SPATIAL PATTERNS AND DRIVERS OF FLOODPLAIN CHANGE IN THE SQUAMISH RIVER, A DYNAMIC GRAVEL BED RIVER

BY

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THESIS

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ABSTRACT

The geomorphic interplay between river channels and their floodplains is important for human society and natural ecosystems. Alluvial floodplains have long been ideal locations for human settlement. Thus, for as long as humans have lived along rivers, flooding and channel erosion have posed a hazard to their settlements. As a result, humans have often sought to restrict the natural river-floodplain interactions, including inundation and erosional-depositional processes, and engineer rivers to allow development of floodplains. These actions have been detrimental to floodplain ecology. Unaltered river floodplains are biologically diverse and highly productive ecosystems. They contain a diverse array of habitats that are important for the survival of aquatic, amphibious, and terrestrial organisms. In order to restore floodplain functions, we need to know more about spatial patterns and drivers of floodplain change.

This thesis examines the spatial patterns and drivers of floodplain dynamics in the Squamish River, in southern British Columbia, Canada, between 2009 and 2019. Patterns and magnitudes of floodplain construction and erosion were identified and measured from annual remotely-sensed data from Planet.com. The area of interest was classified into water, sediment, and vegetation using a simple but effective classification based on the Normalized Difference Vegetation Index (NDVI). Change was quantified by comparing each year with the next using the Change Detection Wizard in ArcGIS Pro.

The effect of three drivers of floodplain change – channel slope, valley confinement, and sediment supply – were examined with regard to rates of floodplain construction and erosion. The calculated rates of change in the Squamish River were in the range of 0.9 m – 13.4 m per year for construction and 1.7 – 15 m per year for erosion. However, no clear driver emerged as the specific cause of the floodplain change; instead, channel and floodplain dynamics seem to be driven by the complicated interplay of multiple limiting factors including channel slope, valley width, and sediment supply, as well as by human interventions and floodplain vegetation.

ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Piotr Cienciała for his eternal patience and faith that I could finish this thesis. I am grateful to Dr. Jim Best and Dr. Mark Lara for serving as my committee, and to the UIUC Geography Department, especially Matt Cohn, for guidance and support. I am thankful for the supportive community I found in my fellow SESE students/Geomorphology Girl Gang Mishel Milagros Melendez Bernardo, Sadia Sabrina, Chelsey Salas, Alexandra Sanchez, Tanya Shukla, and Katherine Strailey, as well as Alec Fojtik (honorary Geomorphology Girl Gang member). I'd also like to thank Sarah Popenhagen for her help in the field.

To my family and friends and anyone else who listened to me excitedly babble about rivers, thank you. Lastly, I want to thank Dan, who fueled my writing with snacks and encouragement, and Xanthippe (cat), who napped on or near me as I wrote. I could not have finished this without you.

My study site is on the traditional, ancestral, and unceded territory of the Coast Salish peoples – Skwxwú7mesh (Squamish), Tsleil-Waututh & Musqueam First Nations. When possible, traditional Skwxwú7mesh names are included parenthetically (Squamish Atlas, 2021; Reimer/Yumķs, 2011; Make a Watershed Model). Any errors in these names are my own.

Heraclitus said, "No man ever steps in the same river twice, for it's not the same river and he's not the same man." This thesis is dedicated to the Squamish River, who taught me it is okay to always keep changing.

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CHAPTER 1: INTRODUCTION

1.1 The Importance of Floodplains

When we think of rivers, we often focus on the channel. But just as important is the floodplain, the surrounding, low-lying land that is inundated by overflow water from the channel (Tockner and Standford, 2002). Floodplains are primarily formed by lateral accretion and overbank vertical accretion. Lateral accretion occurs as rivers migrate downstream or across the floor of the valley and the deposits which have been added to the inside of bends over time are slowly incorporated into the floodplain. Vertical accretion occurs when the river overtops its banks during a high-flow event and deposits its suspended load on the floodplain (Fryirs and Brierley, 2012)

Importantly, river channels and their floodplain change over time, even if these changes occur over imperceptible timescales. These changes occur with respect to various characteristics, including both vertical level and shape of the streambed and floodplain as well as horizontal shifts in the planform boundaries of the channel and floodplain features (Opperman et al., 2017). Equally importantly, these changes can be also highly heterogenous across space. Because the dynamic adjustments in the channel-floodplain system are accomplished by erosion, transport, and deposition of sediment (Church, 2006, 2015), they can be used to infer the rates of such geomorphic processes.

The geomorphic interplay between river channels and their floodplains is also important for human society and natural ecosystems. Alluvial floodplains have long been ideal locations for human settlement. Rivers and floodplains provide transportation, food, building materials, and fertile soil for agriculture. Early civilizations formed along the banks of rivers, learning to harvest, harness and cultivate their resources. Thus, for as long as humans have lived along rivers, flooding and channel erosion have posed a hazard to their settlements (Ham, 2005).

Unaltered river floodplains are biologically diverse and highly productive. They contain a diverse array of habitats that are important for the survival of aquatic, amphibious, and terrestrial organisms. Many species of mammals, amphibians, birds, and macroinvertebrates depend upon riparian areas, whether they visit seasonally or spend their entire lives there. Fish also depend on floodplain wetlands for habitat and spawning locations. Just as the evolution of human civilizations are tied to rivers and floodplains, floodplains are where biological diversification of many species occurred as well. Frequent inundation and disturbance leads to the isolation of populations, furthering speciation by creating a shifting mosaic of habitat which supports some of the most biodiverse and productive ecosystems (Tockner and Stanford, 2002; Stanford et al., 2005; Beechie et al., 2006; Whited et al., 2007; Naiman et al., 2010; Collins et al., 2012; Hauer et al., 2016).

Because of the importance of river-floodplain interactions for the social-ecological systems, they are of great interest to river management. However, the very processes that shape floodplains, including inundation and erosional-depositional processes have long been perceived primarily as a natural hazard (Oppermann et al., 2017). As a result, over the last centuries humans put tremendous effort into engineering and "training" rivers and their floodplains in an effort to enable the development of floodplains and to protect people and infrastructure. However, these efforts often did not succeed in protecting these values (Knox et al., 2022) and often led to degradation of floodplain integrity (Morrison et al., 2023).

This realization has prompted efforts to reconnect rivers and floodplains, or at least allow for some space for their dynamic changes to play out, in a bid to restore the lost ecological values (e.g., Biron et al., 2014). To inform such efforts, we need to know more about the patterns and natural drivers of such processes.

1.2 Drivers of Floodplain and Channel Change

The form and behavior of river-floodplain system are the result of a range of processes operating on a variety of time and spatial scales (Hickin, 1989). River channels and floodplains change via erosion, the shearing off of material from banks. This occurs slowly during everyday flows and is generally accelerated during high floods. Bank erosion also occurs by slumping, when bank material slides off the bank (Sichinagbula, 1989). The rates of sediment erosion and redistribution are driven by flow forces. These forces partly depend on the slope over which the water is flowing. Channel gradient determines the gravitational force available to carry water and sediment (Whiting and Bradley, 1993). Therefore, the gradient is thought as one of the primary factors shaping river-floodplain changes.

Valley width confinement been proposed as another critical control on river behavior (Fryirs et al., 2016) as well as the hydrological regime of the floodplain (Cienciala and Pasternack, 2017). Moreover, valley width also can determine whether debris flows coming off adjacent slopes deposit on the floodplain or are immediately entrained by the channel (Whiting and Bradley, 1993). Channel confinement not only restricts channel migration, but also may control channel's ability to shift course, migrate down valley, or avulse (Cienciala et al., 2020).

Another factor which may regulate channel-floodplain interactions is sediment supply. Increased sediment supply tends to decrease channel stability (Church, 2006; Ham, 2005). Sediment size or caliber is also an important factor. The size of sediment determines the ability of flow to entrain it and, therefore, the resulting rate of sediment transport, the frequency of sediment mobilization, and the process by which sediment is transported, either as bedload or suspended load (Church, 2006; Whiting and Bradley, 1993). Other relevant factors include bank strength, land use patterns, riparian vegetation, and anthropogenic modifications.

1.3 The Squamish River

The Squamish River is an ideal site to study floodplain change and its drivers. It is a dynamic gravel bed river composed of three planform types: braided, wandering, and meandering. Like many rivers, it follows a continuum of channel planform types transitioning between the steep, upstream braided planforms, transitional wandering planforms, and downstream, low slope meandering planforms (Ham, 2005). There are portions of the river completely confined by bedrock and others where the river is free to adjust laterally. Though the estuary and lower river have been altered by human activity, most of the river remains relatively untransformed and unconfined. This is not common, especially in the temperate climate, as most rivers of this size are typically affected by much more extensive watershed transformation.

Moreover, Squamish River is a relatively well-researched fluvial system. As a result, there is a wealth of data dating back over a century, including temperature, precipitation, and discharge values, partial records of landslides and debris flows, and timber harvest records. The river has been also a subject of intensive research on sedimentology (Brierley, 1989; Hickin, 1979; Wooldridge and Hickin, 2005), floodplain development and reworking (Brierley and Hickin, 1991, 1992; Bauch and Hickin, 2011), river morphology and planform (Hickin, 1984;

Hickin and Sichingabula, 1988), and contemporary sediment transport processes (Hickin, 1989; Rood and Hickin, 1989; Paige and Hickin, 2000). These studies provide important background information which helps contextualize and interpret my findings. Many previous studies have focused on the Squamish River, but this thesis will be the first comprehensive description and qualitative measure of erosion covering the entire Squamish River, amalgamating decades of research on the river.

1.4 Aim, Scope and Objectives of Study

The aim of this study is to examine the spatial patterns and drivers of floodplain dynamics in the Squamish River over the last decade. It is hoped this study will contribute to the vast body of work around the Squamish River, a dynamic gravel bed river. This study is limited to assessing floodplain construction and erosion over a short timescale and investigating the drivers and controls that lead to this change. Extrapolation of observed floodplain changes into predictions of long-term landscape evolution is outside the scope of this study. In order to assess and evaluate the geomorphic principle that channel planform and floodplain dynamics are a result of sediment supply, the general objective of this thesis is:

> To examine the spatial patterns and drivers of floodplain dynamics in a diverse and dynamic gravel bed river over a decadal time period.

The research hypothesis states that levels of floodplain dynamics are determined by sediment transport, channel confinement and stream power. To achieve the general objective of this study and to test the research hypothesis, three specific objectives were formulated:

i. To map the extent of the floodplain every year from 2009 to 2019 to determine change between years and over the decade
ii. To characterize floodplain erosion and construction in different planform types
iii. To determine the extent to which three drivers – channel slope (for brevity, referred to below as “slope”), valley confinement (or simply “confinement”), and sediment supply conditions – affect the floodplain construction and erosion rates in its braided/wandering and meandering reaches

These objectives are achieved through a series of steps. They include (i) classifying the active channel of the study reach into water, sediment and vegetation, (ii) quantifying change between categories over the decade between 2009 and 2019 and also between each individual year within the study period (iii) analyzing of the effect of slope, valley confinement, and sediment supply on magnitudes of floodplain change, and (iv) placing spatial patterns, rates of change, and drivers into the context of broader research on both the Squamish River and globally.

A general description of the climate, vegetation, geology and hydrology of the study area is outlined in Chapter 2. The data sources and procedures for mapping and quantifying floodplain dynamics are detailed in Chapter 3. Spatial patterns and drivers of floodplain dynamics are stated and discussed in Chapter 4. Conclusions and implications of results are examined in Chapter 5.

CHAPTER 2: STUDY AREA AND BACKGROUND

2.1 Overview and Structure

Geomorphic interactions between a river and its floodplain are a product of multiple factors – including climate, vegetation, hydrology, geology, and human influences – as well as past and present events that occur in its watershed. The purpose of this chapter is to provide key background information on the biophysical characteristics of the Squamish River watershed, and also describe specific sites (river reaches) that were the focus on this study.

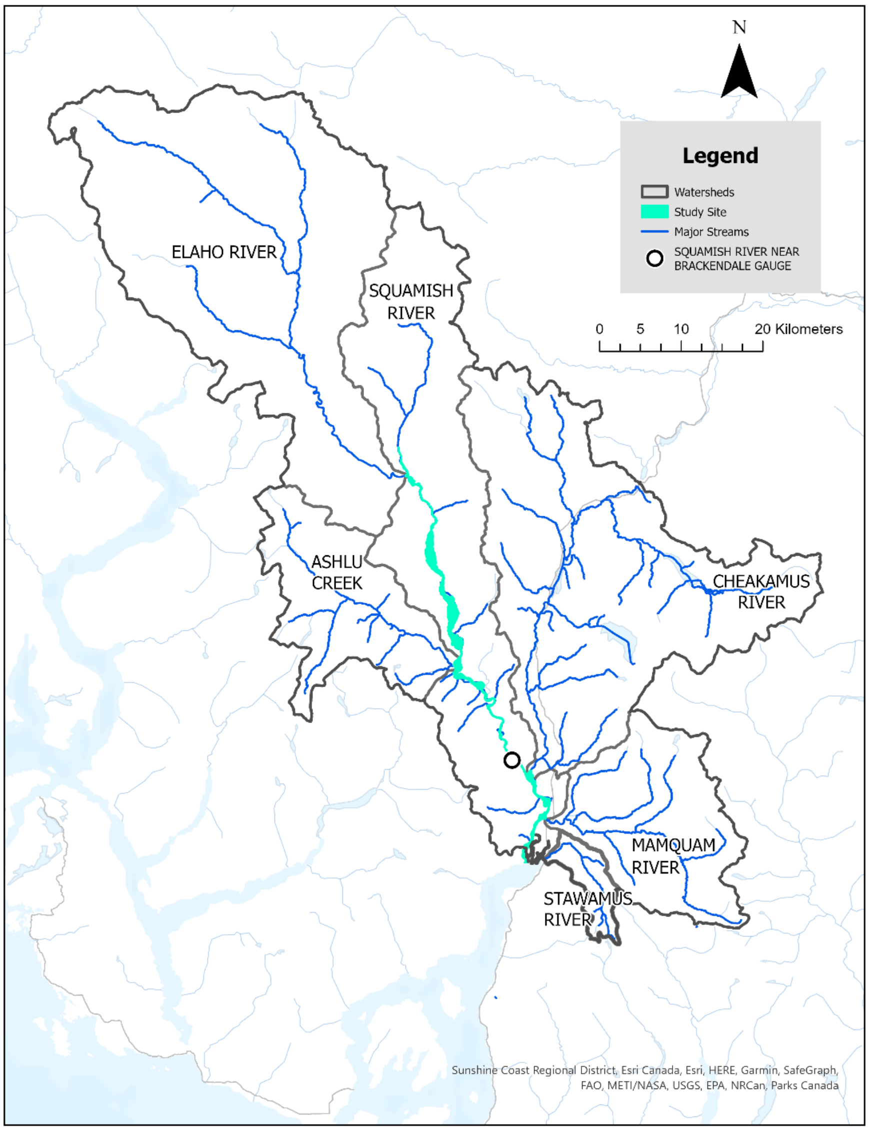


Figure 1: Study site

2.2 Climate and Vegetation

The Squamish River valley is located within the Coast Mountains of British Columbia, at the head of Howe Sound, a prominent fjord. The area has warm, dry summers and cool, wet winters. Precipitation, which is concentrated in the winter months (October-April), occurs mostly when moist air masses flowing into the Squamish valley are forced up the steep walls of Howe Sound (Paige and Hickin, 2000). Squamish receives a mean annual rainfall of 2100 mm and has a mean daily temperature of 8.0º C (Sichinagbula, 1989).

The abundant precipitation results in dense vegetation on the valley floor and lower mountain slopes, with a mixture of coniferous and deciduous trees in three primary biogeoclimatic zones that vary along the elevation gradient (which spans sea level to over 2,500 m.a.s.l.). Areas at low elevations belong to the Coastal Western Hemlock Biogeoclimatic zone. These fluvially modified glacial valleys make up 30% of the watershed. Elevations 1,000 m to 1,500 m represent the Mountain Hemlock zone. Areas above 1,500 m make up 25% of the watershed and include Alpine heather tundra, bare rock, unstable paraglacial sediment, and glaciers, which cover approximately 16% of the watershed (Paige and Hickin, 2000).

As expected in the CWH zone, western hemlock (*Tsuga heterophylla*) and western red cedar (*Thuja plicata*) as the most common conifer species found at the valley floor. Recently disturbed floodplain patches are primarily colonized by early successional species such as willows (*Salix*), black cottonwood (*Populus trichocarpa*), and red alder (*Alnus rubra*) (Pojar et al., 1991).

2.3 Hydrology

The Squamish River flows 115 km through the Coast Mountains, draining an area of around 3,650 km2. It begins in glaciers, including Pemberton Icefield and Elaho Glacier, high in the mountains and flows to Howe Sound which connects to the Salish Sea, a marginal sea of the Pacific Ocean. The stream network is made of five major channels: Upper Squamish River (*Sḵwx̱wú7mesh Staḵw*), Elaho River (*Yalahú Staḵw*), Ashlu River (*Yelhí’xw Staḵw*), Cheakamus River (*Ch’iyáḵmesh Staḵw*), and Mamquam River (*Mámxwem Staḵw*) (Fig. 1). The segment of Squamish River that is of interest in this study extends from the confluence of the Upper Squamish River and Elaho River down along the main stem river to the estuary at the head of Howe Sound (Bauch, 2010).

The river follows a hybrid streamflow regime reflecting the influence of glaciers (covering ~20% of the watershed; BC Regional Flood Analysis Portal), snow, and rainfall. The spring freshet, fed by glacial and snow melt, typically begins in April and peaks in June or July. After a period of declining flows later in the summer, high flows return with the onset of the rainy season. The largest flow events occur during the fall, due to intense, low-pressure weather systems coming north from the tropics. The storms linger for several days and flood magnitudes are often amplified due to rain-of-snow events. Streamflow in Squamish River has been monitored on a nearly continuous basis since 1955, but intermittent records extend back to late 1922. The primary gauging station, operated by Water Survey of Canada (08GA022), is located near Brackendale, 2.5 km upstream of the Cheakamus River confluence and reflect drainage from the mid-to-upper portion of the watershed (2350 km^2). Based on the available records, the mean annual discharge at that station is 250 $m^3 s^{-1}$. Discharge at the peak of the freshet is ~500 $m^3 s^{-1}$ and the low flow in January drop to <100 $m^3 s^{-1}$. Maximum instantaneous discharge during fall to early winter rain-on-snow events can be up to 8 times the mean annual discharge (NHC, 2018; Bauch and Hickin, 2011; Paige and Hickin, 2000; InStream Fisheries, 2019). The largest flow on record was 2630 $m^3 s^{-1}$ and occurred in October of 2003.

2.4 Geology and Geomorphology

As noted above, the Squamish River valley is set within the Coast Mountains and several peaks within the basin rise to the elevation around or in excess of 2500 m.a.s.l. Because many of these peaks flank the principal valley, the local relief approaches 2000 m.

Most of the bedrock in the watershed consists of intrusive and metamorphic rocks belonging to the Coast Plutonic Complex, formed in the early middle to Late Jurassic. Some portions are older rocks of the metavolcanic and metasedimentary Gambier Group, formed in the Cretaceous, as well as other early and late Cretaceous rocks. These rocks are strong and form coarse-grained colluvium (NHC, 2018; Jakob, 1996). A much smaller portion of the watershed are volcanic rocks from the Quaternary Garibaldi Volcanic Belt and are represented prominently in Mount Cayley (*Sxeltskwu7 or T'ákt'akmúten tl'a Ín7inyáx̱a7en*) and Mount Garibaldi (*Nch'kaý*). More broadly, these volcanic rocks are part of the Cascade Volcanic Arc which also includes Mount St. Helens in Oregon, Mount Baker in Washington, and Mount Meager in BC, in the adjacent

Lillooet River basin. Mount Cayley and Mount Garibaldi are composite volcanoes of poorly lithified pyroclastic rocks and lavas. These weak rocks appear to provide a disproportionate amount of sediment to the fluvial system. For example, this volcanic lithology makes up 2% of the Lillooet River watershed, yet as much as 25-75% of the bedload sediment is of volcanic origin (Brooks and Hickin, 1991; Ékes and Friele, 2003, Friele, 2005).

The surficial geology of the Squamish River watershed was heavily affected by glaciation during the late Pleistocene, which ended approximately 12,000 years ago. The Cordilleran Ice Sheet left behind rounded ridges and U-shaped valleys, glacial drift deposits, as well as destabilized slopes on Mount Garibaldi and Mount Cayley. In particular, the Cheekye Fan is a large, paraglacial alluvial fan formed from colluvial debris from Mount Garibaldi (Fath et al., 2018). This event impounded the river and, before being breached by fluvial erosion, created a temporary lake extending back up to the confluence with Ashlu Creek (Brooks, 1994; Friele and Clague, 2009; NHC, 2018).

Unconsolidated sediment generated by the recent glaciation are thought to play an important role in sediment supply to fluvial systems. Two key types of such sediment sources can be distinguished in the Squamish River watershed. Reworked glacial sediment supply (RGSS) comes from the fluvial reworking of glacial deposits and, therefore, is associated with the valley flood environment. Debris avalanche sediment supply (DASS) comes from landslides and debris flows that originate at the steep valley slopes, especially in the Mount Garibaldi and Mount Cayley massifs (Brooks, 1992). Like the Cheekye Fan, these events can form transient dams on the Squamish River and inundate upstream areas, but because volumes of material they mobilize tend to be orders of magnitude smaller, these dams typically are breached relatively quickly by the high energy river.

The geomorphic character of the Squamish River reflects its complex physical setting. The longitudinal profile of its valley generally follows a concave-upwards pattern, with steep headwaters (channel slope >1% at the upstream-most boundary of the study section) and gradient declining to near null towards the mouth. However, because of the legacy of the catastrophic bedrock landslides described above, the profile is stepped, with alternating patterns of low gradient upstream of these grade controls and steeper portions downstream of them (NHC, 2018). In unconfined sections of the valley, the planform morphology of the Squamish River alternates between braided and single-thread meandering planforms (Brierley, 1989; Bauch and Hickin, 2011).

A transitional form, in the literature described as 'wandering channels', is also common (Desloges and Church, 1989). Wandering planforms are visually somewhat similar to both braided and anastomosing channels, but have several distinct characteristics. Wandering rivers are laterally unstable and switch position between channels, which contrasts with stable anastomosing channels. Their channels tend to be irregular, sinuous, and single-threaded, flowing around large, forested islands, unlike braided channels which split around more transient, largely unvegetated bars. Sedimentation zones found in wandering channels fill in over time, leading to overbank flow. This process creates an extensive network of perennial, seasonal, and abandoned side channels, which may be reactivated during high flows, and causes channel and floodplain instability (Brierley, 1989; Ham, 2005).

Confined sections of the valley are typically associated with straight, or low sinuosity, and single threaded channel. Overall, the river can be classified as a gravel-bed channel, although its bed material fines downstream from a dominant mixture of gravels and cobble in the upstream-most part of the study section to a mix of gravel and sand near the mouth. A more detailed description of the study reaches can be found below.

2.5 Human Impact

Humans have lived within the Squamish River watershed for at least 5,000 years, though some estimates put it at as early as 14,000 years ago, and the area is a part of the traditional (overlapping) territories of Squamish Nation and Tsleil-Waututh Nation. Europeans and other non-Indigenous people began to arrive in the early 1800's, initially as traders and trappers. When, in 1858, the Cariboo gold rush brought tens of thousands of newcomers to the area, they also began using the land for mining, timber harvest, and agriculture, officially settling in the Squamish Valley in 1874 (SRWS, 2008).

The natural vegetation cover in the area has been altered considerably by logging, which constitutes one of the major industries in the area. The extent of old-growth forest has been greatly reduced on the valley floor, and younger second growth forest dominates much of the conifer stands. Land cover in the lower watershed has also been fundamentally changed by residential and industrial urban development within and around the town of Squamish. Currently, the town's population is among the fastest growing communities in British Columbia (according to census data, 22.2% increase between 2016 and 2021).

Anthropogenic influence has also left imprint on watershed hydrology and sediment supply. While the mainstem Squamish River remains unregulated, there are several hydropower projects on its tributaries. The 30-m high Daisy Lake dam impounds the Cheakamus River, storing water and trapping sediment, and a number of run-of-river dams have been recently constructed on Ashlu River and Mamquam River. The run-of-river dams, by definition, do not store water and their impact on sediment transport is unknown.

Sediment supply and fluvial transport have been most affected in the downstream-most section of the river, in the most densely settled area. The town of Squamish is almost entirely located on the floodplain of the river and within the estuary. Structures to protect the town and infrastructure have been constructed since the early 1900's, prompted by several major flooding events. As a result, the estuary is heavily altered by a 5 km training dyke installed in 1972. The dyke extends from the confluence of the Mamquam River downstream to Howe Sound. (see Fig. 12). The intention of the dyke was to confine the river to the far west side of the valley, allowing the eastern portion of the estuary to dry out to create a deep-water port. The port was never created, but the dyke remains. Efforts to reconnect the estuary began shortly after construction and continue to this day. The Central Estuary Restoration Project is a multi-year project focused on restoring connectivity and improving fish access between the Squamish River and the central estuary to improve spawning and rearing habitat, particularly for Chinook salmon (Tobe, 2020).

2.6 Ecological Context

The river provides important habitat for all five species of Pacific salmon (PSF, 2022) as well as other salmonid species including steelhead trout (*Oncorhyncus mikiss*) and Dolly Varden (*Salvelinus malma*). As a result, in 2002 the Pacific Salmon Foundation identified the watershed as a priority for the development of salmon recovery plan. Despite several habitat enhancement efforts in the following years, important salmonid habitat along the Squamish River has been assessed to be at moderate risk (PSF, 2005).

2.7 Study Reaches

For the purposes of this study, the study section of the Squamish River was divided into ten reaches. Five of these (Reaches 3, 5, 6, 7, and 9) correspond to those used in previous research by Sichingabula (1989) and Bauch (2007). Sichinagbula (1989) chose these five reaches based on the availability of aerial imagery and on the locations where high levels of change were observed. The five remaining reaches (Reaches 1, 2, 4, 8 and 10) were delineated within the gaps between the preexisting study reaches. For this reason, the reaches are uneven in length.

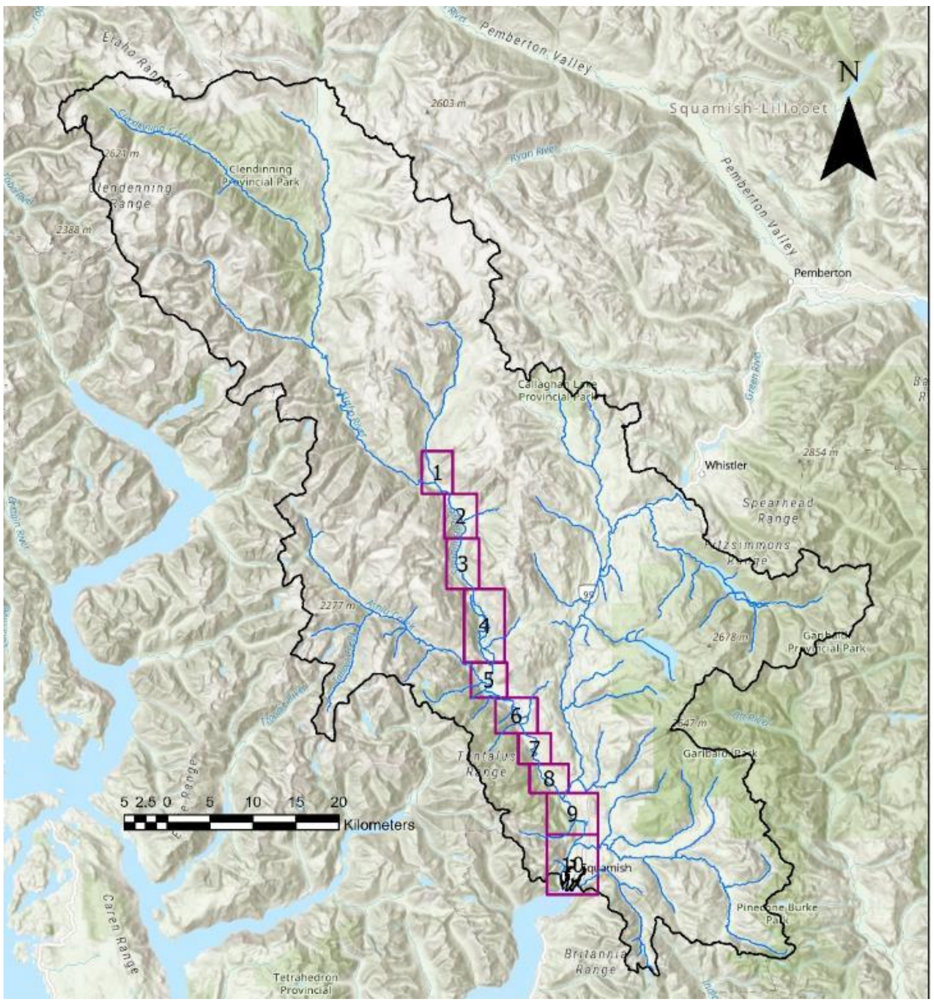


Figure 2: Overview of study reach locations within watershed

2.7.1 Squamish-Elaho Reach

The first study reach is the Squamish-Elaho Reach, located in the Upper Squamish River, where the Elaho River joins to form the mainstem Squamish River. The upstream third of this reach is a single thread channel tightly confined in a bedrock canyon; the remaining two-thirds flows in a somewhat wider valley and has a multi-threaded channel which braids around sediment bars. This reach is located 6450 to 5850 m upstream of the mouth of the Squamish River and 212 to 145 m.a.s.l. The valley floor along the reach is forested and undeveloped, other than the Squamish Valley Forest Service Road (FSR), which runs down the eastern side and crosses just above the confluence with the Elaho River. Currently, the valley sides bounding the reach are mostly forested but imagery from 1984 to present reveals considerable logging activity in this area. Logging also continues into the present in the headwaters, upstream of the study reach.

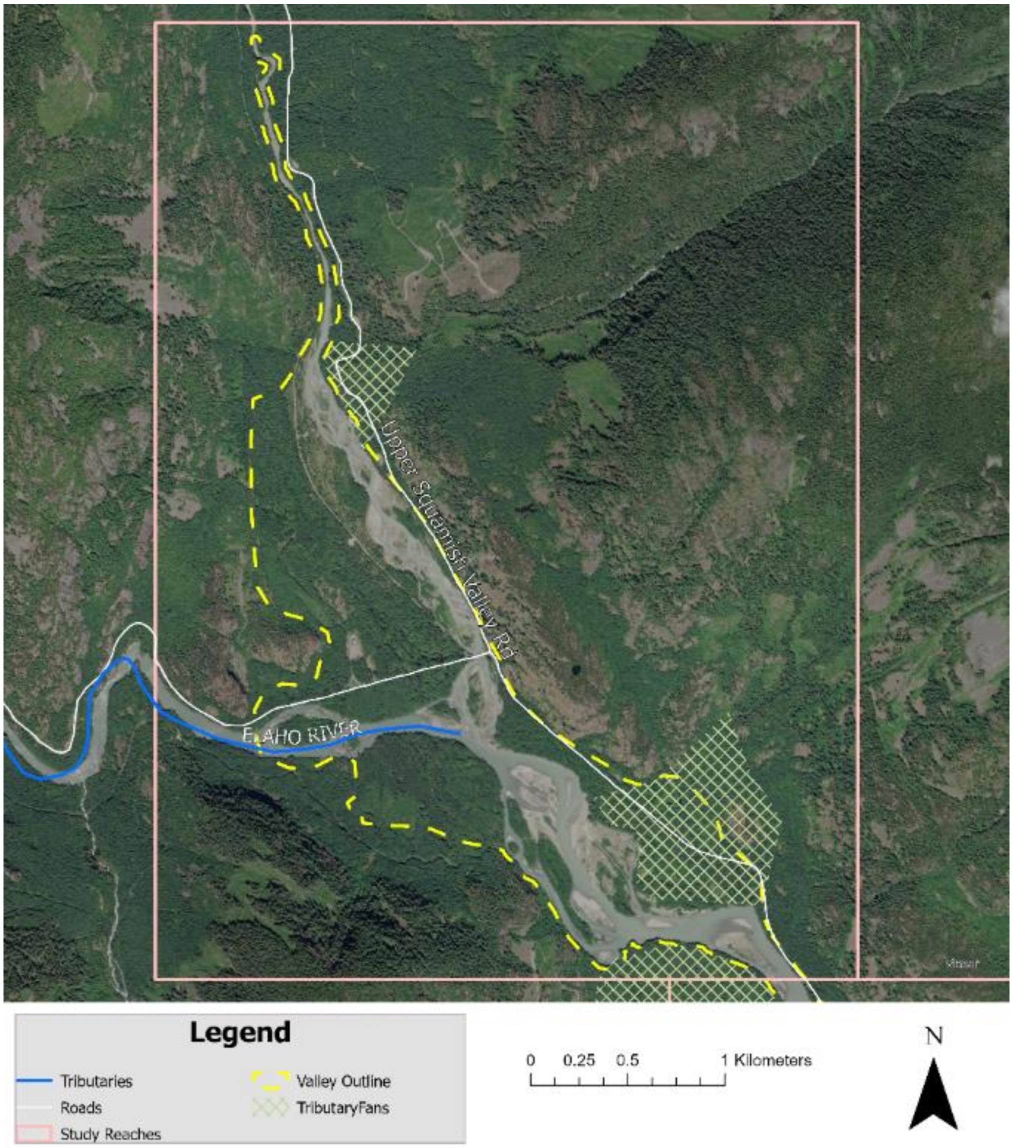


Figure 3 Overview of Study Reach 1, the Squamish Elaho Reach

2.7.2 Terminal-Turbid-Shovelnose Reach

The second study reach is the Terminal-Turbid-Shovelnose Reach, located 5850 to 5200 m upstream of the mouth of the river and 146 to 112 m.a.s.l. The river has a single thread, gravel-cobble bed channel with occasional sediment bars, especially around the outlets of steep tributary creeks from which the name of this reach was derived: Shovelnose Creek, Turbid Creek, and Terminal Creek. The reach is tightly confined by, and incised into, debris avalanche deposits coming off Mount Cayley. The valley floor is narrow but mostly forested and undeveloped other than the Squamish Valley FSR on the eastern side. The adjacent valley sides have a history of considerable logging in the last few decades (e.g., extensive clearcutting in the 1980s and 1990s).

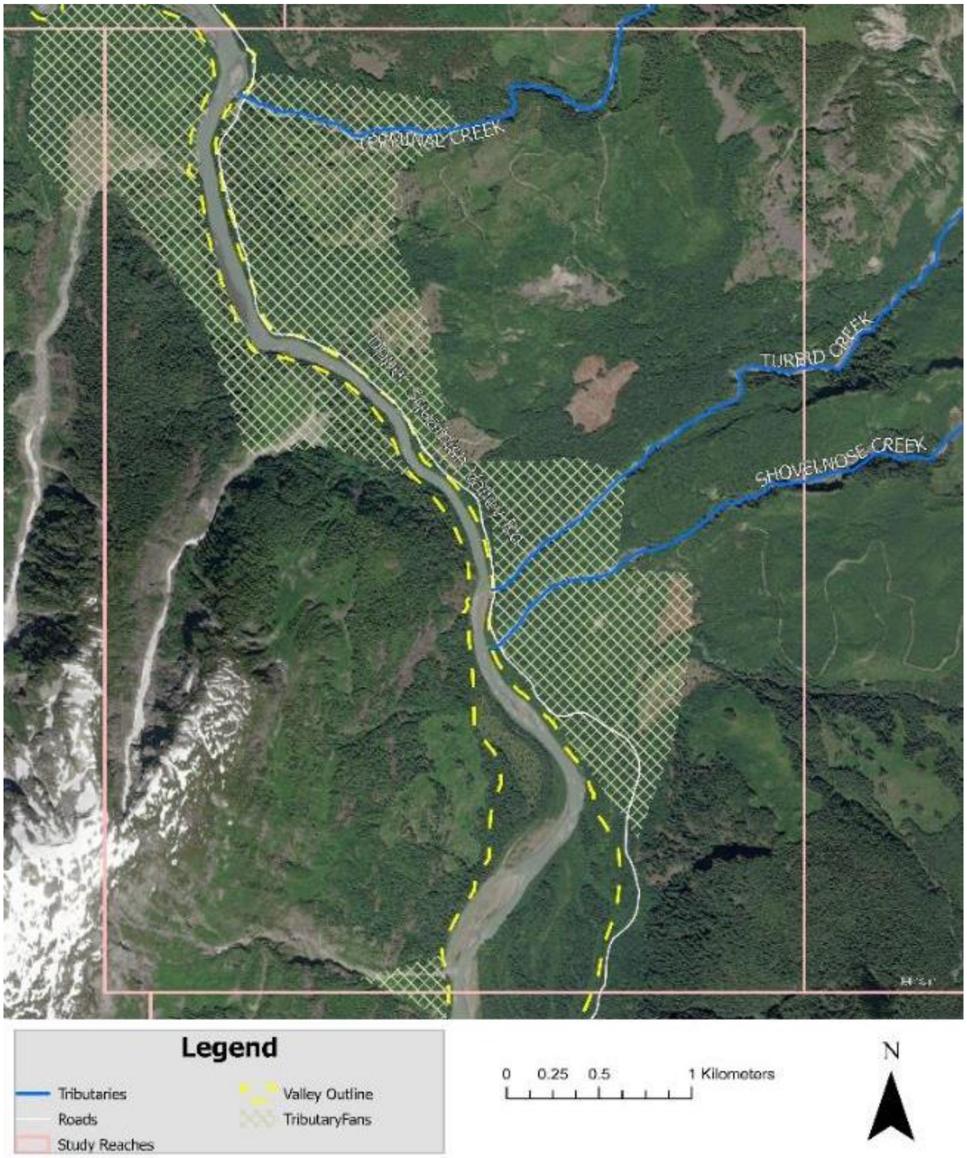


Figure 4: Overview of Study Reach 2, the Terminal-Turbid-Shovelnose Reach

2.7.3 Braided Reach

The third study reach is referred to as the Braided Reach. It is located 5200 to 4550 m upstream of the mouth of the river and 108 to 71 m.a.s.l. The river takes on a complex pattern of anabranching channels weaving around vegetated islands and barren sediment bars. Woody debris can be found in many channels and forms islands and bars. The extensive channel occupies much of the floodplain width and the valley floor is undeveloped other than the Squamish Valley FSR on the eastern side. The valley floor is forested and logging in the last few decades was relatively modest along this reach and the same applies to the valley sides. This reach corresponds with Sichingabula's Reach E, which was selected for the study because of the distinctively braided planform (Sichingabula, 1989).

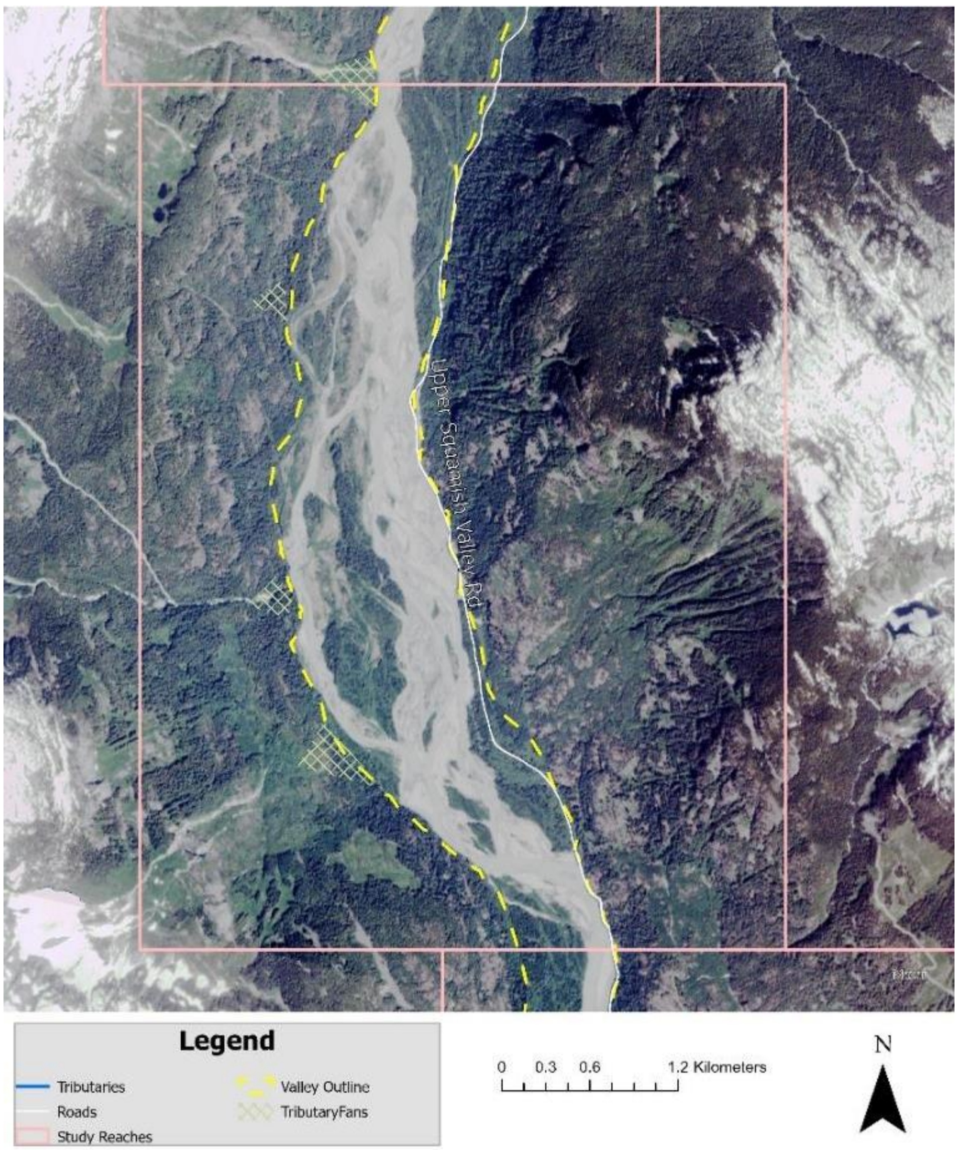


Figure 5: Overview of Study Reach 3, the Braided Reach

2.7.4 Avulsion Reach

The fourth study reach is the Avulsion Reach. It is located 4550 to 3600 m upstream of the mouth of the river and 66 to 43 m.a.s.l. The river has a main and a secondary braided channel belt, separated by a major vegetated island and each splitting into multiple channels around sediment bars. Woody debris is abundant and tends to form islands and bars. Accessory channels also cut across the floodplain in addition to the main channels. The floodplain is forested and mostly undeveloped other than the Squamish Valley FSR on the eastern side. Near the bottom of the reach on the eastern side is the Skowishin Indian Reserve No. 7 (*Skawshn*), which is home to a village. The Cheakamus Generating Station is on the east side of the floodplain, which provides power for the town of Squamish. The forested floodplain was subject to little logging since the mid-1980s but some logging took place on the valley slopes, especially along High Falls Creek. The name of this reach reflects the fact that it underwent a major avulsion during the study period, discussed in detail in the Results section.

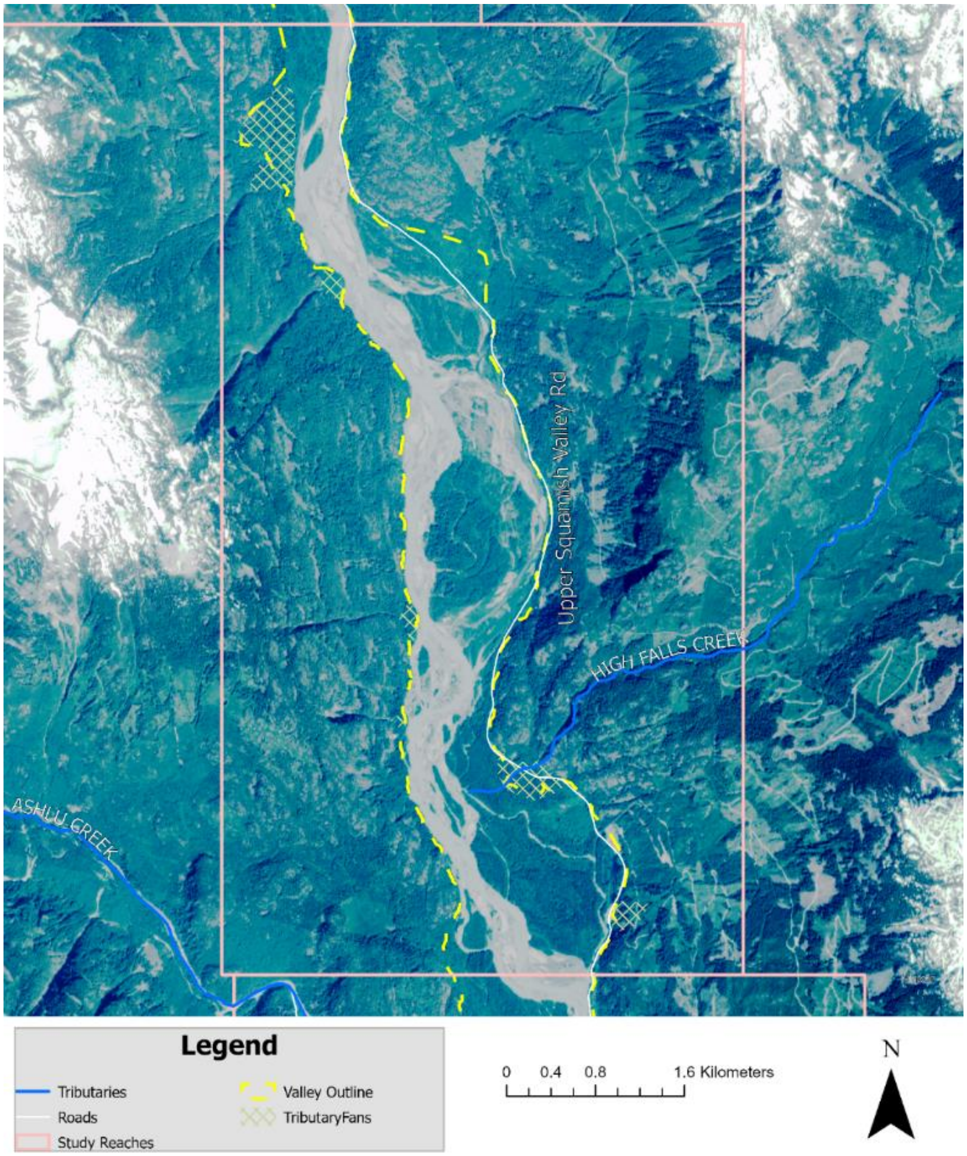


Figure 6: Overview of Study Reach 4, the Avulsion Reach

2.7.5 Squamish-Ashlu Reach

The fifth study reach is the Squamish-Ashlu Reach, where Ashlu Creek meets Squamish River. It is located 3600 to 3000 m upstream of the mouth of the river and 38 to 33 m.a.s.l. The reach has wandering morphology, splitting into two near-parallel channels of similar size separated by a vegetated island as it transitions from weakly braided to meandering planform. The floodplain is forested, with relatively limited logging in the last few decades, and contains some human development (e.g., outdoors outfitters). This reach corresponds with Sichingabula's Reach D and was chosen to assess relative stability of islands and bars in the planform transition zone.

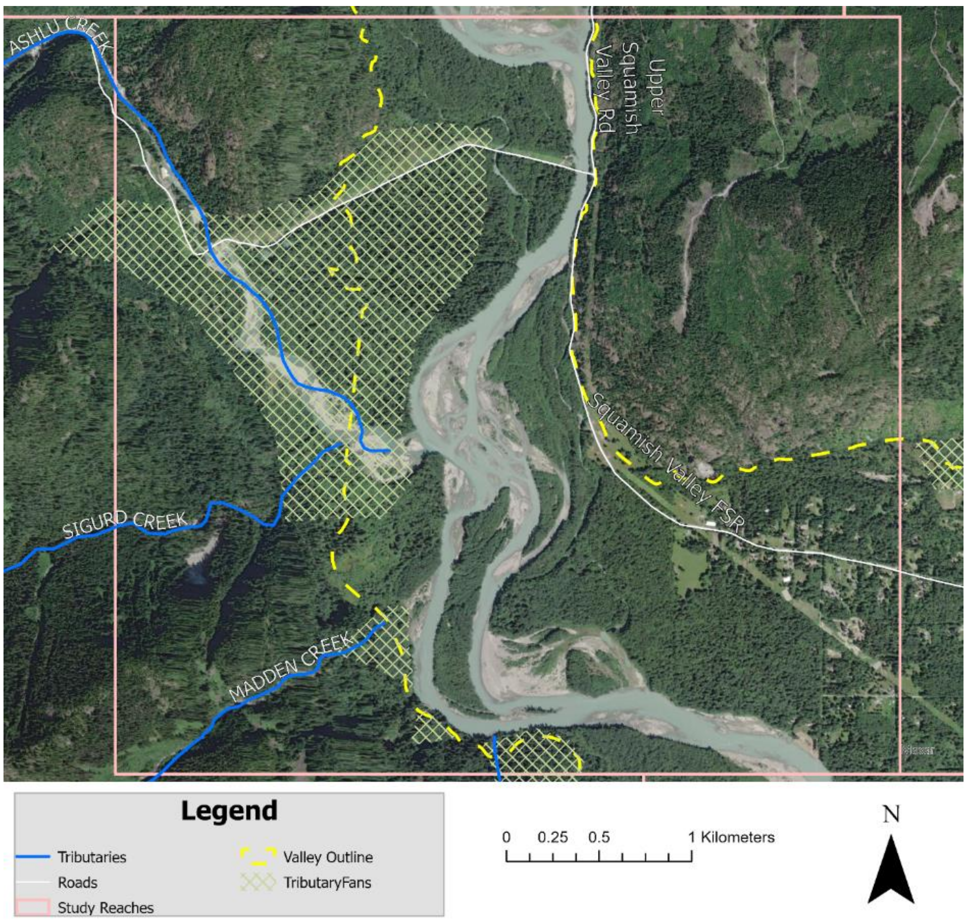


Figure 7: Overview of Study Reach 5, the Squamish-Ashlu Reach

2.7.6 Upper Meandering Reach

The sixth study reach is the Upper Meandering Reach. It is located 3000 to 2300 m upstream of the mouth of the river and 34 to 22 m.a.s.l. The river has a single thread meandering channel with sediment storage in point bars and sporadic mid-channel bars. The floodplain is forested, with little timber harvest in the last few decades, but with some limited development on the eastern side including the Squamish Valley FSR and outdoor facilities. This reach corresponds with Sichingabula's Reach C, which he chose to assess the difference in channel change between confined and freely migrating meander bends.

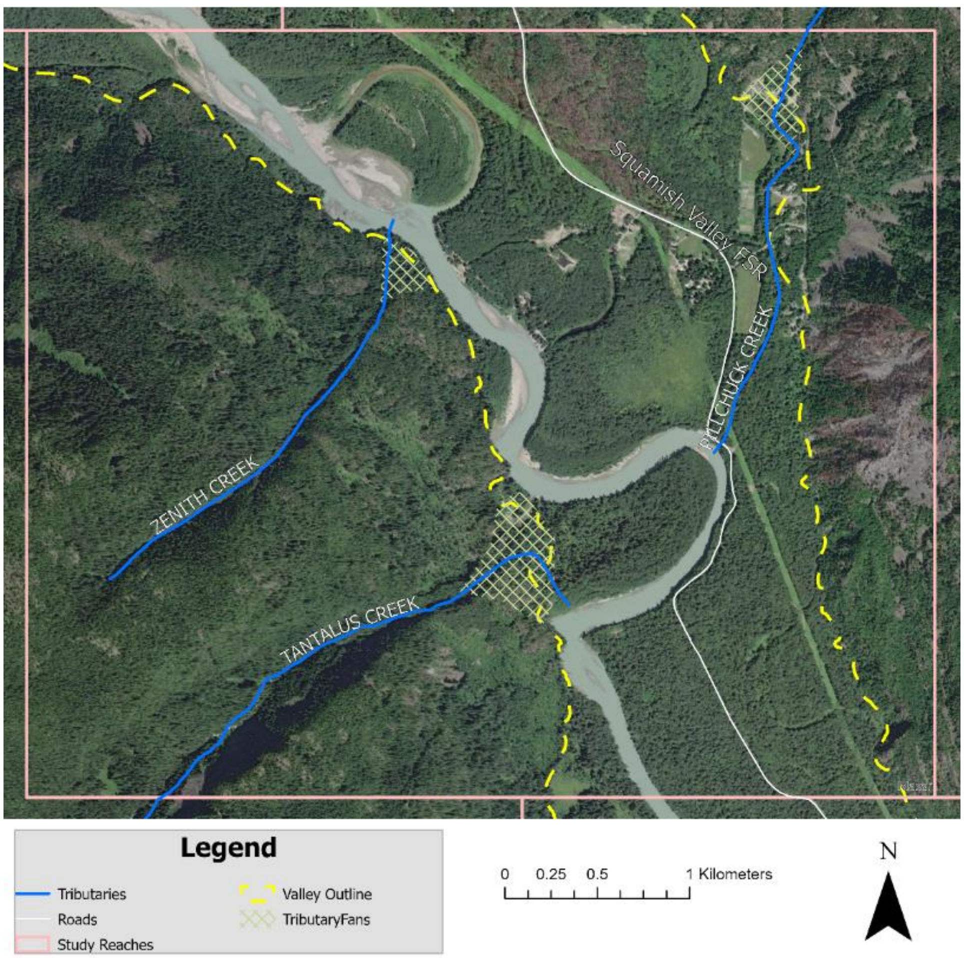


Figure 8: Overview of Study Reach 6, the Upper Meandering Reach

2.7.7 Lower Meandering Reach

The seventh study reach is the Lower Meandering Reach. It is located 2300 to 1800 m upstream of the mouth of the river and 22 to 18 m.a.s.l. The river has single thread meandering channel with in-channel sediment storage in very few point bars. The floodplain is forested, with almost no significant logging in the last few decades (although some logging history on the valley slopes) and largely undeveloped, other than the Squamish Valley FSR on the eastern side. This reach corresponds with Sichingabula's Reach B and was also chosen to assess the difference in channel change between confined and freely migrating meander bends.

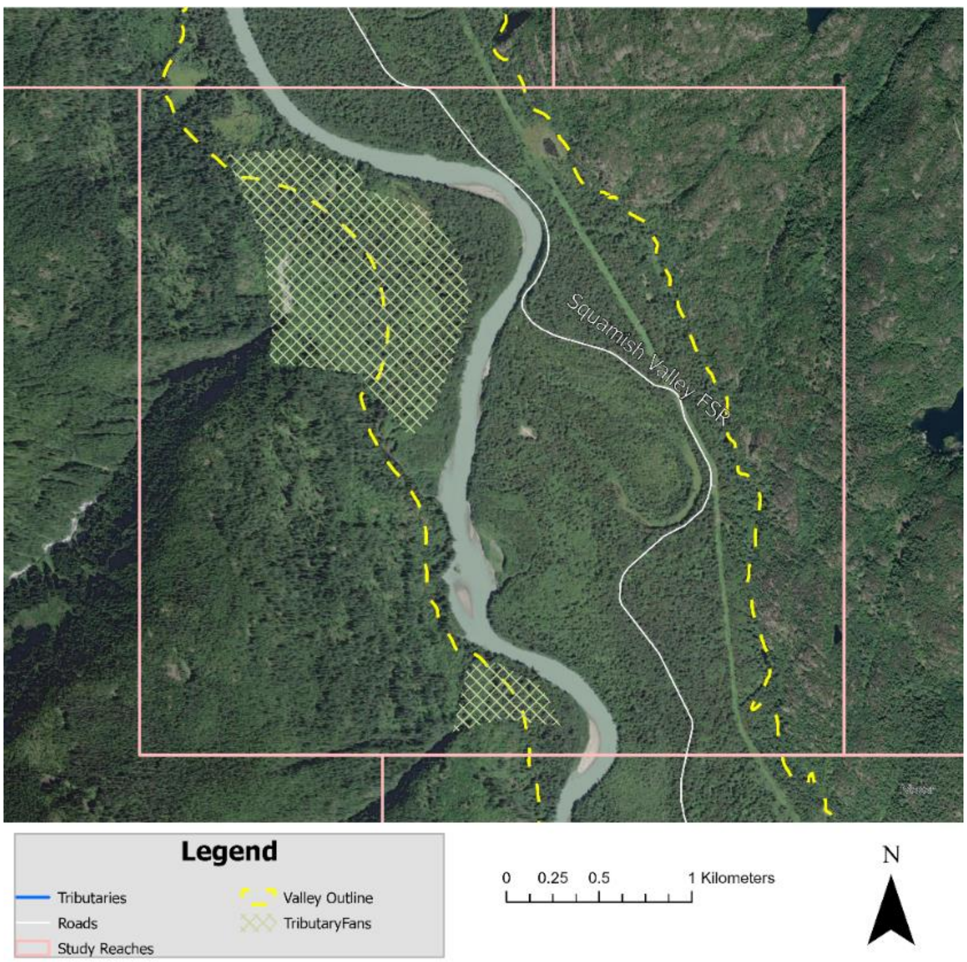


Figure 9: Overview of Study Reach 7, the Lower Meandering Reach

2.7.8 Upper Cheakamus Reach

The eighth study reach is the Upper Cheakamus Reach. It is located 1800 to 1350 m upstream of the mouth of the river and 23 to 19 m.a.s.l. The river has a single thread, meandering channel. The floodplain is forested, with a similar level of timber harvest as in the reach immediately upstream. In addition to the Squamish FSR only development is a low-density settlement (the floodplain of this and the upstream reach falls within the Indian Reserve Cheakamus 11 (*Ch'iyáḵmesh*); as of the 2016 census, the village's population was 57 people).

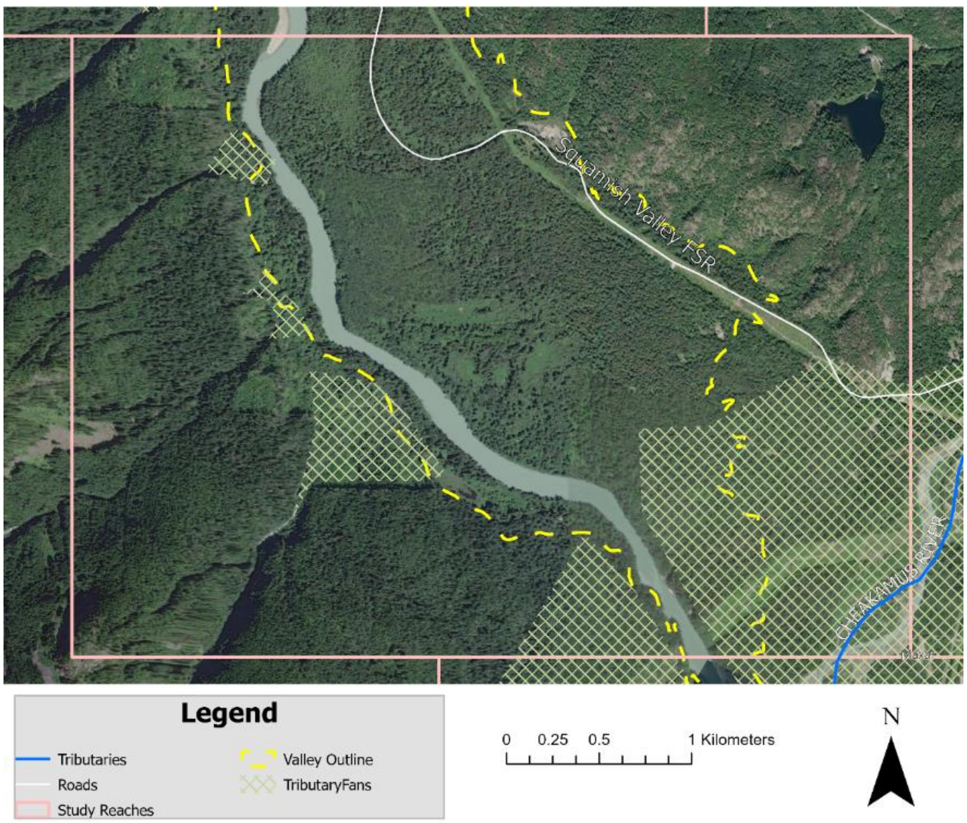


Figure 10: Overview of Study Reach 8, the Upper Cheakamus Reach

2.7.9 Cheakamus-Mamquam Reach

The ninth study reach is the Cheakamus-Mamquam Reach, where the Cheakamus River joins the Squamish. It is located 1350 to 7500 m upstream the mouth of the river, terminating above the Mamquam River confluence, and spans elevation range of 19 to 8 m.a.s.l. Here the river once again takes on wandering morphology, with a single main channel weaving around sediment bars and vegetated islands, and accessory channels cutting across the floodplain. The western side of the river is forested and undeveloped, as it falls within the Brackendale Eagles Provincial Park. However, the valley floor on the eastern side of the river is more highly developed than in any of the previously described reaches, with mostly residential land use including Indian Reserve settlements, and the neighborhood of Brackendale on its eastern bank. The floodplain on this side of the channel is confined by a dyke along the eastern side for erosion and flood control. Other notable land use on the eastern side of the river includes a gravel pit and logging plots located higher on the valley slopes. This reach corresponds with Sichingabula's Reach A, which he chose to study the effects of gravel deposition in a confined straight channel and the effects of the stream bank stabilization dyke.

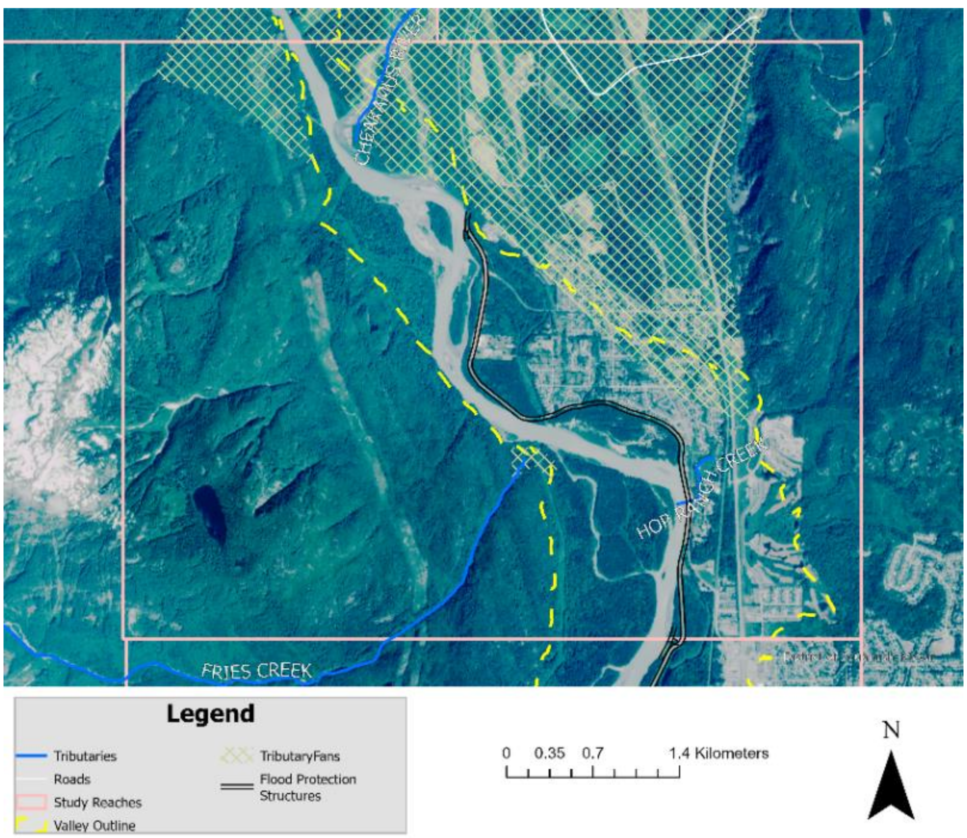


Figure 11: Overview of Study Reach 9, the Cheakamus-Mamquam Reach

2.7.10 Squamish Estuary

The tenth and final study reach is the Squamish Estuary Reach, where the Mamquam River joins Squamish River, and terminating where the Squamish flows into Howe Sound. It is located 7500 m upstream of the mouth of the river and 8 to 6 m.a.s.l. The river is a single thread channel with in-channel sediment storage in point and alternate bars, confined by a flood dyke/training berm running down the eastern side. The floodplain is undeveloped on the western side of the river and highly transformed on the east side, with residential, commercial, and industrial development.

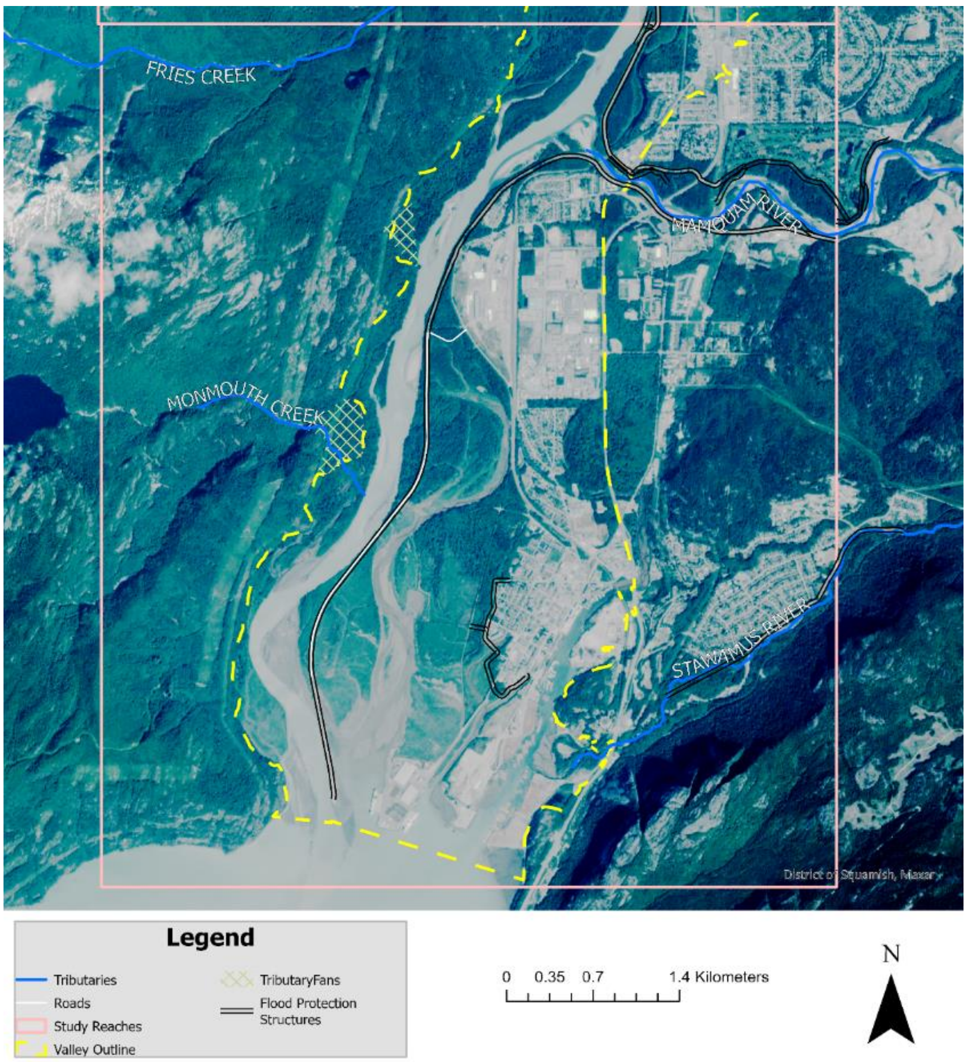


Figure 12: Overview of Study Reach 10, the Squamish Estuary

CHAPTER 3: DATA COLLECTION AND METHODS

3.1 Overview

This section outlines the steps taken to investigate the magnitude and drivers of floodplain change in the study reaches. Satellite imagery showing the river-floodplain environment for each of the 10 years of the study period was classified into the classes of water, sediment and vegetation and the change between the classes was measured and examined. To understand the likely drivers that define the spatial pattern of these changes, channel slope, valley confinement and sediment supply was determined for each reach. This methodology is described in detail below.

3.2 Magnitude of Floodplain Change

3.2.1 Data Sources and pre-processing

In order to determine the magnitude of floodplain erosion and construction throughout the entire study area, imagery from Planet Labs was analyzed (https://www.planet.com/). Through Planet Lab's Education and Research Program, high resolution imagery of the Squamish River is available from 2009 until the present. The original intent was to have two sets of images from each year, one at a low discharge (winter) and one at a high (summer). An advantage of such an approach would be the ability to separate changes occurring due to spring freshet from those attributable to winter floods. However, this proved difficult because snow cover in winter images precluded high-quality classification. Instead, imagery was chosen with discharge rates of 400-500 $m^3 s^{-1}$, roughly double the mean annual flow (estimated as 237 $m^3 s^{-1}$ based on Water Survey Canada records at the gauge 08GA022 during the period 1923-2018), which offered the best choice of imagery from each year. This was accomplished by looking up the daily discharge at the WSC gauge for the date of each available scene, then choosing the ones that fell within this range. The analytical quality of Dove (3.5 m resolution) and Rapid Eye (5 m resolution) image products were downloaded at the Surface Reflectance processing level, with the imagery acquired during the summer months of June, July, or August.

To cover the entire section of interest, each year's data set consisted of 4-9 raw tiles, depending on the satellite used (Dove vs. Rapid Eye). The individual tiles were added to ArcMap and mosaiced (Mosaic tool). Each years' imagery was compared to ascertain any rectification issues. Three years needed some improved georectification, which was done using consistent ground control points such as road intersections. The rectified images had a Root Mean Square error of 1.18 – 2.53 m. The image raster's were resampled so that every year had the same pixel size (5 m) and aligned with the same gridlines. Panel 1 of Fig. 13 shows this image.

Table 1: Properties of imagery used for each year

Date	Discharge (m^3 s^{-1})	Sensor	Tiles
06/04/2009	554	RapidEye	4
07/25/2010	510	RapidEye	4
07/05/2011	481	RapidEye	4
07/08/2012	553	RapidEye	4
07/08/2013	449	RapidEye	4
07/07/2014	470	RapidEye	4
08/18/2015	339	RapidEye	4
06/29/2016	526	Dove	9
07/31/2017	418	Dove	9
07/30/2018	453	Dove	9
06/15/2019	428	RapidEye and Dove	4-9

3.2.2 Classification

Multiple methods of classification were evaluated for effectiveness. The first attempt at an accurate classification used Supervised Classification in ArcMap. At least 10 training samples per category were defined in areas visually identified as water, sediment, or vegetation, then the tool was run. This was attempted with each image as well as the mosaic of images. The results, when examined visually, were not deemed accurate enough at distinguishing water from sediment in the braided reaches.

In the next attempt, classification was attempted using the Normalized Difference Vegetation Index, or NDVI. NDVI is used to quantify vegetation greenness and is useful for understanding vegetation density and assessing changes in plant health (Glenn et al., 2008). NDVI is calculated as a ratio between red and near infrared bands. Using the raster calculator tool, the following formula was followed: (NIR – R) / (NIR + R), where NIR denotes near-infrared band and R red band.

The results were visualized by displaying the values of NDVI along natural breaks (Jenks). A preliminary, visual comparison of each year's NDVI to the true color image suggested that this method performed better than the supervised classification (illustrated in Fig. 13). As NDVI values change intra- and inter-annually (seasonally but also with changing moisture conditions), the inconsistency between years and sensors made it difficult to find a single threshold that accurately divided the categories. The approach based on Natural Breaks appeared to be more effective in separating vegetation from water (and, to slightly lesser extent, water from sediment). In principle, an important shortcoming of the Natural Breaks method is that they identify natural groupings in the data, and as such, is a relative metric in which thresholds may varies from year-to-year. The apparently better performance in this case, compared to supervised classification was somewhat surprising. Therefore, a quantitative accuracy assessment was conducted (see below) to ensure that the performance indeed met an acceptable standard. In this case an acceptable threshold of accuracy was assumed to be 80%. To increase accuracy and decrease the noise from snow and man-made surfaces, a mask was created to clip each year’s image to the farthest extent of the active channel during the 10-year period. The boundary between vegetation and non-vegetation (referred here as “active channel”, because lack of vegetation cover indicates recent geomorphic disturbance) was defined to create this mask. Then the second iteration of the classification was carried out within so-defined area of interest (hereafter AOI), expanded by a 50-m buffer to avoid accidental omission along the edges. After each year’s imagery was clipped to AOI, the classification based on natural breaks in the NDVI values was reexamined. Panel 2 of Fig. 13 shows this classification. The resultant classified images were then formally assessed for accuracy (see next section).

3.2.3 Accuracy assessment

To test the accuracy of each year's classification, the workflow laid out by ESRI was followed in ArcGIS. This was accomplished by creating 501 sampling points, 167 for each class, which then were randomly distributed within the areas of the AOI corresponding to that category (equalized stratified random design). Each point was assigned the reference (“ground truth”) membership based on true color imagery and this membership was used to verify whether the point was classified correctly. This process was repeated with the same points for the image mosaic for all years of interest. A confusion matrix was computed in ArcGIS by comparing the classified values with the ground truth values. In a confusion matrix, user's accuracy shows false positives, where pixels were incorrectly classified, for each class. Producer's accuracy, on the other hand, shows false negatives, where pixels were identified as something other than that class. The kappa index is a value to show the overall accuracy of the classification.

3.2.4 Quantities of Floodplain Change

To identify and quantify values of floodplain dynamics, an ArcGIS Pro tool called Change Detection was used. When given two images with pixels classified as water, sediment, or vegetation, the tool analyzes how many pixels changed for all combination of categories and how many stayed unchanged within each of the three classes. Therefore, the output is a table with the count of pixels for nine total possibilities (water remained water, sediment remained sediment, vegetation remained vegetation, water turned into sediment, water turned into vegetation, sediment turned into water, sediment turned into vegetation, vegetation turned into water, vegetation turned into sediment). Panel 3 of Fig. 13 shows this change.

For the purposes of this study, floodplain construction is defined as water or sediment becoming vegetation. Floodplain erosion is defined as vegetation becoming water or sediment. These definitions are equivalent to how Sichingabula (1989) and Bauch (2007) delineated channel versus floodplain and, therefore, can be directly compared. One important advantage of this binary classification into vegetated floodplain and unvegetated "active channel" is that, as long as flows are below bankfull discharge at the time at which the image was acquired does not introduce error into the classification (Bauch and Hickin, 2011). All images used in this study were indeed well below bankfull which, has been reported to be around the value of 1200 m^3 s^{-1} at the WSC gauge (Bauch and Hickin, 2011). No images are available at bankfull flows, as they tend to occur during storm events with high cloud coverage; however, photos of the river near bankfull can be seen in Fig. 30. This method has been used for other analyses of river and floodplain stability as well (Beaudry, 1990).

As a result, given its robustness, this is the primary analysis. However, analysis was also carried out on in-channel erosion. In the latter analysis, channel deposition is defined as water becoming sediment or vegetation. Channel erosion is defined as sediment or vegetation becoming water. One important shortcoming of this analysis is that, in contrast to that conducted for floodplain change, it is susceptible to the detection of spurious changes which, in reality, reflect changing discharge and the associated fluctuations in the width of the wetted channel. The selection of imagery within a relatively narrow band of discharges was aimed at minimizing such errors but it was impossible to eliminate them. As a result, the in-channel analysis needs to be interpreted with far more caution. Finally, net floodplain/channel change in my study is defined as floodplain construction/channel deposition minus floodplain erosion/channel erosion.

The change detection analysis was carried out at two temporal resolutions, each of distinct advantages and disadvantages. First, year-to-year changes were identified using sequential imagery. The key advantage of this approach is that most of the actual floodplain/channel changes are captured. The key downside, on the other hand, is that detected change may be comparable in magnitude to the error stemming from a variety of reasons e.g., imperfect georectification and misclassification. Second, change detection analysis was conducted between the first and last image in the sequence (2009 vs 2019). In this case, some of the subtle changes might be missed, for example, if deposition was subsequently offset by erosion at the same location. On the other hand, it is reasonable to expect that the magnitude of floodplain/channel changes during the decade far exceeds typical values of error in the analysis of this kind (e.g., Bauch and Hickin, 2011).

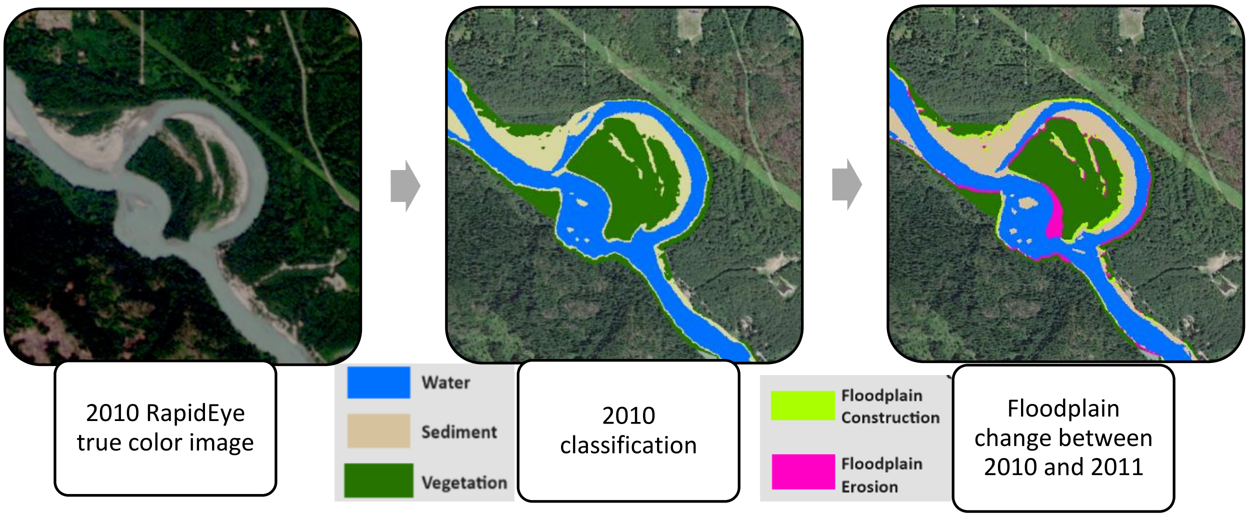


Figure 13: Raw image, classified image, and floodplain change for 2010

3.3 Drivers of Floodplain Change

3.3.1 Slope

Fluvial sediment transport is a function of the hydraulic forces exerted on particles by the moving water. These forces are often represented by either bed shear stress or stream power. Both these parameters are estimated as a function of slope, S: $\tau_0 = \rho g d S$, where τ_0 is bed shear stress, ρ is water density, g is gravitational acceleration, and d is flow depth; and $\Omega = \rho g Q S$, where Ω is stream power and Q is water discharge. Given the inherent difficulties in estimating accurately water discharge and flow depth at ungauged locations, slope alone was used as the proxy for the energy available to mobilize and transport sediment downstream. Because sediment transport is the mechanism that underlies observed channel and floodplain changes of interest here (Church, 2006), it is reasonable to assume that the magnitude of such changes will be correlated with this variable.

To estimate the relevant slope values, as the first step, a centerline of the active channel was created using the tool Collapse Hydro Polygons to collapse the active channel mask into a line. The stream was then divided up into 500 m-long segments by creating evenly spaced lines along the channel centerline. Next, a point was created everywhere a segment dividing line intersected with the centerline, then extracted the elevations from the Digital Elevation Model (Digital Elevation Model for British Columbia – CDED – 1:250,000) for a relatively continuous visualization of the longitudinal profile. As the last step, the 500 m segments were combined into the ten study reaches, and the elevation change between the upstream and downstream boundary of each reach was determined; to obtain slope, this value for each reach was divided by the length of the corresponding centerline. The active channel-based approach described above was adopted because of the difficulty in identifying a single value of wetted channel slope in multi-threaded (braided and wandering) reaches

3.3.2 Valley Confinement

Valley confinement is thought to be an important factor which may, in some cases, limit the lateral activity of alluvial channels (e.g., Whiting and Bradley, 1993; Fryirs et al., 2016). Importantly, confining margins may be either natural or anthropogenic in nature (Fryirs et al., 2016). An example of anthropogenic features that play this role include erosion protection structures, such as training dykes or riprap (e.g., Cienciala et al., 2020; 2021). In this study, both types of confinement were studied jointly.

To quantify confinement, first, valley bottom was created partially by using the Historical Floodplain outline layer downloaded from iMapBC (https://maps.gov.bc.ca/ess/hm/imap4m/). This mapped the floodplain up to the confluence with Ashlu Creek. The rest of the study area floodplain was manually delineated using the DEM. The steep valley slopes make it easy to identify the perimeter of the flat valley floor.

The width of the valley was extracted using lines perpendicular to the centerline, passing through the points previously used to extract elevation at 500 m intervals. These transects were truncated at the intersection with the valley bottom polygon and their width calculated (ArcGIS tool Add Geometry → Length). Three values were subsequently derived: the width of the floodplain to the left of the active channel, the width of the active channel, and the width of the floodplain to the right of the active channel – for every 500 m segment down the valley. These values at individual transects were then averaged for each reach to determine values for Average Width of Active Channel and Average Width of Valley for each reach. A third parameter was considered, Wetted Width. This was calculated by dividing the area of water in each reach by the length of the reach, using the averaged values of area of water for 2009 and 2019.

3.3.3 Sediment Supply

Sediment supply is another important factor known to affect sediment transport rates and, consequently, channel and floodplain changes (e.g., Church, 2006). Unfortunately, sediment supply is exceedingly difficult to quantify – this requires extensive field surveys and measurements.

Because of this challenge, in this study, sediment supply was determined qualitatively. A combination of visual inspection of the imagery and information available from the literature was used for this purpose. In terms of visual assessment, the available high-resolution imagery was used to identify local storage of unconsolidated sediment in various sources outside of the mainstem Squamish River and connected to it, such as in-channel deposits and debris flow tracks/landslide scars. Similarly, peer-reviewed literature (e.g., Brooks, 1994) as well as grey literature (e.g., various consultant reports) describing sediment storage across the watershed was used for this purpose. Based on these sources, each reach was assigned a relative label of high, moderate, or low levels of sediment coming from upstream and from out of channel sources. How these were determined for each reach is expanded upon in Chapter 4.

3.3.4 Flow Data

The flow data came from the Water Survey of Canada (WSC), the National Hydrologic Services, Environment and Climate Change Canada. The WSC is the federal organization responsible for the collection, interpretation, and dissemination of standardized water quantity data and information in Canada. The flow data came from the gauging station Squamish River near Brackendale (see above). Given its location, this station represents ~ 72% of the Squamish River's total flow, and the remaining 28% is added downstream via the Cheakamus and Mamquam Rivers (Bauch and Hickin, 2010).

CHAPTER 4: FLOODPLAIN CHANGE RESULTS

4.1 Overview

In the first part of this section, channel classification results are discussed. Next, moving from upstream to downstream, floodplain dynamics during the study period are described and related to their geomorphic setting, including the location of major tributaries, human activity, and three hypothesized drivers of floodplain change: slope, percent valley confinement, and sediment supply. This section concludes by integrating all this evidence together to analyze the links between the patterns of floodplain change along the entire study domain and the drivers behind them.

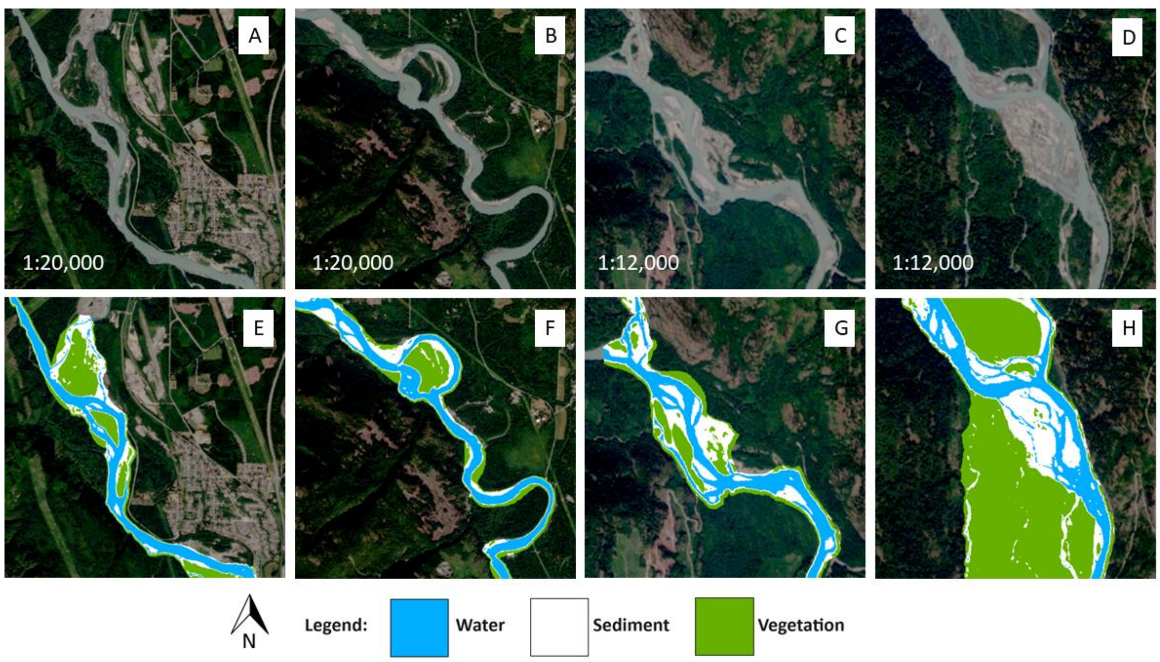


Figure 14: Examples of classification for 2010; A-D show true color portions of the river from RapidEye imagery, while E-H show the classification

4.2 Classification Results

Classification was assessed for accuracy using the workflow laid out in the Methods section. As previously mentioned, a confusion matrix was computed for each year. User's accuracy is defined by false positives, or errors of commission, where pixels were incorrectly classified as one class when they should have been classified as another class. Strictly speaking, user's accuracy is calculated as 100% - error of commission. The obtained values for user's accuracy for water range from 84.4% in 2012 to 98.8% in 2010. The values for sediment range from 90.1% to 98.6%, also in 2012 and 2010, respectively. The values obtained for vegetation range from to 96.4% in 2009 to 99.4% in 2014.

Producer's accuracy, on the other hand, is related to false negatives, or errors of omission, where pixels were identified as something other than the class that they should be. Producer's accuracy = 100% - error of omission. The values for producer's accuracy for water range from 93.6% in 2009 to 100% in 2013. The values for sediment range from 74.2% in 2012 to 98.1% in 2014. The values for vegetation range from 96.6% in 2012 to 100% in 2010, 2017 and 2018. The kappa index is a value which shows the overall accuracy of the classification. The lowest kappa was 86.3% in 2012 and the highest was 98.1% in 2010. Other than 2012, all kappa values were greater than 90%.

Table 2: Kappa value for accuracy assessment of classification for each year

Year	Kappa
2009	0.919
2010	0.981
2011	0.960
2012	0.862
2013	0.975
2014	0.958
2015	0.969
2016	0.966
2017	0.975
2018	0.924
2019	0.975

It is reasonable that vegetation is the most accurate category because the classification was performed on values of NDVI, which is specifically designed for measuring vegetation. Sediment and water were more difficult to distinguish from one another, but for the purposes of examining floodplain change, this accuracy was less important (given that we define only vegetated areas as belonging to floodplain). Sediment and water classes were used for the secondary analysis of in-channel change. As evident in Figure 14, the classification does an excellent job at clearly identifying the edges of vegetation and the main channel. It is somewhat less effective at finer-scale braided areas, such as can be seen by comparing panels C and G.

Overall, the performance of this classification was very strong and exceeded expectations. It is possible that the values obtained in the accuracy assessment, derived from samples spread across the classification domain, are overly optimistic with regard to changes at the boundaries between categories are of interest. For example, when differentiating between water and vegetation on a steep cutbank, shadows cast by the riparian canopy can introduce errors. There is also the problem of differentiating between wet sediment and water, especially when dealing with partially submerged gravel bars. As a result, the accuracy values should be taken with some caution. At the same time, the calculations of floodplain erosion and construction rely on tracking changes in the areal extent of different classes, rather than direct measurements of the linear displacement of boundaries (e.g., bank migration). The change in the areal extent of is later divided by the reach length to express it in length units (equivalent of average active channel width change). This approach, though not without its own flaws, is expected to be more robust with regard to the above-mentioned errors as false positives and false negatives cancel each other to some extent. Taken together, the classification accuracy is sufficient for the purposes of this thesis.

4.3 Results per Reach

4.3.1 Squamish-Elaho Reach

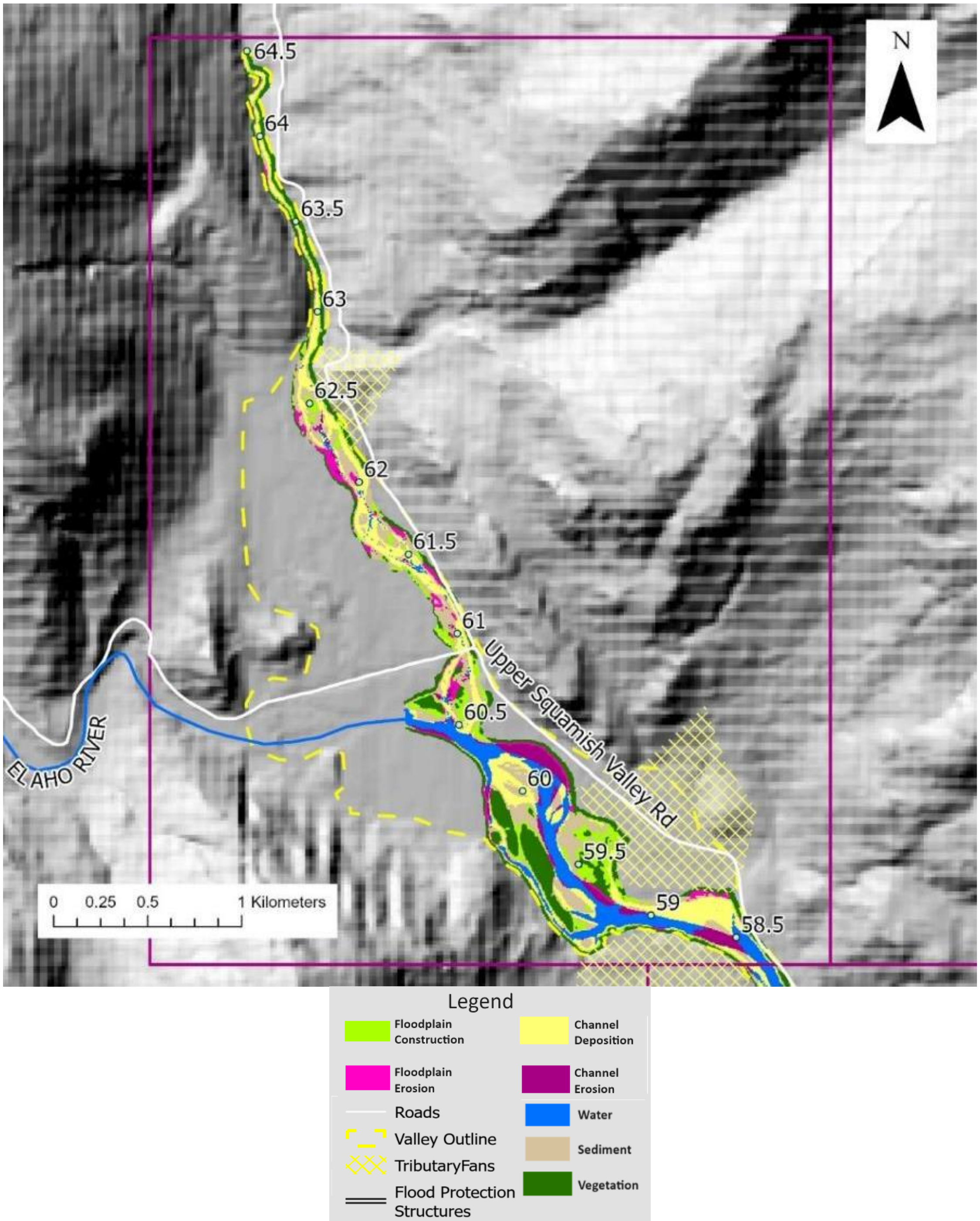


Figure 15: Floodplain and channel change in Squamish-Elaho Reach 2009-2019. Note that Elaho River channel width is not to scale.

Overall, this reach saw an average annual floodplain construction of 3.3 m and 3.2 m of erosion during the period of 2009 to 2019. When the average change was calculated based on multiple year-to-year changes, construction measured 9.4 m and erosion 11.9 m. The main floodplain changes that occurred within this reach were channel abandonment and reactivation in the wandering (weakly braided) section, and concave bank erosion accompanied by bar accretion. The average annual channel change of this reach during the period of 2009 to 2019 measured 5 m of deposition and 3.5 meters of erosion. When change from year to year was averaged, construction measured 15 m and erosion 18.7 m. The 5 meters of channel deposition is an overestimate; because of the very narrow valley, the 2019 classification misclassified much of the upper two-thirds of the reach as sediment when some should have been water. This was the only portion of the study area affected by this artefact and attempts to fix it induced misclassification of sediment as water in the rest of the study area. As this study focused more on floodplain construction and erosion than in-channel, this was considered an acceptable trade-off.

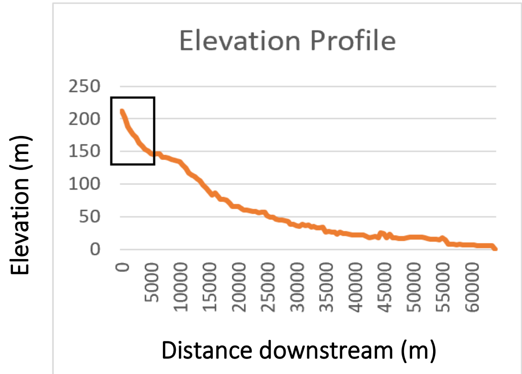


Figure 16: Elevation profile of study site with Reach 1 highlighted

The slope of this reach is 1.1%, and this is the steepest reach along the study section of Squamish River. It transitions from a narrow bedrock canyon to a more open alluvial valley further downstream. When the ratio of wetted channel width to valley width is considered, this reach is, on average, 11% confined, while active channel to valley width is 64% confined (a more detailed explanation of these metrics is discussed in section 4.4.3). This means that while the active channel may span most of the valley floor and floodplain erosion may be to some extent limited, the channel itself is free to sweep across the valley floor. This lateral freedom manifests itself in the wandering form, which takes up more space than a single-thread channel. Importantly, the above metrics are averages and as previously noted, the upstream section of this reach is far more confined. The average widths of the active channel and valley are 255 m and 542 m wide, respectively.

The reach receives sediment from the upstream glacial sources (Pemberton Icefield) (Brooks, 1992), but the magnitude of these inputs is difficult to estimate. A rockslide occurred from an unnamed creek on the eastern side of the valley just above the extent of the study area approximately 1840 years ago, causing a temporary blockage and allowing lake sediments to accumulate 500 m upstream. These deposits remain on terraces, but the river has returned to the same level as before the rockslide (Brooks, 1992; NHC, 2018). Therefore, these deposits are most likely disconnected from contemporary erosion. Along with the presence of some small, proglacial lakes, which likely trap some of the material produced by the glacier upstream, the upstream sediment inputs have been determined to be moderate, though this estimate is uncertain. The amounts of sediment received from tributaries are also assessed as moderate. Elaho River, the major tributary, is blocked by a rockfall at its mouth, which limits how much sediment can reach Squamish River (Brooks, 1992). Endurance Creek has contributed sediment to this reach in the past, impinging the channel, but at present any sediment it contributes flows directly into Reach 2.

The magnitude of floodplain and channel changes varies along the reach. From RK 63 to 64.5 (river kilometers, measured from the river mouth; see Fig. 15), there was minimal change. This is despite the steep slope, which indicates high stream power, sufficient to move large quantities of sediment. Such limited change seems to be a result of the tight confinement by the bedrock canyon with little to no floodplain (Brooks, 1992). Downstream of RK 62.5, the reach becomes braided and more laterally active. Over the study period, the channel has shifted to the east, away from the west margin of the valley. Because there is no increase in slope, which would indicate higher hydraulic forces, this higher activity is interpreted as resulting from lesser confinement. At RK 60.5, the Elaho River meets the Squamish and the reach becomes wider and even more active. In 2009, the channel braided around sediment bars and vegetated islands. Over the study period, the bend at RK 60 increased in curvature, eroding away 80 m of floodplain at the concave bank and shifting the channel towards the eastern bank. This has allowed the islands just downstream on the western side to increase in size and the floodplain on the eastern side to be colonized by vegetation. In 2009, the channel near RK 59.5 impinged on the alluvial fan of Endurance Creek coming off Icecap Peak on its western side, then deflected towards the eastern bank. As this fan eroded away, the channel straightened, eroded away a sediment bar in the convex bend at RK 58.5, allowing sediment bars to grow on the concave side of the bank. All this geomorphic activity appears to be driven by a combination of steep slope (hence high stream power, especially downstream from a significant flow input from Elaho River), low valley confinement, and sediment availability.

4.3.2 Terminal-Turbid-Shovelnose Reach

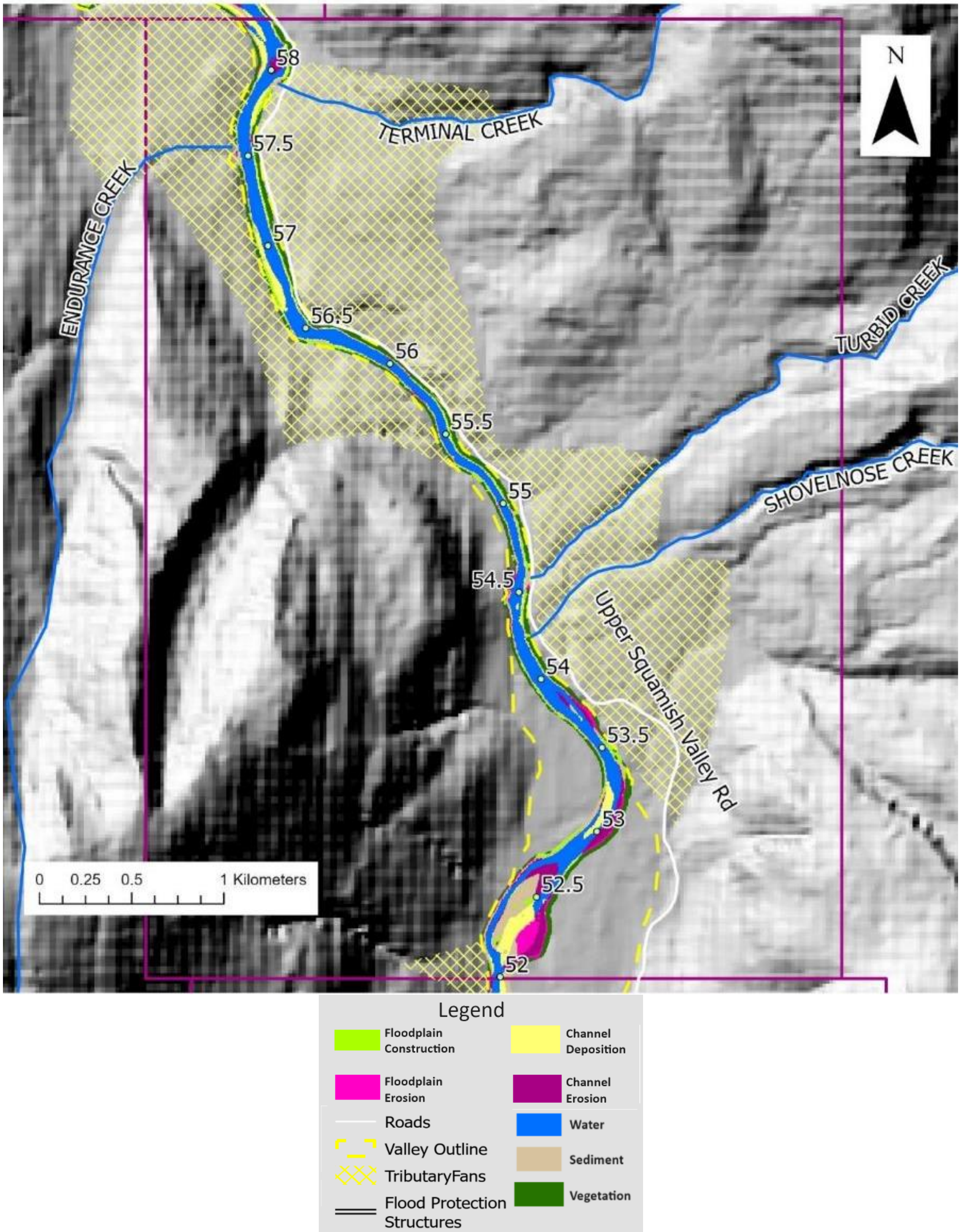


Figure 17: Floodplain and channel change in Terminal-Turbid-Shovelnose Reach 2009-2019. Note that tributary channel widths are not to scale.

This reach saw an average annual floodplain change of 1.4 meters of construction and 2.2 meters of erosion during the period of 2009 to 2019. When change from year to year was averaged, construction measured 5.3 meters and erosion 7.7 meters. The average per annual channel change of this reach measured 2.2 m of deposition and 2 meters of erosion during the period of 2009 to 2019. When change from year to year was averaged, construction measured 8.4 m and erosion 10.9 m.

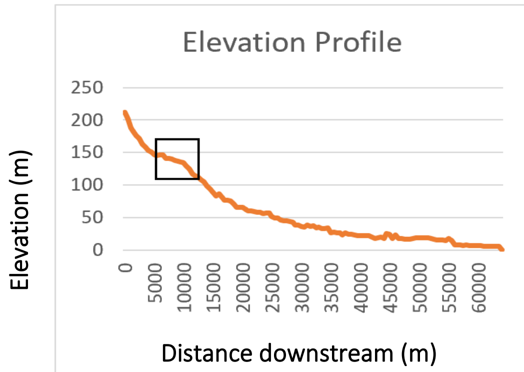


Figure 18: Elevation profile of study area with Study Reach 2 highlighted

The slope of this reach is 0.5% and the profile is convex due to the large influx of sediment. The ratio of wetted width to valley width and active channel to valley width is 22% and 73% confined, respectively. The average widths of the active channel and valley are 155 m and 300 m wide, respectively. However, importantly, the absolute value for wetted channel does not reflect how tightly confined most of this reach actually is, as the flow when the area of water was measured for wetted width was around half of bankfull. In reality, along most of the length of this reach, the channel and narrow valley floor it flows within are flanked by and incised into the deposits of bedrock landslides (Evans and Brooks, 1992; Cruden and Lu, 1992) and tributary fans fed by debris flows coming off Mt. Cayley.

This reach was determined to receive a moderate level of sediment from the reach above, but a high level of sediment from its tributaries. The high lateral inputs from out-of-channel sources are associated with landslides and debris flows from Mount Cayley coming down Terminal, Turbid and Shovelnose Creeks. Small volcanic landslides are generally triggered by runoff mobilizing stored debris that accumulated during summer dry spells. Larger flows can occur after deep-seated slope failures, triggered by earthquakes, intensive precipitation, rapid snowmelt, or a combination thereof (Friele, 2013). For example, between 1963 and 2017, there have been 27 recorded landslide events from Turbid Creek, ranging from 10,000 to 500,000 m^3, including four events in both 2012 and 2016 and one in 2015. This is an average of one event every 2-3 years. These are typically triggered by precipitation events greater than 50mm in 24 hours and greater than 5 mm in an hour (NHC, 2018). Turbid Creek is a transport-limited system, which means that landslide events will occur any time conditions allow, as volcanic debris supply is nearly limitless. It provides the most sediment of any tributary upstream of the Cheakamus. (Jakob, 1996; NHC, 2018).

Terminal Creek is also subject to frequent debris flows and three occurred in 2014, one in 2015, two in 2016 and one in 2017. Jakob (1996) used historic records and dendrochronology to estimate that Terminal Creek has an average debris flow recurrence interval of 11 years. Terminal Creek is a weathering-limited basin, which means that there is not an unlimited sediment supply; transportable sediment is supplied by weathering and mass movement events until it builds up to a critical threshold and a debris flow occurs. After this, the basin sediment must recharge (Jakob, 1989;). There is no long-term record for debris flows coming down Pistol/Hook Creek, but it has a basin similar to Turbid Creek, and debris flows have been observed via aerial photos, most recently in 2003, 2009 and 2015 or 2016 (NHC, 2018).

Shovelnose Creek is yet another tributary which has a history of landslides that supply sediment to Squamish River, though records are also less comprehensive. In the 1980's, a debris slide occurred which altered the course of the distal part of this important fish-bearing tributary. Restoration efforts involved the installation of a 400 m dyke in 1994 to prevent the Squamish flows from reaching Shovelnose Creek and the banks of Squamish River were further stabilized in 2009. This was followed by in-channel restoration of Shovelnose Creek in 1995, 2003 and 2009, including excavation of groundwater channels (Steelhead Society of BC). The berm was overtopped, breached and partially eroded by Squamish River during the September 20, 2015 flood and the flow spilled over to the Shovelnose Creek (1270 $m^3 s^{-1}$ recorded on the Elaho River, the highest flow ever recorded in 34 years of record). There are plans for restoration of this area (Steelhead Society of BC) but it is unclear if they were carried out yet. It is also unclear to what extent the berm and bank stabilization affect lateral activity of the channel or, on the other hand, to what extent the construction might have contributed sediment. However, these effects are likely to be minor given, respectively, the high degree of natural confinement and copious sediment supplied by debris flows.

Catastrophic landslides from Mount Cayley occur less frequently. These are landslides greater than 1 million m^3 material. An event producing 5×10^6 m^3 of material occurred in 1963, and another producing 3.2 x 10^6 m^3 in 1984. These both temporarily dammed the Squamish River. Even larger landslides occurred in the pre-historic period. 7 to 8 events have been dated by backwater sediment accumulation or buried wood. The largest occurred 4,800 years ago, pouring 2-3 x 10^8 m^3 of debris into the valley, forming the 14-meter-thick debris apron which remains at the base of the volcano. Other, smaller events occurred 3200, 1100, and 500 years ago, though this is not a complete record (NHC, 2018).

Across the valley, Endurance Creek is also subject to landslides, despite not belonging to the same Garibaldi volcanic group. Instead, it consists of Jurassic granodiorite basement rock (Jakob, 1996). It experienced landslide events in 1909, 1920, 1934, 1962, 1980, 1984, 1991 and 2003, typically in the range of 10^3-10^4 m^3 in volume. Endurance Creek is also a weathering-limited basin (NHC, 2018; Jakob, 1996).

The main changes that occurred in this reach during the study period were concave bank and bar erosion and deposition. Despite the slightly lower slope than in Reach 1, which is due to the effects of rock avalanches from Mt. Cayley, it is still a high-energy river, able to transport ample amounts of sediment. As described in detail in the preceding paragraphs, the sediment is also very abundant as the channel receives exceptionally high volumes of material from out-of-channel sources. The lack of major floodplain changes suggests that this sediment is efficiently evacuated downstream, instead of contributing to local deposition and erosion. Bank erosion is clearly hampered by bedrock and stable, coarse depositional fans along the channel. This limiting effect of valley confinement is consistent with the location of the most active portion of this reach south of Shovelnose Creek, RK 52-53, where that confinement lessens. The bend at the end of the reach has increased in curvature and translated downstream since 2009, eroding the eastern bank. Most of this change occurred between 2015 and 2016, possibly due to the high flows in 2015. The island at RK 52.5 has grown, narrowing the channel on either side. Hook (also called Pistol) Creek is the last tributary visible on the eastern side in this reach; it enters the river in two channels near RK 52.5 and at RK 53. It may contribute sediment to the large sediment bar between RK 52 and 52.5, or the sediment may flow directly downstream to the next reach. It is worth noting that RK 52-53 were described by Hickin (1989) as part of the braided reach. As long as regular flows keep coming off of Mount Cayley and Endurance Creek, this reach of Squamish River will remain narrow and single-threaded, and will supply abundant sediment to the reaches below.

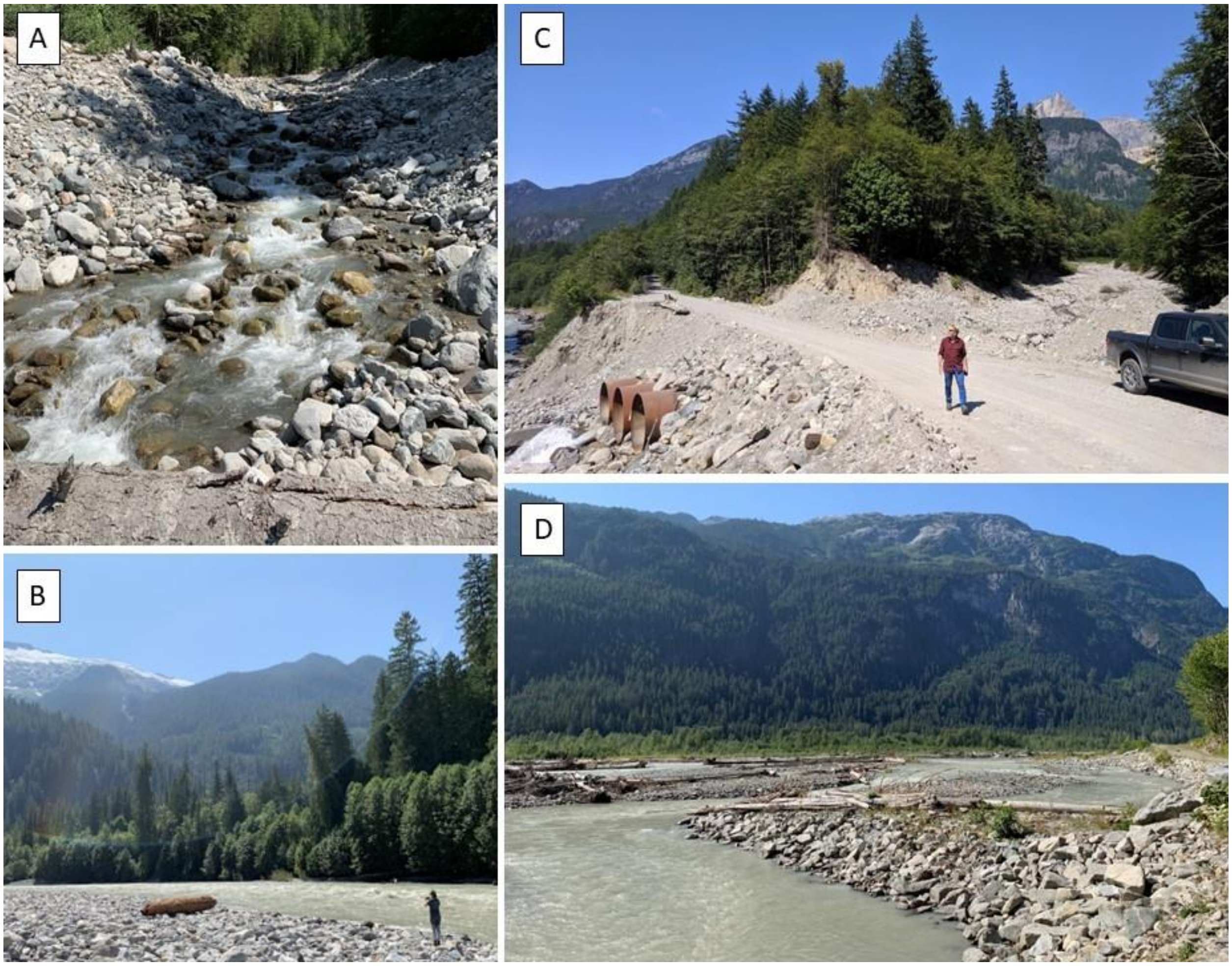


Figure 19: A: Terminal Creek B: Standing on debris deposited by Turbid Creek, Icecap Peak in background, Sarah in foreground for scale C: Flow off Turbid Creek, Mount Cayley in background, Jim/truck for scale D: Squamish confluence with Shovelnose Creek. Note the widening valley floor.

4.3.3 Braided Reach

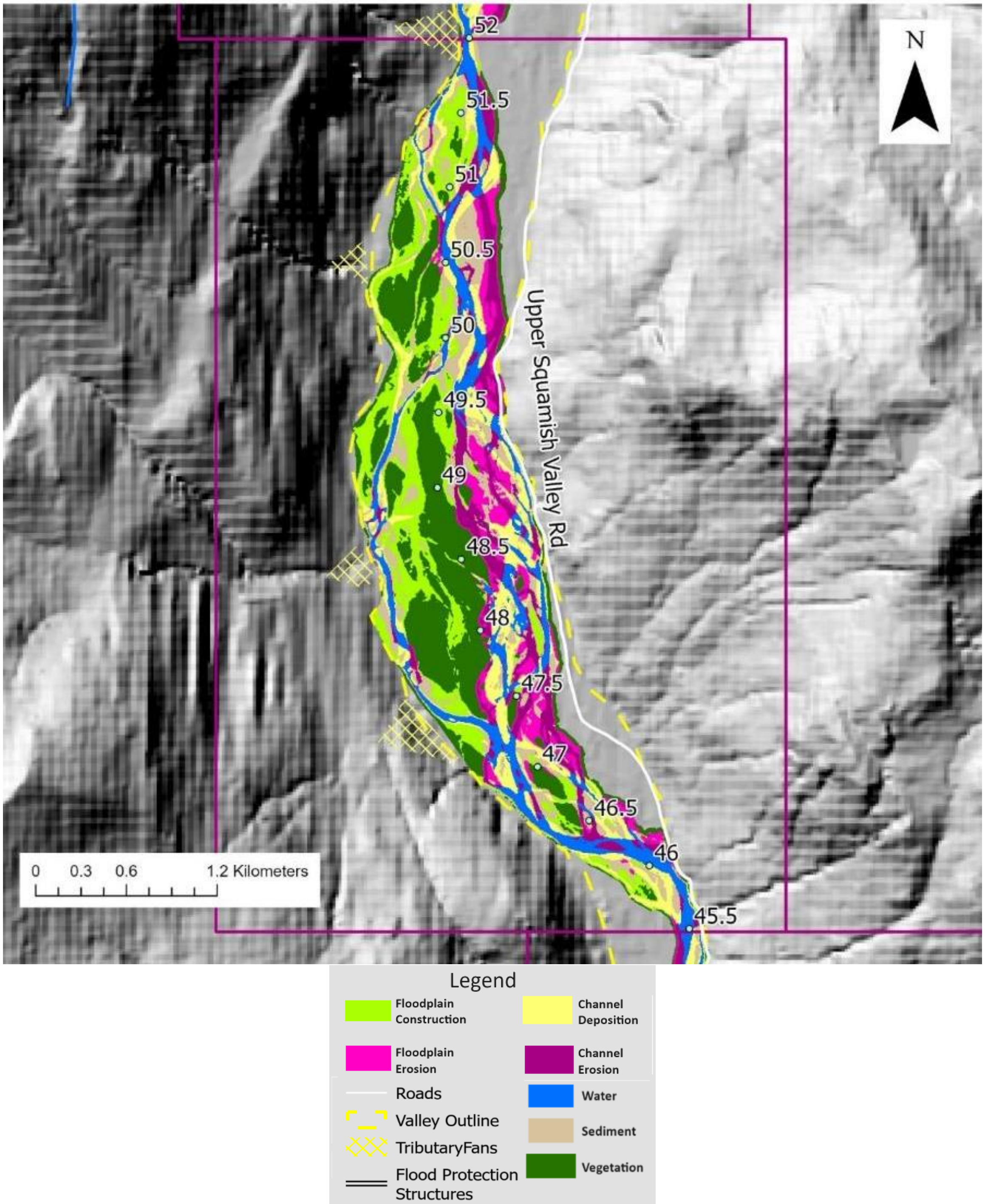


Figure 20: Floodplain and channel change in Braided Reach 2009-2019.

This reach saw an average annual floodplain change of 13.4 m of construction and 13.9 m of erosion during the period of 2009 to 2019. When change from year to year was averaged, construction measured 29.9 meters and erosion 37.9 meters. The average annual channel change of this reach measured 10.4 m of deposition and 12.9 meters of erosion during the period of 2009 to 2019. When change from year to year was averaged, construction measured 49.2 m and erosion 65.1 m.

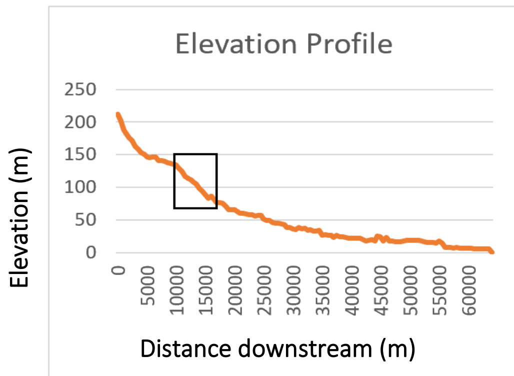


Figure 21: Elevation profile of the study section with Reach 3 highlighted

The slope of this reach is 0.7%, which is steeper than the previous reach. The ratio of wetted width to valley width and active channel to valley width is 18% and 81% confined, respectively. Though the active channel spans nearly the entire valley, it is because the channel planform is braided and so the channel itself is not really confined. At the same time, the space available for the active channel to shift laterally is not as plentiful. The average widths of the active channel and valley are 780 m and 941 m wide, respectively.

High levels of sediment enter this reach from upstream (as discussed for Reach 2), but at best moderate levels from tributaries. While there are several steep tributaries coming off the Icecap Peak, Pykett Peak, and the adjacent mountains, only one reaches the channel at RK 48.5, connecting it to the barren sediment sources observed in the alpine zone. Out of three sources contributing to the tributary connected to Reach 3, two have proglacial lakes, which are expected to trap sediment; this presumably limits to some extent the amount of sediment supplied to the Squamish River through this pathway.

The main changes that occurred were channel abandonment and reactivation, and floodplain construction. Overall, this reach experienced erosion on the eastern side of the channel and floodplain and deposition on the west. The eastern side became the primary channel as the western channel infilled and sediment bars transitioned to floodplain. The upper portion of this reach is narrow due to material from Mt. Cayley entering from the eastern side of the valley. In 2009, the river flowed through this reach in two braided channels separated by sediment bars and vegetated islands. The channel on the western side was already beginning to become less active, the channel narrowing and infilling from RK 50 to 51.5. By 2019, this portion was almost completely abandoned. In 2009 and 2019, the western channel from RK 47 to 50 remained active but secondary to the channel on the eastern side. The Squamish River FSR runs the length of the eastern side of this reach, and there are some structures in place to protect it near RK 50 (see Fig. 22). Near RK 47, the channels converged in 2009 and braided around vegetated islands and sediment bars for the rest of the reach. Between 2009 and 2019, the channels became more complex, converging at RK 46.5 into a single, narrow channel where the valley is impinged by steep valley walls on either side. The channel pushing towards the eastern side laid the groundwork for the large avulsion on the western side just downstream, described in the next reach.

Figure 22: Erosion control measures along the eastern side of the Braided Reach to protect the Squamish Valley Forest Road from Google Earth, 2023

A considerable amount of the floodplain change in this reach is associated with high degree of braiding observed in this reach. Sediment just gets reworked as small channel avulse back and forth, forming a main, braided channel. Log jams help form islands and block off channels (Collins et al., 2012). Woody debris is introduced to river channel when banks erode or slump. While tree roots may offer protection bank protection from erosion, once collapsed, they can also cause currents to deflect into the bank, further concentrating erosion and eventually dislodging the tree from the bank. This high level of geomorphic activity is not surprising, considering the combination of relatively steep slopes, indicating substantial stream power, and the availability of bed-caliber sediments provided by landslides, especially from Mt. Cayley, and evacuated from Reach 2 immediately upstream. In addition, the western channel of this reach is eroding alluvial fan deposits and remobilizing sediment as new channels form. As old channels infill and new channels erode away, sediment is moved downstream to form new bars and islands (Sichingabula, 1989). At the top of this reach, the valley widens and the active channel diverges to fill the entire valley bottom. Energy dissipates and sediment is spread across the valley floor, to be stored as bars and vegetated islands (Brierley, 1989).

As important as the high valley slope and sediment supply, valley confinement does not seem to limit the lateral change. Although currently the active channel occupies much of the valley floor width, it is partly because the abandoned channels have not yet been colonized by vegetation to a sufficient degree to be considered floodplain in our classification scheme.

4.3.4 Avulsion Reach

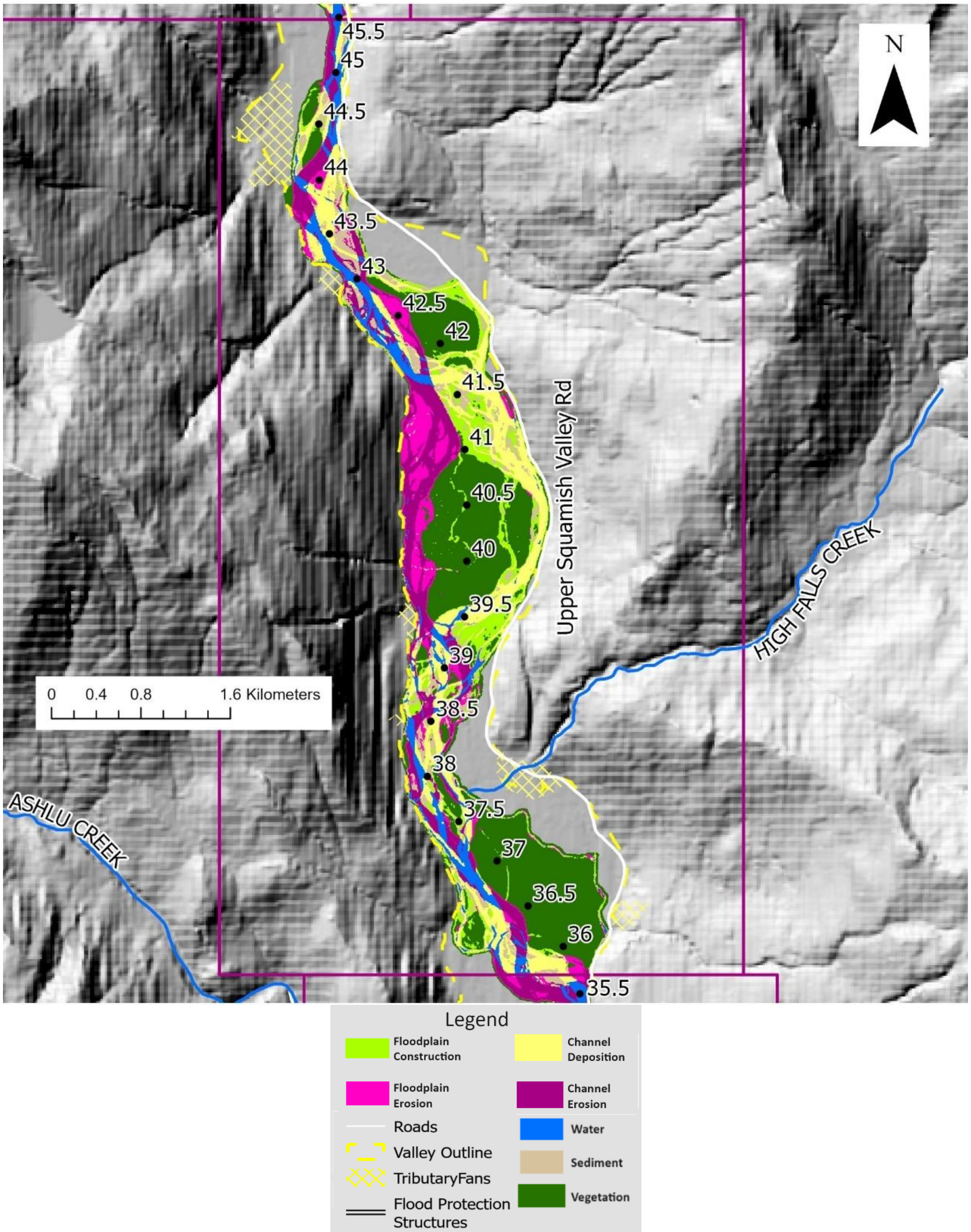


Figure 23: Floodplain and channel change in the Avulsion Reach 2009-2019. Note that tributary channel widths are not to scale

This reach saw an average per annual floodplain change of 9.3 meters of construction and 15 meters of erosion during the period of 2009 to 2019. When change from year to year was averaged, construction measured 26.3 meters and erosion 36 meters. The average per annual channel change of this reach measured 10.4 m of deposition and 12.9 meters of erosion during the period of 2009 to 2019. When change from year to year was averaged, construction measured 48.1 m and erosion 58.2 m.

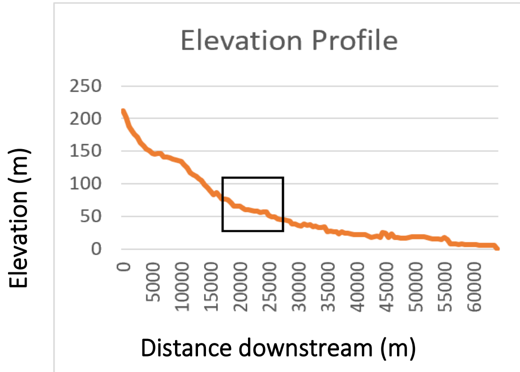


Figure 24: Elevation profile of study site with Study Reach 4 highlighted

This reach has a slope of 0.23%. The ratio of wetted width to valley width and active channel to valley width is 15% and 73% confined, respectively. Like the previous reach, the active channel spans the whole valley width in portions of this reach, but it is in the process of narrowing as the secondary channel cutoff by the avulsion becomes abandoned. The average widths of the active channel and valley are 765 m and 1025 m wide, respectively.

The reach receives high levels of sediment from upstream, associated with the active reworking of the floodplain in Reach 3. At the same time, Reach 4 is assessed as having low levels from tributaries. There are no major tributaries that appear to store significant amount of sediment. The most significant tributary is High Falls, but there are no indications that would suggest that it currently feeds large quantities of material to Squamish River.

The main changes that occurred in this reach were channel abandonment and reactivation, channel deposition and erosion, and floodplain construction and erosion. Like the above reach, this reach is highly active, though on a larger scale. Rather than small scale avulsions and change, this reach underwent a major avulsion which shifted the entire river channel from the east side of the valley to the west, almost completely abandoning the eastern channel in the span of a few years. Between 2009 and 2019, the islands on the western bank at RK 44.5 have grown, pushing the channel towards the east. The channel is deflected off the substantial bar that has grown between RK 43.5 and 44 on the western side, until it hits the forested alluvial fan visible on the western side at RK 43, steering the channel away from the valley wall. At RK 43, the channel splits around a large, vegetated island. Even in 2009, the channel along the eastern bank was becoming abandoned. As the flow through the western channel increased, the concave bank of the bend increased in curvature. In 2009, an accessory channel cut down the valley on the eastern side of the floodplain starting near RK 42. Between 2009 and 2019, a major avulsion occurred in this channel. It eroded large swaths of floodplain to create a new channel between RK 41.5 and 39.5. By 2019, the eastern channel is nearly completely abandoned and gradually colonized by vegetation. Downstream of RK 39, the river remains highly active. High Falls Creek flows in on the eastern side near RK 37.5, narrowing the valley floor and pushing the active channel towards the western valley wall. Between 2009 and 2019, the main channel has migrated laterally and downstream. The channels on the far west were abandoned and in general the main channel has migrated toward the center of the valley, eroding into forested floodplain on the convex bank of the meander bend at RK 36.5. The floodplain narrows considerably at RK 36 at the bottom of this reach, pushed towards the eastern side of the valley by the alluvial fan coming off Ashlu Creek.

This reach was very active because of the major avulsion which was initiated in July of 2011. During the period between images, the flows ranged from 222 to 793 m^3/s, so there were no particularly large floods. This underscores the fact that avulsions can happen due to internal dynamics of the river system, rather than external forcing. However, their frequency is known to increase with increasing sediment supply (Ashworth et al., 2004). It is very likely that the inputs of large quantities of sediment from Reach 3 facilitated the avulsion in this reach. The third element which was critical for the extensive floodplain change to occur was a lack of tight confinement by valley walls. The estimated confinement value reflects the fact that, in addition to the new channel belt formed by the avulsion, the former channel belt has not been entirely revegetated.

The avulsion itself, given its importance for the observed floodplain change, deserved to be evaluated in more detail (Fig 25). Imagery of the last few decades on Google Earth Timelapse was examined to understand the antecedent conditions. In the 1980s, all flow was contained in the eastern channel while the site of the future channel appears to have been an accessory floodplain channel. In 1985, the site of future channel appears to have been clearcut. Between 1987 and 1993, the bend marked with 1 consistently eroded the concave bank until, in 1993, it avulsed into a secondary channel, marked with a 2. This channel slowly became the primary channel. As the former channel abandoned, this caused the meander bend marked with 3 to erode into the floodplain. The channel of this portion widened significantly, eventually avulsing in 2004 through 2008 to occupy its position along the north-eastern valley wall in 2010. This set the stage for the meander bend in the channel marked with 2 to increase in curvature and erode the floodplain towards the accessory channel. The process of avulsion can be tracked in detail using Planet Labs imagery. In early July of 2011, the channel seems to have spilled over its banks into the accessory channel. The steep, new hydraulically favorable channel rapidly became the primary channel. By July of 2012, large swaths of floodplain have eroded and the eastern channel is mostly dry. In July of 2013, the erosion has continued down the new channel as it widens and becomes braided. Between June of 2015 and 2016, large amounts of erosion occurred on the convex bank of the meandered bend marked by 4. A flow of 1540 $m^3 s^{-1}$ (at the gauge near Brackendale) occurred during this time period. Erosion and channel widening continued between 2016 and 2017, helped by a flow of 1690 $m^3 s^{-1}$. These processes are relevant because the new channel sets the stage for the changes in the next reach downstream.

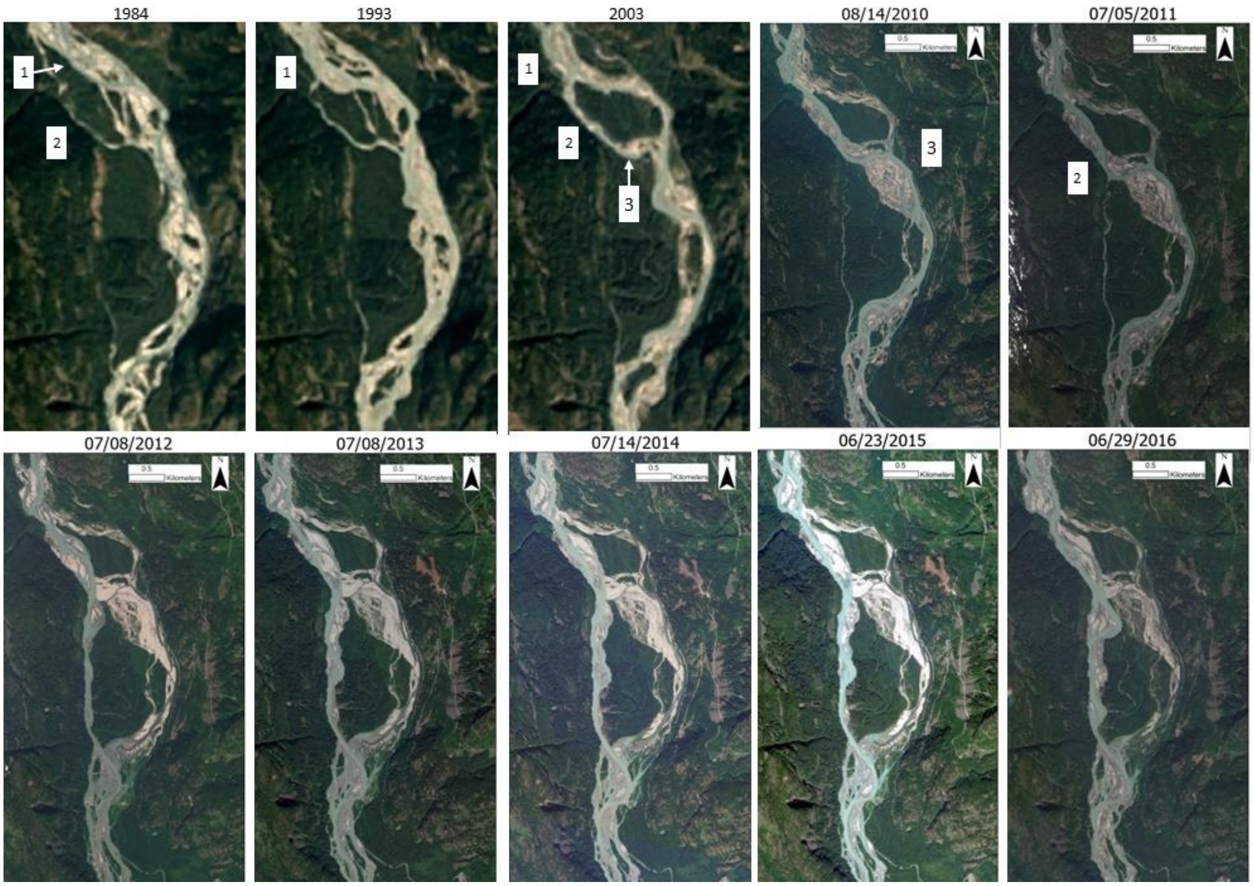


Figure 25: Progress of the avulsion between 1984 and 2016, with referenced channels labelled; the 1984, 1993 and 2003 imagery from Google Earth Timelapse and the rest are from Planet.com

4.3.5 Squamish-Ashlu Reach

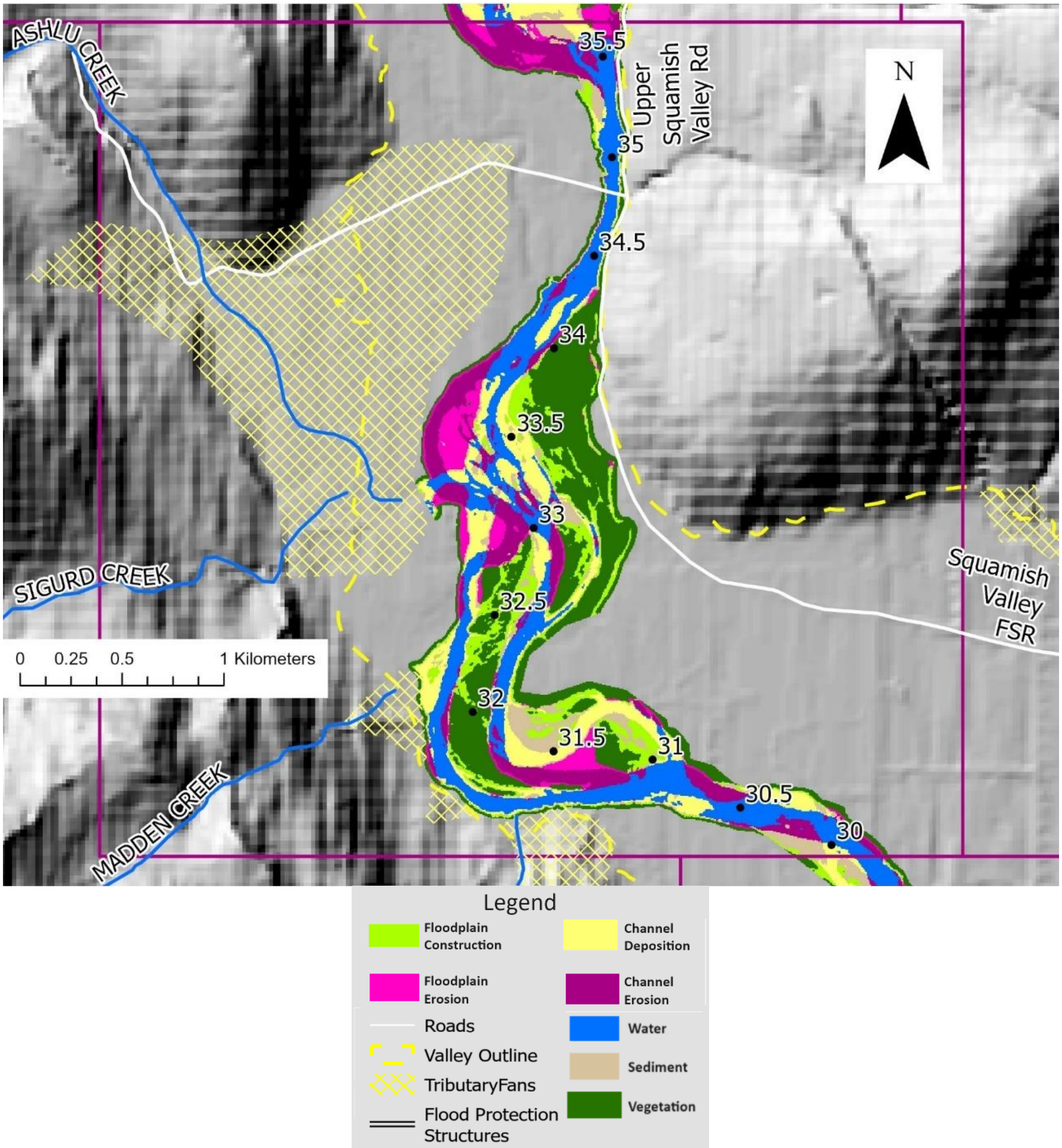


Figure 26: Floodplain and channel change in the Squamish-Ashlu Reach 2009-2019. Note that tributary channel widths are not to scale

This reach saw an average per annual floodplain change of 5.4 meters of construction and 9.6 meters of erosion during the period of 2009 to 2019. When change from year to year was averaged, construction measured 16.7 meters and erosion 21.6 meters. The average per annual channel change of this reach measured 7 m of deposition and 7.9 meters of erosion during the period of 2009 to 2019. When change from year to year was averaged, construction measured 28 m and erosion 32 m.

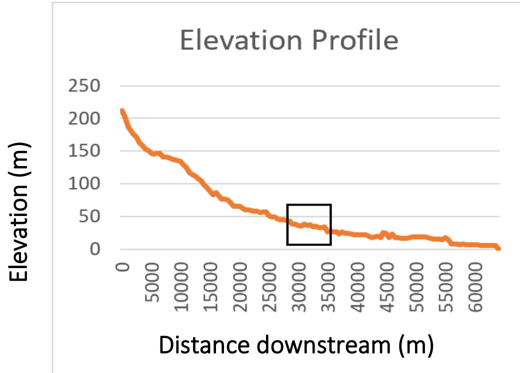


Figure 27: Elevation profile of study site with Study Reach 5 highlighted

The slope of the reach is 0.09% according to Canadian DEM but 0.18% when calculated with the lidar, which is more recent and accurate. The ratio of wetted width to valley width and active channel to valley width is 11% and 41% confined, respectively. This reflects the relatively unconfined character of the valley floor. The average widths of the active channel and valley are 640 m and 1550 m wide, respectively.

This reach receives high levels of sediment from upstream, especially considering the material mobilized by the avulsion in Reach 4, and high levels of sediment supply from its tributaries. Ashlu Creek, one of the major tributaries of Squamish River, joins the main stem within this reach. Although the creek is blocked by a new hydropower generating station, there still is a lot of sediment stored in the confluence fan. According to a recent assessment, this sediment is finer compared to the bed material is Squamish River (NHC, 2018). As a result, it is likely readily mobilized.

The main changes that occurred were concave bank erosion, convex bank deposition, and channel change via cutoff avulsion. Between 2009 and 2019, the channel in the bend at RK 35.5 has migrated downstream and avulsed, switching from flowing along the upper, eastern bank to the lower, western bank, eroding floodplain at the top of this reach. There was little change between RK 34.5 and 35.5 as the channel is confined and artificially stabilized due to the Squamish Valley FSR running alongside and the Ashlu Bridge across the river. A large sediment bar formed near the eastern bank at RK 34 and just downstream, the convex bend at RK 33.5 is growing due to channel deposition and transitioning to floodplain. The concave bend on the west has eroded by over 200 m. The Squamish River has avulsed into the channel of Ashlu Creek in 2016 (other sources indicate that similar events took place previously in 2002 and 2005), causing the Ashlu to meet the Squamish further and further west. Just downstream of the Ashlu confluence, the river splits into two distinct channels separated by a stable vegetated island and sediment bars. In 2009, these two channels remained separate from RK 31 to just above 33. In 2009, the eastern and western channels at RK 33 were straight. The western channel eroded east by 160 m over the study period, eventually meeting the eastern channel. The eastern channel also eroded east by 50 m. Both channels curved along the valley wall. The lower, western channel has become narrower, squeezed by deposition on the convex bank of the island where Mawby Creek meets the channel. The concave bend of the eastern channel eroded at RK 31.5 until it broke through in 2013. This caused the abandonment of the channel on the far eastern bank at RK 31 and the straightening of the channel from RK 30 through 31.

This reach saw high rates of floodplain change because of high sediment supply, both from upstream and lateral sources, and lack of confinement by the valley walls. This reach is considered a wandering planform, and as such is laterally unstable and switches position between channels. These processes create channel and floodplain instability (Brierley, 1989; Ham, 2005). This reach marks the transition between the upstream sediment influences of the landslides coming off Mount Cayley and the downstream sediment influences of the Cheekye Fan. The Cheekye Fan is a large debris slide off Mount Garibaldi which impounded the Squamish River up to the confluence of the Ashlu several thousand years ago. The river eroded the dam, but it had lasting effects that are described in more detail in the next reach.

4.3.6 Upper Meandering Reach

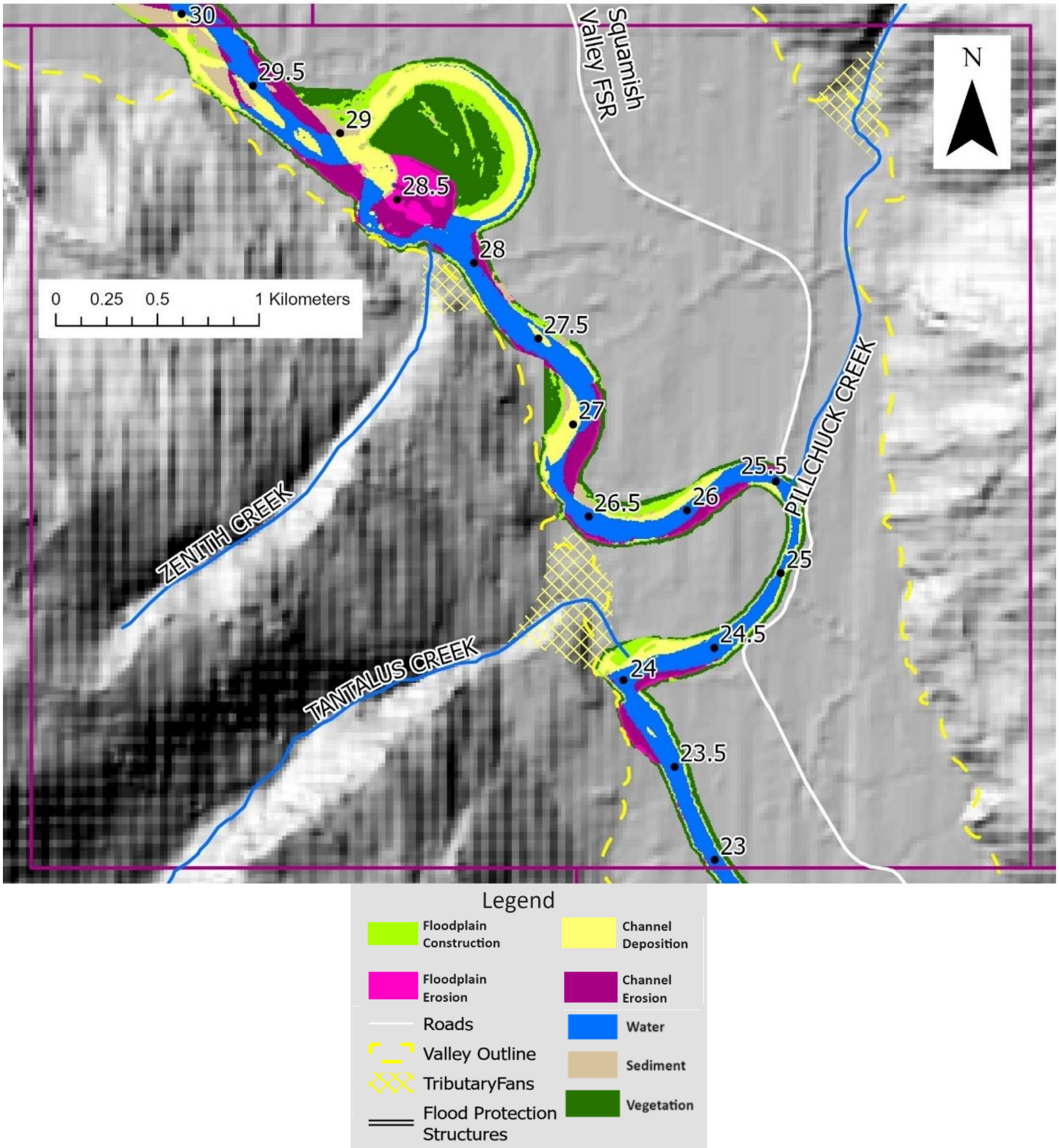


Figure 28: Floodplain and channel change in the Upper Meandering Reach 2009-2019. Note that tributary channel widths are not to scale

This reach saw an average per annual floodplain change of 4.8 meters of construction and 5.4 meters of erosion during the period of 2009 to 2019. When change from year to year was averaged, construction measured 11.2 meters and erosion 12.6 meters. The average per annual channel change of this reach measured 5.3 m of deposition and 4.5 meters of erosion during the period of 2009 to 2019. When change from year to year was averaged, construction measured 17.5 m and erosion 17.4 m.

The slope of this reach is 0.17% on the DEM and 0.09% on the lidar. The ratio of wetted width to valley width and active channel to valley width is 7% and 26% confined, respectively. The average widths of the active channel and valley are 460 m and 1800 m wide, respectively. I assess it that the reach receives moderate levels of sediment from above, and low levels from its tributaries. The decision regarding moderate levels of sediment inputs from the upstream sources is justified by a significant drop in the gradient and, therefore, stream power. This drop indicates that, despite high geomorphic activity in the reach immediately upstream, at least some of the coarse sediment may not be able to traverse this reach. This interpretation is consistent with hydraulic modeling conducted as part of the recent flood risk assessment. As for the tributary inputs, based on their characteristics (lack of indication of significant storage), the streams flowing into this reach are interpreted as not delivering large volumes of sediment to Squamish River.

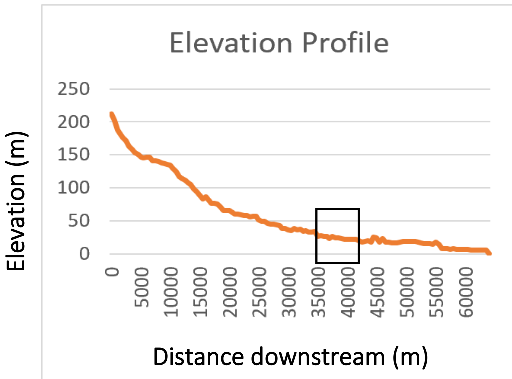


Figure 29: Elevation profile of study site with Study Reach 6 highlighted

The main changes that occurred in this reach were downstream and lateral migration via concave bank erosion and convex bank deposition, island and bar destruction, and deposition and floodplain formation in abandoned channels. Between 2009 and 2019, the two in-channel sediment bars at the very top of the reach just below RK 30 have transitioned to point bar and floodplain, forcing the channel towards the eastern bank, eroding floodplain on the eastern side near RK 29.5. The meander bend at RK 29-28 has been abandoned during the study period, though the cutoff occurred before 2007. The sediment bar that formed at RK 27.5 is pushing the channel towards the western bank, eroding and increasing its curvature. The bend at RK 27 has migrated downstream by 100 m over the course of the study period as the convex bank keeps pace with channel deposition and transition to floodplain. The meander bend between RK 24 and 26.5 is a uniquely shaped bend, with a concave-bank bench (Hickin, 1979). The concave bench bend (RK 24) has migrated downstream by 100 m during the study period from deposition on the concave bank, while the convex bank has eroded by 50 m. It is also worth mentioning that outside of the bend at RK 25.5 erosion control measures that have been in place since 1969 prevent the bank from eroding further, to protect Squamish FSR (see Fig. 30).

The intermediate level of floodplain changes observed in this reach seem to be associated with its transitional character from wandering to meandering morphology. As opposed to the fast and frequent channel avulsions of the upstream reaches, the meandering reaches migrate via gradual, lateral movement and cutoff avulsions of meander bends. The upstream activity is primarily due to the cutoff processes. The level of lateral erosion and deposition declines toward the downstream end of this reach. This is presumably (partly) related to the diminishing influence of the abundant sediment sources upstream. The valley confinement is not limiting at any point of this reach but the low gradient (and therefore stream power) most likely also contributes to less floodplain changes compared to the braided reaches upstream. The slope of this reach, just like two other meandering reaches downstream of it, Lower Meandering and Upper Cheakamus, are highly influenced by the downstream control of the Cheekye Fan.

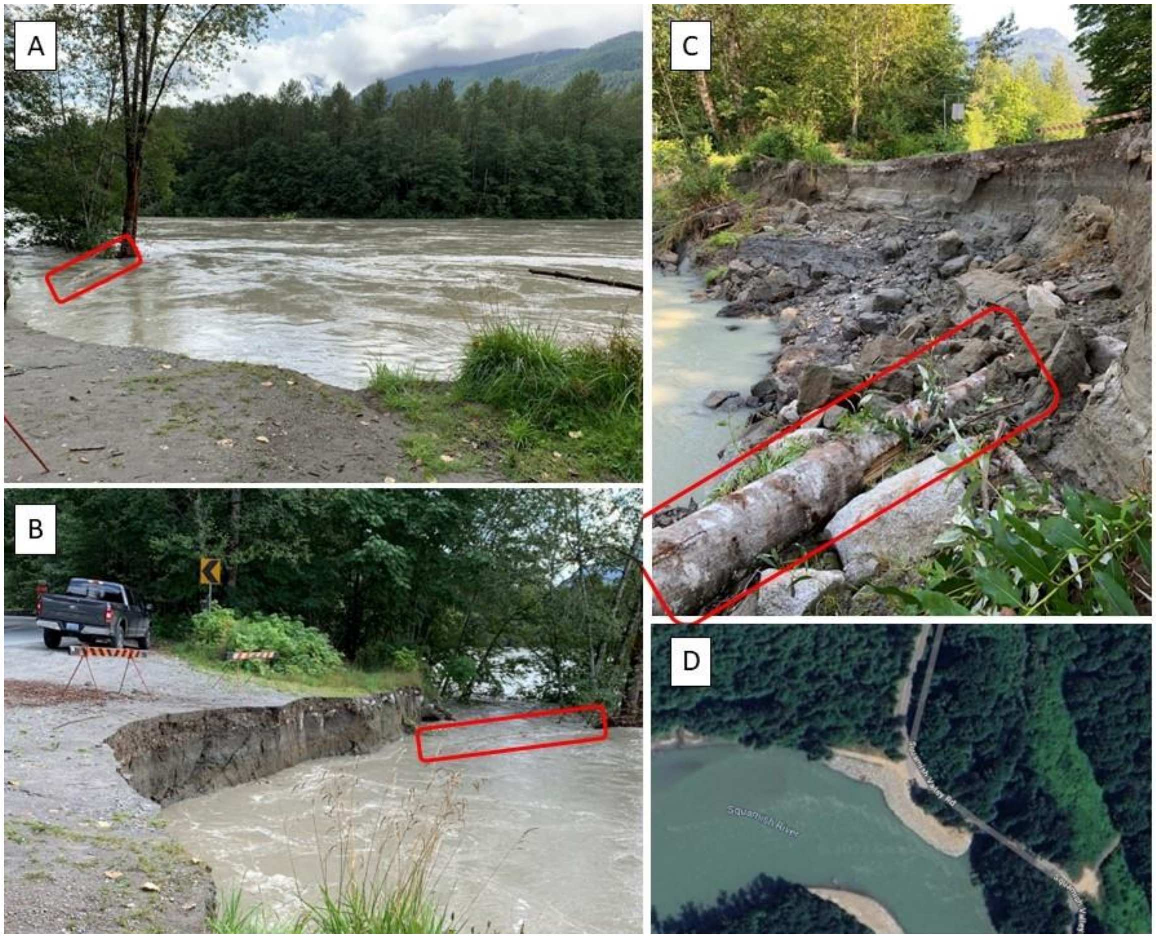


Figure 30: Meander bend near RK 25.5. Note the same tree is outlined. A, B: Near bankfull on August 2, 2019; C: August 5, 2019 after floodwaters have receded Source: Personal photos; D: 2023 Imagery of erosion control structures Source: Google Earth

4.3.7 Lower Meandering Reach

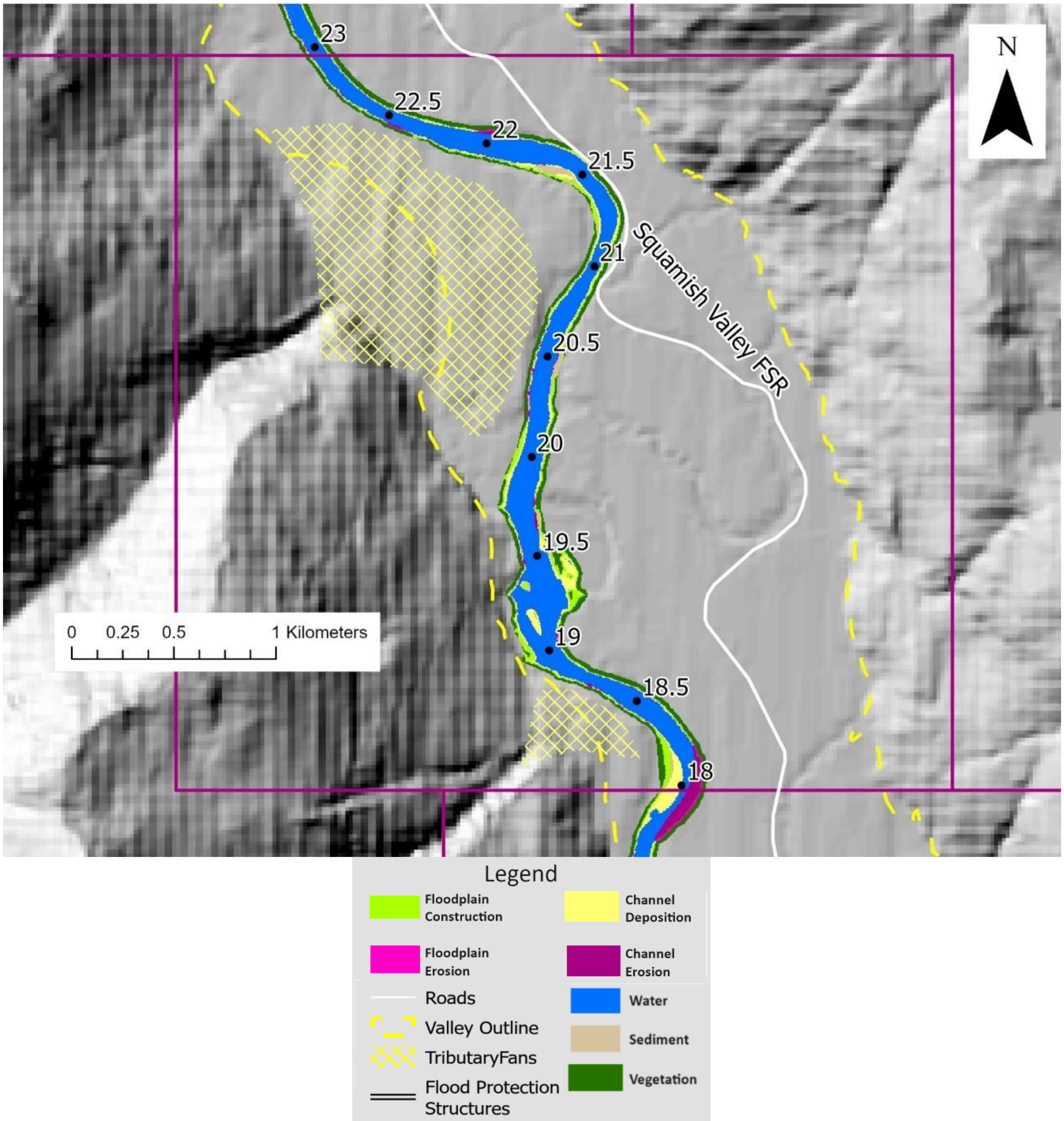


Figure 31: Floodplain and channel change in the Lower Meandering Reach 2009-2019. Note that tributary channel widths are not to scale

This reach saw an average per annual floodplain change of 1.3 meters of construction and 1.7 meters of erosion during the period of 2009 to 2019. When change from year to year was averaged, construction measured 5.8 meters and erosion 6.3 meters. The average per annual channel change of this reach measured 1.5 m of deposition and 1.3 meters of erosion during the period of 2009 to 2019. When change from year to year was averaged, construction measured 7.5 m and erosion 7.8 m.

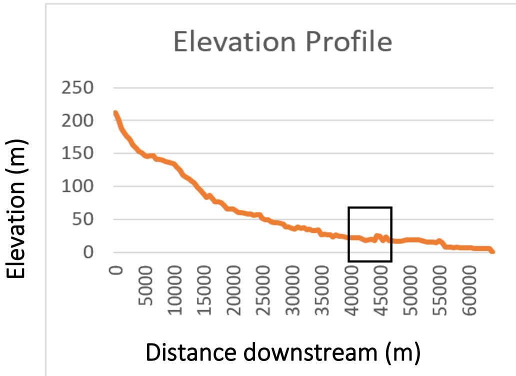


Figure 32: Elevation profile of study site with Study Reach 7 highlighted

The slope of this reach is 0.02% on DEM and 0.04% on lidar. The ratio of wetted width to valley width and active channel to valley width is 6% and 12% confined, respectively. The average widths of the active channel and valley are 175 m and 1570 m wide, respectively. This reach receives low amounts of sediment from upstream and low amounts from its tributaries. The latter is associated with the low slope (and stream power), which implies that some of the coarsest size fraction of the sediment transported from the upstream sources are unlikely to reach this far downstream. This reach also does not have any meaningful tributaries which would contribute appreciable quantities of sediment.

The main changes that have occurred in this reach are channel straightening, concave bank erosion and convex deposition. This reach was less active but there is a small amount of channel and floodplain erosion on the upper convex bank near RK 22, and some channel and floodplain deposition on the convex bank of the same bend. An alluvial fan off the western side pushes the channel to the east, though it does not appear to be active recently. As this bend butts up against the Squamish Valley FSR, erosion control measures are in place to limit how much further it can migrate laterally or downstream which have been in place since 1969 (Sichingabula, 1989). Since the meander bend cutoff near RK 20.5 sometime after 1918 but before 1947, this portion of the channel has remained straight and stable. At RK 19, the channel is straightening. The channel used to deflect off the valley wall just below RK 20 towards the opposite bank, which was also a deep meander bend. Over time, the apex of the bend has shifted downstream past the "hard point," allowing the channel to straighten, the meander on the east side to become abandoned, and bars to form in channel (Bauch, 2009). The bend at RK 18 is active, with channel and floodplain deposition on the convex bank and channel and floodplain erosion on the concave bank. This bend has been pushed to the east by the alluvial fan, but like the upstream one, it also does not appear to be recently active. This bend has not been altered by human activity and will continue to migrate laterally and downstream.

The stable nature of this reach, reflected in the limited amount of observed floodplain change, is interpreted as driven by a combination of low slope, which limits stream power available to erode and redistribute sediment making up the banks, and low sediment supply (relatively speaking, that is compared with other study reaches). As mentioned previously, this reach, the Upper Meandering reach upstream, and Upper Cheakamus just downstream, are highly influenced by the downstream control of the Cheekye Fan. The Cheekye Fan is a large, paraglacial alluvial fan formed by the partial collapse of Mount Garibaldi. Around 7000 years ago, the Cheekye Fan prograded across the valley, temporarily blocking the Squamish River all the way up to the confluence with Ashlu Creek. Though the river eroded through and base level has adjusted from 22 m 13 m, the channel is still pushed to the far western side of the valley. Gentle slopes cause the low-sinuosity meandering planform (Brierley, 1989). Though slope decreases in the downstream direction in these reaches, shear stress – a function of depth and slope – declines less rapidly because the depth of the channel generally increases as the planform shifts multiple, wandering channels to single, meandering channels (NHC, 2018).

4.3.8 Upper Cheakamus Reach

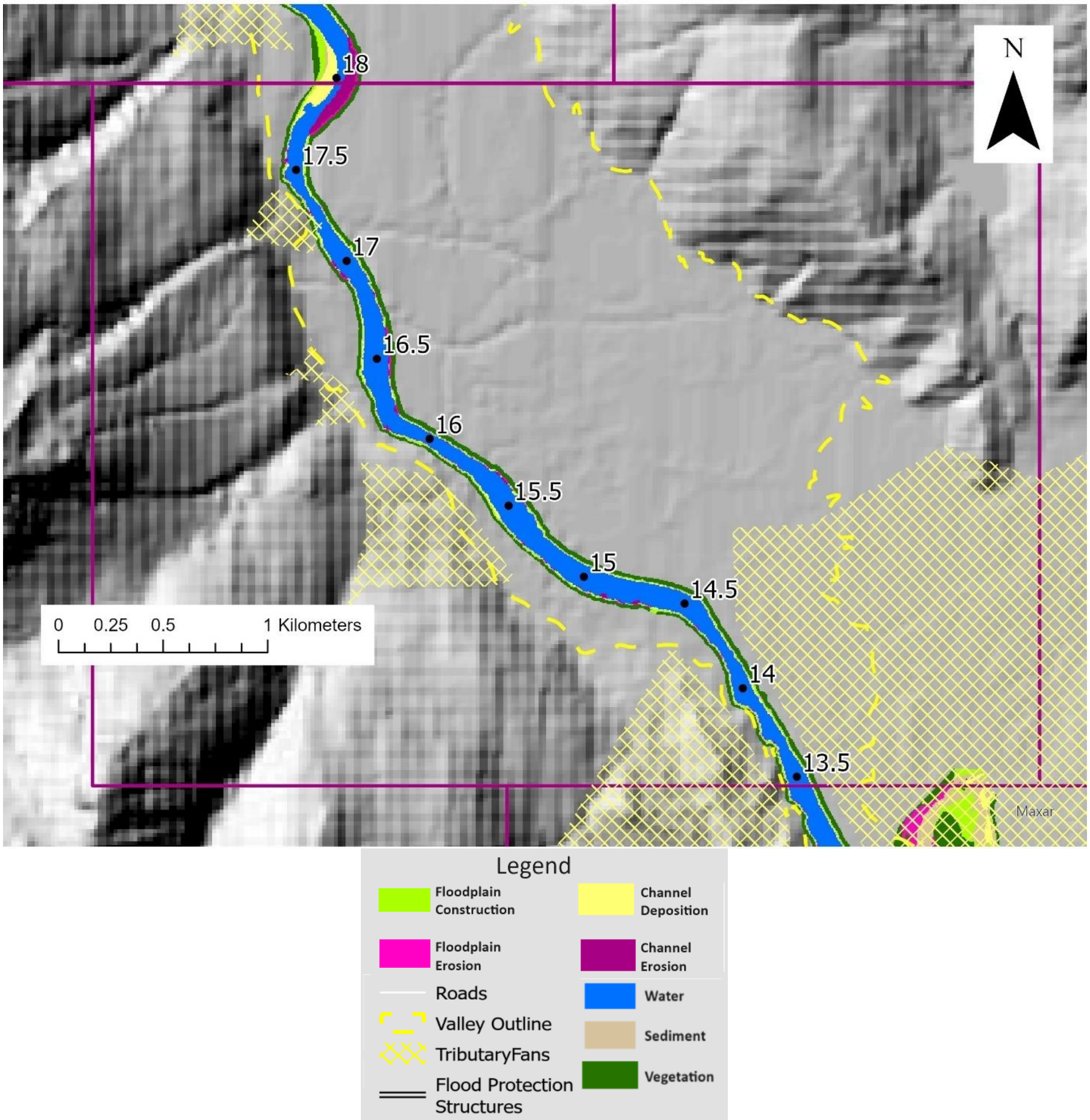


Figure 33: Floodplain and channel change in the Upper Cheakamus Reach 2009-2019. Note that tributary channel widths are not to scale

This reach saw an average per annual floodplain change of 0.9 meters of construction and 1.8 meters of erosion during the period of 2009 to 2019. When change from year to year was averaged, construction measured 4.6 meters and erosion 6.4 meters. The average per annual channel change of this reach measured 1.3 m of both deposition and erosion during the period of 2009 to 2019. When change from year to year was averaged, construction measured 5.3 m and erosion 5.9 m.

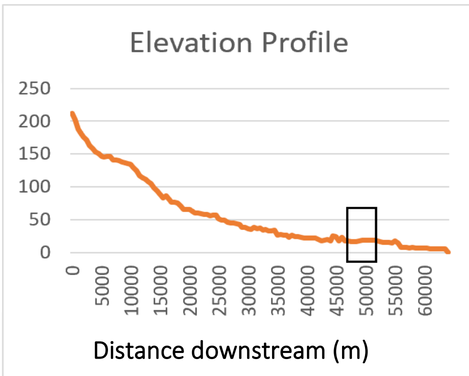


Figure 34: Elevation profile of study site with Study Reach 8 highlighted

The slope of this reach is 0.04%. The ratio of wetted width to valley width and active channel to valley width is 6% and 12% confined, respectively. The average widths of the active channel and valley are 174 m and 1570 m wide, respectively. This reach receives low amounts of sediment from upstream and low amounts from its tributaries. Such an assessment of the upstream sediment inputs once again is motivated by very low gradient, which limits sediment transfer. This interpretation is consistent with the hydraulic modeling recently conducted for this part of the river (NHC, 2018). This is further, even if indirectly, supported by low floodplain and channel change rates in the upstream reach. Similarly, no significant tributaries which would deliver appreciable quantities of sediment to this reach of Squamish River were observed.

The main changes that occurred were a very minor amount of concave bank erosion and convex bank deposition. Between RK 13.5 and 18, the river maintains its single channel, meandering morphology, with a few, very small sediment in-channel and point bars. At the bend at RK 18, the convex bank is aggrading and the concave bank is eroding. Other than this, there is little change in this reach worth note. This reach has a wide-open, forested floodplain and plenty of meander scars providing evidence of past activity. The Cheakamus Indian Reserve continues on the eastern side of the valley down to the confluence of the Cheakamus River. The reserve is home to a small village, but otherwise the floodplain is undeveloped. 9.3 ha of the western side of the floodplain is the Yookwitz Indian Reserve No. 12 (*Yewk'ts*). No roads run near the channel, nor are there any structures affecting the flow.

The low level of floodplain (and channel) change in this reach is interpreted as being limited at least by one, or a combination of, two factors. As mentioned, the low channel slope is clearly important in limiting downstream passage of coarse sediment. This in turn limits local sediment reworking and therefore floodplain change. However, similar conditions upstream mean that relatively little coarse sediment is supplied to this reach, compared with other reaches upstream. This reach is just upstream of the Cheekye Fan, and as with the previous two reaches, this causes a low slope and low activity. Meander scars on the floodplain show that, although this reach is occasionally active, the channel has remained in a consistent location for over a decade (see Fig. 35). It is clear that the wide valley does not impose any significant control on floodplain change in this reach. Even where the channel runs along the valley walls, it is still possible for it to migrate downstream, as described above. Overall, it appears that in the meandering reaches (this and two reaches upstream of it), floodplain dynamic activity decreases downstream. The closer to the Cheekye Fan, the less active the channel and floodplain.

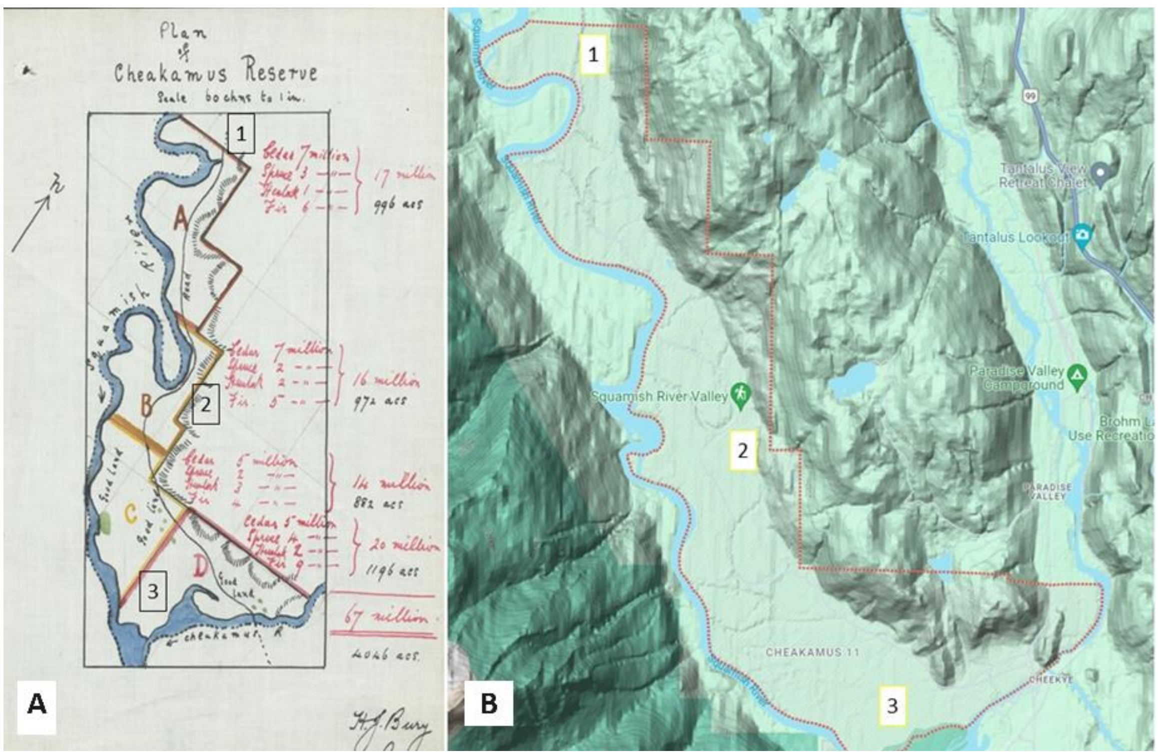


Figure 35: A: 1918 map of the Cheakamus 11 Reserve showing channel location (Bury, 1918) B: Google Maps terrain basemap with Cheakamus 11 Reserve with apparent meander scars. Points 1, 2, and 3 correspond on each panel

4.3.9 Cheakamus-Mamquam Reach

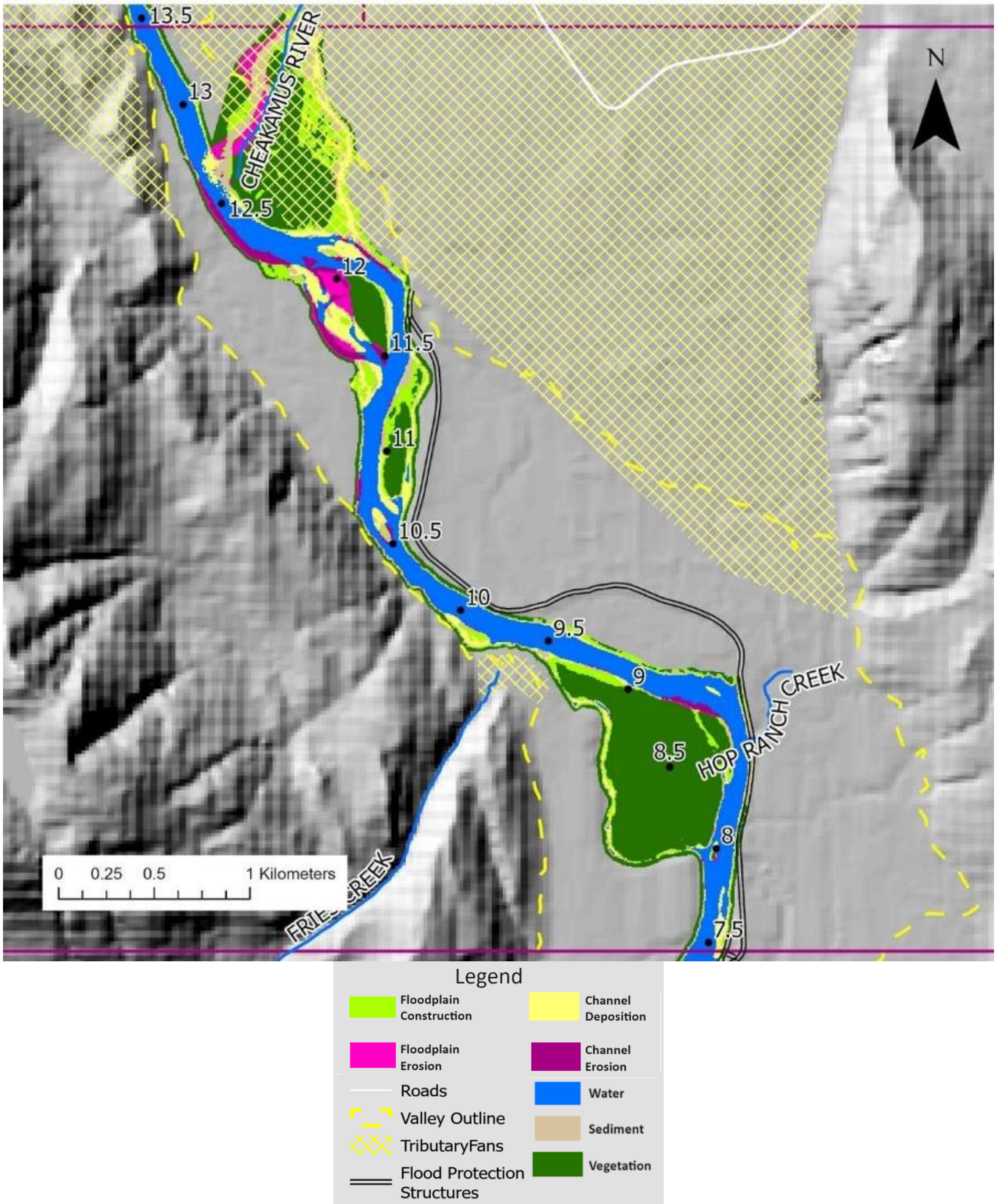


Figure 36: Floodplain and channel change in the Cheakamus-Mamquam Reach 2009-2019. Note that tributary channel widths are not to scale

This reach saw an average per annual floodplain change of 2.9 meters of construction and 3.2 meters of erosion during the period of 2009 to 2019. When change from year to year was averaged, construction measured 9.7 meters and erosion 10.9 meters. The average per annual channel change of this reach measured 3.2 m of deposition and 2.7 meters of erosion during the period of 2009 to 2019. When change from year to year was averaged, construction measured 12.5 m and erosion 14.6 m.

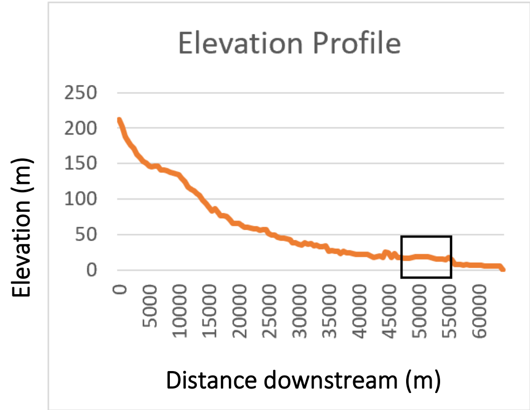


Figure 37: Elevation profile of the study section with Reach 9 highlighted

This reach has a slope of 0.17 to 0.18% and is convex like Reach 2 due to the Cheekye fan. The ratio of wetted width to valley width and active channel to valley width is 18% and 53% confined, respectively. The average widths of the active channel and valley are 380 m and 1230 m wide, respectively, though lateral movement is confined to a floodplain width of 760 m.

This reach receives low amounts of sediment from upstream, but high from its tributaries, particularly the Cheakamus River. The rationale for this assessment of low upstream inputs is consistent with the logic explained above –the low slope upstream of the Cheakamus fan is presumed to be a limiting factor to how much sediment can pass downstream. The Cheakamus River, on the other hand, carries large amounts of sediment and is subject to avulsions on the fan. As described in the Study Site section, the coarse sediment delivered from Cheakamus is probably derived from the slopes of Mt. Garibaldi, via Cheekye River. Transport of sediment from the upper part of Cheakamus River is assessed to be limited by Daisy Lake dam and grade control due to a historical debris flow from Rubble Creek.

The major changes that occurred in this reach are bank erosion, island destruction and formation, and floodplain deposition. The confluence of Cheakamus and Squamish Rivers has shifted over time from primarily flowing through the lower channel (RK 12) to the upper channel (RK 12.5). The confluence is not necessarily moving upstream; in the past it was closer to RK 13, illustrated in Fig. 35. There is channel deposition along the inside of the bend directly downstream of the confluence and erosion on the opposite bank. Baynes Island (*T'eḵt'ḵáy̓*) (RKs 11.5-12) continues to erode. The channel to the west of it is infilling, narrowing and being pushed to the west, while the eastern channel becomes the primary channel. The bar just downstream of the western channel (near RK 11.5) is aggrading and transitioning to floodplain. The island on the opposite bank just downstream (RK 11) is a site of deposition as the channel around it infills and transitions to floodplain. The bar at RK 10.5 is aggrading and becoming vegetated. Where the alluvial fan from Fries Creek meets the channel, channel and floodplain deposition has occurred as the backchannel of a sediment bar infills and the bar is colonized by vegetation. The secondary channel that cuts across the floodplain at RK 9.5 is infilling as the bar in front of it turns from sediment to floodplain. The floodplain on the inside of the bend at RK 8.5 is eroding and depositing around the bend. Though it appeared the accessory channel on this bend was filling in, 2023 imagery shows this bend has eroded. A sediment bar has grown near RK 7.5, narrowing the channel.

The magnitude of floodplain changes in this reach shows an uptick, relative to the meandering reaches upstream of the Cheakamus fan. This may be associated with both higher slope (and therefore stream power) as well as higher sediment supply rates. However, the concentration of the channel and floodplain changes just downstream of the Cheakamus River indicate sediment supply may be the primary driver. The natural valley confinement is not limiting lateral channel movement. However, the eastern side of the floodplain is heavily altered by human activity. A dyke runs down the eastern bank beginning at RK 12, confining the river to the western side of the valley. Some form of bank protection has been in place since the early 1900's. This is in place to protect the infrastructure, businesses and residences on the floodplain. The western bank has been kept relatively untouched, as Baynes Ecological reserve and the Brackendale Eagles Provincial Park. The presence of the dyke complicates the above interpretation. It cannot be ruled out that this structure plays important role in suppressing channel activity downstream. In fact, the presence of the dyke may suggest that the channel used to sweep across the part of the floodplain that is now protected. However, even where the dyke is set back away from the channel, the degree of floodplain change does not match that just downstream of the confluence.

4.3.10 Squamish Estuary

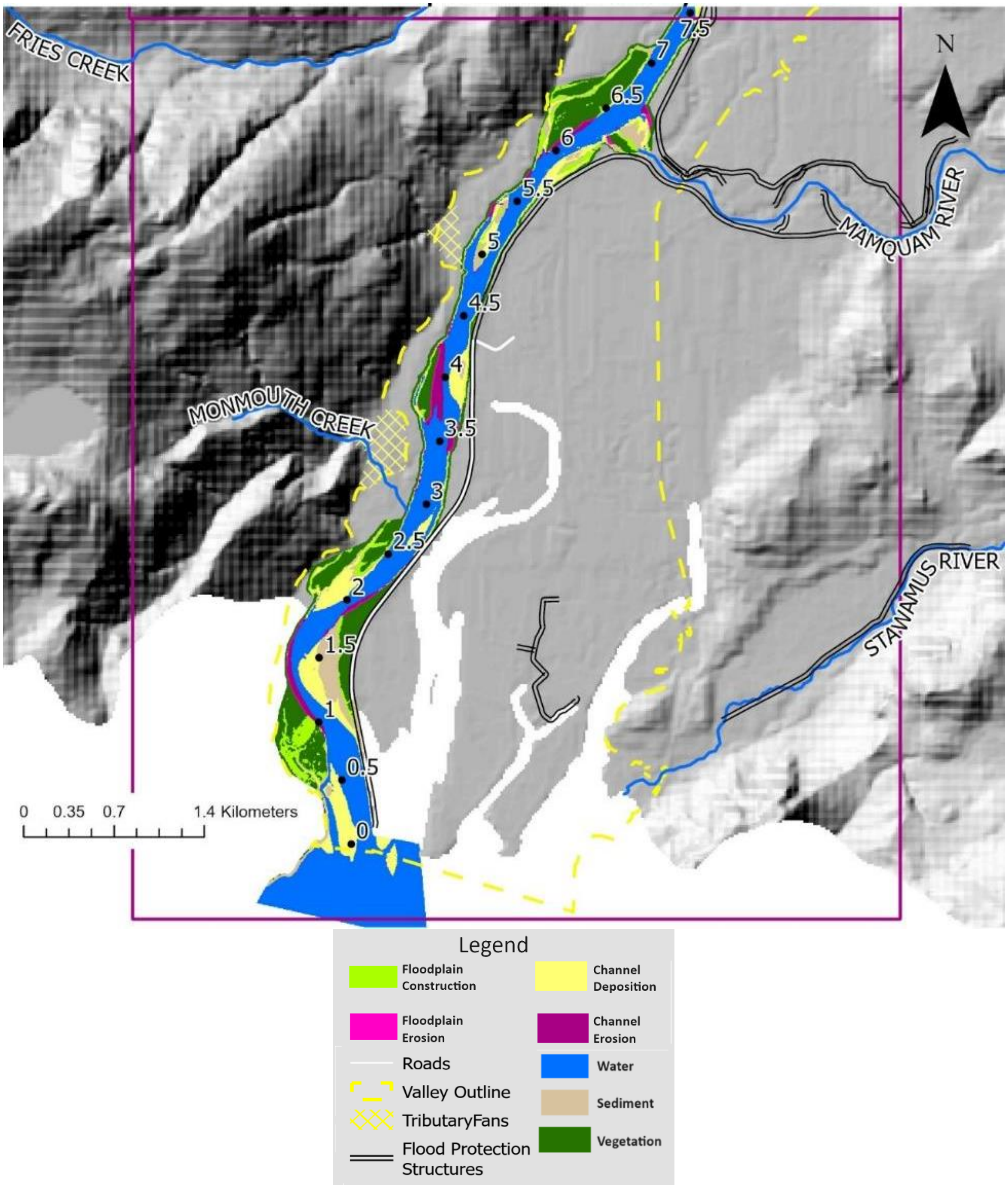


Figure 38: Floodplain and channel change in the Squamish Estuary 2009-2019. Note that tributary channel widths are not to scale

This reach saw an average per annual floodplain change of 3.2 meters of construction and 4.1 meters of erosion during the period of 2009 to 2019. When change from year to year was averaged, construction measured 14.4 meters and erosion 16.6 meters. The average annual channel change of this reach measured 5.4 m of deposition and 3.1 meters of erosion during the period of 2009 to 2019. When change from year to year was averaged, construction measured 22 m and erosion 24.3 m.

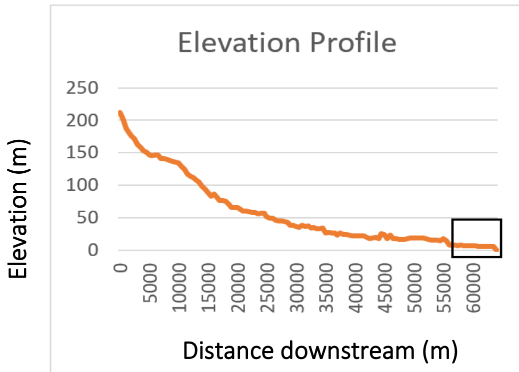


Figure 39: Elevation profile of the study section with Reach 10 highlighted

This reach as a slope of 0.03 to 0.04%. The ratio of wetted width to valley width and active channel to valley width is 40% and 65% confined, respectively. The average widths of the active channel and valley are 415 m and 2070 m wide respectively, but only 650 m are available for lateral migration due to anthropogenic influence, namely river training/flood dyke. This reach receives moderate sediment from upstream, associated with the processes described above in Reach 9, and moderate sediment from its tributaries. The Mamquam River, one of the chief tributaries of Squamish River, appears to deliver substantial sediment to this reach. This interpretation is based on large gravel bars formed along the distal section of Mamquam River, as well as a large confluence bar. Despite itself being protected by a dyke, the natural sediment inputs from this tributary are likely increased by heavy land development.

The main changes that occurred in this reach were convex bank and bar deposition but the classification also captures the growth of delta at the head of Howe Sound. Examples of bar formation can be found at RK 5, where the bar is beginning to be colonized with vegetation, and on the eastern bank at RK 4, the latter being accompanied by erosion on the opposite bank, and at RK 2. An in-channel bar at RK 3 has also grown and shifted downstream.

The observed floodplain changes in this reach in all likelihood reflect a combination of natural and anthropogenic factors. In terms of the latter, despite very low gradient (and therefore low stream power), the reach has relatively abundant sediment supply. Moreover, the depositional nature of the estuary and delta, where sediment brought from upstream accumulates, creates conditions conducive to lateral changes in the position of the channel. The valley is wide and unconfined but as mentioned above man-made erosion control structures heavily limit this activity to the western side of the valley. The anthropogenic influence may have broader implications. In contrast to the majority of Squamish River, this reach has been heavily altered by human activity since the arrival of European settlers. Sometime in the early 1900's, an earthen dam was built to block Kowtain Slough (RK 8), and in 1912, the eastern channel was dredged. It continues to be altered to this day, both though rapid land development as well as the efforts focused on restoring connectivity between channels and the Skwelwil'em Squamish Estuary Wildlife Management Area. The eastern side of the floodplain is highly developed, with the Dentville neighborhood and downtown Squamish whereas the western side remains undeveloped. Heavy development, driven by the fast population growth, also has occurred along the Mamquam River. It is unclear and very difficult to estimate to what extent the historical and ongoing disruptions to the river environment affect fluvial adjustments

4.4 Whole Study Area

Throughout this thesis, slope, valley confinement, and sediment supply have been considered drivers of floodplain change; however, in Squamish River they may be better thought of as limiting factors. A high slope does not always cause high levels of change, but a lower slope does cause lower levels of change. A highly confined reach will generally have lower levels of change, but being unconfined does not necessarily lead to higher levels of change. High levels of sediment do not always lead to higher levels of floodplain activity, but low sediment input will limit floodplain activity. A summary of these factors for each reach is presented below in Table 3.

Table 3: A summary of the characteristics and drivers of each study reach

	Name	River KM	Slope	Confinement	Sediment Supply	Channel Pattern
1	Squamish-Elaho	58.5-64.5	1.12%	Partially confined – natural	Moderate in-channel, moderate lateral	Single channel, braided, wandering
2	Terminal-Turbid-Shovelnose	52-58.5	0.52%	Confined – natural	Moderate in-channel, high lateral	Single channel, wandering
3	Braided	45.5-52	0.57%	Unconfined	High in-channel, moderate lateral	Braided
4	Avulsion	36-45.5	0.23%	Unconfined	High in-channel, low lateral	Braided, wandering
5	Squamish-Ashlu	30-36	0.09%	Unconfined	High in-channel, high lateral	Wandering
6	Upper Meandering	23-30	0.18%	Unconfined	Moderate in-channel, low lateral	Single channel meandering
7	Lower Meandering	18-23	0.08%	Unconfined	Low in-channel, low lateral	Single channel meandering
8	Upper Cheakamus	13.5-18	0.09%	Unconfined	Low in-channel, low lateral	Single channel meandering,
9	Cheakamus-Mamquam	7.5-13.5	0.17%	Confined - anthropogenic	Low in-channel, high lateral	Single channel, wandering
10	Squamish Estuary	0-7.5	0.03%	Confined - anthropogenic	Moderate in-channel, moderate lateral	Single channel, braided

4.4.1 Floodplain reworking

Over the entire study section of the Squamish River, the average annual change between 2009 and 2019 was 5 m floodplain construction and 6.7 m of floodplain erosion. When organized by planform, the values for floodplain construction and erosion were 6.9 and 9.5 m in the predominantly braided/wandering reaches (Reach 1, 2, 3, 4, and 5) and 2.8 and 3.4 m in the predominantly meandering reaches (Reach 6, 7, 8, 9, and 10). Floodplain erosion was much higher than floodplain construction in the braided reaches than the meandering reaches (2.6 m versus 0.6 m difference). It is worth noting that with a pixel size of 5 m, many of these values are within the range of error of this analysis. The braided reaches changes via avulsion, which frequently erodes new, or more frequently, reactivates long-inactive channels. This increases the values for floodplain erosion. Floodplain construction is a much slower process and cannot keep pace. In the meandering reaches, floodplain erosion still outpaced floodplain construction by over a meter. This is due to lateral and down valley migration of meander bends, which slowly but steadily erode floodplain. This is a slower, less violent process of erosion that floodplain construction can keep pace with.

Values for channel change, despite being affected by river stage, were of a roughly similar magnitude. Overall, the river experienced 6 and 5.8 m of channel deposition and erosion, respectively. When divided by planform, the values for channel deposition and erosion were 8.1 and 8.5 m in the braided reaches and 3.7 and 2.7 m in the meandering reaches. Taken together, the Squamish River experienced more floodplain erosion than deposition, yet more channel deposition than erosion. The latter finding needs to be taken with caution, however, because it is influenced by the discharge at the time of the image. Therefore, it is better to view the values of channel change as approximate and not infer net deposition or erosion, as the focus of this thesis is first and foremost on floodplain change.

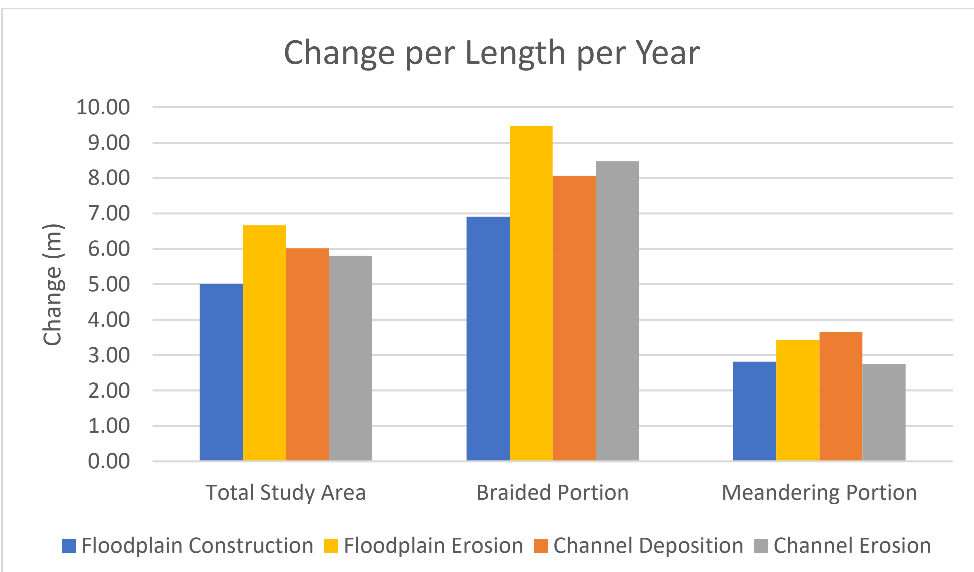
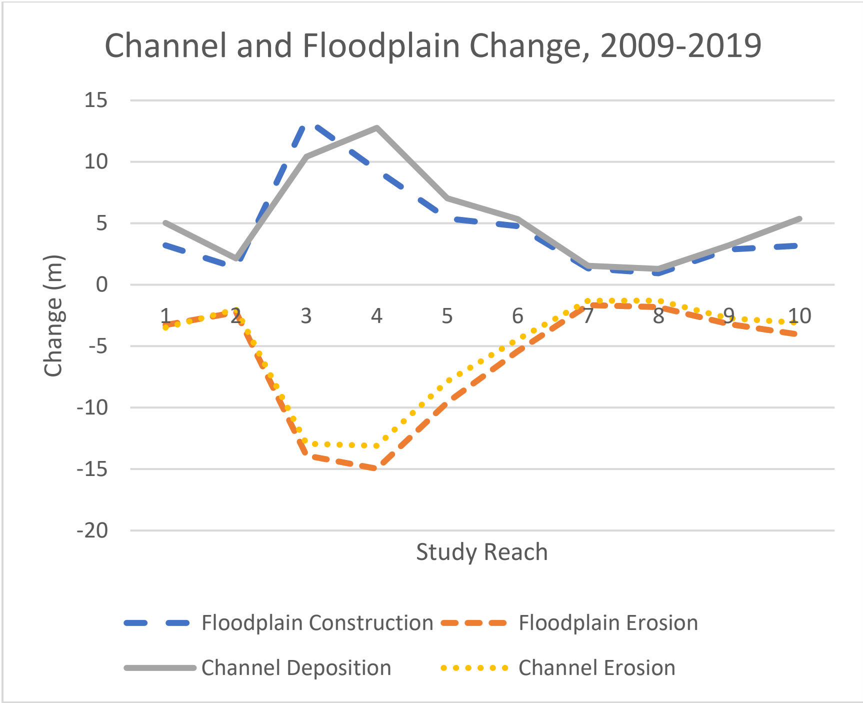


Figure 40: Floodplain and channel change per length per year over the entire study section, the braided/wandering reaches, and the meandering reaches



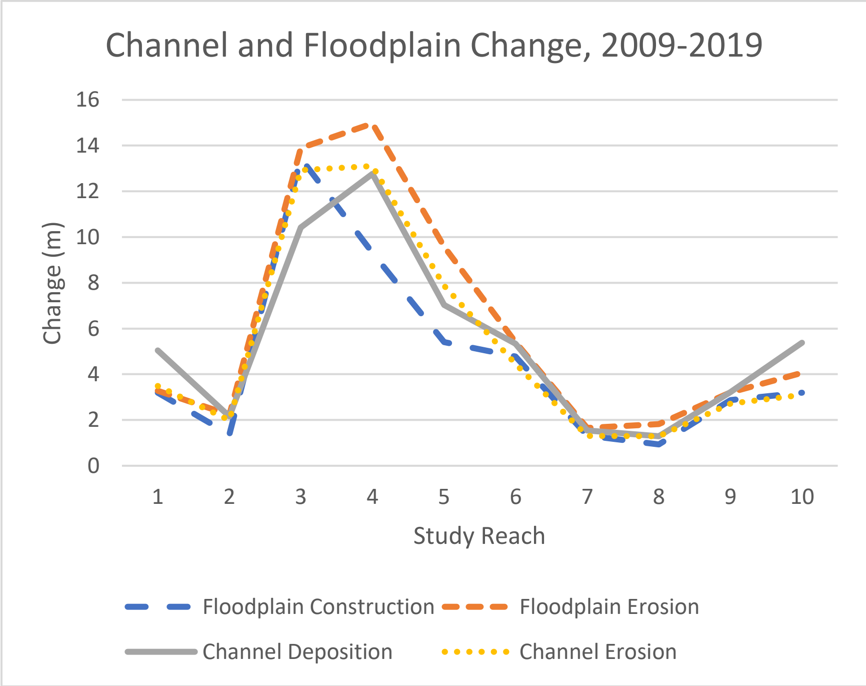


Figure 41: Measured change from 2009 to 2019 divided by years per reach, with the top graph showing erosion as negative and deposition as positive, and the bottom graph showing all on the same axis.

There is no steadily increasing or declining trend in floodplain change along the river. Instead, the pattern of is defined by the spatial configuration of the hypothesized drivers: slope, valley confinement, and sediment sources. Overall, reach 3 and 4 were the most active. These are both steep, braided, and have high sediment inputs from upstream sources. Reaches 1, 5 and 9 are also braided or partially braided in planform. They all have moderate to high levels of floodplain activity. The least active were reaches 2, 7 and 8. Reach 2 is confined and has low levels of activity, even though it has a high slope and sediment supply. Reaches 6, 7 and 8 are meandering reaches with low slope and low sediment input. As sediment supply decreases downstream, they become successively less active. Reach 10 is the estuary so it is considerably different than the other reaches as it is highly altered by human activity and subject to tidal activity as well. Below I review how each of the drivers contributed to the patterns of floodplain change along the entire length of the study section of Squamish River.

4.4.2 Slope

As expected, slope is one factor that drives floodplain change. As seen in Fig. 42, low slope is associated with lower levels of change, but a high slope does not neccesarily lead to high levels of change when all reaches are compared. The highest levels of floodplain change occurred in reaches 3, 4 and 5. These are not the steepest reaches, but they form a long and uninterrupted stretch of relatively high slope and are able to efficiently rework the sediment delivered in by reach 2. The steepest slope occurs in Reach 1, but the confinement of one-third of this reach lowers the floodplain activity.

The lowest amount of activity occurs in reaches 7 and 8, which have the lowerst slope. Stream power in these reaches is low and thus causes comparitively low levels of floodplain change. Reaches 2 and 9 are concave due to their sediment inputs, debris flows from Mount Cayley and Mount Garibaldi. Reach 2 is limited by valley confinement, and reach 9 is limited by the flood control structures, though the channel still has space to migrate laterally and downvalley, as it does.

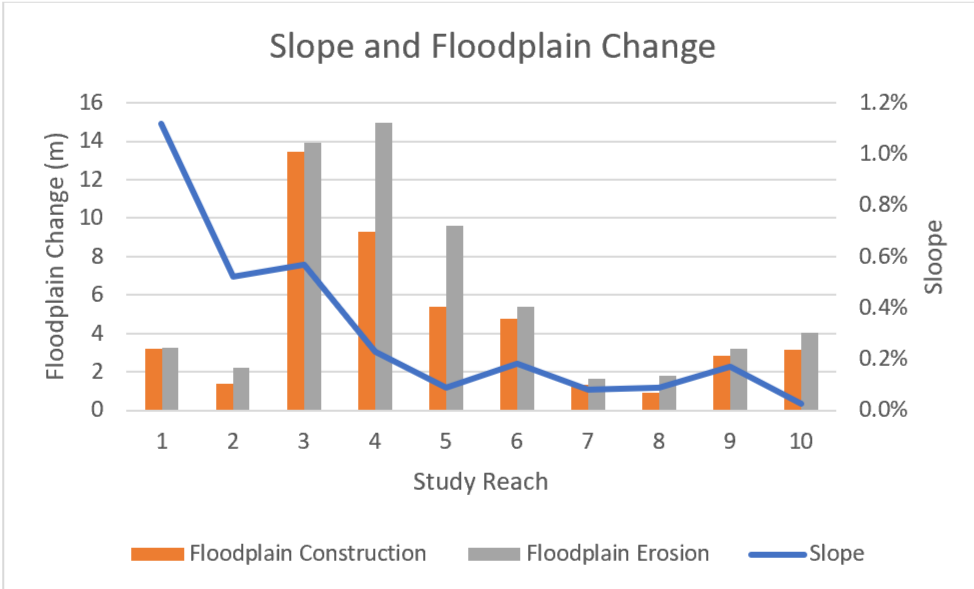


Figure 42: Slope of reach and the amount of floodplain construction and erosion measured between 2009 and 2019

4.4.3 Valley Confinement

Valley confinement is the second factor considered as a possible driver of floodplain change. Before discussing its relationship with the observed changes along the entire study section of Squamish River, it is worth to consider here in more detail what the metric means. The ratio of the average width of the active channel to the valley gives us a valley confinement metric (Figure 43).

Per this metric, reaches 1, 2, 3, 4, 9 and 10 all have values of over 50% confinement. However, this does not tell the whole story. Reach 1 is partially confined and partially unconfined. The active channel in Reach 3 spans almost the entire valley, yet is braided and able to undergo floodplain and channel change. The same is true of Reach 4. To better consider this nuance, the average wetted channel width (for simplicity referred to as "wetted channel width") was used to calculate an alternative metric of confinement. The wetted channel width is the area of the water divided by the length of the segment. This value was divided by the total valley to measure confinement of the channel. However, the reported wetted channel width is narrower than bankfull. For example, for the 2009-2019 change analysis, this was based off levels of water in 2009 and 2019 at 554 m^3 s^{-1} and 429 m^3 s^{-1} respectively. As a result, the estimated values do not encompass the whole channel, as bankfull is around 1000 $m^{3\ s-1}$ (at around the Brackendale gauge). This leads to underestimation of the level of confinement, especially if these values were to be compared to other studies that relied on bankfull values. This needs to be kept in mind when interpreting these results.

When considering the ratio of the wetted width to the entire valley, of the 6 reaches considered confined by the pervious metric, only three reaches have wetted channels confined with ratios of greater than or equal to 20%: Reach 2, Reach 9 and Reach 10. Reach 2 is confined by the alluvial fans coming off Endurance, Terminal, Shovelnose, and Turbid Creeks, impinged from both banks. Reaches 9 and 10 are confined by anthropogenic structures, the training dyke along the eastern bank. All other reaches should be considered unconfined.

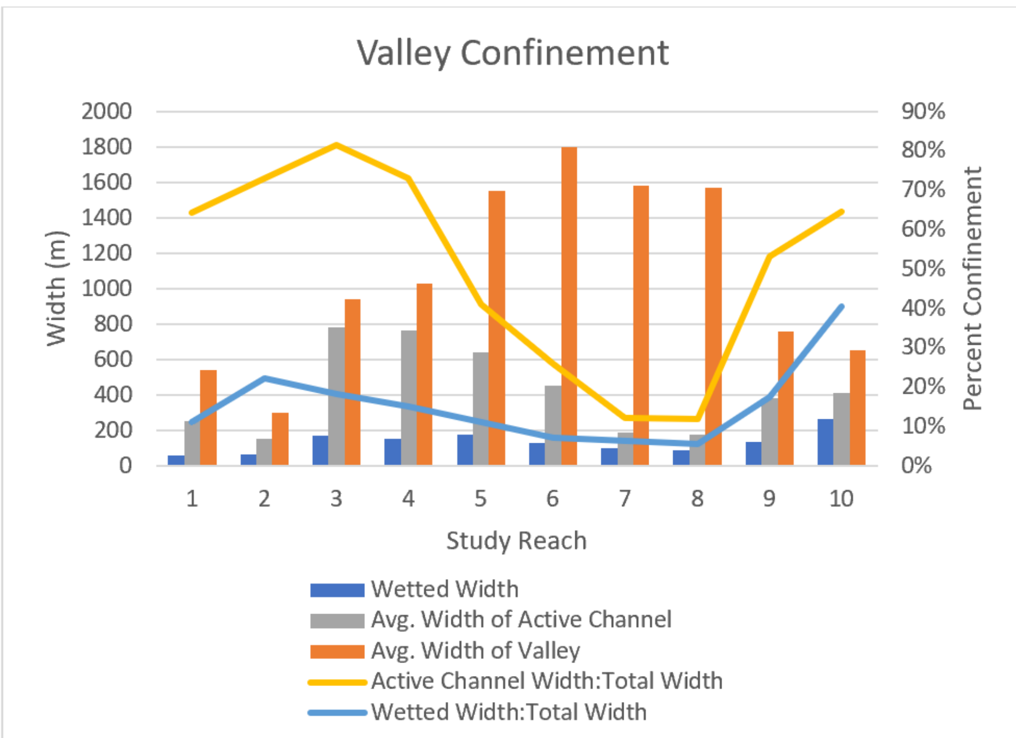


Figure 43: Values for Wetted Width, width of active channel, and total width of the valley for each reach, to illustrate valley confinement metrics

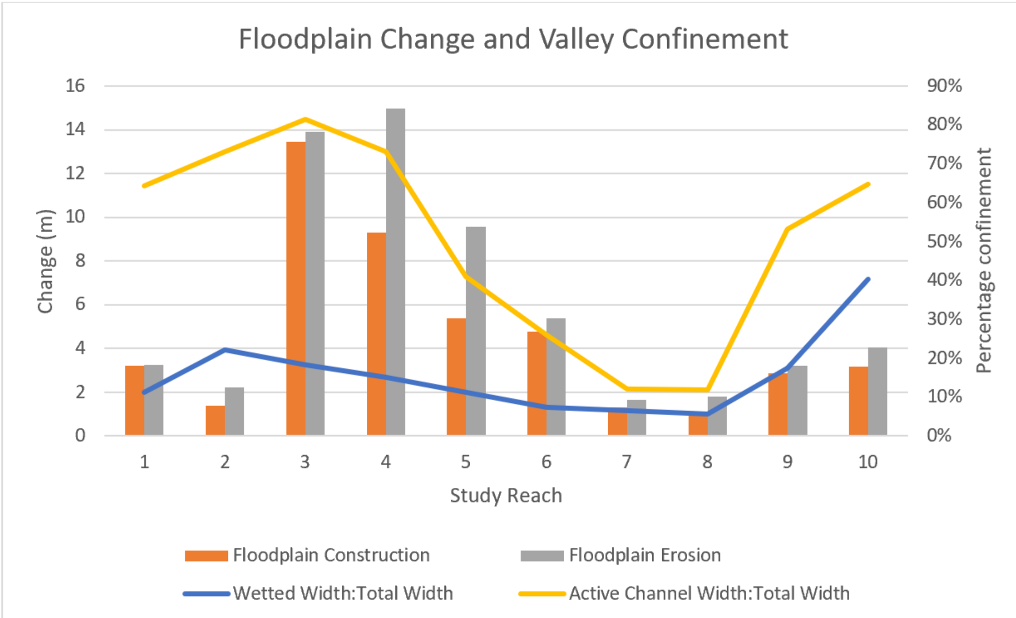


Figure 44: Floodplain change per study reach with valley confinement metrics

After establishing which reaches are confined, the influence of this factor on floodplain change can be considered (Fig. 44). The highest levels of floodplain erosion in the valley occurred in reach 4 the Avulsion Reach. The active channel does span the entire valley in portions of this reach, but the channel is not limited in movement. Normally in this reach, floodplain construction would keep pace with floodplain erosion, but this reach was subject to the large avulsion which scoured away vast amounts of floodplain in a short amount of time. Reach 3, the Braided Reach, was also very active. The active channel spans the entire valley, making it appear confined, but the braided planform of this reach allows it to move freely about the valley. The lowest levels of floodplain activity take place in reaches 7 and 8, which are the least-confined channels, with values of 6% wetted channel and 12% active channel confinement. The channel is able to move freely about the valley, but does not. In conclusion, valley confinement can limit floodplain activity, but having space does not guarantee activity.

4.4.4 Sediment Supply

Sediment supply is the last important factor in floodplain reworking considered in this thesis. It needs to be emphasized that, because of the qualitative nature of my assessment, the results are by far most uncertain and subjective. However, in reality, no good metric exists that would capture accurately this phenomenon.

As with the other two factors, sediment supply alone cannot explain the river-scale pattern. Reach 1 has the slope and therefore the stream power to move sediment, but not space on the floodplain to store it. The active areas of this reach are downstream of the Elaho confluence, where the valley opens up more. Conversely, Reach 2 has high amount of channel sediment levels but not enough stream power to move it – it just has too much sediment from out-of-channel sources that even with high stream power, it can only move sediment out of the reach, not erode the floodplain. However, arguably, it appears that the pattern of floodplain change tracks sediment supply as well or even better than any of the other two factors. For example, Reaches 3, 4 and 5 had the highest levels of floodplain reworking. All of these reaches receive ample sediment from upstream reaches and varying levels of sediment from tributaries and have the stream power to move it. Reach 3 is braided so channels are constantly being abandoned and reactivating, allowing for lots of sediment storage and movement. Reach 4 receives sediment from reach 3 but also entrained a lot of its own when the channel avulsed. Since floodplain erosion outpaced floodplain construction so much in Reach 4, Reach 5 also received a lot of sediment. At Reach 6, the planform transitions from braided to meandering. Sediment supply lessens from out of channel sources and the in-channel sediment sources are stored along the channel as stream power decreases. Reaches 7 and 8 have the lowest level of floodplain activity and the lowest levels of sediment from both in and out of channel sources. Reach 9 receives a new influx of sediment from the Cheekye Fan and the Cheakamus River and fan and thus has higher levels of activity.

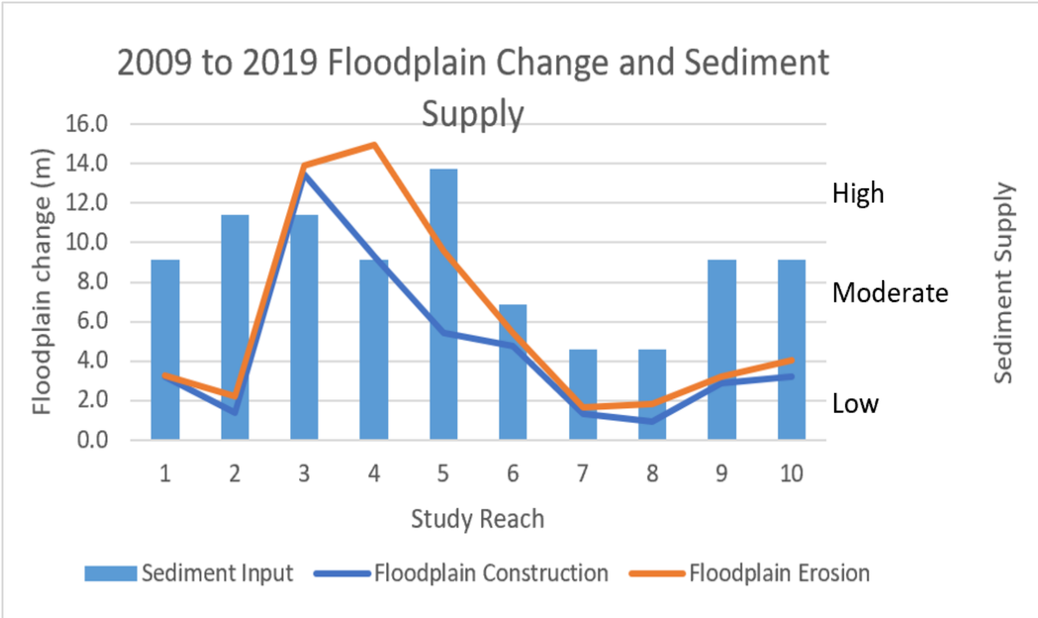


Figure 45: Floodplain change and average sediment supply

CHAPTER 5: CONCLUSIONS AND IMPLICATIONS

The overarching objective of this thesis was to examine the spatial patterns and drivers of floodplain dynamics in the Squamish River over the last decade by mapping floodplain change, characterizing floodplain change, and determining the extent to which slope, valley confinement, and sediment supply affect the floodplain construction and erosion rates and channel planform in its braided, wandering and meandering reaches. The calculated rates of change were high, with construction in the range of 0.9 m – 13.4 m per year and erosion 1.7 – 15 m per year.

For better context, this can be compared with data on lateral erosion collected in other fluvial systems. One valuable source of such information is the global database of channel erosion and accretion rates published by Langhorst and Pavelsky (2020). This study used Google Earth Engine classify water and land from satellite images to determine global observations of riverbank erosion for rivers wider than 150 m. Not all of this study's data can be directly compared to this global data set. In particular, floodplain change is not the same as channel change. Therefore, only the values derived from the meandering reaches of Squamish River are applicable. In these cases, floodplain erosion is closely related to bank erosion. When such a comparison is made, it is clear that this study's values are at least twice the mean global erosion rates (1.52 m; Langhorst and Pavelsky, 2020). As this thesis discusses, Squamish River has relatively little human disturbance except for the downstream-most reach, and especially in the upper part of the watershed. This shows that Squamish River is a naturally very dynamic gravel-bed channel.

These high rates of floodplain change have important implications for the human population along the river as well as the riverine ecosystem. Rapid erosion in the laterally active reaches poses a hazard to population and infrastructure. Importantly, the highest densities of human population are concentrated in the distal reaches of Squamish River, along reaches 9 and 10. Not only do these reaches have lower erosion rates, but they also have erosion and flood control structures. At the same time, this does not mean that floodplain change has no bearing on human population in this watershed. As described in the results of each reach, the floodplain is home to Indigenous Reserves are located outside of the areas protected by dykes. These communities are most vulnerable to flooding and erosional activities (NHC, 2018).

In addition to natural hazards to human population, floodplain change on Squamish River will also have implications for in-channel and floodplain habitats and the species that rely on them. For example, rapid lateral erosion that outpaces re-establishment of the floodplain forest means that many of the side channels used by fish as important juvenile habitat will be devoid of canopy cover and shade. This creates a different habitat type than stable floodplain channels with mature forest canopy. Lateral erosion can affect tributary habitat, important for spawning, as in the described case of Shovelnose Creek.

These social and ecological challenges that arise from floodplain change may become more significant with predicted increases in mean annual flow by the end of the century, due to both the increased melting of glacial ice in the spring, and an increase in discharge from rain and subsurface flow due to fall storms. While discharge from fall storms will increase, the freshet peak will decrease and occur earlier as glaciers and snowpack decrease in size. The highest floods will occur when a cool, wet winter with heavy snowpack accumulation is followed by a warm, wet spring, causing rain on snow events and increased melting and runoff (Wild, 2023). Bauch and Hickin (2011) found that intensifying storms in Squamish River contributed to increased floodplain erosion over during the period 1958 – 2007. This raises important questions about the consequences of the ongoing climate change as well as the impacts of the continued development of the watershed due to rapid population growth. Another consequence of changes to land use and climate patterns is potential changes to sediment delivery rates. Rates of warming are amplified at higher elevations, leading to decreased snow accumulation and increased glacial melt. In British Columbia, sediment yields often increase due to continuous erosion of glacial till deposits within river valleys as glaciers melt (Wild, 2023).

Another central conclusion of this thesis is that no single driver can satisfactorily explain the observed pattern of floodplain change. This emphasizes the notion that rivers are complex systems, with multiple controlling factors and multiple ways to adjust to changing governing conditions. Importantly, the drivers are either entirely related to phenomena outside of the river channel itself (e.g., valley confinement, external sediment sources), or only modifiable to some extent within a short time horizon (e.g. channel slope is strongly influenced by the valley slope). Therefore, any analysis of river systems like Squamish require that the whole surrounding landscape is considered (e.g., Cienciala et al., 2020; Cienciala, 2021). In addition, these observations imply that none of the reaches can be fully understood in isolation. As the analysis of sediment supply conditions highlights, what takes place in one reach upstream may have important consequences for the reach or reaches downstream.

Finally, an additional important take away from this study is that that the interval over which floodplain change in measured has a strong influence on the estimated values. There are two potential sources of this difference. First, it is possible that the larger values of change in the year-to-year approach are caused by errors. Essentially, the magnitude of error, especially the portion of error related to imperfect georectification, is likely to be similar whether analyzing images for two subsequent years or images showing change over a decade. At the same time, the magnitude of floodplain change is much lower in the first case, possibly of the same order of magnitude as the error. However, it is expected that the errors in multiple year-to-year comparisons would, to some extent, cancel each other out. Therefore, the large discrepancy between the values estimated based on year-to-year changes vs. 2009-2019 changes cannot alone be attributed to this factor. The second possible source of this difference is that a decade may be long enough time for erosion to erase effects of temporary floodplain development and the other way around, erosion being obscured by floodplain development. This would be a similar finding to that related to compensatory scour and fill, which reduces the estimated value of channel change as time increment between measurements increases (Lindsay and Ashmore, 2002). The potential for processes to be missed (not captured) is related to how quickly floodplain can establish. If this classification pertained only to floodplain with mature forest cover, that would be impossible. Even if highly productive temperate rainforest of coastal British Columbia, forest requires decades to develop. However, this classification considers areas covered by shrubs as vegetated floodplain as long as they are dense enough to have high NDVI value. Such shrubby surfaces could, feasibly, develop within a few years. Taken together, it is likely that each of these two factors contributes to some extent to the deviation between year-to-year and decadal changes.

REFERENCES

Ashworth, P.J., Best, J.L. and Jones, M., 2004. Relationship between sediment supply and avulsion frequency in braided rivers. Geology, 32(1), pp.21-24.

Bauch, G.D. 2009. Intensifying Storms, Floods, and Channel Change: Squamish River, BC (1956-2007). Thesis submitted in partial fulfillment in the Department of Geography, University of British Columbia.

Bauch, G.D., Hickin, E.J., 2011. Rate of floodplain reworking in response to increasing storm-induced floods, Squamish River, south-western British Columbia, Canada. Earth Surf. Process. Landforms 36, 872–884. https://doi.org/10.1002/esp.2115

Beaudry, P.G., Hogan, D.L., Schwab, J.W., 1990. Hydrologic and geomorphic considerations for silvicultural investments on the Lower Skeena River floodplain. Forest Resource Development Agreement Report (Victoria, BC).

Beechie, T.J., Liermann, M., Pollock, M.M., Baker, S., Davies, J., 2006. Channel pattern and river-floodplain dynamics in forested mountain river systems. Geomorphology, Mountain Rivers Part I: Watershed Scale Processes and Channel Morphology 78, 124–141. https://doi.org/10.1016/j.geomorph.2006.01.030

Biron, P., Buffin-Bélanger, T., Larocque, M., Choné, G., Cloutier, C., Ouellet, M.A., Demers, S., Olsen, T., Eyquem, J. 2014. Freedom Space for Rivers: A Sustainable Management Approach to Enhance River Resilience. Environmental Management. 54. 10.1007/s00267-014-0366-z.

Brierley, G.J., 1989. River planform facies models: the sedimentology of braided, wandering and meandering reaches of the Squamish River, British Columbia. Sedimentary Geology 61, 17–35. https://doi.org/10.1016/0037-0738(89)90039-0

Brierley, G.J., Hickin, E.J., 1991. Channel planform as a non-controlling factor in fluvial sedimentology: the case of the Squamish river floodplain, British Columbia. Sedimentary Geology 75, 67–83. https://doi.org/10.1016/0037-0738(91)90051-E

Brierley, G.J., Hickin, E.J., 1992. Floodplain development based on selective preservation of sediments, Squamish River, British Columbia. Geomorphology 4, 381–391. https://doi.org/10.1016/0169-555X(92)90033-K

Brooks, G. R. 1992. Aspects of Post-Glacial Sediment Supply and Its Control upon the Morphology of Squamish River, Southwestern British Columbia. Thesis submitted in partial fulfillment in the Department of Geography, Simon Fraser University.

Brooks, G.R., 1994. The fluvial reworking of Late Pleistocene drift, Squamish River drainage basin, southwestern British Colombia. Géographie physique et Quaternaire, 48(1), pp.51-68.

Brooks, G.R., Hickin, E.J., 1991. Debris avalanche impoundments of Squamish River, Mount Cayley area, southwestern British Columbia. Canadian Journal of Earth Sciences 28, 1375–1385.

Bury, H.G. Plan of Cheakamus Reserve. Aug. 1918, Archives / First Nations Reserves – Western Canada, Microfiche number: 84275, Item: 2751, Item ID number: 849. September 15, 2023. http://central.bac-lac.gc.ca/.redirect?app=fonandcol&id=3719648&lang=eng

Church, M., 2006. Bed material transport and the morphology of alluvial river channels. Annu. Rev. Earth Planet. Sci., 34, pp.325-354.

Church, M., 2015. Channel stability: Morphodynamics and the morphology of rivers, in: Rowinski, P., Radecki-Pawlik, A. (Eds.), Rivers–Physical, Fluvial and Environmental Processes. Springer, pp. 281–321.

Church, M., Ham, D., 2004. Atlas of the alluvial gravel-bed reach of Fraser River in the Lower Mainland showing channel changes in the period 1912-1999. Department of Geography, The University of British Columbia

Cienciala, P., Bernardo, M.M., Nelson, A.D. and Haas, A.D., 2021. Sediment yield from a forested mountain basin in inland Pacific Northwest: Rates, partitioning, and sources. *Geomorphology*, *374*, p.107478.

Cienciala, P., Nelson, A.D., Haas, A.D. and Xu, Z., 2020. Lateral geomorphic connectivity in a fluvial landscape system: Unraveling the role of confinement, biogeomorphic interactions, and glacial legacies. *Geomorphology*, *354*, p.107036.

Cienciala, P., Pasternack, G.B.. 2017. Floodplain inundation response to climate, valley form, and flow regulation on a gravel-bed river in a Mediterranean-climate region. *Geomorphology*, *282*, p.1-17.

Collins, B.D., Montgomery, D.R., Fetherston, K.L. and Abbe, T.B., 2012. The floodplain large-wood cycle hypothesis: A mechanism for the physical and biotic structuring of temperate forested alluvial valleys in the North Pacific coastal ecoregion. *Geomorphology*, *139*, pp.460-470.

Cruden, D.M. and Lu, Z.Y., 1992. The rockslide and debris flow from Mount Cayley, BC, in June 1984. Canadian Geotechnical Journal, 29(4), pp.614-626.

Desloges, J.R. and Church, M.A., 1989. Wandering gravel-bed rivers. *Canadian Geographer/Le Géographe canadien*, *33*(4), pp.360-364.

Ékes, C., Friele, P., 2003. Sedimentary architecture and post-glacial evolution of Cheekye fan, southwestern British Columbia, Canada. Geological Society, London, Special Publications 211, 87–98. https://doi.org/10.1144/GSL.SP.2001.211.01.08

Evans, S.G. and Brooks, G.R., 1992. Prehistoric debris avalanches from Mount Cayley volcano, British Columbia: Reply. Canadian Journal of Earth Sciences, 29(6), pp.1343-1347.

Fath, J., Clague, J.J., Friele, P., 2018. Influence of a large debris flow fan on the late Holocene evolution of Squamish River, southwest British Columbia, Canada. Canadian Journal of Earth Sciences 55, 331–342.

Friele, P. A., J. J. Clague, K. Simpson, and M. Stasiuk. 2005. Impact of a Quaternary Volcano on Holocene Sedimentation in Lillooet River Valley, British Columbia. Sedimentary Geology 176 (3–4): 305–22. https://doi.org/10.1016/j.sedgeo.2005.01.011.

Friele, P., 2013. Weather thresholds and Operation Safety Planning, Turbid Creek, Mount Cayley, Squamish River Valley, BC.

Friele, P., Clague, J. 2009. Paraglacial geomorphology of Quaternary volcanic landscapes in the southern Coast Mountains, British Columbia. Geological Society, London, Special Publications. 320. 219-233. 10.1144/SP320.14.

Friele, P.A., Clague, J.J., 2002. Younger Dryas readvance in Squamish river valley, southern Coast mountains, British Columbia. Quaternary Science Reviews 21, 1925–1933. https://doi.org/10.1016/S0277-3791(02)00081-1

Friele, P.A., Clague, J.J., 2009. Paraglacial geomorphology of Quaternary volcanic landscapes in the southern Coast Mountains, British Columbia. Geological Society, London, Special Publications 320, 219–233. https://doi.org/10.1144/SP320.14

Friele, P.A., Ekes, C., Hickin, E.J., 1999. Evolution of Cheekye fan, Squamish, British Columbia: Holocene sedimentation and implications for hazard assessment. Can. J. Earth Sci. 36, 2023–2031. https://doi.org/10.1139/e99-090

Fryirs, K. A., & Brierley, G. J. (2012). Floodplain Forms and Processes. *Geomorphic Analysis of River Systems*, 155–173. https://doi.org/10.1002/9781118305454.ch9

Fryirs, K.A., Wheaton, J.M. and Brierley, G.J., 2016. An approach for measuring confinement and assessing the influence of valley setting on river forms and processes. *Earth Surface Processes and Landforms*, *41*(5), pp.701-710.

Glenn, E.P., Huete, A.R., Nagler, P.L. and Nelson, S.G., 2008. Relationship between remotely-sensed vegetation indices, canopy attributes and plant physiological processes: What vegetation indices can and cannot tell us about the landscape. Sensors, 8(4), pp.2136-2160.

Ham, Darren Gary. 2005. Morphodynamics and Sediment Transport in a Wandering Gravel-Bed Channel: Fraser River , British Columbia. Thesis submitted in partial fulfillment in the Department of Geography, University of British Columbia.

Hauer, F. Richard, Harvey Locke, Victoria J. Dreitz, Mark Hebblewhite, Winsor H. Lowe, Clint C. Muhlfeld, Cara R. Nelson, Michael F. Proctor, and Stewart B. Rood. 2016. "Gravel-Bed River Floodplains Are the Ecological Nexus of Glaciated Mountain Landscapes." Science Advances 2 (6): 1–14. https://doi.org/10.1126/sciadv.1600026.

Hickin, E.J., 1979. Concave-bank benches on the Squamish River, British Columbia, Canada. Canadian Journal of Earth Sciences, 16(1), pp.200-203.

Hickin, E.J., 1984. Vegetation and river channel dynamics. Canadian Geographer/Le Géographe canadien 28, 111–126.

Hickin, E.J., 1989. Contemporary Squamish River sediment flux to Howe Sound, British Columbia. Can. J. Earth Sci. 26, 1953–1963. https://doi.org/10.1139/e89-165

Hickin, E.J., Sichingabula, H.M., 1988. The geomorphic impact of the catastrophic October 1984 flood on the planform of Squamish River, southwestern British Columbia. Can. J. Earth Sci. 25, 1078–1087. https://doi.org/10.1139/e88-105

Historic Hydrologic Data for Squamish River near Brackendale (08GA022) [British Columbia] from the Water Survey of Canada (WSC) within the National Hydrologic Services, Environment and Climate Change Canada

InStream Fisheries Research Inc. 2019. Squamish River Central Restoration Effectiveness Monitoring, found within Central Squamish Estuary Restoration Project Final Report: 36-76.

Jakob, M. 1996. Morphometric and Geotechnical Controls of Debris Flow Frequency and Magnitude in Southwestern British Columbia. Thesis submitted in partial fulfillment in the Department of Geography, University of British Columbia.

Jakob, M., Friele, P. 2010. Frequency and magnitude of debris flows on Cheekye River, British Columbia. Geomorphology. 114. 382-395. 10.1016/j.geomorph.2009.08.013.

Knox, R.L., Wohl, E.E., Morrison, R.R., 2022. Levees don’t protect, they disconnect: A critical review of how artificial levees impact floodplain functions. Science of The Total Environment 837, 155773. https://doi.org/10.1016/j.scitotenv.2022.155773

Langhorst, T., Pavelsky, T., 2023. Global Observations of Riverbank Erosion and Accretion From Landsat Imagery. Journal of Geophysical Research: Earth Surface 128, e2022JF006774. https://doi.org/10.1029/2022JF006774

Lindsay, J.B. and Ashmore, P.E., 2002. The effects of survey frequency on estimates of scour and fill in a braided river model. *Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group*, *27*(1), pp.27-43.

Make a Watershed Model. Squamish Rivers and Estuary Educational Resources, Squamish River Watershed Society. https://www.squamishwatershed.com/uploads/1/1/2/1/11216935/ make_a_watershed_model_og2_4.pdf

Morrison, R., Simonson, K., McManamay, R., Carver, D. 2023. Degradation of floodplain integrity within the contiguous United States. Communications Earth & Environment. 4. 10.1038/s43247-023-00877-4.

Naiman, R.J., Decamps, H., McClain, M.E., 2010. Riparia: ecology, conservation, and management of streamside communities. Elsevier.

Northwest Hydraulic Consultants 2018. Squamish-Lillooet Regional District flood hazard mapping and risk assessment Upper Squamish. Final Report. (No. NHC Ref No. 3003329). Vancouver, BC.

Opperman, J., & Moyle, P., Larsen, E., Florsheim, J., Manfree, A. 2017. Floodplains: Processes and Management for Ecosystem Services. 10.1525/9780520966321.

Pacific Salmon Foundation, 2005. Squamish River Watershed Salmon Recovery Plan (Report prepared by Golder Associates Lts, submitted to Pacific Salmon Foundation).

Paige, A.D., and Hickin, E.J,. 2000. Annual Bed-Elevation Regime in the Alluvial Channel of the Squamish River, Southwestern British Columbia. Earth Surface Processes and Landforms 25, 991-1009

Pojar, J., Klinka, K., Dermarchi, D.A., 1991. Coastal western hemlock zone, in: Ecosystems of British Columbia. Citeseer, pp. 95–111.

Reimer, R./Yumķs, 2011. The Mountains and Rocks are Forever: Lithics and Landscapes of the Skwxwú7mesh Uxwumixw. Thesis submitted in partial fulfillment in McMaster University

Rood, K.M., Hickin, E.J., 1989. Suspended-sediment concentration and calibre in relation to surface-flow structure in Squamish River estuary, southwestern British Columbia. Canadian Journal of Earth Sciences 26, 2172–2176.

Squamish Atlas, 2021. Kwi Awt Stelmexw. https://squamishatlas.com/

Squamish River Watershed Society. 2 May 2008. Squamish Estuary/Mamquam Blind Channel Restorations 2007/2008. Final Report

Squamish River Watershed Society. June 2014. Squamish River Watershed Society Blue Carbon Project: Phase One Background Report.

Stanford, J.A., Lorang, M.S., Hauer, F.R., 2005. The shifting habitat mosaic of river ecosystems. Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen 29, 123–136.

Steelhead Society of BC. Not dated, "Shovelnose Creek Off-Channel Complex Berm Repair."

The Great Flood Story. Retrieved from https://www.nchkay.com/great-flood-story/

Tobe, E. 2020. Central Squamish Estuary Restoration Project Final Report. Squamish River Watershed Society.

Tockner, K., Stanford, J.A., 2002. Riverine flood plains: present state and future trends. Environmental Conservation null, 308–330. https://doi.org/10.1017/S037689290200022X

Whited, D.C., Lorang, M.S., Harner, M.J., Hauer, F.R., Kimball, J.S., Stanford, J.A., 2007. Climate, hydrologic disturbance, and succession: drivers of floodplain pattern. Ecology 88, 940–953.

Whiting, P.J. and Bradley, J.B., 1993. A process-based classification system for headwater streams. *Earth Surface Processes and Landforms*, *18*(7), pp.603-612.

Wild, A.L., Kwoll, E., Lintern, D.G., Fargey, S., 2023. Fluvial Response to Climate Change in the Pacific Northwest: Skeena River Discharge and Sediment Yield. Water 15, 167qua

Wooldridge, C.L., Hickin, E.J., 2005. Radar Architecture and Evolution of Channel Bars in Wandering Gravel-Bed Rivers: Fraser and Squamish Rivers, British Columbia, Canada. Journal of Sedimentary Research 75, 844–860. https://doi.org/10.2110/jsr.2005.066