SQUAMISH

HARDWIRED *for* ADVENTURE

DISTRICT OF SQUAMISH

HYDROGEOMORPHIC ASSESSMENT OF SQUAMISH RIVER NEAR THE WASTEWATER TREATMENT PLANT OUTFALL

Polar File No. 910201
FINAL REPORT
September 2020

polar geoscience ltd.

HARDCOPIES

Several pages of this report have been formatted for tabloid (11 x 17) sized paper. If hardcopies are desired, we recommend that all pages be printed "actual size". If tabloid pages are reduced to fit smaller format paper, the presented information may be illegible.

SUGGESTED CITATION

Polar Geoscience Ltd. 2020. Hydrogeomorphic Assessment of Squamish River near the Wastewater Treatment Plant Outfall. Prepared for the District of Squamish. Polar File No. 910201.

COVER PHOTO

View upstream of Squamish River across from the wastewater treatment plant outfall during low flow conditions on January 14, 2015 [69.1 m^3/s discharge for Squamish River near Brackendale (08GA022)].

polar geoscience ltd.
1005 Balsam Place
Squamish, BC, V8B 0W1
(604) 815-4548
www.pgeo.ca

September 3, 2020

Reference: 910201

Mr. Ben Kineshanko
Technical Operations Manager
District of Squamish
PO Box 310
Squamish, BC V8B 0A3

Dear Mr. Kineshanko:

Re: HYDROGEOMORPHIC ASSESSMENT OF SQUAMISH RIVER NEAR THE WASTEWATER TREATMENT PLANT OUTFALL – FINAL REPORT

Polar Geoscience Ltd. is pleased to provide this final report on the above-noted study. The report summarizes our findings and provides conceptual options to improve mixing conditions near the wastewater treatment plant outfall on the Squamish River. We trust this completes our assignment to your satisfaction. Please contact us if you have any questions or comments.

Yours truly,
Polar Geoscience Ltd.

03-Sep-2020

Lars Uunila, *MSc, PGeo (BC), PGeol (AB), PH, CPESC, CAN-CISEC, BC-CESC*L
Senior Hydrologist & Geoscientist

EXECUTIVE SUMMARY

The District of Squamish received complaints regarding undesirable water quality conditions near the wastewater treatment plant (WWTP) outfall on the Squamish River, which were associated with poor mixing conditions during low river flows in winter months. In addition, sediment aggradation and channel shifting along the Squamish River and distributary channels of the Mamquam River alluvial fan, located immediately upstream, have locally changed flow characteristics in the vicinity of the WWTP outfall. Polar Geoscience Ltd. conducted a study to review site conditions and background reports, available hydrometric data for the Squamish, Cheakamus, and Mamquam Rivers, and aerial imagery of the lower Squamish River and tributaries between 1946 and the present to understand the roles of sediment supply, hydrology, and tidal interactions near the site and to understand the driving factors for the recent channel changes.

The analysis showed that undesirable water quality conditions near the WWTP outfall at low flows are not likely associated with changes in hydrology or tidal impacts, but that sediment aggradation is the driving factor leading to these conditions. A gravel bar upstream of the WWTP outfall has accreted laterally and downstream, and the growth of the gravel bar is expected to continue and further restrict mixing processes at the outfall. Given that conditions for mixing are expected to worsen, mitigation should be considered, and four locations for the WWTP outfall were reviewed. Since site-specific flow and sediment transport patterns vary, the expected service life of a WWTP outfall at these locations could range from less than a year to greater than 20 years.

Of the outfall locations considered, one location approximately 300 m to 450 m downstream of the current outfall is recommended for further examination since it not only represents a location where the outfall would intercept the river thalweg (i.e., location of deepest flow on the river cross-section), but also is at a location where sediment accumulation over the long-term (20 years +/-) is unlikely to hamper mixing conditions. Furthermore, construction and maintenance of an outfall near this location should be relatively straightforward and feasible and may not trigger an environmental assessment (Hamelin, T., 2020).

There are however some uncertainties associated with moving the current outfall downstream because of increased proximity to a potential salt wedge and to the intertidal zone. Further studies are needed to assess the desired outfall system and whether its operation is feasible at the proposed location. In addition to developing engineering designs and costs for the relocation of the WWTP outfall approximately 300-450 m downstream, we recommend that the District retain qualified professionals to complete the following:

- Conduct dilution modeling for the recommended outfall location (Option 2) that considers the tidal and hydrological conditions, which includes considerations for climate change and sea level rise and the potential effects of a salt wedge, and the total flows of the Squamish, Cheakamus, and Mamquam rivers at the proposed location to ensure that it meets the relevant regulations and guidelines for the initial dilution zone (IDZ). Based on previous work completed by the District, a Class D estimate of such work approximately $60,000 (Quarmby, 2020); and

- If required by regulators, conduct an environmental impact assessment for the proposed new outfall (Option 2), consistent with all relevant federal, provincial and local regulations and guidelines. Based on previous work completed by the District, a Class D estimate of such work approximately $40,000 (Quarmby, 2020).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION & OBJECTIVES

The District of Squamish has received complaints regarding undesirable water quality conditions near the wastewater treatment plant (WWTP) outfall on the Squamish River (FIGURE 1.1). Such conditions are associated with poor mixing conditions when river flows and levels are relatively low, which typically occur over winter months. In addition, sediment aggradation and channel shifting along the Squamish River and distributary channels of the Mamquam River alluvial fan, located immediately upstream, have locally changed flow characteristics in the vicinity of the WWTP outfall.

The principal objectives of this assessment were to identify the cause(s) of the poor mixing conditions in the river at the WWTP outfall and to identify one or more conceptual solutions to improve WWTP outfall mixing conditions. Site conditions at the WWTP outfall are driven by several interconnected factors which include sediment supply, hydrology, and tidal interactions, and the role of each of these factors at the WWTP outfall is poorly understood. This study reviews each of those factors to understand how they have changed over time in order to identify the driving factors for changes at the WWTP outfall. Finally, in order to support the District’s near-term decision making on WWTP outfall upgrades, optional locations for the WWTP outfall are reviewed and recommended next steps are identified.

1.1 STUDY TEAM

This study was initiated by Ben Kineshanko, Technical Operations Manager with the District of Squamish. Key members of the technical team included Lars Uunila, MSc, PGeo, PGeol, PH, CPESC, CAN-CISEC, BC-CESCL (Senior Hydrologist & Geoscientist, Project Manager of Polar) and Daphnee Tuzlak, MSc, PGeo (Project Geoscientist/Fluvial Geomophologist). Mike Miles, MSc, PGeo (Senior Geomorphologist) of M. Miles and Associates Ltd. served as Senior Advisor and provided independent reviews of preliminary drafts of the report. All comments from the reviews were taken into consideration in preparation of this report. However, all analyses and conclusions remain the sole responsibility of the primary authors, including the Geoscientist of Record (Lars Uunila, PGeo).

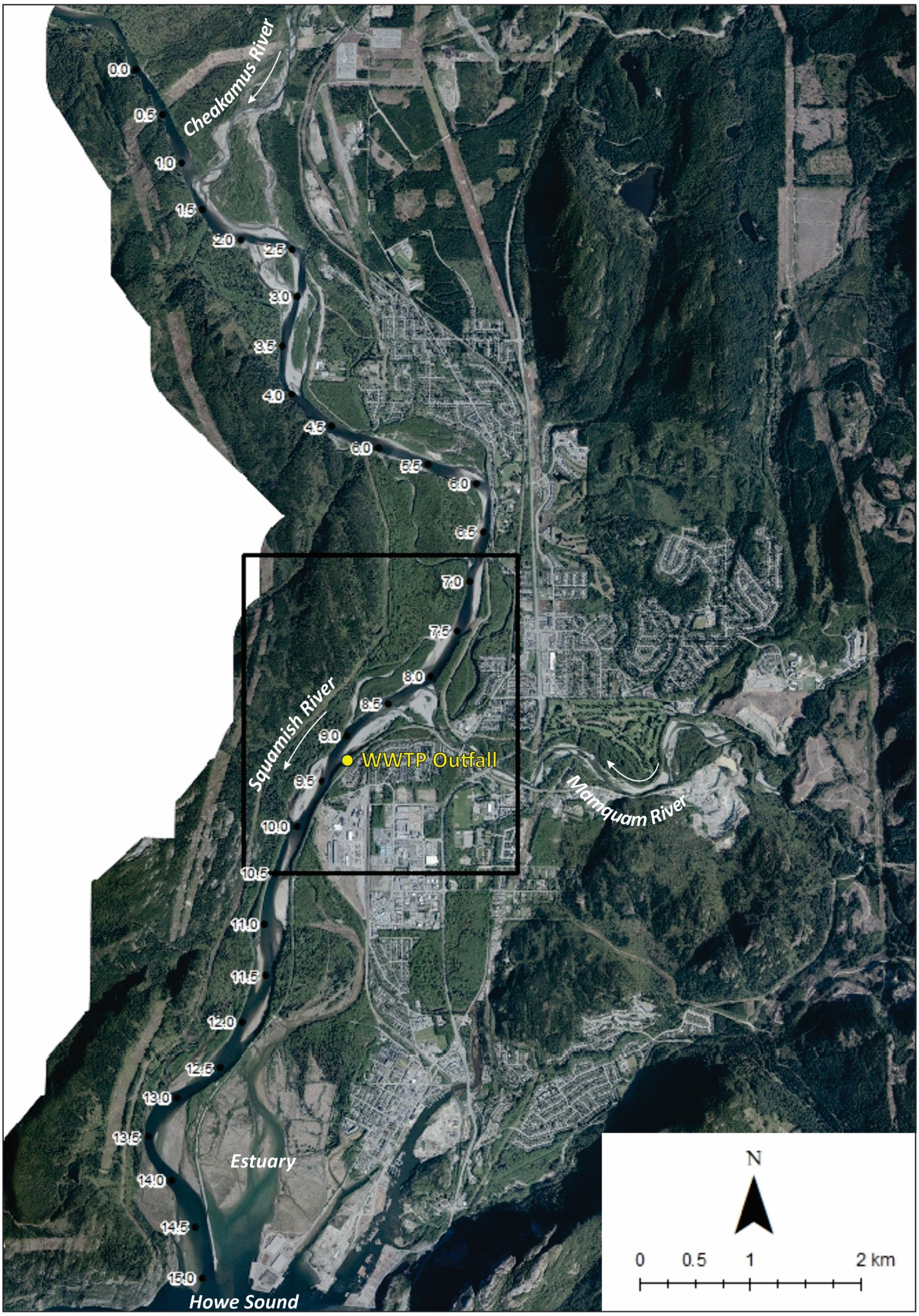


FIGURE 1.1 *Location of the Squamish River study reach between Cheakamus River and Howe Sound. Numbered points along the river indicate distance along the mainstem Squamish River in the area of interest (km). The black rectangle denotes extent of* FIGURE 6.2*,* FIGURE 6.3*,* FIGURE 6.4*, and* FIGURE 6.5*. Image source: District of Squamish, April 28, 2019.*

2. METHODS

Based on the above-noted objectives, the scope of work included:

1. Several field reviews, which included: a field meeting near the WWTP outfall between Ben Kineshanko and Lars Uunila on June 22, 2020 (Squamish River discharge approximately 600 m^3/s), a brief field review near the WWTP outfall by Lars Uunila on July 3, 2020 (Squamish River discharge approximately 400 m^3/s), a field reconnaissance by Lars Uunila and Daphnee Tuzlak along the lower Squamish River to observe site conditions near the WWTP outfall on July 17, 2020 (Squamish River discharge approximately 500 m^3/s), and a field review of the lower Squamish River by Lars Uunila on August 15, 2020 to confirm channel characteristics during lower flows (Squamish River discharge approximately 150 m^3/s).
2. Compilation and review of relevant background reports, including but not limited to KWL's (2011) Squamish River and Mamquam River Survey and Flood Assessment.
3. Compilation and review of hydrometric data for lower Squamish River and tributaries, especially data collected after KWL's (2011) report. This includes Water Survey of Canada (WSC) data from Squamish River near Brackendale (08GA022), Cheakamus River near Brackendale (08GA043), and Mamquam River above Ring Creek (08GA075).
4. Compilation and review of aerial imagery of the lower Squamish River from the mouth of the Cheakamus River to the river's outlet in Howe Sound. Orthophotos for 1999, 2004, 2009 2013, 2016 and 2019 were obtained from the District of Squamish. These were supplemented by nine sets of hard copy historical air photos (1946 to 1994) obtained from the University of British Columbia Air Photo Library and seven sets of air photos (1980-1996) posted on the Province of BC Air Photo Viewer[1]. The purpose of the air photo review was to understand the historical changes in channel morphology that has or could affect conditions near the WWTP outfall. The review of historical imagery spans approximately 74 years (1946 to present).
5. Based on the review, historical channel behaviour along the lower Squamish River was summarized using a selection of the available imagery to demonstrate key events and when they occurred. The summary illustrates the historical context to the issues currently observed near the WWTP outfall and provides a basis to estimate a

[1] https://www2.gov.bc.ca/gov/content/data/geographic-data-services/digital-imagery/air-photos/air-photo-viewer

range of likely future channel conditions. Consideration of the effects of projected climate and sea level changes was also made.

6. Based on expected future channel conditions, four potential locations for a future WWTP outfall were identified. The effectiveness of each location was reviewed, and uncertainties associated with future river channel behaviour were considered. A preferred location for the WWTP outfall was identified, and recommendations for further studies to assess the feasibility of the preferred site were outlined.

3. PHYSICAL SETTING

The area of interest for this study extends for approximately 15 km along the lower Squamish River from the mouth of the Cheakamus River to the Estuary where the river discharges into Howe Sound. The Squamish River is a high-energy gravel-bed river with two major tributaries within the area of interest, the Cheakamus River, and the Mamquam River, which enter the Squamish River approximately 7.5 km and 1.0 km upstream of the WWTP outfall, respectively (FIGURE 1.1, FIGURE 3.2). The morphology of the Squamish River changes with distance downstream; the upper river is confined within a bedrock canyon, then transitions from a steep and braided reach, to wandering morphology, and then to a meandering channel. The reach of the Squamish River within the area of interest is a meandering, single-thread channel containing gravel bars and vegetated islands.

Changes to the planform of the Squamish River in response to flooding within the area of interest varies depending on the morphology of the river (Hickin and Sichingabula, 1988). Bauch and Hickin (2011) found that the rate of geomorphic change in the Squamish River accelerated during the 1980s and mid-1990s. The river's morphology in the area of interest is affected by relatively large sediment inputs and flows from the Cheakamus and Mamquam Rivers (KWL, 2011). Other sources for large sediment inputs include landslides or debris flows in the upper Squamish River (e.g., large landslides associated with volcanic centre Mount Cayley) (NHC, 2018). These sediment sources are considered outside the scope of this study and indirect effects of these sources to the WWTP outfall are not considered. Paige and Hickin (2000) found that bedload movement through the Squamish River upstream of the Cheakamus confluence occurred as coherent waves or pulses at an average velocity of 15.5 m/day. A preliminary sediment budget for the Squamish River indicated net aggradation of approximately 11,500 m^3/yr between approximately 3.5-11.5 km, which may accumulate in localized areas (KWL, 2011). The gradient of the Squamish River steepens downstream of the Cheakamus River fan to 0.0016 (0.16%), and then decreases to 0.0009 (0.09%) near the Mamquam River confluence and decreases further to 0.0005 (0.05%) downstream of the Mamquam River (FIGURE 3.1). As the channel slope decreases, sediment inputs from the Cheakamus and Mamquam Rivers are deposited along the Squamish River in the vicinity of the WWTP outfall, and generally only sand and finer material are discharged into the outlet in Howe Sound (KWL, 2011; Hicken, 1989). There is a distinct slope-break in the longitudinal profile near 10.0 km, which appears to mark a transition in the bed-texture from primarily gravel to an increasing proportion of sand and finer sediments (FIGURE 3.1). However, even near the estuary (13.0-14.0 km), finer-textured gravel was noted along bar surfaces.

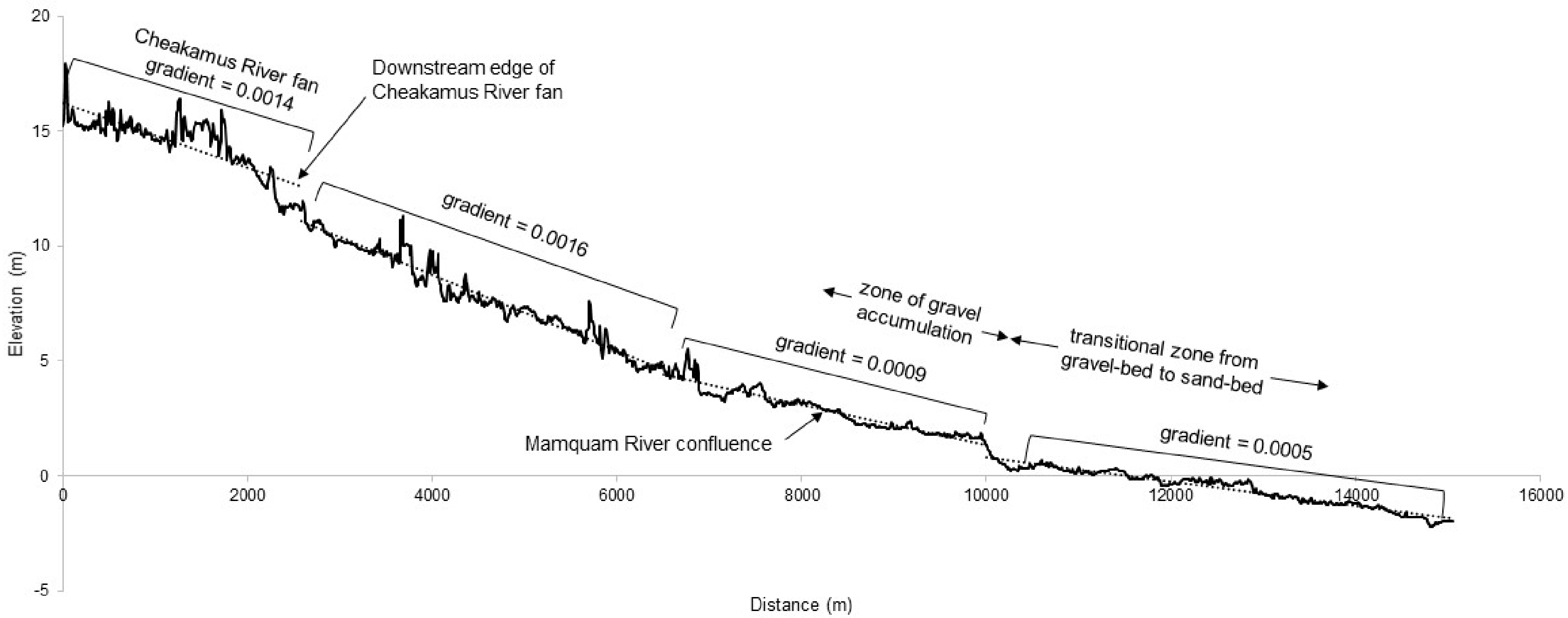


FIGURE 3.1 *Longitudinal profile showing assumed water surface elevations of the Squamish River centreline along 10 m intervals. Note the changes in gradient as the river approaches Howe Sound. Digital Elevation Model (dated 2016) obtained from the District of Squamish.*

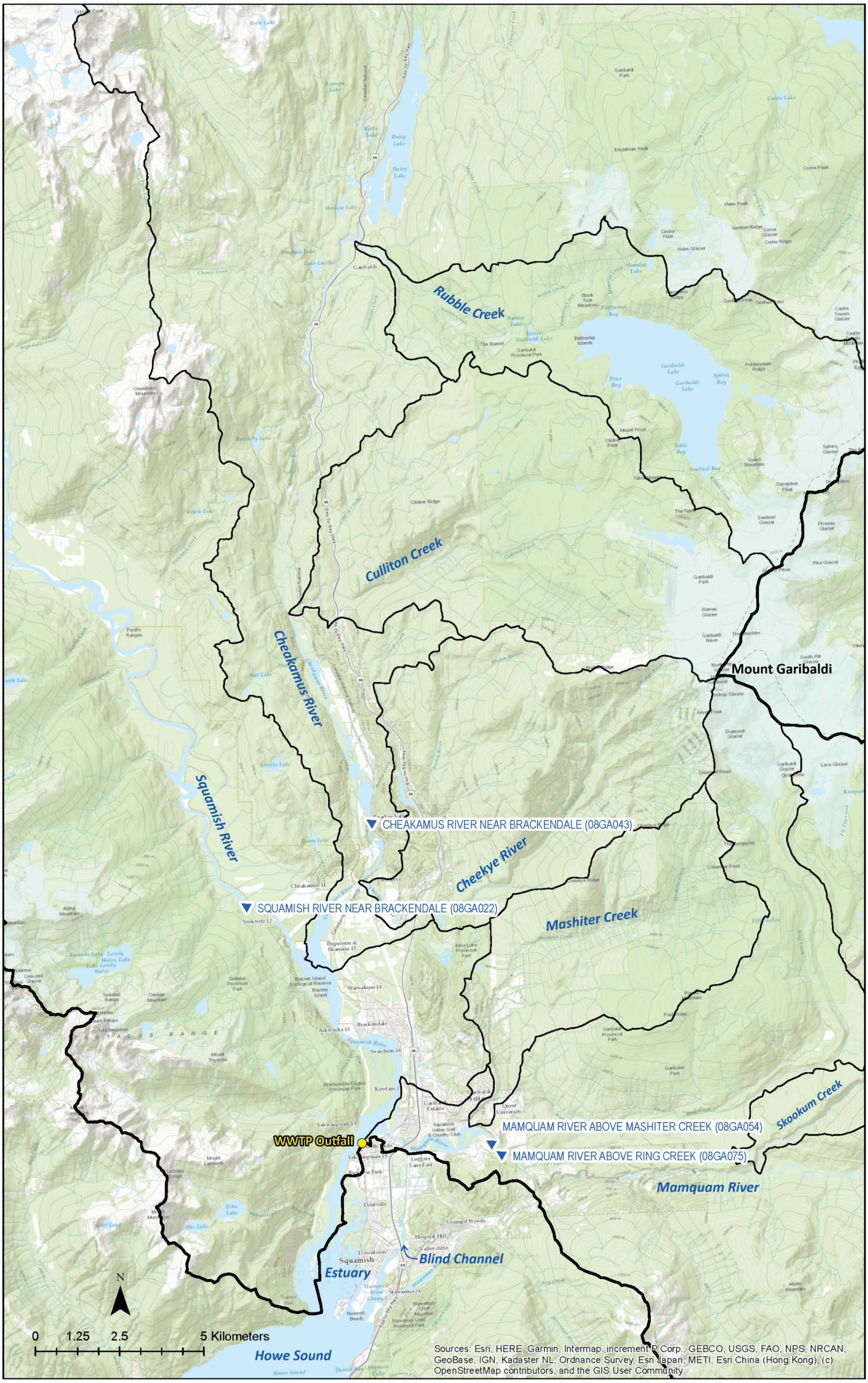


FIGURE 3.2 *Lower Squamish River and its major tributaries. The locations of Water Survey of Canada hydrometric stations referred to in this report are shown.*

The Cheakamus River confluence is situated approximately 7.5 km upstream from the WWTP outfall, and it is an active multi-thread gravel-bed river with a large fan approximately 1.6 km long and 2.0 km wide at its confluence with the Squamish River. Dikes were constructed along the lower reach of the Cheakamus River in the late 1950s for flood protection, which has stabilized the channel and resulted in channel narrowing of the lower reach (Clague et al., 2002). The channel is still braided and active across the fan near its confluence with the Squamish River. The Cheekeye River, Culliton Creek, and Rubble Creek are three tributaries and major sediment sources to the Cheakamus River that are located approximately 3 km, 13 km, and 25 km upstream from the Cheakamus fan, respectively. These tributaries drain the west flank of the Garibaldi massif, which consist of volcanic materials that are prone to failure. Rubble Creek and Culliton Creek contribute high sediment loads, and Clague et al. (2002) observed that a large slope failure on Rubble Creek buried the Cheakamus River in 1855 or 1856. Sediment loads from Rubble Creek and Culliton Creek are not discussed here given the distance from the area of interest. The Cheekeye River provides a significant sediment load to the Cheakamus River. Gravel bars on the Cheakamus River are more frequent downstream of the Cheekeye fan, and past studies have found that the Cheakamus fan has grown over time and the Squamish River has shifted approximately 200 m opposite the Cheakamus fan and eroded its west (right) bank to accommodate the additional sediment supply at that location (KWL, 2011).

The main channel of the Mamquam River enters the Squamish River approximately 1.0 km upstream of the WWTP outfall, and the downstream edge of its fan and distributary channels are approximately 400 m upstream from the WWTP outfall. The Mamquam River exits a steep canyon and forms a fan for approximately 5 km (Sutek and Kellerhalls, 1989). As a result of a large flood in 1921, the Mamquam River shifted course to the west and abandoned a channel that drained southward into Howe Sound (known currently as the Blind Channel). This shift resulted in Mamquam River draining into the Squamish River approximately 7 km upstream of the estuary, where it has since developed a large alluvial fan and impacted flow patterns in the Squamish River. Because of the high sediment supply, gravel was removed from the Mamquam River fan near the confluence of the Mamquam and Squamish Rivers several times between 1979 to 1986 for flood protection. As much as 2 m of localized degradation occurred near the extraction sites (Sutek and Kellerhalls, 1989; KWL, 2011). KWL (2011) found that there was a modest net loss of sediment between 1995 to 2008, but it is expected that the fan will be a net depositional area due to future sediment deposition.

4. HYDROLOGY

The Squamish River has a mixed flow regime and experiences summer flooding from snow and glacier melt and/or summer rainfall events and fall and early winter flooding from large rainstorms (KWL, 2011). Additionally, high water levels can occur in the estuary when seasonal high tides combine with storm surges, such as near the winter solstice (KWL, 2011). Low flows typically occur during winter months. High flows can lead to large shifts in sediment supply and channel changes, whereas variations in low flows may influence mixing conditions at the outfall.

Hydrometric data is available from the Water Survey of Canada for the Squamish River and its tributaries from the Squamish River near Brackendale (08GA022), Cheakamus River near Brackendale (08GA043), and Mamquam River above Ring Creek (08GA075) (TABLE 4.1).

TABLE 4.1. *Hydrometric station information for the Squamish, Cheakamus, and Mamquam Rivers.*

Station ID	Name	Drainage Area (km^2)	Record Period	Record Length (years)
08GA022	Squamish River near Brackendale	2,330	1923-1925, 1955-present	71
08GA043	Cheakamus River near Brackendale	1,010	1958-present	64
08GA054	Mamquam River above Mashiter Creek	334	1966-1986	21
08GA075	Mamquam River above Ring Creek	281	1989-present	32

Five hydroelectric facilities are located within the Squamish River watershed. There are three run-of-river privately operated hydroelectric facilities in the Mamquam River watershed: the Mamquam Generating Station commissioned in 1996, the Upper Mamquam hydroelectric facility commissioned in 2006, and the Skookum Creek Power Project commissioned in 2014. There is also a run-of-river hydroelectric facility on the Ashlu River commissioned in 2009. BC Hydro has operated a hydroelectric facility on the Cheakamus River since the mid 1950s, which includes the Cheakamus Dam and Daisy Lake Reservoir, as well as a penstock from Daisy Lake to the Squamish River above the Ashlu River confluence where a powerhouse is located. This BC Hydro facility generally regulates lower flows and has a limited influence on major floods (KWL, 2011).

Since the run-of-river hydroelectric facilities have minimal storage capabilities (i.e., they lack reservoirs), they have negligible impact to flows in the Squamish River. However, the Cheakamus Dam and Daisy Lake Reservoir may impact low flows of the Squamish River since the Cheakamus River drainage is approximately 30% of the total drainage area of the Squamish and Cheakamus rivers at their confluence. Future changes to the flow regimes of these operating stations and the resulting impact on the Squamish River flows is not considered in this assessment.

Flood frequencies for the Squamish, Cheakamus, and Mamquam Rivers were estimated by KWL (2011), and daily and instantaneous maximum flows for these rivers are presented in FIGURE 4.1, FIGURE 4.2, FIGURE 4.3, and FIGURE 4.4[2].

Maximum flows with a return period greater than 10-years along the Squamish, Cheakamus, and Mamquam rivers are presented in TABLE 4.2. Analysis of the peak flows shows that the timing of peak flows on the Squamish, Cheakamus, and Mamquam rivers are not necessarily synchronous. The largest flood on record on the Squamish and Cheakamus Rivers occurred in October 2003, and it was estimated that the flood event had a return period of approximately 150-years downstream of the Cheakamus River confluence (KWL, 2011). Several high flow events also occurred in close succession on the Squamish and Cheakamus rivers in 1980, 1981, and 1984 (TABLE 4.2). No large floods with a return period greater than 10-years have been recorded on the Squamish and Cheakamus Rivers since 2003; however, the Squamish River experienced a flood with a return period of approximately 10-years in 2015. No large floods with a return period greater than 10-years have been recorded on the Mamquam River since 1995.

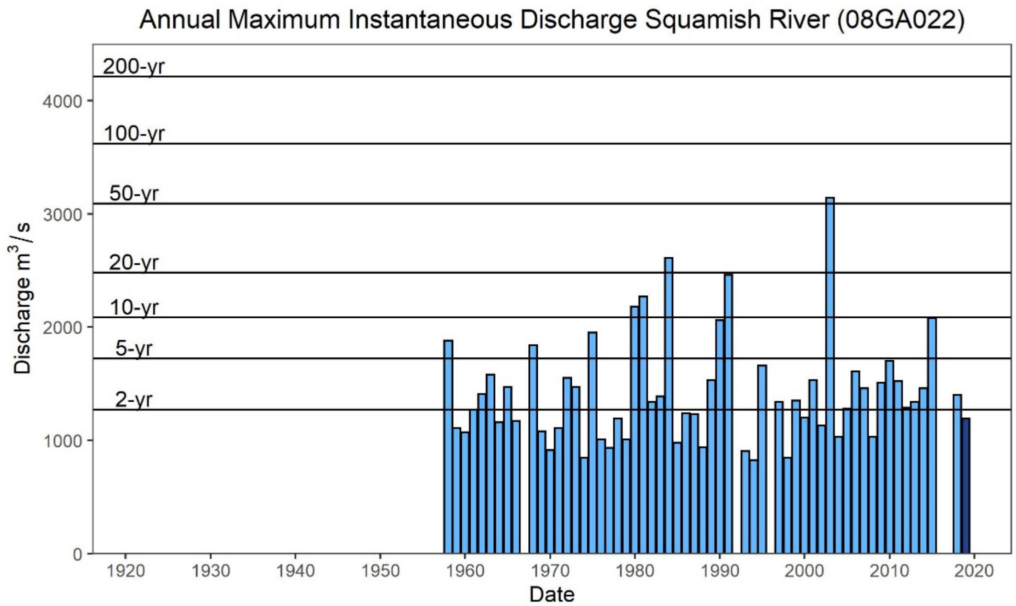
TABLE 4.2 *Notable floods with a greater than 10-year return period along the Squamish, Cheakamus, and Mamquam Rivers.*

Squamish River near Brackendale (08GA022)		Cheakamus River near Brackendale (08GA043)		Mamquam River above Mashiter Creek (08GA054)/ Mamquam River above Ring Creek (08GA075)	
Year	Return Period (years)	Year	Return Period (years)	Year	Return Period (years)
1957	20-50[1]	1961	20-50	1975	10-20
1980	10-20	1963	20-50	1980	20-50
1981	10-20	1980	20-50	1990	10-20
1984	~20	1981	10-20	1995	~10
1991	~20	1984	20-50		
2003	50-70	1989	10-20		
2015	~10	2003	150[2]		

Notes:

1. Estimated from the daily maximum flows recorded at the Squamish River near Brackendale (08GA022) hydrometric station.
2. Return period of 150-years was estimated by KWL (2011).

[2] Updating of these calculations was beyond the scope of this assignment.



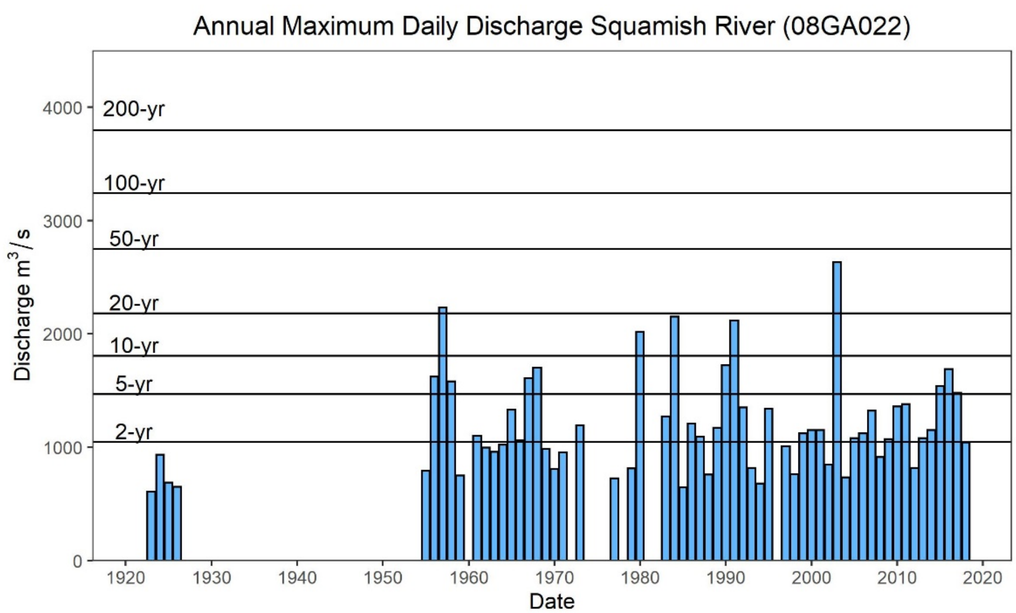


FIGURE 4.1 *Annual maximum instantaneous flows and maximum daily flows for the Squamish River near Brackendale (08GA022). Provisional data is shown in dark blue. Horizontal lines shown on both plots represent the average return period results for instantaneous and daily flows calculated by KWL (2011).*

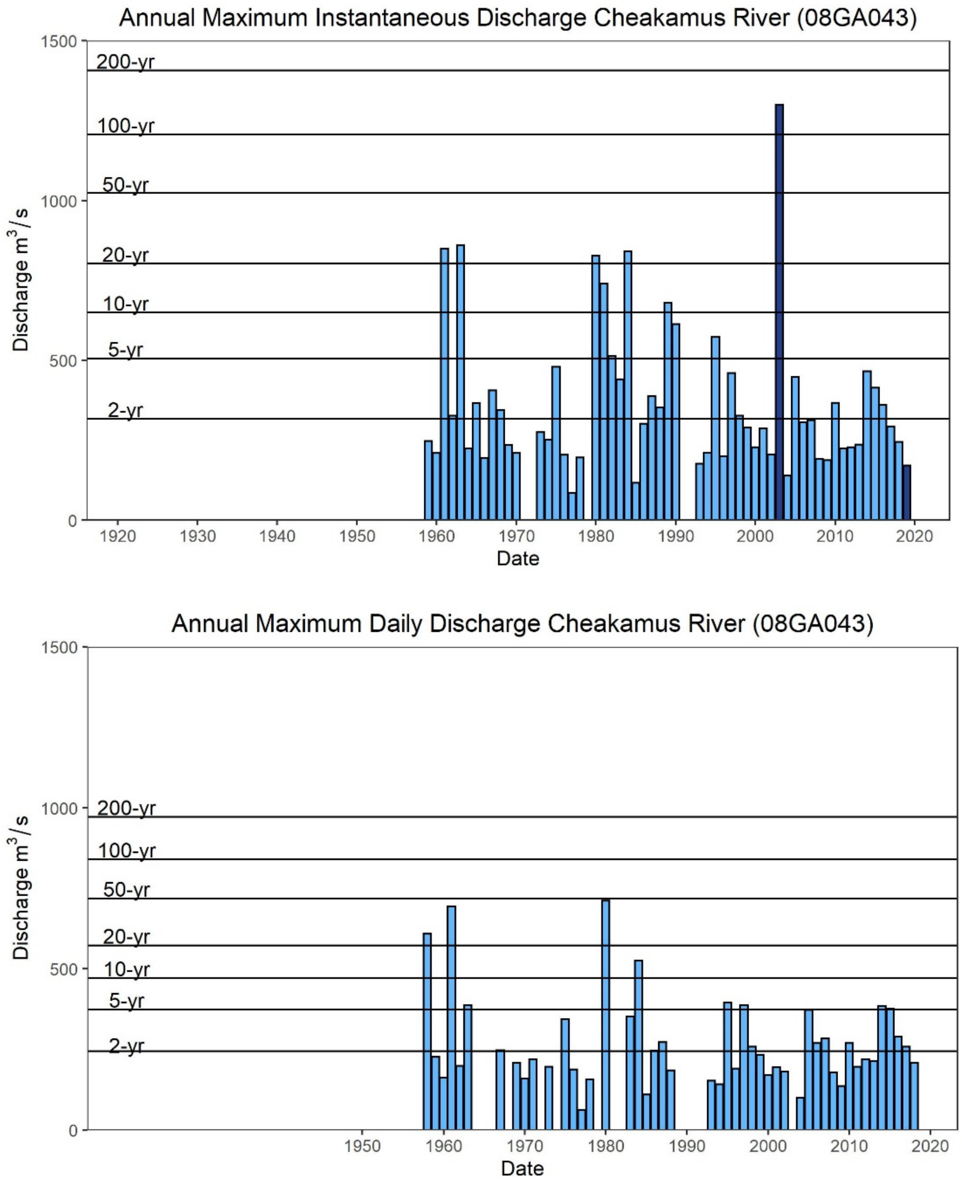
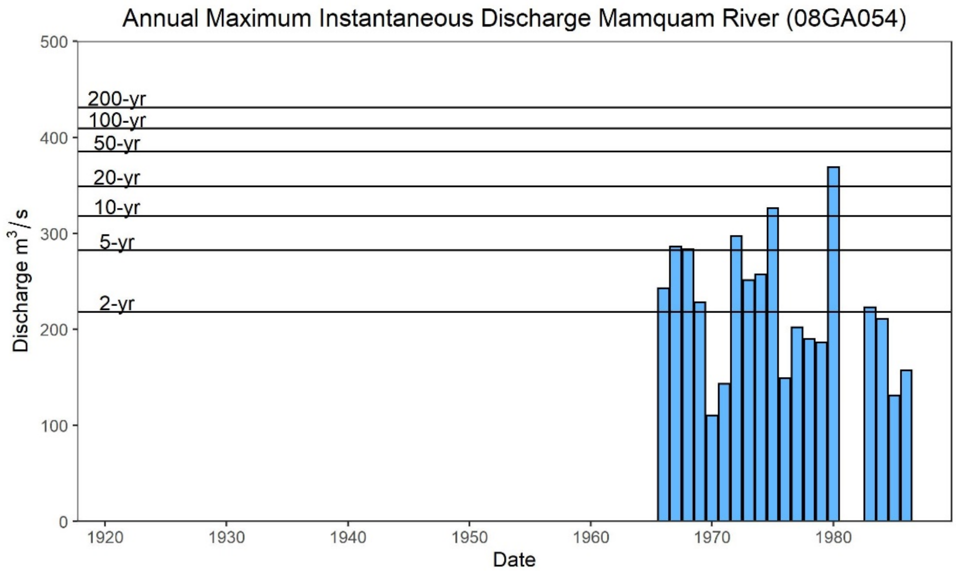


FIGURE 4.2 *Annual maximum instantaneous flows and maximum daily flows for the Cheakamus River near Brackendale (08GA043). Provisional data is shown in dark blue. The instantaneous peak flow in 2003 was estimated by KWL (2011). Horizontal lines shown on both plots represents average return period results for instantaneous and daily flows calculated by KWL (2011).*



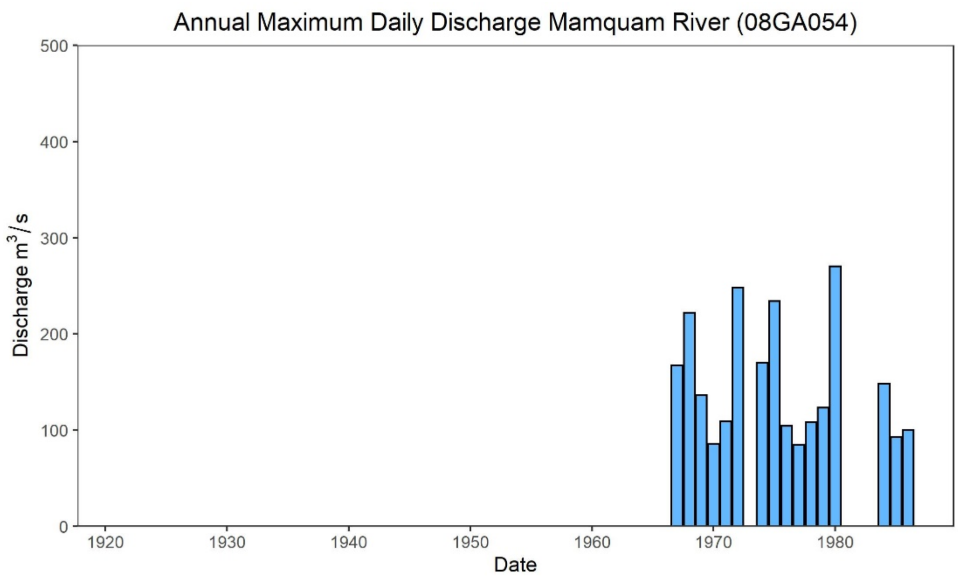


FIGURE 4.3 *Annual maximum instantaneous flows and maximum daily flows for the Mamquam River above Mashiter Creek (08GA054). Horizontal lines shown on the instantaneous plot represents average return period results for instantaneous peak flows calculated by KWL (2011). An average return period result was not calculated for the daily flows due to discrepancies observed between flood frequency distributions (KWL, 2011).*

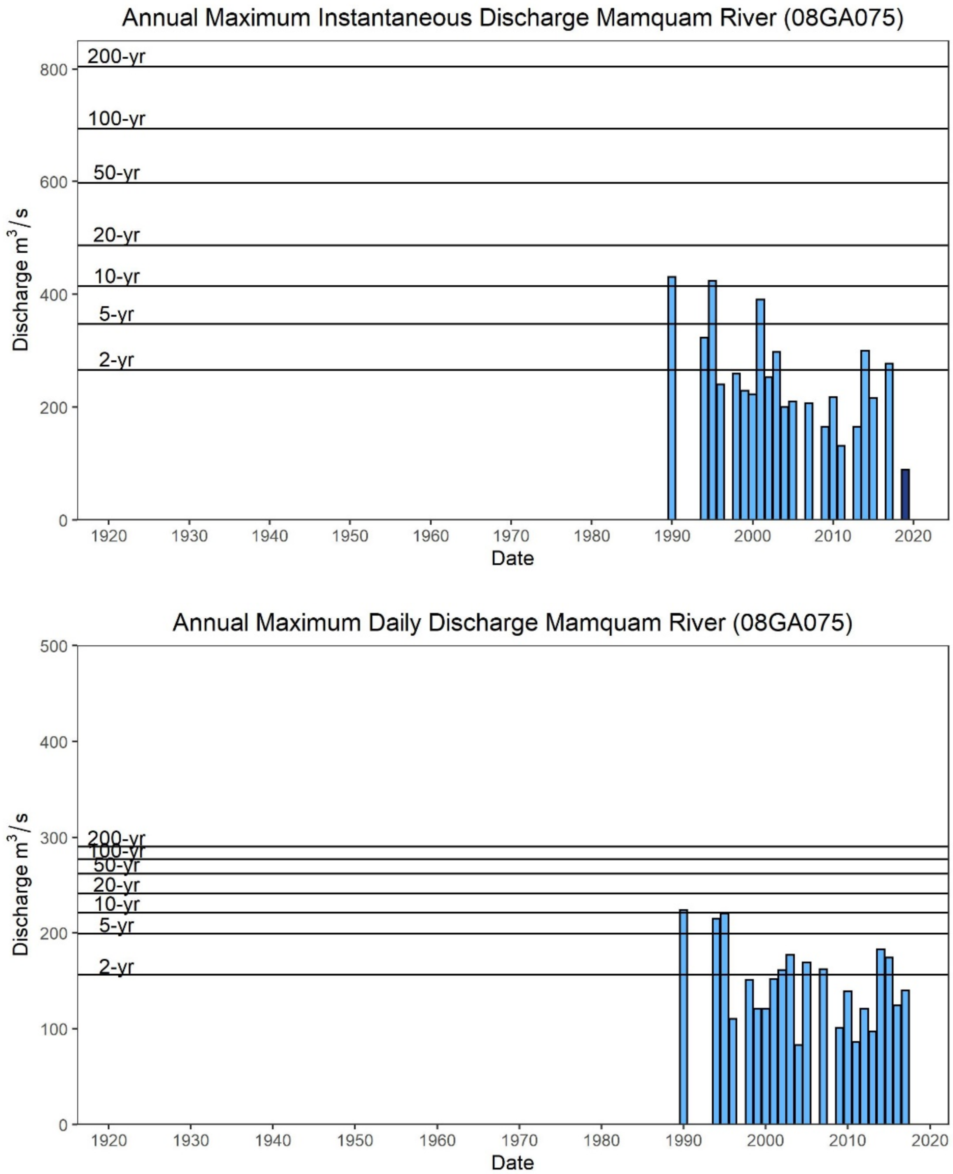


FIGURE 4.4 *Annual maximum instantaneous flows and maximum daily flows for the Mamquam River above Ring Creek (08GA075). Provisional data is shown in dark blue. Horizontal lines shown on both plots represents return periods for instantaneous and daily flows calculated by KWL (2011). Given the relatively short period of record (12 years), these results have relatively high uncertainty.*

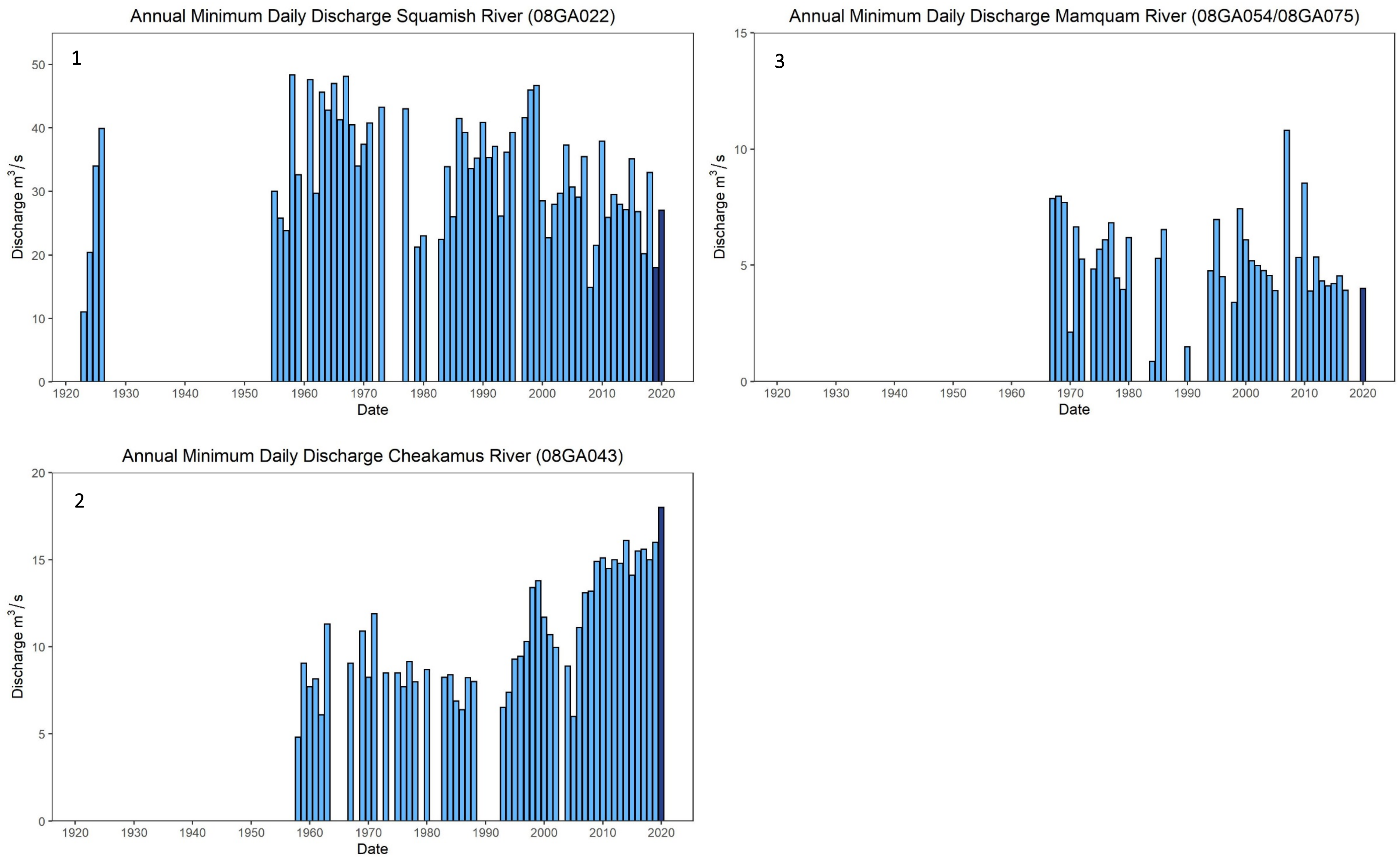


FIGURE 4.5 *Historical variation in annual minimum daily flows for: 1) Squamish River near Brackendale (08GA022) (top left), 2) Cheakamus River near Brackendale (08GA043) (bottom left), 3) Mamquam River above Mashiter Creek (08GA054) between 1966-1986 and Mamquam River above Ring Creek (08GA075) from 1990-2020. Provisional data is shown in dark blue.*

Given that poor mixing conditions have been identified when river flows and levels are relatively low, annual daily minimum flows for the Squamish, Cheakamus, and Mamquam rivers were reviewed (FIGURE 4.5). Low flows on the Cheakamus River are controlled by the Cheakamus Dam, and could at least partially reflect changes in the facility's operating regime. On the Squamish River, low flows appear to be decreasing over the period since the 1960s, with a few years of relatively high low flows in the late 1990s; however, no statistical analysis was completed to assess the trend in these flows. No observable trends in low flows were observed on the Mamquam River.

Daily flows at the WWTP outfall were estimated by summing daily flows from the Squamish River near Brackendale (08GA022), Cheakamus River near Brackendale (08GA043), and the Mamquam River above Mashiter Creek (08GA054) or Mamquam River above Ring Creek (08GA075). The two gauges on the Mamquam River were used to extend the period of record, and it is assumed that the contribution of Ring Creek is minimal at low and high flow events relative to the total discharge at the WWTP outfall. The daily flows were only added together for days that had flow measurements at all stations, which limits the period of record. Additionally, this analysis may exclude some extreme events. For example, the hydrometric station at Cheakamus River near Brackendale (08GA043) did not record a daily flow during the peak of the 2003 flood. A frequency analysis for the minimum and maximum daily flows at the WWTP outfall was calculated using a Log Pearson III distribution and is presented in TABLE 4.3. Estimated minimum and maximum daily flows at the WWTP outfall are presented in FIGURE 4.6 and FIGURE 4.7, respectively. Annual minimum low flows at the WWTP outfall occur between October to March. Annual maximum high flows at the WWTP outfall were recorded to occur in every month of the year except February, and generally occur in June to July and September to November.

TABLE 4.3 *Frequency analysis for estimated minimum and maximum daily flows at WWTP outfall.*

Return Period (years)	Minimum Daily Discharge (m^3/s)	Maximum Daily Discharge (m^3/s)
2	52.3	1,407
5	44.0	1,888
10	41.1	2,231
20	39.3	2,580
50	37.7	3,063
100	36.8	3,451

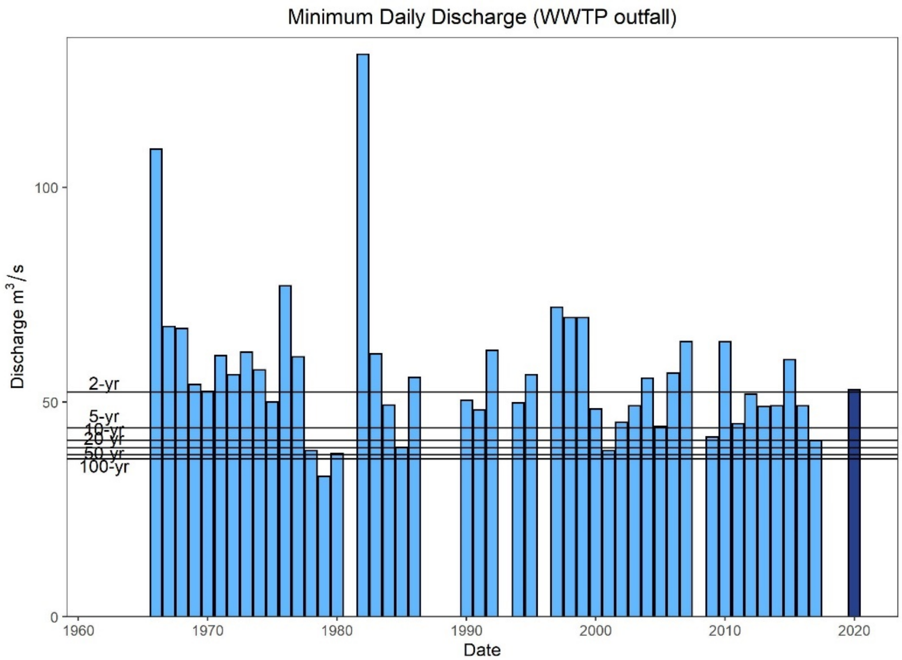


FIGURE 4.6 *Estimated annual minimum daily flows at the WWTP outfall. Provisional data is shown in dark blue. Horizontal lines represent the average return period for minimum daily flows.*

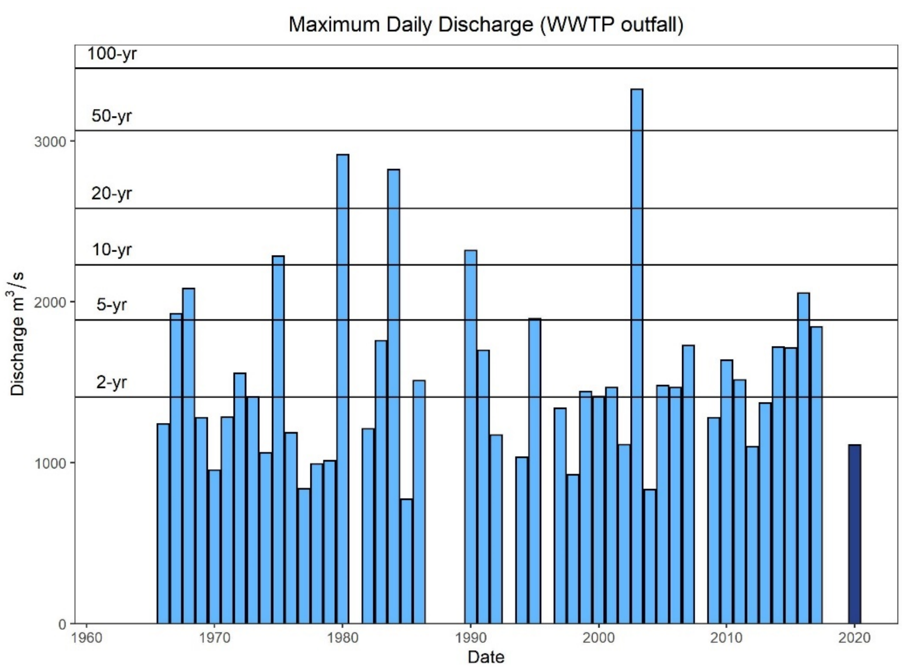


FIGURE 4.7 *Estimated annual maximum daily flows at the WWTP outfall. Provisional data is shown in dark blue. Horizontal lines represent the average return period for maximum daily flows.*

The estimated daily flows at the WWTP outfall show that low flows are much more consistent than high flows observed at the site from year to year. It is possible that low flows are decreasing (i.e., becoming more extreme) at the WWTP outfall; however, the period of record is much shorter than that recorded by the Squamish River near Brackendale (08GA022) station, which makes it difficult to observe a similar trend. The estimated high flows at the WWTP outfall show that large flood events with a greater than 10-year return period occurred near the WWTP outfall in 1975, 1980, 1984, 1990, and 2003.

River levels of the Squamish River are tidally influenced near the WWTP outfall location. Polar Geoscience (2015) noted that at high tides, river velocities decreased and water level increased, and that at low tides river velocities increased and water levels decreased near the WWTP outfall. The mean high tide and mean low tide elevations are 1.32 m and -1.42 m geodetic, respectively (Urban Systems, 2015) (FIGURE 4.8). Additionally, the tide may impact effluent dilution within the initial dilution zone (IDZ), because of the changes in water volume present and the impacts of salinity on effluent mixing. Urban Systems (2015) found that dilution was slightly higher for high tide conditions than low tide conditions and was related to the greater volume of water available at high tide conditions. Urban Systems (2014, 2015) did not consider whether a salt wedge on the Squamish River is near the WWTP outfall; the location of a salt wedge may effect initial mixing of the effluent in the river due to changes in salinity and water density. Levings (1980) found that during low flow conditions, a salt wedge in the Squamish River extended 1.5 km upstream of the mouth (i.e., near km 13.5 and did not reach the location of the WWTP outfall), and that at high flows the salt wedge did not extend upstream of the mouth of the river.

KWL (2011) modelled a 200-year return period flood on the Squamish River, and the flood profile elevation near the outfall is approximately 7.5 m. KWL (2011) varied the tidal boundary condition by ±0.6 m to assess the potential impacts of climate change associated with sea level rise on flood conditions in the Squamish River. Given a change in the tidal boundary condition of ±0.6 m, approximately ±0.08 m of change could be expected at the WWTP outfall. Changes in velocity were not presented by KWL (2011) and could be an area of further study to improve the understanding of how mixing conditions may be impacted by variations in the tidal boundary condition.

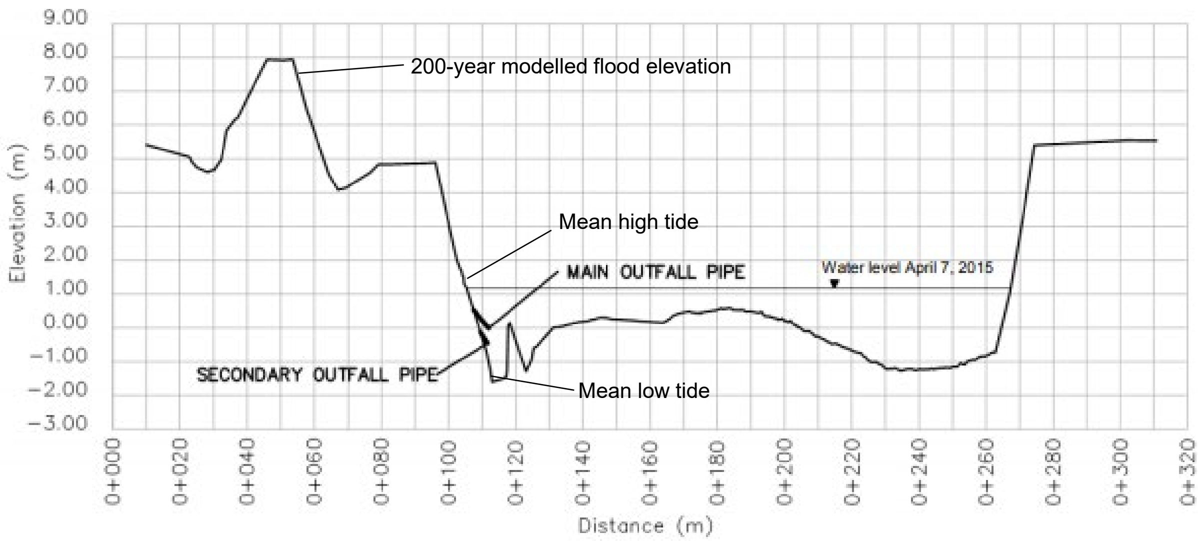


FIGURE 4.8 *Cross-section of the Squamish River at the WWTP outfall from Great Pacific Engineering & Environment and Ocean Dynamics (2015), with elevations for the 200-year modelled flood (KWL, 2011), mean high tide, and mean low tide (Urban Systems, 2015) shown.*

Projected climate and sea level changes may also impact the hydrological conditions of the Squamish River near the WWTP outfall. PCIC (2016a, 2016b) identified that expected climatic changes near Vancouver include: warmer temperatures, decrease in snowpack, longer dry spells in the summer, more precipitation in the fall, winter and spring, and increasing frequency, magnitude and duration of extreme events, and that there is an expected increase in atmospheric rivers and extreme precipitation. In mixed snowmelt/rain-fed catchments, it is expected that more precipitation will fall as rain, and Burn and Whitfield (2015) found that in rain-fed catchments, annual flood magnitudes have increased, and there is an increased flood risk related to heavy or extreme precipitation events. Bauch and Hickin (2011) found that between 1957-2007, extreme flood discharge, duration, and flood volume in the Squamish River increased by approximately 50, 300, and 450%, respectively, and attributed these increases to the intensification of Pacific Storms between August and December. No known studies have been completed to assess the changes in low flow conditions along the Squamish River; however, Ehsanzadeh and Adamowski (2006) have noted a downward trend in 7-day low flows in southern BC. Increases in extreme precipitation events could lead to an increase in sediment delivery and geomorphic changes along the Squamish River (Bauch and Hickin, 2011). The District of Squamish follows the provincial guidelines in preparation of a 1 m of sea level rise by 2100 and 2 m rise by 2200 (KWL, 2017). An increase in sea level rise could lead to decreased flow velocities near the current WWTP outfall and accelerate sediment deposition near the site and upstream. Another factor which may impact the geomorphic and hydrological conditions at the WWTP outfall are changes in landuse in the Squamish River, Cheakamus River, and

Mamquam River watersheds. The potential impact of changes in landuse to the hydrological conditions are outside of the scope of this assessment.

5. WWTP OUTFALL SITE

The WWTP outfall is situated approximately 1.0 km downstream from the Mamquam River confluence along the east (left) bank of the Squamish River near 9.3 km (FIGURE 1.1). The outfall was constructed in 1972 and consists of a 400 mm diameter polyethylene forcemain connected to an approximately 1.2 m long 400 mm diameter steel pipe section (Urban Systems, 2014). The outfall is situated within the Squamish River dike near the east (left) bank and makes a 90-degree bend towards the river. An additional outfall pipe was constructed in 2005 parallel to the original pipe and tied-in to the existing outfall where it makes a 90-degree bend towards the river (Lockerbie Stanley Inc., 2003). At the outfall location, the pipe was placed on the river bed, approximately 0.6 m below the average water level at the time of construction, where it extends approximately 5.8 m into the Squamish River, and the last 4.6 m is exposed (Web Engineering Ltd., 1972, Great Pacific Engineering & Environment, 2015). The terminus of the outfall is not fitted with a diffuser and the top of pipe elevation is 0.01 m (geodetic). As of the last inspection, the outfall at the terminus is unsupported and suspended approximately 1 m above the riverbed. (Great Pacific Engineering & Environment, 2015).

On September 3, 2014, the discharge from the WWTP outfall was carried by the flow of the Squamish River (FIGURE 5.1). An assessment on April 7, 2015 by Great Pacific Engineering & Environment noted that the effluent plume rose to the surface and contacted the riverbank approximately 53 m from the outfall location. During a site visit on July 17, 2020, the brown turbid water in the main flow of the Squamish River was separated from slower flowing water from the Mamquam River that enters immediately upstream. The site was sheltered from the main river flow by the upstream bar resulting in relatively low flow velocities over the outfall even at relatively high flows in the Squamish River (approximately 500 m^3/s) (FIGURE 5.2)[3].

[3] The low velocities over the outfall were observed during low tide. Tidal influence is expected to exacerbate the low velocities over the WWTP outfall.

FIGURE 5.1 *View downstream from the east (left) bank of the Squamish River near the WWTP outfall on September 3, 2014 (discharge approximately 201 m^3/s). Notice the trail of bubbles moving downstream indicating where the WWTP outfall is situated. Photo taken by Lars Uunila.*

FIGURE 5.2 *View downstream from the east (left) bank of the Squamish River near the WWTP outfall on July 17, 2020 (discharge approximately 500 m^3/s). Note that the brown turbid water in the main flow of the Squamish River is separated from slower flowing water from Mamquam River that enters immediately upstream. Even at these relatively high flows, mixing conditions at the WWTP outfall are impaired by low water velocities near the shore. Photo taken by Lars Uunila.*

6. HISTORICAL AIR PHOTO ANALYSIS

Historical air photos were selected for the analysis based on spatial coverage, relatively similar discharge rates when possible, and to bracket large flood events. The historical air photos used in the analysis are summarized in TABLE 6.1.

TABLE 6.1 *Historical imagery used in the analysis.*

Date (YYYY-MM-DD)	Imagery	Source
2019-04-28	Orthophoto	District of Squamish
2013-04-24	Orthophoto	District of Squamish
2004	Orthophoto	District of Squamish
1999	Orthophoto	District of Squamish
1990-08-07	30BCB90103: 14-17, 59-63, 87-91, 126-129, 150-153, 180-185	UBC Air Photo Library
1975-05-08	BC5650: 67-81, 102-116, 124-126, 131-133	UBC Air Photo Library
1964-07-01	BC5099: 117-122	UBC Air Photo Library
1946	BC262: 89-97 BC260: 11-18	UBC Air Photo Library

6.1 CHANNEL CHANGES ON LOWER SQUAMISH RIVER

A summary of the analysis of historical imagery is presented in TABLE 6.2 and indicates that significant morphological changes have occurred along the Squamish River since 1946. Before the dike was constructed along the east (left) bank of the Squamish River, the Squamish River between the Cheakamus River confluence and Howe Sound was an active multi-thread channel, and the flow split around several large mid-channel vegetated islands. Significant bank erosion was observed on the Squamish River in 1964 as the Squamish River shifted laterally across the floodplain. Dikes were observed along the east (left) bank of the Squamish River between 3.0-6.7 km and 8.4-15.0 km in 1975 and several active side-channels of the Squamish River were disconnected from the mainstem. In 1975, fewer mid-channel vegetated islands were observed as the flow became channelized and the river transitioned to a dominantly single-thread channel. Additional dikes were constructed along the east (left) bank between 1975 and 1990 from 6.7-8.2 km, resulting in abandoned side-channels and a general straightening of the Squamish River within the area of interest.

TABLE 6.2 *Summary of the analysis of selected historical imagery within the area of interest.*

Date of Imagery	Estimated Discharge (m^3/s)	Summary of Observations
1946	N/A	• Squamish River is characterized by multi-thread channel morphology; the main flow is split around several mid-channel vegetated islands; there are several active side channels and few exposed bars. • Large active side channels of the Squamish River are located around vegetated islands near 1.4- 3.2 km, 2.8-4.9 km, 5.1- 7.0 km, 7.0-8.2 km, and 11.1-15.0 km. • No exposed mid-channel gravel bars were noted on Squamish River downstream of Mamquam River confluence at 8.1 km. • Squamish River occupies a wide lateral extent across the floodplain.
1964-07-01	510	• The Cheakamus confluence shifted southeast and abandoned a channel on its fan that entered the Squamish River at 0.0 km; pioneer vegetation establishing in abandoned channel. • A sediment pulse and erosion observed along the lower Cheakamus River. • Erosion observed along the Squamish River floodplain downstream of the Cheakamus River confluence and extending downstream of the Mamquam River confluence (2.5-10.0 km). • Significant lateral erosion within floodplain of Squamish River on east (left) bank near 4.9-6.0 km. • Erosion of vegetated islands near Mamquam River confluence observed; the Mamquam River fan has not extended into Squamish River. • Exposed gravel bars observed mid-channel and within side channels, which may be related to relatively lower flows at time historical air photo was taken. • A major channel shift occurred near the estuary, and the main flow of the Squamish River, which used to flow in the eastern channel, now flows into the western channel at 11.0 km.
1975-05-08	164	• Exposed laterally attached gravel bars are noted downstream of Cheakamus River, and a sediment pulse appears to be moving downstream from Cheakamus confluence. • Bank erosion observed downstream of Cheakamus River confluence along both west (right) and east (left) banks of Squamish River near 3.0-4.0 km. • Mamquam River fan extends westward and bank erosion observed opposite the Mamquam confluence near 8.0-9.0 km. • Dikes constructed along the east (left) bank of the Squamish River between 3-6.7 km and 8.4-15.0 km, which extends to the end of the training berm in the Squamish River estuary. A dike also extends approximately 1.4 km on left (south) side of Mamquam River at it's mouth. • Dike construction has resulted in abandonment of several side channels along the Squamish River on the east (left) side including at 3.0-4.8 km, 9.1-9.5 km, and 10.5-15.0 km. • Fewer mid-channel vegetated islands are noted as the river transitions to a more single-thread channel.
1990-08-07	503	• Gravel removal occurred on Mamquam River between 1989 -1990 at several extraction sites; most removals were concentrated at the confluence of the Mamquam and Squamish Rivers and in the lower 1 km of the Mamquam River. • A dike on east (left) bank of Squamish River was completed between km 6.7-8.2 km, and the river has straightened in that reach; additionally, a side channel of the Squamish River has been abandoned from 6.8-8.2 km. • Squamish River eroded eastward into the Mamquam fan, and eroded west (right) bank of the Squamish River where the flow now splits around a vegetated island. • Bank erosion observed along both west (right) and east (left) banks of Squamish River near the estuary from 11.6-14.5 km.
1999	N/A	• Cheakamus fan confluence has moved from 1.4- 1.9 km to 2.1-2.6 km and bank erosion has occurred opposite the confluence on the Squamish River. • Vegetation establishing on gravel bars in Squamish River. • Vegetation is establishing on exposed gravel bars within side channels from 7.7-8.9 km opposite the Mamquam River confluence. • Exposed gravel bars appear more extensive downstream Mamquam River confluence. • No significant morphological changes are observed along Squamish River.
2004	N/A	• Largest flood on record occurred in October 2003 (in the year prior to this imagery). • Large pulse of sediment observed along the Cheakamus River downstream of the Cheekeye River confluence, but little channel change observed along the Cheakamus River. • Sediment deposits are visible in Squamish River downstream of Cheakamus confluence, and some exposed mid-channel gravel bars have shifted downstream. • Little bank erosion and channel change observed along the mainstem Squamish River. • Bank erosion observed along east (left) bank at 10.8-11.2 km and 12.4-12.9 km within the estuary.
2013	N/A	• Vegetation was establishing on gravel bars in the Cheakamus River and a new channel enters the Squamish River on the Cheakamus River fan between 1.2-1.5 km. • Vegetation establishing on gravel bars along the Squamish River downstream of the Cheakamus River confluence. • Exposed gravel bars downstream of Mamquam River confluence have grown and shifted downstream. • Bank erosion on east (left) bank of Squamish River between 7.9-8.2 km, 10.9-11.4 km, and 11.8-12.6 km. • Vegetated island erosion near the west (right) bank of the Squamish River between 10.6-11.8 km, and bank erosion along the west (right) bank of the Squamish River between 13.2-14.0 km.
2019-04-28	106-120 (Provisional)	• Some additional sediment deposition observed in the Cheakamus River, and erosion observed on a mid-channel vegetated island in the Squamish River opposite the Cheakamus River fan. • No significant channel shifting or morphometric changes along the Squamish River are noted; some vegetation establishing on exposed bars. • Enlarged gravel bars downstream of the Mamquam River confluence.

Historical imagery since 1990 shows the morphological response of the Squamish River after dikes were constructed and is likely most representative of future expected changes along the Squamish River. Few significant morphological changes have been observed along the Squamish River since 1990, despite the largest flood on record occurring in October 2003. Since the 2003 flood there has only been one flood of approximately 10-year return period on the Squamish River in 2015. Observations since the 2003 flood indicate that:

- A pulse of sediment was observed in the Cheakamus River following the 2003 flood, but little channel change was observed along the mainstem Squamish River within the area of interest.
- Bank erosion occurred on both west (right) and east (left) banks of the Squamish River with some loss of marshland near the outlet of the river near Howe Sound.
- Establishment of pioneer vegetation has been observed on bar tops and the Squamish River has become increasingly single-threaded.
- Vegetated islands are relatively small and erosion has occurred along several vegetated islands.
- Enlarged gravel bars downstream of the Mamquam River confluence indicate increased sediment accumulation along the mainstem Squamish River between the Mamquam River confluence and Howe Sound (8.1 km- 11.0 km).

These changes suggest that channel constriction from dike construction has led to a general increase in mainstem flow velocity, which may lead to a more rapid transfer of bed material downstream and increased in-channel instability as observed by the erosion of vegetated islands (Church et al., 2011). As sediments are transported through the straightened reaches, they are being deposited at the distal part of the gravel accumulation zone (FIGURE 3.1) where aggradation may be increased near 8.1-11.0 km. As a result, it is expected that sediment accumulation may increase along the depositional reach of the Squamish River between the Mamquam confluence and Howe Sound (8.1-15.0 km).

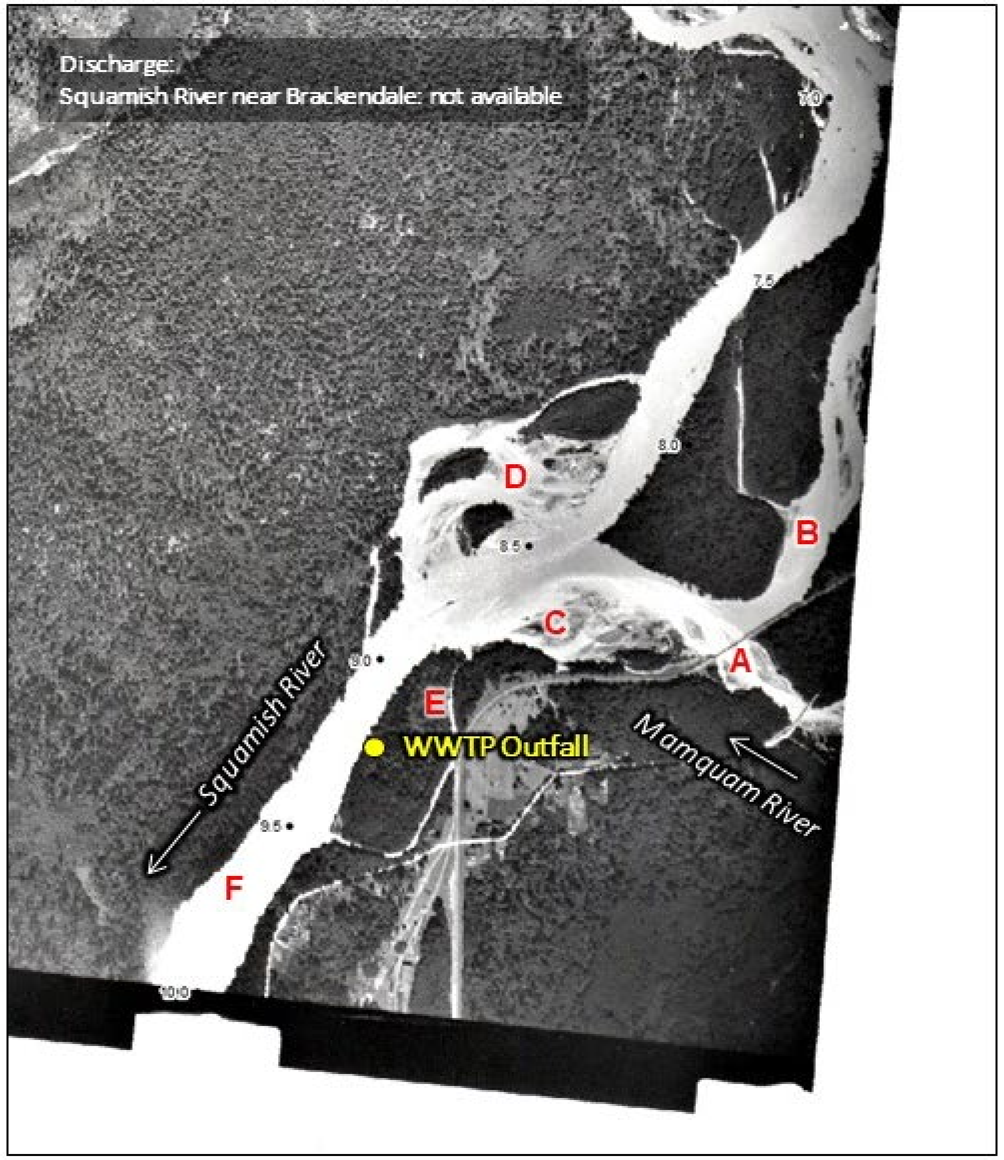
Changes to the Cheakamus River and Mamquam River fans indicate the relative level of activity and sediment supply from both of these rivers. The Cheakamus River fan is highly active and several avulsions occurred over the record of historical imagery. Additionally, several sediment pulses from the Cheekeye River were observed within the fan; a large pulse of sediment was observed along the Cheakamus River fan in 2004 after the October 2003 flood. These sediment pulses were observed to move downstream, as gravel bars below the Cheakamus River confluence and have extended laterally and downstream over time. At the Mamquam River confluence, the fan has grown westward and bank erosion has occurred along the opposite (west) bank of the Squamish River. Historical changes of the Mamquam River fan appear more gradual and few avulsions were observed across the fan. As the Mamquam River recovers from gravel extraction between 1979 and 1986, it is expected that aggradation along the lower 1 km of the Mamquam River will increase, which may result in the fan extending westward thus shunting flows of the Squamish River towards the opposite bank.

6.2 CHANNEL CHANGES IN THE VICINITY OF THE WWTP OUTFALL

A summary of a detailed analysis of historical imagery near the WWTP outfall site is presented in FIGURE 6.2, FIGURE 6.3, FIGURE 6.4 and FIGURE 6.5. Due to the dike along the east (left) bank of the Squamish River, the river bank alignment near the WWTP outfall has not changed significantly since it was constructed; however, geomorphic changes upstream have driven sediment downstream and changed the local conditions at the outfall. Repeated cross-section surveys from 1976 and 2005 near the outfall location indicate approximately 10 m of erosion along the east (left) bank of the Squamish River and approximately 1 m of aggradation in places (KWL, 2011). The historical air photo analysis in the vicinity of the WWTP outfall indicates the following:

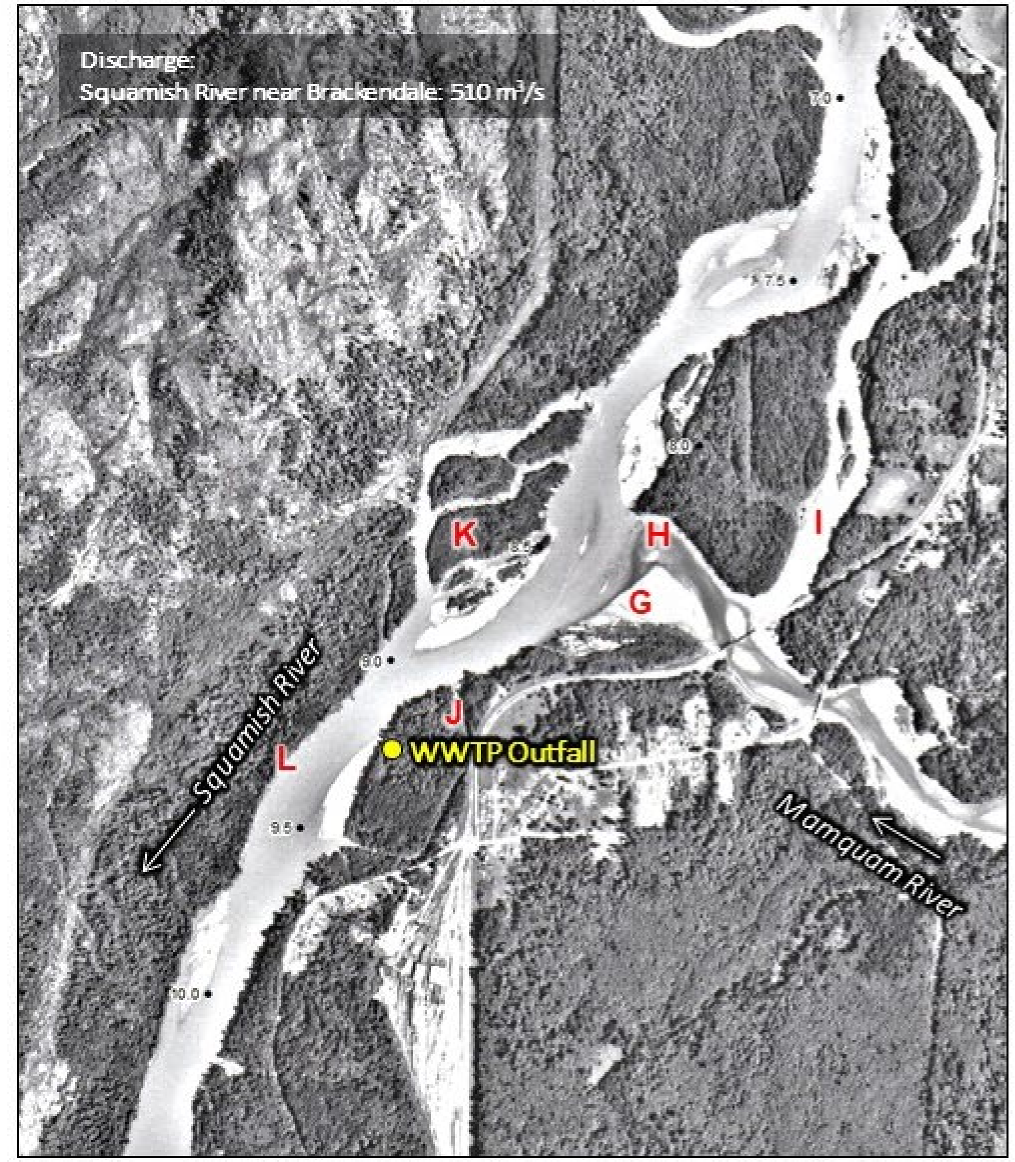
- The gravel bar upstream of the WWTP outfall on the east (left) bank has grown over time since 1999, and growth of the Mamquam Fan has resulted in erosion of the opposite bank, which has led to increased curvature of the mainstem Squamish River near the WWTP outfall.
- As bed material is deposited near the WWTP outfall, the bar has extended downstream and laterally across the channel.
- Establishment and growth of vegetation was observed since 2013 and large woody debris jams were observed in 2019 on the bar top; as the bar becomes more established it will continue to accrete laterally across the Squamish River.
- Bank erosion was observed in 2019 as the enlarging sediment accumulations direct the river flow towards the opposite (west) bank near the Mamquam confluence (FIGURE 6.1).
- As the opposite (west) bank erodes and the curvature increases near the Mamquam confluence, flows may be increasingly forced towards the outside bend resulting in reduced water velocities on the inside of the bend and reducing effluent mixing efficiencies at low flows.

FIGURE 6.1 *View across from the east (left) bank of the Squamish River near the WWTP outfall on July 17, 2020 (discharge approximately 500 m^3/s). Evidence of eroding banks on the west (right) bank near the WWTP outfall appears widespread. Photo taken by Lars Uunila.*



Date: 1946
BC262-93

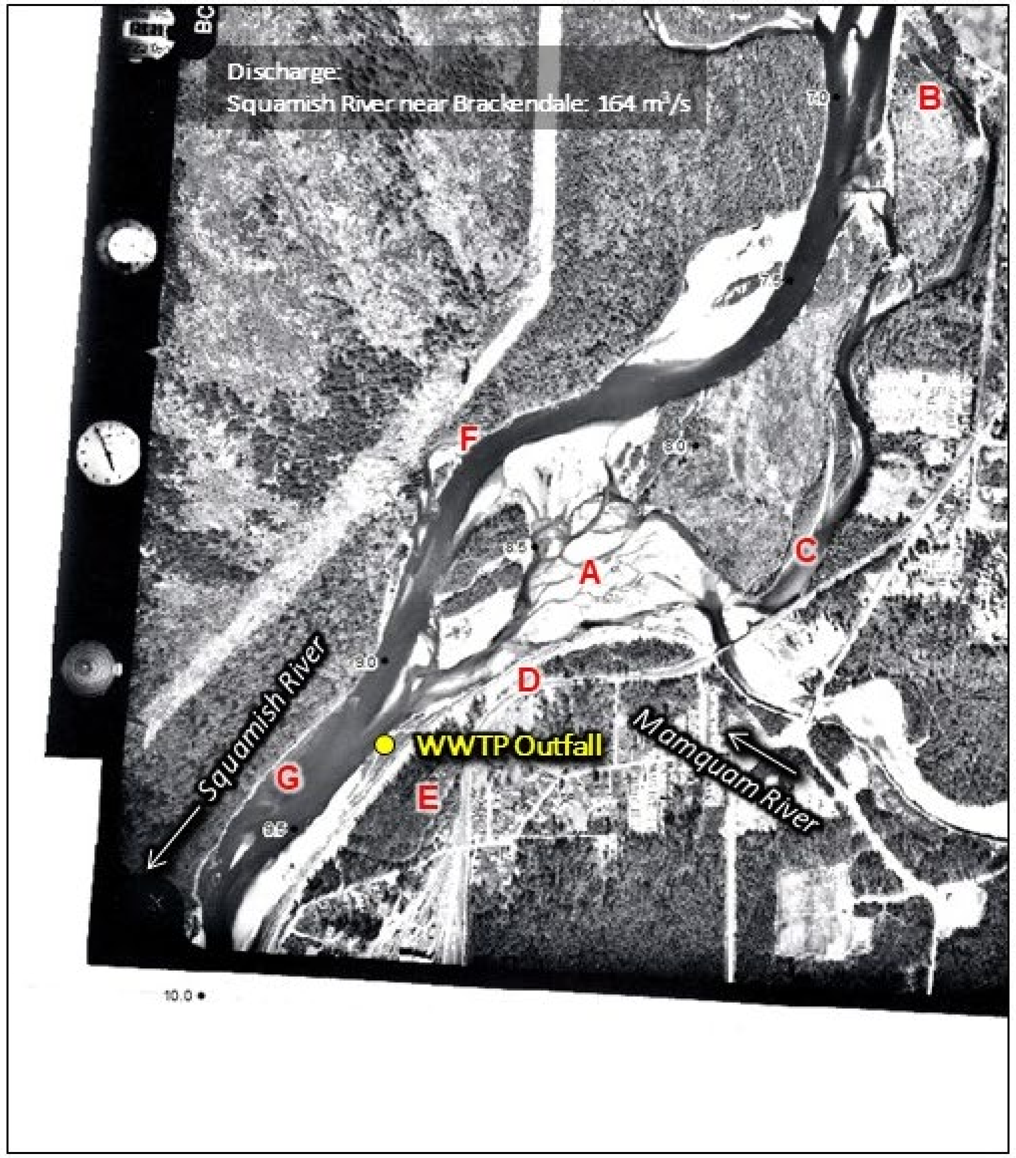
NOTES:
- Mouth of Mamquam River adjacent to railway bridge [A], and active side channel of Squamish River joins confluence of Mamquam River [B].
- Mamquam River fan is relatively small and unvegetated [C].
- Squamish River is multi-threaded and flows around vegetated islands [D]; there is an active side channel downstream of Mamquam confluence [E].
- Squamish River is relatively straight downstream of confluence [F].



Date: 1964-07-01
BC5099-119

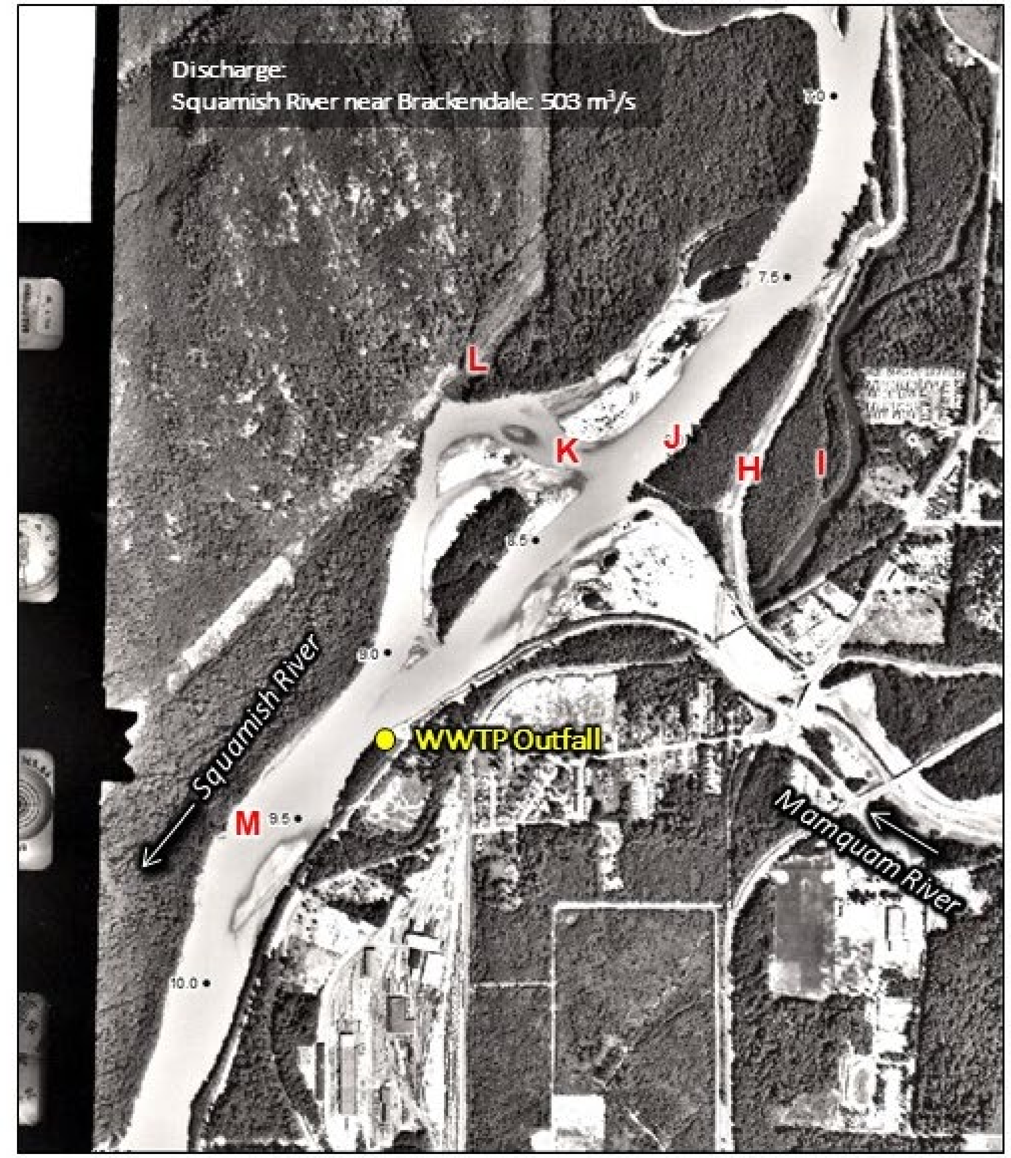
NOTES:
- Evidence of growth of fan at mouth of Mamquam River [G]; Mamquam River confluence moving northwestward into Squamish River [H].
- Gravel exposed within side channels [I, J].
- Vegetation establishing on mid-channel bars [K].
- Bank erosion on opposite bank of Mamquam confluence [L].

FIGURE 6.2 *Historical changes in channel morphology near the WWTP Outfall: 1946 and 1964.*



Date: 1975-05-08
BC5650-109

NOTES:
- Enlarged fan at the mouth of the Mamquam at low flows [**A**].
- Side channel of the Squamish River is becoming disconnected from main stem [**B**, **C**], and Squamish River becoming increasingly single-thread.
- Dike constructed along east (left) bank of Squamish River south of the Mamquam confluence [**D**], and side channel disconnected [**E**].
- Bank erosion as Squamish River shifts westward across and downstream of Mamquam confluence [**F**, **G**].



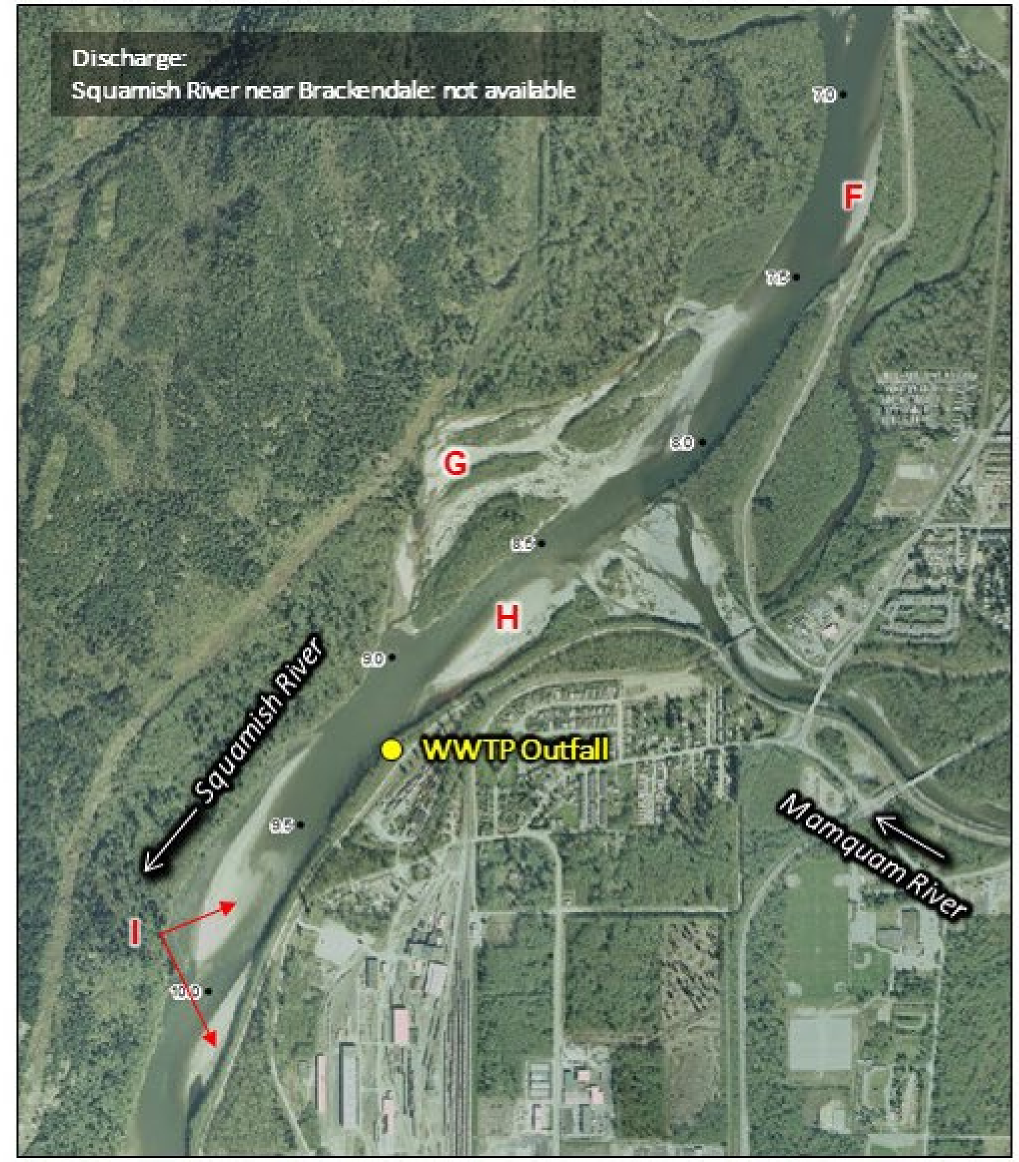
Date: 1990-08-07
30BCB90103-89

NOTES:
- Dike constructed along east (left) bank of the Squamish River north of the Mamquam confluence [**H**], side channel disconnected from mainstem flow [**I**].
- Squamish River eroded northern part of Mamquam River fan [**J**], and bank erosion opposite the Mamquam confluence has created a new side channel [**K**].
- Bank erosion as the Squamish River shifts westward across and downstream of Mamquam confluence [**L**, **M**].

FIGURE 6.3 *Historical changes in channel morphology near the WWTP Outfall: 1975 and 1990.*

Date: 1999
District of Squamish Orthophoto

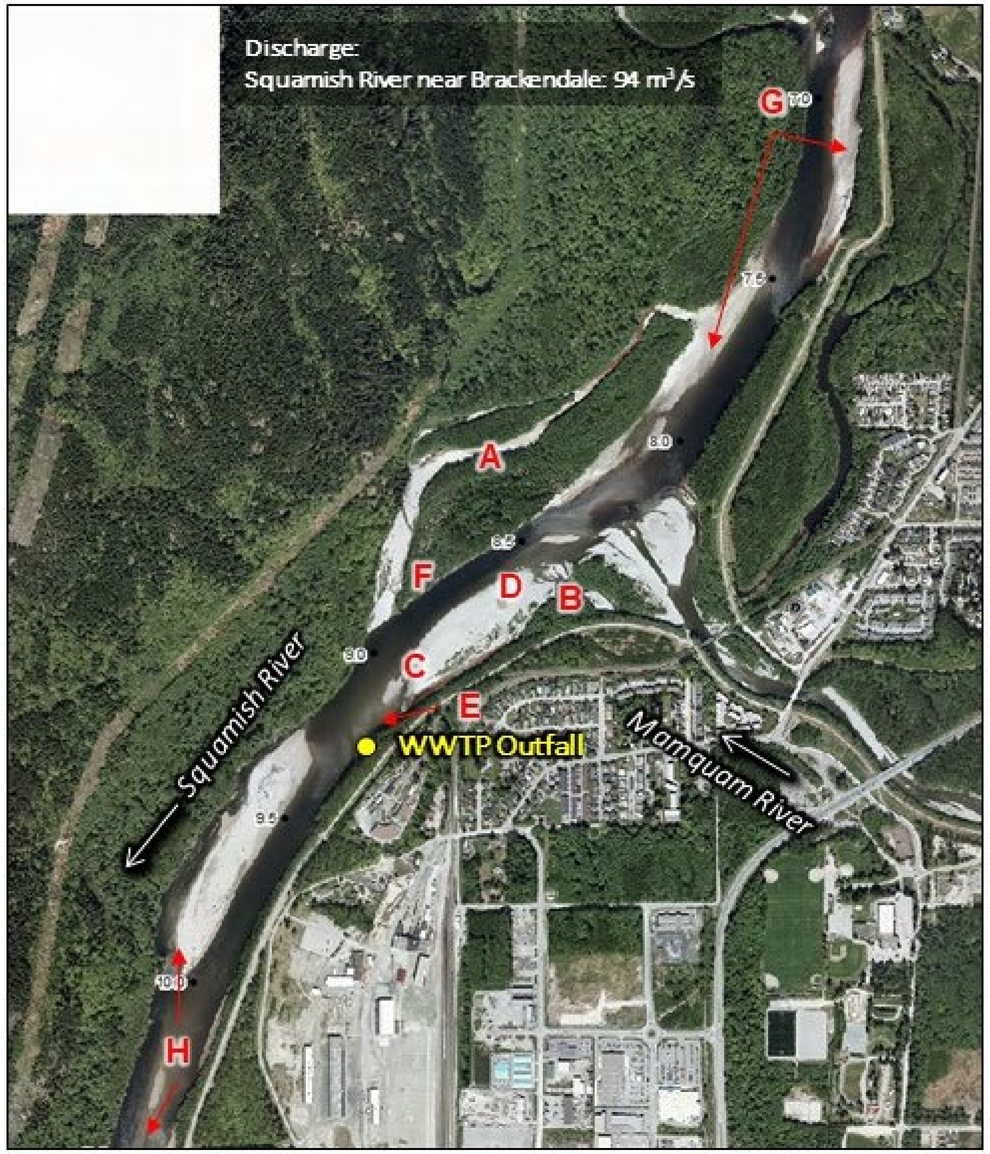
NOTES:
- Squamish River dominantly single-thread morphology [**A**].
- Vegetation establishing in side-channel opposite Mamquam confluence [**B**].
- Clear water plume indicates mixing conditions between Mamquam and Squamish Rivers downstream of Mamquam confluence [**C**].
- Laterally attached gravel bar exposed downstream of Mamquam confluence [**D**], and exposed mid-channel bars [**E**].



Date: 2004
District of Squamish Orthophoto

NOTES:
- No large morphological changes observed from October 2003 flood.
- Generally enlarged instream sediment accumulations [**F**, **G**, **H**, **I**].

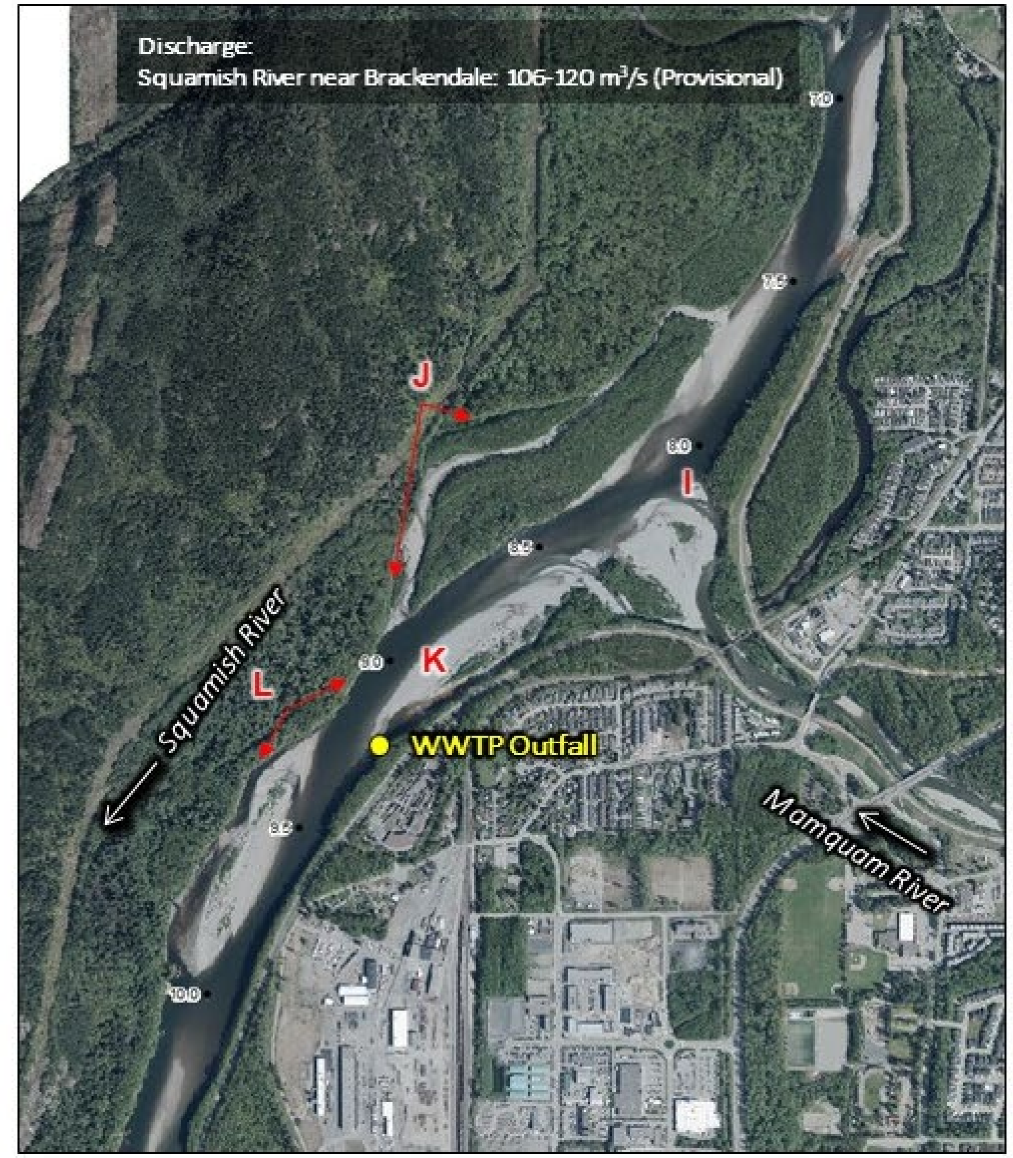
FIGURE 6.4 *Historical changes in channel morphology near the WWTP Outfall: 1999 and 2004.*



Date: 2013-04-24
District of Squamish Orthophoto

NOTES:

- Vegetation establishing on gravel bars [**A**, **B**].
- Laterally accreted bar downstream of Mamquam confluence growing [**C**], woody debris jam forming near head of bar [**D**], and area of low water velocity due to upstream bar starting to form and change in thalweg location at WWTP Outfall [**E**].
- Bank erosion on island opposite Mamquam River confluence [**F**].
- Instream sediment accumulations growing and moving downstream [**D**, **G**, **H**].



Date: 2019-04-28
District of Squamish Orthophoto

NOTES:

- Mamquam River confluence at northern edge of fan [**I**].
- Vegetation growth extending on gravel bars and in side channels [**J**].
- Laterally accreted bar downstream of Mamquam confluence extending downstream, and continued vegetation growth and woody debris accumulation there [**K**].
- WWTP Outfall is located in the lee of bar [**K**] and is no longer exposed to the main stem flow.
- Bank erosion on west (right) bank of Squamish River across from gravel bar extending across the river [**L**].

FIGURE 6.5 *Historical changes in channel morphology near the WWTP Outfall: 2013 and 2019.*

7. CONCEPTUAL MITIGATION OPTIONS

Conceptual mitigation options for improving mixing conditions at the WWTP outfall were identified considering the channel changes that have occurred at the site. This study shows that sediment accumulations upstream of the WWTP outfall are causing low water velocities and poor mixing conditions and are the driving factor for deteriorating conditions near the outfall, particularly at low flows. The key observations of channel change near the WWTP outfall are that:

- In 1990, the WWTP outfall was exposed to the main flow of the Squamish River. Subsequent river bar formation and enlargement has shifted the river thalweg[4] westward and the WWTP outfall is now situated in an area with reduced water velocities.
- The WWTP outfall is currently situated in a depositional environment; lateral accretion of the gravel bar upstream of the WWTP outfall is expected to continue as vegetation and large woody debris stabilize the bar and the river erodes the opposite bank. Gravel deposition is expected to extend downstream and further restrict mixing processes at the outfall.
- As the river continues to erode the outside bend across from the WWTP outfall site, the water will be increasingly forced towards the outside bend and water velocities near the WWTP outfall could decrease further, exacerbating issues at low flows.

Four locations of the WWTP outfall were considered during our evaluation of conceptual mitigation options. These locations are shown in FIGURE 7.1 and discussed below. Additional considerations were also made regarding the Municipal Wastewater Regulation (Province of BC, 2012), particularly to the conditions with respect to outfall design. These conditions are that the initial dilution zone must be located at least 300 m away from recreational areas, shellfish harvesting areas, water intakes, and any sensitive areas requiring protection, and that the outfall location allows the maximum trapping of effluent below the surface of the water, the maximum dilution with the receiving environment, and the effluent to be intercepted by the predominant current. Additionally, a diffuser must provide a minimum dilution ration of 10:1 at the end of the IDZ,

[4] Thalweg refers to line of maximum depth along a river channel.

based on the river low flow criteria of the 2-year return period 7-day low flow. Outside of the IDZ, the discharge must not cause water quality parameters to be beyond the appropriate water quality guidelines (Province of British Columbia, 2012, Urban Systems, 2014).

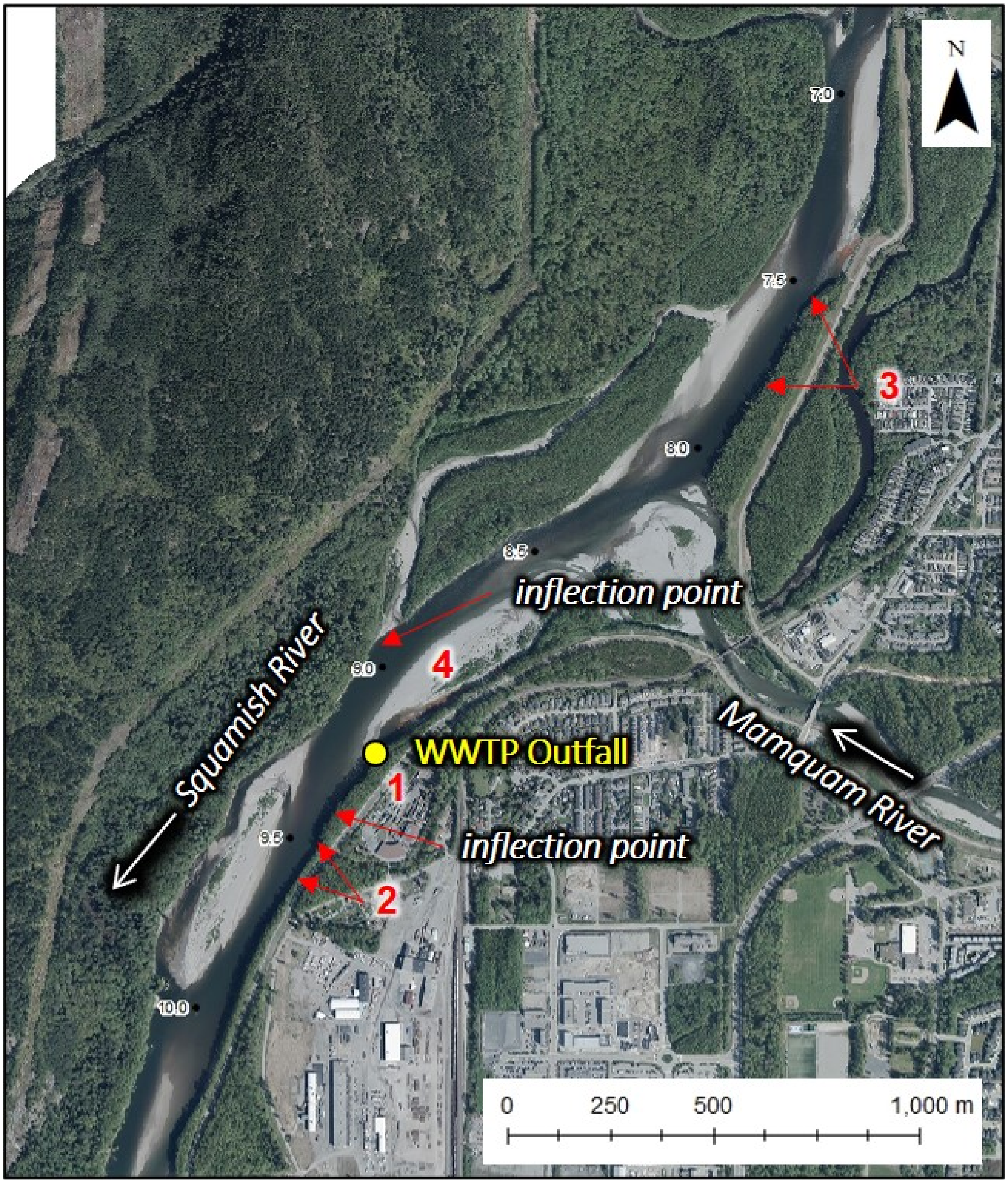


FIGURE 7.1 *WWTP outfall locations considered during identification of conceptual mitigation options.*

7.1 OPTION #1: KEEP WWTP OUTFALL IN SAME LOCATION

There are several potential options at the current WWTP outfall site, which include:

a. No changes to the WWTP outfall;
b. Updating the current outfall at the same location so that it disperses the effluent over a larger area; or
c. Extending the WWTP outfall pipe for approximately 80 to 90 m towards the thalweg of the Squamish River.

Each of these options is discussed below.

a. No changes to the WWTP outfall:

Given that lateral accretion of the bar upstream is expected to continue and flows may be increasingly directed towards the opposite bank of the river, it is expected that additional sediment deposition and poor mixing conditions will be exacerbated at low flows. As a result, it is expected that conditions at the current WWTP outfall will worsen in the future.

The current WWTP outfall configuration is undesirable because poor mixing conditions are present at low flows and Great Pacific Engineering & Environment and Ocean Dynamics (2015) noted that the terminus of the outfall was suspended 1 m above the river bed in 2015, and that there was no scour protection along the outfall pipe.

b. Updating the current outfall at the same location so that it disperses the effluent over a larger area:

Upgrading the outfall in its current location is considered a short-term solution but may be desirable because no additional construction to the effluent pipe would be required along the dike. Given that the outfall was suspended 1 m above the riverbed, and that it currently does not have a diffuser, by upgrading the pipe outlet, mixing conditions may be improved. However, since the gravel bar is expected to continue to aggrade, this solution may only provide short-term improvements (<5 years).

c. Extending the WWTP outfall pipe 80-90 m perpendicular to the river bank into the Squamish River at its current location to intercept the thalweg:

The third potential mitigation option at the current WWTP outfall site is to extend the pipe further into the current of the Squamish River. Given the current morphology of the gravel bar near the outfall, the pipe would have to be extended approximately 80-90 m into the river for the outfall to intersect with the thalweg. As the pipe is extended further into the river, the pipe will need to withstand scour and possible impacts from bedload material and will be more difficult to monitor/maintain. Considerations need to be made about the extent of the initial dilution zone (IDZ) as the pipe extends towards the thalweg so that it remains within the maximum allowable 100 m length. Conditions for construction become increasingly challenging the further the pipe extends into the river, and the area may need to be dewatered during construction. Extending the pipe may be a short- to mid-term solution (5 years +/-); however, due to the engineering challenges associated with extending the pipe 80-90 m into the river, this may not be a feasible or cost-effective option and more analysis is needed.

7.2 OPTION #2: MOVE THE WWTP OUTFALL DOWNSTREAM (SOUTH)

Downstream of the WWTP outfall site, the river straightens, and flow is directed towards the east (left) bank of the Squamish River. The inflection point of the Squamish River where it transitions from an inside bend to a straighter reach is approximately 250 m downstream of the WWTP outfall. The east (left) bank of the Squamish River, approximately 300 m to 450 m (9.50-9.65 km) downstream of the WWTP outfall would be suitable for a new outfall. There is a culvert and gate to permit outflows from the slough approximately 320 m downstream of the WWTP outfall, which may also be a suitable location for an outfall. The channel configuration in this section is on an outside bend, so gravel is less likely to deposit there. Moving the outfall downstream will require a new section of pipe, which could be installed along the dike. Mixing conditions downstream of the WWTP outfall may be more impacted by tidal conditions, which is a potential issue that would require further study. Urban Systems (2015) found that the dilution ratios were slightly higher during high tide than low tide due to the amount of volume of water available for dilution. Despite some evidence suggesting a salt wedge does not reach the proposed location (Levings, 1980), the potential effect of the salt wedge should also be considered. KWL (2011) estimated that a ±0.6 m variation in sea level would generate approximately ±0.1 m of variation to the 200-year modelled flood level near the proposed location. Depending on the effects of tidal conditions on the mixing conditions, it is expected that moving the WWTP outfall downstream could be an effective mid- to long-term solution (20 years +/-).

7.3 OPTION #3: MOVE WWTP OUTFALL UPSTREAM OF THE MAMQUAM RIVER CONFLUENCE

Upstream of the Mamquam River confluence, the Squamish River along the east (left) bank is relatively straight and also has some slight curvature along an outside bend. The east (left) bank approximately 1 km north of the WWTP near 7.50-7.75 km could be suitable for a new outfall location. The east (left) bank near 7.50 km is considered slightly more suitable as it is located upstream of the side channel near the west (right) bank on the Squamish River at 7.65 km. Given that this side channel has been active historically, there is the possibility for the Squamish River to occupy more of that side channel in the future, which could divert water away from the mainstem of the river. However, this is more likely to occur at high flows rather than at low flows. Moving the outfall upstream would require a new section of pipe and outfall, which could be placed along the dike. Additionally, because the outfall is upstream, it may require additional pumping requirements depending on the elevation gradient between the WWTP and the outfall location. Erosion has been observed near that location in the past, and bank protection may be required to protect the outfall there. Further studies would be required to assess the mixing of effluent with the Squamish River upstream of the Mamquam River confluence to understand any potential impacts to the water quality of the Mamquam River near its confluence, and to ensure that the IDZ was an adequate distance from any recreation areas. The historical air photo analysis indicates that there is a clear water plume from the Mamquam River, which may also be important aquatic habitat.

It is acknowledged that locating the WWTP outfall at this location may be undesirable given the potential for detrimental water quality impacts on environmental and social values (e.g., recreation). Without considering these potential impacts, it is expected that moving the WWTP outfall upstream could represent a medium to long-term (20 years +/-) option. We understand that due the potential environmental and social impacts near the confluence of the Squamish and Mamquam Rivers is not one the District is currently interested in pursuing (Roulson, D, pers. comm., 2020).

7.4 OPTION #4: INSTREAM WORKS (EXCAVATE GRAVEL NEAR THE EXISTING WWTP OUTFALL)

Excavating the distal edge of the gravel bar near the WWTP outfall and/or excavating gravel along approximately 500 m of the side channel immediately upstream of the WWTP outfall could provide temporary improvement in flow circulation and mixing conditions near the current WWTP outfall site. However, since gravel is expected to continue to aggrade in this area this option is not appropriate as a long-term or sustainable solution.

During gravel removal on the Mamquam River, a hole that was excavated filled in during high flows the following year (Sutek and Kellerhalls, 1989). Additionally, the persistent removal of material in one place can interrupt downstream progression of the bed material load, and may reduce topographic variability, which has habitat concerns (Church et al., 2011). Gravel removal has a high level of uncertainty, is expensive and requires on-going maintenance. Any in-stream excavation would be considered a temporary (1 year +/-) solution, or perhaps be used as an emergency measure to improve mixing conditions under low flows.

8. SUMMARY & FUTURE WORK

Site conditions at the WWTP outfall are driven by several interconnected factors including sediment supply, hydrology, and tidal interactions. A review of hydrometric data and a historical air photo analysis showed that undesirable water quality conditions near the WWTP outfall at low flows are likely associated with channel changes at the site, and that sediment aggradation is the driving factor. A gravel bar upstream of the WWTP outfall has accreted laterally and downstream, and the growth of the gravel bar is expected to continue and further restrict mixing processes at the outfall. Given that conditions for mixing are expected to worsen, one or more options for mitigation should be considered. Four options for the WWTP outfall were reviewed in this study:

1. Keep the WWTP outfall at the same location (i.e., no change),
2. Move the WWTP outfall downstream 300 m to 450 m,
3. Move the WWTP outfall upstream of the Mamquam River confluence, or
4. Excavate gravel in the vicinity of the existing WWTP outfall.

Since site-specific flow and sediment transport patterns vary by location, the expected service life of a WWTP under these four options could range from less than a year to 20 years +/-.

The current conditions, represented under Option 1 are expected to worsen with time as the outfall becomes increasingly disconnected from the thalweg during low flows. The addition of a diffuser may improve conditions, but only temporarily. Option 4 also maintains the outfall at its current location, but involves excavation of gravel to improve flow conditions near the outfall. There are however large uncertainties associated with gravel removal, which can be costly and require on-going maintenance. Since aggradation is likely to continue following excavation, Option 4 is considered a temporary or emergency measure only.

Options 2 (move outfall downstream) and 3 (move outfall upstream) are more desirable in the long-term (20 years +/-). Between the two options **we recommend further examination of Option 2 should be a priority since it has not only represents a location where the outfall would intercept the river thalweg, but also is at a location where sediment accumulation over the long-term is unlikely to hamper mixing conditions**. Furthermore, construction and maintenance of an outfall near this location should be relatively straightforward and feasible and may not trigger an environmental assessment (Hamelin, T., 2020).

Although Option 3 may also have satisfactory mixing conditions over the long-term, there are expected to be considerably greater potential environmental and social concerns since the IDZ could affect flows around the confluence of the Mamquam River. As a result, Option 3 we do not recommend the District pursue this option at this time.

Although Option 2 shows good promise from a hydrogeomorphic perspective, there remain some uncertainties given the increased proximity to a potential salt wedge and the effects of the intertidal zone on effluent mixing. Given these uncertainties, further detailed studies are required to assess the feasibility of Option 2. In addition to developing engineering designs and costs for the relocation of the WWTP outfall approximately 300-450 m downstream, we recommend that the District retain qualified professionals to complete the following:

- Conduct dilution modeling for the recommended outfall location (Option 2) that considers the tidal and hydrological conditions, which includes considerations for climate change and sea level rise and the potential effects of a salt wedge, and the total flows of the Squamish, Cheakamus, and Mamquam rivers at the proposed location to ensure that it meets the relevant regulations and guidelines for the initial dilution zone (IDZ). Based on previous work completed by the District, a Class D estimate of such work approximately $60,000 (Quarmby, 2020); and
- If required by regulators, conduct an environmental impact assessment for the proposed new outfall (Option 2), consistent with all relevant federal, provincial and local regulations and guidelines. Based on previous work completed by the District, a Class D estimate of such work approximately $40,000 (Quarmby, 2020).

9. STATEMENT OF LIMITATIONS

This report incorporates and is subject to the following general conditions.

9.1 USE OF REPORT

This report pertains to a specific location (e.g., watershed), a specific development, and a specific scope of work. It is not applicable to any other locations nor should it be relied upon for types of development other than to which it refers.

This report and the recommendations contained herein are intended for the sole use of the District of Squamish. Polar does not accept any responsibility for the accuracy of any of the data, the analysis or the recommendations contained or referenced in the report when the report is used or relied upon by any other party than the District of Squamish unless otherwise authorized in writing by Polar and the District of Squamish. Any unauthorized use of the report is at the sole risk of the user.

This report is subject to copyright and shall not be reproduced either wholly or in part without the prior, written permission of the District of Squamish.

9.2 SOIL, SURFICIAL MATERIAL AND/OR ROCK DESCRIPTIONS

Classification and identification of soils, surficial materials, and rocks are based upon commonly accepted methods employed in geoscience practice. This report relies work conducted as a part of previous investigations of subject area.

The present report represents the current information available; it is valid for the condition of the study area as of the date of the information, verified by observations on the date of the associated field review. If further information or observations become available, the interpretations and conclusions contained within this report may require updating.

Polar does not warrant conditions represented herein as exact but infers accuracy only to the extent that is common in geoscience practice.

9.3 SURFACE WATER AND GROUNDWATER CONDITIONS

Surface water and groundwater conditions that are mentioned in this report are those observed or inferred at the times recorded in the report. These conditions vary with location, time, development activity, and in response to local meteorological conditions. Interpretation of water conditions from observations and records is judgmental and constitutes an evaluation of circumstances as influenced by geology, meteorology, and development activity. Deviations from these observations may occur during the course of development activities. Where surface water or groundwater conditions encountered during development are different from those described in this report, qualified professional(s) should revisit the site and review recommendations in light of actual conditions encountered.

9.4 STANDARD OF CARE

Services performed by Polar for this report have been conducted in a manner consistent with the level of skill ordinarily exercised by members of the profession currently practicing under similar conditions in the jurisdiction in which the services are provided. Professional judgment has been applied in developing the conclusions and/or recommendations provided in this report. No warranty or guarantee, express or implied, is made concerning the results, comments, recommendations, or any other portion of this report.

9.5 ENVIRONMENTAL AND REGULATORY ISSUES

Unless stipulated in the report, Polar has not been retained to investigate, address or consider and has not investigated, addressed or considered any environmental or regulatory issues associated with development at the subject location.

10. REFERENCES

Bauch G. D., and Hickin E.J. 2011. Rate of floodplain reworking in response to increasing storm-induced floods, Squamish River, south-western British Columbia, Canada. Earth Surface Processes and Landforms: 36, 872-844.

Burn, D. H., & Whitfield, P. H. 2016. Changes in floods and flood regimes in Canada. Canadian Water Resources Journal/Revue Canadienne des Ressources Hydriques, 41(1-2), 139-150.

Church, M., Ham., D., and Weatherly, H. 2011. Gravel management in lower Fraser River. Prepared for the City of Chilliwack.

Clague J.J., Turner, R.J.W., Reyes, A.V. 2002. Record of recent river channel instability, Cheakamus Valley, British Columbia. Geomorphology. Vol 53: 317-332.

Ehsanzadeh, E. and Adamowski, K. 2007. Detection of Trends in Low Flows across Canada. Canadian Water Resources Journal. Vol 32(4): 251-264.

Great Pacific Engineering & Environment and Ocean Dynamics. 2015. Squamish River Outfall 2015 Inspection. Prepared for the District of Squamish.

Hamelin, T. 2020. Email correspondence with Benjamin Kineshanko of District of Squamish. Senior Environmental Protection Specialist, Municipal Liquid Waste Authorizations – South, BC Ministry of Environment and Climate Change Strategy.

Hicken E.J., 1989. Contemporary Squamish River sediment flux to Howe Sound, British Columbia. Canadian Journal of Earth Sciences 26:1953-1963.

Hickin, E. J., and Sichingabula, H. M. 1988. The geomorphic impact of the catastrophic October 1984 flood on the planform of Squamish River, southwestern British Columbia. Canadian Journal of Earth Sciences, 25(7), 1078–1087. doi:10.1139/e88-105.

Kerr Wood Leidal (KWL). 2011. Squamish River and Mamquam River Survey and Flood Assessment. Revised Final Report, July 2011. KWL File No. 463.186-300. Prepared for District of Squamish.

KWL (Kerr Wood Leidal Associates Ltd.). 2017. Integrated Flood Hazard Management Plan (IFHMP). Prepared for the District of Squamish. KWL file no. 463.278.

Levings, C.D. 1980. Consequences of training walls and jetties for aquatic habitats at two British Columbia estuaries. Coastal Engineering 4: 111-136.

Lockerbie Stanley Inc. 2003. Sanitary Wastewater Treatment Outfall. Approval for Construction. Prepared for District of Squamish.

Northwest Hydraulic Consultants (NHC). 2018. Squamish – Lillooet Regional District Flood Hazard Mapping and Risk Assessment Upper Squamish. Prepared for Squamish – Lillooet Regional District.

Paige, Alan & Hickin, Edward. 2000. Annual bed-elevation regime in the alluvial channel of Squamish River, Southwestern British Columbia, Canada. Earth Surface Processes and Landforms. 25. 991 - 1009.

PCIC (Pacific Climate Impacts Consortium) 2016. Climate Impacts Summary: Vancouver. Available from: https://pacificclimate.org/sites/default/files/publications/VancouverSummary_Final.pdf

PCIC (Pacific Climate Impacts Consortium). 2016. PCIC Science Brief: Storm Surges and Projected Changes to Atmospheric River Events in Coastal BC. Available from: https://pacificclimate.org/sites/default/files/publications/PCIC_Science_Brief_Sept_2016_Final.pdf

Polar Geoscience. 2015. Squamish River survey near the Mamquam Sewage Treatment Plant Effluent Discharge Outfall. Prepared for District of Squamish.

Province of British Columbia. 2012. BC Municipal Wastewater Regulation B.C. Reg. 87/2012. Accessed at: https://www.bclaws.ca/civix/document/id/crbc/crbc/87_2012

Quarmby, J. 2020. Email correspondence with Ben Kineshanko of District of Squamish. Water and Wastewater Specialist, Urban Systems.

Roulston, D. 2020. Email communication with Benjamin Kineshanko of District of Squamish. August 24, 2020. Manager of Municipal Infrastructure, District of Squamish.

Sutek Services Ltd. and Kellerhalls Engineering Services Ltd. 1989. Assessing Gravel Supply and Removal in Fisheries Stream. Report prepared for Department of Fisheries and Oceans and BC Ministry of Environment.

Urban Systems. 2014. Environmental Impact Study Effluent Discharge to the Squamish River. Prepared for the District of Squamish.

Urban Systems. 2015. Outfall Assessment and Environmental Impact Study Review. Prepared for the District of Squamish.

Web Engineering Ltd. 1972. Mamquam Sewage Treatment Plant Effluent Line & Discharge Outfall Plan & Profile. As-built. Prepared for District of Squamish.