Groundwater-surface water interactions in a constructed side channel complex

by

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Abstract

Constructed groundwater-fed side channels are a common restoration tool used in the Pacific Northwest to mitigate loss of floodplain features important for salmon spawning and rearing. The former floodplain of the Mamquam River, in Squamish, British Columbia, has a series of groundwater-fed side channels that consistently lose surface flow during the dry season, stranding juvenile coho salmon (*Oncorhynchus kisutch*). This study characterizes temporal and spatial patterns of streamflow in a side channel relative to mainstem streamflow, shallow groundwater levels, and local water use through synoptic flow measurements, water quality tracers, and a relative elevation transect. The construction and subsequent removal of a beaver dam enables a natural experiment, establishing a hydraulic connection between the side channels and a nearby water rights holder. Results suggest that the side channels become a local surface water sink and are susceptible to water withdraw under certain conditions during the dry season.

Keywords: Side channel; Groundwater-surface water interactions; Streamflow; Coho salmon; Hydraulic connectivity, Side channel

Dedication

This body of work is dedicated to my parents, Maria Power and Robert Harvey, for their unwavering confidence and support in everything that I do.

I also dedicate this work to the salmon who provided me purpose and inspiration throughout my journey.

Acknowledgements

First, a big thank you to Shawn Chartrand for your thoughtful and kind mentorship throughout this process. Thank you, Craig Orr for your support and expertise in project planning and writing. Thank you, Chessy Knight and Edith Tobe at the Squamish River Watershed Society, for allowing me to pursue this project, providing local knowledge and connections, and supporting my Mitacs Accelerate Program application. Thank you, Braydon Foster for your survey expertise. Thank you, Ryan Pierce, for your assistance in the field and continual moral support throughout this process. Thank you, Zachary Deziel, for your technological support in mapping, GIS, and coding. Thank you to the facilitators of the SFU thesis writing group for providing me with writing tools and reminding me to take ownership over my work. And last but not least, thank you to the beaver for keeping me on my toes.

Land Acknowledgement

I respectfully acknowledge that this study was conducted on the traditional and unceded territories of the Sḵwx̱wú7mesh (Squamish) Nation who have been stewards of the Mamquam River watershed and beyond for time immemorial. I am grateful for their consent and support throughout this process and sincerely hope that the findings of this study benefit the Sḵwx̱wú7mesh people and non-human residents of this land.

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List of Acronyms

BC	British Columbia
BCIT	British Columbia Institute of Technology
DEM	Digital Elevation Model
DFO	Department of Fisheries and Oceans Canada
DO	Dissolved Oxygen
FOI	Freedom of Information
GWSI	Groundwater-surface water interactions
LMR	Lower Mamquam River
PNW	Pacific Northwest
REM	Relative Elevation Model
SFU	Simon Fraser University
SPC	Specific Conductance
SVGC	Squamish Valley Golf Club
WSC	Water Survey of Canada

The Mamquam side channel complex at the confluence of the Lower Mamquam River mainstem (SC-07). Photo taken by Erica Harvey on November 5, 2022.

1. Introduction

Gravel bed river ecosystems along the Pacific Northwest (PNW) coast are seasonally vulnerable to the effects of local water use due to the hydroclimatology and ecology of the region (Clark 2010; Abatzoglou et al. 2014). The PNW hydroclimatology includes a spring freshet, followed by a summertime dry season, and fall rain (Wu et al. 2012). Climate change is intensifying PNW dry season characteristics with warming air temperatures and earlier snowmelt causing earlier spring runoff, lower summer streamflow, and higher water temperatures (Stewart et al. 2005; Clark 2010; Wu et al. 2012; Foster and Allen 2015). Water demand is also elevated during the dry season which can further reduce streamflow (Abatzoglou et al. 2014; Baalousha 2016). Several life stages of anadromous fish rely on side-, off-channel, and floodplain habitats along gravel bed river corridors in the PNW (Hauer et al. 2016). These features offer refugia for juvenile fish, and spawning adults by providing moderate temperatures and low flows year-round (Sheng et al. 1990). Surface flows in these features rely on interactions with groundwater and streamflow, where lower summer streamflow and elevated water demand can reduce surface flow in side channel features, thus reducing the functionality of these channels for anadromous fish (Clark 2010; Baalousha 2016). Understanding local groundwater conditions in relation to the functionality of available side-, off-channel, and floodplain habitats is important for managing water resources and protecting anadromous fish populations in the PNW.

Groundwater and surface water are dynamic elements of the same hydrologic system, where understanding their interactions and the impact of water use on those interactions is integral to the management and function of riverine ecosystems (Sophocleous 2002; Hauer et al. 2016). Water use for anthropogenic activities can interrupt natural groundwater-surface water interactions (GWSI) by changing, for example, the hydraulic gradient between neighbouring surface water bodies that are groundwater-fed. The hydraulic gradient is a primary characteristic that determines whether a stream or pond is gaining water through groundwater discharge or losing water to groundwater recharge (Sophocleous 2002; Baalousha 2016). In a system that is seasonally water limited, nearby water use may cause a stream to change from gaining to losing, resulting in reduced or eliminated surface flow, and ultimately reduce the functionality of important ecosystem attributes such as side-, off-channel, and floodplain features.

The former floodplain of the Mamquam River in Squamish, British Columbia (BC) has a series of groundwater-fed side channels constructed by the Department of Fisheries and Oceans Canada (DFO) as part of a chum (*Onchorhynchus keta*) and coho salmon (*Oncorhynchus kisutch*) enhancement project in 1983 (Foy et al. 1996; Foy et al. 1999). The Lower Mamquam River (LMR) was dyked along its north and south banks in 1922 following a flood event in 1921 (Table 1; SRWS 2008; KWL 2017). The dyke along the north bank was expanded and improved in the 1980s following another flood event where the LMR overtopped its banks (Table 1; Banbury 1994; Foy et al. 1996). In conjunction with dyke improvements, the Mamquam side channel complex was constructed to mitigate the loss of natural floodplain features (Table 1; Banbury 1994; Foy et al. 1996). Despite modifications in 1996 and later to make the side channels more resilient to flood and drought events, large sections of the side channel complex consistently lose surface flow during the dry season (Table 1; Foy et al. 1996; Thuncher 2021; P. Comm. Knight 2022). Population estimates between 1983-1996 reveal that the side channels are highly productive juvenile coho rearing sites (Foy et al. 1996; Foy et al. 1999). Coho reside in side channels for a full year before migrating to the ocean (DFO 2019). This life history strategy makes coho susceptible to seasonal drying events, as they become stranded in the isolated and diminished pools remaining of side channels in the summer (Sheng 1990; Thuncher 2021; Knight 2022). Despite efforts by community stewardship groups to salvage stranded juvenile coho from dry channel segments, seasonal stranding of coho in the side channels is likely impacting the distribution and rearing success of juvenile coho within the side channel complex (Manson 2022).

Water use in the Mamquam River watershed may be altering GWSI in the mainstem and side channels, therefore exacerbating seasonal reductions in surface flow. Surface water licenses and groundwater wells upstream and next to the side channels permit diversion of surface water and groundwater from the LMR and associated unconfined shallow aquifer, respectively (Table 1; Fig. 1). Coast Aggregates, a construction and landscape aggregate supplier with three groundwater wells that are uncorrelated with the shallow alluvial aquifer, is just upstream and east of the side channels (Gov BC 2019). An uncorrelated well is defined by the Government of British

Columbia as a well that falls within an aquifer polygon, but it is unconfirmed whether the well was completed in the aquifer, within an aquitard, or within another aquifer at a different depth. The Squamish Valley Golf Club (SVGC) is immediately north of the side channels (approximately 20 m) and is permitted to use up to 110 acre-feet/annum or 135,593 m^3/year from its irrigation pond between April 1 and September 30 (Gov BC 1985; Fig. 1). The irrigation pond passively fills, presumably by the same shallow alluvial aquifer that fills the side channels, and the invert elevation is estimated to be close to or lower than the invert elevations of the side channels. The water in the irrigation pond then flows into a wet well via an intake where the water is pumped throughout a sprinkler system. The water license was first issued in 1968 and renewed in 1983 following the construction of the side channels and dyke improvement (Table 1; Sheng 1990; Gov BC 2019). There are two flow-controlled intakes south and west of the side channels with surface water licences each permitted to divert 0.57 m^3/sec for other off- and side-channel restoration projects (DFO 2011; Gov BC 2019). Several other wells are located within the aquifer, 3 are correlated and 4 are uncorrelated (Gov BC 2019). Given the location, relative magnitude of use, and project constraints, this study assesses the potential impact of irrigation by the SVGC on surface flow persistence and continuity in the Mamquam side channel complex.

Table 1 A brief history of relevant natural events, construction works, and restoration activities in and near the side channels.

Year	Activity or Event	Description	Source
1921	Flood	High flows in the Mamquam and Squamish Rivers flooded the valley floor in October 1921. The Mamquam River travelled across the alluvial fan to its current course, abandoning the Mamquam River Blind Channel	SRWS (2008); KWL (2017)
1922	Dyke construction	The Lower Mamquam River was dyked along its north and south banks.	SRWS (2008); KWL (2017)
1968	Surface water license	SVGC was authorized to divert and use 125 acre ft/annum from the Mamquam River. Authorized construction of pond, pump, pipe, and sprinkler system	Gov BC (1969)
1980	Flood	Rain event on January 1, 1980 caused the Mamquam River to overtop the dyke along the north bank of the river.	Banbury (1994); Foy et al. (1996)
1982-1986	Gravel Removal	Removal of 573,500 m^3 of gravel from the Lower Mamquam River	KWL (2011)
1983	Surface water license	SVGC water license renewed. Authorized to divert and use 110 acre ft/annum from the Mamquam River. Authorized construction of sump, pond, pump, and sprinkler system	Gov BC (1985)
1983	Mamquam channel habitat improvement	Completion of Mamquam River groundwater-fed side channels. Project provided 2100 m^2 of spawning gravel and 6700 m^2 of rearing habitat. Estimated to produce 500,000 chum fry, 3,350 coho smolts, and 300	Banbury (1994); Foy et al. (1996)

Year	Activity or Event	Description	Source
	project & Dyke upgrade	trout smolts annually. Excavation of channels used as a gravel source for dike upgrading following 1980 flood event. Dyke was extended ~1.6 km and raised by ~3.6 m	
1996	Mamquam side channels improvements	Initial channels were found vulnerable to flood and drought thus project was to extend and stabilize side channels constructed in 1983.	Foy et al. (1996)

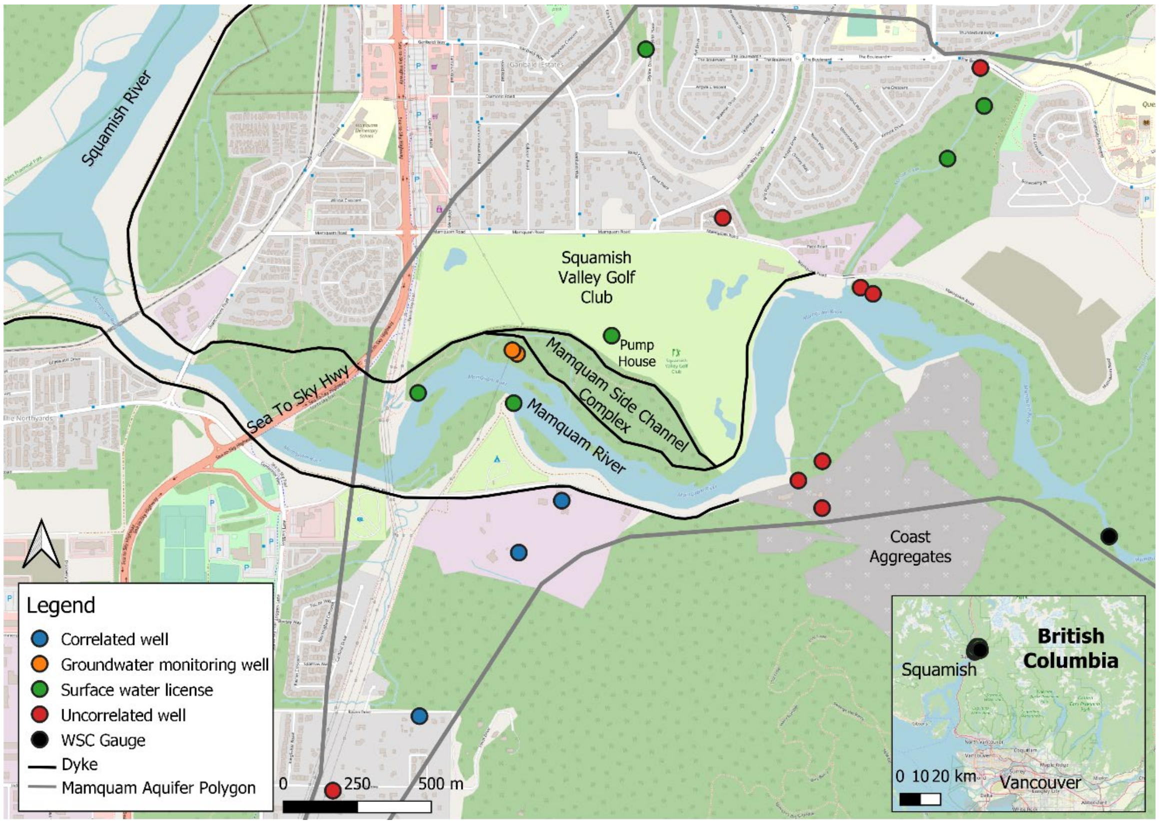

Figure 1 **The location of relevant land uses (Coast Aggregates and Squamish Valley Golf Club), flood protection dykes (black lines), surface water licenses (green circles), wells (correlated = blue circles, uncorrelated = red circles; groundwater monitoring wells = orange circles; Gov BC 2019), and water survey of Canada (WSC) hydrometric gauge (black circle) in relation to the Mamquam side channel complex and within the Mamquam Aquifer polygon (grey line) in Squamish, British Columbia (BC). Inset map (bottom right) shows the location of the study site within Lower Mainland BC.**

This study characterizes GWSI within the Mamquam side channel complex and examines whether operation of the SVGC irrigation pond is reducing or eliminating surface flow in the side channels. The Mamquam side channel complex provides an opportunity to observe and characterize the seasonal dewatering of a constructed groundwater-fed side channel in the context of a changing climate and elevated water demand. Research questions include: (1) What is the spatial and temporal distribution of streamflow in the side channels during the dry season? (2) Do the side channels become a local surface water sink during the dry season? (3) How do surface flow conditions in the side channels compare to the LMR and local shallow groundwater levels throughout the dry season? These questions are investigated with synoptic flow measurements, passive water quality tracers, and a relative elevation survey while using a water budget approach as a guiding principle. In the context of this study, the water budget refers to changing storage conditions in the side channels, the irrigation pond, and shallow alluvial aquifer. Information gathered from this study may be used to better understand impacts to fish habitat due to local water withdraws associated with existing water rights. Findings will also inform management decisions for the Mamquam side channel complex and other off-channel features to increase the resiliency and functionality of these features for juvenile coho salmon.

2. Goals and objectives

Goal 1: Collaborate with rights holders through a consensual and reciprocal exchange of knowledge, services, and in-kind support.

> Objective 1.1: Provide an employment opportunity as a field research assistant in summer 2022 for a member of the Squamish Nation. This opportunity aimes to enrich the research assistant with technical skills they can provide their community. This also provides a valuable learning experience for the student in First Nations engagement protocols.

> Objective 1.2: Involve rights holders in the discussion of results and how the findings of the study inform management decisions, future restoration works, and monitoring.

Goal 2: Characterize the flow relationships between the side channels, the SVGC irrigation pond, and the shallow alluvial aquifer throughout the dry season.

> Objective 2.1: Determine the net flow and directionality (i.e. into or out of the side channels) of surface water within the side channels by measuring water temperature, specific conductance, and streamflow discharge twice a week from the end of freshet to the beginning of fall rains in the year 2022.

> Objective 2.2: Estimate relative water level elevations in the side channels, irrigation, and groundwater monitoring wells by launching continuous recording pressure transducers and observing water depth three days a week. These measurements are paired with measurements from Objective 2.1 and therefore follow the same timeline.

> Objective 2.3: Analyze and summarize the spatial and temporal patterns in water level and directionality of streamflow throughout the dry season to determine the relationship between surface water in the side channels and local surface water withdrawal by April 2023.

Goal 3: Gain community support and increase the likelihood of success for future restoration actions through public outreach activities that educate community members in the research project.

Objective 3.1: Add project page to SRWS website by end of June 2022. Interest in project can be measured using website analytic software.

Objective 3.2: Post project updates once every two weeks during field season on SRWS's Facebook and Twitter pages. Engagement analytics are provided on every post and can be used to determine the change in project interest over time.

Objective 3.3: Create and present a family friendly poster for Squamish Rivers Day 2022. Engagement will be measured by counting number of visits to the poster, number of social media followers gained following the event, and number of visits to project webpage.

3. Materials and methods

3.1. Site Description

The Mamquam side channel complex is located along the north bank of the LMR, directly adjacent to the SVGC in Squamish, BC (Fig. 1). The mainstem of the Mamquam River is approximately 29 km long and flows west until it drains into the Squamish River, about 5 km north of the Howe Sound estuary (KWL 2011; Abdelhady et al. 2021). The side channels are located approximately 3.5 km downstream of the Water Survey of Canada (WSC) hydrometric flow gauge 08GA075, Mamquam River above Ring Creek, and approximately 1.9 km upstream from where the river drains into the Squamish River (Fig. 1; Google Earth 2022).

The Mamquam River watershed is approximately 270 km^2 in area and is rain and snowmelt dominant (Fig. 2; Abdelhady et al. 2021). The main tributaries are Crawford Creek, Skookum Creek, Raffuse Creek, Ring Creek, and Mashiter Creek (KWL 2011; Abdelhady et al. 2021). A run-of-river hydroelectric plant (the Lower Mamquam hydroelectric project) located immediately upstream of the WSC gauge divides the watershed into upper and lower sections. Two run-of-river hydroelectric facilities (Upper Mamquam and Skookum) are in the upper watershed. A sediment budget analysis found widespread degradation of the LMR due to large gravel removals between 1981 and 1995 (Table 1; KWL 2011). The LMR has been further degraded through surface water diversions, dyking along its north and south banks, and extensive historical logging in the upper and lower sections (Foy et al. 1999; KWL 2011).

The LMR flows across a historical alluvial fan at a gradient of approximately 0.5% (KWL 2011). This section of the LMR is wandering and is irregularly sinuous with large gravel bars. A flood event in 1921 caused the LMR to travel across the fan to its current course, at which time dykes were constructed along the north and south banks to maintain the river’s current flow position (Table 1). The abandoned channel (the old river flow path) is known as the Mamquam River Blind Channel. The Blind Channel was reconnected to the LMR through a flow-controlled intake that diverts 0.57 m^3/sec (Gov BC 2019).

The side channels are fed by the LMR and the Mamquam Aquifer (Aquifer 398) and consist of complexed channels, pools and ponds armored with rip-rap (Fig. 3; Sheng 1990; Foy et al. 1996; Foy et al. 1999). The original northernmost channel, channel 1, was constructed in 1983 (Fig. 3; Foy et al. 1996; Foy et al. 1999; Foy 2021). The side channel complex was expanded in 1996 to include the southernmost secondary channel, channel 2, and includes deep pools designed to remain wetted during the dry season (Foy 2021). Material excavated from channel construction was used to upgrade the dyke system that bounds the side channels to the north and south (Table 1; Banbury 1994; Foy et al. 1996).

The Mamquam Aquifer is an unconfined sand and gravel aquifer with a surface area of 6.0 km^2 and is estimated to be 50.3 m deep (Fig. 1; Piteau 1995). The Mamquam Aquifer likely receives recharge from the LMR, the Mashiter Creek valley, and the Ring Creek Valley (Piteau 1995). It is bound by bedrock to the northeast, east, and south, and by Squamish River sediments to the west and northwest (Piteau 1995).

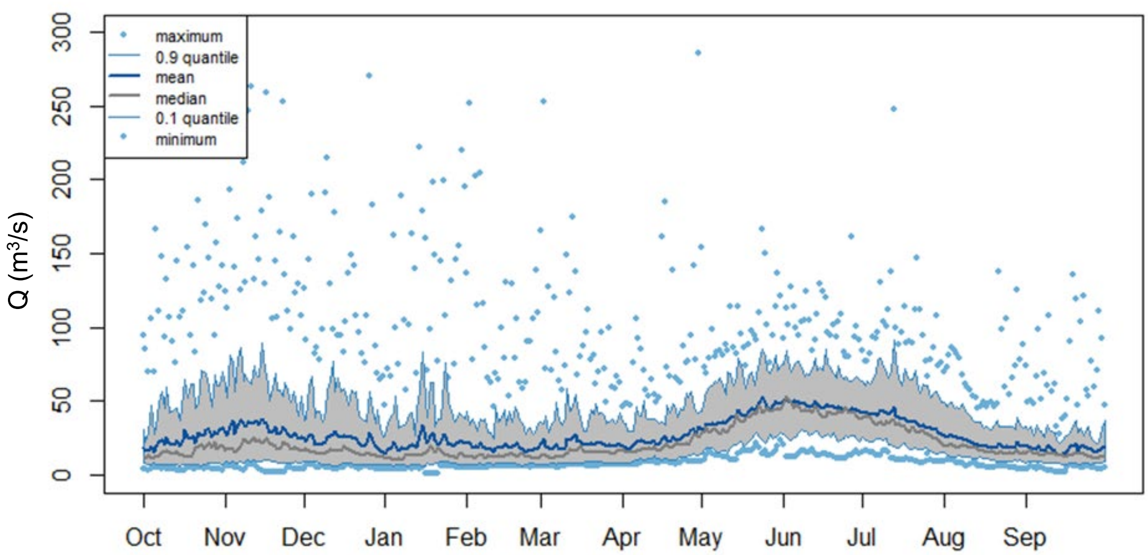

Figure 2 **The annual hydrograph for the Mamquam River watershed where the average distribution of daily streamflow, Q (m^3/s) throughout a water year is shown. Time series streamflow data from 1966 to 2018 was used to determine the daily means (dark blue line), daily maximums and minimums (light blue points), medians (dark grey line), and the range between the 0.1 and 0.9 percentiles (shaded grey area; Dierauer et al. 2017).**

3.2. Water budget approach

A general water budget approach guided the study design which applied synoptic flow measurements, passive water quality tracers, and a relative elevation transect. This approach allowed GWSI during the dry season to be inferred, and specifically to determine when and where the side channels were a net sink or source of water for the LMR in the summer of 2022. The side channels become more at risk to local water withdrawal and extraction when they are a net sink, and primarily groundwater supported. Surface flows in the LMR are generally too high, and river conditions difficult to be safely waded and measured. Therefore, the water budget focused on the side channels and is assumed to be defined as:

$$\Delta S = Q_{in} - Q_{out} - (PEt + Ev), \quad (1)$$

where ΔS is the change in storage within the side channels (L^3), Q_{in} are inflows to the side channels (L^3/t), Q_{out} are outflows from the side channels (L^3/t), PEt are losses due to potential evapotranspiration from local riparian vegetation (L/t) and Ev are losses due to evaporation from the water surface within the side channels (L/t). Positive trends in ΔS indicate that the side channels are gaining water from the river, the shallow aquifer, or both, whereas negative trends indicate a losing condition (Objective 2.2). Furthermore, losing flow conditions represent the onset when habitat quality for juvenile coho may become challenging and diminished. In this study PEt and Ev were not measured, and it is assumed that changes to surface flow conditions in the side channels were primarily due to seasonal reductions to water availability, and trends of water use and demand.

3.2.1. Synoptic flow measurements

The side channels receive inflow, Q_{in}, from springs along its length as there is no upstream surface water connection to the LMR (Fig. 3). The side channels flow downstream (west) until the LMR confluence, Q_{out}. Likely source(s) of water in the side channels, $Q_{in,}$ were qualitatively determined to be related to contributions from rainfall, the river, groundwater, or a combination of water sources based on synoptic flow and basic water quality measurements. Direct rainfall was assumed to be negligible relative to other inputs therefore, this term was ignored. Outflows from the side channels, Q_{out}, are due to surface flows directed out of the channels, seepage into the shallow aquifer, plus evaporative-related losses. Direct evaporative losses from the water surface were assumed to be minimal thus, this term was also ignored.

Measurements were taken along channel 1 every two to four days at approximate 200 m increments to create a temporal and longitudinal profile of surface flow conditions (Objective 2.1; Fig. 3). Flow measurements were along channel 1 as it is historically more susceptible to drought and loss of surface flow. The monitoring period was from June 30 to November 5, 2022 and was timed to capture flow and water quality conditions in the side channels at the end of freshet and the beginning of fall rains. The overall state and flow regime of the watershed was determined by observing real-time hydrometric data provided by the WSC gauge. Local precipitation data was provided by Environment and Climate Change Canada and was taken from the Squamish Airport (Site 10476F0) at 53.70 m elevation (ECCC – MSC 2023). Sampling sites were distributed along the length of the side channel complex to capture surface flow and water quality upstream of the irrigation pond (SC-01 to SC-03), along an elevation transect from the irrigation pond (SC-04), and downstream of the irrigation pond (SC-05 to SC-07; Fig. 5). Positive differences in flow (ΔQ) between cross-sections were interpreted as gaining, while negative differences in flow were interpreted as losing. Measurements were made using a Price AA bucket wheel style velocimeter or a Hach FH950 Velocity Flow Meter following standard surface water gauging protocols as specified by the Resources Information Standards Committee of British Columbia (RISC 2018).

Local changes in shallow groundwater levels were tracked throughout the dry season with depth to water measurements at accessible groundwater wells. Depth to water measurements were taken at groundwater monitoring wells (SC-11 and SC-12) with a Solinst TLC meter three times per week. These measurements were used to better understand the changing flow conditions in the side channels in relation to local groundwater levels and the LMR.

3.2.2. Passive water quality tracers

Basic water quality was measured in the side channels, the irrigation pond, and the shallow alluvial aquifer through accessible wells. Water temperature (T_w), specific electrical conductance (SpC) and dissolved oxygen (DO) concentration was measured at all surface water monitoring locations (SC01 to SC10) using a YSI Professional Plus Multiparameter meter. At groundwater monitoring wells, T_w and SpC was measured using a Solinst TLC meter (SC11 & SC12). T_w and SpC are natural passive water quality tracers, and the results of our measurements helped interpret likely sources of water to the side channels. Groundwater is typically warmer and has a greater concentration of salt pairs present relative to surface runoff (Freeze and Cherry 1979). Thus, it was hypothesized that as the dry season progressed, water in the side channels would become warmer and saltier relative to the water in the LMR and would reflect increasing inflow from the shallow alluvial aquifer. DO was measured to determine if concentrations were suitable for Pacific salmon throughout the dry season (Appendix A).

Air temperature, T_a, was also measured to qualitatively assess the relative contribution of T_a to water temperature, T_w, changes in the side channels. T_a was measured at 15-minute intervals with a HOBO Tidbit v2 temperature data logger. The channels are heavily shaded from riparian vegetation and therefore are not expected to have a significant effect on T_w relative to other factors such as, inflow from groundwater and streamflow.

3.2.3. Relative elevation transect

In general, water level and basic water quality measurements were used to understand the changing storage conditions in the side channels, and to provide context for interpretation of associated streamflow measurements in the side channels, as well as conditions in the nearby irrigation pond (Objectives 2.1 & 2.2). Solinst Levelogger 5 Junior pressure transducers were placed with stilling wells in the irrigation pond (SC-08), the side channel pond (SC-09), and the flow site nearest to the point of connection with the LMR (SC-07; Fig. 3). A pressure transducer was placed at SC-09 rather than SC-04 as it was expected to remain wetted during the dry season. Staff plates were also placed alongside the pressure transducers, as well as at SC-04 (Fig. 3). The pressure transducers recorded water level, h, and water temperature, T_W, at 15-minute intervals.

A field survey was conducted on November 18, 2022 to determine the invert and surface water elevations of the irrigation pond (SC-08), the side channels (SC-04 and SC-09), and the LMR in relation to each other (Fig. 3; Appendix B). This survey was done using an auto-level and stadia rod and was performed when understory vegetation was expected to be minimal. Unfortunately, vegetation was still substantial enough to disrupt line-of-site along the transect and prevent estimations of horizontal distance in the field. Therefore, only relative elevation data was gathered from the survey and horizontal distance was estimated using a relative elevation model (REM). The REM was generated by first creating a digital elevation model (DEM) from LiDAR data (LidarBC 2021). The river's elevation was then subtracted from the DEM to make the meanders of the river and the fine structure of the side channel complex more visible.

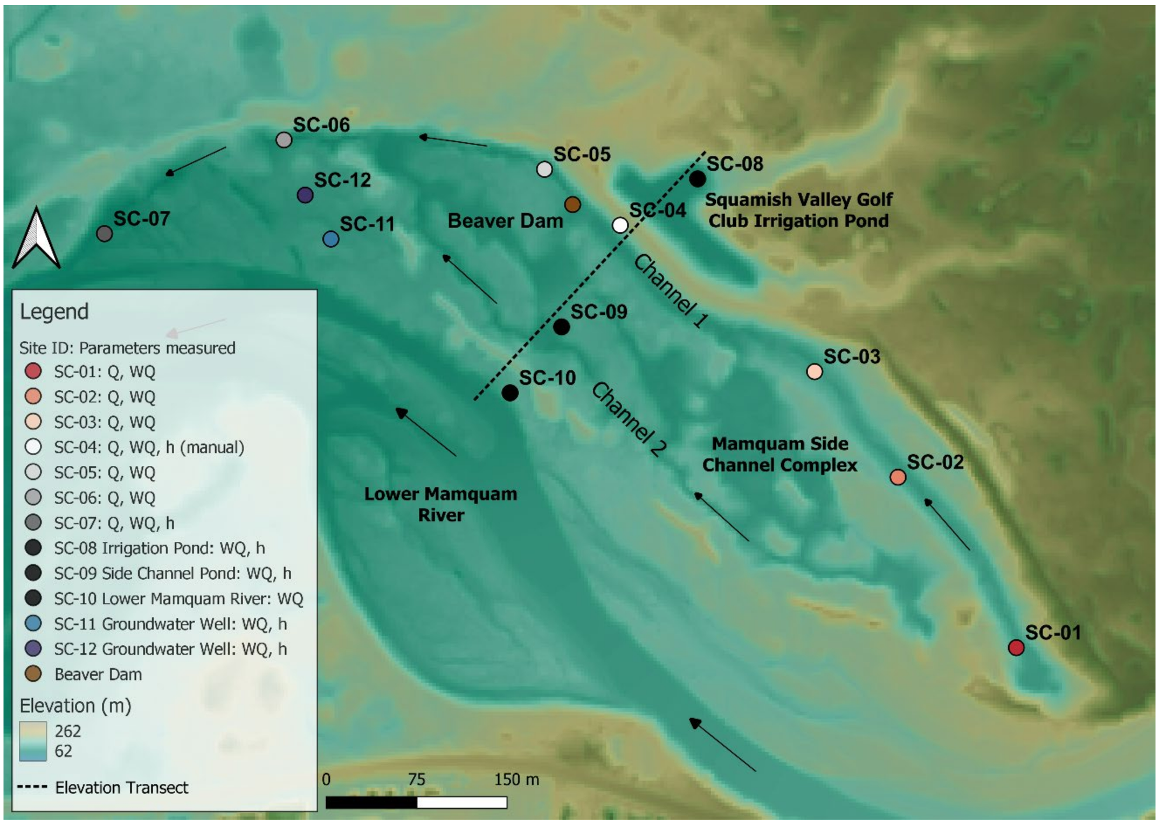

Figure 3 **A relative elevation model generated from a digital elevation model of pixel size -1 x 1 m (LidarBC 2021) showing the fine structure of the Mamquam side channel complex, location of sample sites (SC01 to SC12), parameters measured (Q = streamflow; WQ = water quality; h = water level), and elevation transect (dotted line).**

4. Results

4.1. Streamflow and Shallow Groundwater Level

Throughout the monitoring period, broad-scale surface flow and water level trends in the side channels followed patterns similar to streamflow in the LMR and local groundwater levels (Fig. 4, 5, and 6). Surface flow, Q, in the channels and the LMR began with a gradual decline, followed by a steady period, and ended with sporadic rises and falls (Fig. 4 and 5). This is reflective of changes between snowmelt, baseflow, and rainfall flow regimes. Surface water levels in the lower reaches of the side channels (SC-07) and local groundwater levels (SC-11 and SC-12) never entered a steady period but instead gradually declined until fall rains began in late October (Fig. 6 and 7). Despite declining water levels, the channels remained wetted throughout the entire dry season (Fig. 8).

During freshet, streamflow in the LMR gradually declined from the beginning of the study period (June 30, 2020) until September 18, 2022 (Fig. 4). Near the beginning of freshet (July 3, 2020) peak streamflow was 63.0 m^3/s and decreased by approximately 10-fold over two and half months to a minimum streamflow of 6.45 m^3/s on September 9, 2022 (Table 2). The LMR remained in baseflow until the first significant rainfall on October 24, 2022. During baseflow average streamflow was 5.99 m^3/s (SE 0.72), and ranged from 4.08 and 16.8 m^3/s. The LMR rose and fell in response to rainfall events on October 24, 25, 27, 30 and November 5, 2022. Similarly, streamflow in the side channels gradually declined from the beginning of the study period until reaching baseflow on August 14, 2022, about a month prior to the mainstem reaching baseflow (Fig. 5). The side channels remained in baseflow until October 28, demonstrating a lag in response to rising levels in the mainstem.

Local groundwater levels gradually declined from 0.66 m and 0.88 m below the surface on June 27, 2022 to a seasonal low of 1.09 m and 1.34 m on October 21, 2022 in SC-11 and SC-12, respectively (Fig. 6; Table 2). On the day of the first rainfall, groundwater levels began to rise, peaking on October 30, 2022 with depth to water measurements of 0.61 m at SC-11 and 0.81 m at SC-12. Depth to water at SC-12 was consistently 0.21 to 0.27 m deeper than SC-11, which may be due to the elevation differences between the wells.

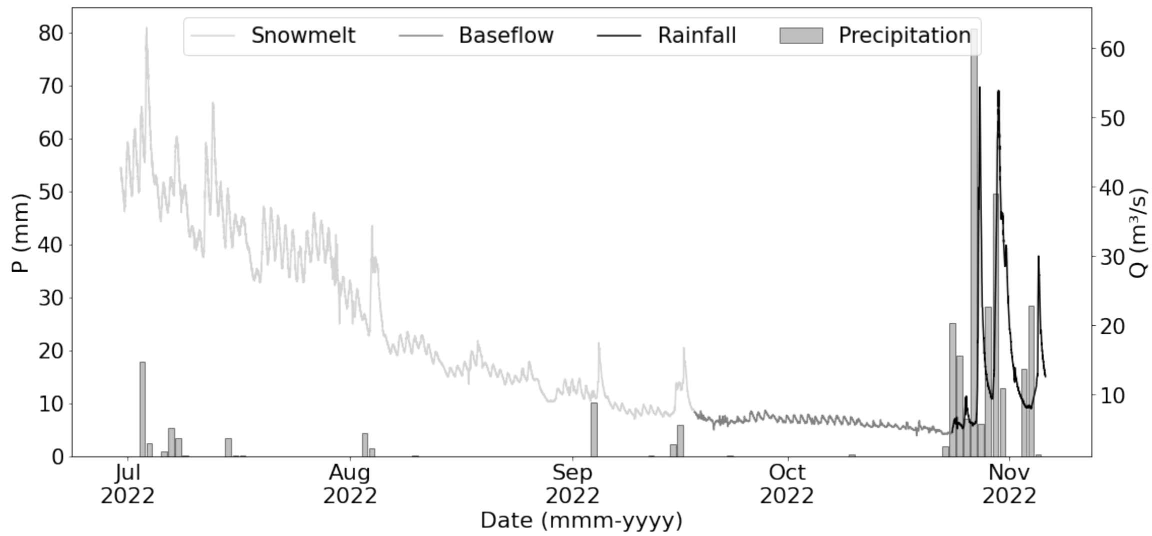

Figure 4 **Real-time hydrometric data (Q) of the Mamquam River WSC gauge 08GA075 denoting the changes in flow regime (light grey = snowmelt, grey = baseflow, black = rainfall) throughout the study period, June 30 to November 4, 2022. Historical precipitation (P; grey bars) data was taken from the Squamish Airport (Site 10476F0) at 53.70 m elevation (ECCC – MSC 2023).**

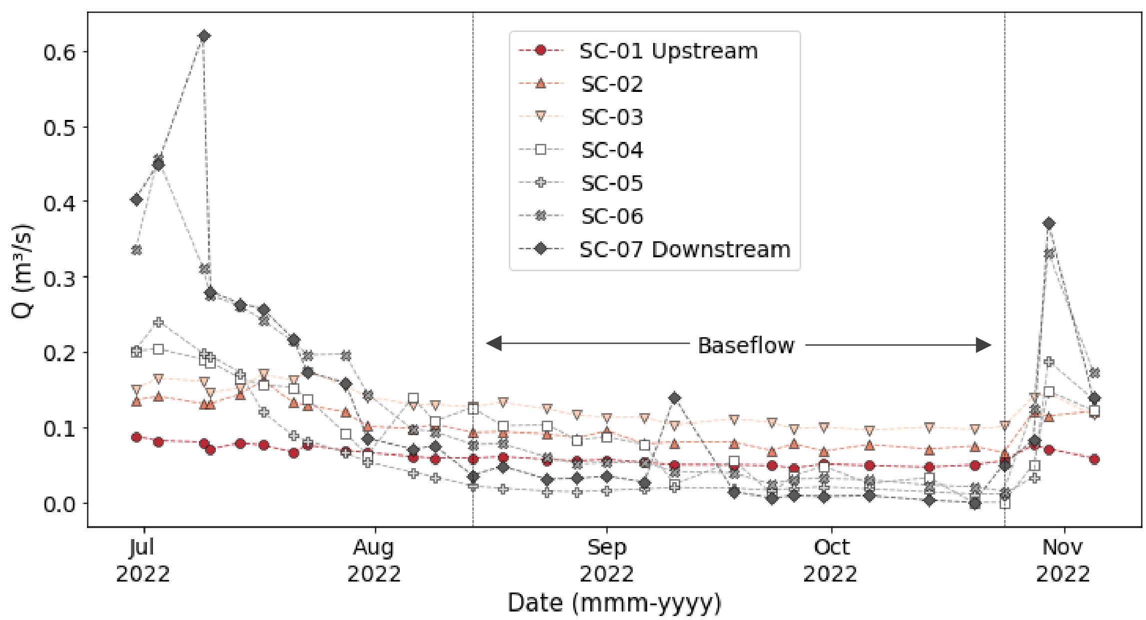

Figure 5 **Streamflow, Q, over time (June 30 to November 5, 2022) at all flow sites (SC-01 to SC-07) demonstrate the broad-scale streamflow trends in the Mamquam side channel complex throughout the Monitoring period. Dotted lines added to aid reader in tracking trends at each location.**

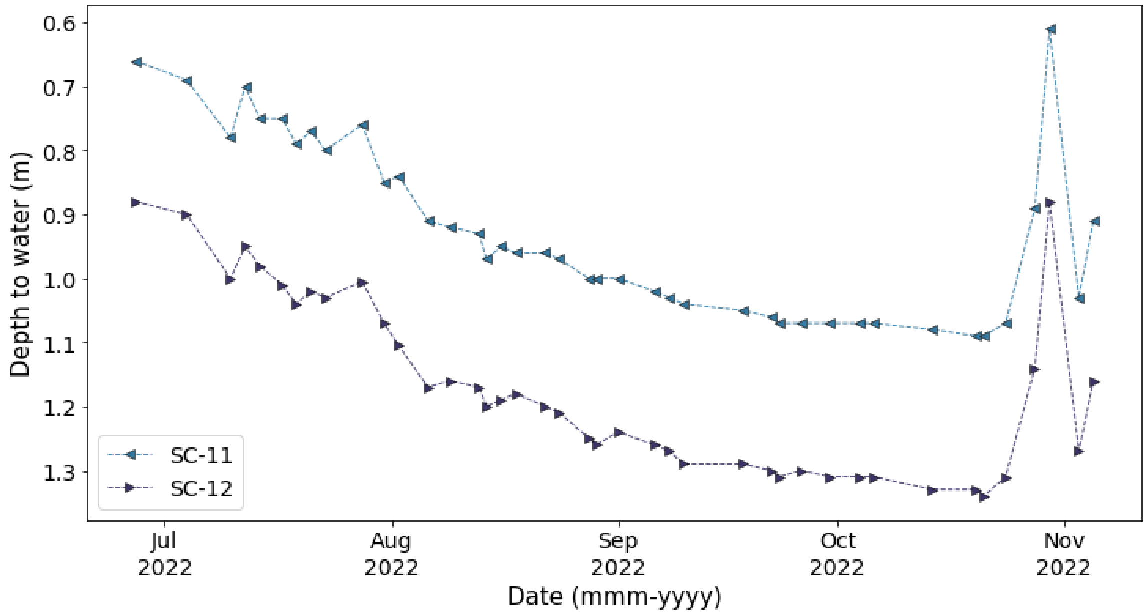

Figure 6 **Depth of the water table at groundwater wells SC-11 (light blue right triangles) and SC-12 (dark blue left triangles) from June 30 to November 5, 2022. Dotted lines added to aid reader in tracking trends at each location.**

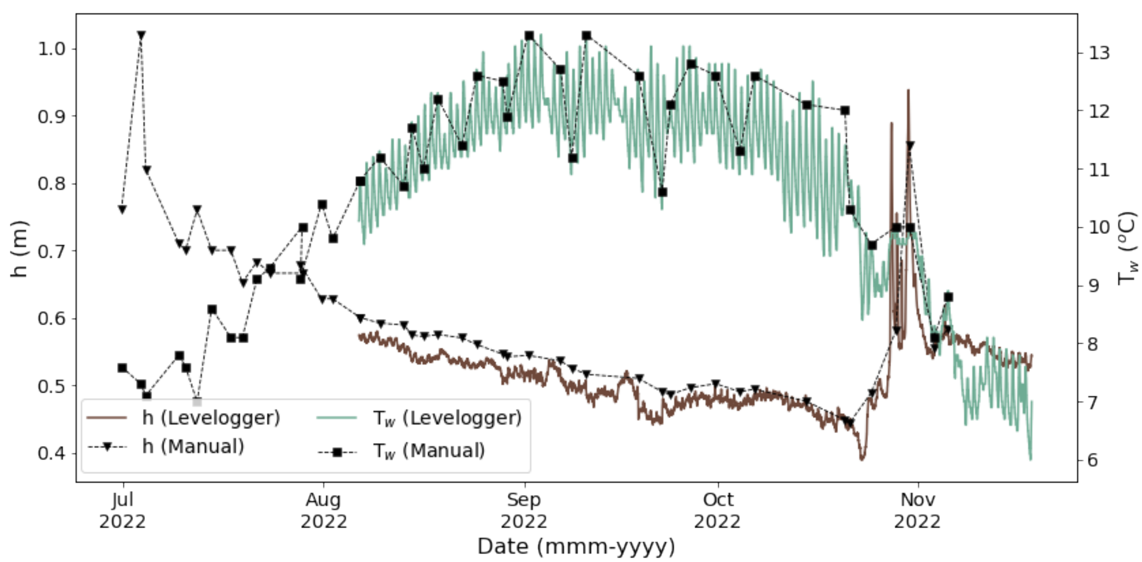

Figure 7 **Water level, h, (brown) and water temperature, T_w, (green) data at SC-07 recorded in 15-minute intervals via pressure transducer as well as manually (black triangle, black square). Dotted lines added to aid reader in tracking trends for each parameter.**

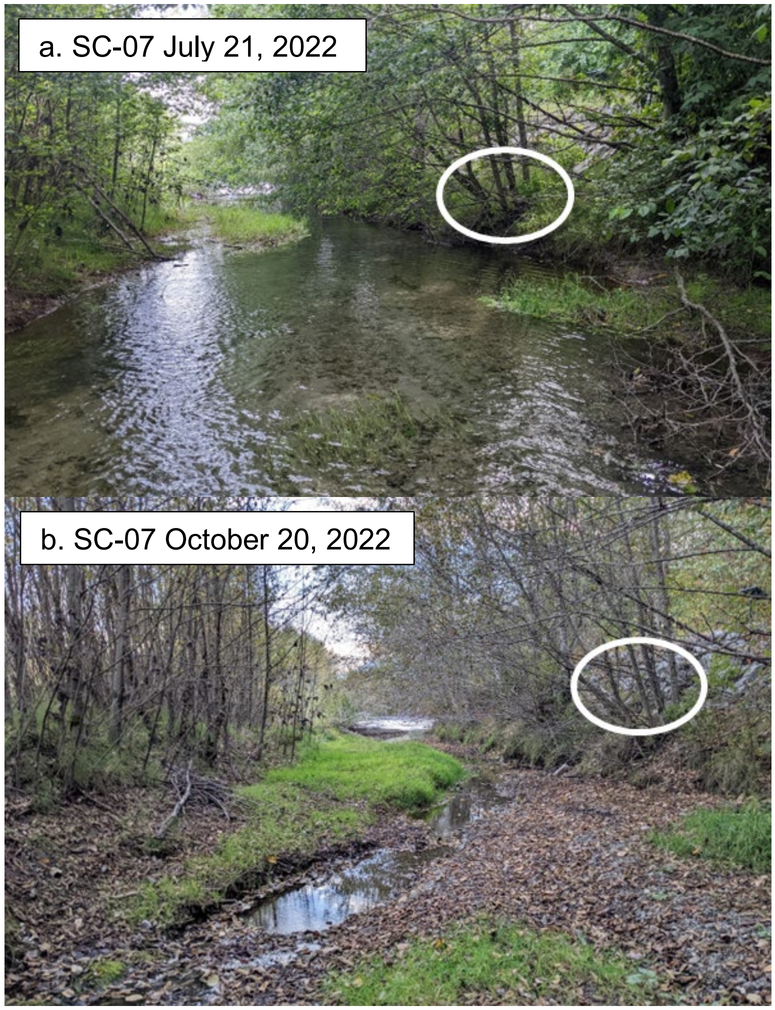

Figure 8 **Pictures of water level changes at SC-07 at (a) beginning of dry season and (b) end of dry season. Photos taken by Erica Harvey.**

The magnitude of streamflow varied in the side channels throughout the study period, where variability in streamflow increased from upstream to downstream (Fig. 9). Across all sites streamflow ranged from 0.000 m^3/s to 0.620 m^3/s over the course of the monitoring season (Table 2). The site furthest downstream, SC-07, showed the biggest range in streamflow, with a seasonal high of 0.620 m^3/s on July 9, 2022 and a seasonal low of 0.000 m^3/s on October 20, 2022 (Table 2; Fig. 9). In contrast, the site furthest upstream, SC-01, showed the smallest change in flow magnitude, varying from 0.088 m^3/s on June 30 to 0.046 m^3/s on September 26, 2022 (Fig. 9).

Percent change in streamflow was also significantly different between upstream sites (SC-01 to SC-03) and downstream sites (SC-04, to SC-07; Table 2). Streamflow in upstream sites changed on average by 50.6% (SE 7.63), whereas in downstream sites streamflow changed by 98.0% (SE 2.3) on average. SC-03 had the lowest percent change in streamflow, varying by 44.8%, while SC-04 and SC-07 had the greatest change in streamflow, varying by 100.0% (Table 2).

Table 2 **A summary table of streamflow, Q (m^3/s), at the WSC gauge 08GA075 and flow sites, SC-01 to SC-07, as well as depth to water (m) at groundwater wells, SC-11 and SC-12, over the monitoring period (June 30 to November 4, 2022).**

Site	Parameter	Units	Min.	Max.	Mean	SE	% change
WSC gauge (Freshet)	Q	m3/s	6.45	63.0	21.97	12.18	89.8
WSC gauge (Baseflow)	Q	m3/s	4.08	16.8	5.99	0.72	75.7
SC-01	Q	m3/s	0.046	0.088	0.062	0.120	47.7
SC-02	Q	m3/s	0.066	0.162	0.103	0.027	59.3
SC-03	Q	m3/s	0.096	0.174	0.129	0.025	44.8
SC-04	Q	m3/s	0.000*	0.204	0.097	0.062	102.9
SC-05	Q	m3/s	0.011	0.241	0.070	0.074	95.4
SC-06	Q	m3/s	0.015	0.457	0.136	0.120	96.7
SC-07	Q	m3/s	0.000	0.620	0.137	0.157	100.0
SC-11	Depth to water	m	1.09	0.61	0.93	0.14	44.0
SC-12	Depth to water	m	1.34	0.88	1.17	0.14	34.3

*Negative value adjusted to 0.00 m^3/s

Table 3 **A timeline of events that occurred throughout the monitoring period.**

Date	Event
June 30, 2022	Beginning of monitoring period
July 11, 2022	SVGC began irrigating consistently
July 14, 2022	Stilling well replaced at SC-08
July 14, 2022	Beaver dam first noted
October 24, 2022	First significant rainfall of season
October 28, 2022	Beaver dam dismantled
November 3, 2022	SVGC turned off irrigation system for the season
November 5, 2022	End of monitoring period
November 18, 2022	Relative Elevation Survey

SC-04 was backwatered by a beaver (*Castor canadensis*) dam located approximately 100 m downstream. Backwatering was first observed on July 14, 2022 and persisted until the dam was dismantled on October 28, 2022 (Table 3). Backwatering from the dam accompanied with seasonal reductions in flow resulted in negative streamflow values of -0.006 and -0.003 m^3/s on October 20 and 24, 2022 (i.e.

flow in the upstream direction) that were adjusted to 0.000 m^3/s. Lower flows were also observed immediately downstream of the beaver dam following its construction, causing a skewed flow distribution at SC-05 (Fig. 9).

The net flow of surface water in the side channels throughout the study period can be separated into two gaining phases separated by a losing phase in conjunction with observed flow trends (Fig. 5 and 10b). The side channels are gaining from the beginning of the study period until reaching baseflow on August 14, 2022 (Fig. 5 and 10b). From August 14 until October 24, the side channels are a local surface water sink. The exception throughout this 72-day period is a positive net total streamflow, $\Sigma\Delta Q$, value of 0.09 m^3/s on September 10. On this day, streamflow at SC-07 spiked, alongside the LMR in response to a rain event (Fig. 4 and 5), which may account for the rise in net total streamflow. Excluding observations on September 10, negative net total streamflow values ranged from -0.05 m^3/s on October 20 and -0.005 m^3/s on October 24. After October 24 and until the end of the study period, the side channels are gaining.

The location of net water loss and gain along the length of the side channels changed during the monitoring period and appear to coincide with the construction and subsequent removal of a beaver dam, irrigation by the golf course, and seasonal reductions in streamflow. At the beginning of the study period, all flow sites were gaining water (Fig. 10a). After July 14, 2022, when backwatering by the beaver dam was first observed, SC-04, SC-05, and SC-07 began losing water (Fig. 10a). Three days prior, on July 11, 2022 the SVGC also began irrigating daily (Table 3). These sites remained losing until the first day following the beaver dam removal. Following this event all flow sites began gaining water. However, more data following this event is necessary to observe a trend.

4.2. Water Quality

The side channels and the mainstem had diverging water quality trends, while the side channels and the local groundwater levels had converging trends. As predicted, water temperature in the side channels increased over time and became warmer than the mainstem by mid-summer (Fig. 11). Specific electrical conductance in the side channels also increased as predicted but did not become saltier than the mainstem as the season progressed (Fig. 14). Dissolved oxygen concentration in the side channels declined steadily with rising water temperatures and at some locations fell below the chronic and acute oxygen requirements for Pacific salmon for extended periods (Appendix A1). Overall, there was low longitudinal variability in water temperature, specific conductance, and dissolved oxygen in the side channels.

4.2.1. Water Temperature

Water temperature, T_w, in the side channels increased gradually until early fall then began to decrease (Figure 11). It diverged from the LMR (SC-10) beginning on August 22, as the LMR decreased in temperature at a more rapid rate than the side channels. In contrast, water temperature in the side channels converged with local groundwater temperature (SC-11 and SC-12) at the end of July. The LMR appears to have a stronger relationship with air temperature, T_a, than the side channels, and groundwater temperature.

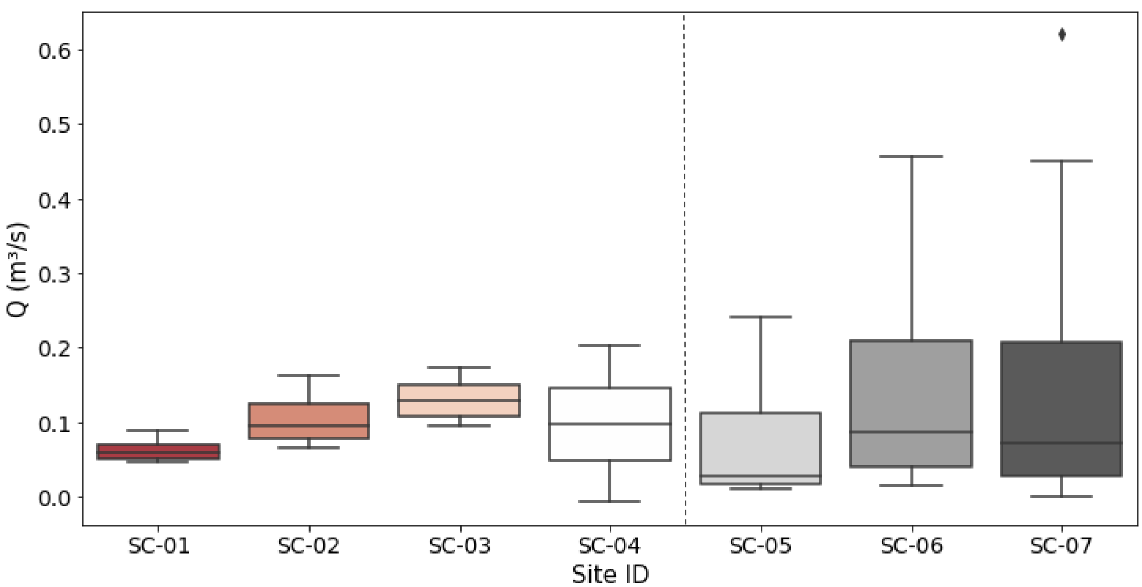

Figure 9 **Boxplot of streamflow, Q, at all flow sites (SC-01 to SC-07) in the Mamquam side channel complex over the monitoring period. Sites are arranged upstream to downstream with the dotted vertical line denoting the location of a beaver dam. The medians (dark grey), 25th and 75th quartiles (box), minimum and maximum values (whiskers), and outliers (diamond) at each site are shown.**

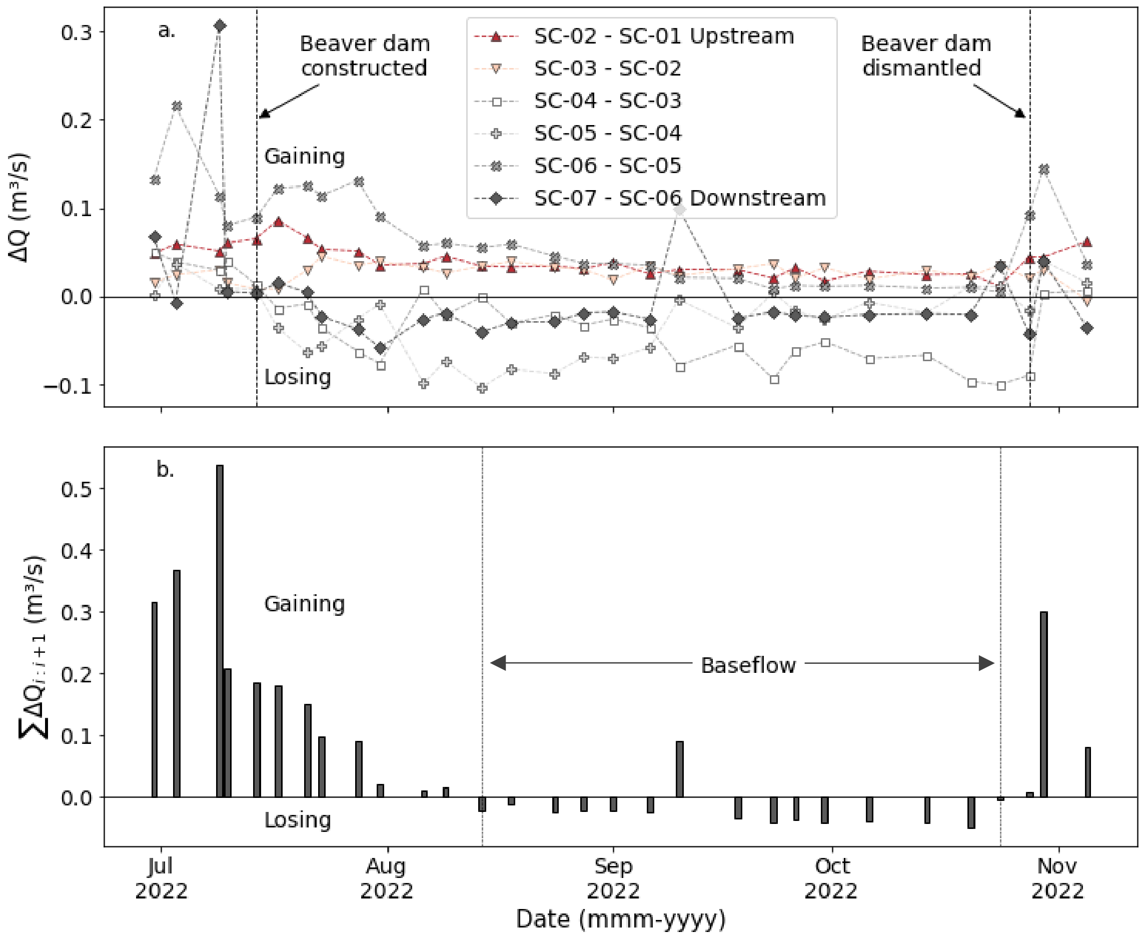

Figure 10 **(a) The difference in discharge, ΔQ, between two adjacent flow sites ($\Delta Q = Q_{downstream} - Q_{upstream}$). Dotted lines between points were added to aid reader in tracking trends at each location. (b) The sum of ΔQ (i.e. net total streamflow) over time (June 30, 2022 to November 5, 2022). Positive values indicate the side channels are gaining water (net source) while a negative value indicates that the side channels are losing water (net sink).**

Overall, water temperature in the side channels ranged by 6.7°C over the entire monitoring period with seasonal lows of 6.6°C on July 3 and highs of 13.3°C on September 10 (Table 4). The LMR (SC-10) had the greatest range in water temperature of all flowing water sites (Fig. 12) changing by 67.5% with seasonal lows of 3.9°C on November 3 and highs of 12.0°C on August 22 (Table 4). This range is second only to the irrigation pond (SC-08) which changed by 74.0%, ranging from 4.0°C to 15.4°C (Table 4). Groundwater temperatures had changed by 44.0% (SC-11) and 34.3% (SC-12) with seasonal lows of 7.5°C on June 17 and highs of 15.5°C on September 10 (Fig. 12; Table 4). SC-12 was on average 1.1°C colder than SC-11.

In the side channels, water temperature consistently increased moving downstream (Fig. 13) with the average range and percent change in temperature between upstream and downstream sites being 1.3°C (SE 0.45) and 11.7% (SE 3.5), respectively (Table 4). These longitudinal differences in water temperature were largest at SC-06 and SC-07 as they were consistently warmer than adjacent upstream sites and the difference in temperature increased over time until the first rainfall event on October 24 (Fig. 13). Two exceptions were on July 28 and October 30 when SC-07 was 0.7 and 1.9°C colder than SC-06, respectively.

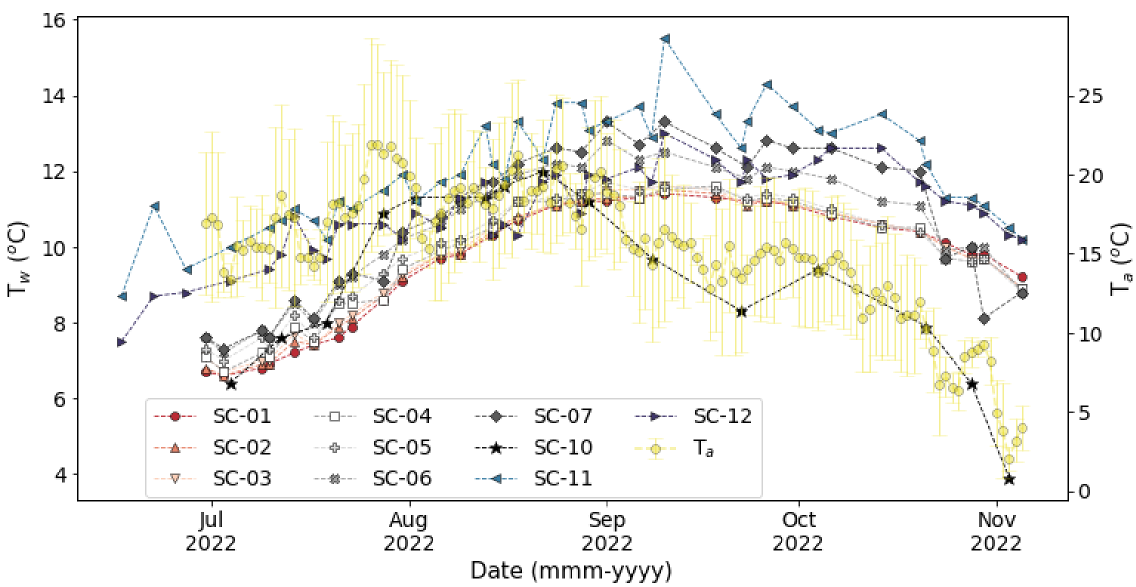

Figure 11 **Water temperature, T_w, at flow sites (SC-01 to SC-07) in the Mamquam side channel complex and the Lower Mamquam River (SC-10) over the monitoring period (June 30 to November 5, 2022). Daily average air temperature, T_a, in the shade is plotted along the secondary y-axis with ± 1 SD. Dotted lines between points are to aid reader in tracking trends at each location.**

4.2.2. Specific Conductance

Specific conductance, SpC, levels in the side channels, the LMR, and the groundwater showed differing trends throughout the monitoring period. SpC levels along the length of side channels followed a close relationship and steadily increased by approximately two-fold throughout the study period (Fig. 14). SpC also increased in the LMR (SC-10), but at a faster rate (Fig. 14) than the side channels and with a larger range (Fig. 16). Groundwater SpC did not follow a clear trend and therefore did not have a strong relationship with SpC in the side channels (Fig. 15).

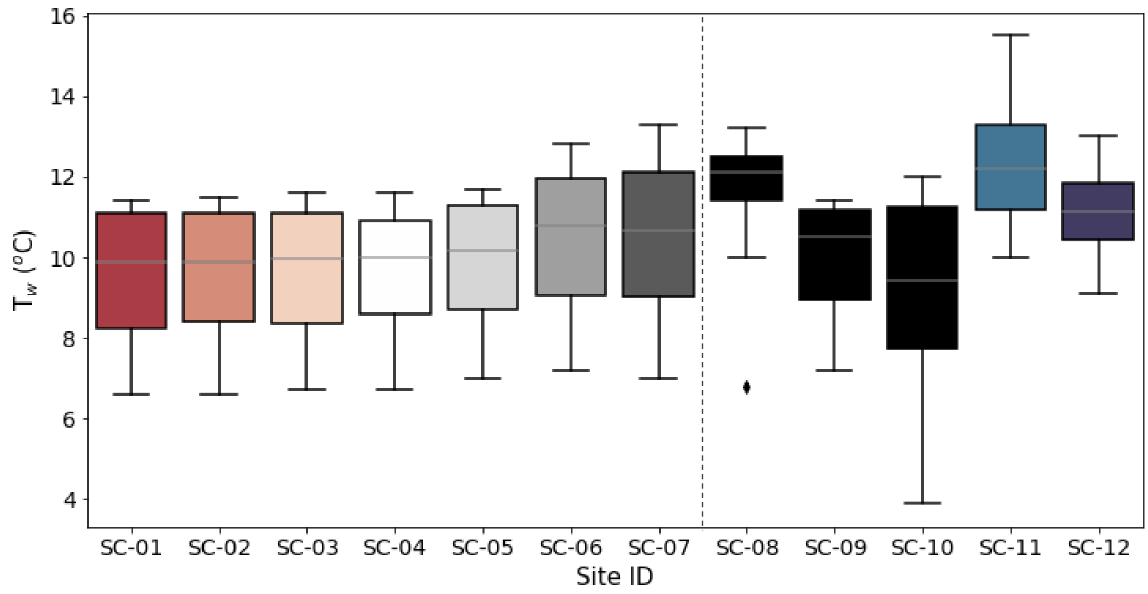

Figure 12 **Boxplot of water temperature at all sites (SC-01 to SC-12) over the study period. The medians (light grey), 25th and 75th quartiles (box), minimum and maximum values (whiskers), and outliers (diamond) at each location are shown.**

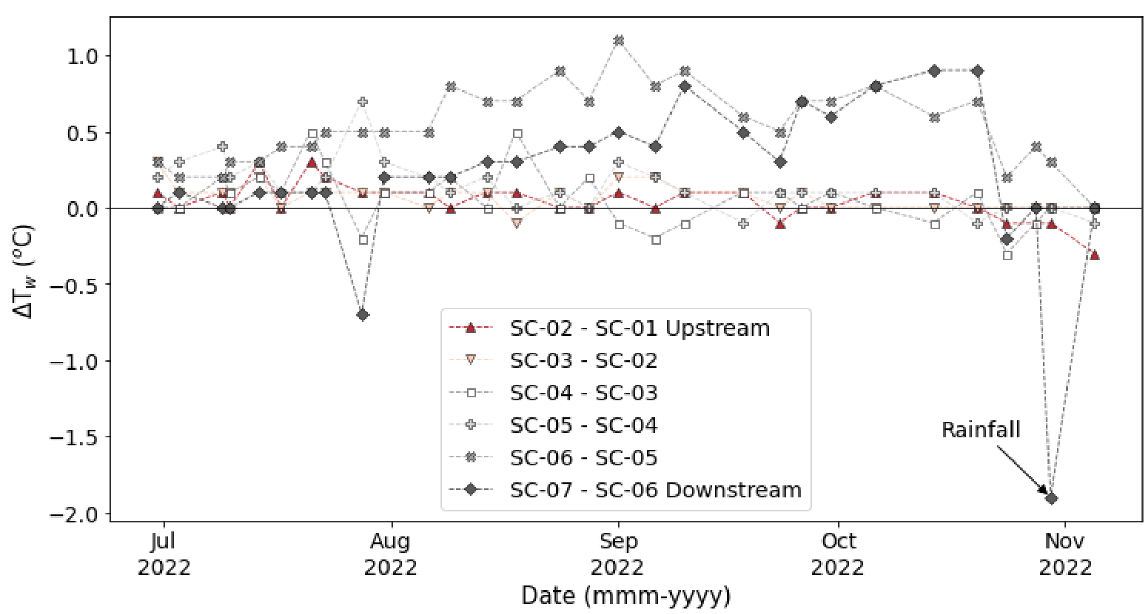

Figure 13 **The difference in water temperature, ΔT_w (°C), between upstream and downstream flow sites over time. A positive value indicates that the water at the downstream site is warmer relative to the adjacent upstream site and a negative value indicates that the water is colder. Dotted lines between points are to aid reader in tracking trends at each location.**

Table 4 **A summary table of water temperature (°C) descriptive statistics reported at all sites, SC-01 to SC-12 over the entire monitoring period.**

Site	Min.	Max.	Mean	SE	% change
SC-01	6.6	11.4	9.6	1.7	45.1
SC-02	6.6	11.5	9.6	1.6	42.6
SC-03	6.7	11.6	9.7	1.6	42.2
SC-04	6.7	11.6	9.7	1.6	42.2
SC-05	7.0	11.7	9.9	1.5	40.2
SC-06	7.2	12.8	10.4	1.7	43.8
SC-07	7.3	13.3	10.6	2.0	45.1
SC-08	4.0	15.4	10.9	2.5	74.0
SC-09	6.8	11.9	10.0	1.5	42.9
SC-10	3.9	12.0	9.1	2.4	67.5
SC-11	8.7	15.5	12.0	1.5	43.9
SC-12	7.5	13.0	10.9	1.2	42.3

SpC in the side channels gradually increased as the dry season progressed with the only observed decrease in SpC following the onset of fall rain (Fig. 14). SpC in the side channels began with an overall low of 27.5 µS/cm on June 30, 2022 and ended with an overall high of 64.1 µS/cm on October 30, 2022. Variability in SpC decreased slightly moving downstream as SC-01 had the greatest variability, ranging from 27.5 to 64.1 µS/cm and changing by 57.1% while SC-07 had the lowest variability, ranging from 31.2 to 61.1 µS/cm and changing by 48.9% (Fig. 16; Table 5). SpC in the LMR (SC-10) also steadily increased until the onset of fall rain (Fig.14). SpC in the LMR changed by 65.0% throughout the monitoring period, increasing from a low of 23.1 µS/cm on July 4, 2022 to a high of 66.5 µS/cm on October 21, 2022 (Table 5). SpC levels in groundwater sites (SC-11 and SC-12) were sporadic, ranging from 37 to 129 µS/cm (Figure 15; Table 5).

Longitudinal trends in SpC reversed directions mid-summer. SpC in the side channels initially increasing (i.e. saltier) downstream but reversing on August 6 (Fig. 14). After August 6, SPC decreases (i.e. more fresh) moving downstream. The difference in SpC (ΔSpC) between adjacent flow sites also increases over the monitoring period, where downstream sites were increasingly saltier than upstream sites (Fig. 17).

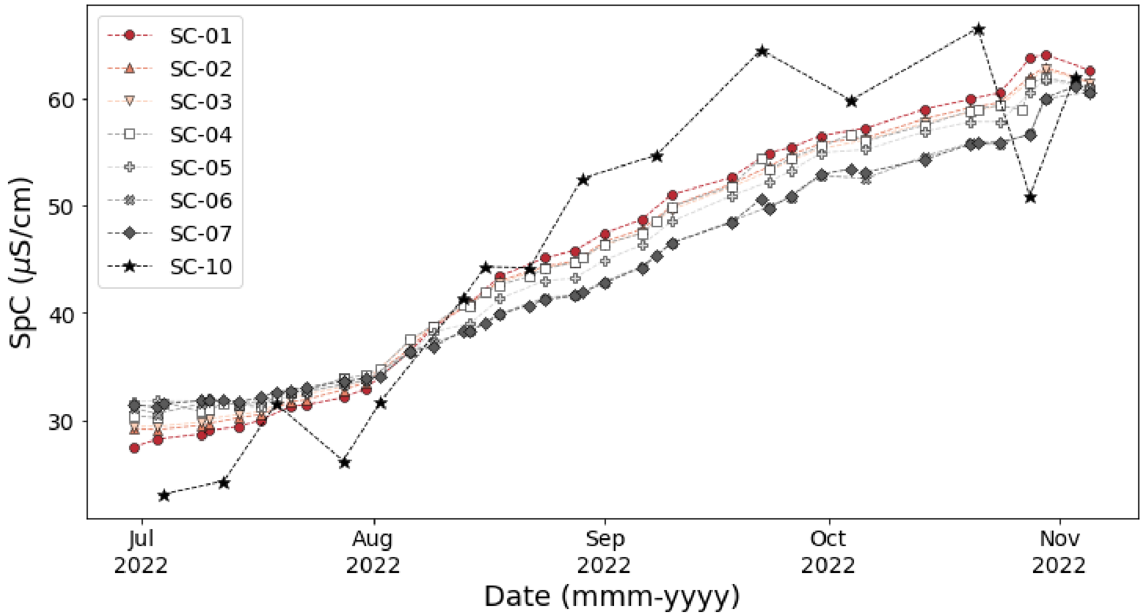

Figure 14 **Specific conductance, SpC, at flow sites (SC-01 to SC-07) and the Lower Mamquam River (SC-10) throughout the study period (June 30 to November 5, 2022). Dotted lines between points are to aid reader in tracking trends at each location.**

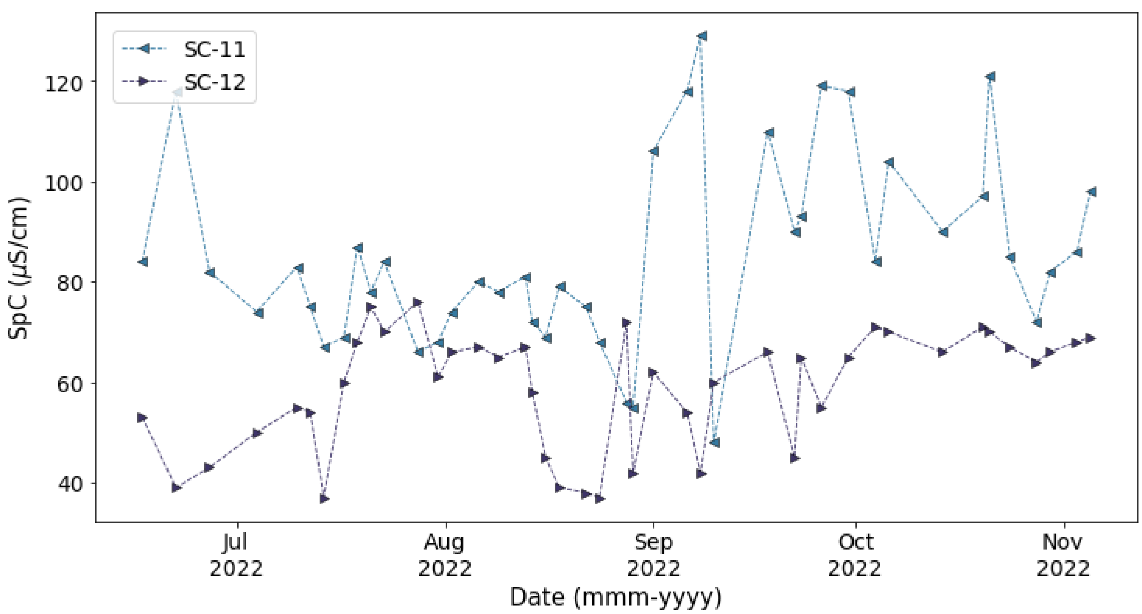

Figure 15 **Specific conductance (µS/cm) in groundwater wells SC-11 and SC-12 over the monitoring period (June 30 to November 5, 2022). Dotted lines between points are to aid reader in tracking trends at each location.**

Table 5 **A summary table of specific conductance (μS/cm) descriptive statistics reported at all sites, SC-01 to SC-12 over the entire monitoring period.**

Site	Min.	Max.	Mean	SE	% change
SC-01	27.5	64.1	44.8	12.7	57.1
SC-02	29.1	62.9	44.6	11.9	53.7
SC-03	29.4	62.7	44.5	11.6	53.1
SC-04	30.2	61.9	44.8	11.0	51.2
SC-05	31.4	61.7	44.2	10.8	49.1
SC-06	30.6	60.6	42.9	10.0	49.5
SC-07	31.2	61.1	42.7	9.7	48.9
SC-08	37.7	104.5	50.3	18.1	63.9
SC-09	28.7	58.5	40.9	10.1	50.9
SC-10	23.1	66.5	45.2	15.0	65.0
SC-11	48	129	85	19	63
SC-12	37	76	59	12	51

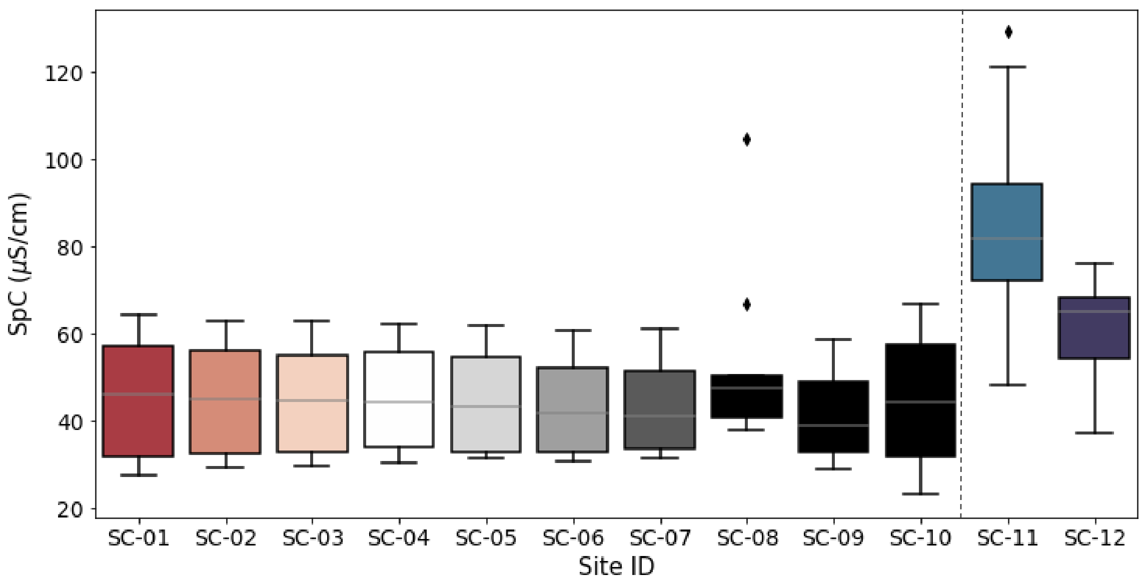

Figure 16 **Boxplot of specific conductance, SpC (μS/cm), at all sites (SC-01 to SC-12) over the study period. The medians (light grey), 25th and 75th quartiles (box), minimum and maximum values (whiskers), and outliers (diamond) at each site are shown.**

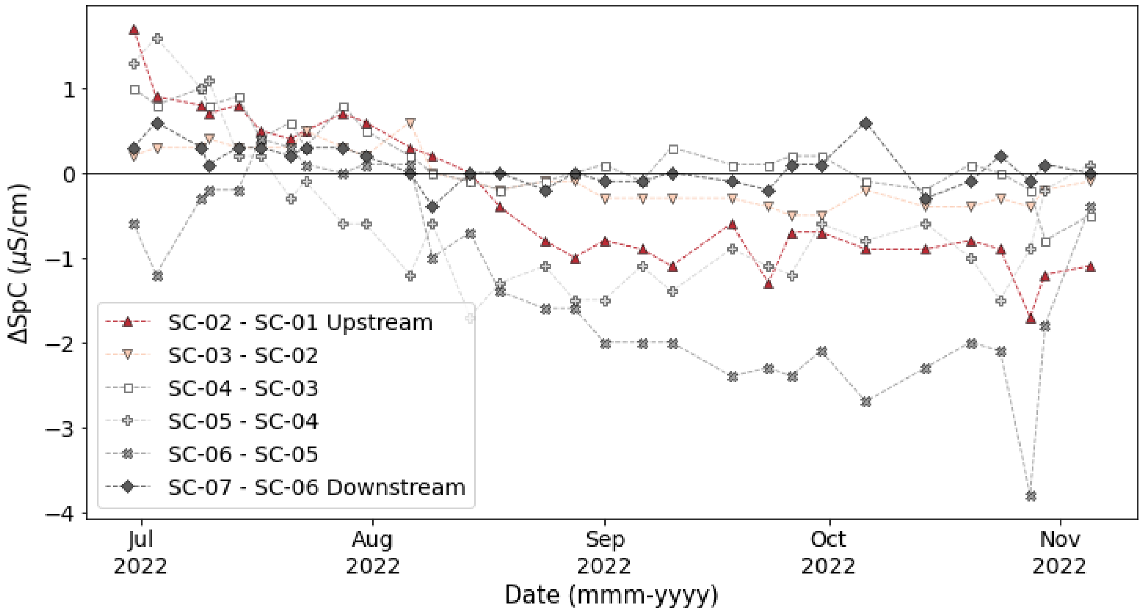

Figure 17 **The difference in specific conductance, ΔSpC (µS/cm) between upstream and downstream flow sites over time. A positive value indicates that the water at the downstream site is fresher relative to the upstream site and a negative value indicates that the water is saltier.**

4.3. Hydraulic Connectivity

Water level in the irrigation pond (SC-08) and the side channel pond (SC-09) begin to drop immediately following the release of water behind a beaver dam on October 28, 2022 at approximately 1:30 pm. Water levels in the side channel pond began to level off on October 29 at 10:15 pm (Fig. 18). Following beaver dam removal, the change in water level (Δh) at SC-09 was 0.416 m. Water level in the irrigation pond continued to drop until November 3 at 6:30 am. Similarly, the change in water level (Δh) following beaver dam removal in the irrigation pond (SC-08) was 0.427 m.

A lagged response in water temperature was observed in both the irrigation pond and side channel pond (Fig. 18). Water temperature in the irrigation pond began to drop from 9.2°C at 11:15 pm on October 31, about two and a half days after water level. Water temperature continued to drop for approximately 8 days, finally leveling off at 4.0°C on November 8 at 4:00 pm. Temperature in the side channel pond began to drop from 10.4°C on October 31 at 5:00 pm and continued to drop until it reached 7.3°C on November 9 at 7:45 am.

The hydraulic conductivity (K) of the sediment between the irrigation pond and the side channels is estimated to be 0.0054 m/s, which is within the range expected of gravel substrate. This hydraulic conductivity estimate is based on an estimated 1147.6 m^3 water lost from the irrigation pond over the 137 hours that water levels took to adjust with a flow area of 51.4 m^2. Streamflow during this period was estimated to be 0.312 m^3/s or 0.003 $m^3 s^{-1} m^{-1}$ of dyke length.

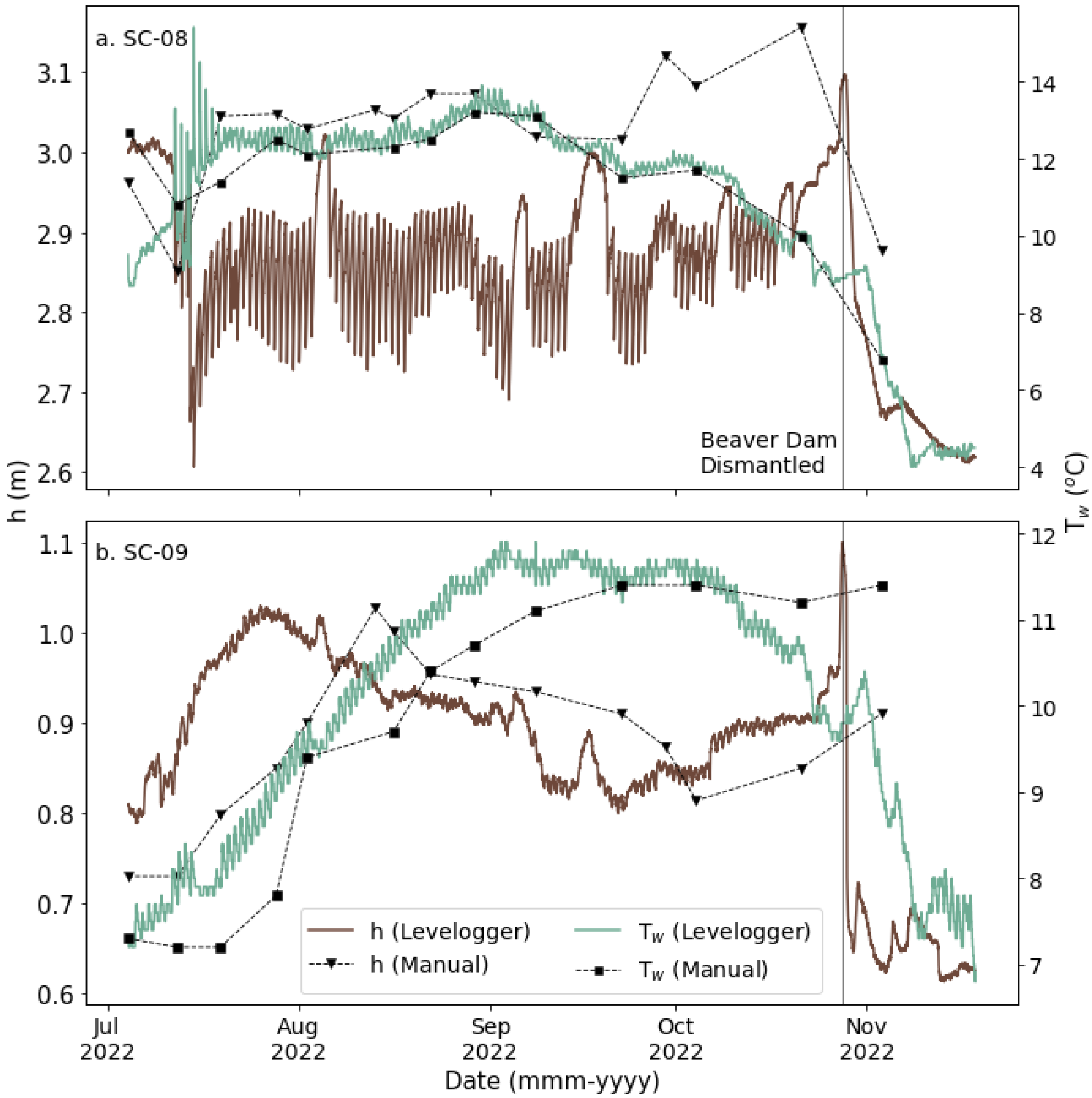

Figure 18 **Water level, h, (brown) and water temperature (green) recorded at 15-minute intervals from June 30 to November 18, 2022 via pressure transducer in the (a) irrigation pond (SC-08) and (b) the side channel pond (SC-09). Manual readings of water level (inverted triangle) and water temperature (square) are also shown.**

The bottom of the irrigation pond at its deepest point is 3.3 ± 0.05 m lower in elevation than the bed elevation of the side channels (SC-04), and 2.9 ± 0.05 m lower than the bed elevation at the stilling well in the side channels pond (SC-09; Fig. 19). Note that SC-09 is not located at the deepest point in the side channels pond therefore, the relative elevation of the deepest point in the side channels pond is unknown. The bed elevation of the LMR (SC-10) was approximately equal in elevation to the side channels (SC-04 and SC-09).

On the day of the survey, the surface of the water in the side channels (SC-04) was 1.2 ± 0.05 m higher in elevation than the surface of the water in the irrigation pond (SC-08). The surface of the water in the side channels pond (SC-09) was 0.91 ± 0.05 m higher in elevation than the surface water elevation in the irrigation pond (SC-08). Prior to beaver dam removal, the high-water mark was 0.65 ± 0.05 m higher in elevation than on the day of survey.

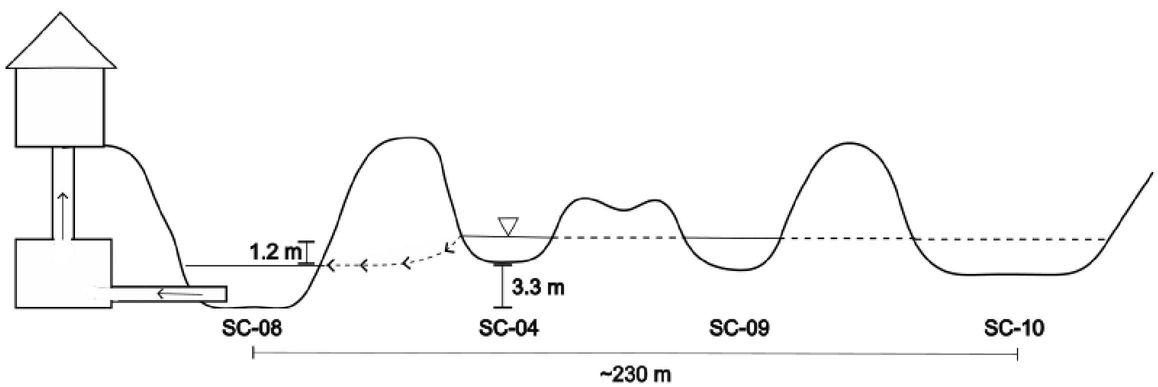

Figure 19 **A conceptual model of the relative elevation survey results. The deepest point in the irrigation pond (SC-08) is 3.3 ± 0.05 m lower in elevation than the side channels (SC-04 and SC-09) and the Lower Mamquam River (SC-10). The survey was conducted on November 18, 2022. Model is not to scale.**

5. Discussion

The observations made in this study provide important information regarding the influence of changing flow regimes and local water use on GWSI in a constructed groundwater-fed side channel during the summer dry season. Given the popularity of groundwater-fed channels as a restoration technique in the PNW (Sheng 1990; Bonnell 1991; Morley et al. 2005), their importance as rearing sites for juvenile coho (Sheng 1990), and their susceptibility to dewatering events (Bradford 1998; McMichael et al. 2005; Thuncher 2021; Brend 2022), this study provides important information to practitioners on challenges and opportunities to be aware of when managing and designing similar features in the future. In this context, the most notable finding from this study is that under specific environmental conditions the Mamquam side channel complex can be a local surface water sink, as observed during the 2022 dry season (Fig. 10 and 20b). The data also suggests that the side channel complex is hydraulically connected to the SVGC irrigation pond. Temporal and spatial patterns of streamflow in the side channels are influenced by streamflow in the LMR, water level in the shallow alluvial aquifer, and local water use. Temporally, the side channels become progressively more reliant on groundwater as streamflow in the LMR diminishes throughout the dry season. Spatially, losing and gaining sections in the side channel complex vary throughout the dry season.

Climate change and elevated water demand pose additional challenges regarding the design and management of side channel features in mountainous river watersheds in the PNW. For example, projections made for Western Canada suggest glacial melt at an accelerated rate, and near to a complete loss (70 to 90%) of mountain glaciers in BC by the end of the twenty-first century (Clarke et al. 2015; Anderson and Radić 2021). The potential loss of glaciers will have a significant and detrimental impact to summertime streamflows, and streamflow distributions in affected basins as glacial melt waters are an important component of the summertime water budget. How the issue evolves in the future will bring further challenges because streamflow will exhibit two contrasting responses. First, streamflow is expected to peak with accelerated glacial melt, perhaps increasing summertime flow distributions relative to historical records (Clarke et al. 2015). Second, streamflows will gradually decline over several decades as glacial meltwater contributions wane from glacier loss (Clarke et al. 2015; Anderson and

Radić 2021). Following this second period of response, some, if not many, affected basins could routinely experience periods of no sustained surface flows along mountain stream reaches during the summer months, representing a dramatic departure in general habitat conditions for anadromous fish. Other aspects of climate change bring new planning challenges into focus, compounding the issues that must be addressed. For example, an increase in the intensity and severity of rainfall events during the wet season is already being observed in the PNW causing unprecedented flooding (Gillett et al. 2022). Dry season characteristics in the PNW are also intensifying with warming air temperatures and snow drought causing earlier spring runoff, lower summer streamflow, and high water temperatures (Stewart et al. 2005; Clark 2010; Wu et al. 2012; Foster and Allen 2015). These changes in climate are expected to increase the likelihood of hillslope failures, and extreme high and low flow events, bringing additional stress to the riverine ecology of gravel-bed streams and surrounding infrastructure of coastal mountainous watersheds (Gillett et al. 2022). The Mamquam River is an example of a coastal mountainous watershed that may undergo such changes in streamflow distribution as the Mamquam Icefield and Garibaldi Glaciers are located in the watershed's headwaters and are likely to experience accelerated melt and associated hillslope instability with climate change.

The LMR flows across an alluvial fan which is a naturally dynamic and responsive system (KWL 2011; Castro and Thorne 2018). The river tends to change flow paths during rainfall and flood events, as observed during the 1920 flood when the river changed course (Béll 1975). The dykes along the north and south banks of the river have restricted the channel in an artificially constrained configuration (Foy et al. 2008; Castro and Thorne 2018). With high flow events projected to occur at higher frequencies (Clarke et al. 2015; Gillett et al. 2022), there is an increased likelihood of the LMR overtopping its banks, perhaps in association with debris flows or other mass transport events from the upper watershed or creating new flow paths through the side channel complex causing a change in their form and function.

Progressively lower summertime streamflow in the LMR increases the probability of the side channel complex losing surface flow during the dry season. GWSIs in the side channel complex were strongly influenced by changing flow regimes in the LMR. During the 2022 dry season, streamflow in the side channel complex declined (Fig. 5) as snowmelt supported streamflow in the LMR diminished (Fig. 4). Simultaneously, water temperature (Fig. 11) and specific conductance (Fig. 14) in the side channels gradually increased, indicating that the side channel complex becomes progressively more groundwater supported as the LMR transitions from snowmelt to baseflow flow regimes. The period that the side channels are groundwater supported is when they are most susceptible to water withdraw because they are not receiving recharge from the LMR (Fig. 10), and the side channel complex can function as a surface water sink under specific environmental conditions (Fig. 20b; Bierkens et al. 2021). The period that the side channels are a surface water sink is expected to increase in duration as summertime streamflow in the LMR reaches new lows and water demand is elevated relative to storage availability in the shallow alluvial aquifer.

Water demand and water scarcity is expected to increase with increasing air temperature and deglaciation (Anderson and Radić 2020), exasperating seasonal lows in local groundwater levels and streamflow (Abatzoglou et al. 2014; Baalousha 2016;). Relative elevation and hydraulic conductance estimates support the hypothesis that the side channels are a source of water to the irrigation pond during baseflow conditions (Fig. 20b). Thus, drawdown of water in the irrigation pond during the dry season has the potential to drawdown and potentially dewater the side channel complex when they are in baseflow (Abatzoglou et al. 2014; Baalousha 2016).

Although the Mamquam side channel complex has been effectively managed as spawning and rearing habitat for chum and coho salmon for over 30 years, climate change and elevated water demand bring unprecedented challenges. To continue to manage the side channel complex with these challenges, come opportunities for adaptive management and collaboration. Adaptive management strategies should focus on improving water conservation during low flow periods and collaboration amongst water rights holders, community stewardship groups, federal agencies, the public, and Squamish First Nation.

Working with beaver to improve summertime streamflow is an adaptive management strategy being employed in salmon bearing streams (Pollock et al. 2011; Bouwes et al. 2016). Beavers were historically widespread in the region and coexisted with Pacific salmon (Bouwes et al. 2016). Beavers are known to improve water conservation in streams as the impoundment of water behind their dams alters streamflow and GWSIs (Majerova et al. 2015). Juvenile salmonids typically exist in higher densities and display higher growth and survival rates in streams with beaver dams than streams without (Pollock et al. 2011; Majerova et al. 2015; Bouwes et al. 2016). These benefits are in part due to increased flows during low periods (Majoerova et al. 2015). Ponding behind beaver dams also allows opportunities for groundwater recharge, thus increasing groundwater elevations locally (Fig. 20b; Majerova et al. 2015). Streams have been found to transition from losing to gaining following construction of a beaver dam, specifically areas upstream of a dam transition to gaining, and areas downstream of a dam remain losing (Majerova et al. 2015).

The effects of beaver were observed in this study, where the construction of a beaver dam downstream of SC-04 altered the spatial distribution of streamflow throughout the side channels. Following construction of the beaver dam, significant ponding was observed upstream while low flows were observed downstream. As streamflow in downstream sites diminished throughout the dry season, upstream sites sustained surface flows and ponded conditions (Fig. 5 and 9). GWSIs were also altered by the beaver dam, where upstream sites remained gaining while downstream sites transitioned to losing (Fig. 10a). The exception to this is the site adjacent to the irrigation pond, SC-04, supporting the hypothesis that the side channels were contributing water to the SVGC irrigation pond during baseflow (Fig. 20b). More evidence to support this hypothesis is provided below.

The natural construction of the beaver dam and its subsequent removal during the monitoring period enabled an unplanned natural experiment whereby hydraulic connectivity of the side channels with the irrigation pond was established. The removal of the beaver dam provided the opportunity to observe the change in water level in the side channels and the irrigation pond in response to the release of water impounded by the dam (Fig. 18). Water level in the side channels and the irrigation pond began to lower immediately following the removal of the dam and lowered by similar amounts ($\Delta h = 0.416$ m and 0.427 m, respectively). The drop in water level in both water bodies following the release of impounded water demonstrates that the water impounded by the beaver dam raised water levels locally, benefiting the irrigation pond and the side channels. Pressure transducers positioned in the irrigation pond and the side channels captured the changes in water level and water temperature, allowing estimates of hydraulic conductivity to be calculated. The substrate of the dyke between the irrigation pond and side channels was estimated to be highly permeable ($K = 0.0054$ m/s) and within the expected range of a gravel substrate (Freeze and Cherry 1979). This aligns with the physiogeography of the area, and the reported methods used to construct the dyke (KWL 2011; Foster and Allen 2015).

5.1. Recommendations for further study

Dismantling beaver dams is a practice in the Mamquam side channel complex due to concerns of inhibiting passage of spawning salmon. According to local stewards, the beavers have a propensity to build dams in the same locations every summer. Currently the strategy is to leave the dams constructed during the dry season and remove them when water levels rise, and salmon come to spawn in the fall. This is a sufficient short-term strategy in balancing priorities of retaining water for juvenile salmonids in the summer and ensuring passage for spawning salmon in the fall. However, there may be sufficient space in this location to allow the side channels to create a new path around the dam without danger of overtopping the dyke when water levels rise. The creation of a new flow path at high flows would increase stream complexity and render removal of the beaver dam in the fall unnecessary to ensure fish passage. Studies have shown that the ability of spawning salmon to navigate around beaver dams depends on the species, height and length of the dam, pool depth at the base of the dam, and stream velocity (Mitchell and Cunjak 2007; Lokteff et al. 2013). A fish passage study may provide insight into how beaver dams should be managed in the Mamquam side channel complex into the future.

Assuming that the irrigation pond and the side channel complex are indeed hydraulically connected, collaborating with the SVGC on further study and water use during the dry season has the potential to mitigate the seasonal drying or drawdown of both water bodies. An additional season of streamflow and water level monitoring would strengthen the findings of this study as interannual streamflow can be variable (Fig. 4). Collaborating with the SVGC to perform pump tests would allow testing of hypotheses presented in this study (Fig. 20). Specifically, a pump test would allow calculations of transmissivity and understanding of how water levels in the irrigation pond and the side channels are influenced under various flow conditions (Fig. 20). Knowing the conditions that the side channels experience diminished habitat conditions could benefit new thinking around operations of the irrigation pond in relation to the side channels, and coho rearing habitat conditions. This information will also help to determine if the dyke between the irrigation pond and the side channels should be made less permeable with a clay core or liner, to decrease hydraulic conductivity between the water bodies.

Long-term management solutions may be found at the watershed or reach scale. Large gravel removals from 1981 to 1995 and a sediment balance analysis suggest that the side channels were constructed at a time when the LMR was not in dynamic equilibrium (KWL 2011). The function of groundwater-fed side channels is greatly reliant on the elevation of the side channel relative to the river and baseflow conditions (Sheng 1990; Bonnel 1991). Thus, understanding the sediment balance and changing bed elevations in the LMR may provide reach-scale insight that is important for improving the expression of surface flow in the side channels long-term. In addition to a sediment budget analysis, a professional elevation survey is recommended to understand the longitudinal elevation of the side channels relative to the SVGC irrigation pond and LMR.

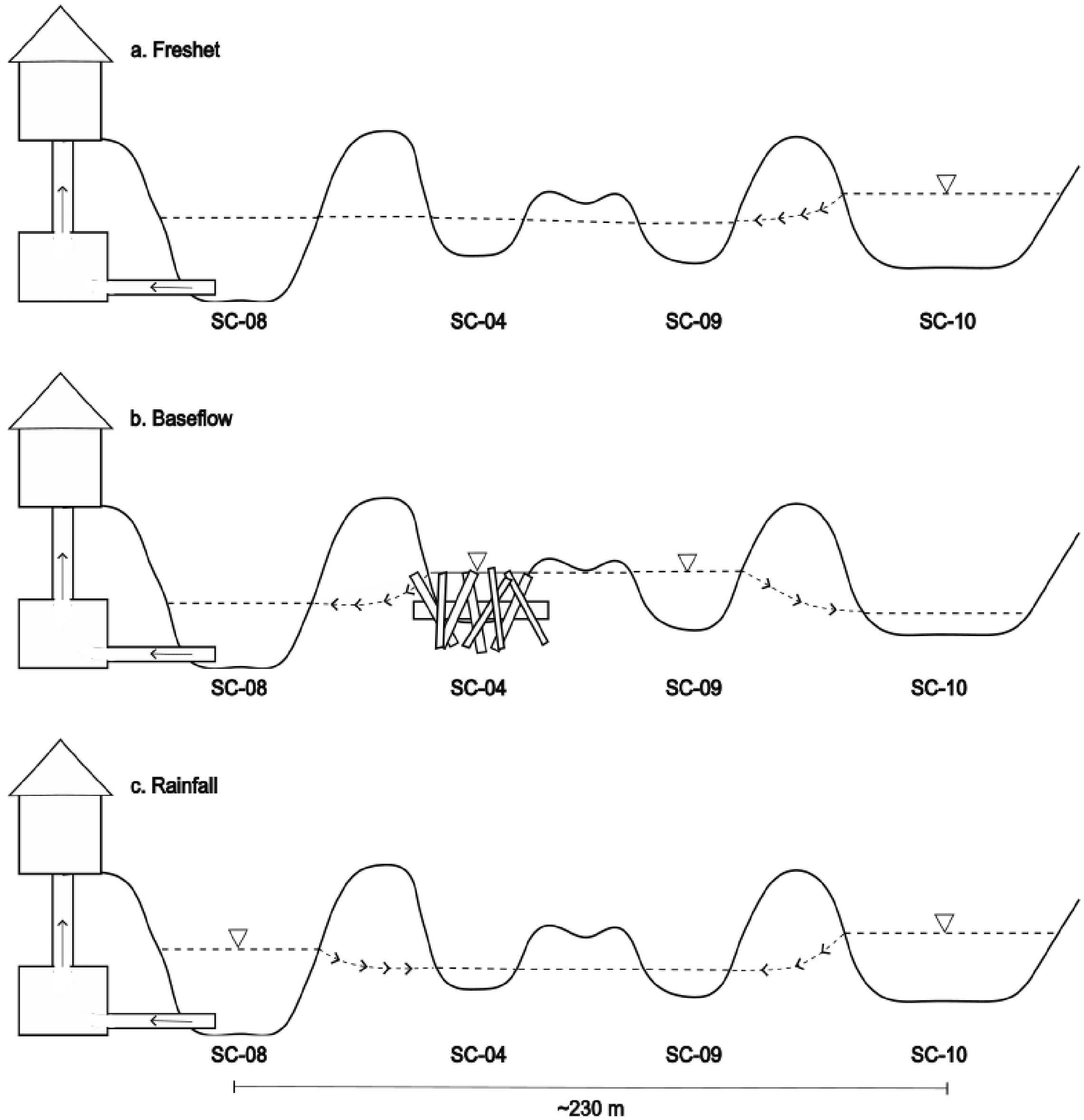

Figure 20 **A conceptual model hypothesizing changing groundwater-surface water interactions (GWSI) between the irrigation pond (SC-08), the side channels (SC-04 and SC-09), and the Lower Mamquam River (SC-10) along a transect. GWSI changes as the watershed transitions from gaining during (a) freshet, losing during (b) baseflow, and gaining during (c) rainfall flow regimes. Note the removal of the beaver dam caused the water level in the side channels to lower.**

6. Conclusion

This study was successful in characterizing the temporal and spatial patterns of surface flow in a constructed groundwater-fed side channel throughout the dry season. The commencement and conclusion of the monitoring period was properly timed through understanding of the Mamquam River flow regime, diligent monitoring of the WSC gauge, and anecdotal weather observations. Manual streamflow measurements, although laborious, were taken at appropriate time and spatial intervals to detect broad-scale flow and water quality trends. A longitudinal profile of streamflow and water quality was effectively created by taking measurements at defined and appropriately spaced cross-sections along the length of the side channels. Water quality measurements, particularly SpC, in groundwater wells could have been improved by purging the wells prior to sampling. Still, clear trends are observed in groundwater level and water temperature data. Finally, the position of the pressure transducers allowed the detection of hydraulic responses to changing storage conditions.

In summary, this study found that the Mamquam side channel complex is a surface water sink during the dry season and is susceptible to water withdraw by the SVGC. Climate change and elevated water demand pose challenges for the design and management of similar features in the future. Opportunities arise in adaptively managing changing flow conditions and collaborating amongst the community and water rights holders. Working with beaver is recommended as they improve water conservation and juvenile salmonid survival. This study provides an initial assessment of GWSIs in the Mamquam side channel complex and identifies needs for further study to inform future work. Research recommendations in order of priority include; (1) An additional season of streamflow and water level monitoring; (2) Collaboration with the SVGC to perform pump tests; (3) Commissioning of professionals to perform an elevation survey of the side channels and LMR. (4) Conducting a sediment budget analysis of the LMR and; (5) Performing a fish passage study to inform beaver dam management.

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Appendix A. Dissolved Oxygen

DO concentration in the side channels decreased over the monitoring period and at certain times and locations declined beyond the chronic and acute limits of Pacific salmon (Figure 19). DO in the LMR remained steady and fully saturated throughout the duration of the dry season (Fig. B1). The side channel pond (SC-09) showed the greatest change in DO, as well as the lowest average concentration of all fish bearing surface water sites (Fig. B1; Table B1). SC-09 also persisted the longest below the chronic and acute requirements for Pacific salmon (Fig. B1; Table B1).

DO at flow sites showed little longitudinal variability with no clear trend moving downstream (Fig. B1 and B2). Overall, DO in flow sites (SC-01 to SC-07) ranged from 4.32 mg/L on September 10 to 11.42 mg/L on June 30. Sites SC-01, -02, -04, -05, and -09 all declined below the chronic DO tolerance for Pacific salmon over extended periods (Fig. 19 and Table 6). SC-09 was the only fish bearing surface water site that fell below the acute tolerance level for Pacific salmon. SC-09 was below 3 mg/L from August 16 to October 21, a total of 66 days.

Table A1 A summary table of dissolved oxygen (mg/L) descriptive statistics reported at surface water sites in the Mamquam side channels complex over the course of the monitoring period (June 30 to November 5, 2022).

Site	Min.	Max.	Mean	SE	% change	No. of days <6 mg/L	No. of days <3 mg/L
SC-01	4.32	11.42	7.08	2.33	62.17	57	0
SC-02	5.87	11.35	7.77	1.82	48.28	22	0
SC-03	5.97	11.26	8.00	1.74	46.98	0	0
SC-04	4.90	11.30	7.15	1.87	56.64	27	0
SC-05	4.61	10.72	7.21	2.16	57.00	36	0
SC-06	5.20	10.63	7.65	1.39	51.08	0	0
SC-07	5.24	11.08	8.14	1.35	52.71	0	0
SC-09	1.55	9.19	3.87	2.31	83.13	107	66
SC-10	11.09	14.31	12.65	0.91	22.50	0	0

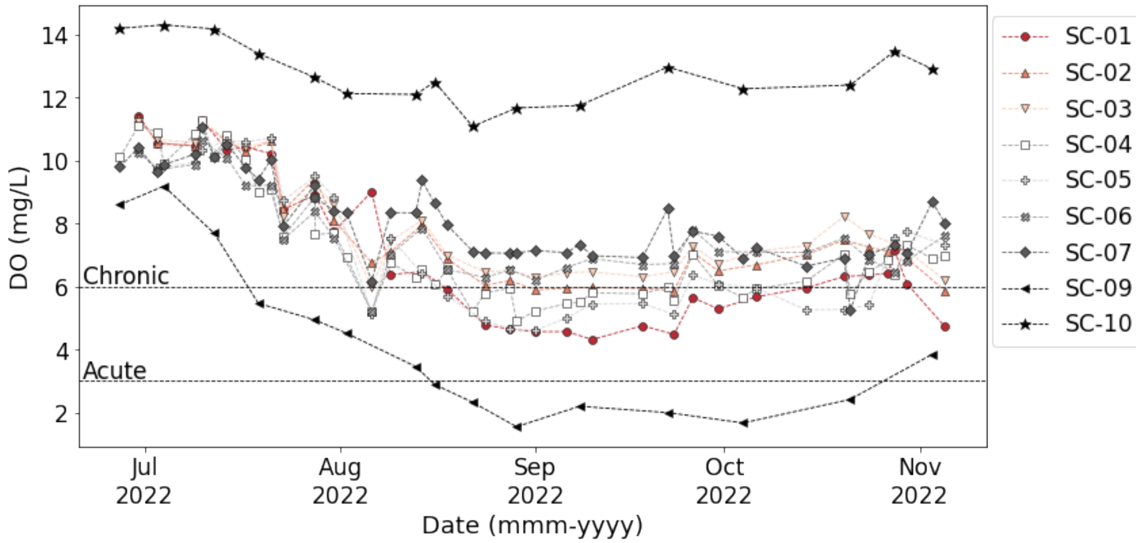

Figure A1 **Dissolved oxygen over time at all surface water sites in the side channels. The chronic (6 mg/L) and acute (3 mg/L) minimum oxygen requirements for *Oncorhynchus spp.* are delineated by horizontal dotted lines.**

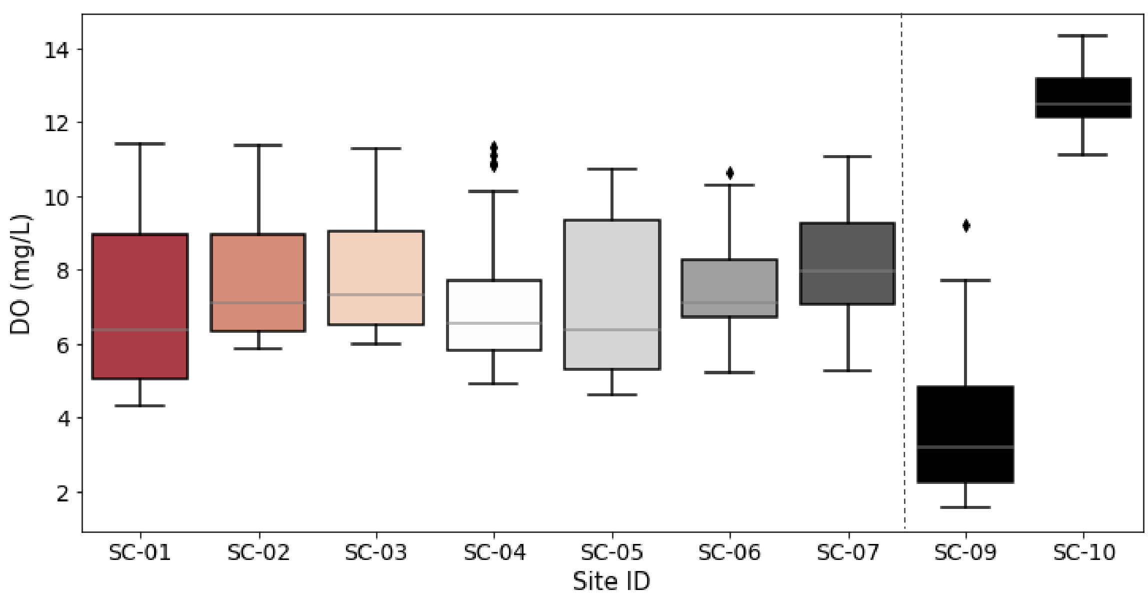

Figure A2 **Boxplot of dissolved oxygen (mg/L) at all surface water sites in the side channels over the study period. The medians (light grey), 25th and 75th quartiles (box), minimum and maximum values (whiskers), and outliers (diamond) at each site are shown.**

Declining DO concentrations are a concern during the side channel baseflow period as DO concentrations fall below the critical limits for Pacific salmon at certain locations. DO concentrations in the side channel pond (SC-09) are of particular concern as concentrations fell below the acute limits (<3 mg/L) for Pacific salmon for 66 days during the dry season. Coho salmon are typically transferred into these ponds when the side channels dewater in the summer months and ponds may pose an ecological trap for Pacific salmon if they are hypoxic for most of the summer.

Appendix B. Survey Data

Table B1 Field notes from relative elevation survey conducted on November 18, 2022. Survey began at the Squamish Valley Golf Club irrigation pond (SC-08), went south west across of the Mamquam side channel complex (SC-04 and SC-09), and ended at the Lower Mamquam River (SC-10).

PT	BS	FS	HI	Low	HT	Elev.	Notes
TBM1		0.135	0.210	0.110		100	Water Marker
Stilling		3.610	3.720	3.490		96.39	11'7 1/5" @ top of S.W.
-	moved	-	-	-			
TBM1	1.410	1.430	1.380			100.1	
TBM2		0.380	0.680	0.120		101.13	8th post, north side
Setup2		1.260	1.280	1.225		100.26	8th post, north side
-	moved	-	-	-			
Setup2	1.870	2.240	1.500				
TBM1	2.020					100.1	8th post, north side
TBM2	1.050		1.100	0.900		101.07	8th post, north side
Setup3						100.65	Height from GR.: 1.470 m
TBM3		1.690	2.130	1.250		100.43	Top of slope heading down
-	moved	-	-	-			
TBM3						100.43	Height from GR. 101.24, 0.81 m
Setup3	0.570					100.67	
TBM4		3.855	3.990	3.715		98.155	Top of beaver stump
-	moved	-	-	-			
TBM4					98.905	98.155	height from stump: 0.75
SC-04		2.605				96.3	on river bed
							staff reading: 0.510
BDHWM		1.450				97.455	beaver dam HWM
BDBed		2.700					bed @ beaver dam
TBM5	0.210				98.905	98.695	Cottonwoods south of SC-04
-	moved	-	-	-	-		
TBM5					99.975		height from G.S.: 1.28 m
TBM4	1.840					98.135	
TBM6		1.940				98.035	N of SC-09
-	moved	-	-	-	-		
TBM6					99.245		height from G.S.: 1.21 m
TBM7	1.715					97.53	Erica GPS the PT.
-	moved	-	-	-	-		
TBM7					99.160		height from G.S.: 1.630
SC-09		3.260				95.9	on the pond bed
							staff reading: 0.618

PT	BS	FS	HI	Low	HT	Elev.	Notes
							tidbit/LL removed 13:10
TBM8		0.635				98.525	root on trail
-	moved	-	-	-	-		
TBM8					100.015		height from G.S.: 1.49 m
TBM9		2.250				97.765	
-	moved	-	-	-	-		
TBM9					99.490		height from G.S.: 1.725
TBM10		0.050				99.44	
-	moved	-	-	-	-		
TBM10					100.715		HT. from G.S.: 1.275
TMB11		2.220				98.495	
-	moved	-	-	-	-		
TBM11					99.295		HT. from G.S.: 0.80
SC-10		2.965				96.330	River bed @ riprap

Appendix C. Additional Figures

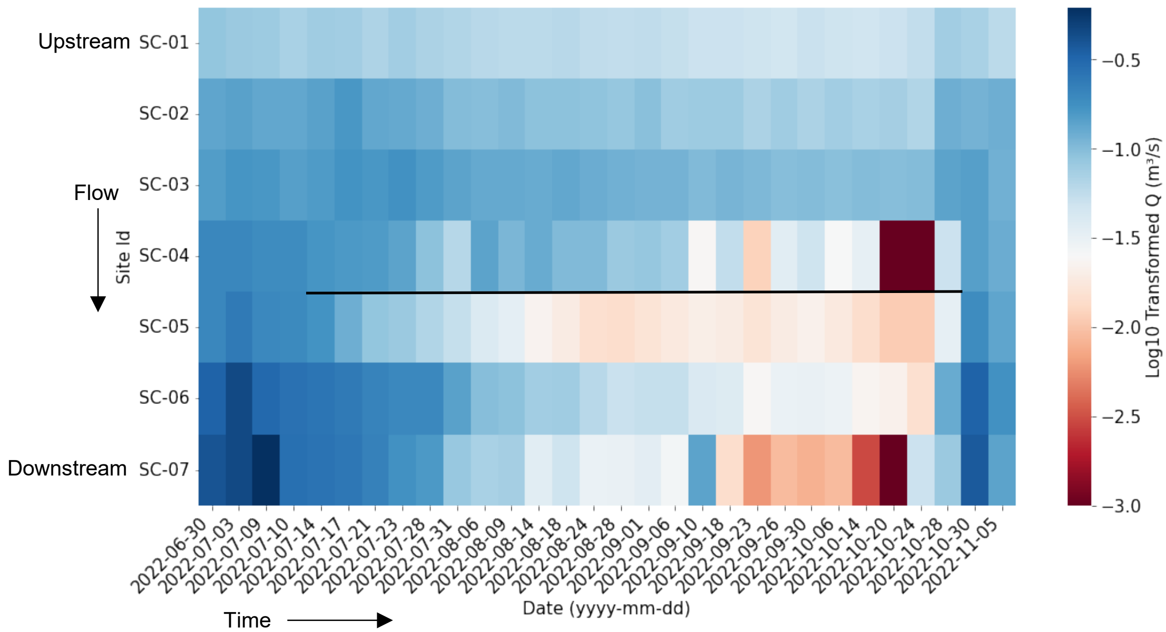

Figure C1 **Heat map of streamflow, Q, at each site and over time. Solid black line dictates the position and timing of beaver dam construction (July 14, 2022) and removal (October 28, 2022). Progressively lower streamflow at SC-04 is due to ponding upstream of the beaver dam.**