In-River Gravel Mining as a Flood Mitigation Tool: Impacts on Pacific Salmon and Alternative Solutions

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Chilliwack River near Slesse Park, Chilliwack. Photo by Suman Bhattacharyya.

Disclaimer

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Executive Summary

Gravel mining is a prevalent practice in many river systems, including the Chilliwack/Vedder River in British Columbia. While it is essential for various construction and infrastructure needs, gravel mining significantly impacts river ecosystems, particularly salmon habitats. This report presents a literature review that examines the effects of gravel mining on salmon habitat and outlines alternative nature-based flood management techniques that can be implemented in gravel bed systems, to lower the need for regular gravel mining.

Impacts on Salmon Habitat

- Gravel mining disrupts the natural riverbed structure, destroying critical spawning and rearing habitats for salmon, affecting the survival of eggs and alevin.
- Changes in channel morphology also affect flow and sediment transport and can reduce habitat diversity and quality.
- Mining operations can increase sedimentation rates, leading to sediment loading in the river. This sediment can smother spawning beds, reduce water quality, and alter the flow dynamics, further impacting salmon.
- Clearing of in channel woody debris and clearing of riparian cover during mining and transportation reduces the quality of rearing habitat.

Current flood management techniques in the Chilliwack/Vedder River include flood infrastructures like dikes, bank protection using riprap, and biennial extraction of gravel from the channel to maintain a 200-year flood level.

Other nature-based flood and sediment management techniques that can be implemented in the river basin include:

- Reclaim the Sumas Lake with strategic relocation to higher areas during flood season (see page 19).
- Rehabilitate floodplains to improve flood resilience and provide additional habitat for salmon. Floodplain restoration involves reconnecting rivers with their natural floodplains and wetlands to enhance flood storage and habitat quality (see page 20).
- Manage sediment upstream and in headwaters to reduce erosion and landslides, and construct healthy riparian buffers along watercourses into the lowlands/floodplains (see page 21).
- Reduce and slowly pause development in the floodplain OR implement building policies that allow for safe and temporary inundation and adopt flood-resilient building practices (see page 21).
- Adopt 'living with floods' practices as exemplified by many global floodplain communities (see page 21).

Addressing the impacts of gravel mining on salmon habitats requires a combination of restoration efforts and proactive river management practices. By implementing effective flood and sediment management techniques, it could be possible to mitigate negative effects and support the recovery and sustainability of salmon populations. Collaborative efforts involving stakeholders, conservation organizations, and regulatory agencies, are essential to achieving these goals and ensuring the long-term health of river ecosystems. Additionally, it is important to amplify the voice of the Semá:th and other Stó:lō communities in flood management decision

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1. Introduction

Mining of instream sand and gravel for commercial and industrial usage is a global phenomenon with diverse impacts ranging from modifying channel morphology, and sediment transport to affecting aquatic habitats of macroinvertebrates and fish. Sediments found in floodplains and channels in the form of sand, gravel, cobbles, and boulders provide a ready and cheap source of raw material for the construction industry for building roads, railways, dams, buildings, and other structures. Mining of these materials, often termed aggregate mining, is widespread in North America, especially in previously glaciated river basins of the Pacific Northwest. With a history of glaciation coupled with different episodes of mountain building associated with tectonic processes, the rivers in this region are reliable sources of quality gravel and have been exploited historically. Importantly, these rivers provide critical habitat for different aquatic species including the Pacific wild salmon. For fish species like salmon, gravel is essential in providing valuable spawning and rearing habitat before they migrate to the ocean. Salmon use gravel beds in streams and lakes as spawning grounds and after hatching the gravel nests or redds provide the rearing habitats and protection from predators.

Coarse sediment (e.g., cobbles, gravels, pebbles) supplied from upstream areas and riverbanks can lead to channel bed aggradation which reduces the channel's capacity to convey floodwater and ultimately increases flood risk. Removing instream sediment to increase the channel depth has long been debated as a flood control method in gravel-bed rivers. It has been proven that even during gravel-deficit years (when gravel supply from upstream is lower than downstream transport), gravel mining has been proposed and takes place under the banner of 'flood control' (Rosenau, 2023). In addition, the mining of gravel during peak salmon spawning years is also common, causing conflict between mining agencies and salmon conservationists (Bridge, 2010; McSheffrey & Johnson, 2023).

To better protect salmon populations and their habitats, it is crucial to understand the impact of instream mining on salmon. Coupled with impacts of global warming and projected higher frequency and volume of precipitation, the nature and impacts of floods are changing globally and being experienced regionally. A major tributary that has high salmon values and is a frequent target for gravel extraction as flood remediation is the Chilliwack-Vedder River system in the Lower Fraser watershed. Through a general literature review and a more specific case study, we will explore the known impacts of gravel extraction on a glacial river system and provide alternatives and suggestions for flood adaptations in the Chilliwack-Vedder River.

2. Review questions

Human intervention since European colonization in the Lower Fraser region, has rapidly modified the landscape by changing land use and cover by clearing old-growth forests, ditching, draining and diking wetlands and floodplains for agriculture and city-building, and dam construction affecting several critical habitats including pacific salmon. With no surprise, the salmon population has declined markedly in these river basins. It's therefore crucial to understand the impacts of such interventions on salmon populations. Because gravel mining impacts on stream morphology and salmon habitat have been documented, it's often contested as a flood control method. To address this sustainability threat, we want to answer the following questions: What are the impacts of gravel extraction on fish and fish habitat? Assuming that gravel extraction is not the only tool in managing floods in glaciated river basins, what are some other options?

3. Method

To answer these questions, a review of past studies is presented below. This review is based on a thorough search in several literature databases using the PRISMA framework. Different sets of search strings were developed for each question as the questions are mutually exclusive. Databases like Google Scholar, Web of Science, and Scopus are the primary sources considered first, but considering the limited number of studies, gray literature like published reports, master's theses, and PhD dissertations were also considered. Considering the *lack of studies directly investigating gravel mining impacts on salmon habitat or survival*, a general summary of past research is presented here. Similarly, for the identification of potential flood mitigation strategies, a summary is presented mainly focusing on nature-based solutions that have multiple co-benefits.

4. In-channel gravel mining as a flood mitigation method

4.1. Types of in-channel gravel mining

Different techniques have been used to extract gravel from riverbeds with varied impacts on channel morphology, aquatic communities, and salmon habitat. Here, most of the common practices that have been used are briefly introduced to aid the discussion on their impacts on salmon habitat.

Skimming or scalping of gravel bars (Fig. 1) is a widely used practice for removing gravel in most parts of British Columbia (Weatherly and Michael Church 1999, Rampel and Church, 2009), Alaska, Washington, and Californian rivers (Collins, 1995; Norman et al., 1998) and it's practiced mainly during dry or low-flow periods when the gravel bars are exposed (Kondolf 1994, 2002). Historically, bar scalping often left the modified bar area with an irregular surface where the stranding of migrating salmons in shallow holes after high flows can occur (Collins, 1995) affecting spawning success. Scalping can also lead to featureless flat surfaces, loose gravel and sand (Rampel, 2004) that can modify the preexisting riffle-pool dynamics and hydraulic control of the bar top (Kondolf et al., 2002).

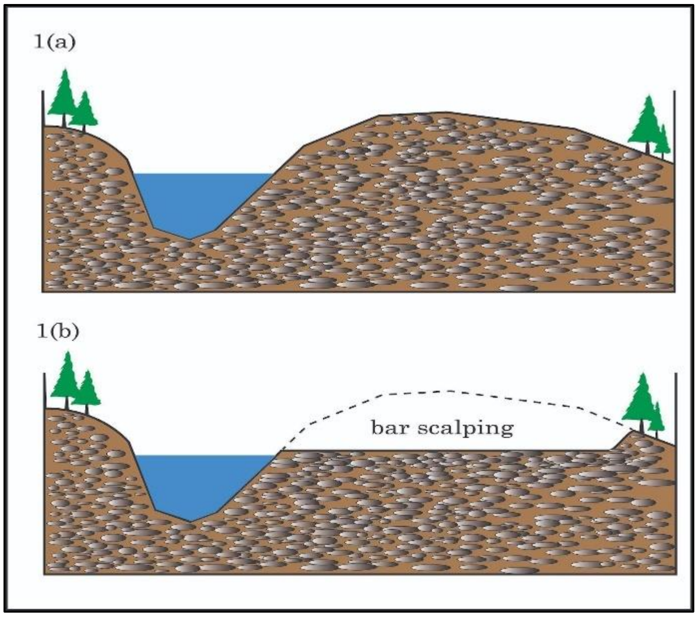

Figure 1 *Bar scalping modifies the existing river profile by removing the bar top and replacing it with a flat surface. (From Kondolf, 1994)*

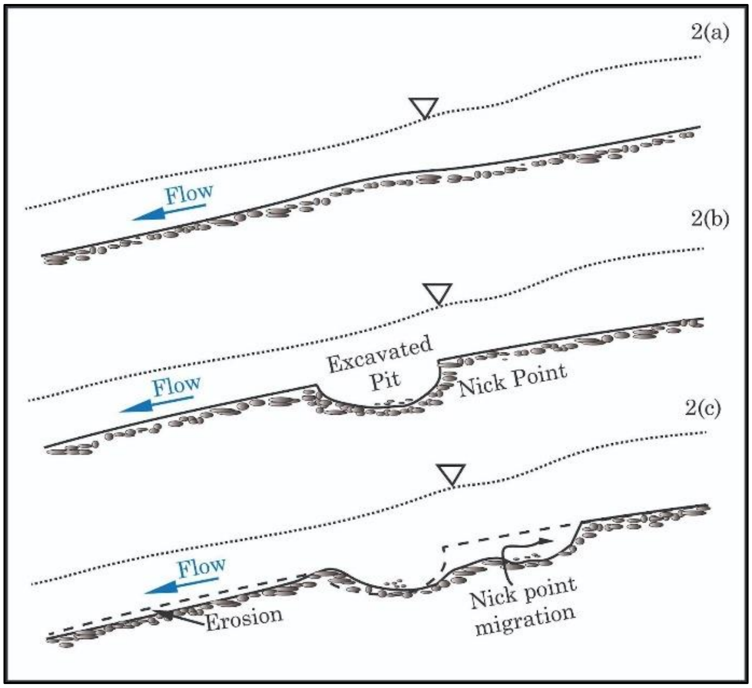

Figure 2 *Instream pit excavation leading to channel incision by headward migration of the nick point. (From Kondolf, 1994)*

Like other forms of mining, the *excavation of pits* to remove gravel is also common to many PNW rivers (Collins, 1995; Kondolf, 2002). Dry pits are excavated in seasonal or ephemeral streams using excavators when the riverbed is dry or at bar top (Collins, 1995). Wet pits are excavated below the water line using a hydraulic excavator to extract gravel from active channels (Kondolf et al., 2002). Another form of wet pit mining involves excavation of linear instream trenches (Fig. 2) to remove gravels and to create missing pool habitats (Kondolf, 2002). These pits often leave the channel with sharp pit margins that can propagate upstream by headward erosion during high flows, causing bed-lowering and channel degradation (Fig. 3). Sometimes, a pit is excavated beside or below the gravel bar to avoid negative impacts (Kondolf, 1997).

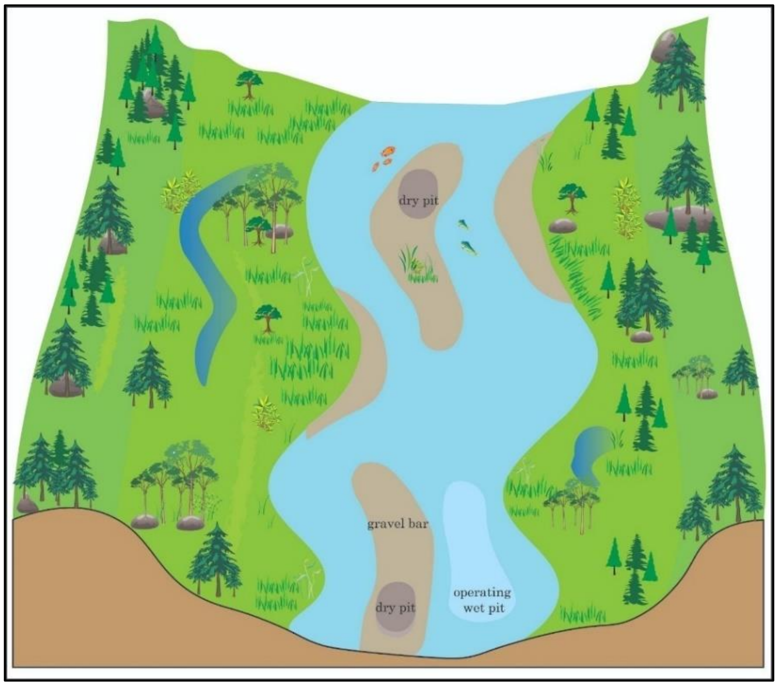

Figure 3 Dry pit mining from bars and wet pits in the active channel area.

During dry periods, removing gravel from the entire stretch of the channel has also been noted in many parts of PNW (Kondolf 2002). This is known as *channel-wide mining*, where the entire stretch is evened out and uniformly lowered, affecting local sediment balance and aquatic habitat. Due to concerns about habitat impact, it has not been in practice for the last two decades (Norman et al., 1998). Channel dredging is common for mining instream gravel and maintaining depth for navigation. Disturbance during wet pit mining and dredging creates plumes of fine sediment that transport downstream with the flow, affecting turbidity.

4.2. Gravel mining as a flood mitigation method

High streamflow or floods transport gravels, cobbles, and pebbles as bedload from the upstream sections of a stream, depositing them in downstream sections of channels. The filling of the channel bed by depositing gravel from upstream areas can reduce the channel's capacity to convey water due to the reduction in channel depth. Therefore, during high-flow events, reduced channel capacity may cause flooding and damage to floodplain infrastructure like roads and buildings, and different land uses such as agriculture and industry. It has been commonly accepted that removing sediment from rapidly aggrading channels is crucial to maintaining the channel capacity to convey flood water (Kondolf 1994). In-stream mining of sand and gravel has been widely proposed and practiced globally to address flood control in gravel-rich environments e.g. UK (Brooks 1988), New Zealand (Carson and Grifliths, 1989), USA (Collins, 1995, Norman et al., 1998), and Canada (Church, 1999). Coupled with the local demand for gravel, commercial extraction has been promoted to enjoy the co-benefits of gravel removal for maintaining channel capacity and flood control. *However, local demand often undermines gravel removal's environmental impacts, especially on aquatic habitats.* In-channel gravel mining still prevails in various PNW river systems, which provides critical spawning habitat for Pacific salmonids.

The disruption of the natural balance of sediment transport and the destruction and degradation of aquatic habitats associated with sediment removal is well understood. However, the extraction of in-channel sediment is widespread under the guise of local flood control, as it provides a cheap and readily exploitable source of gravel. Although sediment removal, in the form of gravel and sand mining for commercial and industrial use is common in many parts of the world, its effectiveness in flood control has rarely been assessed. A recent modelling study by Fraser Basin Council shows even extensive removal of sediment is ineffective in mitigating floods in Fraser River (NHC, 2019). Church, (2010) also argued that the effect of sediment removal on water levels at removal sites is very small when simulated using 2-dimensional hydraulic modeling and the differences in water levels are comparable to the probable error associated with the modelling. Overall, individual sediment removal projects have very limited impacts on *local* and *downstream water levels*, and their effectiveness is very small, especially over the long-term (Church, 2001; Church, 2010) suggesting it is "*not a practical means to achieve water level 'control' locally and in the short term*".

4.3. Other existing flood control measures in gravel-bed streams

Considering the complex interaction between seasonality of regional streamflow and sediment dynamics several flood management practices exist in gravel reaches. Below are different structural, non-structural, and natural flood management alternatives discussed with consideration of their effectiveness, challenges, and environmental implications:

Structural measures in terms of constructed storage structures, dams, and reservoirs are widely adopted worldwide to control floods in gravel bed reaches and serve other purposes like water supply, irrigation, and power generation. While their effectiveness in reducing flood peaks has been documented, they pose significant geomorphic and ecological challenges. For example, the retention of sediments in reservoirs disrupts the natural sediment transport process, causing channel degradation and coarsening leading to habitat degradation, especially for salmons. These formidable barriers also present significant challenges for fish migration, even with the use of fish ladders (Chen et al., 2023).

Inspired by natural levees, the construction of *dikes and floodwalls* parallel to the channel are also very common flood control measures as they provide direct physical protection to floodplain infrastructures during flood events. However, they can lead to increased peak flow in downstream regions. Dikes when placed at distance from the channel, termed as set-back dikes, provide the river with space to convey flood water and are also beneficial to fish as refuge areas where the flood flow is less extreme. The failure of such structures can lead to devastating consequences for infrastructure and crops. Disruption of linear channel and lateral floodplain connectivity is often associated with habitat loss and fragmentation, affecting biodiversity e.g., fish and bird species.

Channelization to increase the capacity and efficiency of flood water is another way of managing floods that requires planned engineering interventions. However, in gravel-bed rivers, channelization often leads to destabilization of the riverbed, increased erosion, and loss of habitat complexity. The rigid nature of channelized rivers contrasts with the dynamic behaviour of gravel-bed rivers, resulting in long-term ecological and geomorphological degradation.

Considering the multiple negative impacts of structural measurements, use of non-structural measurements like restoring riparian buffer zones, floodplain restoration, and other approaches are discussed later.

5. Gravel beds are essential salmon habitat

Gravel plays a crucial role in the life cycle of salmonids, especially during their spawning and early developmental stages. Both migratory and non-migratory salmon need gravel beds for spawning and incubation of embryos that take place in gravel nests or redds (Groot and Margolis, 1991). Some anadromous salmon spend their vulnerable juvenile phase (a year or two) in freshwater before migrating to the ocean.

Female salmon use their tail to create a suction effect for lifting gravel from stream beds (Kondolf et al., 1993). The flowing water carries the lifted sediments downstream and creates nests, or redds, where they deposit their eggs. The gravel offers crucial protection from predators and ensures that the eggs are well-aerated, which is vital for their survival. This process of creating redds is similar across salmon but the depth and size of redds vary across species depending on their size and the quality of available gravels (Groot and Margolis, 1991). In general, larger fish lay their eggs deeper as they can dig larger redds and withstand stronger currents that further help dislocate gravels during digging. After redds excavation, the female drops into the pits to lay eggs, and the male positions beside her to express milt (sperm). Once the eggs are laid and fertilized, the female will dig gravel upstream that flows over and cover the eggs. Depending on species and water temperature, the incubation period of eggs varies and can take weeks to months to hatch. Newly hatched salmon termed alevins, continue to live and grow within the protection of the gravel redds, taking nourishment from their abdominal yolk sacs. The gravel nest provides hiding spots and protection from predators and strong currents during this period. These gravel beds also support a diverse community of invertebrates, which serve as a primary food source for the young salmon as they grow (Kondolf et al., 1993).

The quality and quantity of gravel are critical factors in this process. Clean, well-sorted gravel with the right size distribution ensures optimal water flow and oxygen levels, essential for the survival and development of salmon eggs and alevins (Groot and Margolis, 1991). Sufficient quantities of appropriately sized gravel are necessary to maintain these conditions across spawning habitats. Conversely, the presence of fine sediment and silt can clog the gravel beds, reducing oxygen availability and increasing egg and alevin mortality rates.

In summary, the quality and quantity of gravel are pivotal for the successful reproduction and early development of Pacific salmon. Gravel beds provide both a physical substrate for egg deposition and a protective habitat for the young fish. The health and availability of these gravel habitats directly impact salmon populations, highlighting the importance of their preservation and restoration in salmon conservation efforts.

6. In-channel gravel mining – a sustainability threat to salmon habitat

Removing sediment from a stream bed or its vicinity directly influences various aspects of the stream's physical habitat, including its channel shape, bed height, makeup and stability of its substrate, presence of natural elements like large woody debris and boulders, depth, flow speed, clarity, movement of sediment, volume of water flow, and temperature.

The effects of in-stream gravel extraction on Pacific salmon habitat are summarized and discussed as follows:

6.1. Disruption of spawning habitat

One of the most immediate and devastating impacts of gravel mining is the disruption of salmon spawning grounds. Pacific salmon rely on clean, well-sorted gravel beds to lay their eggs. Gravel mining disturbs riverbeds, either by directly removing the substrate or by altering the riverbed morphology. This disturbance can destroy existing redds and make the habitat unsuitable for future spawning. Also, gravel mining often selectively removes quality gravels with a median diameter between 15 – 45 mm which is preferred by salmon for spawning (Kondolf and Wolman, 1993; Kondolf, 2000).

6.2. The problem of fine sediment and increasing turbidity

Gravel mining increases fine sediment concentration in rivers and streams, which can have severe consequences for salmon eggs and alevins. Fine sediment and silt generated during mining can infiltrate gravel beds, reducing the spaces between gravel particles. This clogging effect impairs water flow and decreases oxygen levels in the substrate, which are critical for the development of salmon eggs and the survival of alevins. High sediment loads in the water column can also reduce light penetration and impair the feeding efficiency of juvenile salmon. Silt deposition in gravel spaces blocks oxygenated waters from reaching the incubating eggs and prevents the removal of waste materials. Additionally, high concentrations of suspended sediments can smother embryos or sac fry, and emerging fry may become trapped if enough sediment accumulates on the redd.

6.3. Clearing and Removal of large wood for gravel removal

Living and dead vegetation supplied from the upstream catchment section and the riparian zone are critical inputs to fluvial systems in forested and mountain streams. These large woody debris (LWD) play important roles in shaping and maintaining channel morphology by altering flow patterns and sediment transport processes and are common in streams in the PNW regions (Hassan et al., 2024). Their role in forested ecosystem streams is well recognized (Clark et al., 2019, Hassan et al., 2024). LWD is recognized globally as being critical to salmon life cycles and their habitats (Bretzel et al., 2024). LWD helps create *diverse habitat structures* such as pools, riffles, and logjams which are essential for various life stages of salmon, including spawning, rearing, and foraging activities. LWD in streams and rivers provides vital *shelter and cover* for salmon, protecting them from predators and adverse environmental conditions. Fallen trees and branches contribute to the input of organic matter into the water, promoting *nutrient cycling* and supporting the growth of aquatic insects and other prey for salmon. Shade provided by large wood debris helps *regulate water temperature*, creating cooler areas that are crucial for salmon survival, especially during hot summer months.

As LWDs and log jams are numerous in forested mountain streams, their removal as part of channel cleaning is a prerequisite for gravel extraction from streams. Sometimes the riparian vegetation cleaning has also been done for accessing channels from roads and recognizing the importance of LWD. Several habitat restoration projects have re-introduced LWD and observed positive impacts on salmon restoration, increasing salmon population and salmon size (Whiteway et al., 2010; Johnson et al., 2005).

6.4. Effect on channel morphology and sediment transport regime

Instream gravel mining changes channel shape, removes vegetation, diverts flow, and creates sediment deficits. It disrupts existing morphology and disrupts the pre-existing balance between sediment supply and transport and can cause channel degradation due to bed incision. Gravel removal pits trap sediments during the next floods which can cause "hungry water" effects below the removal site causing channel degradation. This can impact the survival of juvenile salmon in the redds and rearing habitats. Gravel beds are often characterized with armour layers and the removal of gravel can break this armor layer and cause rapid erosion of channels and bars. This can migrate upstream and downstream and can impact downstream sediment transport impacting the spawning and rearing habitat of salmon.

7. Natural flood mitigation methods for flood management in gravel-bed rivers

Natural flood management (NFM) has gained significant attention worldwide as a sustainable alternative to managing floods that promotes natural processes by manipulating flow at the catchment scale (Lane 2017). In contrast to traditional flood management techniques, it emphasizes promoting and using natural processes for managing flood water and provides multiple co-benefits like improved water quality, habitat restoration, and increased biodiversity and ecosystem health. Following Lane (2017) and Raška et al., (2022) different types of catchment intervention techniques are summarized below:

7.1. Reducing rapid runoff generation

Different interventions can be implemented to increase infiltration and reduce rapid runoff generation. Land use practices that enhance infiltration like grassland creation, reforestation, creation of woodland-buffer zones, vegetation stripe zones, riparian forest, reduction in livestock density, managing tillage practices, adding organic matter to increase infiltration and covering bare soil with vegetation are known ways of increasing infiltration and reducing rapid run-off generation.

7.2. Room for safe flooding

Room for safe flooding is another popular approach that considers a wider catchment level intervention for reducing flood risk. "Making space for water" by creating wetlands and washlands in rural areas adjacent to rivers to allow deliberate flooding during high flows has long been advocated for as a flood management strategy in England and Wales. Another initiative in The Netherlands is making "room for river" by allowing more space for the river to flow naturally so that it can redistribute floodwater and sediment during floods, helping maintain its natural dynamics. Adopting these approaches to other regions require consideration of local geography, hydrology and ecology and could provide multiple co-benefits in restoring critical habitat and enriching biodiversity. Nelson et al. (2024) provide a recent process-based approach for demarcating healthy riparian zones to better optimize river corridors for coastal Pacific Northwest rivers.

7.3. Storing flood water

Increasing storage areas in hillslopes, floodplains, and foothill zones for retention of stormwater. Small-scale features include ditches, ponds, and bunds. Large-scale storage such as retention basins, and polders can be useful. Besides, by careful engineering design, impounded storage space can be created, connected with the river to abstract flood water when it reaches a critical level. However, it's important to properly evaluate its effectiveness to avoid uncertainties arising from potentially conflicting interests like power generation, water supply, and irrigation where the storage is expected to be full versus empty for flood control (Lane, 2017).

7.4. Reducing conveyance

Another intervention can be the reduction of flood water conveyance by reducing connectivity between major runoff-producing areas and channel or drainage networks to reduce hillslope-channel coupling to delay flood flow and peak timing. The use of woody structures to control channel flow is another popular flood management technique used widely worldwide (Lo et al., 2021), especially in upland areas and headwater catchments. The most common among these techniques is to create longitudinal woody structures mimicking small dams or weir to store flood water and delay their concentration time, thereby reducing the peak flow and timing in target locations.

Another involves restoring river channels and banks by planting riparian vegetation. Introducing native plants and grasses in riparian zones can reduce overland flow convergence into rivers. Transforming straight, single-thread channels—often a result of poor river restoration management—into multi-threaded, meandering channels can significantly enhance flood safety. This strategy helps divert peak flows and reduce the impacts of a flood. Additionally, creating complex channel planforms increases surface roughness, slows downstream flood flows, and provides ecological benefits.

7.5. Barriers to NFM

Despite numerous possible benefits of NFM several barriers impede the implementation of NFM in different parts of the world or remain under-utilized. The availability and cost of land can pose significant challenges for the implementation of NFM, especially in residential units. Significant uncertainty exists in the effectiveness of different catchment scale intervention techniques and their role in flood control when used individually or combined with other methods as they are not widely tested for major floods and rare events (Dadson, 2017). Another uncertainty stems from the transferability of different NFM techniques across different climate and physiographic conditions. Most interventions are implemented in small watersheds therefore, the question remains of how effective they would be for large areas with diverse landscape characteristics. The use of hydrologic and hydraulic modelling can be useful in this regard, where an improved representation of watershed physical properties and types of intervention can be tested for multiple intervention techniques using high-performance computing and high-quality datasets (Black et al., 2021; Hill et a., 2023).

Case Study of the Chilliwack/Vedder River

Pink Sunset at Vedder River: Photo by Angela Painter

8. Case Study of the Chilliwack/Vedder River

The Chilliwack River is located in the southwestern part of British Columbia, Canada, and has a rich and dynamic history that intertwines natural processes, Indigenous heritage, and European settlement. The Chilliwack River starts in North Cascades National Park in Washington State, crosses into Canada, enters Chilliwack Lake, and flows west for 40 km. It becomes the Vedder River at Vedder Crossing, crosses the floodplain, turns into the Vedder Canal, and joins the Sumas River before flowing into the Fraser River (Chui and Nynatten, 2016). The Vedder River and Canal in Chilliwack and Abbotsford, BC, convey water from the Chilliwack River to the Fraser River. The Vedder River and Canal system is about 12 kilometres long and has a 200-year designed flood capacity of 1,470 m^3/s. It offers prime habitat for chinook, chum, coho, pink, and sockeye salmon, as well as rainbow and steelhead trout, making it a popular fishing spot. Historically this river system has experienced catastrophic floods, and in response to that flood control setback dikes are installed to protect the cities of Abbotsford and Chilliwack. However, the river system looked completely different a century ago, especially before the impacts of European settlement started degrading the system.

8.1. Historical Background

Prior to 1875, the Chilliwack River flowed north from Vedder Crossing to the Fraser River over a broad alluvial fan. Heavy rains in 1875 caused a logjam, diverting the river into Vedder Creek, which flowed west, and Luckakuck Creek, which flowed north. In 1882, another logjam shifted several streams westward, forming the Vedder River, which flowed into what was then Sumas Lake (now Sumas Prairie). In the early 1900s, the river was diked and channelized for flood protection, to promote settling and agricultural activities.

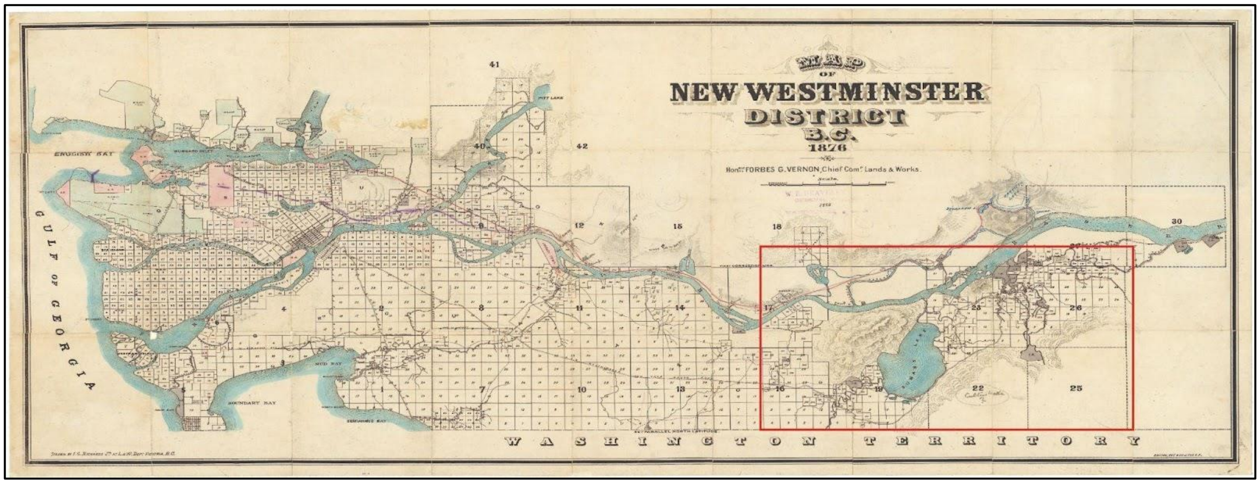

Figure 4 Historical map of the lower Fraser Valley from 1876 with the Sumas Lake, large body of water on the eastern end of the valley (British Columbia Department of Lands and Works, 1876).

Sumas Lake used to flood from the Sumas, Fraser and Vedder Rivers during the spring freshet (Fig. 4). During spring floods, the lake would expand from 4,050 hectares to 13,000 hectares. In the early 1910s, engineer Frederick (Fred) Sinclair from the BC Electric Railway proposed draining Sumas Lake, satisfying the colonial mindset of the European settlers that saw the land being wasted (Reimer, 2018) and thus they 'reclaimed' it for flood control and farming the fertile lakebed. The settlers did not consider the ecosystem and the traditional way of living of the Semá:th people. To the Sumas First Nation, the lake was life, providing 85% of their food (Reimer, 2018). As part of the plan, the Vedder Canal was built to divert the Vedder River into the Sumas River. This diversion was completed by 1922, and lake draining began in 1923, with water pumped over the dikes into the Fraser River by the old Sumas Station. Upgraded in 1975, this facility is now known as the Barrowtown Pump Station, the sole drainage point for the Sumas Lake bottom area and one of Canada's largest drainage pump stations. The project ended when Semá:th fully lost their access to resources of the land and forced onto a reserve that was 3% of their original territory and never compensated for the loss of the lake (Reimer, 2018).

The Vedder River Management Plan, adopted in 1983, aims to "ensure the integrity of the Vedder River floodway while maintaining and enhancing the area's natural resources (Chui and Nynatten, 2016). It also seeks to incorporate recognized historical uses and educational programs, where compatible and desirable, for the benefit of British Columbia residents" (BC Ministry of Environment 1983). The area includes land managed by the cities of Chilliwack and Abbotsford, the provincial government, and private owners. The Vedder River Management Area Committee (VRMAC) oversees the ongoing implementation of the management plan. VRMAC comprises representatives from the City of Chilliwack, City of Abbotsford, Ministry of Water, Lands and Resource Stewardship (WLRS), and the federal Department of Fisheries and Oceans. It also includes stakeholders and rightsholders such as local First Nations. the Fraser Valley Regional District, and fishing groups. Every two years, a technical committee develops and recommends a sediment removal plan to VRMAC, scheduled to avoid disrupting the spawning of pink salmon.

8.2. Gravel removal as flood control technique

Natural river processes carry sediment from the upstream Chilliwack River Basin into the Vedder River and Canal, depositing about 50,000 cubic meters annually. Bedload transport rate during 1983 – 1991 was estimated to be around 55,000 ± 10,000 m^3/year. During the last half of the 20th century (1952 – 1991) in response to the increase in magnitude and frequency of large floods, bank erosion increased causing channel widening, and availability of bed load for transportation especially in the area between the Vedder Crossing and Vedder Canal. Large floods that exceed a flow volume of 500m^3/sec are common once in 5-years and are significant in changing channel morphology and cause channel aggradation due to bank erosion (Ham, 1996).

This sediment reduces the channel's capacity to handle the Design Flood Event (DFE), increasing flood risks for nearby communities. Sediment removal is essential to maintain the provincially recommended 200-year flood protection level, ensuring adequate freeboard along the diking system during the DFE (Fig. 5). The VRMAC managed annual sediment removals for flood control from 1990 to 1997 and switched to biennial removals from 1998 onward. Prior to 1990, sediment was removed, but these efforts were not coordinated by VRMAC. The sediment removal program, funded by the cities of Chilliwack and Abbotsford and the WRLS, occurs in two phases: planning, and removal and assessment.

8.2.1. Planning phase

Planning begins with a survey of over 70 permanent cross-sections along the system every second winter. Data collected calculates changes in sediment volume over two years and runs through a hydraulic model to determine the DFE water surface profile and dike freeboard changes. Sediment removal sites are selected with input from a registered professional biologist, focusing on improving channel capacity while considering vegetation, habitat proximity, access for machinery, and potential impacts on existing channel features.

8.2.2. Removal and assessment phase

Sediment removal is tendered jointly by the involved agencies according to site jurisdiction. A registered professional biologist monitors the removal activities. Post-removal surveys determine the actual sediment removal volume. One year later, a registered professional biologist conducts a biological assessment to evaluate the impact on river and canal habitats, concluding this phase.

Figure 5 Excavation of gravel bars in in Vedder River and Canal (A) leaving irregular bar surface and local increased turbidity (B). [Photo by VERMAC (A), Jakes Construction Ltd. (B)]

8.3. Past gravel mining

Publicly available reports from the Vedder River Management Area Committee were obtained and reviewed for past gravel removal in the river system. These sediment management reports are available from 2016 onwards. Sediment removal reports prior to 2016 were not available and therefore not included in this review.

In 2016, Jakes Construction Ltd. was awarded five excavation sites (Giesbrecht, Lickman, Bergman, Railway, and Yarrow bars), while Walter's Bulldozing Ltd. handled the Keith Wilson Bar site. The sediment removal work began on August 9, 2016, and continued until September 29, 2016, extending 14 days beyond the original September 15 end date. This extension was authorized by the Department of Fisheries and Oceans (DFO) on September 13, 2016. The proposed and authorized sediment removal volume from seven sites was 105,350 m^3. Upon completion, 92,485 m^3 of material was removed from six sites, representing 88% of the authorized volume. The seventh site, "Downstream Rail Bridge," was not excavated due to access issues.

Surveys on the channel conducted in 2018 revealed net degradation of 1300 m^3/year between 2016 - 2018 indicating the removal in 2016 was *higher* than the natural deposition during this period. Based on the survey and modeling, the calculated deposition rate in the Vedder River was 25,900 m^3/y, and degradation of 27,200 m^3/y in the Vedder Canal. The long-term deposition rate for the Vedder River and canal was 41,500 m^3/y during 1996 – 2018 and 42,200 m^3/y during 1981 – 2018. The annual deposition rate has fallen below the long-term average since 2008 in response to the decrease in significant flood events since 2006. The sediment removal plan was canceled because of the overall degradation of the channel bed and lowered water surface profile relative to 2016.

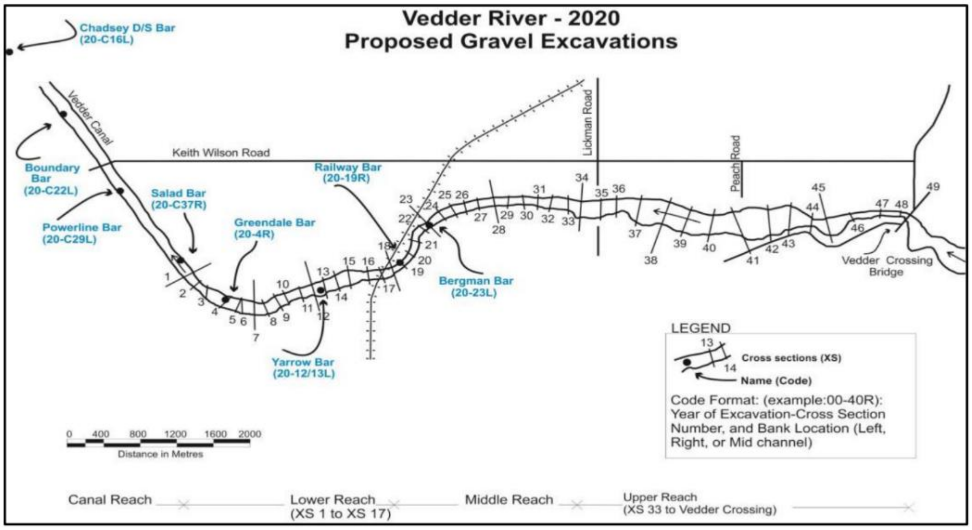

Figure 6 Location of proposed gravel removal sites in 2020. Figure taken from KWL (2020).

In 2020, continuous degradation was also observed in the Vedder River and Canal. Between 2018 and 2020, 16,600m^3/y of sediment were deposited annually in the Vedder Canal, while 24,700 m^3/y were degraded from the Vedder River. The downstream movement of sediment from the upstream section of the Vedder River caused an increase in both the bed surface and water surface elevation in the Vedder Canal and the lower reach of the Vedder River. Overall, the entire reach experienced a *net degradation* of 8,100 m^3/y during 2018 - 2020 and a net degradation of 4,800 m^3/y during 2016 - 2020. This reduction in sediment deposition is associated with lower flood peaks since 2008. Based on modeling studies, it was suggested to remove sediment from the Vedder Canal (Fig. 6), but it was canceled considering the deficit (Rosenau, 2023).

In 2022, the proposed and authorized removal volume from eleven sites was 110,000 m^3. However, due to time constraints, the target volume was reduced to 47,000 m^3 from five sites (Fig. 7). Upon completion, 35,129 m^3 of material was removed from these five sites, representing 74.7% of the revised target volume and 31.9% of the originally authorized volume. In 2022, Jakes Construction Ltd. completed work at three sites (Boundary, Powerline, and Railway), while Walter's Bulldozing Ltd. handled two sites (Salad and Greendale). The sediment removal took place from August 30th to September 13th, 2022.

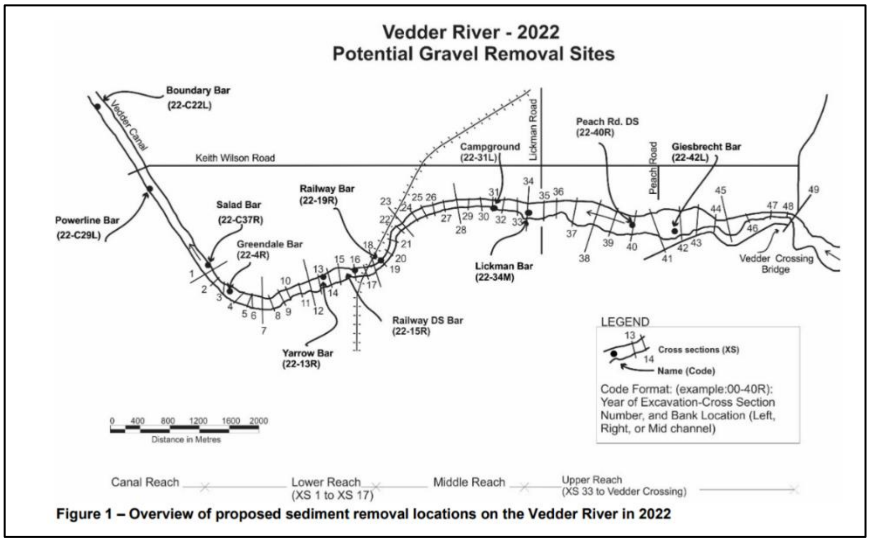

Figure 1 – Overview of proposed sediment removal locations on the Vedder River in 2022

Figure 7 Location of proposed gravel removal sites in 2022. Figure taken from KWL (2022).

In 2023, as part of the remediation work of the Novembre 2021 flood, the British Columbia Ministry of Environment and Climate Change Strategy (MECCS) was supposed to take the role of managing sediment removal from the Vedder River and Canal (Rosenau, 2023). The proposed volume of extraction of up to 364,000 m^3. of sediment which has been downgraded to 135,000 m^3. due to extensive stewardship lobbying and media coverage. It was a pink salmon spawning year, therefore removal of any amount of sediment could have caused catastrophic damage to pink salmon run. The Ministry of Environment and Climate Change Strategy (MOE) finally postponed this "unprecedented" scale gravel removal plan, putting a halt to further over exploitation of gravel from the Vedder River.

Gravel Removal is Unnecessary and Costly

The economics of gravel removal are shifting dramatically. Presently, the local sediment supply far surpasses market demand, making gravel removal more of a financial burden than a profit. For instance, in 2022, the City of Chilliwack was willing to pay up to $500,000 to Jakes Construction Ltd. to remove 100,000 m^3 of sediment from the Vedder Canal and River. This situation highlights the growing economic unviability of gravel removal, with potential for increasing future costs if current practices persist.

Therefore, gravel removal is not only unnecessary but also economically not viable.

8.4. Assessment of mining on fish habitat

Very limited studies are available on the effect of gravel mining on fish habitat in this river system. One publicly available report from the Vedder River Management Area Committee is available for the 2016 removal assessment by Wright et al (2018). They used habitat mapping techniques developed in 2014 for salmon habitat mapping in this river system that can be implemented in a GIS environment to find suitable habitats of salmon based on the physical characteristics of the removal site. Using aerial photos of pre- and post-excavation conditions that were taken during the low flow, at six gravel mining sites. The report indicates that except for one removal site, habitat rating has increased by 2 – 30% and all the overall habitat ratings at all of the excavation sites ranged between neutral to positive changes. It should be noted that LWDs were introduced at some sites to improve habitat however their effectiveness in improving spawning and rearing habitat is not clear. Also, the LWDs at some sites did not survive the first spring freshet.

Due to the limited availability of such reports for other gravel mining years, it's difficult to comment on the overall impact of mining on salmon habitat in this river system. Besides, a quantitative assessment of salmon spawning and their survival at or downstream of these removal sites is not available.

Salmonid habitat consists of physical, chemical and biological attributes that are crucial for the success of hatching, survival and growth. Therefore, any habitat assessment study should consider these attributes together as disruptions caused by gravel mining affects all these aspects of salmon habitat. Considering parameters that control salmonid growth and survival, such as the turbidity, concentrations of trace metals, and the availability of suitable invertebrate prey, and hiding spots from predators, riparian vegetation cover are some crucial parameters to include. Comparison of hatching success at the removal sites and their survival rate at the downstream raring sites during gravel mining and non-mining areas or comparison with nearby rivers can be used for assessment. Besides, increasing sampling to capture the seasonal variation of fish numbers and focusing more on bottom dwelling invertebrates or benthos could be more beneficial (Church, 2010). However, it should be noted that several other factors (e.g. deforestation in upstream areas could increase turbidity affecting egg survival) can contribute to the overall survival rate and bring uncertainties about mining related impacts.

Aquatic habitat can be altered directly from the construction of mine infrastructure or indirectly via modified streamflow and sediment regimes. Tailings and other fine sediments from mined areas can be transported into streams by erosion, potentially resulting in clogging of coarse bed material and even stream blockage, and flooding.

8.5 Geomorphic Perspective on Gravel Removal

From a fluvial geomorphology standpoint, understanding the differences in channel morphology and functionality between natural rivers, dyked rivers, and canals is crucial. Natural rivers, such as the Chilliwack River, are dynamic systems adept at adjusting to fluctuations in sediment supply. They achieve this through various processes, including channel widening or narrowing, changes in sinuosity (gradient), and bed aggradation or degradation. These rivers can also experience coarsening or fining of the bed material in response to changes in sediment input.

In contrast, dyked rivers like the Vedder River, while somewhat adaptable, are more limited in their capacity to adjust compared to natural rivers. They can accommodate some sedimentary changes but lack the flexibility of natural systems. Canals, by design, are engineered infrastructure intended to maintain a stable sediment regime. A well-designed canal is constructed to transport sediment through it without significant changes in stored volume, thereby preventing aggradation or degradation over time.

The Chilliwack River, as a natural river, exemplifies these dynamic adjustments effectively. The Vedder River, although a dyked system, has limited adaptability compared to the Chilliwack. The Vedder Canal, over 100 years old, reflects an outdated and suboptimal design. Its poor design necessitates regular gravel removal to maintain functionality, similar to the continual reinforcement required for a poorly constructed bridge to prevent collapse.

The Vedder River, while not as poorly designed as the Vedder Canal, still encounters challenges. The dikes, though set back in some areas from the active channel, cannot fully address sediment accumulation. Elevating the dikes continually is not a sustainable solution. Relocating the dikes further back could alleviate sediment build-up, but this solution is complicated by the encroachment of residential development on potential setback areas. Residential land is significantly more valuable than agricultural land, making such setbacks economically challenging.

Both the Vedder River and the Vedder Canal could theoretically be redesigned to better handle current and future climatic conditions, potentially reducing the need for ongoing gravel removal. However, such redesigning of the Vedder River and Canal is difficult as they are part of the alluvial fan system with a natural tendency to accumulate sediment over time. Maintaining the river in a balanced regime would require transporting sediment further downstream up to the Fraser River, which could negatively impact habitat quality in altered reaches.

For the Chilliwack River, the natural capacity for sediment adjustment negates the need for gravel removal, given its ability to adapt to changes in sediment supply.

8.6. Potential flood mitigation strategies

The Chilliwack/Vedder system experiences annual high flows during the spring freshet when snowmelt occurs. Rainfall over snow can speed up the process of snow-melting and with changing seasonal temperatures and rainfall patterns this can lead to catastrophic floods. Besides, the region experiences extreme rainfall from the arrival of narrow concentrated bands of moisture-rich air, termed as Atmospheric Rivers (ARs). Over the west coast of BC, ARs have increased in the recent past (Sharma and Déry, 2020) and future climate change projections suggest AR-driven floods are also likely to increase.

During the November 2021, when an atmospheric river hit parts of British Columbia and Washington (USA), the area experienced catastrophic flooding resulting in high water levels in the Sumas, Nooksack, Chilliwack and Vedder River systems, which led to the evacuation of over 3,000 people in Abbotsford, BC and the stranding of hundreds in Chilliwack and along the Chilliwack River valley. Over two days, southwestern BC (e.g., Abbotsford, Agassiz) reported over 200% of normal (1981–2010) precipitation in November 2021 (Environment and Climate Change Canada, 2021; Sepúlveda et al., 2022). The flood caused over 670,000 livestock deaths, contamination of fish-bearing waters, and millions in damages (Finn et al., 2024). In the aftermath of this flood, many residents learned for the first time that their homes and farms are located on the former lakebed of Sumas Lake (Finn et al., 2024). It is estimated that climate change made this extreme precipitation event 60% more likely (Gillett et al., 2022). This calls for reconsidering regional flood mitigation and adaptation strategies under global warming scenarios.

Several nature-based solutions can be implemented in the Chilliwack/Vedder River system with proper consideration of the available scope for their implementation and their effectiveness. The present flood mitigation strategy mainly focuses on engineered solutions by relying on dike structures and removing gravel to maintain a 200-year flood capacity. The strategic construction of dikes and channelization of rivers through engineering solutions, often termed as 'flood defence' has several limitations, including incorrect design assumptions, limited funding, and poor maintenance, and these limitations increase under future climate change scenarios.

8.6.1. Reclaiming the Sumas Lake

The draining of Sumas Lake and converting it to an agricultural prairie was one of many land dispossessions and genocidal acts carried out by European colonizers on the Indigenous people across Canada. Based on a multidisciplinary group of Indigenous and non-Indigenous scholars, lawyers, and land stewards Finn et al., (2024) argue for a "Lake Back" movement as a potential climate resilience solution for mitigating flood in this river system. The historical Sumas Lake has always been part of a dynamic floodplain system that supported a wide variety of plant and animal life including multiple species of Pacific salmon and has been a central part of Indigenous food systems. As part of the flood management the city of

Chilliwack and Abbotsford allocates millions of dollars for managing flood infrastructure such as dikes (City of Chilliwack, 2024). Recently, as part of flood mitigation planning, the City of Abbotsford has proposed four proposed recovery options with a cost ranging from $200 million for upgrading the pump system to ensure the lake from returning, to $2.4 billion for constructing a new floodway.

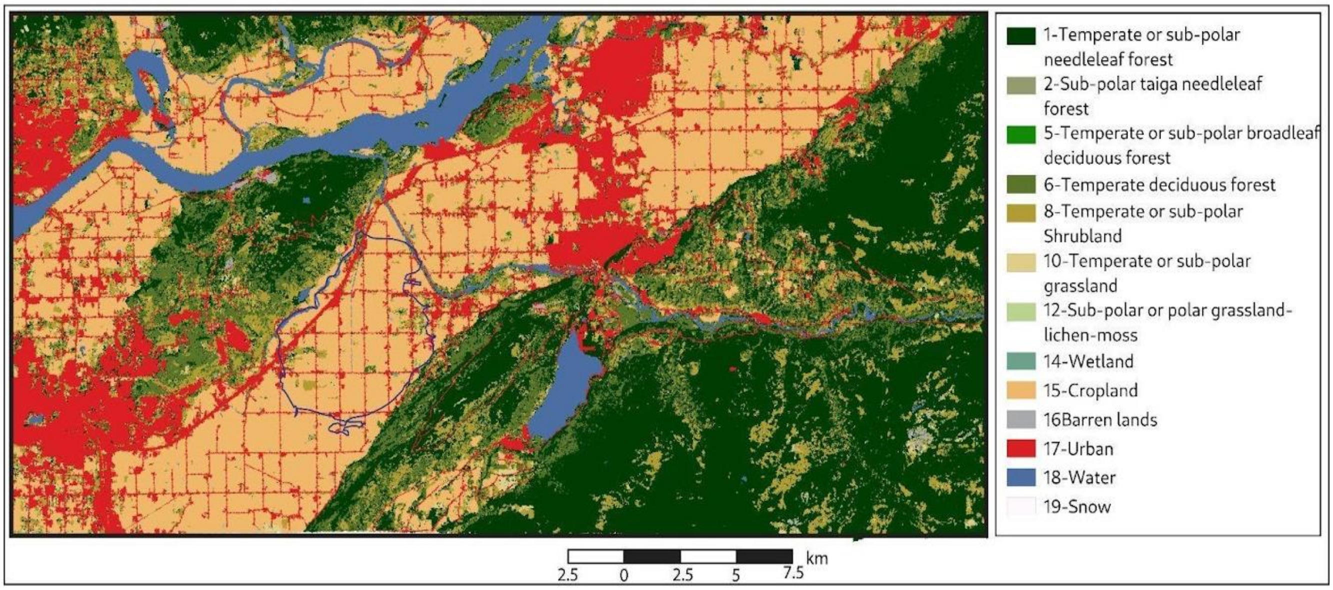

Figure 8 Present day land use land cover map of the surrounding region of the Chilliwack/Vedder River with former Sumas Lake demarcated in blue polygon (Data Source: Natural Resources Canada).

By analysing these scenarios Finn et al., (2024) argue that through revitalizing and reviving the Sumas Lake through acquisition of properties to allow flooding and with strategic relocation of people and infrastructure would be the best economic solution in this region. Based on the 2020 Assessed Land values for BC, estimated cost of such manage retreat would cost around $1 billion and have several co-benefits (Finn et al., 2024). The City of Chilliwack can also make use of the existing wetland system surrounding the Chilliwack River and consider using the Sumas Prairie to allow flooding by the Vedder canal (Fig. 8). Such effort could directly benefit regional flood management strategies without the need for the biennial sediment removal strategies that have limited effectiveness in terms of flood control (Church, 2010). Restoring the lake would reestablish critical habitats for endangered Pacific wild salmon, sturgeon, and migratory birds, as well as for food plants and medicinal resources valued by the *Semá:th* People. Research indicates that restoring Indigenous water and land governance can lead to significant co-benefits, such as increase in food sovereignty, reduced reliance on the healthcare system, increased labor productivity, enhanced social cohesion, nation-building and resurgence, and better biodiversity stewardship (Per et al., 2020; Rose et al., 2016; Traditional Owner Partnership and Alluvium, 2022).

8.6.2. Construction of floodways

Another potential solution could be to use the historical channel of the Chilliwack River for conveying flood water to the Fraser River. In addition, construction of new floodways that mimic the old Chilliwack River system/channel network can be beneficial considering their usage for other aquatic species and overall flood mitigation. Such engineering solutions can be costlier and must consider flood risk scenarios that include climate change projections in this region. Future flood mitigation studies and analyses must consider these options along with their co-benefits while planning flood mitigation strategies.

8.6.3 Upstream erosion zones and riparian management

This approach necessitates a catchment-scale management strategy that focuses on controlling and trapping sediments in high-yield areas and establishing healthy riparian buffers along river channels to prevent bank erosion. It is also vital to relocate development away from active floodplains, reduce the occurrence of landslides and fires, and enhance the abundance of functional woody debris within the channel. Furthermore, mitigating land use practices that increase sediment yield, such as clear-cutting, is essential for managing sediment input into rivers during extreme rainfall events. Establishing and maintaining riparian buffer zones along riverbanks can help reduce sediment runoff and improve water quality. Vegetation in these zones can stabilize banks, filter pollutants, and provide shade that benefits salmon.

8.6.4 Adapting to floods

“Living with floods” is another popular adaptation measure in many parts of the world. Instead of combating floods with structural measures, experts suggest large-scale adaptation to floods are much more beneficial (Cuny, 1991; Tewari & Bhowmick, 2016). This alternative strategy encourages people to adapt to floods by harnessing the benefits for economic development. With help from local governments and development agencies, communities can adapt to living with floods to avoid recurring and capital-intensive structural flood control measures (e.g. dikes) that have long-term recurring maintenance costs (Cuny, 1991). This can be effective in remote rural areas and could benefit from Indigenous knowledge of flood adaptation. Adaptation in terms of buildings and housing are most visible in flood-prone regions of Bangladesh, Thailand and India where buildings and houses on stilts are common to allow flood waters to pass underneath. Another popular solution is to build houses above flood levels on raised platforms or plinths. Adaptation measures in terms of choosing and embracing flood resistant crops that can grow and withstand flood waters could reduce crop losses. Adjusting crop cycles, so that crops can be harvested before the peak flood months could be adopted to avoid maximum damage. Using mixed crop practice by growing high-yield varieties of flood resistant crops and leaving some lands for long-stem crops to reduce flood damage is another popular way for crop management in flood prone regions.

Most riverine societies around the world are living with floods and adopting in unique ways. Such Indigenous knowledge from around the world can be taken into consideration to plan adaptation strategies in areas where unusually large floods are becoming more common with global warming. Traditional ways of moving valuables, food-grains and animals to higher areas as a precautionary measure by temporary relocation during flood periods could be beneficial.

8.7. Remaining questions and conclusion

The assessment of gravel removal on fish habitat is done through mapping of salmon habitat based on some physical criteria developed in 2014 as mentioned earlier. However, the impact of past gravel removal especially during 1990 to 1997 when gravel was removed annually under the leadership of VRMAC is unknown. Before 1990, sediment was removed, but their efforts were not coordinated by VRMAC and their impact on fish habitats is also unknown. Besides, habitat mapping alone cannot holistically assess the impact of gravel removal of salmon and that needs focused study on different salmon species survival, population and size distribution, and historical changes in this river system. Such specific study focusing on gravel removal effects on the long-term habitat and population distribution is lacking in the Chilliwack/Vedder River system.

The current flood control plan considers a design flood discharge of 1470 m^3/s that has a 200-year return period. As global warming is making such events more likely and the risk of compounding events cascading from rain-on-snow events could worsen the impacts in the floodplain. Therefore, flood mitigation plans should take into consideration the projected impacts of global warming in this river basin.

The current estimates of water level are based on a one-dimensional hydrological model that can be improved with more sophisticated high-resolution data-driven models with improved calibration and validation. Such improved models can be coupled with different floodplain management strategies such as strategic relocation, wetland reconnection or set back dikes under future global warming scenarios. Besides, with improved data collection and modelling can better assess the effectiveness of sediment removal in flood control in this river system and would allow comparison with other nature-based flood control strategies.

More importantly, the implementation of the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) through the Declaration on the Rights of Indigenous Peoples Act (DRIPA) in BC should amplify the voice of the Semá:th and other Stó:lō communities in flood management decisions. This will ensure that all rightsholders affected by flooding can participate in exploring and discussing alternative solutions for the future.

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