Average number of days per year from 2007 – 2018 when discharge was >25<80 m^3s^{-1} (panel D).

4.0 DISCUSSION

Following recommendations put forth in a recent synthesis and annual report for CMSMON1b (Fell et al. 2018; Middleton et al. 2018), BC Hydro continued to implement experimental 'pulse flows' (discharge >25 and <80 m^3s^{-1}) during the 2018 Fall adult Chum Salmon migration. This was done to further assess the effects of the WUP discharge regime on groundwater upwelling, adult spawning site selection, and stock-recruitment relationships. The following discussion focuses on the effects of these pulse flows and their utility in addressing the uncertainties identified in Fell et al. (2018) and Middleton et al. (2018) and guiding management questions for CMSMON1b (BC Hydro 2007).

4.1 MQ1: What are the effects of discharge on adult distribution, spawning site selection, groundwater, and incubation conditions?

Despite more discharge variability from pulsed flows in the last two years and improved resolution in tracking of tagged fish, 2017 and 2018 models of detection probability above the Bailey Bridge for radio-tagged individuals do not support the hypothesis from the 10-year synthesis that Fall pulse flows may increase the probability of adults moving into these upper river habitats (Fell et al. 2018). In contrast, the 2018 models of maximum migration distance indicated that the distance adult Chum Salmon travelled upstream during spawning was reduced by increasing maximum discharge and by fewer days of pulse flow conditions. We also observed that 23 radio-tagged individuals returned to the Cheakamus – Squamish River confluence (RK 0.0) during flows that exceeded 150 m^3s^{-1}. Indeed, discharge variability is known to influence the behaviour, distribution, and spawning success of numerous species of salmonids, including Chum Salmon (Hunter 1959; Telzlaff et al. 2005; Taylor and Cooke 2012). It has also generally been concluded that high flows can decrease upstream migration success and that entry into spawning tributaries or shallow spawning areas requires optimal flows (Jonsson & Jonsson 2002; Jonsson et al. 2007). Our results suggest that increasingly high Fall discharges (>100 m^3s^{-1}) may inhibit migrants from reaching lower river spawning areas and that maintaining variable discharge within the 25-80 m^3s^{-1} pulse flow range may be used as a management tool for creating optimal migration conditions in the Cheakamus River for adult Chum Salmon.

Contrary to model predictions of maximum migration distance, we tracked 2 radio-tagged individuals and visually observed >20 unmarked adult Chum Salmon spawning in the low-velocity groundwater influenced side-channel habitats proximate to RK 14.6 (Road's End) following flow pulses in Fall 2018. Successful spawning was confirmed by the presence of Chum Salmon fry in these habitats during Spring 2019 stranding surveys (Jody Schick; personal communication, June 2019). Usage of this low-velocity groundwater-fed habitat is consistent with preferred conditions for Chum Salmon spawning throughout their range (Geist et al. 2002) and with observations that salmon can exhibit delayed behavioural reactions to flow changes and move into spawning habitats more than a day after a flow increase (Sparholt et al. 2018). Given the record low adult escapement/density in Fall 2018, we suspect that rather than the density-dependent relationship we hypothesized was responsible for movement into habitats above the Bailey Bridge (Fell et al. 2018), discharge pulses also likely play an additional role in regulating how adult Chum Salmon detect suitable spawning habitat in the upper river. Indeed, discharge likely affects the amount of groundwater present in the olfactory cues that adult salmon use to navigate to suitable spawning areas (Bett and Hinch 2015). Pulse flows may increase the amount of navigational cues signalling groundwater to adult Chum Salmon, thus encouraging movement into these upper river habitats. Unfortunately, the small sample of individuals detected in the upper river through radio-tracking and limited groundwater data across all years of monitoring means our ability to statistically detect any effects of pulse flows on fish behaviour as it is related to groundwater or discharge is limited (Fell et al. 2018; Middleton et al. 2018). Regardless, this is an important observation with respect to addressing Management Question 1 in that discharge is likely related to multiple nuanced behavioural aspects of adult Chum Salmon distribution and spawning site selection, and provides further support to the leading hypothesis that optimal discharge likely varies between 25 and 80 m^3s^{-1} during the fall migration period.

In 2018, Chum Salmon did not appear to increase entry into side channels with pulsed flows, as was detected during the Fall 2017 migration (Middleton et al. 2018). However, despite no statistically detectable effect, data patterns were similar to those of 2017 and indicated a trend of increased side-channel entry with pulse flows (Middleton et al. 2018, Figures 8 & 9). Indeed, there was a distinct peak of daily entries in 2018 that occurred in mid-November, approximately 2 days after an increase in mean daily discharge from 38 m^3s^{-1} to 160 m^3s^{-1}. This behaviour is also consistent with observations by Sparholt et al. (2018) that adult Atlantic Salmon (*Salmo salar*) enter into spawning tributaries of the River Dee in Scotland approximately 1 day after high flow events. A similar relationship may exist where side-channel entries increase following pulse flows in the Cheakamus River, though the reduced escapement estimate and proportion of adults utilizing side-channels in 2018 likely limits the ability of the models to detect such an effect. Mechanisms driving this behaviour could be that of adults responding to the elevated olfactory cues flushing from groundwater fed channels during flow pulses, or the opportunity for refuge during periods of elevated discharge. Such behavioural responses to environmental conditions that enhance the probability of entry into side channels could increase Chum Salmon productivity, as egg-to-fry survival is consistently higher in side-channels relative to the mainstem river (Fell et al. 2018).

The location of hyporheic exchange between groundwater and surface water is known to be an important driver of Chum Salmon spawning site selection (Leman 1993; Geist et al. 2002). We explored the presence of groundwater upwelling at spawning sites in previous years of monitoring, but data were inconsistent and often limited to only one year (Fell et al. 2018). Monitoring in 2017 found evidence of groundwater upwelling throughout the study site that varied substantially both within and between sites (Middleton et al. 2018). Although such variability is typical of upwelling characteristics in rivers (Malcom et al. 2004, Winter 1995), variability can also be attributed to uncertainty in the burial depth of loggers and their partial or complete displacement. This was particularly problematic at upstream sites proximate to Road's End (RK 15) where flow pulses often resulted in temperature loggers being displaced, making interpretation of results difficult. In 2018/2019 we improved deployment methods, which confirmed the presence of groundwater and corroborates previous monitoring results.

Evidence of groundwater upwelling in established spawning locations downstream of the Bailey Bridge (RK 7.5) was consistent among monitoring years and rejects H_2 that spawning Chum Salmon do not select areas of upwelling groundwater for spawning in the mainstem (Middleton et al. 2018). In 2018/2019, all monitoring suggested little to no evidence of upwelling within ~1km downstream of the bridge, where few Chum Salmon are ever observed spawning, and strong evidence at known spawning locations near the Cheakamus Centre spawning channels (RK 6.5) and Moody's Bar (RK 4.5). Further upstream in the middle reaches of the river (RK 8.0 – 13.0) there has continued to be no evidence of groundwater upwelling. In 2018/2019, improved monitoring techniques established that most upstream sites near Road's End (RK 15) do appear to show groundwater upwelling despite being characterized by weak or inconsistent groundwater evidence in previous years, potentially due to logger displacement. In all cases, monitoring sites with evidence of groundwater upwelling were associated with observations of spawning adult Chum Salmon and fry.

Continued redd temperature monitoring in 2018/2019 further supports rejecting H_3 (Middleton et al. 2018) that discharge during the Chum Salmon spawning and incubation period does not affect the upwelling of groundwater in mainstem spawning areas. Throughout all years of monitoring, we have observed that at sites with both strong and weak groundwater upwelling, short-duration pulses of discharge influenced redd temperature, but not river temperature. Indeed, variability in the effect of discharge pulses between sites highlights the heterogeneity of groundwater upwelling in the Cheakamus River mainstem and makes developing predictive models of discharge and redd temperature relationships very challenging. However, evidence and experience compiled over the years of monitoring does suggest that discharge pulses during the Fall migration make groundwater-influenced spawning sites near Road's End more readily available for Chum Salmon to opportunistically utilize after flow pulses. With respect to Management Question 1, discharge should be considered to be related to spawning site selection and incubation conditions and should be taken into account when developing flow regimes given the potential effects these relationships may have on overall Chum Salmon productivity.

4.2 MQ1: What is the relationship between WUP discharge and juvenile productivity?

Historically, the hypothesis for the Cheakamus River WUP flow regime was that discharge during the Chum Salmon spawning and incubation period did not affect productivity (BC Hydro 2007). However, the past two years of CMSMON1b have identified a positive relationship between the number of pulse flow days during the adult migration and juvenile productivity (Fell et al. 2018; Middleton et al. 2018). In 2018, BC Hydro continued to implement periods of experimental pulse flows during the Fall adult migration period (piloted in 2017) that were designed to add more contrast and variability to the WUP flow regime and further help answer Management Question 1 by generating more confidence in stock-recruitment model predictions.

Experimental manipulation of discharge resulted in a distinctly more variable hydrograph, with nearly two-times the days of Fall pulse flows – days with discharge between 25 and 80 m^3s^{-1} during adult migration – in 2018 relative to previous years. Yet despite this markedly more 'natural' Fall discharge regime, egg-to-fry and adult-to-fry stock-recruitment relationships were very similar to the previous 11-year mean. Nonetheless, both the egg-to-fry and adult-to-fry stock-recruitment models continued to support the hypothesis that more variability in flows during adult migration increases productivity. Consistent with the 2017 egg-to-fry model, the top-ranked model in 2018 included a positive effect of pulse flows during the peak adult migration period. These results suggest that pulse flows do positively affect egg-to-fry survival. This detection of a positive effect of pulse flows on productivity without a change to egg-to-fry and adult-to-fry stock-recruitment relationships across monitoring years could be explained by side-channel usage. Pulse flows during Fall migration appear to increase side-channel usage by adults, where egg-to-fry survival is known to be higher (Middleton et al. 2018). Therefore, increased spawning in side-channels could explain why Fall pulse flows may increase egg-to-fry survival.

The 2018 adult-to-fry stock-recruitment models further support the leading hypothesis that more variability in flows during the adult migration increases productivity. Consistent with previous analyses (Fell et al. 2018; Middleton et al. 2018), modeling suggests that more pulse flows during peak adult migration can increase adult-to-fry recruitment. Although increased side-channel usage by adults may lead to higher egg-to-fry survival and hence better juvenile recruitment (Middleton et al. 2018), greater variability in Fall discharge may also provide access to additional spawning habitat via groundwater effects as discussed previously. Indeed, we observed spawning adult Chum Salmon in upper river habitats near Road's End following pulse flows – habitat that is not usually available during standard WUP flows. Both mechanisms would reduce spawner densities in mainstem habitats, thereby reducing density-dependent mortality and increasing overall juvenile productivity.

In addition to positive effects of pulse flows, egg-to-fry and adult-to-fry analyses indicated that increased discharge during the Winter/Spring incubation period may negatively affect recruitment. Indeed, large discharge pulses or sustained periods of high flows could have many negative effects on incubating gametes. For example, increased discharge can affect redd temperatures and the development of eggs or alevin by increasing scour and egg removal from redds, or the time required for gametes to reach adequate accumulated thermal units necessary for emergence (Casas-Mulet et al. 2014).

We also fit both egg-to-fry and adult-to-fry stock-recruitment models with an interaction to explore whether juvenile productivity was related to different combinations of yearly adult escapement and pulse flows. Overall confidence and accuracy in the results from these models would be improved by the addition of more data (i.e. a greater sample size); however, general predictions from both indicated that greater pulse flow days during the fall migration may have a greater effect on juvenile productivity during years of higher adult abundance – we suspect multiple mechanisms contribute to this effect. For example, more pulse flows during Fall likely increases the availability of groundwater cues Chum Salmon use to navigate to suitable spawning habitat during their migration. This could in turn lead to individuals utilizing more of the available groundwater influenced spawning habitat in the upper river during such periods. During years of high adult escapement, density dependent effects would also drive adults to seek out additional available spawning habitat – likely in upper river reaches where pulse flows may contribute to increased spawning habitat availability. Following adult spawning, negative density effects on incubating and rearing juveniles would also be reduced because of more available habitat, thus overall productivity could be increased. Of course this interaction needs to be tested with a more complete dataset to make these predictions more robust and accurate, but overall the results continue to support that discharge is indeed related to productivity, and that regulating flows during adult migration and juvenile incubation could be used as a management tool to increase productivity, particularly in years of high adult escapement.

A key component of addressing Management Question 1 was determining what effects the WUP discharge regime has on Chum Salmon productivity, and ongoing stock-recruitment analyses based on the past 12 years of monitoring for CMSMON1b have provided a substantial amount of insight into this question. Indeed, results from all modelling exercise clearly suggest that maintaining a more variable discharge regime – one that emulates more natural flow patterns – during the fall migration period could potentially be used as a management tool to increase Chum Salmon productivity in the Cheakamus River. However, we caution that because Chum Salmon are a long-lived species with highly variable abundances, inferences drawn from stock-recruitment relationships with relatively small sample sizes (i.e. years of monitoring), could be biased or inaccurate (Korman and Higgins 1997; Babcock et al. 2010; Fell et al. 2018). For instance, experimental pulse flows in Fall 2018 produced more variable discharge conditions above base WUP flows relative to any other previous year of monitoring. However, adult escapement and juvenile productivity in 2018/2019 were the lowest since the monitor began; as a result, stock recruitment models including this year’s data were reduced in their fit and confidence in their predictions relative to previous years.

Keeping in mind the caveats of the main- and interaction-effect stock-recruitment analyses described above, we recommend a precautionary approach to any management decision made based on their results. Accurate stock-recruitment relationships are currently the best tool for understanding whether annual fluctuations in productivity are related to adult escapement or characteristics of the WUP discharge regime (i.e., Fall discharge pulses) (Bradford et al. 2005), and only continued monitoring of adult and juvenile Chum Salmon escapement and recruitment in the Cheakamus River will improve the robustness of these models; this will ensure that management decisions are made considering the most complete information possible.

Moreover, it would be remiss to attribute the predicted increases in productivity solely to the effects of discharge; 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. Despite not accounting for these factors, the effects of discharge in the above analyses have been identified as predictors of juvenile abundance and salmonid productivity and are biologically related to mechanisms known to affect different salmonid life-history stages (Arthaud et al. 2010; Zeug et al. 2014; Rebenack et al. 2015; Zimmerman et al. 2015).

5.0 CONCLUSION

A great deal of work has gone into the past 12 years of monitoring for CMSMON1b and many aspects of the Management Questions and hypotheses described in the Terms of Reference (BC Hydro 2007) have been addressed (see Fell et al. 2018). In an effort to reduce uncertainties that still remained with respect to the effects of the WUP discharge regime on adult distribution, groundwater-influenced incubation conditions, and stock-recruitment, BC Hydro continued monitoring in 2018. This monitoring was highlighted by the continuation of experimental pulse flows during the Fall migration to bolster stock-recruitment analyses, improved groundwater monitoring, and refined tracking of migrating adults – all designed to increase confidence in conclusions made regarding the guiding management questions and hypotheses of this monitor.

Results from 2018 reinforce that the habitat downstream of the Bailey Bridge (RK 7.0) is critical to Chum Salmon productivity, particularly the artificial side-channels and spawning sites with dominant groundwater inflows. Discharge pulses also likely increase side-channel usage by adults and thus may increase productivity as these habitats are characterized by higher egg-to-fry survival. We also made multiple observations of adult Chum Salmon spawning in groundwater influenced habitat near Road's End (RK 15.0) following pulse flows in 2018 suggesting that variation in Fall discharge may also provide access to additional spawning habitat in the upper river, irrespective of density driven spawning behaviour below the Bailey Bridge.

Groundwater inflows are an important component of effective Chum Salmon spawning habitat. In past monitors, groundwater data were often scarce or incomplete, and the groundwater relationship with discharge was inconclusive. In 2018 we improved monitoring to address this uncertainty and continued to observe groundwater in heavily utilized spawning sites below the Bailey Bridge; we also confirmed evidence of groundwater in Chum Salmon spawning sites near Road's End. Upwelling was highly variable between sites and there was a high degree of heterogeneity in the amount of groundwater both within and between known and potential spawning habitats. However, there was still evidence of a relationship whereby discharge pulses affect groundwater presence at these sites, which likely has an effect on Chum Salmon spawning site selection.

Results from egg-to-fry and adult-to-fry stock-recruitment modelling in 2018 continue to support the leading hypothesis that Fall discharge variability has a positive effect on recruitment. In addition, general predictions from interaction models suggest pulse flows may have a greater effect on juvenile productivity in years of high escapement. Though caution needs to be taken with this interpretation given the limited sample size of interaction models, this relationship makes sense biologically as density dependent effects in years of high escapement may drive adults into additional spawning habitats following increased periods of fall pulse flows, which would in turn reduce density driven juvenile mortality and thereby improve productivity. Together, model predictions highlight how maintaining a variable Cheakamus River hydrograph above the current WUP base flows may be used as a potential management tool to increase Chum Salmon productivity. However, relatively low sample sizes and changes in the magnitude of pulse flow effects and fit of stock-recruitment relationships form year to year highlight how variable these model predictions can be.

In the coming years, only continued baseline monitoring of adult and juvenile Chum Salmon escapement would improve the stock-recruitment relationships established for CMSMON1b. However, it would also be beneficial to consider developing additional study components that measure productivity, and/or a statistical power analysis to help guide the scope of future stock-recruitment monitoring. Additionally, upcoming 'performance measure' exercises will help evaluate how productivity in the Cheakamus River may vary using future projected BC Hydro discharge data fit to the current stock-recruitment relationships.

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7.0 APPENDIX 1

Table 8. Index of discharge covariates used in egg-to-fry and adult-to-fry stock-recruitment analyses calculated for distinct adult migration and juvenile incubation time periods.

Covariate number	Discharge covariate	Time Period
1	Spawning season minimum discharge	Entire Spawning Season: October 15 - December 15
2	Spawning season maximum discharge	Entire Spawning Season: October 15 - December 15
3	Spawning season median discharge	Entire Spawning Season: October 15 - December 15
4	Spawning season average discharge	Entire Spawning Season: October 15 - December 15
5	Spawning season discharge std. dev.	Entire Spawning Season: October 15 - December 15
6	Spawning season discharge variance	Entire Spawning Season: October 15 - December 15
7	Upstream migration minimum discharge	Upstream Migration: October 15 - November 7
8	Upstream migration maximum discharge	Upstream Migration: October 15 - November 7
9	Upstream migration median discharge	Upstream Migration: October 15 - November 7
10	Upstream migration average discharge	Upstream Migration: October 15 - November 7
11	Upstream migration discharge std. dev.	Upstream Migration: October 15 - November 7
12	Upstream migration discharge variance	Upstream Migration: October 15 - November 7
13	Peak spawning minimum discharge	Peak Spawning: November 1-15
14	Peak spawning maximum discharge	Peak Spawning: November 1-15
15	Peak spawning median discharge	Peak Spawning: November 1-15
16	Peak spawning average discharge	Peak Spawning: November 1-15
17	Peak spawning discharge std. dev	Peak Spawning: November 1-15
18	Peak spawning discharge variance	Peak Spawning: November 1-15
19	Incubation period minimum discharge	Incubation period: December 1 - March 31
20	Incubation period maximum discharge	Incubation period: December 1 - March 31
21	Incubation period median discharge	Incubation period: December 1 - March 31
22	Incubation period average discharge	Incubation period: December 1 - March 31
23	Incubation period discharge std. dev.	Incubation period: December 1 - March 31

24	Incubation period discharge variance	Incubation period: December 1 - March 31
25	Peak migration discharge days >25<80 m^3s^{-1}	Peak Upstream Migration: October 25 - November 7

All tables presented hereafter are of DIC model ranking statistics and coefficient estimates for Ricker models with covariate effects of different discharge metrics on Chum Salmon egg-to-fry and adult-to-fry recruitment (specified) in the Cheakamus River across different habitat types (combined mainstem and side-channels, or individual 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. Each covariate index number corresponds with a different discharge metric presented in Table 1.

Egg-to-fry recruitment models

Table 9. Main effects of discharge on Chum Salmon egg-to-fry recruitment across *all habitat types* (combined mainstem and side-channels). ΔWAIC is a measure of the change in fit between the main-effect model and interaction model (table below) of the corresponding covariate.

Covariate index (Base Ricker +)	Coefficient estimate (γ)	Lower 95% CI	Upper 95% CI	*prob.* γ > 0	R^2	DIC	ΔDIC	Model Rank	ΔWAIC
Base Ricker	-	-	-	-	0.32	25.39	0.37	3	0.00
25	0.26	-0.12	0.65	92.0	0.34	25.02	0.00	1	1.03
20	-0.30	-0.63	0.03	3.1	0.52	25.24	0.22	2	-1.51
22	-0.30	-0.62	0.03	3.3	0.52	25.75	0.74	4	0.88
4	-0.19	-0.58	0.17	13.6	0.35	26.19	1.18	5	-0.13
9	-0.21	-0.58	0.17	12.1	0.28	26.32	1.30	6	0.59
23	-0.28	-0.61	0.07	5.1	0.49	26.47	1.46	7	-2.84
6	-0.24	-0.60	0.12	8.0	0.42	26.50	1.48	8	0.52
18	-0.19	-0.59	0.20	15.8	0.28	27.03	2.01	9	0.04
12	-0.20	-0.57	0.17	11.9	0.38	27.06	2.04	10	1.17
10	-0.19	-0.59	0.21	15.3	0.28	27.25	2.23	11	0.31
24	-0.25	-0.60	0.12	7.9	0.49	27.26	2.24	12	-1.22
14	-0.15	-0.56	0.25	22.3	0.25	27.42	2.40	13	-0.65
5	-0.21	-0.57	0.15	10.6	0.38	27.44	2.42	14	-2.55
15	-0.10	-0.55	0.34	31.1	0.24	27.47	2.45	15	0.55
21	-0.28	-0.61	0.08	5.3	0.53	27.57	2.55	16	2.50
19	-0.14	-0.54	0.25	21.5	0.27	27.69	2.67	17	2.87
2	-0.22	-0.59	0.16	11.0	0.34	27.72	2.70	18	-3.45
16	-0.09	-0.50	0.34	33.3	0.24	27.75	2.73	19	2.21
17	-0.12	-0.51	0.28	26.8	0.27	27.81	2.80	20	0.39
3	-0.11	-0.53	0.34	29.0	0.24	27.88	2.86	21	0.08

11	-0.14	-0.53	0.24	21.0	0.31	27.95	2.93	22	-0.01
8	-0.13	-0.51	0.24	23.1	0.30	28.19	3.18	23	0.68
13	0.09	-0.37	0.54	67.0	0.38	28.37	3.35	24	2.63
7	-0.01	-0.44	0.44	48.6	0.31	28.41	3.40	25	4.02
1	0.15	-0.25	0.55	79.2	0.43	28.74	3.73	26	-0.20

Table 10. Interaction effects of discharge and yearly adult escapement on Chum Salmon egg-to-fry recruitment across *all habitat types* (combined mainstem and side-channels).

Covariate index (Base Ricker +)	Coefficient estimate (γ)	Lower 95% CI	Upper 95% CI	*prob.* γ > 0	R^2	DIC	ΔDIC	Model Rank
Base Ricker	-	-	-	-	0.32	25.76	4.87	5
23	-0.83	-1.40	-0.22	0.6	0.23	20.89	0.00	1
20	-0.77	-1.33	-0.17	0.9	0.29	21.93	1.04	2
24	-0.76	-1.47	0.14	4.2	0.19	23.10	2.21	3
22	-0.71	-1.42	-0.03	2.2	0.27	25.11	4.22	4
25	0.08	-0.56	0.73	59.7	0.39	26.87	5.98	6
1	0.46	-0.18	1.10	93	0.08	27.64	6.75	7
5	-0.50	-0.99	0.06	3.3	0.33	29.19	8.30	8
6	-0.48	-1.01	0.08	4.3	0.37	29.49	8.59	9
14	-0.45	-1.19	0.32	10	0.19	30.05	9.15	10
9	-0.44	-1.02	0.14	7	0.29	30.15	9.26	11
12	-0.46	-1.09	0.26	7.8	0.27	30.45	9.56	12
13	0.51	-0.70	1.74	81.5	0.00	30.54	9.65	13
21	-0.35	-1.14	0.44	17.4	0.46	30.56	9.66	14
8	-0.41	-1.01	0.20	7.6	0.16	30.66	9.77	15
3	-0.62	-1.62	0.36	9.3	0.13	30.85	9.95	16
4	-0.47	-1.01	0.08	4.8	0.28	30.93	10.04	17

2	-0.56	-1.06	-0.01	2.4	0.30	31.02	10.13	18
19	-0.17	-0.90	0.60	29.5	0.23	31.04	10.15	19
11	-0.39	-0.96	0.20	7.9	0.24	31.43	10.53	20
18	-0.40	-1.01	0.24	9.2	0.27	31.62	10.73	21
16	-0.42	-1.73	0.85	24	0.09	31.64	10.75	22
10	-0.38	-0.97	0.26	9.2	0.28	31.80	10.90	23
15	-0.91	-2.58	0.68	11.6	0.11	31.87	10.98	24
17	-0.35	-0.99	0.32	12.7	0.20	33.18	12.29	25
7	-0.08	-1.38	1.00	45.6	0.23	45.17	24.28	26

Adult-to-fry recruitment

Table 6. Main effects of discharge on Chum Salmon adult-to-fry recruitment across *all habitat types* (combined mainstem and side-channels). ΔWAIC is a measure of the change in fit between the main-effect model and interaction model (table below) of the corresponding covariate.

Covariate index (Base Ricker +)	Coefficient estimate (γ)	Lower 95% CI	Upper 95% CI	*prob.* γ > 0	R^2	DIC	ΔDIC	Model Rank	ΔWAIC
Base Ricker	-	-	-	-	0.34	25.24	2.69	7	-0.06
25	0.32	-0.02	0.67	96.7	0.40	22.55	0.00	1	0.39
20	-0.32	-0.62	0.00	2.5	0.57	24.05	1.50	2	-2.01
22	-0.32	-0.62	-0.03	1.8	0.61	24.08	1.53	3	-0.62
21	-0.31	-0.60	-0.01	2.3	0.63	24.55	2.00	4	2.07
6	-0.26	-0.60	0.06	5.1	0.47	24.98	2.43	5	-0.07
23	-0.30	-0.61	0.02	3	0.56	25.14	2.59	6	-5.27
9	-0.23	-0.60	0.14	9.8	0.31	25.35	2.80	8	-0.84
10	-0.21	-0.57	0.15	12.6	0.33	25.59	3.04	9	-0.45
18	-0.22	-0.62	0.17	11.6	0.26	25.75	3.20	10	-0.44
2	-0.22	-0.58	0.11	8.9	0.39	25.90	3.35	11	-5.95
12	-0.24	-0.59	0.10	7.9	0.43	25.90	3.35	12	0.38
24	-0.28	-0.59	0.05	4.8	0.56	26.19	3.64	13	-2.61
4	-0.20	-0.58	0.16	11.7	0.36	26.25	3.70	14	-1.71
14	-0.15	-0.55	0.23	19.4	0.25	26.26	3.71	15	-0.74
11	-0.18	-0.53	0.18	14.4	0.35	26.28	3.73	16	-0.58
15	-0.13	-0.55	0.29	24.4	0.23	26.33	3.77	17	-0.42
5	-0.22	-0.57	0.15	9.7	0.43	26.36	3.81	18	-3.52
17	-0.13	-0.52	0.23	24	0.29	26.62	4.07	19	-0.15
3	-0.12	-0.53	0.30	28.9	0.25	26.75	4.19	20	-0.29
8	-0.16	-0.52	0.20	18.6	0.34	26.84	4.29	21	-0.58

19	-0.14	-0.53	0.23	20.3	0.30	26.84	4.29	22	2.44
16	-0.11	-0.55	0.30	28.9	0.24	26.98	4.43	23	0.51
7	0.02	-0.41	0.42	54	0.36	27.40	4.85	24	2.23
13	0.04	-0.40	0.46	57.8	0.38	28.40	5.85	25	1.76
1	0.17	-0.24	0.54	81.4	0.48	28.50	5.95	26	-0.54

Table 7. Interaction effects of discharge and yearly adult escapement on Chum Salmon adult-to-fry recruitment across *all habitat types* (combined mainstem and side-channels).

Covariate index (Base Ricker +)	**Coefficient estimate (γ)**	**Lower 95% CI**	**Upper 95% CI**	***prob.* γ > 0**	R^2	**DIC**	**ΔDIC**	**Model Rank**
Base Ricker	-	-	-	-	0.34	25.01	8.57	6
23	-0.87	-1.33	-0.28	0.4	0.28	16.44	0.00	1
20	-0.74	-1.26	-0.15	0.9	0.36	19.41	2.97	2
24	-0.75	-1.32	0.08	3.1	0.27	19.85	3.40	3
22	-0.73	-1.33	-0.10	1.3	0.36	20.66	4.22	4
25	0.12	-0.43	0.69	66.5	0.44	23.61	7.16	5
1	0.46	-0.11	1.02	94.9	0.07	25.42	8.98	7
2	-0.59	-1.02	-0.12	1	0.36	26.84	10.40	8
21	-0.36	-1.07	0.27	14	0.59	27.21	10.77	9
9	-0.45	-1.02	0.12	5.5	0.33	27.66	11.22	10
15	-0.87	-2.20	0.58	9.8	0.14	27.97	11.53	11
5	-0.52	-0.97	-0.05	1.8	0.37	28.45	12.01	12
12	-0.47	-1.07	0.17	6.3	0.35	28.59	12.14	13
6	-0.49	-0.99	0.04	3.2	0.42	29.17	12.73	14
19	-0.16	-0.81	0.46	30.1	0.25	29.22	12.78	15
13	0.32	-0.79	1.42	72.8	0.03	29.44	12.99	16
3	-0.53	-1.45	0.42	12.6	0.16	29.53	13.08	17

8	-0.43	-0.96	0.16	6.1	0.25	29.83	13.39	18
4	-0.46	-0.95	0.08	4.3	0.32	30.03	13.59	19
11	-0.41	-0.95	0.13	6.2	0.29	30.06	13.62	20
10	-0.42	-0.93	0.16	6.7	0.32	30.15	13.70	21
16	-0.49	-1.55	0.60	16.5	0.16	30.20	13.76	22
17	-0.34	-0.91	0.25	11.6	0.25	30.23	13.78	23
14	-0.44	-1.13	0.28	9.6	0.23	30.24	13.80	24
18	-0.43	-0.96	0.15	6.2	0.32	30.37	13.93	25
7	-0.01	-0.94	0.86	48.2	0.34	31.00	14.56	26