INTEGRATED FLOOD HAZARD MANAGEMENT PLAN

SQUAMISH

Background Report

Final Report
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Executive Summary

The District of Squamish (District, DoS) is set in a beautiful but hazardous natural environment that includes:

- flood hazards from the Squamish, Mamquam, Cheakamus, Cheekeye, and Stawamus Rivers;
- debris flow hazards from the Cheekeye River and smaller local creeks; and
- coastal flood and tsunami hazards from Howe Sound.

The District lies within traditional territories claimed by the Squamish Nation. Ten Squamish Nation reserves located throughout the shared floodplain create an inseparable common interest in flood protection. The District also lies within traditional territories claimed by the Tsleil-Waututh Nation.

In 1994, the District of Squamish completed a Flood Hazard Management Plan (FHMP) to help achieve an appropriate balance between flood protection and community development. Twenty years after its release, key parts of the 1994 FHMP have become obsolete as a result of community growth, improved understanding of flood hazards, and the emergence of new tools for flood hazard management.

Integrated Flood Hazard Management Plan

In February 2014, the District retained a multi-disciplinary consulting team led by Kerr Wood Leidal Associates Ltd. (KWL) to prepare a new Integrated Flood Hazard Management Plan (IFHMP). The IFHMP project was supported by a multi-stage community engagement process and a technical working group that includes regulators, key major industry representatives, and the Squamish Nation.

This Background Report is the first major deliverable of the IFHMP. The Background Report provides an overview of:

- specific hazards that are addressed in the IFHMP and the areas at risk from each;
- the state and context of the District's flood protection program prior to the IFHMP, including policy instruments as well as the local portfolio of structural flood protection works;
- regional, provincial, national and international guiding principles for the IFHMP process;
- pre-requisite technical updates including river modelling, coastal flood analysis, and a high-level geohazards assessment; and
- preliminary conclusions and recommendations that arose during the compilation of background materials.

River Hazards

Most river floods within the District occur in the fall and early winter when large and intense multi-day storms create high flows on the local rivers, and when precipitation falling as rain throughout the watershed can bring additional runoff contribution from alpine snowmelt. Sediment aggradation gradually or periodically increases the flood risk in some areas by filling in the river channels. Erosion is a separate but related hazard where riparian development has encroached into the flood corridor.

Areas at risk of river flooding include Paradise Valley (Cheakamus River), the low-lying corridor that follows Highway 99 from Brackendale to Downtown Squamish (Squamish and Mamquam River), and from Valleycliffe to Stawamus I.R. No. 24 (Stawamus River). The value of infrastructure vulnerable to the Squamish River alone exceeds $2.4 billion. The majority of community services and commercial areas are at risk of flooding, as are most of the local Squamish Nation reserves.

Coastal Hazards

Coastal water levels at Squamish are a function of tide, storm surge, local effects, and wind waves. Coastal floods typically occur when external storm surges combine with the highest tides of the year during the winter storm season. The IFHMP has adopted the Province's climate change guidelines, which recommend an allowance of 1 m of Sea Level Rise (SLR) by year 2100. The coastal flood assessment identified other key gaps in the District's understanding of tsunami hazards, subsidence, datum adjustments, wind set-up, and wave generation.

Debris Flow Hazards

Debris flows involve very large peak discharges of substantial-sized material moving at relatively high velocities. The Cheekeye River is one of the most studied debris flow hazards in BC; the corresponding hazard area includes the entire Cheekeye Fan from Cheakamus I.R. No. 11 to Brackendale. Other small creeks around the District are potentially subject to debris flows, and previous studies have found the Stawamus River may be subject to a transitional process referred to as a debris flood.

Policy

In 2004, responsibility for development in flood hazard areas was shifted from the provincial government to local municipalities. The District's 2009 Official Community Plan (OCP) provides strategic policies for flood hazard management planning and protection but does not specify Development Permit Areas for flood and erosion hazards. The District does not have a floodplain bylaw. Hazard assessments are currently mandated under rezoning, subdivision and building permit processes through provincial statutes such as the *Land Title Act* and the *Community Charter*. The District's complex hazards are frequently beyond the scope of these site-specific reviews.

This Background Report includes a review of flood hazard management policy measures adopted by Canadian jurisdictions ranging from nearby local municipalities to the federal government. Many international jurisdictions face even higher levels of flood risk and have naturally developed more sophisticated flood hazard management policies. International examples reviewed for this report include case studies from Europe and the United States.

Structural Protection

In addition to implementing policy and planning measures, the District maintains a portfolio of structural flood protection works to protect the Squamish community. The District portfolio primarily consists of dikes, riprap erosion protection revetments, and ancillary structures regulated under the *Dike Maintenance Act.* The District's structural flood protection works are complemented by a number of unregulated First Nation, privately-owned, "orphaned", and *de facto* dikes and training berms on many of the local creeks and rivers.

The most significant element of the District portfolio is the integrated ±20 km-long Squamish River and Mamquam River dike system constructed by the province in the early 1980s. Other structural flood protection works are located throughout the Paradise Valley (Cheakamus River), along the Cheekeye River upstream of Highway 99, and adjacent to the Valleycliffe neighbourhood (Stawamus River). Updated hydraulic modelling, including an allowance for flow increases as a result of climate change, confirms that some structures currently do not provide the intended level of flood protection.

Coastal flood protection is currently provided by a variety of low, non-standard works around downtown. The District's only regulated sea dike extends from the foot of Cleveland Avenue around to the west end of Winnipeg Street. Conflicts with development have created challenges for future dike raising.

Flood Protection Gap Analysis

The Background Report closes by contrasting current and future flood hazards against the District's flood hazard management program, drawing conclusions about where the existing program would be unable to deliver the desired level(s) of protection. These conclusions take the shape of a gap analysis focussed on both policy and structural program elements.

Key policy gaps were identified in the categories of risk management and analysis, regulation, and public education. The most notable gaps included planning for climate change, particularly SLR, and the need for a floodplain bylaw and/or flood hazard development permit areas. Key structural flood protection gaps were identified in the categories of design standards, jurisdiction and access, inspection, reporting and compliance, and environment and community. The most notable gaps included coastal defences, access challenges, particularly the lack of a continuous Statutory Right-of-Way, and outstanding maintenance issues.

The subject matter for this report was discussed by the IFHMP Technical Working Group at a meeting on June 16, 2014. The draft report was presented to District Mayor and Council on August 19, 2014. While the report was essentially complete as of February 2015, at the District's request it remained as a final draft document until the completion of the IFHMP. The September 2017 final report incorporates minor updates made throughout the balance of the IFHMP.

1. Introduction

The District of Squamish (District) is located in a spectacular natural setting that brings together rugged mountain slopes, pristine rivers and one of BC's most beautiful fjords. The natural advantages of this setting also mean that Squamish is exposed to an imposing scope of natural hazards, including:

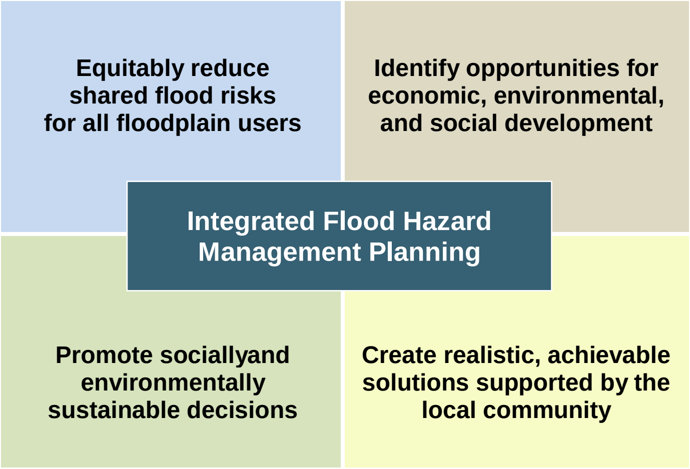
- floods on the Squamish, Mamquam, Cheakamus, and Stawamus Rivers;
- debris floods and debris flows on the Cheekeye[1] River and other local watersheds; and
- coastal flooding and tsunamis from Howe Sound.

The District of Squamish is responsible for managing development in floodplain areas, as well as for providing the community of 19,500 people with an adequate level of flood protection. In 1994, the District completed a Flood Hazard Management Plan (FHMP) that provided guidance for urban development within flood hazard areas. Flood protection measures recommended in the 1994 FHMP reflected the standard of the day, particularly in regard to known hazards and technical tools.

Since 1994, there have been significant changes in the field of flood hazard management. These changes include an evolving understanding of climate change, improvements in hazard assessment tools and approaches, and changes in the respective roles of regulatory authorities and the Qualified Professional (QP). In addition, the District has experienced over two decades of community development and population growth. A generation after it was prepared, the 1994 FHMP no longer provided sufficient support to address the District's flood protection needs.

To maintain and enhance the liveability and sustainability of the Squamish community, the IFHMP updates the 1994 FHMP to incorporate the latest flood management guidelines, tools and best practices at regional, provincial, national and international scales. This section provides context for that update.

1.1 IFHMP Project Context



In February 2014, the District initiated a multi-year project to produce an updated FHMP. Where possible, the FHMP update integrates economic, environmental, social, and cultural considerations to produce an Integrated Flood Hazard Management Plan (IFHMP).

The IFHMP must also recognize existing constraints, including floodplain jurisdiction shared with the Squamish Nation, the alignment of the current dike system, and the historic development of the protected floodplain.

District Council adopted the final IFHMP to guide flood mitigation planning and support responsible, sustainable development for years into the future.

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[1] Records show that the name "Cheekeye" was derived by local pioneers from the Squamish Nation (Skwxwú7mesh Úxwumixw) name Nch'kaý, pronounced *in-ch-KAI*. While the English name is officially recorded as "Cheekye"; the Squamish Nation confirmed a preference for the "Cheekeye" variant. The IFHMP adopts the Squamish Nation's preferred spelling for the river and fan.

The IFHMP project scope included an intensive technical work program, a series of stakeholder workshops with a Technical Working Group, presentations to District council, and three public open houses. Effective implementation of the new IFHMP will depend on public support, and public engagement will be an essential part of the update process. To this end, the project produced a number of key deliverables, each building on the last. These deliverables will ultimately be compiled into the IFHMP report.

IFHMP deliverables are outlined in the table below.

Table 1-1: IFHMP Deliverable Reports

Deliverable Report
Framework for Community Engagement
Electronic Forum (updated throughout project)
Background Report (this document)
Coastal Flood Risk Mitigation Options Report
River Flood Risk Mitigation Options Report
Final Integrated Flood Hazard Management Plan

1.2 Purpose and Structure of Background Report

The outcome of the District's IFHMP is a plan which incorporates the latest flood management guidelines, new engineering modelling tools and techniques and best planning practices. The project process itself was instrumental in defining the community's desired level of flood risk mitigation.

This Background Report provides a technical foundation for the study: a broad overview of flood and related hazards, a comprehensive list of reference materials, a summary of the current state of the flood hazard management program, and a comparison of hazards against hazard management in the context of District and external best practices. The Background Report helped the IFHMP process identify key focus areas where the District could most effectively reduce risk to the community.

The IFHMP Background Report introduces the IFHMP process (Section 1) and summarizes the existing state of knowledge around:

- history and inventory of known flood-related hazards within the District of Squamish, including climate change assumptions and timelines (Section 2);
- pre-existing policy tools for flood hazard management and IFHMP guiding principles (Section 3);
- District-wide inventory of existing structural flood protection works (Section 4); and
- updated local hazard analyses (Section 5.5).

Conclusions regarding current gaps in both policy and structural flood protection aspects of the District's flood hazard management program are provided in Section 6. These conclusions effectively constitute a Gap Analysis of the District's flood protection program.

Gap analysis (also referred to as need-gap analysis, need analysis or need assessment) is used as a management tool in a wide range of applications. The primary purpose of a gap analysis is to assess an organization's current state relative to its desired state. This analysis can yield insight into an organization's performance, including areas for improvement, items that have been deliberately omitted, accidentally left out, conflicts, newly emerging needs or areas not yet defined. It provides a foundation for measuring the allocation of time, money and human resources required to achieve the desired outcome.

A partial draft of this Background Report was reviewed with the IFHMP Technical Working Group at a meeting held in Squamish on June 16, 2014 and subsequently circulated for comment. The Background Report was presented to District Council on August 19, 2014. A copy of the August 19, 2014 Report to Council is attached as Appendix A.

A final draft version of this report was made available to the public in February 2015.At the District's request, this report was not finalized until the completion of the IFHMP. Revisions included in this September 2017 final report are limited to minor updates made throughout the balance of the IFHMP.

1.3 IFHMP Project Team

The District of Squamish IFHMP initiative was led by Municipal Engineer David Roulston, P.Eng. and Planner Matt Gunn, MRM, RPP with direction and participation from senior District staff as well as Mayor and Council.

The multi-disciplinary consulting team included:

- **Kerr Wood Leidal Associates Ltd.**: project management, hydrotechnical and civil engineering;
- **Arlington Group Planning + Architecture Inc.**: planning, policy and public consultation services;
- **SNC-Lavalin Inc.**: coastal engineering;
- **Thurber Engineering Ltd.**: geotechnical engineering and geoscience expertise; and
- **Cascade Environmental Resource Group**: environmental science.

For this report, background and hydrotechnical information was prepared by David Roche, M.A.Sc., P.Eng.and Alisson Seuarz, M.Eng., EIT of KWL. Graham Farstad, MA, MCIP of Arlington Group Planning + Architecture prepared the sections addressing planning and policy issues, while John Readshaw, M.Sc., P.Eng. of SNC-Lavalin provided support and input for the coastal engineering sections. David Sellars, M.Sc., P.Eng. of KWL provided technical review of the full report.

Ten Squamish Nation reserves are located throughout the floodplain, creating an inseparable common interest in flood protection between the District and the Squamish Nation. Technical input and co-ordination of feedback from the Squamish Nation was provided on behalf of Chiefs and Council by Capital Projects Director Buddy Joseph and Squamish Valley Administrator Paul Wick.

Stakeholders invited to participate in the District's Technical Working Group included:

- Indigenous and Northern Affairs Canada (INAC);
- BC Ministry of Forests, Lands & Natural Resource Operations (MFLNRO) Water Management Branch;
- BC MFLNRO Ecosystems Branch;
- BC Ministry of Justice – Emergency Management BC;
- CN Rail;
- Transport Canada; and
- Vancouver Coastal Health.

The composition of the stakeholder group was adjusted in later phases of the project to incorporate additional interests under discussion during the IFHMP process.

2. Natural Hazards in Squamish

The District of Squamish is located at the head of Howe Sound where five rivers converge. These mountain rivers, fed by glaciers, snowmelt and precipitation, descend from their steep, incised upper reaches carrying volumes of water, sediment, and on occasion, rocks and large woody debris. When fast-flowing alpine rivers reach gently sloping valley bottomlands, they have a tendency to reduce their velocity, deposit their sediment and spread out. The terms alluvial fan and floodplain are commonly used to describe riparian and low-lying areas along these lower reaches.

Gently sloping lands near water have historically been viewed as the most suitable for human settlement, agricultural and transportation. Flooding has been a continuous risk in the Squamish area since the current interglacial period began over 10,000 years ago, first for the local First Nations and more recently for European settlers.

The oral history of the Squamish First Nation has a legend called the Flood. According to the legend, when the people began to forget their old ways and failed to listen to their elders, the game began to disappear and then the fish and the berries. People became hungry and began to quarrel. Still they wouldn’t listen to their elders and change their ways. Then the rains came. The waters rose and the people had to anchor their canoes to Mount Garibaldi. When the waters receded, the people who survived came to their senses and listened to their elders. Then the game and the fish and the berries returned in abundance.

The recorded history of the Squamish community shows a constant struggle to protect human settlement from the natural forces that have frequently led to flooding. Over the past century, Squamish has experienced numerous floods as outlined in the table below.

Table 2-1: Overview of Historic Floods in Squamish

River(s)	Date	Consequence
Squamish River	1890s	Early settlement period. Squamish river dike first proposed in 1890.
Squamish River	Sept. 1906	Myrtle Herndl, daughter of Brackendale pioneer, Henry Judd, reported “Many settlers were completely wiped out” by the flood.
Mamquam River Squamish River	Oct. 1921	Flood covered valley floor with several feet of water. PGE railway submerged for several miles. The tops of Brackendale farm fences were under water (Feeney, 1950). A completely new channel west to the Squamish River was created when the Mamquam River overflowed its banks. The former channel flowed south to Mamquam Blind Channel. Prior to the flood, Judd Slough was the main channel of the Squamish River.
Howe Sound	Dec. 1932	A 15-foot tide and a very strong south wind led to overtopping of the sea dike in Downtown Squamish before Christmas.
Squamish River	Oct. 1940	Extreme rainfall and snowmelt caused flooding which led to evacuations from Brackendale to Downtown Squamish. Flood damage was heavy in what was considered the largest in the century.

River(s)	Date	Consequence
Squamish River	Oct. 1950	Flooding caused damage to roads and rail bridges.
Howe Sound	Dec. 1951	Tidal flooding occurred in Downtown Squamish after the sea dike was breached in 2 places. Houses and stores were flooded and River Road was partially washed out.
Mamquam River	Oct.1955	Mamquam Bridge washed out by flooding for 10th time in 28 years. Many homes were flooded.
Cheekeye River	Aug.1958	A major debris flow occurred following a sudden rainstorm. This resulted in a 15 foot-high dam that partially blocked the Cheakamus River at the mouth of the Cheekeye River. No damage to buildings resulted.
Squamish River	Oct. 1958	Flooding led to 4 feet of water over the main road in Brackendale.
Howe Sound	Dec. 1967	Tidal flooding in Downtown Squamish occurred after the sea dike was overtopped.
Mamquam River	Nov. 1968	Flooding damaged a trailer park, highways and the railway.
Squamish River Cheakamus River Mamquam River Stawamus River	Dec. 1980	Record peak flows on Boxing Day caused logjams on 3 rivers which led to damages to 200 homes. Highway 99 and Government Road were closed and Fergie's Bridge was washed out. Extreme inflow into Daisy Lake Dam reservoir led to water level rising to within 45 cm of the dam crest. Upper Squamish Valley and most of Brackendale were evacuated. Flood frequency was estimated to be from 1 in 30 to 1 in 90 Annual Exceedance Probability (AEP, equivalent to 30-year to 90-year return period). Estimated recovery costs were $313,000. This was the second flood of the storm season.
Squamish River	Oct. 1981	177 mm of rain fell in 48 hours and mild temperatures led to flooding along the BC Rail line, the Spiral Mobile Home Park and at the confluence of the Mamquam and Squamish Rivers. Squamish area damages were $404,000.
Cheekeye River Cheakamus River Stawamus River	Oct. 1984	180 mm of precipitation over 3 days in October inundated many homes in the Squamish Valley and destroyed a log bridge across the Cheakamus River. Damages to homes were estimated at several million dollars plus watercourse damages of $623,000 and a bridge replacement cost of $300,000.

River(s)	Date	Consequence
Squamish River Cheakamus River Cheekeye River	Aug. 1991	Flood resulted in $2,400,000 in costs to Provincial Emergency Program. Peak flow of 2,610 m^3/s recorded on Squamish River. Houses were flooded, residents were evacuated and the access road to Paradise Valley was washed out. Riprap was damaged at 4 locations on the Mamquam River and 2 on the Squamish River. The Cheakamus community on Squamish Nation I.R. No. 11 was flooded (15 homes), residents evacuated by helicopter and the native graveyard washed out. The Mashiter Creek dam was removed after a debris jam rendered the water intake inoperable.
Cheakamus River Squamish River	Oct. 2003	Rains of 369 mm in 4 days caused the largest flood since continuous hydrometric records began on the Squamish River and Cheakamus River in the 1950s. Peak flows significantly exceeded the next largest flood in 1984. The flood caused District evacuations, damage to flood protection structures, breached dikes in Paradise Valley and damaged the BC rail line further upstream in the Cheakamus Canyon. Paradise Valley Road was washed out and upper Paradise Valley was cut off. In general, dikes considered “standard” dikes (i.e., designed for 1 in 200-year return period floods) were not overtopped; however, freeboard at some locations was as little as 0.5 m.

Several conclusions can be drawn from the flood history in Squamish.

1. All the rivers in Squamish pose a risk of flooding. All have caused multiple and damaging floods in the past.
2. Damaging floods have also occurred because of coastal inundation.
3. The flood risk in Squamish has strong seasonal variations. Most flooding has taken place between October and December. Major floods have also taken place in August.
4. Contrary to the experience of many communities in BC, the freshet (late May, June and early July) has not been a major cause of flooding on local rivers.
5. The frequency of flood damages over the past 30 years has decreased compared to earlier time periods. This is attributed to investments in structural flood protection works (e.g. dikes).
6. Extreme precipitation events have occurred on at least five occasions since 1980. These continue to test the limits of flood protection structures.

2.1 Watershed Characteristics

This section provides general information on District watersheds. Subsequent sections provide a synopsis of the various hazards by hazard type and watershed.

Topography

The Squamish River drains a steep, mountainous watershed over 3,800 km² in area that is covered by extensive glaciers and forested valleys. Elevations in the watershed range from tidewater at Howe Sound up to mountain peaks of over 3,000 m. The river has its source in the Pemberton Icefields, and about 20% of the watershed is glaciated (Paige and Hickin, 2000).

The Cheakamus River and the Mamquam River flow into the Squamish River within the District. Two other major tributaries, the Elaho River and Ashlu Creek, join the Squamish River upstream of the District boundary. Cheakamus River tributaries of note for this study include:

- Rubble Creek, which drains Garibaldi Lake past the well-known Barrier lava formation north of the District boundary;
- Culliton Creek, which joins the Cheakamus River close to the District's northern boundary; and
- Cheekeye River, which experiences frequent debris flows from the flanks of Mount Garibaldi.

The Stawamus River flows directly into Howe Sound; however, its watershed abuts the Squamish River watershed and shares many of the same climatic and hydrologic characteristics. The most notable differences are its lower headwater elevations and lack of glacier coverage.

The District's land area covers over 100 km² of the southern portion of the Squamish River and Cheakamus River watersheds, the eastern part of the Cheekeye River and Mamquam River watersheds, and the northern part of the Stawamus River watershed. Headwaters for all the major watersheds are outside the District. To the south, the District boundary extends along the west side of Howe Sound to Woodfibre and along the east side of Howe Sound to Watts Point.

Figure 2-1 provides an overview of the District and its flood hazards as well as its inventory of structural flood protection works.

Climate and Hydrology

The District watersheds have a temperate maritime climate with warm, dry summers, cool and wet winters, and they experience strong precipitation and runoff gradients. Snow is rare in the valley bottoms; however, alpine areas accumulate significant annual snowpacks. Much of the approximately 2,800 mm mean annual runoff occurs during the spring freshet.

High flows on the local rivers can be generated by snowmelt, intense and/or prolonged rainfall, or a combination of the two processes. Extreme floods on the Squamish River and its major tributaries are most often associated with intense rainfall events.

During rainstorms, it is possible for freezing levels to rise rapidly from the lower valleys to over 2,000 m (P. Jordan& Associates, 1987). Fall and early winter rainstorms can be exacerbated by these rapid rises in temperature, which are commonly associated with warm fronts arriving from subtropical zones in the central Pacific. This pattern is often referred to as a "Pineapple Express".

If the warm front is preceded by a wet and cool period, the warm rain will fall on a thin, ripe snowpack and can contribute to rapid snowmelt. This type of flooding usually occurs in October or November since the early snowpack cannot absorb much rain before releasing runoff, and the temperature is typically warm enough that precipitation falls as rain throughout the watershed.

The response of the District's major watersheds to rain, snowmelt, and rain-on-snow conditions varies based on their size and elevation. Smaller, lower-elevation watersheds produce more rain-driven floods, while snowmelt plays a more significant role for larger, higher-elevation watersheds.

A review of local hydrometric data collected by the Water Survey of Canada (WSC) led KWL (2011a) to conclude that the largest peak flows on the Squamish River and Cheakamus River tend to occur on or about the same day. Correlations with floods on smaller rivers and creeks are present but less significant.

Natural Environment

The Squamish River watershed is the largest watershed within the Strait of Georgia region and supports a great abundance of flora and fauna. The Squamish River Estuary is a particular biodiversity hotspot, offering a diverse range of habitats including salt marshes, mudflats, rocky intertidal shore, sea grass beds, tidal streams and barrier beach habitats.

The watershed provides important wintering, migration, feeding and/or breeding habitats for a variety of migratory and resident waterfowl, shore birds, raptors, and song birds, including the Red listed spotted owl, Blue listed blue heron and fourteen other listed bird species. The watershed offers feeding, spawning and rearing grounds for four listed aquatic species, including Green sturgeon, Cutthroat trout, coho salmon and bull trout. The Squamish River and its tributaries support regionally-important anadromous runs of Chinook, coho, pink and chum salmon.

The Squamish River watershed area falls within the Coastal Western Hemlock, Mountain Hemlock, and Alpine Tundra biogeoclimatic zones. Eight listed mammals, three amphibians and two reptiles call the watershed home, including the Red listed Pacific water shrew, Blue listed grizzly bear and Blue listed coastal tailed frog. Harbour seals, river otters, black-tail deer, black bears, cougars, coyotes, mole, voles, and rabbits add further diversity to the watershed.

The watershed and estuary have been significantly altered by past and present human use, and, as such, the ecosystem and associated habitats are under significant pressure of fragmentation, degradation and loss. Significant pressures include residential and industrial developments, hydroelectric power projects, railway corridors, mercury contamination, former garbage dumps, invasive species, and development of the local dike system.

Historic construction of flood protection dikes isolated former side channels like Judd Slough, Harris Slough, Whittaker Slough, and Crescent Slough. Diking also isolated the present-day Mamquam River from its former alignment, which flowed south to Mamquam Blind Channel. Diking along the Cheakamus River in the 1950s helped to re-stabilize the river channel following a massive 1885/86 landslide on Rubble Creek (Clague et al., 2003), while diking along the Squamish River favours the present river alignment between the Cheakamus River and the Mamquam River. While there are benefits to favouring channel stability, the increased stability also makes it less likely that land previously lost to river erosion will be replaced by natural processes (e.g., Feeney, 1950).

Numerous parks have been created to protect the natural areas and provide recreational opportunities throughout the watershed. Significant parks within the District include:

- Alice Lake Provincial Park;
- Stawamus Chief Provincial Park;
- Brackendale Eagles Provincial Park;
- Shannon Falls Provincial Park;
- Murrin Provincial Park;
- Smoke Bluffs Park;
- Tiampo Park;
- Baynes Island Ecological Reserve, and
- Rose Park.

In addition to the significant park areas listed above, the District includes many smaller parks, greenways, and limited use natural areas. Portions of the Cheakamus River and Squamish River floodplains are within the provincial Agricultural Land Reserve, and the watersheds also support provincial Wildlife Habitat Areas for species such as the Marbled Murrelet (Cheekeye River, Mamquam River), Grizzly Bear (Squamish River), and Spotted Owl (Squamish River, Cheakamus River).

In the 1970s, development proposals threatened the remaining functional fish & wildlife habitats of the Squamish River estuary. As a result, the Federal Minister of Fisheries and Oceans and the Provincial Minister of Environment commissioned a management plan for the entire estuary. The aim was to establish a balance between protecting the area's biological productivity and achieving the full economic potential of the region. Continued work in the following decades resulted in the signing of the Squamish Estuary Management Plan (SEMP) in 1999 by the federal, provincial, and municipal governments, and invested stakeholders (SECC, 1999). The 1999 SEMP identified that most of the conservation area should become a Wildlife Management Area (WMA), and on February 28, 2007, the Skwelwil'em Squamish Estuary Wildlife Management Area was designed under the Wildlife Act. The WMA encompasses 673 hectares and provides exceptional habitat for fish and wildlife as well as hunting and fishing opportunities for people. Other recreational opportunities occur within the WMA and management must focus on minimizing recreation impacts to fish and wildlife.

Local stewardship groups continue to lead ongoing restoration and conservation efforts. District community plans acknowledge the ecological and social significance of the Squamish River Watershed, and co-operative ventures have led to recent successes such as the Mamquam Reunion project, which re-introduced freshwater drainage from the Mamquam River into Mamquam Blind Channel. The annual Brackendale Eagle Count is an example of how the local environment has been integrated into the economic and social fabric of the District.

Community and Culture

Squamish is an active, modern and multi-cultural community with a population of 19,500 living, working and playing within the District's watersheds. The District markets itself as the outdoor recreation capital of Canada, capturing the importance of the natural environment to residents and visitors.

The majority of community gathering places are located within flood hazard areas, including the historic town centre of Downtown Squamish. In addition, many of the unique recreation opportunities offered by the District have evolved directly or indirectly from the local river and marine systems; examples include kiteboarding on Howe Sound, biking on the local dike trails, fishing at the Mamquam River confluence, or counting eagles during the salmon run in Brackendale.

The Squamish Nation has a well-established cultural interest in the local watersheds that is strongly rooted in their history and traditions. Cultural uses of the watersheds include, but are not limited to, food fishing, hunting, and plant and herb cultivation and harvesting. Cultural and archaeological sites of significance are located throughout the watersheds. The Squamish Nation has an abiding interest in protecting the land and its resources; this interest extends far beyond the designated local reserves to encompass the full extent of traditional territories claimed by the Squamish Nation.

The majority of District lands also fall within the consultation area and traditional territories claimed by the Tsleil-Waututh Nation. Traditional territories claimed by the Tsleil-Waututh Nation and Squamish Nation overlap in the Squamish Valley area. While the two First Nations have separate governments and decision-making processes, Tsleil-Waututh and Squamish Nation share an interest in protecting aboriginal rights and title, preserving opportunities for cultural use, and environmental stewardship (e.g., Tsleil-Waututh Nation, 2009).

Industry and Development

The Squamish River watershed provides the stage and setting for most of the commercial and industrial operations carried out within the District of Squamish. Primary industries supported within the watershed include tourism, recreation, transportation, and forestry.

Development within the District consists of a mix of established neighborhoods and rural outlying areas. Most people within the District are dependent to some degree on regional transportation links for employment, recreation, or supplies. Several major employers (e.g., Squamish Terminals) and employment areas (e.g., Squamish Business Park) as well as businesses and institutions are in areas potentially vulnerable to flooding.

BC Hydro operates a major storage-supported hydroelectric generation facility at Daisy Lake on the Cheakamus River, about 13 km upstream of the District boundary. Several Independent Power Producers (IPPs) also operate run-of-river generation facilities on local rivers, including Ashlu Creek upstream of the Squamish River, two facilities on the Mamquam River mainstem, and a newer facility on Skookum Creek upstream of the Mamquam River. Run-of-river facilities typically generate power using only the natural flows in the river, and do not have significant storage capability.

2.2 Squamish River

Squamish River is a high-energy gravel bed river, with a morphology that changes as it flows downstream. The District of Squamish boundary is located approximately 2 km upstream of the Squamish River's present-day confluence with the Cheakamus River.

Upper River

About 50 km upstream of Howe Sound, the Squamish River is confined within a canyon. In this reach, Turbid Creek, Terminal Creek and Shovelnose Creek provide the river with substantial landslide debris from the Mt. Cayley volcanic complex. Debris avalanches and debris flows originating from the Mt. Cayley complex have temporarily impounded Squamish River on several occasions over the last 5,000 years (Brooks and Hickin, 1991). Eyewitness reports confirm that the June 1984 debris flow partially blocked the Squamish River; the resulting floodwave was detectable at a WSC station some 34 km downstream (P. Jordan & Associates, 1987). Debris flows in Turbid Creek have occurred multiple times since 1987, although none of these events are known to have dammed the river.

Lower River

Downstream of the canyon reach, the river assumes a steep, multi-channel braided morphology. It is likely that much of the coarse sediment delivered to the river from the Mt. Cayley complex is stored in this reach. As the river slope declines downstream, the river transitions from braided to wandering to meandering planform. The Cheekeye Fan, located approximately 12 km upstream of the delta, exerts local base control on the river gradient. The gradient increases again downstream of the Cheekeye Fan.

Within the District, two major side channels (Brackendale Slough and Baynes Slough) provide flood conveyance through the right bank floodplain. Two major side channels on the left bank (Judd Slough and Harris Slough) have been cut off from the mainstem by the Squamish River dike.

Historical reports indicate that Judd Slough and Brackendale Slough were part of the main river channel until 1908, when a logging barge ran aground near the inlet of what is now Brackendale Slough. Debris accumulated within Judd Slough and the main flow of the river was diverted into the present-day channel farther to the west. Near the south end of Judd Slough, the bouldery Stoney Creek fan redirected flow from the new main channel into Schonover Slough, which eroded to become the present-day channel through Squamish Nation Seaichem I.R. No. 16 and Eagle Run. Unsuccessful attempts were made to return the river to its previous course as early as 1911 (Feeney, 1950).

These extensive changes eroded considerable amounts of land and created challenges for properties whose legal limits were defined using the pre-1908 river course. Subdivisions, properties, and Squamish Nation reserve areas were now located wholly or partly within the main channel or on the inaccessible right (west) bank. Feeney (1950) measured land loss for five Squamish Nation reserves (Waiwakum I.R. No. 14, Aikwucks I.R. No. 15, Seaichem I.R. No. 16, Kowtain I.R. No. 17, and Yekwaupsum I.R. No. 18) and found a total loss of over 90 acres (37 ha) to river erosion prior to 1950. The most extreme loss occurred at Seaichem I.R. No. 16, where the Squamish Nation lost a total of 39 acres (16 ha) or 58% of the original reserve area.

Subsequent construction of the flood protection dikes followed the river channel, which had remained relatively stable since the mid-1900s (e.g., Feeney, 1950). By isolating Judd Slough and Harris Slough, the dike created hydraulic conditions that continue to favour the current river alignment, making it unlikely that the river will naturally return to its pre-1908 course. The Squamish Nation has expressed concerns about the dike alignment and its impacts for reserve lands, particularly because it “locks in” past losses while leaving unprotected parts of the riverbank vulnerable to continued flooding and further erosion.

Aerial photographs and field review confirm field observations of significant woody debris accumulation at the upstream end of Baynes Slough (opposite the Judd Slough pump station) and at the upstream end of the point bar across from the Eagle Viewing Area. These areas experienced some of the highest water levels (relative to dike crest) during the 2003 flood.

Water Survey of Canada (WSC) operates hydrometric station 08GA022 – Squamish River near Brackendale upstream of the District boundary. There are no bridges across the Squamish River within the District, and no development on the right (west) bank of the river.

Estuary and Delta

The Squamish River estuary extends only 6 km upstream from the delta, even at low flow, due to the relatively steep slope of the river (Hickin, 1989). Historically, the Squamish River flowed into Howe Sound through multiple channels. Human interference dates back many decades; Feeney (1950) states that Wilson Slough was cut off from the Squamish River by railroad operations sometime prior to 1950. In 1972, the BC Railway (now CN Rail) constructed a training berm to support the construction of a proposed coal terminal (Bell, 1975). While the coal terminal was never built, the training berm still confines virtually all Squamish River flow to the westernmost channel of the historic estuary.

Hickin (1989) estimated that the mean flux of sand and finer sediments from Squamish River to Howe Sound was about 1.3 million m^3 per year for the 1930 to 1973 period. The same study also confirmed that the delta was prograding into Howe Sound and increasing in height. As the delta progrades beyond the influence of the training berm, sedimentation is expected to become more dispersed and the rate of delta advance is expected to decline.

Numerous more recent studies have investigated the behaviour of the delta front in more detail and confirmed that the delta front experiences high-frequency small-scale mass wasting events (e.g., Clarke et al., 2012).

Hazards

The primary hazard associated with the Squamish River at Squamish is flooding. High flow on the Squamish River can typically occur because of:

- freshet snow and glacier melt, often combined with moderate rainstorms;
- intense summer rainfall events; and
- fall and early winter flooding from intense rainstorms or rain-on-snow events.

The average annual hydrograph of WSC hydrometric station 08GA022 is dominated by the snowmelt freshet, which peaks between June and August. However, extreme floods on the Squamish River are most often associated with intense rainfall events. About two-thirds of the annual maximum discharges at 08GA022 have been recorded during the fall/winter storm season, and only two of the largest fifteen floods on record occurred during the summer months. Of the two summer floods, the damaging August 1991 event was caused by intense rain and did not have a significant snowmelt component.

The flood of record on the Squamish River occurred in October 2003. Peak discharges recorded at upstream WSC hydrometric stations suggest that the return period of the flood was likely less than the historically-accepted “provincial standard” 200-year return period design flood.

High water events are often associated with high-velocity flows that can cause erosion and transport debris. Debris impact can damage or compromise bank protection works. Unprotected or compromised riverbanks can be washed out leading to a semi-permanent or permanent loss of floodplain land, as documented by Feeney (1950) for several local Squamish Nation reserves. Other examples of historical Squamish River erosion can be found in the flood damage recovery reports for the floods of 1980 (MacFayden, 1983), 1984 (BC Ministry of Environment [MOE], 1984), 1991 (Brown, 1991) and 2003 (KWL, 2004a; 2004b).

The post-1908 shift of the main channel from Judd Slough to its current alignment (Feeney, 1950) demonstrates the potential for significant channel changes. Significant changes in the channel can have mixed impacts on the community. For example, re-occupation of Brackendale Slough by the main river channel could locally reduce flood risk but could also have a negative impact on the recreational value of the Eagle Viewing Area.

In addition to rapid changes during flood events, evidence shows more gradual but significant changes occurring over time. In particular, sediment deposition can reduce the hydraulic cross-section and increase water levels at a given discharge. KWL (2011a) prepared a preliminary sediment budget that estimates average net aggradation of 11,500 m^3 per year for the reach between the Cheekeye fan and CN Rail North Yards. Work by Hickin (1989) suggests that a much larger volume of sediment regularly moves through the system to Howe Sound.

The Squamish River has not experienced any significant landslide dam-breach flood events in recent history; however, there is a possibility of such events happening in the future. A preliminary modelling study by Woods (1987) concluded that rapid breaching of a 35 m-high blockage could result in a large floodwave at Brackendale, but that the floodwave would not exceed the 200-year return period flood. The last blockage in excess of 35 m height occurred some 4,800 years before present (Brooks and Hickin, 1991). The conclusions of Woods (1987) were confirmed by KWL (2003) using more advanced software and more conservative blockage and breach conditions.

While landslide dam-breach floods do not provide governing conditions for the IFHMP, it should be recognized that water levels would rise much more quickly and with less warning than a rainfall-driven flood. The rapid, surging nature of the wave front would also likely initiate significant transport of sediment and woody debris.

Areas at Risk

A significant fraction of the District's developed area is located in the Squamish River left(east) bank floodplain, as well as the Highway 99 and CN Rail regional transportation corridors. Vulnerable neighborhoods include Brackendale, Eagle Run, Garibaldi Estates, North Yards, Squamish Business Park, Dentville, and Downtown Squamish.

The floodplain also supports many services relied on by residents who work and live outside the floodplain. Key community infrastructure within the floodplain includes numerous commercial and industrial facilities as well as the Municipal Hall, Emergency Operations Centre, Tantalus Fire Hall, RCMP Station, Wastewater Treatment Plant, Public Works Yard, Animal Control & Pound Office, Squamish Elementary School, Mamquam Elementary School, Howe Sound Secondary School, Brennan Park Recreation Centre, Squamish Public Library, West Coast Railway Heritage Park, BC Hydro's Squamish substation, and emergency response services. A recent business case for flood protection upgrades (KWL, 2013e) estimates a total value of dike-protected assets of nearly $2.4 billion. Approximate floodplain limits are shown in the BC Ministry of Environment's Squamish South Dike Inventory Map, included in Appendix B for ease of reference.

The Squamish River left bank floodplain also encompasses Squamish Nation communities at Seaichem I.R. No. 16, Kowtain I.R. No. 17, and Yekwaupsum I.R. No. 18 as well as undeveloped reserves or parts of reserves at Cheakamus I.R. No. 11, Poquiosin & Skamain I.R. No. 13, Waiwakum I.R. No. 14, and Aikwucks I.R. No. 15. Four other Squamish Nation reserves are located along the left bank of the Squamish River upstream of the District boundary.

The right bank of the Squamish River is undeveloped, but does encompass a series of parks between the Cheakamus River confluence and Howe Sound. The parks include (from upstream) Tantalus Provincial Park, Baynes Ecological Preserve, Brackendale Eagles Provincial Park and Tiampo Park. The remaining section of right bank between Brackendale Eagles Provincial Park and Tiampo Park falls within Spotted Owl Wildlife Habitat Area 2-517 and is designated as "Greenway Corridor and Recreation" in Schedule B of the District's Official Community Plan.

Undeveloped Squamish Nation Yookwitz I.R. No. 12 is located on the right bank of the Squamish River near the upstream District boundary, while Yekwaupsum I.R. No. 19 is located on the right bank opposite the Mamquam River confluence.

Significant portions of the Squamish River floodplain are held within the Agricultural Land Reserve (ALR), including areas on both banks at and upstream of the District boundary, the right bank at Baynes Slough, both banks along Brackendale Slough approximately from the north boundary of Squamish Nation Seaichem I.R. No. 16 to the Mamquam River, and the right bank approximately from the Mamquam River to the north end of Downtown Squamish.

2.3 Mamquam River

The Mamquam River drains an area of approximately 377 km^2 and flows into Squamish River about 5 km upstream of Howe Sound. Major tributaries on the north side of the Mamquam River mainstem include (from upstream) Skookum Creek, Ring Creek and Mashiter Creek, all of which drain the south flank of Mount Garibaldi. Raffuse Creek joins the Mamquam River from the south. Mean basin elevation for the Mamquam River is about 1,300 m, and alpine and glaciated areas constitute about 19% of the drainage area upstream of WSC hydrometric station 08GA075 – Mamquam River above Ring Creek. Most of the lower elevation valley terrain and slopes have historically been clear-cut.

The river exits a steep canyon just upstream of WSC hydrometric station 08GA075 and forms a fan that extends for about 5 km to the confluence with the Squamish River. The fan gradient is about 0.5%

(Sutek & Kellerhals, 1989). The active channel on the fan is irregularly sinuous with large gravel bars. Secondary channels convey flow around the bars, overtopping them at higher flow. The District boundary is located about 2.5 km upstream of the Raffuse Creek confluence, or about 13 km upstream of the Squamish River confluence.

There are three major bridges across the Mamquam River within the District, including (from upstream) Highway 99, Government Road, and CN Rail. A Forest Service Road (FSR) bridge crosses the river about 1.5 km upstream of Ring Creek.

Historically, the Mamquam River flowed to Howe Sound roughly following the alignment of the recently completed Mamquam Reunion Project to Britannia Slough and Mamquam Blind Channel. The river changed to its current course during the 1921 flood. The current river alignment is maintained by the dikes, which also cut off overtopping that would periodically re-water the old channel in the decades following the 1921 flood (Feeney, 1950). Recently, the District worked with a number of environmental stakeholders to complete the multi-year Mamquam Reunion project, which installed structures and upgraded channels to provide divert a small amount of flow from the Mamquam River to Loggers Lane Creek and Mamquam Blind Channel. Early indications are that this high-profile restoration project has had significant environmental benefits (e.g., SRWS, 2007).

A preliminary sediment budget prepared by KWL (2011a) estimates that there was a net accumulation of gravel between Mashiter Creek and the Squamish River for the 1981 to 1995 period (averaging about +20,000 m^3/year). Conversely, the 1995 to 2008 period saw modest net degradation averaging about -2,300 m^3/year. This change in sediment regime occurred in the context of gravel removals in the 1980s that were about 5.5 times larger than the estimated rate of gravel supply (Sutek & Kellerhals, 1989).

The net accumulation that occurred during the 1981-1995 period is in contrast with expected temporary bed lowering that often follows sediment removal. This apparent discrepancy may be a result of the multiple large peak flow events that occurred during the same time period, since significant bed material transport usually accompanies periods of sustained high flows.

In comparison, the later period of observed bed lowering did not see many high flows, and the high flows were not particularly large floods on the Mamquam River. It is expected that once the river fully recovers from the large removals in the 1980s, the fan will return to a net depositional regime again and the channel bed will start to rise more uniformly (KWL, 2011a).

Mashiter Creek, which joins the Mamquam River at the upstream end of the developed area, was diverted to its present course a short distance upstream of the Mamquam River confluence, having previously flowed to the Mamquam River through the Squamish Golf & Country Club area (NHC, 1997). The District maintains a backup water supply intake on Mashiter Creek. The operation of the intake has been affected by sediment accumulation and must be cleaned out by the District from time to time, most recently in 2013 (M. Simmons, pers. comm.).

Hazards

Flooding is the primary hazard on the lower Mamquam River. Floods are caused by intense rain events, although the average annual hydrograph shows a sustained period of sustained high flows during the freshet. High flows on the Squamish River can also cause backwater conditions on the lower Mamquam River. Backwater conditions are typically present (to varying degree) during Mamquam River flood events.

High water events are typically associated with high-velocity flows that can result in erosion and transport debris. Debris impact can damage or compromise in-stream structures and bank protection works. Unprotected or compromised slopes can be washed out leading to a permanent loss of floodplain land.

The active sediment transport regime of the Mamquam River makes channel aggradation a reasonable hazard consideration even though there has been recent channel degradation (KWL, 2011a).

While newer bridges were designed to pass conservative peak discharges (e.g., NHC, 2006), the low chord of the CN Rail bridge is well below the top of the adjacent dikes. The bridge structure also has numerous piers within the high-flow channel that could increase the potential for debris jams and conveyance reductions. During the peak of the 2003 flood, the lower reach of the Mamquam River was backwatered by the Squamish River and there was minimal freeboard to the low chord of the CN Rail Bridge (KWL, 2004a).

Although no significant landslide dam-breach flood events have been experienced in recent history, there is a possibility of such events happening in the future. Flood waves may also be produced by catastrophic failure of IPP intake works. Given the limited quantity of storage at run-of-river facilities, it is not expected that an IPP dam-breach floodwave could approach design flood levels within the District reaches of the Mamquam River.

Areas at Risk

A significant fraction of the developed area of the District of Squamish is located in the Mamquam River floodplain, as are the Highway 99 and CN Rail regional transportation corridors. Vulnerable neighborhoods include Garibaldi Estates, North Yards, Squamish Business Park, Dentville, and Downtown Squamish. The Mamquam River floodplain also encompasses the Squamish Nation community at Kowtain I.R. No. 17 and a flood could potentially also affect the community at Yekwaupsum I.R. No. 18.

The floodplain also supports many services relied on by residents who work and live outside the floodplain. Key community infrastructure within the floodplain includes numerous commercial and industrial facilities as well as the Emergency Operations Centre, RCMP Station, DistrictPublic Works Yard, Animal Control and Pound Office, Brennan Park Recreation Centre, Howe Sound Secondary School, Squamish Elementary School, Mamquam Elementary School, Squamish Montessori School, West Coast Railway Heritage Park, Downtown Squamish including the Municipal Hall, BC Hydro Squamish substation, Public Library, and emergency response services. Approximate floodplain limits are shown in the BC Ministry of Environment's Squamish South Dike Inventory Map, included in Appendix B for ease of reference.

Key environmental assets at risk include fisheries channels on the north and south banks of the river as well as the intake and conveyance works for the Mamquam Reunion project.

Significant erosion of the unprotected floodplain upstream of Mashiter Creek occurred during the 2003 flood. Progression of this erosion could potentially threaten future District potable water production wells and eventually Mamquam Road (KWL, 2005).

2.4 Cheakamus River

The Cheakamus River drains a large mountainous basin with a total drainage area of about 1,040 km². Its headwaters are located in the Fitzsimmons Range within the Resort Municipality of Whistler. The Cheakamus River flows through the District for over 13 km from Culliton Creek to the Squamish River at the northern margin of the Cheekeye Fan.

Three major lakes are located in the watershed: Cheakamus Lake, Garibaldi Lake and BC Hydro's Daisy Lake reservoir. Cheakamus Lake is a mainstem lake located in the upper watershed. Garibaldi Lake is located upstream of the Barrier lava formation and flows into Rubble Creek, which in turn meets the Cheakamus River downstream of Daisy Lake dam.

Since Daisy Lake dam was completed in 1957, BC Hydro has diverted water from Daisy Lake reservoir to a powerhouse on the Squamish River via an 11 km tunnel. The maximum diversion flow is 65 m^3/s (BC Hydro, 2005). While storage and diversion at Daisy Lake are significant in terms of hydropower operations and average annual flows, the available (or "live") reservoir storage is not sufficient to provide reliable flood protection for downstream communities (Nichols, 1986). This was clearly demonstrated by the damaging floods of 1980, 1984, 1991, and 2003. In recent years, BC Hydro has worked with a group of local and regional stakeholders to develop a comprehensive Water Use Plan that considers a variety of stakeholder interests (BC Hydro, 2005).

Downstream of Daisy Lake dam, the river flows through the well-confined reach of Cheakamus Canyon before emerging onto a relatively narrow floodplain a short distance upstream of Culliton Creek. The BC Hydro dam presents a barrier to sediment and woody debris transport, and the Cheakamus River mainstem does not supply any significant amount of material to the upstream end of the canyon reach. Natural input of sediment and debris from tributaries between Daisy Lake and the District boundary at Culliton Creek is estimated at a relatively modest 1,700 m^3/year (NHC, 2001). An air photo review completed by EBA (2012a) suggests that the mainstem Cheakamus River channel has been downcutting (lowering) since Daisy Lake Dam was completed in 1957. In addition to downcutting and related changes in downstream morphology, the loss of woody debris can negatively impact habitat values.

While baseline sediment and debris inputs do not offset the loss of mainstem sediment above the dam, tributaries such as Rubble Creek and Culliton Creek are still capable of delivering large pulses of sediment to the river mainstem as debris flows. The most famous example of a tributary debris flow reaching the Cheakamus River is the ca.1855 slide on Rubble Creek. These events have the potential to dam the river until the mainstem flow overtops and breaches the landslide dam, resulting in an outburst debris flood.

Further downstream, the Cheekeye River delivers large, frequent pulses of sediment that can backwater the Cheakamus River to varying degrees. Cordilleran Geoscience (2008) notes that partial or momentary blockage of the Cheakamus River has occurred on average every twenty years over the last two centuries (Cordilleran Geoscience, 2008). However, high flows and floods on the Cheakamus River will usuallymove most of the Cheekeye sediment downstream toward the Squamish River. Historical records show that the Cheakamus River channel elevation downstream of the Cheekeye confluence has varied by up to 3.6 m over relatively short periods (Bland Engineering Ltd., 1996).

The 1991 Cheekeye River debris flow demonstrated that some debris carried into the Cheakamus River may be too large to be re-mobilized by Cheakamus River floods. Such deposits can create semi-permanent local grade control without human intervention (Bland Engineering Ltd., 1996).

Three bridges cross the Cheakamus River below Cheakamus Canyon, including (from upstream):

- A pedestrian suspension bridge at Misty's Lane, about 6.5 km upstream of the Bailey Bridge along Paradise Valley Road.
- Paradise Valley Road bridge (known as the Bailey Bridge), located about 3 km upstream from Fergie's Bridge along Paradise Valley Road; and

- Squamish Valley Road bridge (known as Fergie's Bridge), located 3.1 km upstream of the Squamish River.

The Cheakamus River breaks into a network of distributary channels downstream of Fergie's Bridge. The channel has been observed to shift with significant peak flow events (KWL, 1998a).

WSC hydrometric station 08GA043 – Cheakamus River near Brackendale has measured flow between the Bailey Bridge and the Cheekeye River since the late 1950s. Discontinued hydrometric station 08GA017 – Cheakamus River at Garibaldi operated further upstream near the Rubble Creek confluence from 1916 to 1969.

Hazards

Flooding and erosion from the Cheakamus River constitute the primary flood hazards. High flows on the Cheakamus River typically result from:

- freshet snow and glacier melt, often combined with moderate rainstorms;
- intense summer rainfall events;
- fall and early winter flooding from intense rainstorms or rain-on-snow events; and
- infrequent landslide dam breach outburst debris floods that occur after a debris flow from a tributary blocks the main channel.

The annual hydrograph for WSC hydrometric station 08GA043 is dominated by the snowmelt freshet, which peaks between June and August. However, extreme floods on the Cheakamus River are most often associated with intense rainfall events.

BC Hydro operations at Daisy Lake transfer water from the Cheakamus River to the Squamish River for hydropower generation. Historically, this has reduced peak flows in the lower Cheakamus River. However, it is possible that the hydropower diversion may be shut down during an extreme flood event. BC Hydro routinely provides confirmed notice of spill to the District (BC Hydro, 2013). Expected floodwave travel time from Daisy Lake dam to the District boundary at Culliton Creek is about 45 minutes.

Despite the interruption to sediment transport processes imposed by Daisy Lake dam and EBA's (2012a) conclusion that the mainstem channel is generally downcutting, KWL (1998a) notes that site-specific aggradation within the District reaches is still a possible hazard for any given location and flood event. Floods on the lower Cheakamus River can still be accompanied by significant bedload movement and debris transport. High-flow events can mobilize (erode), transport, and deposit material at different locations during different events. High velocity and debris impact can damage or compromise bank protection works and in-stream structures. Unprotected or compromised slopes can be washed out leading to a permanent loss of floodplain land.

Sediment processes have a particularly strong localized effect at the Cheekeye River confluence. The August 1958 debris flow raised the bed for several hundred metres downstream by several feet (Klohn Leonoff, 1994a). Survey records summarized by Bland (1992c) show that the August 1991 debris flow raised the bed by about 3 m at Fergie's Bridge. Similar behaviour on a lesser scale has been observed during more recent events in 2009 (KWL, 2013a) and 2013 (M. Simmons, pers. comm.). Documented sediment and debris removals at or near the mouth of the Cheekeye River have taken place in 1981, 1983, 1985, 1995, 2012, and 2016 (Thurber & Golder, 1993; Bland Engineering Ltd., 1996; KWL, 2013a; CERG, 2016).

The magnitude and frequency of the Cheekeye River sediment inputs are likely responsible for the historic channel migration evident in historic aerial photographs as well as the network of side channels and relict channels both at and downstream of Fergie's Bridge. Of particular note, Bland Engineering Ltd. (1996) refers to strong evidence that the river had a 1921 active channel on the far side of the existing Squamish Nation Cheakamus community on I.R. No. 11.

Channel obstructions at the Cheekeye River confluence can create flood conditions both upstream (i.e., prior to landslide dam breach) and downstream (immediately following a landslide dam breach). Fergie's Bridge and the Bailey Bridge cannot pass the full range of flood flows (Bland Engineering Ltd., 1996; AMEC, 2002) and present additional potential for debris blockage. Thurber & Golder (1993) and Bland Engineering Ltd. (1996) recommend that any residential development on the lower Cheakamus make allowance for complete channel blockage at Fergie's Bridge.

Cheakamus River Landslide Dam Outburst Floods

As previously noted, debris flows on Cheakamus River tributaries such as Rubble Creek and Culliton Creek can reach and block the mainstem Cheakamus River. While the creek fans and corresponding runout zones are largely outside the District boundary, such blockages could conceivably increase flood hazards downstream of the creek confluence (i.e., by generating an outburst flood surge when the landslide dam fails). This process is called a Landslide Dam Outburst Flood (LDOF). LDOFs are a type of debris flood.

Cordilleran Geoscience (2008) concludes that Culliton Creek debris flows have:

- backwatered the Cheakamus River at least four times over the last 5,400 years; and
- affected Paradise Valley with an average annual exceedance probability of 1 in 4,000 to 1 in 6,000.

EBA subsequently completed a detailed geohazard review (EBA, 2012a) of the hazards identified in the Cordilleran Geoscience report. EBA (2012a) recommends annual probabilities for debris flood scenarios as follows:

- **1 in 5,000**: a debris flow on Culliton Creek creates a 5 m-high landslide dam during the 1 in 500-year return period Cheakamus River flood.
- **1 in 10,000**: a larger debris flow on Culliton Creek creates a 10 m-high landslide dam during the Cheakamus River Mean Annual Flood.
- **1 in 5,000**: a debris flood originates within the canyon reach due to a wall collapse.

LaCas Consultants (2012) completed hydrodynamic modelling of EBA's Culliton Creek debris flood scenarios. Results indicate that attenuation would be rapid and significant: by 2 km downstream of Culliton Creek, debris flood water levels are less than those obtained by modelling the 500-year return period clear-water peak flow under steady-state conditions, even after applying an additional allowance for sediment deposition. The LaCas report was reviewed by EBA (2012b) and peer reviewed by KWL (2012).

Independent modelling by KWL (2010b) confirms the significant attenuation noted in the LaCas report. KWL concludes that hydraulic discharge (i.e., before bulking) from a 10 m-high debris dam failure during the Mean Annual Flood would approximate the 200-year return period peak flow. Attenuation saw KWL's peak discharge drop to about 1,200 m^3/s (or about 75% of the present-day 200-year return period clear-water flood) by the time the flood wave reached the Cheakamus Centre (formerly North Vancouver Outdoor School). Significant attenuation was also observed in the real-world example of the massive Capricorn Creek debris flow that dammed Meager Creek near Pemberton in 2010 (Guthrie et al., 2012).

The 1885/86 debris flow on Rubble Creek demonstrated that Rubble Creek is also capable of blocking the Cheakamus River. EBA (2012a) cites a previous report that assigned a probability of between 1 in 3,700 and 1 in 5,500 to the 1885/86 event. While the event itself was very significant, Clague et al. (2003) suggest that subsequent sediment redistribution to downstream areas resulted in 1 to 2 m of aggradation at the Cheakamus Centre over the years following the landslide. Baumann (2012) and EBA (2012) conclude that a repeat of the 1885/86 Rubble Creek event would have no direct impact on a development site about 2 km inside the District's northern boundary. Similar conclusions are reached in an earlier report on the 1855/56 event (P. Jordan, 1987).

While detailed analysis of landslide dam-breach floods is outside the scope of the IFHMP, it should be recognized that these rare events can still cause a significant increase in risk (i.e., beyond the clear-water flood hazard), particularly for development within the narrow upper Paradise Valley. Peak flows would be accompanied by water levels that rise much more quickly and likely with less warning than a rainfall-driven flood. The rapid, surging nature of the wave front would also likely initiate significant transport of sediment and woody debris.

Very Low Probability Hazards

The high vertical cliff at the Barrier has long been debated regarding its potential for catastrophic collapse. The well-documented potential for rockfall, landslides and debris flows led to creation of the Garibaldi Civil Defense Zone in 1980 and the subsequent relocation of the Garibaldi community. A catastrophic collapse could release water from Lesser Garibaldi Lake and Barrier Lake, and could initiate a debris flow capable of blocking the Cheakamus River or running out into Daisy Lake.

Some people think that catastrophic collapse of the Barrier could also release water from the much larger Garibaldi Lake. A much-quoted Wikipedia article on the Barrier (Wikipedia, 2017) speculates that collapse of the barrier could generate a floodwave capable of reaching Vancouver Island. However, the IFHMP team confirmed that the research cited by the Wikipedia article was taken out of context.

Baumann (2012) states categorically that there has never been any suggestion in any scientific study that the Barrier will eventually collapse to the point of creating an uncontrolled release of Garibaldi Lake. EBA (2012a) states that the probability of this event would be less than 1 in 10,000, and that there is no reason to expect a change in behaviour over time.

Another very remote but high-consequence flood scenario involves rapid failure of Daisy Lake dam. If this were to happen during high-flow conditions, it could overtop the dikes in Squamish. However, BC Hydro dams are designed to very stringent standards that make allowance for extreme events. Like a catastrophic collapse of the Barrier, the likelihood of dam failure at Daisy Lake is sufficiently remote that it typically falls within the purview of emergency response planning rather than flood hazard mitigation.

Areas at Risk

The primary area at risk for Cheakamus River flooding is Paradise Valley, referring to the area roughly bounded by Fergie's Bridge in the south and Cheakamus Canyon in the north. The floodplain throughout Paradise Valley is developed at a rural level. A small community at Misty's Lane is located in the floodplain north of the District boundary and falls under the jurisdiction of the Squamish-Lillooet Regional District (SLRD). Paradise Valley Road provides the only road access to the area via Fergie's Bridge and the Bailey Bridge. Previous floods have washed out roads and bridges and cut off access to the valley (e.g., KWL, 2004a).

The Cheakamus River right bank floodplain includes the Cheakamus and Moodyville communities on Squamish Nation Cheakamus River I.R. No. 11. The Cheakamus community is located a short distance downstream of Fergie's Bridge, while the Moodyville community is located a short distance upstream of the Cheekeye River confluence. Poquiosin & Skamain I.R. No. 13 is located immediately upstream of the Squamish River confluence. Erosion of reserve land is a significant concern for the Squamish Nation at Cheakamus I.R. No. 11 and Poquiosin & Skamain I.R No. 13, particularly where it has affected archaeological sites.

In addition to rural development throughout the Paradise Valley, the CN Rail mainline traverses sections of the left bank in an alignment directly adjacent to some reaches of the Cheakamus River.

An environmentally-significant fish hatchery and spawning channel network are located at BC School District No. 44's Cheakamus Centre, formerly (and still locally) called the North Vancouver Outdoor School (NVOS). Significant portions of the floodplain have been diked off in the vicinity of NVOS. Fisheries stakeholders are currently developing plans to extend the network of channels southward through Squamish Nation I.R. No. 11, rejoining the mainstem upstream of Cheekeye River. Ongoing bank erosion near the Squamish Nation community of Moodyville could allow the river to reactivate some of these side channels.

Portions of the Cheakamus River floodplain are held within the Agricultural Land Reserve (ALR), including areas on both banks for a distance of about 1,800 m north of the Bailey Bridge and most of the right bank from the Bailey Bridge to the Squamish River confluence.

Approximate floodplain limits are shown in the BC Ministry of Environment's Squamish South Dike Inventory Map, included in Appendix B for ease of reference. BC Hydro dam breach inundation mapping is not publicly available.

2.5 Cheekeye River

The Cheekeye River watershed has a drainage area of about 58 km² with one major tributary, Brohm River. The Brohm River flows into the Cheekeye River just upstream of the Highway 99 bridge. The Cheekeye River joins the Cheakamus River about 200 m upstream of Fergie's Bridge.

The Cheekeye River is unique among the District's five large rivers, being subject to periodic debris flow events as well as more modest, annual rainfall-generated and snowmelt-generated floods. Debris flows may be thought of as water-saturated 'channelized landslides': they have very high sediment concentrations that alter the physics of the flow.

Debris flood peak flows are much higher than would be observed for corresponding clear-water floods. For example, the 200-year return period flood for the Cheekeye River has been estimated as high as 300 m³/s (Thurber & Golder, 1993); in comparison, the estimated 200-year return period debris flow discharge has been estimated an order of magnitude higher (e.g., BGC, 2008).

The highest elevations of the watershed include the slopes of Mt. Garibaldi (2,670 m elevation), while the ground elevation near the Cheakamus River is about 25 m. The channel gradient is very steep in the headwaters and declines with distance downstream. This causes the river to lose energy as it travels, which in turn promotes deposition. As the Squamish Nation name for the river (meaning "dirty water") suggests, so-called "clear-water" peak flows are rare on the Cheekeye River and even these "clear-water" high-flow events are accompanied by significant bedload movement.

Factors that govern whether a given event on the Cheekeye River becomes a flood, debris flood or debris flow include the amount of sediment available for entrainment (e.g. was there a landslide into the channel, or did the event simply entrain ravelled material stored in upper watershed gullies?) and the runoff intensity (e.g. the rainfall and/or snowmelt associated with the event). The largest debris flows are expected to originate as landslides in the upper watershed.

The Cheekeye River has a substantial fan below about 600 m elevation that stretches from its current northerly confluence with the Cheakamus River southward to the community of Brackendale. There is a significant body of research into the Cheekeye River, with particular emphasis on the fan feature and the processes governing its formation. A comprehensive listing is provided by Clague et al. (2014).

Due to its active sediment transport regime, fisheries values on the Cheekeye River are lower than other local rivers. The lower Cheekeye River does provide anadromous fish with access to more favourable spawning and rearing areas on the Brohm River.

The Cheekeye River is crossed by two bridges: Highway 99 near the fan apex and the CN Rail bridge near the Cheakamus River confluence. A temporary private bridge between Highway 99 and the CN Rail bridge provided intermittent property access until it was removed by BC MFLNRO in 2015 (M. Simmons, pers. comm.).

Hazards

Debris flows and channel avulsion are the primary hazards associated with the Cheekeye River. Debris flows have the potential to cause massive damage and catastrophic loss; however, events of this magnitude represent a special class of hazards far more severe but often less likely than those normally considered for conventional flood protection. As such, both planning and protection require input from experienced specialists. A panel of distinguished experts has recently provided a comprehensive hazard assessment report for the Cheekeye Fan (Clague et al., 2014).

In addition to quantifying an appropriate magnitude for the 10,000-year debris flow, the expert panel's report provides a magnitude-frequency relationship for debris flow events that characterizes the range of debris flow hazards posed to existing development and future development opportunities.

While the existing Cheekeye River channel appears well-established to the casual observer, debris flows and sediment floods create conditions that could support a process of extreme and rapid change called avulsion. Paleochannels across the Cheekeye Fan offer historical examples of this behaviour. Avulsions may see the river form a new channel, re-occupy an old channel, or flow diffusely over the fan surface. The most likely locations for an avulsion to initiate are upstream of the Highway 99 bridge, at the sharp bend in the channel alignment (sometimes referred to as the "dogleg"), or upstream of the CN Rail bridge (Thurber & Golder, 1993).

Smaller flood and debris flow events also contribute to on-going channel aggradation, which increases more conventional flood hazards to adjacent properties. It is possible for material transported and deposited by a debris flow to remain in place for an extended period (i.e., years to decades or longer). Historically, aggradation impacts on flood hazard have been mitigated to varying degree by in-channel sediment removals, including larger removals upstream of the CN Rail Bridge in 1985 and 1991, as well as a series of smaller removals downstream of the CN Rail bridge (Thurber & Golder, 1993; KWL, 2013a).

The Cheekeye Fan is a largely depositional environment, but erosion remains a potential hazard, primarily for bridge abutments and riparian structures.

Following the 1991 flood, a pair of studies (Bland, 1992b; Thurber & Golder, 1993) reviewed the potential for erosion near the fan apex to induce a flood by releasing Cat Lake. The reports conclude that the amount of erosion required was improbable in a single event, and that a large flood may not develop even if lateral erosion did reach Cat Lake. The authors of the 1992 and 1993 studies recommend periodically reviewing this conclusion in response to any ongoing gradual erosion.

Areas at Risk

The expert panel's recent report (Clague et al., 2014) concludes that all areas of the Cheekeye Fan are exposed to risk from extreme debris flows. This encompasses an area bounded by the existing channel of the Cheekeye River, Cheakamus River, and Squamish River, including parts of Brackendale and Alice Lake Provincial Park. Development in this area is generally rural at present, except for the suburban Brackendale community.

Key infrastructure on the Cheekeye Fan includes BC Hydro's Cheekye substation, the CN Rail mainline, Highway 99, Brackendale Elementary School, Don Ross Secondary School, and Squamish Municipal Airport. The area at risk also includes Squamish Nation communities at Waiwakum I.R. No. 14 and the Cheakamus community on I.R. No. 11, as well as undeveloped reserves Poquiosin & Skamain I.R. No. 13 and Aikwucks I.R. No. 15.

The Sunwolf recreational facility and Cheakamus community on Squamish Nation I.R. No. 11 are among the most at-risk areas, as theyare directly exposed to conjoined Cheekeye River and Cheakamus River hazards and the potential interactions thereof.

The District's current Cheekeye Fan Hazard Areas can be found on Sheet 1 of the 1994 FHMP's Flood Hazard Management Planning Map (Klohn Leonoff, 1994b). The District is reviewing debris flow risk mitigation for the Cheekeye fan in a separate but parallel process to the IFHMP.

2.6 Stawamus River

The 55 km² Stawamus River watershed drains a steep, heavily-forested glacially-carved watershed ranging from over 2,000 m elevation at Sky Pilot Mountain to tidewater at Howe Sound. Watershed slopes are very steep between about 1,000 m elevation and 200 m elevation.

The watershed has one significant tributary, Ray Creek. The District boundary is located downstream of Ray Creek and about 900 m upstream of the Mamquam Forest Service Road (FSR) bridge. A number of other forestry bridges are located throughout the upper watershed. A smaller tributary, Little Stawamus Creek, joins the Stawamus River between the Valleycliffe neighbourhood and Squamish Nation Stawamus I.R. No. 24. On Stawamus I.R. No. 24, the river passes under bridges at Highway 99 and the CN Rail mainline.

The Mamquam FSR Bridge is a clear-span bridge, but may be a hydraulic constriction at high flows.

The Highway 99 Bridge is also a clear-span bridge; however, a June 2014 field visit by KWL found that abutments from the previous bridge remain in place below the current clear-span bridge deck. The old abutments constrict the available conveyance to significantly less than the new bridge dimensions suggest.

The CN Bridge is a low-clearance reinforced-concrete structure with a single pier located mid-span. Hydraulic capacity of the CN Rail bridge opening is less than either of the two upstream bridges.

Downstream of the CN Rail bridge, the Stawamus River flows along the south side of a low-lying part of Squamish Nation Stawamus I.R. No. 24 (sometimes referred to as "the island"). Industrial activity previously filled in and blocked a former channel to the northwest of the current river alignment (KWL, 1998b). Both the current river and the former channel drain directly into Mamquam Blind Channel.

Substrate in the upper District reaches of the Stawamus River is coarse and bouldery. A predictable change to progressively finer materials can be observed as the channel gradient drops from several percent to nominal on the fan.

WSC operated hydrometric station 08GA064 – Stawamus River below Ray Creek from 1972 to 1989, measuring discharge from a reported watershed area of 40.4 km². WSC has operated active hydrometric station 08GA076 – Stawamus River at Highway No. 99 since 1991, measuring discharge from a reported watershed area of 52.8 km².

The District maintains a backup water supply intake on the Stawamus River about 400 m upstream of the Mamquam FSR Bridge (KWL, 1998b). A natural gas pipeline and BC Hydro transmission lines also traverse the watershed. Baumann (1994) carried out extensive terrain mapping and identified the potential for landslides reaching and damming the mainstem, resulting in dam breach outburst floods. The potential for debris floods has not been addressed in subsequent peak flow assessments and to KWL's knowledge has not been quantified by an engineering study.

Hazards

The primary hazard on the Stawamus River is flooding. In the higher-elevation areas of Valleycliffe, the primary hazards are overbank flooding and lateral erosion of the channel. The river breached its banks near the elementary school during the December 1980 flood (MacFayden, 1983). Bridge blockage at the Mamquam FSR could exacerbate the hazards in the upstream District reaches adjacent to Valleycliffe.

Low-lying areas at the base of Hospital Hill, including the Highway 99 and CN Rail rights-of-way and Squamish Nation Stawamus I.R. No. 24 are likely to experience lower velocities but more widespread inundation. Valley Drive between Highway 99 and Guilford Drive is inundated and closed during relatively moderate peak flow events, most recently in February 2015.

Channelization and diking in the Valleycliffe area (see Section 4.5) may have facilitated greater sediment transport and thereby increased the potential for flooding in flatter depositional areas further downstream (KWL, 1998b). Downstream of Highway 99, the river has limited channel capacity as a result of sediment aggradation and low-elevation riparian topography. Flooding could be exacerbated if sediment or debris were to obstruct the bridge openings at Highway 99 and/or the CN Rail crossing.

Gravel has been removed from the Stawamus River in the past (KWL, 1999), and in 2013 the District dredged about 100,000 m³ of material from the Mamquam Blind Channel at the Stawamus River confluence. KWL (1998b) previously recommended that the Squamish Nation consider the need for sediment management as part of a larger flood and erosion hazard management program.

Landslide dam-breach debris floods are possible in the Stawamus River watershed (Baumann, 1994). The concerns raised in Baumann's 1994 report are validated by a subsequent report that reviews an area of instability along the FortisBC Vancouver Island gas main installed in 1996(D. Roulston, pers. comm.). The FortisBC post-project report could not be obtained for this study. This hazard was not considered in the 1994 FHMP (Klohn Leonoff, 1994a) and is not presently identified in Schedule D1 of the District's Official Community Plan (DoS, 2009).

Peak flows for debris floods are commonly 2 to 5 times that of the 200-year return period clear-water flood (Jakob & Jordan, 2001). However, debris floods are poorly understood and the reported range should only be used as a preliminary guideline. The 1994 FHMP assumed a relatively high 200-year return period daily-average peak flow of 410 m³/s (8.2 m³/s/km²) for dike breach simulations (Klohn Leonoff, 1994a). This value is overly conservative for clear-water floods but is considered more reasonable for a possible debris flood scenario.

The Stawamus River estuary is also subject to coastal backwater flooding from Howe Sound as described in Section2.8.

Areas at Risk

Provincial floodplain mapping has not been completed for the Stawamus River; however, Klohn Leonoff produced hazard mapping as part of the 1994 FHMP. The Stawamus River area is shown on Sheet 3 of the Flood Hazard Management Planning Map.

Areas at risk generally include the Valleycliffe residential neighborhood, Valleycliffe Elementary School, areas surrounding the lower part of Little Stawamus Creek, and low-lying areas of Squamish Nation I.R. No. 24. Key infrastructure includes Highway 99, Valley Drive and the CN Rail mainline. The Squamish Nation gas station and Chances Squamish (casino) are located adjacent to the river immediately upstream of the Highway 99 Bridge.

2.7 Smaller Creeks and Landslide Hazards

In addition to the five major rivers and their tributaries, the District's land area also includes numerous small, steep creeks that can present flood, debris flow, sedimentation, and erosion hazards. Of these hazards, debris flows are the most severe and often the most difficult to characterize.

The 1994 FHMP identifies a number of local streams as candidates for potential debris flow hazards based on a topographic assessment of channel gradients. Named creeks include (Klohn Leonoff, 1994a):

- **Monmouth Creek** on the west side of the Squamish River near the mouth;
- **Fries Creek** on the west side of the Squamish River across from Brackendale;
- **UnnamedCreek** on the west side of Squamish River north of Squamish Nation Yookwitz I.R. No. 12;
- **Gonzales Creek** below Petgill Lake, south of Shannon Falls Provincial Park;
- **Olesen Creek** draining the back side of the Stawamus Chief massif;
- **Ring Creek** above Mamquam River; and
- **Mashiter Creek**, including both south fork and north fork.

The 1994 FHMP categorizes these creeks by debris flow potential as very low (Fries), low (Monmouth, Olesen, and Mashiter North Fork), moderate (Unnamed, Gonzales, Ring) and moderately high (Mashiter South Fork). The screening level applied in the 1994 FHMP was based on general guidelines and available mapping. This general screening process is still considered reasonable and was not revisited for the current IFHMP.

In addition to the creeks listed in the 1994 FHMP, EBA (2012a) confirms that Culliton Creek at the District's northern boundary can also produce debris flows.

Landslides

Debris flows represent an intermediate stage of a continuum of gravity-driven transport processes that spans from floods to landslides and rockfall. Landslide and rockfall hazards are possible in any area of steep relief and are usually quite site-specific.

Evaluating landslide and rockfall hazards requires specialized engineering or geoscience input that is outside the scope of the IFHMP. Nonetheless, the District should consider making allowances to incorporate landslide, rockfall and slope stability hazards in any future comprehensive natural hazard mitigation policy initiatives.

2.8 Howe Sound and Coastal Sloughs

Coastal flood hazards at Squamish are driven by a combination of astronomic tide, external storm surge, local wind and wave setup effects, and wave interaction with the shoreline. Decision-makers and design professionals must consider the expected combined effects of all processes to establish an appropriate level of safety for coastal protections and protected areas. Each of these processes is described below.

Astronomical Tide

Astronomic tide is the regular and predictable variation in water levels caused by the gravitational interactions of the Earth, Sun, and Moon. The highest tides (technically called “perigean spring tides”, but sometimes less accurately referred to as “King Tides”) occur when the sun and moon are aligned and the moon is at its closest point of approach to the earth.

Tides vary with the fortnightly, seasonal, and 18.6-year lunar cycles. Each 18.6-year cycle is referred to as a “tidal epoch”, usually rounded to 19 years for convenience. The highest tides of each year typically occur in the winter around the New Year.

The Canadian Hydrographic Service (CHS) regularly calculates tide predictions for Squamish (#7810). Predictions are based on short-term data collected in the 1970s, 1990s and 2000s. The nearest long-term gauging station is located at Point Atkinson (#7795) in West Vancouver.

CHS publishes tide predictions and observed water levels in Chart Datum (CD). Chart datum is selected to represent a level that the water seldom falls below. The CHS chart datum is the plane of Lowest Normal Tide (LNT), which is equivalent to Lower Low Water, Large Tide for most modern charts (FOC, 2014).

The appropriate conversion from CD to local geodetic benchmarks can change gradually over time in response to processes such as Sea Level Rise and local subsidence. Mean Water Levels (MWL, expressed in CD) are included in the CHS publications (e.g., FOC, 2014) and provide an approximate conversion between CD and geodetic datum. More accurate conversions can be obtained directly from CHS.

External Surge

Water levels along BC’s coast are affected by offshore ocean-scale processes in the Pacific Ocean basin. These processes include atmospheric pressure, wind, wave momentum, and ocean currents, oscillations and temperature. Together, these conditions explain mostobserved differences between measured water levels and predicted tides (Ausenco Sandwell, 2011a). These differences are often referred to as Residual Water Levels (RWLs). The latest available information cites no evidence to suggest that the frequency or magnitude of RWL events will change significantly because of climate change (Ausenco Sandwell, 2011c).

Residual water levels exhibit typical seasonal (summer / winter) and annual patterns. The El Niño Southern Oscillation (ENSO) is one example of an ocean-scale process that has a well-documented inter-annual effect on the local RWL. The BC Government maintains a storm surge forecasting program[2] and releases both an annual almanac of predictions prior to the onset of each year’s storm season (e.g., Tinis, 2013) and a mid-season update.

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[2] http://www.stormsurgebc.ca/files/reports/2014-2015.pdf

The largest RWL recorded at Point Atkinson was 1.03 m in March 1999. The highest total water level of 5.61 m CD was recorded at Point Atkinson in December 1982 and reached about 2.5 m above MWL (approximately 2.5 m geodetic elevation). The 1982 observation included a predicted tide of 4.71 m CD and a RWL of 0.8 m (Tinis, 2013).

Local Effects

Local and site-specific processes can affect both nominal and extreme coastal water levels. Primary contributors include long-term effects such as uplift and subsidence as well as transient storm-related phenomena such as wind setup and wave setup.

Processes such as tectonic uplift, isostatic rebound and subsidence result in vertical ground displacement relative to MWL. The magnitude of these effects varies considerably around BC and the net effect can be either positive (upward) or negative (downward). Changes due to tectonic effects may be rapidly reversed during a major earthquake.

A measured or estimated rate of movement is usually applied over an assumed time horizon to determine the total effect of uplift and subsidence on future water levels. Uplift and subsidence rates for a number of locations in BC are documented in Appendix B of the provincial Sea Dike Guidelines (Ausenco Sandwell, 2011b); however, Squamish is not included in the list. CHS is presently reviewing data that suggest areas of downtown Squamish may be subsiding (B. de Lange Boom, pers. comm.).

Wind setup is a local increase in water depth near the shoreline caused by the shear force of an onshore wind blowing over the water surface. Strong inflow winds are a local example of conditions that could promote wind setup. The magnitude of wind setup can increase locally in extensive areas of shallow water such as the tidal flats along Crescent Slough.

Wave setup is an upward change in mean sea level that results from wind waves shoaling in the near-shore area, and is typically accounted for as part of the assessment of wave effects (e.g., as part of wave run-up calculations). Wave setup varies locally with the wave climate and its contribution must be calculated explicitly if a static water level is required for design purposes.

The draft amendment to the 2004 Flood Hazard Area Land Use Guidelines (BC MFLNRO, 2013b) includes uplift and subsidence in its recommended procedure for assessing coastal flood hazard water levels. Wind setup is not mentioned explicitly in the draft amendment, but is accounted for as part of total storm surge in the guidelines prepared by Ausenco Sandwell (2011a; 2011b). KWL expects that wind setup will be addressed more explicitly in the final amendment to the 2004 MFLNRO guidelines.

Wind Waves

Waves are generated by a sustained wind field over deep water. Their state undergoes a predictable but complex evolution as they refract, shoal, break, and run up on the shoreline. Waves have potential to overtop and breach coastal dikes and flood low-lying coastal areas. Waves also present significant erosion hazards that may trigger dike breaches or submarine slides.

Because the shoreline itself alters the characteristics of approaching waves, the effect of waves for planning and design must be evaluated in the context of each specific planning or engineering situation. The effect is typically considered in terms of wave run-up, the vertical height that the wave can reach on the seaward face of a structure or shoreline (Ausenco Sandwell, 2011a).

Offshore-generated swell is not significant at Squamish and the design waves are generated locally by inflow winds blowing up Howe Sound. For the present study, SNC-Lavalin completed an updated wind and wave modelling study that incorporates the latest available information on bathymetry, local wind effects and climate change. The updated modelling results will support site-specific analyses that consider the local topography of exposed foreshore areas. The modelling and results are summarized in Section 5.5 and described in more detail in Appendix C.

The 1994 FHMP (Klohn Leonoff, 1994a) observed that the seastate (wave climate) along the District's coastal margins is sensitive to, and affected by, the Squamish Spit (Squamish River South Training Berm) and the terminal landfill at Squamish Terminals. The seastate along the west side of downtown Squamish is also sensitive to the existing CN Rail embankment. These observations are supported by the updated coastal modelling described in Appendix C. Decommissioning or failure of these facilities could increase the wave hazards at Downtown Squamish.

Regional or Far-Field Tsunamis

All communities on the BC Coast face a common threat from tsunamis generated by major earthquakes around the Pacific Rim. Communities on the Strait of Georgia are favoured by topography since an offshore tsunami would lose considerable energy passing through the Juan de Fuca Strait and Salish Sea. However, the 1964 tsunami in Port Alberni, BC also demonstrated that fjords like Alberni Inlet and Howe Sound can amplify the damaging tsunami effects. A tsunami hazard assessment for Squamish must consider or allow for shoaling, convergence, and resonance effects.

Local Tsunamis

Local tsunami waves could be generated by a large landslide within Howe Sound. A 1975 landslide in Kitimat Inlet resulted in a local tsunami with a measured wave height of 8.2 m (Conway et al., 2012). The 1964 earthquake in Alaska caused a number of larger landslide-generated tsunami waves, with the largest vertical run-up exceeding 60 m (NRC, 1972).

Possible tsunami-inducing mechanisms for Howe Sound include a sub-aerial slide from one of the steep slopes surrounding Howe Sound or a large submarine slide from the leading edge of the Squamish River delta. A local tsunami could also result from a large submarine slide on the Fraser River delta front.

On-going monitoring of the foreslope of the Squamish River delta front indicates that small regular slope failures are common at the existing active delta on the west side of the estuary (Clarke et al., 2012). Separate geotechnical analyses have concluded that the delta may be subject to liquefaction-induced flow slides.

Section 5.6describes engineering assessments of the potential for a large slope failure to initiate a tsunami wave train near Squamish.

Areas at Risk

The District has a long coastal margin at Howe Sound, extending from Watts Point in the east to Woodfibre in the west. Much of the foreshore is relatively steep and undeveloped; notable exceptions include Woodfibre and the area from Crescent Slough to Squamish Nation Stawamus I.R. No. 24. Between Crescent slough and Stawamus I.R. No. 24, river estuaries and sloughs allow coastal hazards to penetrate deep into the community.

The coastal flood hazard area includes a significant fraction of the developed area of the District of Squamish, as well as Highway 99 and CN Rail regional transportation corridors. Vulnerable neighborhoods include North Yards, Squamish Business Park, Dentville, and Downtown Squamish. In addition to Squamish Nation Stawamus I.R. No. 24, the area at risk of coastal flooding also includes Squamish Nation Yekwaupsum I.R. No. 18 and undeveloped Squamish Nation Yekwaupsum I.R.

No. 19. Other Squamish Nation reserves are located on the islands and shoreline of Howe Sound outside the District boundary.

The coastal floodplain supports many services relied on by residents who work and live outside the floodplain. Key community infrastructure includes the numerous commercial and industrial facilities as well as the Municipal Hall, Squamish Elementary School, Howe Sound Secondary School, Squamish Public Library, BC Hydro’s Squamish substation, many commercial services, and emergency response services.

2.9 Climate Change

According to the Intergovernmental Panel on Climate Change (IPCC), the rapid increase in greenhouse gases within the atmosphere over the last half century has resulted in changes to global and regional climate that are unprecedented over time scales ranging from decades to millennia (IPCC, 2013). Based on peer-reviewed and published climate change information, the IPCC reports represent the largest co-ordinated effort within the scientific community to understand these complex and ongoing changes.

Among other conclusions, the IPCC’s 5th Assessment Report (AR5) concludes that an increase in frequency, intensity, and/or amount of precipitation is very likely over most mid-latitude land masses into the later 21st century. Similarly, increases in incidence and/or magnitude of extreme high sea level are very likely over the same period.

Rising sea levels pose a significant threat to coastal systems and low-lying areas from inundation, coastline erosion, and salt-water intrusion into groundwater or fresh-water sources. AR5 assessments conclude that global sea levels are rising faster than previously assumed, largely due to accelerated glacier loss and contributions from ice shelf melting in Greenland and Antarctica. Post-AR5 investigations conclude that Arctic ice cover is also thinning and reducing faster than anticipated in previous studies, and will also tend to accelerate.

Confidence in predictions for both increased precipitation and rising sea levels has increased since the IPCC’s previous report.

With regard to temperature, cold days are expected to become warmer and less frequent (“virtually certain”), warm days are expected to become warmer and more frequent (“virtually certain”), and warm spells are very likely to increase in frequency and/or duration. Even if greenhouse gas emissions halt tomorrow, the impacts of climate change will continue long into the future.

A discussion of regionally-specific climate change events was provided previously by KWL (2011a). In general, for the District these changes mean that sea levels will increase, and flooding on rivers and creeks could become more frequent and/or more severe.

IFHMP Climate Change Considerations

Possible climate change effects on river flood hazards could be both direct (i.e., through increased rainfall intensity) and indirect (i.e., through warmer temperatures that increase the likelihood of rain-on-snow conditions during the storm season).

The increase in the coastal flood hazard is also expected to be both direct (i.e., through higher mean sea level) and indirect (as deeper water allows higher waves to reach the shoreline before breaking).

Numerous documents have been prepared to help municipalities and decision-makers in addressing both the legal and policy implications of climate change (e.g., WCEL, 2012). Local municipalities must look ahead decades to centuries and begin to develop planning strategies such as (Arlington Group et al., 2013):

- **Protect** existing development in its current form and location, balancing costs and increasing vulnerability against societal cost and risk associated with other strategies;
- **Accommodate** the potential consequences of ongoing changes by changing human activities and/or infrastructure to increase resilience;
- **Manage Retreat** by gradually withdrawing potentially-vulnerable infrastructure and services from hazard areas in recognition of their increasing vulnerability; and/or
- **Avoid** increasing the presence or density of potentially-vulnerable populations, infrastructure or services within hazard areas.

In addition to the four key strategies outlined in the table above, communities must **Accept** that some risk will be irreducible, and identify an appropriate standard that is “safe enough”. An accept strategy may endorse the status quo level of mitigation (i.e., if existing risk is considered acceptable), but is more frequently an implied part of a more comprehensive strategy that is focussed on defining and advancing the concept of “safe enough”. Guidance as to what might constitute “safe enough” (and in some areas, minimum requirements) are available from local, provincial, national, and international sources; however, at this time local communities in BC remain largely responsible for defining the amount of risk the community is willing to accept.

Another type of strategy, **Attack**, involves reclaiming land from an existing natural coastline or floodway. This strategy is most often considered in countries and regions where severe land constraints, very high population densities, and skyrocketing land values justify the substantial costs, risks, and environmental impacts. A typical attack strategy would be in conflict with the principles of integrated flood hazard management, and is not considered appropriate for Squamish.

Different strategies may apply to different areas within the same municipality. In Squamish, a **Protect** strategy has been the historic and predominant approach where development has occurred. More recently, this has been combined with an **Accommodate** strategy where on-site floodproofing has been required for habitable development in flood hazard areas. An **Avoid** strategy applies to much of the Squamish estuary and other environmentally sensitive areas where protection of the environment is considered the most important policy objective. An Avoid strategy also applies to the Cheekeye Fan due to the high-intensity debris flow hazard.

Over time, one strategy within a particular geographical area may be complemented and/or superceded by another strategy in response to changing conditions or an updated risk assessment. For example, over the next century, sea level rise is expected to justify the introduction of **Managed Retreat** in areas subject to increased risk where the cost of Protection is considered excessive or the consequences of inundation are unacceptable.

Such changes in strategy typically proceed on an opportunistic basis that reflects the redevelopment cycle. For example, the District could initiate a strategy of Managed Retreat by relocating critical municipal flood response facilities (e.g., Municipal Hall and District Operations Yard) to areas outside the floodplain rather than redeveloping at their current locations.

Climate change and its related implications are not purely planning issues; they also create significant challenges for engineers charged with safely designing flood protection works and the infrastructure they protect. In 2014, APEGBC published a policy paper affirming the relevance of climate change to professional practitioners in BC and mandating that practitioners routinely consider climate change impacts on their professional activities.

To assist practitioners, various agencies have provided technical guidance concerning climate change impacts. While these guidelines are based on uncertain and evolving science, they represent the latest standard of practice regarding climate change assumptions and have therefore been adopted for the District's IFHMP. Specific climate change guidance relevant for this study includes:

- Apply a 10% upward adjustment in design discharge for river and creek systems where no historic trend is detectable (APEGBC, 2012);
- Where historic trends in river and creek discharge are statistically significant, adjust design discharge in accordance with future climate predictions, or by 20% where future predictions cannot provide reliable guidance (APEGBC, 2012); and
- Allow for 1 m of Sea Level Rise (SLR) by year 2100 and 2 m SLR by year 2200 (Ausenco Sandwell, 2011c). An average rate of 10 mm/year is implied for intermediate time horizons.

These criteria are reviewed in the context of the IFHMP hydrology and coastal flood updates in Sections 5.1 and 5.4, respectively.

2.10 IFHMP Hazard Summary

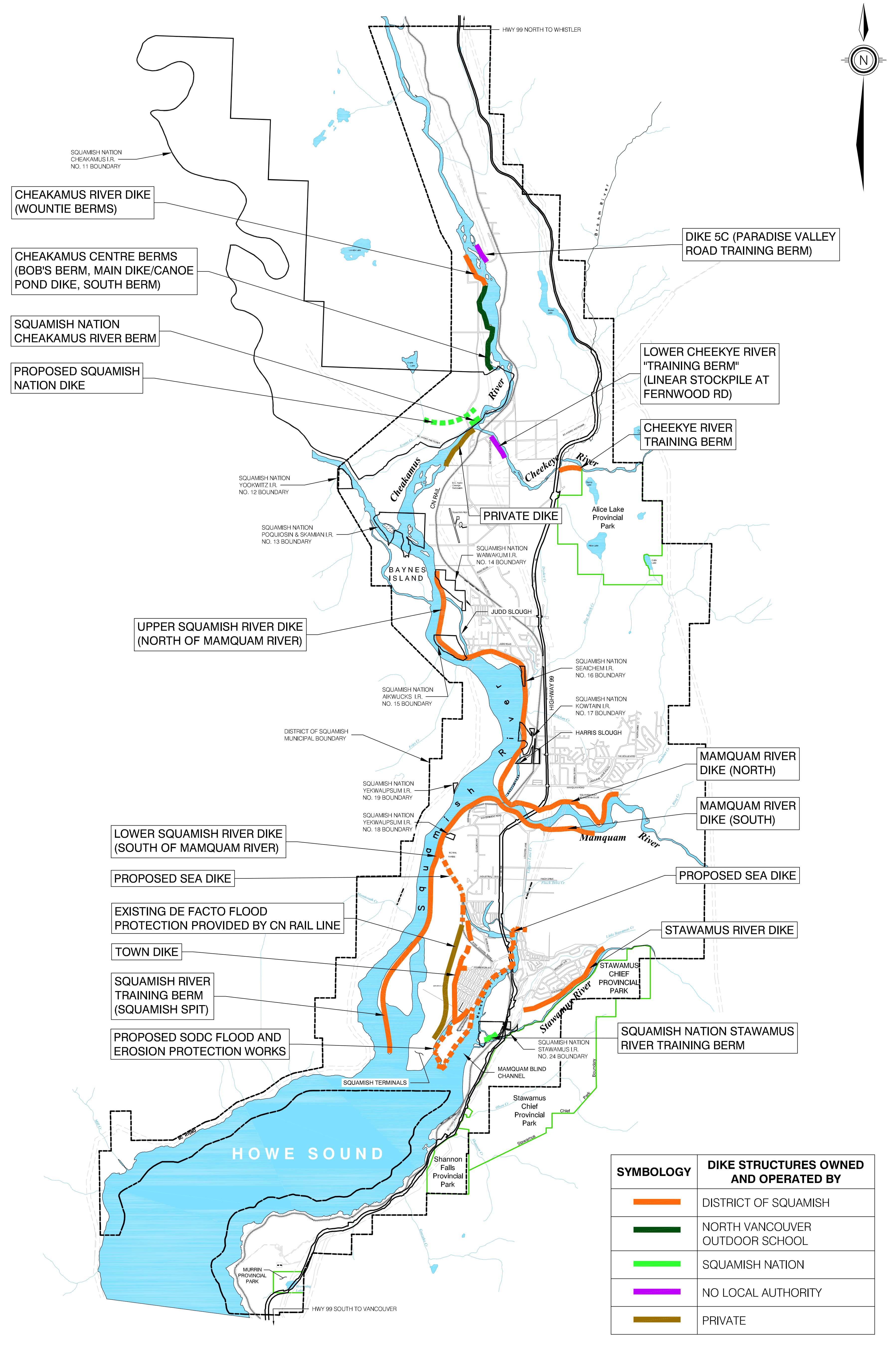
The previous sections have outlined the natural hazards posed to District areas. The hazards are summarized in the table below. The table includes some general high-level and qualitative guidance regarding the relative importance of each hazard to the District's flood protection interests. The ratings are subjective and intended only to help the District understand and prioritize hazards. The ratings do not necessarily represent an exhaustive and comprehensive inventory of all hazards in the District.

Table 2-2: Summary and Relative Significance of Natural Hazards

Source of Hazard	Type of Hazard											
	Flood	Erosion	Sedimentation & Aggradation	Debris / Bridge Blockage	Dam Failure	Landslide Dam Breach	Debris Flow	Channel Avulsion	Landslides	Wave Overtopping	Far-Field Tsunami	Local Tsunami
Squamish River	🟥	🟧	🟨	🟨		🟨						
Mamquam River	🟥	🟧	🟧	🟧	🟨	🟨						
Cheakamus River	🟥	🟥	🟧	🟧	🟨	🟧		🟨				
Cheekeye River	🟧	🟨	🟥	🟥			🟥	🟥				
Stawamus River	🟧	🟧	🟧	🟥		🟥						
Local Creeks	🟧	🟧	🟧			🟨	🟧	🟨				
Steep Slopes		▨							▨			🟨
Howe Sound	🟥	🟥								🟥	🟨	🟨
Climate Change	🟥									🟧		
Internal Drainage	▨											

🟥 Higher 🟧 Moderate 🟨 Lower ▨ Hazard Not Applicable for IFHMP

O:\0400-0499\463-278\501-Drawings\b_Figures\StructuralFloodWorks-LocationMap-Fig2-1.dwg SAVED 28/03/2017 1:11:03 PM



Scale:
1:75,000

District of Squamish
Integrated Flood Hazard Management Plan - Background Report

Project No.: 463-278

Date: August 2017

KERR WOOD LEIDAL
consulting engineers

Squamish Area Structural Flood Protection Works
Location Map

Figure 2-1

3. Flood Hazard Management Program

Three primary elements form the core of the District's pre-existing flood hazard management program. All of them are identified in the District of Squamish 2009 Official Community Plan (DoS, 2009).

The first element is collaboration with senior governments and affected property owners to maintain 200-year return period protection standards along the Squamish, Mamquam, Stawamus, Cheekeye and Cheakamus Rivers as well as to maintain the sea dikes in Downtown Squamish (Policies 25-11 & 25-12).

The second element is documentation of areas prone to flood hazards and debris flow hazards in Schedule D1 of the OCP (Policy 25-1).

The third element is to avoid permitting development in areas subject to unacceptable flood and debris flow hazards, and to require a report by a qualified engineer in any hazard area that establishes the suitability of the land for development as well as any required mitigation measures (Policies 25-3 & 25-5).

Other important flood protection elements include the following:

- use of a save harmless covenant under Section 219 of the Land Title Act prior to any rezoning, subdivision or building permit approval in any area subject to natural hazards (Policy 25-6);
- minimal use of fill placement and building construction in the emergency floodway area between Highway 99, Loggers Lane and the Mamquam Blind Channel (Policy 25-14);
- periodic gravel removal in riverbeds to maintain channel capacity and dike protection (Policy 25-16);
- restricted use of the Cheekeye Fan due to its debris flow hazard (Policies 25-17 to 25-23); and
- use of the 1994 Flood Hazard Management Plan as a background reference.

A complete list of all elements is provided in Section 3.1 below.

3.1 Policy and Planning Elements

Pre-IFHMP flood hazard management relied primarily on the District of Squamish Official Community Plan(OCP) Bylaw 2100 (adopted in June 2010) for guidance. The following guiding principles and policies concern flood hazard management, whether directly or indirectly.

District of Squamish Official Community Plan Bylaw 2100 (2009)

The District's OCP includes the following key Guiding Principles and Policies concerning flood hazard management and related subjects such as natural hazards, dike trails, climate change and cooperation with other stakeholders.

Guiding Principles

None of the 10 Guiding Principles specifically mention flood hazard management but three indirectly address the subject as follows:

- Principle 1 –Environmental Stewardship

Ensure the protection, restoration and management of aquatic and terrestrial habitats and the maintenance of ecological health for present and future generations. Minimize conflicts by developing and applying clear growth management and land use policies.

- Principle 2 – Natural Resource Conservation

Support smart growth land use principles and minimize the use of energy and material resources by endorsing sustainable design and land and management practices.

- Principle 6 – Community Livability

The District will strive to enable a high quality of life for its residents, where everyone enjoys a safe, vibrant and healthy community, and has access to education, jobs, public services, culture, recreation and the natural environment.

Policies Concerning Parks & Recreation

15-34 The municipal Trail Network is identified on Schedule F [of the 2009 OCP]. The trail network is intended to:

> a. Provide a corridor trail network connecting one end of the Squamish Valley with the other – preferably on each side of Highway 99;
>
> b. Connect the designated neighbourhood centres with one another and with Downtown Squamish;
>
> […]
>
> e. Provide waterfront access and riverfront access, including access along the dyke system;
>
> […]

15-39 River and sea dykes are recognized as critical components of the District's trail system. The District shall secure public rights of access through the land development process or other means.

15-40 The District will work with Squamish Nation and private landowners to facilitate uninterrupted public access to the dyke system.

Policies Concerning the Natural Environment

16-16 The District will consider 'Green Shores' principles in the planning and design of developments adjacent to coastal areas to recognize and address the ecological features and function of coastal systems.

Policies Concerning Employment and Industrial Lands

20-11 The use of industrial in the Cheekeye Fan debris flow hazard is restricted to industrial uses not requiring municipal services or permanent buildings (e.g. log sorts). Such uses shall be subject to provision of a geological hazard study and mitigation strategy prepared by a qualified professional engineer.

Policies Concerning General Natural Hazards and Constraints

25-1 Schedule D1 identifies areas prone to flood hazards and debris flow hazard areas. Debris flow areas consist of the Cheekeye fan, parts of Alice Lake Provincial Park, upper Mashiter Creek catchment, Ring Creek catchment, Olesen Creek and Gonzales Creek. Flood hazard areas consist of the Cheakamus Valley, Brackendale, Valleycliffe, Downtown Squamish, Dentville, Mamquam/Garibaldi

Estates, North Yards, Squamish Business Park, Loggers Lane/Finch Drive/Brennan Park, Oceanfront Peninsula, Mamquam Blind Channel, and Squamish Estuary.

25-3 Development shall not be permitted in areas subject to unacceptable flood and debris flow hazards, rockfall, land slip, seismic, or other natural hazards.

25-5 A report prepared by a qualified engineer will be required for all development proposals for land located within an identified natural hazard area. The report shall establish the suitability of the land for development and any required mitigation measures.

25-6 For any area of the community identified as being subject to natural hazards, the District shall require a “save harmless” restrictive covenant pursuant to Section 219 of the *Land Title Act* prior to any subdivision, rezoning or building permit approval.

Policies Concerning Cooperation and Coordination

25-7 The District of Squamish shall work in co-operation with provincial and federal agencies and the Squamish Nation to identify, assess, and manage risk associated with natural hazards within the municipality. This may include the acquisition of private properties and the cancellation of subdivisions that do not have development potential.

25-8 The District will work in co-operation with provincial agencies to minimize the risk associated with development on land identified with high risk from natural hazards.

25-9 The District shall consider undertaking a multiple hazard risk assessment in conjunction with federal and provincial agencies.

25-10 The District will consider undertaking the identification and assessment of disaster risk reduction strategies in conjunction with federal and provincial agencies.

Policies Concerning Flood and Debris Flow Hazards

25-11 The District will collaborate with relevant federal and provincial agencies, and affected property owners in an effort to maintain 200-year flood protection standards along the Squamish, Mamquam, Stawamus, Cheekeye and Cheakamus Rivers.

25-12 The District of Squamish will collaborate with relevant federal and provincial agencies, and affected property owners in an effort to develop and maintain sea dykes and provide continuous protection to Downtown Squamish.

25-13 The District shall prepare and maintain a comprehensive flood hazard plan or bylaw to address land use and mitigation strategies.

25-14 Building construction and fill placement should be minimized in the corridor between Highway 99, the Mamquam Blind Channel and Loggers Lane in order for the area to serve as an emergency floodway and enable reduced Flood Construction Levels (FCLs) to be established in Dentville and the Downtown.

25-15 To preserve the historic streetscape, the District shall consider exempting non-residential uses in the Downtown from the required flood construction elevation, subject to other mitigation measures endorsed by a qualified professional engineer.

25-16 Periodic gravel removal within riverbeds may occur in order to maintain existing channel capacity and dyke protection, and the District will work with the relevant Provincial and Federal governments to achieve this safeguard.

Policies Concerning Cheekeye Fan

25-17 The Cheekeye Special Study Area is identified on Schedule B. The Special Study Area identifies the Cheekeye Fan as a debris flow hazard area. Additional study and requirements will be required before any changes to the existing land use designations will be considered.

25-18 The District recognizes the complex nature of the multiple hazards in the Cheekeye Fan area and will consider undertaking studies in an effort to identify compatible land uses and mitigation strategies.

25-19 Schedule D1 designates four Alluvial Fan Hazard Areas (Zones 1 to 4), a Cheakamus and Squamish River Flood Plain Area (Zone 5), and a Cheakamus River Displacement Flood Area (Zone 6) that have been defined by a geotechnical study.

25-20 The Cheekeye Fan flood hazard zones identified in Schedule D1 are based on past geotechnical studies and may be reviewed when new natural hazard and risk management studies and information become available and in conjunction with discussions regarding the Cheekeye Special Study Area.

25-21 The Cheekeye Fan alluvial fan hazard zones 1 and 2 are not suitable for land subdivision or permanent buildings and structures.

25-22 The District will consider open space, outdoor recreational uses and restricted industrial uses in portions of the Cheekeye Fan identified on Schedule B, subject to risk assessment. The District acknowledges the environmental and habitat value of the Cheekeye Fan.

25-23 Building development in accordance with Schedule B, will only be allowed in hazard zones 3 or 4, as shown on Schedule D1, and will require:

a. a Debris Flow Management Plan; and
b. Implementation of appropriate mitigation measures.

Policies Concerning Climate Change Impacts & Adaptation

25-35 The District will work in collaboration with federal and provincial agencies, the Squamish Lillooet Regional District, First Nations, research organizations, the academic sector, and others to understand the nature of climate change impacts locally and Squamish's vulnerabilities to climate change impacts.

25-36 The District will seek opportunities to develop strategies to reduce vulnerability to and adapt to climate change impacts in collaboration with federal and provincial agencies, the Squamish Lillooet Regional District, First Nations, research organizations, the academic sector, and others.

25-37 The District will review the flood hazard plan and municipal utility plans to ensure that climate change predictions regarding precipitation events are considered in the identification of the appropriate design events for infrastructure development and when reviewing relevant design standards.

District of Squamish Zoning Bylaw No. 2200, 2011

The key role of the zoning bylaw is the regulation of land use. Council has no obligation to rezone land to permit development. This means that Council need not approve a rezoning application due to concerns about flood hazard mitigation or for any other reason. Council can also establish conditions under which rezoning is allowed. These can include restrictions on land use, the siting of land uses to reduce hazards, the elevation of land uses to meet flood construction levels, requirement for structural protection and the use of a covenant to reduce risk including the use of a save harmless clause.

The zoning bylaw also has several provisions that directly or indirectly affect flood mitigation.

In Section 1 – Interpretation, the definition of Floor Area Ratio means the figure obtained when the Gross Floor Area of all buildings is divided by the area of the lot.

The definition of Gross Floor Area excludes the area required for elevator shafts, crawl spaces, ENERGY STAR furnaces, boilers and hot water tanks, garages up to 55.7 m^2 and common stairwells, corridors, recreation areas, garbage, recycling, service areas, and bicycle facilities in Multiple-Unit zones. Parking, storage and mechanical spaces below Height Datum are also excluded from the Gross Floor Area definition.

The definition of Natural Grade includes a requirement that the minimum Flood Construction Level be 0.6 m above the highest elevation of the crown of any abutting highway.

The definition of Habitable Space means the interior space of a building that is designed for living, sleeping, eating or food preparation, and excludes bathrooms, utility rooms, work rooms, furnace rooms and storage rooms.

Section 4 – General Regulations Section 4.24 states that any enclosed spaces in residential premises below the Flood Construction Level, other than concealed parking areas and entrance foyers, shall be limited to a ceiling height of 1.5 m as determined by a professional engineer. The purpose of this regulation is to allow only a crawl space (i.e. cellar) below the Flood Construction Level and prevent the construction of habitable space.

As part of the rezoning process, a covenant can require the siting of building elements vulnerable to damages by floodwaters (e.g. furnaces, boilers and hot water tanks) to be located above the Flood Construction Level.

District of Squamish Site Alteration Bylaw No. 1885 (2005 as amended)

The site alteration bylaw requires a permit for any tree cutting or site alteration including the removal or deposit of soil including on the same site in Development Permit Area 1 (Protection of the Natural Environment) or Development Permit Area 11 (Riparian Area Protection). This bylaw prohibits development in the affected areas without a permit. While the Site Alteration Bylaw cannot ensure appropriate development, it serves as an early warning mechanism and can stop inappropriate development.

Other Legislative Provisions

Other legislative provisions that are part of the District of Squamish flood hazard management toolkit consist of the following:

Sections 85 and 86 of the *Land Title Act*

This authorizes the Approving Officer to refuse to approve a subdivision if the land is subject to flooding and to require a report certified by a professional engineer or geoscientist that the land may be used safely for the use intended.

Section 55 and 56 of the *Community Charter*

If the Building Inspector considers that construction would be on land subject to flooding, mud flows, debris flows, debris torrents or other specified risks, the Building Inspector is authorized to require the owner of land to provide a report certified by a qualified professional that the land may be used safely for the use intended. If the qualified professional determines that the land may not be used safely for the use intended, the Building Inspector must not issue a building permit.

Section 524 of the *Local Government Act*

Section 524 of the *Local Government Act* permits local governments to enact a bylaw that designates land as a floodplain and establishes specific building and siting requirements therein. The 1994 FHMP (Klohn Leonoff, 1994b) recommended that the District adopt a floodplain bylaw under similar provisions of the predecessor *Municipal Act*. To date, the District has not enacted a floodplain bylaw under either legislation.

3.2 Guiding Principles for Squamish IFHMP

Squamish is subject to a range of flood and debris flow hazards which, if unmitigated, pose an unacceptable level of risk to the community. Land subject to these risks should not be developed unless the risks can be mitigated to an acceptable level.

The determination of an acceptable level of risk should be based on a combination of the best available data, engineering analysis and climate science supported by public consultation and community buy-in. The management of risk should align the interests of the District with both present and future property owners as well as senior levels of government. Technical information, including climate science, will be accessible to the general public to facilitate informed decision making.

Selected mitigation strategies will depend on site specific circumstances and location. Strategies may include over-arching land use policy such as “avoid” or “managed retreat” as well as site specific floodproofing measures (“accommodate”) and area-wide structural flood and erosion protection works (“protect”). Where risks are found to be acceptable, the status quo may be maintained (“accept”). Collaboration between all levels of government and relevant stakeholders is recognized as an important contribution to effective decision making.

Development should not rely solely on existing or proposed off-site structural protection (i.e., a strategy of “protect”) to mitigate risk; rather, off-site structural protection works such as dikes and rock revetments should be complemented by on-site floodproofing. Risk-appropriate living shorelines and related bioengineering approaches should be actively considered based on a long-standing history of environmental protection and cost effectiveness in other jurisdictions.

Provincial Resources

In 2010, the release of BC’s Adaptation Strategy – Preparing for Climate Change (BC MoE, 2010) began to indicate that adaptation was a current priority for the Province. The provincial adaptation strategy recognizes that historical experiences are no longer sufficient for addressing future risks, that adaptation needs to be incorporated into future planning, and that cross-government coordination and stakeholder engagement is essential. A series of provincial resources and guidelines are available to support local municipalities grappling with these issues.

The Flood Hazard Area Land Use Management Guidelines (BC MWLAP, 2004; BC MFLNRO, 2013b) make provision for buildings to be set back from the natural boundary of the sea and other water bodies in a variety of situations. They also provide guidance for establishing the structural elevation of buildings and other floodproofing measures. The Guidelines specifically refer to floodplain bylaws adopted under Section 910 (now Section 524) of the *Local Government Act* but are more generally intended to help local governments, land-use managers and approving officers develop and implement land-use management plans and make subdivision approval decisions in all flood hazard areas.

Beginning in 2009, the BC Regional Adaptation Collaborative (RAC), funded by Natural Resources Canada, the BC government, local governments and other key stakeholders (including the Fraser Basin

Council) have supported many projects focused on sea level rise and flood hazard management, including:

- Climate Change Adaptation Guidelines for Sea Dikes and Coastal Flood Hazard Land Use (Ausenco Sandwell, 2011a; 2011b; 2011c)
    - Updated Provincial Guidelines for sea dike design and coastal flood hazard land management to address climate change factors in coastal waters of BC.
- Coastal Floodplain Mapping Guidelines and Coastal Flood Hazard Areas (KWL, 2011b)
    - Standardized methodology to produce floodplain maps that account for sea level rise for coastal communities.
- APEGBC Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC (APEGBC, 2012)
    - Guides professional practice for flood assessments, to help identify the circumstances when risk assessments are needed and to emphasize the need to consider climate change and land use changes in such assessments.
- Cost of Adaptation – Sea Dike and Alternative Strategies (Delcan, 2012)
    - Provided a $9.47 billion estimate for upgrading infrastructure works required along 250 km of diked shorelines and low-lying areas in Metro Vancouver to meet the rise in sea level predicted for 2100, including necessary seismic upgrades.
- Sea Level Rise Adaptation Primer – A toolkit to Build Adaptive Capacity on Canada's South Coasts (Arlington Group, 2013)
    - Offers a toolkit for coastal management authorities to help identify, evaluate and compare options for adapting to the impacts of sea level rise and associated coastal hazards. Included are 21 tools. The Government of Canada published a related document supporting climate change adaptation via Canadian case studies titled *Land use planning tools for local adaptation to climate change* in 2012.

Additional provincial documents addressing flood hazard mitigation include:

- Seismic Design Guidelines for Dikes (Golder, 2014)
    - Describes factors that need to be considered in the seismic deign of *High Consequence* dikes located in Southwestern BC and establishes performance targets.
- Guidelines for Management of Flood Protection Works in British Columbia (BC MELP, 1999a)
    - Consolidates current practices with respect to the management of flood protection works in BC to assist diking authorities and flood protection professionals fulfill dike safety requirements.
- Flood Protection Works Inspection Guide (BC MELP, 2000)
    - Identifies field conditions that may jeopardize the safety of the dike. Also provides information on scheduling inspections, inspection methods and tips.
- Dike Design and Construction Guide: Best Management Practices for British Columbia (Golder & Associated Engineering, 2011)
    - Presents basic principles used in the design and construction of dikes.

- Riprap Design and Construction Guide (NHC, 2000)
  - Discusses the design and construction of protective works to prevent erosion of river banks and dike slopes from stream flow.
- Environmental Guidelines for Vegetation Management on Flood Protection Works to Protect Public Safety and the Environment (BC MELP & FOC, 1999)
  - Presents minimum standards under the *Dike Maintenance Act* for managing vegetation on flood control structures in a manner that protects public safety, and identifies opportunities to protect and/or enhance habitat for the benefit of the environment.

Since 2007, the Flood Protection Program in BC has been assisting local governments and communities with funding for flood protection works. The British Columbia Flood Response Plan (EMBC, 2012) describes the methodology the Province will utilize for coordinating activities to manage response to a flood event. The Flood Planning and Response Guide for British Columbia (BC MELP, 1999b) assists Local Authorities and Diking Authorities in preparing flood response plans to guide activities during flood events. Emergency Management BC provides additional flood information toolkits on Critical Infrastructure Rating, Preparing Your Business for Flooding, and Community Flood Preparedness. These toolkits can assist local governments in developing fact sheets, public service announcements, web site materials and articles to help inform residents in risk areas on how to prepare for a possible flood event.

Emergency Management BC is also responsible for administering BC's Compensation and Disaster Financial Assistance (DFA) Regulation under the *Emergency Program Act*. The DFA program provides federal and provincial financial assistance to restore uninsurable private property and/or public infrastructure damaged in a declared disaster. Federal cost-sharing arrangements are described under the National Resources section below; the provincial government remains responsible for the balance of disaster assistance costs. BC sets the maximum allowable homeowner assistance at $239,200 based on the maximum claim amount of $300,000, a deductible of $1,000 and 80% reimbursement. Assistance is not available for expenses recoverable at law or where insurance was reasonable and readily available.

Some provisions of the DFA regulation may provide a disincentive for local governments to designate a floodplain under Section 524 of the *Local Government Act*; since such a designation may jeopardize future eligibility for DFA where structures are not "properly flood protected". This is potentially problematic for historically non-conforming areas of the District such as Downtown Squamish or North Yards.

National Resources

The federal government also provides a set of tools for flood hazard mitigation, but unlike the provincial resources and guidelines, national resources are typically strategic initiatives applicable across all regions of Canada. These national resources generally take the form of funding programs for flood preparedness and response.

National interest in flood protection has historically focused on mitigating negative economic disruptions and reducing disaster assistance payments. The federal government created Disaster Financial Assistance Arrangements in 1970 to cost share disaster assistance with the provinces. Historically, federal assistance started when eligible costs exceeded $1 per capita and increased to a maximum of 90% of eligible costs when those costs exceed $5 per capita. Effective February 1, 2015, federal assistance commences when eligible costs exceed $3 per capita and does not reach 90% until costs exceed $15 per capita. The new thresholds will continue to be indexed to 50% of the national inflation rate. The February 2015 changes in the federal program were made unilaterally and their significance may not be fully appreciated until the next major disaster.

A national Flood Damage Reduction Program was in place from 1975 until 1998. This provided for a floodplain mapping program cost-shared between the Government of Canada and each province. In BC, 77 communities (including Squamish) benefited from this program. The flood hazard standard chosen by BC was a 200-year return period flood event to reflect conditions faced in this mountainous province. All other provinces adopted the 100-year return period flood event except Saskatchewan, which adopted a 500-year return period flood.

After the Flood Damage Reduction Program ended, Natural Resources Canada provided some funding for floodplain mapping on a case by case basis. There has been an ongoing grassroots movement being led by the real estate and insurance industries to revive public interest and investment in flood risk mapping (e.g., BCREA, 2014). In June 2014, the federal government released a final report that reviewed the need for updated floodplain mapping. The final report calls for a new National Floodplain Management Framework that will develop updated flood hazard mapping and a flood risk database covering 90 to 95% of the population in flood-prone areas at a 2014 cost of about $365 million (MMM Group et al., 2014).

In response to recent costly floods (e.g., summer 2013 in southern Alberta), the Federal government has renewed its commitment to flood protection works. May 2014 saw the announcement of $27 million in cost-shared federal, provincial and local funding to support 26 flood mitigation projects throughout BC.The funding will help communities address existing flood concerns and take proactive steps to prevent future flooding emergencies. Projects were selected from local applications that offered cost-effective solutions for areas at risk. The District of Squamish received $1.8 million for the continued improvement of flood protection works. Federal and provincial governments will provide up to two-thirds of the funding for eligible project costs, with local governments and diking authorities covering the remainder of the project funding.

Infrastructure Canada's New Building Canada Plan (Infrastructure Canada, 2014) allocates $53 billion to be invested across the country in the next 10 years (2014-2024). The $53 billion total includes existing programs such as the Gas Tax Fund and the GST rebate for municipalities, as well as a new $14 billion Building Canada Fund. BC can expect $1.1 billion under the new Building Canada Fund and approximately $2.76 billion from the federal Gas Tax Fund. Project categories of local roads, culture, tourism, recreation and sport are now eligible under this Gas Tax Fund.

The new $14 billion Building Canada Fund includes a $4 billion National Infrastructure Component to support projects of national significance and a $10 billion Provincial-Territorial Infrastructure Component (PTIC). The PTICwill support support projects of national, regional and local significance with $1 billion dedicated for projects in communities with fewer than 100,000 residents. The latter is referred to as the PTIC - Small Communities Fund (SCF).

Disaster mitigation infrastructure projects are eligible for funding through the PTIC-SCF along with a diverse range of other initiatives. The federal overview of projects eligible for the PTIC-SCF provides a definition of disaster mitigation infrastructure projects that includes projects "supporting an all-hazard risk assessment and related mitigation plan to address disaster risks". Eligible projects are generally cost-shared federally on a one-third basis.

In addition to continuing a long history of funding flood protection works, in the spring of 2015 the federal government announced the creation of a $200 million National Disaster Mitigation Program (NDMP). The NDMP is intended to help mitigate, prepare for, respond to, and recover from flood risks by building a knowledge base and investing in foundational risk mitigation activities. The program includes four "streams" of funding: risk assessment, floodplain mapping, mitigation planning and non-structural / small-scale mitigation projects. These areas have been characteristically ineligible for funding programs focused on infrastructure. The NDMP is administered through provincial agencies, with EMBC taking the lead in receiving applications and coordinating adjudication with Public Safety Canada. Four NDMP intakes have been completed as of September 2017 with a fifth intake expected in 2018.

3.3 Policy and Practice in Other Jurisdictions

In addition to local policy and planning elements, existing provincial resources, and national assistance programs, the Squamish IFHMP can be guided and inspired by policy and practice in other jurisdictions. Lessons may be learned at scales ranging from local to international.

Local and Regional Jurisdictions

The Fraser Basin Council has become a key source of regional information on flood hazard management since the *Flood Hazard Statutes Amendment Act* and related legislative changes were enacted in 2003 and 2004. These amendments to the *Land Title Act*, *Local Government Act* and three other statutes shifted most responsibility for flood hazard management to local governments. The Fraser Basin Council is in the process of developing a regional flood hazard management strategy with Metro Vancouver, and is currently undertaking a regional-scale coastal and river flood risk assessment.

The Fraser Basin Council, through the BC Regional Adaptation Collaborative (RAC), has also been working with the provincial government and local partners on floodplain mapping and flood mitigation. Local resources from this collaboration include the Participatory Flood Management Planning project in Delta, which raised community awareness of climate change and coastal flood risk (FBC, undated). Results included recommendations for bylaw revisions, design guidelines, and building and zoning stipulations as well as a technical report with recommendations on enhanced processes for developing coastal flood management plans and scientific visualizations on climate change impacts.

After the 2005 Berkley Road landslide, the District of North Vancouver (DNV) adopted a new approach to natural hazard risk management, which includes allocating funding for risk assessment and mitigation, and providing greater public access to hazard and risk information. Currently, DNV uses the CAN/CSA-Q850-97 Natural Hazard Risk Management Framework and has designated Natural Hazard Development Permit Areas under their new Official Community Plan (DNV 2012; DNV 2014). DNV has also implemented quantitative Risk Tolerance Criteria, which states the risk level for new development (at 1:100,000 risk to life per year for individuals) and utilizes the ALARP principal (As Low As Reasonably Practicable). DNV's adoption of Risk Tolerance Criteria, including the use of a so-called "F-N Curve" to assess societal risk, is consistent with growing international acceptance of such metrics (KWL, 2014a). DNV received the UN Sasakawa Award for Disaster Risk Reduction in 2011.

The District of West Vancouver (DWV) developed a Shoreline Protection Plan 2012-2015 to protect DWV's biggest public amenity – the Waterfront (DWV, 2012). DWV's Plan encompasses shoreline and infrastructure protection, sediment deposition, creek and stream rehabilitation, and habitat enhancement. DWV manages a head lease for all intertidal and foreshore areas except those managed by BC Ferries and Port Metro Vancouver. This includes marinas, docks, log storage, aquaculture and water-based industrial uses. Under this arrangement, the local government is granted long-term tenure of up to 30 years over a foreshore area subject to a revenue-sharing arrangement with the Crown. In return, the head lease transfers all responsibility for management and environmental issues to the local government.

The City of Vancouver recently completed a coastal flood risk assessment for those areas subject to flood risks along Burrard Inlet, False Creek and the North Arm of the Fraser River (CoV, 2014). The City's study adopted a continuous simulation (joint probability) approach to provide probabilistic estimates of ocean levels affected by meteorological and oceanographic conditions under five separate scenarios. These scenarios consist of different combinations of sea level rise (0, 0.6, 1.0 and 2.0 metres) and storm hazard conditions (500-year to 10,000-year return period static water levels).

The Vancouver study also included an assessment of social and economic vulnerability. Natural Resources Canada's adaptation of the US HAZUS model was used for the calculation of potential flood damages based on BC Assessment Authority data.

Lessons from the 2013 Alberta Flood

Like the Saguenay, Quebec flood of 1996 and Manitoba's floods on the Red River in 1997 and the Assiniboine River in 2011, the 2013 flood in southern Alberta provided some key object lessons in flood response and has had a strong influence over evolving national and provincial (Alberta) flood hazard management policy.

The June 2013 floods in southern Alberta caused the death of four persons, displaced 100,000 persons as well as many businesses, and represented the highest financial cost for a natural disaster in Canada to date. Total costs are expected to exceed $6 billion, not including $1.7 billion in insured costs (e.g. residential sewer backup, commercial insurance). The Town of High River and the City of Calgary were most affected, although significant impacts were also experienced upriver in the hamlet of Bragg Creek and the Town of Canmore and downriver in the City of Lethbridge.

In the mountains upstream of High River, rainfall of up to 325 mm occurred in less than 48 hours. The extreme rainfall fell on already saturated ground and was compounded by the melting of snow remaining in the Rocky Mountains. Some residents received as little as 10 minutes warning of the impending disaster. The flood was much larger than any other flood on record, and was about twice the magnitude of the 100-year flood used to prepare the local floodplain maps. As a result, flooding occurred in parts of the community that were thought to be outside the flood hazard area. Over 90% of all municipal facilities in High River were rendered unusable during the flood and its aftermath. Over 1,400 pets were left in homes, and subsequently occupied a large amount of time for disaster assistance crews.

In Canmore, 220 mm of rainfall fell in 36 hours, nearly half the town's annual average. This led to a debris flow on Cougar Creek, which washed out the Trans-Canada Highway and severely damaged 44 homes located along the Bow River tributary.

In November 2013, the federal government set aside $2.8 billion for its 90% share of $3.1 billion of eligible flood related costs under Disaster Financial Assistance Arrangements. This was later revised downward to $1.6 billion in the November 2014 Economic and Fiscal Projections of the Department of Finance.

In the aftermath of the 2013 floods, the Government of Alberta announced several policy decisions pertaining to development in and around floodplains as well as its disaster response program. Some of these decisions involved expenditures outside the scope of federal-provincial financial assistance arrangements which means the Government of Alberta will be fully responsible for the costs. Some of these decisions are outlined below.

1. Funding based on 2013 assessed values was made available for homes within the floodway through the Disaster Recovery Program to enable homeowners to rebuild or relocate to a new location outside the flood hazard area. Land acquired from homeowners moving away from the

flood hazard area will either become a part of municipal flood mitigation infrastructure or used for recreational purposes.

2. In addition to the funding available for eligible expenses, homes in flood fringe areas that were heavily damaged or require reconstruction will have access to additional funding through the Disaster Recovery Program. The money "must be spent" on flood mitigation measures approved to provide sufficient protection for a 100-year return period flood event. Specific mitigation infrastructure (such as berms or water control infrastructure) will also be provided to protect buildings within the flood fringe areas.
3. In the event of future flooding, homeowners in flood fringe areas who do not implement approved mitigation measures will not be eligible for future Disaster Recovery Program assistance.
4. The Province passed the *Flood Recovery and Reconstruction Act*, which is intended to prevent future development in designated floodways. Regulations pertaining to the *Act* remain under development as of September 2017.

The Alberta Government specified that a "Disaster Recovery Program" notice will be placed on homeowners' land title if the property is located within a floodway or flood fringe, or if the property took advantage of 2013 Disaster Recovery Program funding to rebuild. Properties that did not receive Disaster Recovery Program funding will not have the notice placed on their land title. This notice may be removed if a property owner in a flood fringe submits proof of flood mitigation to the Land Title office; however for properties in the floodway, the land title notice will remain so that future owners will be aware that no additional funding will be provided in the event of future floods.

International Jurisdictions

Many international jurisdictions have a long history of dealing with hazards and consequences that are similar but potentially even more severe than those currently faced by the District. It is perhaps not surprising that these jurisdictions have become leaders in the evolution of hazard mitigation policy. Selected examples considered particularly relevant for the District's IFHMP are described below.

Netherlands

The Dutch Cabinet tasked the Delta Committee with investigating strategies for the future long-term development of the Netherlands coast (2100-2200), paying attention to both safety and environmental quality (Deltacommissie, 2008). The Committee was asked to consider innovative measures to protect the coast and low-lying hinterland against the consequences of climate change, and to include the interaction with increased river discharge in its recommendations. The Dutch coastline spans a distance of approximately 350 km in length with 3,600 km of primary flood defenses, predominately dikes. A majority of the country's population lives in low-lying adjacent areas that are below sea level. This region of the Netherlands is home to nearly 9 million people and also generates 65% of the Netherlands' Gross National Product (GNP).

The strategy for future centuries is based on two pillars: flood protection and sustainability. The Committee's vision went beyond flood protection to embrace interactions with life and work: agriculture, nature, recreation, landscape, infrastructure and energy. The Delta Committee stated that a regional sea level rise of 0.65 to 1.3 m by 2100and 2 to 3 m by 2200 should be taken into account, including the effect of land subsidence. These values were considered plausible upper limits based on the latest scientific insights.

The study concluded that the Netherlands must accelerate its efforts because the current standards of flood protection are not being met everywhere, are out of date, and must be raised to address rapid climate change. Risk management recommendations were based on a combination of factors to reduce probability and consequences. Variable safety standards were set corresponding to:

- 250-year return period (1 in 250 AEP) for freshwater rivers;
- 2,000-year return periods (1 in 2,000 AEP) for lower tidal reaches of rivers and estuaries;
- 4,000-year return periods (1 in 4,000 AEP) for extreme water events (e.g. storm surge) in coastal regions other than Central Holland; and
- 10,000-year return periods (1 in 10,000 AEP) for coastal regions in Central Holland.

Measures proposed to limit the consequences of flooding included zoning regulation, compartmentalisation of areas subject to flooding, early warning systems, crisis management and contingency planning.

The study contained 12 recommendations based on a conclusion that the current level of flood protection must be increased by at least a factor of 10. The recommendations included strengthened storm surge barriers, including island polders. The cost of implementing the Delta Programme was estimated to be €1.2 to €1.6 billion per annum until 2050, and €0.9 to €1.5 billion per annum thereafter to 2100. Costs include strategic land acquisitionas well as compensation for damages and loss of benefits. Including maintenance and management, the total costs of growing with the climate and ensuring improved protection are €2.4 to €2.8 billion per annum up to 2050.

United Kingdom

In the United Kingdom (UK), the Department for Environment, Food and Rural Affairs (Defra) is the lead authority for managing the risk of river and coastal flooding and erosion; however, delivery is often provided at a local level. The UK has a National flood and coastal risk management strategy, which establishes the flood and coastal erosion risks, framework and principles for flood risk management, the roles and responsibilities of various authorities, how flood risk management is funded, and the need to develop local solutions to flood risks.

The winter of 2013-2014 was the wettest winter on record in the UK since 1910, and since 1766 for England and Wales. Before the winter storms, Defra had already been allocated £2 billion ($3.3 billion CAD) to implement warning system improvements, flood defence testing, and to improve flood protection works between April 2011 and May 2014. An additional £120 million ($200 million CAD) was allocated for flood defences in England at the end of 2012to expedite the process. The winter storms of 2013-2014 battered the UK, breaking many rainfall and river level records and setting the stage for loss of life and flooding of over 5,000 homes and businesses.

Defra and the UK Environment Agency were active in public outreach during the winter season. Flood alerts are available by phone, email, text message as well as online. Twitter was used widely by local authorities.

The UK Land Registry, Risk Management Services, now offers a Flood Risk Indicator service for properties within England and Wales. The general public can purchase reports on a property's risk of flooding from rivers and seas. The reports are instantly available and indicate the likelihood of flooding on any registered piece of land.

The National Flood Forum provides cost estimates to find out how much it would cost to protect a property as well as information on what to do before and in the event of a flood. The Environment Agency has published a Guide to the rights and responsibilities of those who own riverside property

The UK uses four major strategies when it comes to coastal flood defences – no active intervention, holding the existing line of defence, managed realignment (retreat), and advancing the line (land reclamation). A multi-media map presents the government's plans how to manage coastal erosion, using those 4 strategies, by 2030, 2060 and 2110.

State of Maryland, USA

The US State of Maryland is one of numerous jurisdictions that have moved away from hard protection measures to address coastal flood hazards and future SLR. Faced with an annual loss of over 235 hectares (580 acres) of coastal shoreline, the state was not satisfied with the performance of revetments and other hard protection measures. Based on extensive documentation concerning the effectiveness of soft armouring, and in response to private initiatives, the state changed the ground rules for coastal protection.

Under the *Living Shoreline Protection Act of 2008*, the State of Maryland adopted non-structural "living shorelines" erosion control measures as the preferred method to address the impacts of shore erosion induced by SLR, wherever technologically and ecologically appropriate. The legislation does not prevent "hard" structural measures but requires "soft" or non-structural measures to be considered first. Environmental benefits of living shorelines include trapping sediment, filtering pollution, and providing important aquatic and terrestrial habitat. Extensive documentation has occurred in the Chesapeake Bay estuary and other areas.

San Diego, California

A 2012 sea level rise adaptation strategy for San Diego Bay (ICLEI, 2012) identified the most vulnerable sectors of the community and the reasons for their vulnerability. In the next few decades, the greatest regional concern will be increased flooding due to El Niño events and very high tides. Key sectors threatened by inundation and/or erosion include ecosystems and critical species in San Diego Bay, stormwater, wastewater, potable water and energy infrastructure. Local transportation is vulnerable to saturated and pavement degradation from regularly occurring flood events.

Shoreline parks and recreational facilities were considered extremely vulnerable but also with a higher adaptive capacity than most other systems. Given these findings, the report called for a comprehensive strategy including public education, stakeholder engagement, incorporation of future risks from sea level rise in floodplain maps associated with flood insurance risk assessments, incorporation of sea level rise into local and regional plans, and clear and consistent regulatory guidance from regulatory agencies.

New York City

After Superstorm Sandy in October 2012, New York City put together a Special Initiative for Rebuilding and Resiliency (SIRR) taskforce which resulted in a $14 billion dollar plan – PlaNYC (NYC, 2013). Key funding sources were the City's capital plan and existing federal government programs, which accounted for $10 billion. The plan proposed over 250 initiatives designed to strengthen and protect the built environment and citywide infrastructure. Areas addressed include NYC's shoreline, diverse building stock, economic recovery, concerns over insurance loss, utility distribution, healthcare provision, local community preparedness, environmental protection and remediation, water and wastewater improvements and the development of other critical networks, such as food supply and solid waste.

The Department of City Planning of New York City published *Coastal Climate Resilience – Designing for Flood Risk* and *Urban Waterfront Adaptive Strategies* as part of their coastal climate resilience initiative. These documents present strategies to shift the urban design paradigm to one that both addresses "life on the streets" as well as coastal resilience and protection. The NYC Building Code includes minimum structural and programmatic requirements for any new, or renovated, building within the new Special

Flood Hazard Areas (SFHA). NYC Base Flood Elevation (BFE) begins at a 1% annual chance of storm event.

Copenhagen, Denmark

The City of Copenhagen, operating under the award-winning Copenhagen Climate Adaptation Plan (City of Copenhagen, 2013), is targeting three key levels of climate adaptation – to minimize potential damage from climate change, develop warning and response systems to deal with abnormal conditions, and provide preventative infrastructure to minimize damage, loss and disruption in traffic flows. The Plan highlights a few key factors to support successful implementation of their climate adaptation measures while maintaining an attractive, adaptable city, including flexible adaptation initiatives, synergy with other planning initiatives, and a high degree of technical information. The Plan breaks down risk by scale (region, municipality, district, street and building) and by three measures (reducing the likelihood, the severity and then the vulnerability of an event at each scale). To accommodate the uncertainty of climate change challenges the City has committed to a regular revision process, as new information becomes available.

4. Structural Flood Protection Inventory

The District of Squamish has an extensive portfolio of structural flood protection works along its major rivers and coastal margins. In addition to works operated and maintained by the District, separate structural flood protection works are owned and maintained by the North Vancouver Outdoor School, Squamish Nation, and private landowners. Some works on the Cheekeye River and Cheakamus River have no local maintenance authority. Other structures, both municipal and private, currently provide *de facto* flood protection for Downtown Squamish.

The IFHMP is primarily focused on structural flood protection works falling under District jurisdiction, but cannot ignore other works that affect the District's interests and responsibilities. The area protected by the District's structural flood protection works includes all or parts of Squamish Nation I.R. Nos. 14 (Waiwakum), 15 (Aikwucks), 16 (Seaichem), 17 (Kowtain) and 18 (Yekwaupsum).

The District's portfolio of official and *de facto* structural flood protection elements includes a combination of dikes, training berms, erosion protection revetments, railway and road embankments, storm water detention areas, flood boxes, drainage pump stations, and channel improvements. An overview of key flood protection elements is shown in Figure 2-1.

In general, the local dikes were constructed using alluvial sand and river gravel and do not contain an impermeable core. They are constructed on top of coarse alluvial sediments, which are in places overlain by a silt cap of up to several metres in thickness. Seepage through and beneath the dikes is common as a result of their construction and foundation conditions. High river stages do not occur for extended periods of time and some seepage has been deemed acceptable provided it does not result in internal erosion (Klohn Leonoff, 1994a).

Historic vegetation management has been good in many areas, usually those areas most easily accessed by maintenance crews. A number of other areas are now overgrown with mature vegetation. Mature vegetation is often considered valuable riparian habitat. This can lead to conflict between flood protection interests and internal environmental values as well as external stakeholders. The District completed a mature vegetation management program along the Mamquam River as a pilot exercise in 2014 (M. Simmons, pers. comm.).

In March 1999, BC MELP (1999c) prepared an Operation and Maintenance (O&M) Manual for the District's flood protection system. The O&M Manual is now 15 years old and does not reflect the latest state of knowledge regarding the status of the dike system.

Comprehensive dike inspections were completed by KWL in 2007 (KWL, 2007a) and 2015 (KWL, 2016). The Inspector of Dikes carried out a dike audit in 2011 and provided an audit report (BC MFLNRO, 2012).

The sections below describe the existing structural flood protection and mitigation measures on a reach and river basis.

Internal Drainage Systems

Sea level rise and higher future peak flows on local rivers will reduce the outflow capacity of internal drainage systems, which could indirectly increase related flood hazards. The District has excluded internal drainage from the IFHMP, since these issues are better addressed through watershed-specific Integrated Stormwater Management Plans (ISMPs). IFHMP comments on these issues are limited to interactions with river or coastal flooding and flood protection works. While their primary drainage function is not addressed, pump stations and floodboxes remain relevant to the IFHMP where they are integral to the flood protection works.

4.1 Squamish River

The Squamish River dike system consists of two main reaches totaling about 12.5 km in length:

- an upper dike reach extending from the Cheekeye Fan downstream to the Mamquam River; and
- a lower dike reach from Mamquam River downstream to Howe Sound.

The lower dike reach includes the Squamish River training berm, known locally as the Squamish Spit. Both upper and lower dikes are contiguous with corresponding dikes on the Mamquam River. The Squamish River dike is regulated under the *Dike Maintenance Act* and the District is the designated Local Authority.

The current comprehensive diking system was constructed by the Province in the early 1980s, replacing earlier remnant structures. Granular material for dike construction was sourced from a large sand/gavel bar immediately south of the confluence of the Squamish and Mamquam Rivers, while riprap was sourced from a large talus deposit near Alice Lake (Thurber, 2008).

From the mid-1980s to the mid-2000s, work on the dykes was generally limited to post-flood repairs funded by the BC Provincial Emergency Program (PEP), most notably following significant flood events in 1991 and 2003 (Brown, 1991; KWL, 2004a; KWL, 2004b). More recently the District has initiated both internally-funded and cost-shared upgrades that include dike raising (2008, 2013 and 2015), erosion protection works (2008, 2011 and 2015) and toe berms (2013 and 2015/16). Additional improvement projects have been completed for ancillary pump stations.

The Squamish River dike protects a mixed-use area about 500 ha in size that includes 500+ buildings with significant areas of residential, commercial, industrial and institutional infrastructure (BC MFLNRO, 2013a). The dike supports recreational trails and is generally over-width relative to minimum geometric standards (Golder & Associated Engineering, 2011); however, not all sections meet minimum width requirements established by a Squamish-specific 2008 geotechnical investigation to control seepage. Thurber (2008) provides a list of 27 locations where the dike slopes are oversteepened, the base width and/or dike section are inadequate, or where evidence of boiling was observed following the 2003 flood. An additional section of geotechnical concern resulted when the dike downstream of the CN Rail bridge was partially upgraded (raised with 2H:1V landside slope) in 2008. Some sections of concern were addressed by dike upgrades in 2013 and further planned upgrades in 2015.

Additional detail on the upper and lower reaches of the Squamish River dike is provided below.

Upper Squamish River Dike (Cheekeye Fan to Mamquam River)

The upper Squamish River dike extends approximately 6.1 km from Squamish Nation Waiwakum I.R. No. 14 in the north to the Mamquam River CN Rail Bridge near the Harris Slough pump station. This reach of the dike protects the neighborhoods of Brackendale, Eagle Run and Garibaldi Estates as well as Squamish Nation Waiwakum I.R. No. 14, Aikwucks I.R. No. 15, Seaichem I.R. No. 16, and Kowtain I.R. No. 17. BC Hydro high-voltage transmission lines cross the dike in a right-of-way at Fisherman's Park near the Judd Slough pump station.

Most of the upper Squamish River dike is set back from the river by varying amounts of vegetated overbank. Exceptions include short sections of riverside alignment at the dike's upstream end and near the Judd Slough pump station, as well as a longer section of riverside dike at the popular public Eagle Viewing Area. Thurber (2008) includes a sketch prepared by R. Cameron of MoE showing a length of dike built out into the river channel on rock fill to avoid encroaching on private property (Thurber, 2008).

All riverside dike sections have full-height riprap erosion protection. Set back dike sections generally have continuous riprap erosion protection of varying quality. Some areas of riverbank also have older riprap erosion protection works.

The dike does not have a continuous Statutory Right-Of-Way (SROW) over its length. The area with SROW extends from Judd Slough pump station downstream to Squamish Nation Seaichem I.R. No. 16. Private fencing currently obstructs access along the dike crest in this area. Remaining portions of the dike are a combination of Crown land, First Nations reserves, District-owned land, and private land without SROW (BC MFLNRO, 2012).

The legal status of the dike where it crosses First Nations land is unclear. KWL has been unable to confirm whether there is a legal agreement between District and Nation, or between the Squamish Nation and the Crown, governing construction and maintenance of the dikes. Persistent on-reserve dike deficiencies such as the gabions at Seaichem I.R. No. 16 serve as reminders of bipartisan challenges shared by the District and Squamish Nation.

The upper Squamish River dike cuts off large side channels at Judd Slough and Harris Slough. There are currently no inlet structures at the upstream end of either slough, although the Mid-Island floodbox can provide inflow near the mid-point of Harris Slough. An old inlet structure still visible in the riverside slope at the upstream end of Judd Slough was reportedly deactivated during dike repairs in 1991 (KWL, 2005).

The dike is supported by four ancillary pump stations (Judd Slough, Eagle Run, Dryden Creek, and Harris Slough) and six floodboxes (Judd Slough, Horse Creek, Eagle Run, Dryden Creek, Mid-Island, and Harris Slough). At Judd Slough, Dryden Creek, and Harris Slough, the presence of a pump station forebay adjacent to the dike increases the apparent dike height.

An illustrative overview of the upper Squamish River dike is provided in Figures 2-1 and 2-2 of KWL's 2006/2007 Dike Inspection report (KWL, 2007a).

Lower Squamish River Dike (Mamquam River to Howe Sound)

The lower Squamish River dike extends from the CN Rail Mamquam River Bridge to the Squamish Spit, including 2.7 km officially recorded as the Squamish River South Training Berm. The BC Inspector of Dikes' database (BC MFLNRO, 2013a) reports that the training berm is owned by BC Rail; however, the District has confirmed that it holds the lands through Crown land lease and is responsible for maintenance of the training berm. The training berm is not regulated by the *Dike Maintenance Act*.

The lower Squamish River dike protects the neighborhoods of Downtown Squamish, Dentville, North Yards and the Squamish Business Park as well as Squamish Nation Yekwaupsum I.R. No. 18.

The crest of the lower Squamish River dike is accessible over its entire length and supports significant public traffic to and from the spit via vehicle access from Government Road.

Government Road and its parallel overhead utilities are located immediately adjacent to the landside dike toe midway between Whittaker Slough and the Squamish Spit access. The nearest utility supports had to be relocated to accommodate dike upgrades in 2013.

Near the Squamish Spit access, the dike is crossed by the FortisBC natural gas mains serving the Sunshine Coast and Vancouver Island.

Sewage effluent is pumped from the District Wastewater Treatment Plant (WWTP) at the north end of the Mamquam River CN Rail Bridge across the bridge and along the lower Squamish River dike. The WWTP outfall is located about 800 m downstream of the CN bridge.

An active railway spur track is located immediately adjacent to the landside dike toe near the West Coast Railway Heritage Park. KWL (2005) reports that a section of the Squamish River dyke downstream of the BCR Bridge follows a previous railway alignment and, as a result, was constructed over rail embankment fill.

The lower dike isolates one minor side channel (Whittaker Slough) from the river mainstem. The dike has no ancillary pump stations, although previous drainage studies have proposed one at Whittaker Slough (SRK, 1995). There is currently one small floodbox at the downstream end of Whittaker Slough.

A number of large-diameter culverts allow free hydraulic exchange across the training berm to provide freshwater exchange between the river and historic estuary. The most upstream culverts are located at the upstream end of Crescent Slough. Crescent Slough was an active part of the Squamish River estuary until to construction of the Squamish River South Training Berm in the 1970s. The lower Squamish River dike is not contiguous with any coastal flood protection works.

The lower Squamish River dike proper (excluding the training berm) is set back from the river and protected by a vegetated overbank of varying width. While vegetation management is generally good on the upper part of riprap slopes, there are large trees commonly growing on the lower slopes.

Set back dike sections generally have continuous riprap erosion protection of varying quality. Some areas of riverbank also have riprap erosion protection works, however, these are believed to be of lower quality and are not regularly inspected. The dike does not have a continuous SROW. Areas with SROW include from the CN Rail Bridge to Edgewater Park and the lower portion of the Squamish Spit. Remaining portions of the dike are a combination of Crown land, District-owned land, and private land without SROW (BC MFLNRO, 2012). The existing SROW over private land south of the CN Rail Bridge has insufficient width to accommodate future dike raising.

An illustrative overview of the upper Squamish River dike is provided in Figure 2-3 of KWL's 2006/2007 Dike Inspection report (KWL, 2007a).

4.2 Mamquam River

The Mamquam River dike system includes a north (right bank) dike and a south (left bank) dike, described separately below. Both dikes commence near the apex of the Mamquam River fan and tie into the Squamish River dike at the CN Rail Bridge. The dikes were designed and constructed in their current form using alluvial materials as part of the comprehensive provincial diking program in the 1980s. Both dikes are regulated under the *Dike Maintenance Act*. The District is the designated Local Authority for these structures.

Post-flood repairs were undertaken by the BC Ministry of Environment following the 1991 flood, mostly relating to riprap reconstruction (Brown, 1991). The 2003 flood was not a particularly significant flood for the Mamquam River (KWL, 2011a); however, a subsequent high-flow event in 2007 caused some minor damage (SRWS, 2007).

Thurber (2008) assessed the north (right bank) dike and part of the south (left bank) dike as part of a high-level geotechnical report. Ten sections on the north dike were assessed as having oversteepened slopes and/or inadequate cross-sections. Two sections on the south dike were also found as having oversteepened dike slopes and inadequate base width; however, only a short section of the south dike was assessed.

An illustrative overview of the Mamquam River dikes is provided in Figures 3-1 of KWL's 2006/2007 Dike Inspection report (KWL, 2007a).

Mamquam River North Dike (Mashiter Creek to BCR Bridge)

The north (right bank) dike commences near Mashiter Creek, runs along the river frontage of the Squamish Golf & Country Club, crosses Highway 99 and Government Road, then ties into the Squamish River dike at the BC Rail Bridge. The north dike protects the neighbourhood of Garibaldi Estates as well as Squamish Nation Kowtain I.R. No. 17.

There is a low point in the dike where it is crossed by Highway 99. The low point was designed to be rapidly closed off by building a temporary berm from an adjacent stockpile of suitable material. KWL was unable to confirm the present-day location of the stockpiles; conversations with local residents suggest that the pre-existing stockpile of gravel may have been repurposed or removed at some point during the reconstruction of Highway 99. KWL understands that the need for an emergency dike closure at this location will be reflected in the District’s forthcoming updates to its Emergency Plan.

The north dike also has at-grade crossings with Government Road and the CN Rail mainline. BC Hydro transmission lines cross the dike at two separate locations upstream of Highway 99.

The north dike is predominately set back from the river by a large overbank containing several significant back channels that provide fisheries habitat. The only portion of the dike located directly adjacent to the Mamquam River is a reach about 800 m in length at the upstream end. The north dike is located on a combination of District-owned land and Crown land (BC MFLNRO, 2012).

Past assessments (e.g., KWL 2007a) have noted that some areas of the Mamquam north dike are less than 4 m in width while other areas are oversteepened and dependent on vegetation for continued stability. Ponds adjacent to the landside dike slope increase the apparent height of the dike at some locations.

Erosion protection works on the Mamquam River north dike are limited to a short reach of lower-slope revetment near Government Road, and a reach of oversteepened riverside slope near the golf course. The Inspector of Dikes Squamish South Dike Inventory Map (Appendix B) also shows river bank protection works along the vegetated overbank between the BC Hydro crossings. Evidence of ongoing bank erosion in the form of toppling trees upstream of Highway 99 was pointed out to KWL by District staff during a site visit in late 2014.

Two drainage culverts with flap gates are located in this dike, located upstream and downstream of Highway 99 respectively. Both floodboxes discharge to side channels.

The dike crest is accessible along the full length of the Mamquam River north dike.

Mamquam River South Dike (Coast Aggregates Quarry to BCR Bridge)

The Mamquam River south (left bank) dike commences at the entrance to the Coast Aggregates Quarry, crosses Highway 99 and Government Road, and ends at the BCR Bridge. The dike is predominately located along the river with the exception of about 600 m where the dike is set back with a wide overbank. Brennan Channel, a small man-made spawning back channel, is located in the overbank area and is protected by a small berm. Along the upper reach of the dike, Centennial Way follows the dike crest.

Riprap bank protection revetments exist along the riverside sections of the dike and along portions of the remaining overbank. Riprap quality varies, with moderate to heavy vegetation and limited toe protection in some areas. Evidence of overbank erosion is visible in areas where the bank slopes are unprotected (KWL, 2005).

The dike crest is accessible along its entire length, and is paved where it shares alignment with Centennial Way. Many sections of the dike crest are overwidth (e.g., Centennial Way) or appear overwidth (e.g., between Government Road and Highway 99 where fill was wasted against the dike without provincial authorization). The District holds SROW tenure for all portions of the dike between Centennial Way and the CN Rail bridge (BC MFLNRO, 2012).

The Mamquam River south dike has no ancillary floodboxes or pump stations; however, a gated intake culvert was constructed through the dike at Brennan Channel as part of the Mamquam Reunion project. The south dike is crossed by two BC Hydro transmission rights-of-way. Highway 99 and Government Road cross the dike at grade, while the BC Rail crossing is a visually-apparent low point in the dike.

Together with the lower Squamish River dike, the Mamquam River south dike provides contiguous protection for the neighborhoods of Downtown Squamish, Dentville, North Yards and Squamish Business Park as well as Squamish Nation Yekwaupsum I.R. No. 18.

4.3 Cheakamus River

The Cheakamus River has no comprehensive diking system, but there are a number of dike structures protecting discrete sections of floodplain. All Cheakamus River dikes are non-standard structures (with respect to BC Ministry of Forests, Lands and Natural Resource Operations criteria for a standard dike). A number of these informal structures have been linked together and now function as *de facto* primary flood protection works for the right floodplain of the Cheakamus River at the Cheakamus Centre (formerly NVOS). Multiple intakes through the NVOS berms supply water to habitat channels on the floodplain.

None of the flood protection works along the Cheakamus River were constructed to meet 200-year return period water levels. Repairs to several of the works including the Wountie West berm (Old Quarry Road) and NVOS structures were carried out by the Province following the 1991 flood (Klohn Leonoff, 1994a). Some of the structures were breached during in the 2003 flood and subsequently re-built as part of the post-flood recovery program.

Cheakamus River structural flood protection works are described individually below, commencing from the northern District boundary. An illustrative overview of the District and NVOS Cheakamus River dike structures is provided in Figure 4-1 of KWL's 2006/2007 Dike Inspection report (KWL, 2007a).

Bank Protection Works at Culliton Creek (Jack Webster Bridge)

The Jack Webster Bridge carries Paradise Valley Road traffic over Culliton Creek a short distance upstream of the Cheakamus River. The bridge abutments and the upstream right bank are protected by riprap revetments.

The province also constructed a riprapped berm on the right bank downstream of the road bridge following the 1980 flood (MacFayden, 1983). The upstream portion of the berm was constructed on private property (presumably without a SROW) while the downstream portion was constructed on Crown land (Bland, 1991).

Riprap near the bridge and along the berm was damaged during the 1984 flood and was repaired by the BC Ministry of Environment (BC MOE, 1984). Riprap was damaged again in the 2003 flood and subsequently repaired by the District (KWL, 2004c). These structures are located near the northern District boundary and may be located all or partly within the jurisdiction of the Squamish-Lillooet Regional District (SLRD).

KWL does not have any detailed information regarding any private flood protection structures at or north of Culliton Creek.

Dike 5C above Government Road (Paradise Valley Road Berm)

The Paradise Valley Road berm is a narrow, low river training structure several hundred metres in length that trains the river to the severe constriction imposed by the Bailey bridge. The berm protects the north approach where the road was constructed across an old high-flow channel. The berm also protects the base of some BC Hydro transmission towers. The berm does not tie into high ground, and relatively small floods (less than a five-year return period) can outflank the bridge at its upstream end (AMEC, 2002).

The structure was built in 1983 and upgraded in the 1990s (AMEC, 2002). It was overtoppedand breached during the 2003 flood, and was repaired as part of the flood recovery program (KWL, 2004a). The post-2003 repairs realigned the berm along the north bridge approach. A portion of the paved berm crest was left at the approach grade so that relief flow can bypass over the road before flow starts to impinge on the Bailey Bridge structure.

While the sections repaired post-2003 are well-armoured, the original riprap appears undersized and does not extend to the top of the structure. According to the Inspector of Dikes' database (BC MFLNRO, 2013a), the berm has no designated Local Authority and is not regulated under the *Dike Maintenance Act*.

Cheakamus River Training Berm (Wountie West Berm and Wountie East Berm)

These two paired training berms do not meet the definition of a standard dike, serving primarily to train flows through and past the Bailey Bridge. The Wountie berms provide some protection to fisheries channels, Paradise Valley Road and NVOS.

The Wountie West berm extends from the south side of the Bailey Bridge about 600 m upstream to an abandoned quarry. A length of 200 m at the upstream end was reconstructed in 2004 as part of a joint Fisheries and Oceans / NVOS fisheries enhancement project. As part of these works, the berm was realigned and constructed with BC Inspector of Dikes approval using competent material. The upgrades achieved standard dike dimensions and the met the accepted flood construction level of the day. Although there is no record of subsequent upgrades, KWL's 2007 dike inspection noted up to 0.5 m depth of fresh track-packed fill on the crest of the Wountie West berm (KWL,2007a).

There is a submerged fisheries intake with a landside gate near the upstream end of the Wountie West berm. The works also include a 600 mm-diameter steel drainage culvert with a flap gate approximately 100 m downstream of the Mykiss Channel intake.

The Wountie East berm extends approximately 550 m downstream from the Bailey Bridge and does not tie into high ground at its downstream end. The berm was overtopped and breached during the 2003 flood. The District completed repairs shortly following the flood; however, riprap repairs were deferred to the unfunded Phase 2 recovery program. The downstream 350 m of the Wountie East berm is narrower than the upper portion and is not armoured.

Ancillary works for the Wountie East berm include the Gorbushca West channel intake immediately downstream of Paradise Valley Road (BC Hydro et al., 2003).

According to KWL's records, the District is the Local Authority for the Wountie West and Wountie East berms. The structures are regulated under the *Dike Maintenance Act*.

The Inspector of Dikes' database (BC MFLNRO, 2013a) identified the District as Local Authority for the Cheakamus River Training Berm, which has a reported total length of 570 m. The reported length of 570 m matches the dike chainage shown on the Squamish North Dike Inventory Map at Paradise Valley

Road (Appendix B). This is in conflict with IOD's 2011 Dike Audit Report (BC MFLNRO, 2012) and KWL's records of District responsibility for both Wountie berms.

Recent discussions with District staff confirm that there is some confusion regarding responsibility for these structures. IOD advised that they would update their records to correctly reflect the District's responsibility for the 570 m-long Wountie West Berm and the 500 m-long Wountie East Berm.

The IOD report notes that all lots south of Paradise Valley Road are owned by NVOS; however, the IOD audit did not identify a SROW in favour of the District's Wountie flood protection structures.

Cheakamus Centre (NVOS) Dikes and Berms

The NVOS works consist of about 1,700 m of low dikes, berms, and riprap that are not tied into high ground. The structures are therefore susceptible to overtopping and outflanking. The fill quality is variable, and is generally sourced from nearby floodplain excavations. The Inspector of Dikes database indicates that the structures are regulated under the *Dike Maintenance Act*, and that NVOS is the owner and maintenance authority (BC MFLNRO, 2013a). The structures are located on land owned by NVOS (BC MFLNRO, 2012).

At the upstream end of the NVOS works is Bob's Berm, a particularly low-profile structure with non-standard dike dimensions that has no bank protection works. Bob's Berm terminates at the confluence of the Cheakamus River and a local side channel. It does not tie into high ground at either end.

The Main Dike is located downstream of Bob's Berm and provides a degree of flood protection for the majority of the buildings at NVOS. The Main Dike commences at floodplain level upstream of the buildings and therefore cannot provide comprehensive protection. During the 2003 flood, the Main Dike was outflanked and nearly overtopped. The Main Dike meets geometric requirements for a standard dike. The riprap bank protection revetment along the Main dike was damaged during the 2003 flood and subsequently repaired.

The Canoe Pond dike is contiguous with the Main Dike and terminates at higher ground adjacent to the Big House. The Canoe Pond dike was constructed from processed Cheekeye Fan deposits to meet geometric requirements for a standard dike. It breached during the 2003 flood over a length of 150 m. Repairs shifted the alignment of the dike away from the river to increase channel capacity. WSC Station 08GA043 (Cheakamus River near Brackendale) is located adjacent to the Canoe Pond dike.

The south berm is the most downstream of the NVOS structures and extends from the Big House to the southern boundary of NVOS property. The downstream end of the berm does not tie into high ground. The berm appears to be constructed of local and particularly low-quality material, and the cross-section is narrow with steep slopes in places. The berm was breached in 2003 and subsequently reconstructed to its previous width and slope.

The slopes of Bob's berm, the Canoe Pond dike (except areas restored in 2003) and the South berm are generally not armoured and are heavily vegetated. Cottonwood trees on some of the berms have grown to trunk diameters of 600 mm.

Cheakamus River Indian Reserve Dike (Fergie's Bridge Training Berm)

In 1993, a 150 m-long dike was constructed on the right bank of the Cheakamus River opposite the mouth of the Cheekeye River, replacing the remnants of an old levee found in 1991 (Bland Engineering Ltd., 1996; KWL, 1998a). The 1993 dike spans between Fergie's Bridge and upstream high ground at a natural rock outcrop. The riverside slope is armoured with heavy riprap and the dike has no ancillary structures. The dike is located entirely on Squamish Nation Cheakamus I.R. No. 11. It is reported in the provincial database with a length of 180 m but is not regulated under the *Dike Maintenance Act*.

The crest elevation approximates the low chord elevation of Fergie's Bridge. This reduces the risk of flooding on reserve at flows less than the bridge capacity, but still allows relief flow to commence before flows impinge on the bridge deck.

The dike protects the low-lying Cheakamus community on I.R. No. 11. The Squamish Nation has an approved but unfunded Capital Funding Submission on file with Indigenous and Northern Affairs Canada (INAC) to support a more comprehensive diking project for this community.

The Cheakamus I.R. No. 11 dike is located opposite a District riprap revetment on the left bank that trains flow approaching Fergie's Bridge. The District riprap was damaged and subsequently repaired in the floods of 1980, 1984, and 1991, and was extensively reconstructed after being damaged in the October 2003 flood.

Cheakamus River Works Downstream of Fergie's Bridge

A private dike with riprap slope protection was constructed on the left bank of the river in the early 1980's. The structure extends downstream approximately 1 km from Fergie's Bridge. The private dike has cut off a portion of the left bank floodplain and may have increased the potential for flooding and erosion of Squamish Nation lands on the opposite (right) bank.

On the right bank downstream of Fergie's Bridge, BC Hydro constructed approximately 100 metres of bank protection works and some nominal berming to mitigate erosion at the foot of the hydro tower (KWL, 1998a). The protection provided by these works is nominal at best and the works are not reported in the Inspector of Dikes database.

4.4 Cheekeye River

The Cheekeye River has two recorded flood protection structures at different locations, built to different standards for different purposes. At the time of IFHMP review, records for Cheekeye River structures in the Inspector of Dikes database (BC MFLNRO, 2013a) conflicted with KWL's field observations (KWL, 2007a). The IOD database reported two structures:

- the Cheekye Berm, total length 1.17 km, maintained by the District and regulated under the *Dike Maintenance Act*; and
- the Fernwood Road berm, reported as 550 m of "remnant emergency works" with no designated maintenance authority that is not regulated under the *Dike Maintenance Act*.

KWL's 2006/2007 dike inspection report also identifies two structures, but with different extents, including:

- a well-defined but poorly-maintained berm upstream of Highway 99 with a length of about 500 m; and
- a poorly-defined, heavily-vegetated possible structure in the vicinity of Fernwood Road with a length of about 650 m.

The total combined length of these structures is approximately 1.15 km.

The apparent discrepancy between IOD records and KWL field observations is resolved by referencing reports prepared following the 1991 debris flow event (Bland, 1992a; Bland, 1992b). The reports describe two structures, as follows:

- a ±500 m long berm and associated erosion protection works on the left bank of the Cheekeye River upstream of Highway 99, constructed by the BC Ministry of Transportation and Highways to mitigate overland flooding and reduce the likelihood of a subsequent avulsion; and
- material from a 1985 gravel removal project that was bulldozed to form a linear stockpile along the left bank. This stockpile is shown on one of Bland's 1992 drawing as an "existing berm" extending about 650 m from the BC Rail right-of-way to approximately 550 m upstream of Fernwood Road.

The structures identified in KWL's 2006/2007 dike inspection report match those described by Bland (1992a; 1992b). In response to this report, IOD has confirmed that it will update the current length 1.17 km length of the "Cheekye Berm" listed in the provincial records to reflect only the 500 m length of the 1991 Cheekeye training berm upstream of Highway 99.

Based on Bland's descriptions of each structure, the lower berm was never intended to be a formal flood protection structure, and the upper berm does not meet provincial standards for a "standard dike". Neither berm has any ancillary structures. The riprap revetment at the upstream end of the upper berm was constructed using comprised of boulders salvaged from the channel and material from a nearby talus slide (Bland, 1992b).

Bland also confirms that the structure upstream of Highway 99 was turned over to the District for maintenance following construction. Recent discussions with District staff suggest that there is some confusion regarding responsibility for these structures. The structure does not have a SROW (BC MFLNRO, 2012).

While the Cheekeye River training berms provide some protection against floods, they could be overwhelmed or outflanked by even moderately severe debris flows. The District and its partners will need to carefully consider the role of these structures within a comprehensive Cheekeye fan protection strategy.

The provincial 1980 flood recovery report also notes that the Cheekeye River left bank riprap revetment located downstream of the CN Rail bridge has been repaired or reconstructed multiple times following the major regional floods (e.g., MacFayden, 1983; Brown, 1991).

An illustrative overview of the Cheekeye River berms and Cheakamus River works near Fergie's Bridge is provided in Figure 6-1 of KWL's 2006/2007 Dike Inspection (KWL, 2007a).

4.5 Stawamus River

The District's Stawamus River dike is a large, wide-crested berm on the north (right) side of the river that protects the Valleycliffe area. The 2,400 m-long dike was originally constructed in 1985, commencing at the Mamquam FSR Bridge and terminating approximately 50 m upstream of Little Stawamus Creek. The dike ties into the Mamquam FSR at its upstream end. It does not tie in to high ground at its downstream end and can be outflanked.

The dike ranges in height from nominal (where the steep river channel is well incised) to about 2 m and is regulated under the *Dike Maintenance Act*. The District is the designated Local Authority for dike maintenance and holds a SROW for the entire length of the dike (BC MFLNRO, 2012).

The riversideslope of the Stawamus River dike is generally armoured with riprap protection. The toe of the dike was damaged during the 1991 flood and subsequently repaired (Brown, 1991). A length of about 250 m of riprap revetment downstream of the FSR Bridge was reconstructed in 2012, although due to funding constraints the heavy riprap revetment does not extend up to the dike crest (KWL, 2013b).

Except for the 2012 upgrade, riprap slopes are oversteepened and moderately to heavily vegetated. In some locations, there is a small to significant width of low-relief vegetated overbank between the toe of the dike slope and the active river channel, with large trees established in the dike toe.

There are no ancillary structures along the Stawamus River dike. Two water mains parallel the landside dike toe between the parking lot and the Mamquam FSR. There is a stormwater detention pond next to the dike just upstream of the parking lot at Plateau Drive. It appears as though the stormwater detention pond is designed to overflow across the dike crest in the event of a storm exceeding its capacity. This could result in damage to the dike crest.

The dike crest is accessible along its entire length. An illustrative overview of the Stawamus River dike is provided in Figure 5-1 of KWL's 2006/2007 Dike Inspection report (KWL, 2007a).

Stawamus I.R. No. 24 Dike

In 1998, KWL completed a flood and erosion study of the Lower Stawamus River on behalf of the Squamish Nation. KWL recommended a ±300 m-long dike to raise a low-lying portion of Billy Drive on the left bank of the Stawamus River. The riverbank in this area had been overtopped several times in the past, most recently in 1995 (KWL, 1998b).

The Stawamus I.R. No. 24 dike was constructed under the federal Department of Indian and Northern Affairs' (DIAND, now Indigenous and Northern Affairs Canada or INAC) April 1999 Urgent Mitigative Flood Works program. The Stawamus I.R. No. 24 works include approximately 300 m of setback dike up to about 2.5 m high that follows and extends the alignment of Billy Drive. Riprap armouring was also provided along the west (right) bank of the river and along the riverside slope of the setback dike (KWL, 1999).

Drainage structures for the Stawamus I.R. No. 24 dike include one 600 mm-dia. culvert with flapgate located a short distance upstream of the point where Billy Drive diverges from the dike alignment. A second 600 mm-dia. culvert with flapgate was installed near the upstream tie-in between the 1999 riverbank revetment and pre-existing abutment riprap downstream of the CN Rail bridge. The second culvert does not penetrate the dike (KWL, 1999).

Provincial dike regulation does not apply on reserve lands and there is therefore no formally-designated Local Authority for the Stawamus I.R. No. 24 dike. However, post-construction documentation included a Capital Assets Inventory System (CAIS) form that enables the Squamish Nation to obtain operation and maintenance funds for the Stawamus I.R. No. 24 dike from INAC (KWL, 1999). As a result, the Squamish Nation has operation and maintenance responsibility for the Stawamus I.R. No. 24 dike.

4.6 Howe Sound

Squamish does not currently have a continuous perimeter of comprehensive coastal flood protection works; at present, the community is served by a network of non-standard official and unofficial works. These structures are described below.

Town Dike

The Town Dike (sea dike) is a low, narrow-crested, non-standard informal structure that provides protection against coastal floods for over 250 buildings in downtown Squamish. The dike extends just over 1,000 m in length from the foot of Cleveland Avenue west and north along the tide flats to the west end of Winnipeg Street near Pemberton Avenue.

The Town Dike was likely constructed during the development of downtown Squamish in the early 1900s, and has been modified since with land-use changes and drainage works. The dike is regulated under the *Dike Maintenance Act*, and the District is the designated Local Authority for dike maintenance. The dike is situated on District-owned land adjacent to the Skye and Aqua developments (Main Street to Vancouver Street). Other portions of the dike have no SROW recorded (BC MFLNRO, 2012).

The dike is set back a fair distance from the wave environment of Howe Sound and is protected along much of its length by Bridge Pond (discussed below). The majority of the Town Dike does not have bank protection works. A short section of well-constructed riprap works along Cattermole Slough protects the east end of the dike. Toward its west end, the dike is located along the bank of the Main Street Slough (Cattermole Creek). Expansion of the dike to achieve a standard cross-section would likely encroach on the slough and/or several adjacent private properties.

Setbacks from the waterside face of the stacked-rock Bridge Pond seawall to the adjacent buildings are on the order of 10 m. At the June 2014 meeting of the District's Technical Working Group, the Deputy Inspector of Dikes (DIOD) advised that DIOD had reviewed and approved the current configuration as part of the adjacent development proposal. The DIOD's authorization assumed the Town Dike would eventually be replaced by a new dike along the alignment proposed by Bland Engineering Ltd. (1999). KWL understands that a developer has recently made application to resume construction on the adjacent partially-built phase of development, also located immediately behind the Town Dike.

The Town Dike has ancillary floodboxes at 4th Avenue, 6th Avenue, and Pemberton Avenue. IOD records also document a sanitary sewer pipeline in the sea dike (BC MFLNRO, 2012).

Much of the Town Dike crest serves as a popular public trail. The section between gates at Vancouver Street and Victoria Street is accessible to authorized vehicles. Dense vegetation on the dike crest inhibits vehicle access from 3rd Avenue and from Pemberton Avenue.

Previous studies have recommended comprehensive upgrades to the District's coastal flood protection system (Klohn Leonoff 1994b, Bland Engineering Ltd., 1999). Downtown stormwater studies have also recommended a future ancillary drainage pump station at the Sixth Ave. (Hayco, 2004).

An illustrative overview of the Town Dike is provided in Figure 7-1 of KWL's 2006/2007 Dike Inspection report (KWL, 2007a).

Cattermole Creek Estuary (Bridge Pond)

The downtown Squamish stormwater system drains to Cattermole Creek estuary (locally known as Bridge Pond) adjacent to Howe Sound. The Bridge Pond area is protected from Howe Sound by the 3rd Avenue embankment and CN Rail line serving Squamish Terminals. The pond is bounded on the downtown side by the Town Dike and the 6th Avenue spur dike.

The 3rd Ave. embankment and CN Rail line were constructed as transportation arteries rather than sea dikes, and are not regulated or maintained as flood protection works. Nonetheless, these structures provide *de facto* coastal flood protection for Bridge Pond and Downtown Squamish.

Since 1984, the District has operated a tide gate structure adjacent to the 3rd Avenue vehicle bridge over Cattermole Creek. The automated tide gates form part of the *de facto* flood protection perimeter, reducing downtown flood hazards by closing as ocean water levels rise and re-opening when the ocean water level falls below the estuary water level. This gives the District the ability to limit water levels against the Town Dike during any coastal flood that does not overtop or breach the Bridge Pond perimeter.

Limiting the natural fluctuation of water levels has resulted in predictable patterns of ecological succession within the estuary flats. Bridge Pond therefore represents an area where the District's objective of environmental stewardship isin conflict with its mandate to manage flood hazards. To help resolve this conflict, in 2013 the District began an optimization project (KWL, 2013d) to balance flood protection and environmental goals. The engineering work is now complete, and the project has moved to the implementation phase with the gates remaining open much longer under favourable weather conditions.

Previous internal drainage assessments for downtown Squamish (e.g., Hayco, 2004) have made allowances for a future drainage pump station. These studies have shown that stormwater storage capacity at Bridge Pond must be considered in conjunction with any future upgrades to the District's downtown coastal flood protection works.

Lower Mamquam Blind Channel

There are currently no designated or regulated structural flood protection works along the Mamquam Blind Channel downstream of Highway 99. Previous reports (e.g., Klohn Leonoff, 1994b; Bland Engineering Ltd., 1999) have proposed comprehensive flood protection connecting a dike or seawall along the west side of the Mamquam Blind Channel to an upgraded Town Dike. Only one small section of this vision was implemented at the Marina Estates development in the late 1990s.

While continuous protection works would mitigate coastal flood hazards, the 1994 FHMP also points out that introducing a continuous perimeter of coastal flood protection works could create a "bathtub" effect during an upstream dike breach (Figure 4-1). This possibility led the 1994 FHMP to propose downtown FCLs 0.3 m above the proposed coastal flood protection perimeter.

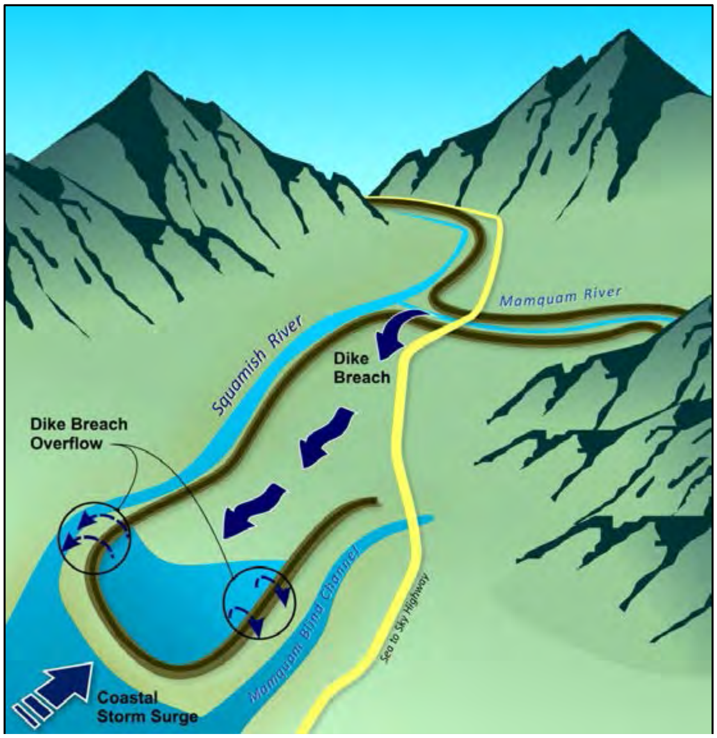


Figure 4-1: Conceptual Illustration of Coastal/Dike Breach Flood Protection Conflicts

The District's long-term planning objectives call for a continuous waterfront walkway that can be integrated into any coastal flood protection works (KWL, 2013c). As originally envisioned, these works would tie into high ground near the Highway 99 Bridge. To date, only one section of seawall has been completed at the Marina Estates development. Independent engineering reports prepared for other proposed developments mention that historic fill has been placed along the foreshore for flood protection purposes (e.g., GeoPacific, 2014).

Most recently, KWL (2013c) has provided provisional guidance for coastal flood hazard management at West Mamquam Blind Channel. KWL's guidance is intended to help the District continue with development while the three-year IFHMP update is in progress.

The east side of Mamquam Blind Channel is generally steeper and not subject to coastal inundation. The Waterfront Landing development does not currently propose any structural flood protection works (Tetra Tech EBA, 2014).

Upper Mamquam Blind Channel / Wilson Slough

Flow between Mamquam Blind Channel and Loggers Creek / Wilson Slough is controlled by floodboxes passing beneath Loggers Lane. The floodboxes have a combination of manual tide gates and flap gates in varying states of repair. During the IFHMP field visit, some flapgates appear to have been damaged or removed.

According to the operations protocol for the Upper Mamquam Blind Channel floodbox structure (FOC &DoS, 2012), the tide gate is to remain open until water levels rise above 14' chart datum (4.27 m CD or 1.21 m geodetic elevation). In December 2014, coastal water levels reached 5.5 m CD (2.44 m CD). The missing flapgates allowed localized flooding to occur along Wilson Slough upstream of Loggers Lane. The District is planning to repair the flapgates to prevent this situation from recurring and allow the structure to be operated in accordance with its agreed protocol.

The road grade where Loggers Lane crosses the Mamquam Blind Channel is below the 3.3 m geodetic elevation recommended in the 1994 FHMP. Previous drainage studies (SRK, 1995) have proposed an ancillary pump station to support the floodboxes at Loggers Lane.

5. Updated Hazard Assessments

This section provides an overview of updated hazard assessments completed for the IFHMP. Updates have been completed for:

- peak flow hydrology (Section 5.1);
- hydraulic modelling of all rivers except Cheekeye River (Section 5.2and Section 5.3);
- still-water coastal flood conditions (Section 5.4); and
- updated wind and wave modelling for Howe Sound (Section 5.5).

In addition, the IFHMP team undertook a high-level qualitative review of the various geohazards identified in Section 2. The results of that assessment are detailed in Section 5.6.

5.1 Hydrology Update

Work completed for KWL's 2011 Squamish River / Mamquam River modelling study (KWL, 2011a) will form the basis for IFHMP modelling of the Squamish River and Mamquam River floodplain. As part of the IFHMP, river modelling efforts will also be expanded to include the Cheakamus River and Stawamus River.

Although KWL's Squamish River / Mamquam River modelling report was not finalized until 2011, the supporting hydrology assessment actually dates back to 2007. The IFHMP technical work program requires an update to the peak flow estimates provided in the 2011 report.

The planned simple update became more complex when the hydrological assessment results indicated significant revisions (some downward) to the peak flow estimates. Peak flow estimates have now been revisited for all rivers and relevant tributary areas within the District. New peak flows had to be estimated where they were not previously required (e.g., Stawamus River). The update generally followed the approach outlined in the 2011 report. Changes relative to the 2011 report include:

- adding up to seven years of additional peak flow data (2008 through 2014);
- additional data screening and quality control;
- applying new frequency analysis software (HYFRAN);
- checks on methodology, including process separation for statistical analysis;
- use of water-year daily-average peak flow data to maximize record length and provide hydrologic consistency for at-site Flood Frequency Analysis (FFA);
- redevelopment of the regional peak flow analysis;
- application of a climate change allowance to peak flows to represent the year 2100 planning horizon; and
- extrapolating estimates to include peak flows up to the 1,000-year return period.

KWL has completed internal due diligence and reviewed the values with the Inspector of Dikes office. The Inspector of Dikes has agreed to accept the revised 200-year return period peak flows presented herein as the basis for future flood protection planning and design. Their decision recognizes the balance of increases and decreases in peak flows as well as the addition of climate change factors as per APEGBC (2012) guidelines.

Climate Change Allowance for River Floods

To check for climate change-induced trends in the peak flow series, KWL reviewed the longest available WSC peak flow record among the local rivers as well as regional hydrometric stations with longer records. These stations included:

- 08GA022 – Squamish River near Brackendale (up to 60 years of peak flow record);
- 08GA010 – Capilano River above Intake (up to 97 years of record, watershed located immediately south of Stawamus River); and
- 08MG005 – Lillooet River near Pemberton (up to 93 years of record, watershed located immediately north of Squamish River).

The statistical Mann-Kendall test was used to analyze peak flow records for each of the three stations. Each of the records was tested for the full length of the record and for the most recent 30-year period, using both instantaneous peak flow series (by calendar year) and daily-average peak flow series (by water year). The Squamish River was also re-tested using only non-freshet daily-average peak flows.

Of the 14 scenarios described above, only one indicated a statistically-significant upward trend. The sole exception was the full record of instantaneous peak flows for 08GA010 (1958 – 2012, 56 years of record). However, a number of factors suggest that this result is an artefact of the sampling period:

- The trend for the most recent 30 years of instantaneous peak flow at 08GA010 is downward.
- The trend for the most recent 30 years of daily-average peak flow data at 08GA010 is downward.
- The daily-average series shares the same pattern (lower peak flows for the 1961-1978 period) as the instantaneous record.
- Re-sampling the daily average peak flow record to match the dates of the instantaneous peak flow record (1958-2012) produces a statistically-significant upward trend, despite the fact that tests on both shorter and longer intervals show downward trends.

On the basis of the above analysis, the significantly significant upward trend in the instantaneous record of 08GA010 is interpreted as an artefact of the sampling period. The Mann-Kendall analysis therefore confirms that there is no statistically-significant upward trend detectable in peak flows at this time.

On the basis of the Mann-Kendall analysis, the 10% upward adjustment recommended by APEGBC (2012) is deemed most appropriate for District design flows. It is expected that the test for trend will be updated as new information becomes available.

Squamish River

A mixed-population flood frequency analysis (i.e., conventional FFA) was carried out using the 60 years of daily-average annual peak flow records and the 53 years of instantaneous annual peak flow data available for WSC hydrometric station 08GA022 - Squamish River near Brackendale.

For this update, the analysis considered the daily-average peak flow series based on water years (October 1 to September 30) rather than calendar years. Water years preserve the hydrologic integrity of the fall/winter storm season as well as the logical relationship between fall/winter snow accumulation and the subsequent spring freshet.

The results of the FFA represent the average of three statistical distributions:

- Generalized Extreme Value (GEV) -fitted by the Method of Weighted Momentsmethod.
- Three Parameter Lognormal (3LN) -fitted by the Maximum Likelihood method.
- Log Pearson III (LP3) - fitted by the US Water Resources Council method.

Visual assessment of the instantaneous and daily-average FFA results concluded that all three distributions provide an acceptable fit. An average of the three values was used to acknowledge the uncertainty associated with selecting a single "best-fit" distribution for extrapolation of a relatively short record, particularly out to the 1,000-year return period.

FFA results for the daily-average peak flow series show a reduction of approximately 10% to 15% from the values used in the 2011 modelling study (KWL, 2011a). A more significant reduction is indicated for the instantaneous peak flow series.

Table 5-1: Squamish River (WSC 08GA022) Peak Flow Estimates

Flood Return Period	Drainage Area (km^2)	Daily-Average Peak Flow (m^3/s)			Instantaneous Peak Flow (m^3/s)	
		KWL, 2011a*	IFHMP, CY*	IFHMP, WY**	KWL, 2011a*	IFHMP, CY*
1 in 200	2,350	3,797	3,310	3,390	4,213	3,610
1 in 1000		N/A	4,400	4,640	N/A	4,710

*Peak flow series based on Calendar Year **Peak flow series based on Water Year
Note: values shown are based on IFHMP 2014 flood frequency analysis and do not include +10% climate change allowance.

To validate the 2014 results, KWL repeated the 2014 FFA using the legacy Consolidated Flood Frequency Analysis (CFA-3) software used for the analysis reported KWL's previous study (KWL, 2011a). The 2014 CFA-3 estimates were slightly greater than the 2014 HYFRAN estimates, but were still significantly less than the 2007 CFA-3 estimates. This confirms that the reduction in peak flow is primarily a result of the longer peak flow series rather than the change in frequency analysis software.

A combined-population analysis was also completed to evaluate the effect of differentiating between freshet and non-freshet peak events. Results were similar to the mixed-population analysis at longer return periods and did not justify the additional effort required for the more complex analysis.

Cheakamus River

Similar to the Squamish River FFA, a mixed-population flood frequency analysis was carried out using the water-year annual maximum daily average peak flow series from WSC station 08GA043 - Cheakamus River near Brackendale. Its 52 years of daily-average and instantaneous peak flow data cover the period 1958-2013 and include estimates for the 2003 flood of record. The 2003 flood breached a dike opposite the hydrometric station and peak flow estimates are subject to significant uncertainty. Extrapolation of WSC stage and discharge records suggests a peak flow of about 1,300 m^3/s. An independent analysis by BC Hydro suggests a slightly higher 2003 instantaneous peak flow of about 1,390 m^3/s (LaCas, 2012).

Unsurprisingly, the 2003 flood estimate has a strong effect on the tail of any single-site frequency analysis for WSC station 08GA043. To balance this effect, the peak flow data series were extended by transposing results from the historic WSC gauge 08GA017 – Cheakamus River at Garibaldi. The older hydrometric station is located about 18 km upstream of the present-day station and captured more than 80% of the present-day station's watershed area.

To transpose older peak flows from 08GA017 to 08GA043, KWL applied a conservative scaling factor of 1.24 based on the ratio of contemporaneous watershed area measurements. The area ratio was applied as a linear transformation (scaling exponent 1.0), since the increase in watershed area is offset by strong runoff gradients that decrease moving inland from Howe Sound.

Instantaneous peak flows were not recorded at WSC 08GA017. To extend the instantaneous peak flow series, KWL applied an instantaneous to daily average (I:D) peak flow ratio to the transposed daily-average data. The station-average I:D ratio of 1.38 for WSC 08GA043 was selected based on the scatter of I:D values and the conservative scaling factor applied at the transposition step.

The combined records for 08GA017 and 08GA043 provide an 88-year peak flow series that covers the period 1917 to 2013 and includes major regional floods in 1921 as well as 2003.

Daisy Lake dam was completed in 1957. Peak flows recorded after this date are classified as regulated. Daisy Lake reservoir does not have sufficient storage to attenuate large peak flows, and past studies have neglected reservoir effects (Nichols, 1986). However, BC Hydro diverts up to 65 m^3/s from the Cheakamus River to the Squamish River for power generation.

For the purposes of the IFHMP, KWL assumes that the generating station was operating at full capacity during all significant peak flow events. Post-1957 peak flows were naturalized by adding 65 m^3/s prior to the frequency analysis. The average and standard deviation of transposed pre-1957 data from 08GA017 compare well against corresponding values for naturalized at-site data from 08GA043.

A mixed-population flood frequency analysis was carried out using the 88 years of combined and naturalized instantaneous and daily-average annual peak flow data. The results of the HYFRANFFA represent the average of two statistical distributions:

- Generalized Extreme Value (GEV) -fitted by the Method of Maximum Likelihood.
- Log Pearson III (LP3) - fitted by the US Water Resources Council method.

The three-parameter log-normal distribution (3LN) was rejected due to poor fit. Visual assessment of FFA results concluded that the 3LN distribution systematically underestimates the largest flood peaks.

FFA results were re-regulated by subtracting the assumed BC Hydro diversion of 65 m^3/s. This is consistent with past studies (Nichols, 1986) and is reasonable given the already-significant increase in peak flows from those used in the 2011 modelling study (KWL, 2011a). Frequency analysis results match the 200-year return period design flood of 1,600 m^3/s adopted for the historic Cheakamus River floodplain mapping (Nichols, 1986).

Table 5-2: Cheakamus River (WSC 08GA043) Peak Flow Estimates

Flood Return Period	Drainage Area (km^2)	Daily-Average Peak Flow (m^3/s)			Instantaneous Peak Flow (m^3/s)	
		KWL, 2011a*	IFHMP, CY*	IFHMP, WY**	KWL, 2011a*	IFHMP, CY*
1 in 200	965***	972	1,220	1,160	1,407	1,600
1 in 1000		N/A	1,940	1,800	N/A	2,450

*Peak flow series based on Calendar Year **Peak flow series based on Water Year
*** Drainage area published by WSC has been updated from area of 1,010 km^2 cited in KWL's 2011 hydraulic modelling report.
Note: values shown are based on IFHMP 2014 flood frequency analysis and do not include +10% climate change allowance.

A report by EBA (2012a) concludes that debris floods could initiate at or upstream of Culliton Creek with an annual probability of 1 in 5,000. To represent the higher sediment concentrations associated with a debris flood, EBA recommends that a bulking factor of 1.5 be applied to the 200-year return period and 500-year return period peak flow.

KWL supports the use of a bulking factor when determining the appropriate background flow for a debris flood originating with failure of a landslide dam. However, the 5,000-year return period debris flood event identified by EBA is beyond the scope of the IFHMP. KWL is not aware of any studies that suggest debris floods could affect Paradise Valley at return periods of 1 in 200 or 1 in 500. For the purposes of the IFHMP, the bulking factor recommended by EBA has **not** been applied to the peak flows listed in Table 5-2.Appropriate bulking factors should be applied as part of any site-specific debris flood study for properties upstream of the Cheekeye River confluence.

KWL assumes that Cheekeye River debris flow and debris flood runout as well as debris dam outburst floods on the Cheakamus River will be assessed separately as part of the Cheekeye Fan mitigation assessment.

Regional Index Flood Analysis

As part of the 2011 modelling study, KWL (2011a) used a regional index flood analysis to produce peak flow estimates for the Mamquam River and local Squamish River tributaries. The IFHMP extended the regional peak flow analysis to other watersheds, including watersheds smaller than any considered in 2011.

When the 2011 regional peak flow analysis was extended to these smaller watersheds (e.g., Little Stawamus Creek), inconsistencies in the extrapolated results become apparent. While conservative small-tributary discharges were acceptable for the 2011 modelling, the IFHMP focus on multiple watersheds and the need to balance flood protection priorities requires a more refined analysis.

KWL completed a detailed review of the 2011 regional analysis and produced the following key observations:

- The 2011 regional analysis appears to have incorporated a transcription error in the peak flow records for Rutherford Creek.
- None of the available WSC station records is long enough to statistically support FFA extrapolation to a 1,000-year return period flood; however, extrapolation of the relatively short records available for existing reference stations would introduce an even greater degree of uncertainty.
- The regional value for the Mean Annual Flood (MAF) at Mamquam River is 67% greater than the scaled-up MAF recorded at WSC hydrometric station 08GA075 – Mamquam River above Ring Creek, and 76% greater than the scaled-up MAF recorded at WSC station 08GA054 – Mamquam River above Mashiter Creek. Combined, these gauges have over 35 years of annual flood data and their re-scaled MAF values are relatively consistent. While there is some uncertainty in the MAF observations, it is unlikely that observation error could explain the discrepancy.

Based on KWL's review, the 2011 regional analysis was updated as follows:

- FFA results were updated independently for each reference station.
- Two new long-term (±100 year) reference stations were introduced to help stabilize extrapolation.
- Transcription errors were corrected.
- Parameters were re-fit to obtain a more reasonable MAF estimate for the Mamquam River.

Since the initial index flood analysis was based on daily-average peak flows, an instantaneous-to-daily (I:D) peaking factor of 1.9 was applied to obtain instantaneous peak flow estimates at all locations of interest. An I:D ratio of 1.9 reflects the average observed values for WSC records on both the Mamquam River and the Stawamus River, and is therefore considered appropriate for applying regional peak flow results to the smaller IFHMP watersheds.

Results from the regional analysis were validated by comparing regional estimates against independent site-specific estimates for the largest and smallest watersheds of interest. The largest watershed of interest is the Squamish River at WSC hydrometric station 08GA022; regional results compared well against the at-site 200-year return period peak flow estimates provided in Table 5-1. The smallest watershed of interest is Little Stawamus Creek, a tributary to the Stawamus River with an area of 5.7 km²; regional results compared well against the 200-year return period estimate previously obtained from rainfall-runoff modelling (KWL, 2007b).

Regional results were used to generate peak flows for the following ungauged tributaries:

- Fries Creek: drainage area of 20 km^2;
- Squamish Area A (local inflow over a distributed area; see KWL, 2011a): drainage area of 19 km^2;
- Squamish Area C (local inflow over a distributed area; see KWL, 2011a): drainage area of 14 km^2;
- Cheakamus River below WSC 08GA043 (including Cheekeye River): drainage area of 71 km^2;
- Stawamus River above Mamquam Forest Service Road Bridge: drainage area of 49 km^2; and
- Stawamus River below FSR Bridge (including Little Stawamus Creek): drainage area of 6 km^2.

These peak flows were modelled as steady-state discharges except for the largest, Cheakamus River below 08GA043. For the Cheekeye River / Cheakamus River local area, the 2003 flood event hydrograph for WSC 08GA043 – Cheakamus River near Brackendale was scaled down to match the regional analysis peak flow.

Mamquam River

The updated Mamquam River 200-year peak flow estimate summarized in the table below is significantly less than the 2011 estimate but is significantly greater than other independent third-party estimates (e.g., NHC, 2006).

Table 5-3: Mamquam River (WSC 08GA075) Peak Flow Estimates

Flood Return Period	Drainage Area (km^2)	Instantaneous Peak Flow (m^3/s)	
		KWL, 2011a	IFHMP, CY
1 in 200	377	1,200	910
1 in 1,000		N/A	1,260
Peak flow series based on Calendar Year.			

Past single-site FFA results for Mamquam River WSC gauges were not updated for this study. However, KWL's 2011 report provides a FFA instantaneous peak flow estimate of 804 m³/s at WSC hydrometric station 08GA075 – Mamquam River above Ring Creek (KWL, 2011a).

Stawamus River

The updated regional analysis was used to estimate instantaneous peak flows for the Stawamus River at the Mamquam FSR Bridge and for Little Stawamus Creek. All tributary areas downstream of the Mamquam FSR Bridge were combined with Little Stawamus Creek. Peak flows for the Stawamus River were not estimated in KWL's 2011 river modelling report, since the Stawamus River is not part of the Squamish River watershed.

Instead, the table below compares the 2014 regional analysis against at-site FFA results prepared by KWL for a 2012 riprap upgrading project. KWL's 2012 FFA transposed and combined data from WSC 08GA064 – Stawamus River below Ray Creek and WSC 08GA076 – Stawamus River at Highway 99 to form a composite 30-year series of instantaneous peak flows.

Table 5-4: Stawamus River Peak Flow Estimates

Flood Return Period	Watershed	Drainage Area (km^2)	Instantaneous Peak Flow (m³/s)		Debris Flood Peak Discharge (m³/s)
			KWL, 2012	IFHMP, CY	2014
1 in 200	Above Mamquam FSR	48.8	152	200	300
	Little Stawamus Creek	6.2	N/A	42	42
1 in 1,000	Above Mamquam FSR	48.8	N/A	270	410
	Little Stawamus Creek	6.2	N/A	59	59

Area of 48.8 km^2 corresponds to Stawamus River at Mamquam FSR Bridge.
Balance of watershed area is 6.2 km^{2}and includes Little Stawamus Creek.
Peak flow series based on Calendar Year.

The at-site FFA and regional analysis estimates (152 m³/s and 200 m³/s, respectively) bracket the 200-year return period flood estimate published by BC MOE (1994). However, both are considerably less than the upper-envelope clear-water flood peak discharge suggested by Baumann (1994) based on previous work by Thurber Engineering at Britannia Creek.

To account for the possibility of debris floods as documented by Baumann (1994), the estimated clear-water peak flows for the Stawamus River mainstem were increased by a 'bulking factor" of 1.5 to 2.0. This factor is at the lower end of the range of factors proposed by Jakob & Jordan (2001); however, it is considered sufficiently conservative for an initial high-level assessment given that these highly-transient flows will be modelled as steady-state. A factor of 1.5 to 2.0 was also validated by detailed landslide dam-breach modelling carried out by for the comparably-sized Chapman Creek watershed near Sechelt, BC (KWL, 2010a).

Instantaneous Peak Flow Hydrographs

Updated peak flow estimates for the Squamish River, Cheakamus River and Mamquam River must be converted to a flood hydrograph to support hydrodynamic modelling.

The October 2003 flood event is the largest recorded flood for both the Squamish River and Cheakamus River. The modelling approach used for the 2011 river modelling report was to "scale up" the 2003 hydrographs to match the peak flow estimates. A complete description of the rationale and process is described in KWL's modelling report (KWL, 2011a) and is reapplied for the IFHMP.

For the Squamish River, the design flood hydrograph was obtained by scaling up the October 2003 hydrograph to match the updated daily-average peak flow estimate. This approach provides an instantaneous peak flow of 4,070 m³/s, which is more conservative than the updated 200-year return period instantaneous peak flow estimate of 3,610 m³/s. A conservative approach is appropriate given the uncertainty in peak flow estimates and the net reduction from the 2011 estimates.

Scaling the 2003 Cheakamus River hydrograph to match the updated daily-average peak flow estimate would yield an instantaneous peak flow of about 1,400 m³/s. This value is less than the updated instantaneous peak flow estimate of 1,600 m³/s and would not be conservative.

In selecting an approach for scaling the Cheakamus River hydrograph, the IFHMP must consider two key factors:

- The maximum daily-average discharge (by calendar day) from the 2003 flood hydrograph aligns very closely with the maximum 24-hour discharge (by continuous 24-hour period), which results in a relatively low I:D ratio; and
- During the 2003 flood, dike breaches in the vicinity of WSC station 08GA043significantly increased the uncertainty of the stage-discharge relationship during the flood event. WSC does not publish 2003 peak discharge estimates for 08GA043 as a result of this uncertainty.

Based on the above rationale, KWL chose to adopt a more conservative approach. The 2003 hydrograph was scaled up to match the updated instantaneous peak flow estimate of 1,600 m³/s.

For the Mamquam River, the peak flow hydrograph was obtained by scaling up the observed 2003 event hydrograph so that the instantaneous peak of the hydrograph would match the required instantaneous peak flow. This is consistent with the approach outlined in the 2011 report.

Timing of Peak Flows

The Mamquam River and Squamish River respond to different types of events and are less likely to experience concurrent flood peaks than the Squamish River and Cheakamus River. In 2003, the Mamquam River hydrograph peaked about 16 hours prior to the Squamish River; however, the 2003 flood was not particularly severe on the Mamquam River. Concurrent application of the scaled-up 2003 hydrographs at the Mamquam River, Squamish River and Cheakamus River is considered reasonably conservative for the purposes of the IFHMP. Additional discussion is provided in the 2011 modelling report (KWL, 2011a).

Squamish River Tributaries

Squamish River minor tributaries are modelled as steady-state (constant) inputs and do not require a flood hydrograph.

Final Peak Flows for Updated Hydraulic Modelling

A summary of the final 200-year return period instantaneous peak flow estimates extracted from the design flood hydrographs is provided in Table 5-5 below. The Year 2100 values shown in the summary table include the 10% upward adjustment recommended by APEGBC climate change guidelines (APEGBC, 2012). The climate change adjustment should be applied both for planning scenarios and for conceptual design of mitigation works, which have a design life extending forward from current conditions. In special cases the District may wish to consider whether an additional allowance for climate change might be appropriate.

Table 5-5: Summary of 200-Year Return Period Peak Flows for Hydraulic Modelling

River/Creek	200-Year Return Period Instantaneous Peak Discharge (m^3/s)			Notes
	KWL, 2011a	IFHMP, Present-day	IFHMP Year 2100 (2014 + 10%)	
Squamish River	4,213	4,070	4,480	• at WSC 08GA022 (2,350 km^2) • Q200i from scaled 2003 hydrograph
Cheakamus River	1,407	1,600	1,760	• at WSC 08GA043 (965 km^2) • Q200i from scaled 2003 hydrograph
Cheekeye River	270	260	290	• IFHMP includes Cheakamus local inflow • Q200i from regional analysis (71 km^2)
Mamquam River	1,200	910	1,000	• at mouth (377 km^2) • Q200i estimated from regional analysis
Ring Creek	N/A	N/A	N/A	• accounted for in Mamquam River flow
Mashiter Creek	N/A	N/A	N/A	• accounted for in Mamquam River flow
Fries Creek	90	100	110	• at mouth (20 km^2) • Q200i estimated from regional analysis
Squamish Tributary Area 'A'	200	100	110	• total area 19 km^2 • Q200i estimated from regional analysis
Squamish Tributary Area 'C'	82	77	85	• total area 14 km^2 • Q200i estimated from regional analysis
Stawamus River at Mamquam FSR	152	300	330	• total area at Mamquam FSR 48.8 km^2 • Q200i from regional analysis (200 m^3/s) • IFHMP estimates include debris flood bulking factor of 1.5
Little Stawamus Creek at Stawamus River	N/A	42	46	• at mouth (6.2 km^2) • Q200i estimated from regional analysis

Table 5-6: Summary of 1,000-Year Return Period Peak Flows for Hydraulic Modelling

River/Creek	1,000-Year Return Period Instantaneous Peak Discharge (m^3/s)			Notes
	Previous Estimate	2014	Year 2100 (2014 + 10%)	
Squamish River	N/A	5,570	6,130	• at WSC 08GA022 (2,350 km^2) • Q1000i from scaled 2003 hydrograph
Cheakamus River	N/A	2,450	2,700	• at WSC 08GA043 (965 km^2) • Q1000i from scaled 2003 hydrograph
Cheekeye River	N/A	360	400	• Incl. Cheekeye and Cheakamus local inflow • Q1000i from regional analysis (71 km^2)
Mamquam River	N/A	1,260	1,390	• at mouth (377 km^2) • Q1000i estimated from regional analysis
Ring Creek	N/A	N/A	N/A	• accounted for in Mamquam River flow
Mashiter Creek	N/A	N/A	N/A	• accounted for in Mamquam River flow
Fries Creek	N/A	140	150	• at mouth (20 km^2) • Q1000i estimated from regional analysis
Squamish Tributary Area 'A'	N/A	140	150	• total area 19 km^2 • Q1000i estimated from regional analysis
Squamish Tributary Area 'C'	N/A	110	120	• total area 14 km^2 • Q1000i estimated from regional analysis
Stawamus River at Mamquam FSR	N/A	410	450	• total area at Mamquam FSR 48.8 km^2 • Q1000i from regional analysis (270 m^3/s) • 2014 includes debris flood bulking factor 1.5
Stawamus River at Little Stawamus Creek	N/A	59	65	• at mouth 6.2 km^2 • Q1000i estimated from regional analysis

5.2 River Modelling Update

The District of Squamish's main river systems have been analyzed using three hydraulic models:

- a hydrodynamic one-dimensional model for the diked channels of the Squamish River / Mamquam River system (updated from KWL's 2011 modelling report);
- a hydrodynamic one-dimensional model for the Cheakamus River; and
- a steady-state one-dimensional model for the Stawamus River.

Mike 11 software by DHI was chosen for hydrodynamic simulations of unsteady (time-varied) flow because of its quasi-two-dimensional floodplain modelling capabilities, its stable resolution of diverse hydraulic conditions, and its ability to integrate seamlessly with the forthcoming IFHMP two-dimensional floodplain model.

The US Army Corps of Engineers HEC-RAS model was selected as a well-known and reliable tool for more simplistic steady-state modelling of the Stawamus River system.

Both models apply standard one-dimensional modelling assumptions, including fixed bed and vertical extrapolation at the edge of defined cross-sections.

Squamish River / Mamquam River Model

Cross-section data for the Squamish River and Mamquam River are described in KWL's 2011 modelling report (KWL, 2011a). The model includes the Squamish River from Howe Sound to about 1 km upstream of the Cheakamus River confluence, and the Mamquam River for about 4.6 km upstream of the Squamish River. Cross-section data are based on photogrammetric mapping, topographic survey, and bathymetric survey completed between 2005 and 2008. The cross-sections do not reflect the new LiDAR data recently collected by the District.

A short reach of the Cheakamus River model (approximately 3.5 km in length) was added to the model using archived provincial cross-sections to accommodate backwater effects at the Squamish River-Cheakamus River confluence.

Calibration of the model is described in the 2011 modelling report. No new calibration information was available, and no further calibration was undertaken for the IFHMP.

Inflow boundary conditions were based on the updated hydrology described in Section 5.1, including the application of re-scaled hydrographs from the 2003 flood.

Coastal boundary conditions were based on a time series for the month of December 1991, which saw some of the largest astronomic tides within the 19-year tidal epoch. The time series was shifted so that the high tide would occur concurrently with the peak river discharge.

A correlation analysis of concurrent peak flows on the Squamish River and CHS residual water levels at Point Atkinson concluded that it would be overly conservative to combine the most extreme external storm surge with Squamish River peak discharges. IFHMP coastal engineering sub-consultant SNC-Lavalin recommended combining the December 1991 tide series with a long-duration mean annual storm surge and a reduced allowance for local effects. KWL incorporated allowances for external storm surge and local effects such that the peak water level corresponds to a 10-year return period coastal flood (based on joint probability results described in Section 5.4).

Severe (but independent) coastal flood processes can govern the flood profile in downstream portions of the estuary. For this update, KWL compared water surface elevations at the downstream end of the model against design still-water coastal flood levels to determine the upstream extent of coastal flood influence.

The Squamish-Mamquam River model was run for two scenarios:

- "Present Day", based on the input boundary conditions as described above; and
- "Year 2100", based on adding a 10% upward adjustment to peak flows and 0.85 m SLR allowance (10 mm/year from 2015 to 2100) to all coastal water levels.

Allowances for long-term channel aggradation were considered but a detailed analysis is beyond the scope of the model update. No allowance was made for the Squamish River, which has a relatively modest net sediment influx of about 11,500 m^3/year. To support dike freeboard assessments and dike breach modelling, a nominal uniform aggradation allowance of 0.3 m was applied to the Mamquam River, increasing locally to 0.6 m at the Mashiter Creek confluence in recognition of the tributary's ability to deliver pulse loads of sediment during high flows. Future studies may want to give further consideration to whether and how much aggradation allowance is appropriate, particularly for the Mamquam River given its historically higher bed levels and the effects of past sediment removals. In recognition of these and other similar uncertainties, the BC Inspector of Dikes required that a 0.6 m freeboard be applied to results.

Mike11 model results for each cross-section and peak flow scenario were compared with the corresponding coastal DFL (still water coastal flood level) and the higher of the two values was adopted to create a composite flood profile. Results were found to be relatively insensitive to intermediate combinations of river and coastal flood scenarios. The model update assumed that large waves would not propagate up the estuary into reaches where the design flood elevation is controlled by peak river discharge.

Cheakamus River Model

KWL prepared a Mike 11 model of the Cheakamus River extending over 14 km from the Squamish River confluence to upstream of Culliton Creek. An early version of the Squamish River / Mamquam River model was coupled to the Cheakamus River model to provide a realistic downstream boundary condition for the Cheakamus River.

Consideration was given to formally combining the Cheakamus River model with the Squamish River/ Mamquam River model. However, significant differences in the source and accuracy of the cross-section data make it prudent to maintain two separate models at this time.

Inflow boundary conditions were based on the updated hydrology described in Section 5.1. For simplicity, peak flows estimated at WSC station 08GA043 near NVOS were transposed upstream to the District boundary near Culliton Creek. Similarly, clear-water peak flows from the Cheekeye River were combined with distributed inflow from other local tributary areas and applied at the Cheekeye River confluence.

Cross-section data for the Cheakamus River was taken from the old Ministry of Environment database, dating back to 1978 and 1983. These data are publically available from the BC Ministry of Environment through the Ministry's online Ecological Reports Catalogue (EcoCat) and are provided with disclaimers and without warranty of any kind. The BC MOE cross-sections are the same ones used to develop floodplain mapping for the Cheakamus River in the 1980s.

The 1978 and 1983 cross-sections extend from the Squamish River confluence to downstream of Culliton Creek. Additional EcoCat cross-sections from a 1993 survey are used to represent the uppermost ±2 km of river within the District.

The Cheakamus River is morphologically active at some locations and substantial changes in channel geometry have occurred in the decades since the EcoCat cross-sections were surveyed. For example, KWL (2011a) reports that the Cheakamus River fan has extended about 200 m further west into the Squamish Valley since the cross-section data were surveyed in the 1970s. The most significant changes may occur near the Cheekeye River confluence; Bland (1992c) highlights a difference of over 3 m in elevation from surveys completed in 1989 and 1991; however, it is expected that a significant fraction of the debris flow deposits would be mobilized and transported further downstream during a large Cheakamus River flood. KWL assumes that the Bailey Bridge on Paradise Valley Road will remain unblocked and in place during the design flood.

In addition to the above cross-section uncertainties, some cross-sections are widely spaced, many cross-sections do not extend to high ground on either side of the floodplain, and there is little to no calibration data available for recent floods. The 1993 cross-sections are subject to a higher degree of uncertainty regarding plan location and cross-section width.

NHC (2001) estimates a relatively modest 1,700 m³/year input of sand, gravel, cobble and boulder sediment between Daisy Lake Dam and Culliton Creek. Some of this sediment will be transported through the reach, resulting in a net input of less than 1,700 m³/year. In addition, a historical air photo review by EBA (2012) concluded that the channel has been downcutting since Daisy Lake Dam was completed in 1957. KWL assumes that the downcutting observed by EBA has lowered the 30+ year-old cross-sections enough to offset any net sediment input above the Cheekeye River confluence. The lack of a long-term aggradation allowance for the IFHMP is in keeping with the provincial floodplain mapping (Nichols, 1986).

Appropriate deposition allowances should be incorporated into any subsequent debris flood assessment, particularly downstream of the Cheekeye River where previous studies have recommended that flood studies consider a complete bridge blockage. In addition, it is still possible for any given site to experience local aggradation as channel morphology evolves. The cross-sections used for this Background Report also do not reflect District, NVOS, BC Hydro, Squamish Nation and private dikes constructed over the last three decades. These dikes are discontinuous, non-standard, and have been overtopped and/or breached at multiple locations in different floods. This is considered a significant source of uncertainty for the analysis.

In the absence of field calibration data, the model was calibrated to the 1983 floodplain mapping profile based on the steady-state discharge of 1,600 m³/s reported in the floodplain mapping brief (Nichols, 1986). An acceptable fit to the 1983 flood profile was obtained; however, the original roughness values from the 1983 study were not available for comparison. Specific uncertainties affecting calibration include the imposition of vertical boundaries at the edges of narrow cross-sections, bridge capacity limitations and the lack of validation for flow splits and floodplain connectivity.

Without minimizing their significance, the uncertainties discussed above must be considered in the context of the morphological uncertainty associated with any assessment of a large flood. Such floods themselves usually create very significant changes; the 1991 flood demonstrated that a single event can change bed elevations at the Cheekeye River confluence by several metres. From this perspective, cautious interpretation of the old Ministry data can still provide a reasonable approximation of potential flood consequences for planning purposes. Results must be interpreted with regard to the uncertainties described above, as well as:

- fixed-bed assumptions (i.e., cross-section geometry does not change during a flood event);
- the exclusion of debris flood bulking factors from the peak flow analysis;
- the potential for log jams and transient flood surges; and
- re-regulation of the flood frequency analysis results (i.e., assuming that BC Hydro continues to divert water to the Squamish River during the design flood).

Sensitivity analysis carried out by KWL applied Manning's equation at selected sections to evaluate the difference between the historical MoE cross-sections (as used in the model) and corresponding full-floodplain cross-sections that can be extracted from the 2013 LiDAR. Results suggest that the hydraulic model is sufficiently conservative to account for the various uncertainties in most areas, and that freeboard allowances need not exceed the typical recommended allowances. The notable exception is the Cheekeye River, where debris flows beyond the scope of this study must be considered separately.

The Cheakamus River model was run for two scenarios:

- "Present Day", based on the input boundary conditions as described above; and
- "Year 2100", based on adding a 10% upward adjustment to peak flows.

As resources permit, the Cheakamus River model should be updated to take advantage of new information that is beyond the scope of the IFHMP, including District 2013 LiDAR and more recent channel surveys. The District may want to explore a collaborative application of recent more detailed modelling completed by BC Hydro for the Cheakamus River mainstream below Daisy Lake Dam.

Stawamus River Model

The Stawamus River is modelled in HEC-RAS using LiDAR-derived cross-sections over a ±4 km-long reach extending from the Mamquam River FSR Bridge to tidewater. The Stawamus River did not experience particularly high flows on the day the LiDAR data were collected, and errors associated with bathymetry below the water surface are assumed to be negligible.

KWL previously prepared a survey-based HEC-RAS model covering several hundred metres downstream of the Mamquam FSR Bridge. While surveyed cross-section data are typically preferred over LiDAR, in this case the surveyed data are only available for a short portion of the modelled reach and were replaced with LiDAR cross-sections to ensure consistency.

Supplementary field visits to the Highway 99 Bridge and CN Rail Bridge were undertaken to verify bridge opening geometry. The field visit confirmed that bridge abutment and deck geometry should not be neglected for this study. As noted in Section 2.6, the old bridge abutments beneath the existing Highway 99 bridge deck will reduce the flood conveyance of the bridge opening and must be incorporated in the hydraulic model.

Channel roughness was estimated based on previous site visits, aerial photos and gradient-based formulae (e.g., Jarrett, 1984). Estimated roughness values in all reaches are considered reasonably conservative; this is appropriate given the LiDAR-based data, the uncertainty associated with debris flood processes, and the lack of calibration data. Roughness values are significantly higher in steeper sections to capture the energy-dissipating levels of turbulence associated with steep slopes and boulder substrate. Roughness values decrease to more “typical” levels (i.e., approaching Chow, 1959) as the slope declines and the substrate becomes more gravelly. Model results should be interpreted with due regard for the assumed roughness values.

The lack of historical water level data precludes model calibration at this time. The applicability of the WSC stage-discharge curve at Highway 99 for model calibration could be explored at a future stage of the IFHMP; however, calibration at Highway 99 will reflect the local effects of the bridge crossing and is not expected to significantly reduce uncertainty in the steeper reaches upstream. In addition, KWL’s field visit confirmed that the old bridge abutments still in place below the new bridge deck would be outflanked at flood discharges. The resulting shift in the stage-discharge curve could invalidate extrapolation from measured high flows to more extreme peak flows. This limits the value of historical high-flow stage-discharge measurements for calibration purposes.

Upstream boundary conditions include steady-state peak flows at the Mamquam FSR Bridge as described in Section 5.1. One steady-state flow change location was specified at the Little Stawamus Creek confluence and represents all inflows below the Mamquam FSR Bridge. The downstream boundary was set at a static water level equal to the 10-year return period coastal flood plus allowance for local effects. This is consistent with the downstream boundary condition applied for the Squamish River / Mamquam River model.

A subjective allowance of 1 m aggradation was applied above the invert of all cross-sections to allow for some deposition concurrent with the peak discharge debris flood scenarios.

The application of steady-state analysis using an instantaneous clear-water peak flow can provide a conservative but reasonable approximation of the flood profile over relatively short reaches such as those modelled for the Stawamus River. A steady-state analysis is usually more conservative for the scenario of a landslide dam-breach induced debris flood; by definition, such debris floods represent a rapidly-varying and transient flow condition. KWL's landslide dam breach modelling of mid-watershed outburst floods for Chapman Creek (KWL, 2010a) confirmed the effects of rapid attenuation as the floodwave travels downstream.

Analysis of a debris flood scenario was not originally proposed for the IFHMP. In KWL's opinion, the combination of a conservative steady-state analysis and a bulking factor of 1.5 to 2.0 times the clear-water flood peak provides the most reasonable representation that can be achieved within the current IFHMP scope. If the IFHMP identifies significant flood hazard management challenges, the District may wish to consider a more detailed assessment of landslide potential, geometry, and breach mechanics to support a more accurate hydrodynamic simulation.

Additional uncertainty is created by attempting to represent two-dimensional overland flow downstream of Highway 99 in a one-dimensional model. Two-dimensional or quasi-two-dimensional modelling for the lower Stawamus River is beyond the scope of the IFHMP. However, more detailed modelling should be considered prior to detailed flood planning or design of flood protection works on Squamish Nation Stawamus I.R. No. 24.

The Stawamus River model was run for two scenarios:

- "Present Day" debris flood, based on 1.5 to 2.0 times the 200-year return period clear-water peak flow; and
- "Year 2100" debris flood, based on adding a 10% upward adjustment to present-day debris flood peak flows and 0.85 m SLR allowance (10 mm/year from 2015 to 2100) to all coastal water levels.

HEC-RAS model results for each cross-section and debris flood scenario were compared with the corresponding coastal DFL (still water coastal flood level) and the higher of the two values was adopted to create a composite flood profile. The presence of the CN Rail Bridge makes the model results generally insensitive to intermediate combinations of river and coastal flood scenarios.

5.3 Updated River Model Results

Squamish River

Updated profile drawings for the Squamish and Mamquam River are included in Appendix D. Results focus on the Year 2100 (+10% peak flow) scenarios. The Year 2100 scenarios are now the relevant scenarios for design of structural flood protection works, planning and review of proposed development, and the forthcoming IFHMP dike breach analysis. Profiles are shown for the 200-year return period and 1,000-year return period flood events, both with and without 0.6 m freeboard.

The results indicate conditions more severe than those documented in the 2011 report and comparable to those documented in KWL's 2013 climate change update (KWL, 2013g). Based on the Year 2100 200-year flood profile, overtopping would occur at:

- mid-Judd Slough
- near the Horse Creek floodbox
- downstream of the Squamish Spit access road
- Dryden Creek
- West Coast Railway Heritage Park

Insufficient freeboard is indicated at:

- upper Judd Slough
- from near the Judd Slough pump station to Squamish Nation Seaichem I.R. No. 16

- from Seichem I.R. No. 16 to downstream of the Mid Island floodbox, and
- alongside the West Coast Railway Heritage Park.

A dike raise project was completed in 2015 at the West Coast Railway Heritage Park. Areas downstream of the Squamish Spit access road are considered lower priority than other reaches of the dike since overtopping or dike breach floodwaters would spill into the natural estuary.

Water levels associated with the coastal flood govern for about 800 m upstream from the estuary mouth along the Squamish River South Training Berm, but do not affect the flood profiles shown in Appendix D. Coastal flood modelling and wave allowances should be revisited before using model results to undertake any detailed analysis of the spit itself.

Mamquam River

The reduction in peak flow estimate for the Mamquam River (relative to the previous results from KWL, 2011a) is significant enough to be reflected in the updated water levels for the 200-year return period flood that are shown in Figure 5-1. The reduction is noticeable even after adding the +10% climate change allowance for the Year 2100 scenario and assumed aggradation allowance. The right bank at Highway 99 and left bank at the CN Railway remain low; however, the updated profiles suggest any overtopping would be minimal at these locations.

Squamish River water levels still backwater the Mamquam River from the confluence to about Government Road. The model confirms that the low chord of the CN Rail Bridge will be submerged; however, the structure has minimal impact on upstream water levels due to backwater conditions imposed by the Squamish River.

For the Year 2100 1,000-year return period peak flow scenario shown in Figure 5-2, water is expected to overtop the right bank at Highway 99 and the left bank at the CN Railway bridge. Year 2100 1,000-year flood levels exceed the existing dike crest elevation downstream of the CN Railway bridge. Freeboard on the Mamquam River dikes is compromised between the CN Railway bridge and Government Road, while there are varying degrees of freeboard available further upstream.

Modelled conditions are based on cross-section data collected c.2008 and presently include a nominal allowance for aggradation. The 2011 preliminary sediment budget noted that the trend for the 1995-2008 period was one of slight net degradation (KWL, 2011a). However, there is potential for this trend to reverse, particularly at the Year 2100 horizon. Independent hydraulic modelling of the Mamquam River near the Highway 99 Bridge linked local aggradation of up to 1.2 m to a 0.2 m rise in modelled water levels (NHC, 2006). Water level response is expected to vary depending on the location and magnitude of the aggradation, as well as the degree of channel constriction. Projects with long time horizons may wish to consider an additional sediment allowance.

Cheakamus River

Updated water levels for the Year 2100 200-year return period flood exceed bankfull and occupy the full width of most of the cross sections along the Cheakamus River. Conditions for the Year 2100 1,000-year return period flood event are proportionally more severe. Water depths for the two scenarios were compared to top of bank elevations and are shown in Figure 5-3 and Figure 5-4, respectively.

The cross-section data used in the Mike 11 model are now several decades out of date, and the dikes and berms described in Section 4.3 are not captured in the model. Modelled water levels may be too low in these areas and results should be interpreted with caution.

Conversely, where cross-sections do not extend to the floodplain limits, the model adds a vertical wall at the limit of the available data. This will tend to produce conservatively high flood levels. Updated cross-sections and calibration data are required to significantly improve model accuracy.

Bridges across the Cheakamus River were not included in the model in light of the additional effort required and the large residual uncertainty created by decades-old cross-section data. Based on model results, field observations and reports by others, KWL expects that Year 2100 200-year return period peak flows would overtop the Bailey Bridge. Water would also outflank Fergie's Bridge via Sunwolf and Squamish Nation Cheakamus I.R. No. 11, and may also impinge on the bridge deck.

KWL's results do not include a long-term aggradation allowance. However, KWL's 200-year return period flood levels were calibrated to the provincial floodplain mapping and are similar to those obtained by LaCas Consultants (2012) from a more detailed sub-reach model. The LaCas Consultants results include both a bulking factor of 1.5 and a long-term aggradation allowance of 0.5 m.

Stawamus River

Based on KWL's uncalibrated HEC-RAS results for the Year 2100 200-year return period debris flood scenario (Figure 5-5), there is sufficient freeboard along the Stawamus River dike at most locations, with the notable exception of a relatively short section near Plateau Drive. The areas most vulnerable to overtopping during a debris flood (assuming no blockage at the Mamquam FSR Bridge) are upstream of the FSR Bridge and near Plateau Drive. The LiDAR indicates that some of the properties behind the dike at Plateau Drive may have been filled above the dike grade, which could reduce the magnitude and/or consequences of overtopping in this area.

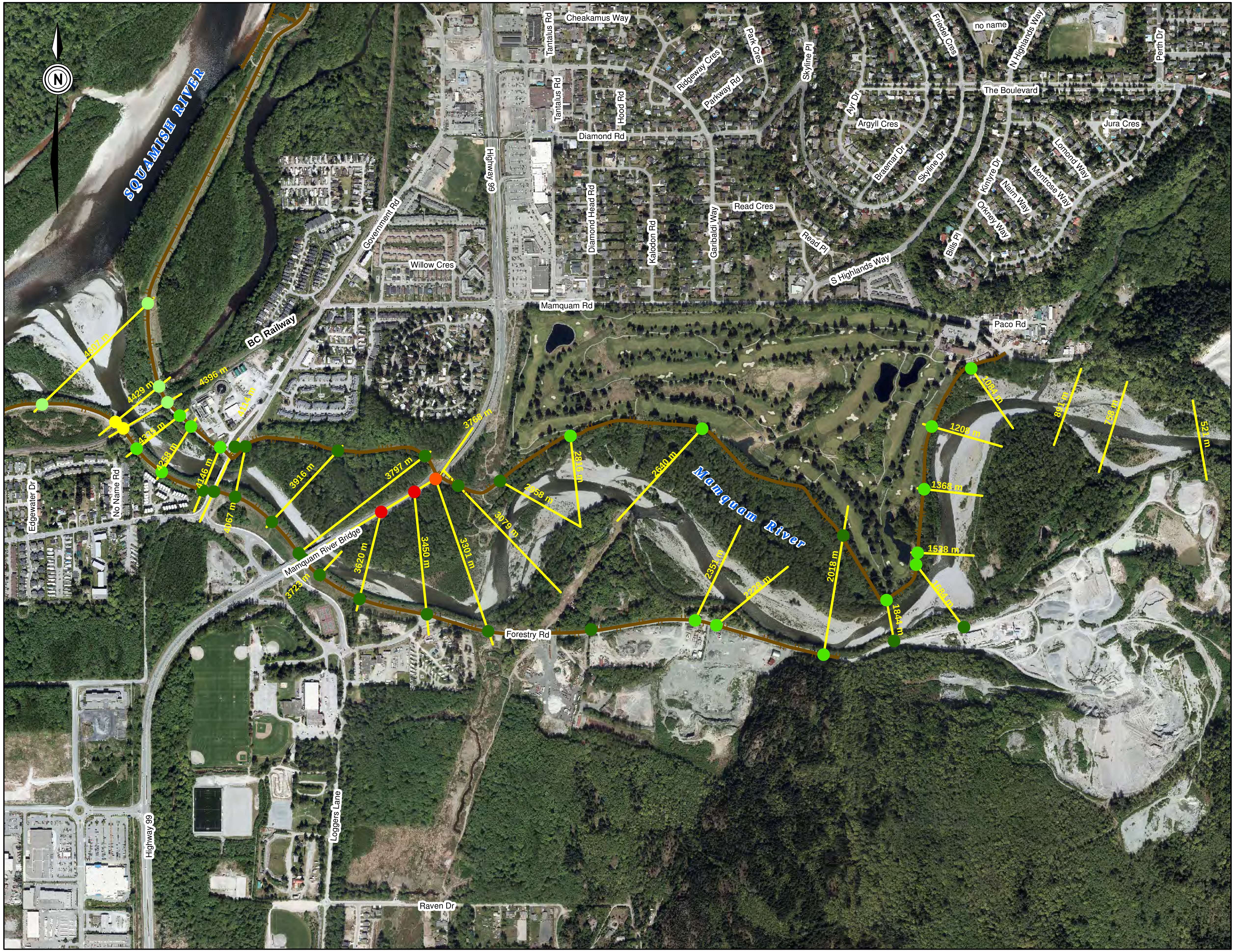
The results presented in Figure 5-6suggest that the upper dike is at considerably greater risk during the Year 2100 1,000-year return period debris flood scenario, or if a debris flood study were to conclude that a higher debris flood bulking factor is required.

The model suggests that an extreme debris flood could exceed the hydraulic capacity of the Mamquam FSR bridge opening. The District may wish to consider a more detailed 2D or quasi-2D hydrodynamic assessment that can incorporate a debris flood hydrograph, bridge blockage and a potential avulsion through Valleycliffe. This may be the governing scenario for flood hazard management planning, and would be particularly important for evaluating any new development proposal upstream of the existing community.

For the lower part of the river, the results suggest that the debris flood peak discharge would create relief flow at the Highway 99 Bridge, mainly via the Valley Drive intersection. Inundation would be expected at the Squamish Nation gas station and the casino during the Year 2100 200-year return period flood event.

Water will also overtop the CN Rail Bridge. Both bridge structures (Highway 99 and CN Rail) create significant backwaters and increase upstream flood depths. The backwater effect of the Highway 99 bridge is exacerbated by the conveyance reduction associated with the old abutments remaining in place below the new bridge deck. Water levels would be higher if either bridge becomes obstructed by debris.

Inundation depths on the fan – including much of Stawamus I.R. No. 24 – are subject to uncertainty arising from on 1-D modelling simplifications of the 2-D flow patterns and should be interpreted with caution. The uncertainty is greater for areas of the fan upstream of the CN Rail mainline, since the Year 2100 200-year return period coastal flood levels appear to govern downstream of the CN Rail bridge for all debris flood scenarios.



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Author: YBrugman

District of Squamish
Integrated Flood Hazard Management Plan
Background Report

Legend

Flood Level relative to dike crest or natural bank elevation

- ● 2 m below
- ● 1.0 m to 2.0 m below
- ● 0.6 m to 1.0 m below
- ● 0.1 m to 0.6 m below
- ● 0.1 m below to 0.1 m above
- ● 0.1 m to 0.5 m above
- ● Greater than 0.5 m above
- Existing Primary Dike
- Model Cross Section and Chainage

Note 1: Relative flood levels calculations based on cross sections from 2011 report (KWL)

Note 2: Dots refer to depth above/below natural channel bank or dike crest (where present).

Note 3: Modelling calculations include sediment allowance of 0.3 m, locally increased to 0.6 m in the vicinity of the Mashiter Creek confluence.

Reference: 2013 District of Squamish Orthophoto.

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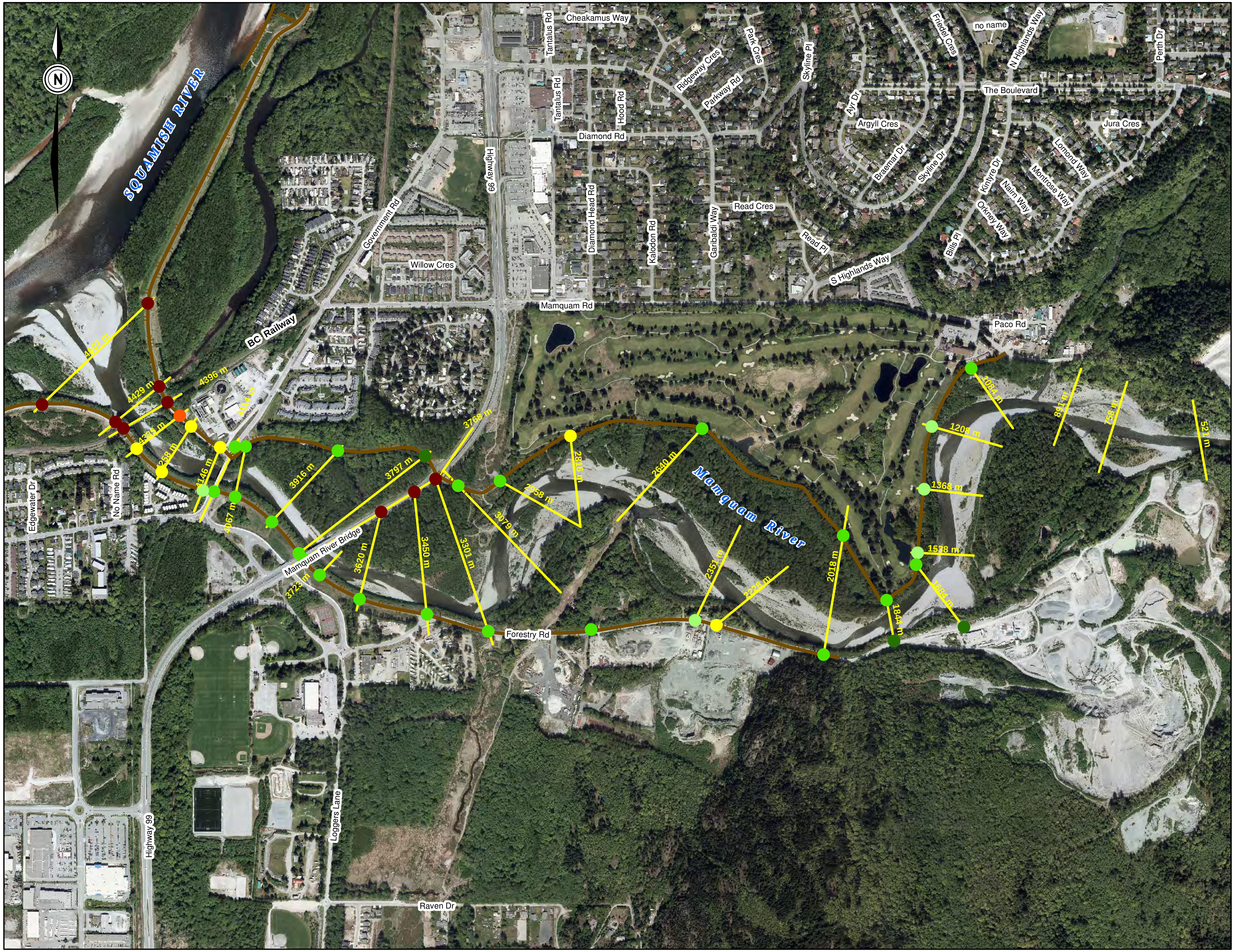
Project No.	Date
463-278	September 2017

Mamquam River Relative Flood Levels Year 2100 200-Year Flood

Figure 5-1



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Author: YBrugman

District of Squamish
Integrated Flood Hazard Management Plan
Background Report

Legend

Flood Level relative to dike crest or natural bank elevation

- ● 2 m below
- ● 1.0 m to 2.0 m below
- ● 0.6 m to 1.0 m below
- ● 0.1 m to 0.6 m below
- ● 0.1 m below to 0.1 m above
- ● 0.1 m to 0.5 m above
- ● Greater than 0.5 m above
- ━ Existing Primary Dike
- — Model Cross Section and Chainage

***Note 1:** Relative flood levels calculations based on cross sections from 2011 report (KWL)*

***Note 2:** Dots refer to depth above/below natural channel bank or dike crest (where present).*

***Note 3:** Modelling calculations include sediment allowance of 0.3 m, locally increased to 0.6 m in the vicinity of the Mashiter Creek confluence.*

Reference: 2013 District of Squamish Orthophoto.

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Project No.	Date
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Mamquam River Relative Flood Levels Year 2100 1000-Year Flood

Figure 5-2

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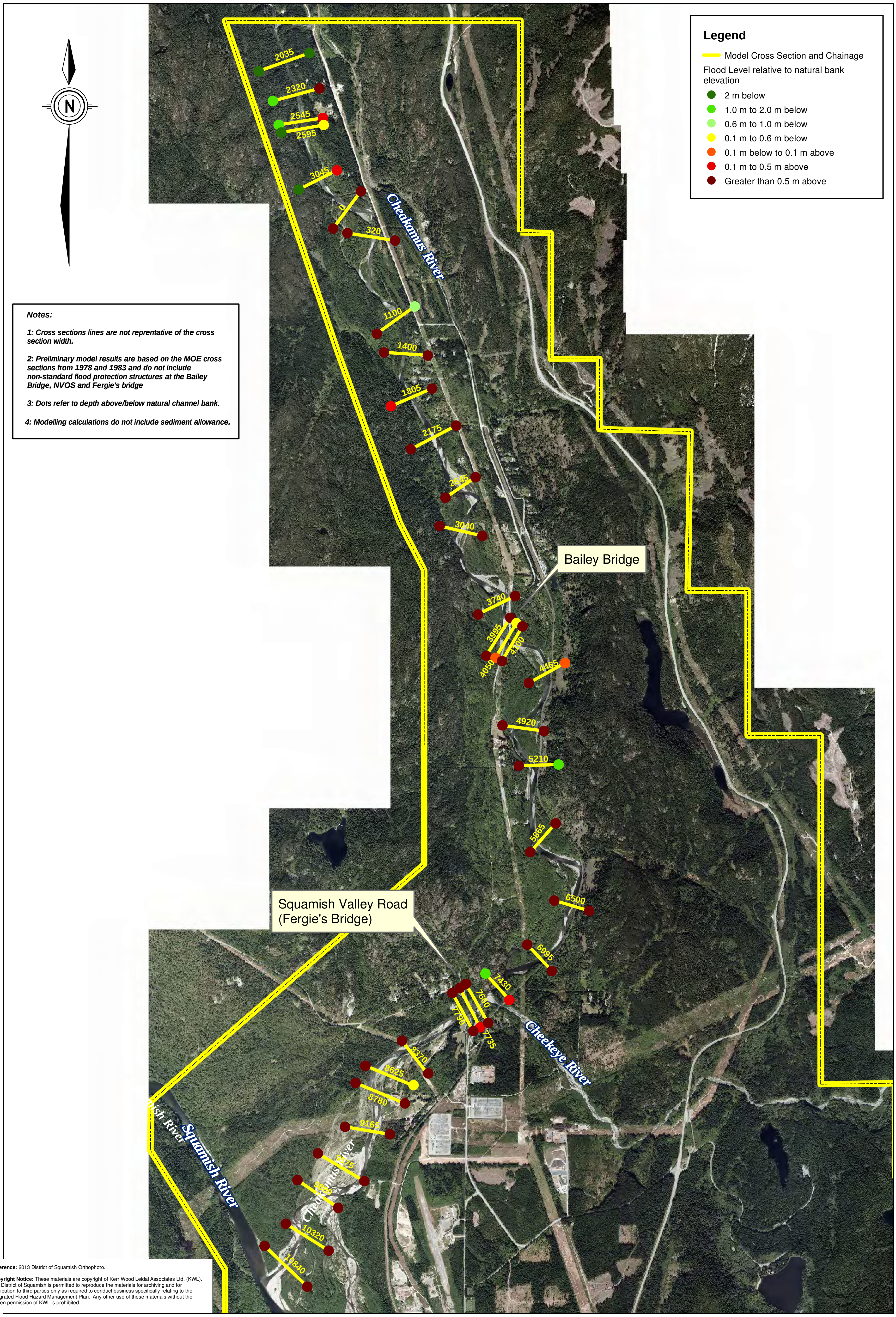
Author: YBrugman



Legend

- Model Cross Section and Chainage

Flood Level relative to natural bank elevation

●	2 m below
●	1.0 m to 2.0 m below
●	0.6 m to 1.0 m below
●	0.1 m to 0.6 m below
●	0.1 m below to 0.1 m above
●	0.1 m to 0.5 m above
●	Greater than 0.5 m above

Notes:

1: Cross sections lines are not reprentative of the cross section width.

2: Preliminary model results are based on the MOE cross sections from 1978 and 1983 and do not include non-standard flood protection structures at the Bailey Bridge, NVOS and Fergie's bridge

3: Dots refer to depth above/below natural channel bank.

4: Modelling calculations do not include sediment allowance.

Reference: 2013 District of Squamish Orthophoto.

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Background Report

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463-278

Date
September, 2017

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Cheakamus River Relative Flood Levels
Year 2100 200-Year Flood

Figure 5-3

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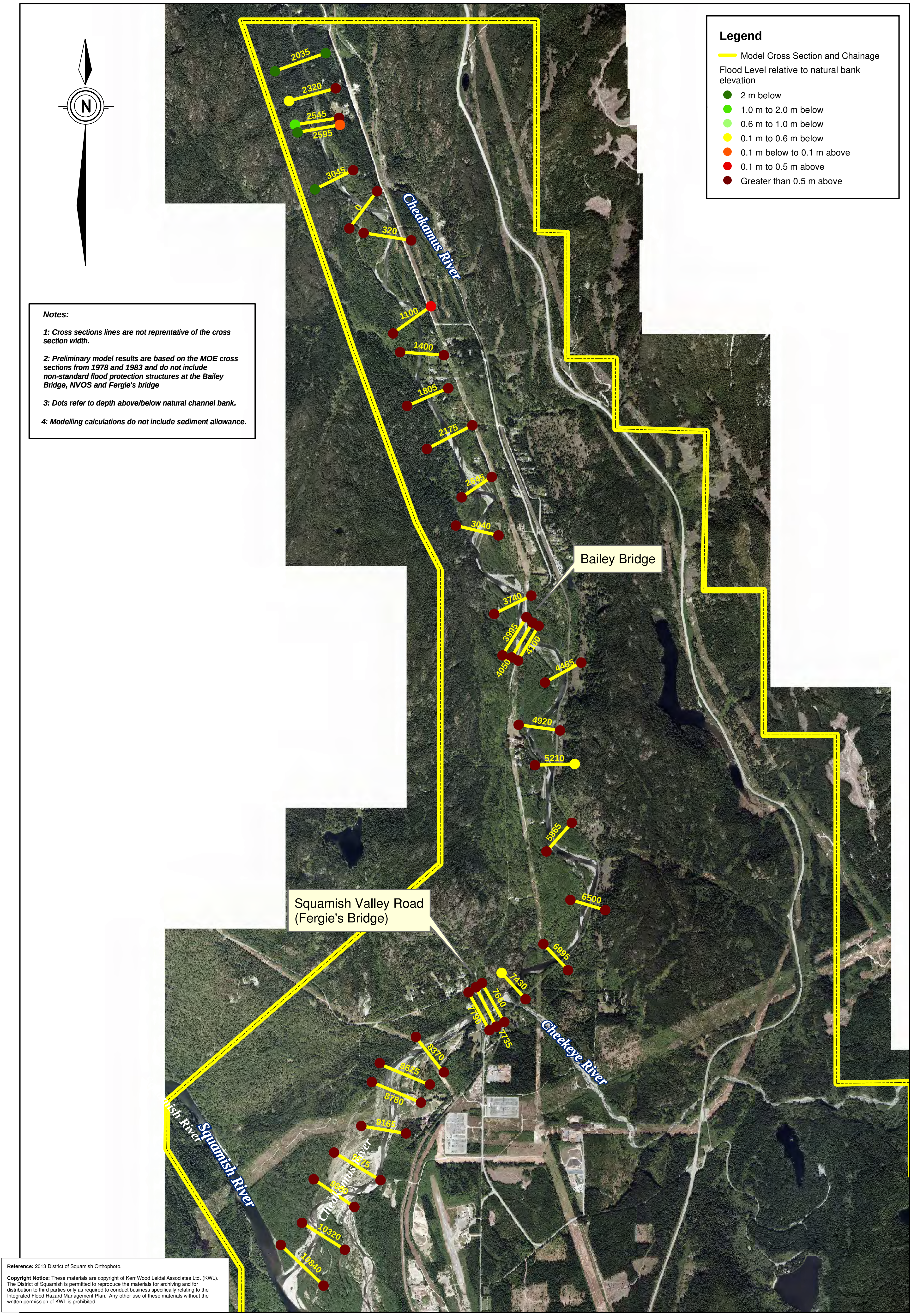
Author: YBrugman



Legend

Model Cross Section and Chainage

Flood Level relative to natural bank elevation

- ● 2 m below
- ● 1.0 m to 2.0 m below
- ● 0.6 m to 1.0 m below
- ● 0.1 m to 0.6 m below
- ● 0.1 m below to 0.1 m above
- ● 0.1 m to 0.5 m above
- ● Greater than 0.5 m above

Notes:

1: Cross sections lines are not reprentative of the cross section width.

2: Preliminary model results are based on the MOE cross sections from 1978 and 1983 and do not include non-standard flood protection structures at the Bailey Bridge, NVOS and Fergie's bridge

3: Dots refer to depth above/below natural channel bank.

4: Modelling calculations do not include sediment allowance.

Reference: 2013 District of Squamish Orthophoto.

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Cheakamus River Relative Flood Levels
Year 2100 1000-Year Flood

Figure 5-4

District of Squamish
Integrated Flood Hazard Management Plan
Background Report

Legend

Existing Dike

Model Cross Section and Chainage

Flood Level relative to dike crest or natural bank elevation

- ● 2 m below
- ● 1.0 m to 2.0 m below
- ● 0.6 m to 1.0 m below
- ● 0.1 m to 0.6 m below
- ● 0.1 m below to 0.1 m above
- ● 0.1 m to 0.5 m above
- ● Greater than 0.5 m above

Note1: Dots refer to depth above/below natural channel bank or dike crest (where present) based on cross sections from 2013 LiDAR.

Note2: Debris flood peak discharge based on 1.5 to 2.0 x 200-Year Return Period clear-water peak flow.

Note3: Model results based on steady-state modelling with 1m sediment allowance throughout.

Reference: 2013 District of Squamish Orthophoto.

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Project No.	Date
463-278	September 2017

Stawamus River
Relative Flood Levels
Year 2100 200-Year
Debris Flood

Figure 5-5

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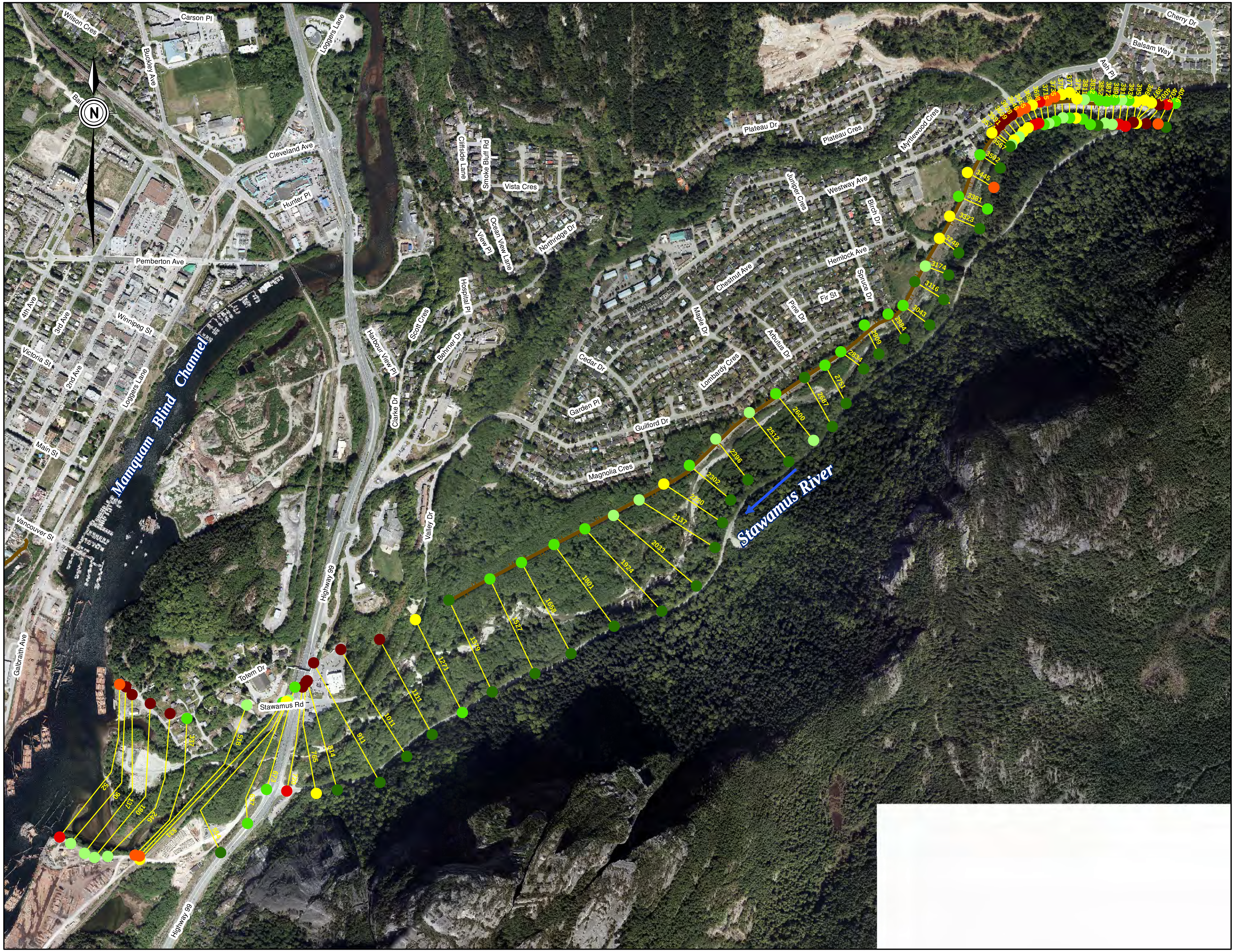
Author: YBrugman



District of Squamish
Integrated Flood Hazard Management Plan
Background Report

Legend

━ Existing Dike

— Model Cross Section and Chainage

Flood Level relative to dike crest or natural bank elevation

- ● 2 m below
- ● 1.0 m to 2.0 m below
- ● 0.6 m to 1.0 m below
- ● 0.1 m to 0.6 m below
- ● 0.1 m below to 0.1 m above
- ● 0.1 m to 0.5 m above
- ● Greater than 0.5 m above

Note1: Dots refer to depth above/below natural channel bank or dike crest (where present) based on cross sections from 2013 LiDAR.

Note2: Debris flood peak discharge based on 1.5 to 2.0 x 1000-Year Return Period clear-water peak flow.

Note3: Model results based on steady-state modelling with 1m sediment allowance throughout.

Reference: 2013 District of Squamish Orthophoto.

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Project No.	Date
463-278	September 2017

Stawamus River Relative Flood Levels Year 2100 1000-Year Debris Flood

Figure 5-6

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Author: YBrugman

5.4 Coastal Design Flood Level Update

As outlined in Section 2.8, coastal flood hazards arise from combinations of various components including tide, external surge, local effects and waves. Increases in sea level will also contribute to the future coastal flood hazard.

The IFHMP requires an updated coastal flood hazard assessment for the District's coastal margin from the Squamish Spit to the Stawamus River estuary. The two main components of a hazard assessment include:

- still-water level ("Designated Flood Level" as defined by Ausenco Sandwell, 2011b), which includes tide, external surge, local effects, and sea level rise; and
- wave effects.

Each of the still-water components is discussed separately below. Wave effects are discussed in Section 5.5.

Astronomic Tide

CHS routinely calculates astronomic tide predictions for Squamish (#7810). For this study, several decades of predicted tide data were provided by CHS using the latest tidal constituents. The predictions cover the period 1914 – 2014, and include both 15-minute and daily high/low data. CHS review of the tidal constituents for Squamish is ongoing, and it is possible that further adjustments could result in small changes to predicted values.

The latest data for Squamish #7810 indicate a value of 5.00 m for Higher High Water Large Tide (HHWLT), defined as the average elevation of the highest predicted tide of the year for a 19-year period. CHS considered the revised HHWLT value to be accurate based on KWL's calculations from the period of record. There is a difference of about 0.15 m between the HHWLT value calculated by KWL for Squamish #7810 and value published in the 2014 Canadian Tide and Current Tables (FOC, 2014). CHS indicated that they will be updating the HHWLT value published in the tide tables in the near future.

CHS also provided the latest and best predicted tide data for Point Atkinson (#7795).

External Surge

Provincial guidelines prepared by Ausenco Sandwell (2011b) recommend applying a single frequency-magnitude relationship for external surge throughout the West Coast, Juan de Fuca Strait and Strait of Georgia. The recommended external surge ranges from a median (average-year) value of 0.73 m to a 1,000-year return period) period value of 1.4 m. The 200-year return period value for external storm surge recommended by Ausenco Sandwell is approximately 1.25 m.

The external surge relationship provided by Ausenco Sandwell is based on a preliminary frequency analysis of the residual water level record for the CHS station at Tofino, BC (#8615). Ausenco Sandwell notes that residual values for individual surge events vary approximately ±0.1 m between Tofino and other stations throughout the West Coast, Juan de Fuca Strait, and Strait of Georgia. The Guidelines do not comment on whether the observed differences are random or biased. A range of ±0.1 m covers an order of magnitude of exceedance probabilities in the frequency-magnitude relationship provided for Tofino.

The Ausenco Sandwell guidelines adopted the Tofino data because it provided the longest and most reliable series of residual water levels (J. Readshaw, pers. comm.). In many other situations, the

50+ years of reliable residual water level data available for the nearby CHS station at Point Atkinson (#7795) would be considered an acceptable record for engineering analysis.

The suitability of Point Atkinson as a reference station for Howe Sound is well established (e.g., Thomson, 1981). Several recent coastal engineering studies within the District of Squamish (EBA, 2010; Tetra Tech EBA, 2014), the City of Vancouver (CoV, 2014), and the lower Fraser River (BC MFLNRO, 2014) have chosen to rely on Point Atkinson's shorter but more local record.

KWL completed a peaks-over-threshold frequency analysis of Point Atkinson Residual Water Levels for this study. The Generalized Pareto Distribution was applied to 1 hour, 2 hr, 6 hr, 24 hr and 120 hr average RWL exceedances for both storm season (October-March) and summer season (April-September). KWL's results are comparable to Ausenco Sandwell's Tofino results for frequent events but are up to about 0.15 m lower for more extreme events. A similar pattern is apparent in results presented by others (e.g., EBA, 2010; Abeysirigunawardena et al., 2011).

Continued data collection at Point Atkinson is expected to reduce the uncertainty associated with extreme value extrapolation of that record over time. There is no practical way to reduce the uncertainty of transposing an extrapolated value from Tofino to Howe Sound.

The Qualified Professional (QP) undertaking a specific coastal flood analysis is ultimately responsible for selecting the most appropriate reference data. In each situation, the QP must balance the relative uncertainties associated with data quality, extrapolation, and spatial transposition.

For this study, KWL recommends adopting an external storm surge allowance based on data from Point Atkinson. This assumption diverges from the assumptions made by SNC-Lavalin for the wave modelling assessment in Appendix C; however, using Point Atkinson data will allow the District to remain consistent with previous local studies as well as the provincial government's recent Fraser River study (BC MFLNRO, 2014). It is reasonable to attribute any uncertainty associated with this decision to the required freeboard allowance.

Combining Tide and External Surge

For the purposes of determining FCLs, a draft amendment to the province's 2004 Flood Hazard Area Land Use Management Guidelines (BC MFLNRO, 2013b) recommends combining tide and surge using a joint probability analysis. Joint probability analysis involves a statistical or empirical recombination of the full range of independent tide and surge components.

The draft BC MFLNRO amendment also allows QPs to adopt the "combined" approach presented by Ausenco Sandwell (2011a; 2011b; 2011c). The combined approach involves a simple addition of HHWLT and the surge value for a Designated Storm at a given return period.

For the combined approach, return periods and corresponding probabilities are determined by replacing complex statistical analysis with a set of simplifying assumptions. Key assumptions implicit in the final combined-approach AEP values include:

- Storm surges will follow the appropriate frequency-magnitude distribution, but only occur between mid-October and mid-January. No storm surges occur outside this period.
- Each storm surge lasts for six hours.
- Astronomic tides equivalent to HHWLT will occur three times in every two-week period during each year's storm surge season.
- Water levels equal to HHWLT last for 2.8 hours during each high tide.

- The longer duration of a typical storm surge (6 hours) relative to the assumed high tide (2.8 hours) means that the probability of a surge occurring at the same time as a high tide is twice that of the high tide occurring alone.
- Extreme water levels cannot result from superimposing storm surge on tides lower than those described above.

These key assumptions include both conservative and non-conservative elements. Parallel investigations of the joint probability approach and the "combined" method have shown that the simpler combined method produces more conservative results when compared across a range of equivalent probabilities (e.g., CoV, 2014; this study).

The QP is ultimately responsible for selecting the most appropriate method for combining tide and surge. The decision will typically depend on the specifics of each coastal flood analysis.

Given the importance of the IFHMP study for the District, KWL recommends the more complex joint probability approach to determining water levels. This assumption diverges from the assumptions made by SNC-Lavalin for the wave modelling assessment in Appendix C; however the strategic importance of the IFHMP justifies the additional level of detail.

While the IFHMP does not have the resources to develop a static water levels from a full hindcasting assessment (e.g., CoV, 2014), KWL has implemented a simpler approach based on incremental probabilities that produces comparable results.

KWL's incremental joint probability analysis applies the following simplifying assumptions:

- A 19-year time series of astronomic tide data covers a complete lunar cycle and provides a complete description of tide behaviour.
- Storm surges have a typical duration ranging from one hour to several days and can be characterized by a set of water levels averaged over each duration.
- Surge behaviour is focussed within the October to March period and must be considered on a seasonal basis.

Applying an incremental probability analysis with these simplifying assumptions generates a frequency-magnitude relationship for the combined effect of tide and external storm surge. KWL's results are within 2 cm of the values adopted by BC MFLNRO (2014) for the Fraser River for all published return periods, from 50-year to 1,000-year and within 5 cm for the 10,000-year event. As expected, KWL's results are also very close to the frequency analysis of Point Atkinson annual maximum observed water levels previously presented by EBA (2010) and Tetra Tech EBA (2014).

Uplift and Subsidence

KWL is not aware of any engineering studies that document subsidence and uplift processes in Squamish.

In the absence of any site-specific data, provincial guidelines prepared by Ausenco Sandwell (2011b) assume no adjustment is required at Squamish to account for long-term changes in land elevation due to subsidence, isostatic rebound, or tectonic uplift. However, in summer 2014 correspondence related to this study, CHS has advised KWL that their local benchmarks in the vicinity of Squamish Terminals show evidence of significant subsidence. KWL's requests for further information led CHS to identify some inconsistencies within their records and begin an internal investigation.

While CHS benchmarks cannot provide definitive answers on the rate of subsidence at this time, CHS did direct KWL's attention to historic published elevations for GSC benchmark 1274-J (B. de Lange Boom, pers. comm.). Comparing GSC elevations published for 1958 (2.230 m) and 1993 (2.175 m) gives a difference of -0.055 m. Applying this difference as a gradual change over time gives an annual change of -1.6 mm/year.

A subsidence rate of -1.6 mm/year is compatible with typical rates found in subsidence-prone areas of the Fraser Valley (D. Hill, pers. comm.) and is less than the rate of -2.1 mm/year published by Thomson et al. (2008) for Richmond, BC. Extrapolating a subsidence rate of 1.6 mm/year from 2015 to 2100 (85 years) would result in a subsidence allowance of 0.14 m.

This estimate is derived from a single pair of measurements for a single benchmark. The benchmark (now destroyed) was attached to a building foundation and may have experienced structural settlement in addition to any regional rate of subsidence.

In addition, elevations for many local benchmarks were adjusted in 1993 as part of Natural Resources Canada's major western Canada integration project. Other downward adjustments included contemporaneous J-series benchmarks at bridge abutments on Shannon Creek and Deeks Creek. These sites would have very different geotechnical conditions than the BMs in downtown Squamish. BC's MASCOT benchmark database shows contemporaneous adjustments to published provincial benchmark elevations that were also made "for better integration" (e.g., 77HA927).

Finally, surveys completed in 2013 by CHS and in 2014 by the District have used Global Navigation Satellite System (GNSS) data to establish elevations at published benchmarks in downtown Squamish. The results indicate an offset of about 0.14 m between published elevations and GNSS values. This difference is generally consistent with offsets previously identified by KWL (0.13 m at the Mamquam River confluence) and Bunbury Associates (0.12 to 0.14 m at Judd Slough).

The factors noted above – reliance on a single destroyed benchmark that was located on a building foundation, updates to the published elevation that were part of a regional integration project, and consistent GNSS to historic benchmark offsets throughout the lower Squamish Valley – all suggest that there may be explanations other than subsidence for the difference in published 1958 and 1993 values for BM 1274-J.

Although the evidence is not conclusive, a subsidence rate of 1.6 mm / year is considered too conservative for the present IFHMP. The allowance for local effects (discussed below) may be considered to include a subsidence allowance of up to 1 mm / year from 2015 to year 2100, depending on the values assumed for the other contributing components.

Allowance for Local Effects

For the purposes of this report, local effects include wind setup, local surge effects, unexplained residuals, sub-hourly tidal peaking, and subsidence (as discussed above). Wave setup and site-specific wind setup are *not* included, since these effects will vary significantly along the District's coastal margin and must be assessed on a site-specific basis. Site-specific wind setup may be significant along the long, shallow inter-tidal flats of Crescent Slough.

The 1994 FHMP applied an allowance of 0.1 m for wind setup and local surge effects (Klohn Leonoff, 1994a). EBA (2010) estimated a wind setup allowance of 0.02 m at SODC, while Tetra Tech EBA (2014) adopted a slightly larger allowance of 0.05 m further up the Mamquam Blind Channel. A simple assessment by KWL based on the 200-year return period one-hour inflow wind condition and a profile of Howe Sound estimated wind setup of 0.09 m. None of these previous estimates have considered site-specific setup effects, and none had access to observed wind setup data to support their conclusions.

Without conclusive data, it is appropriate to assume that wind setup can contribute to local effects observed at Squamish.

Tide predictions show that hourly tide records (such as those used to develop the joint probability surge + tide component of the DFL) can underestimate the actual maximum tide level by 0.00 m up to 0.03 m. This “sub-hourly peaking” is another factor that could contribute to local effects observed at Squamish.

The District has recently started archiving water level data to support operation of the 3rd Ave. tide gates. This data provides the District with the means to develop a more empirical allowance for observed local effects. At present, the available data record is short and has historically been subject to significant quality control issues. Analysis of the data is further complicated by datum and subsidence issues currently under investigation by CHS.

The District’s 2014 survey confirmed that the staff gauge datum used for manual and automated data collection at the 3rd Ave. tide gates is offset by -0.1 m relative to the CHS Chart Datum. Based on this offset, a reading of 5.0 m at the staff gauge corresponds to a water level of 4.9 m CD.

An initial review of short-duration provisional data from the 3rd Ave. tide gates was undertaken by SNC-Lavalin in Summer 2014 and is described in Appendix C. A more rigorous review was completed by KWL in winter 2015 once more and better data was available. While still a relatively short record, data quality improved significantly between the SNCL and KWL reviews. The updated analysis is sufficient to support preliminary conclusions.

After correcting from CHS Chart Datum to the District’s tide gauge datum, KWL found that observed data were still consistently about 0.1 m higher than expected values (i.e., Squamish tide + Point Atkinson RWL). The offset persists regardless of tide level or RWL (storm surge). There is a characteristic scatter of up to about 0.15 m about the mean offset value of 0.1 m. The magnitude of the offset varies with the tide cycle and does not typically reach its maximum value at high tide. A small part of the offset could be explained by time delay attributed to the basin effects of Cattermole Slough.

Offsets applicable to maximum daily high tides were calculated by subtracting the maximum expected water level from the maximum observed water level over a moving 24-hour window. The result does not appear to be correlated with storm surgeor inflow wind and has an upper envelope of 0.17 m for the available short-duration record.

Based on all the above factors, KWL recommends a generic allowance of 0.3 m to account for local effects. This provides a reasonable allowance for all the above factors taken together, recognizing their contributing uncertainties and acknowledging that critical values are unlikely to occur in combination. KWL considers a combined allowance compatible with the District’s direction to consider a 200-year return period coastal DFL.

Datum Adjustment

CHS reports their predicted and observed water levels in Chart Datum. The IFHMP requires that these predictions and observations be converted from Chart Datum to geodetic datum.

When asked to provide the latest conversion for this study, CHS discovered that the Chart Datum at Squamish had never been tied to what CHS would consider a stable reference benchmark. CHS planned to address this deficiency by establishing a new tide station for Squamish. Until their update is complete, the conversion of Chart Datum to geodetic datum cannot be confirmed.

The District commissioned a survey to establish relative elevations for the CHS tide station benchmarks, local geodetic benchmarks, and staff gauge at the 3rd Avenue pump station. Based on the District’s survey results, KWL adopted a conversion of -3.06 m from CD to GSC for the IFHMP. This value ties the newest and the most stable of the CHS benchmarks to local geodetic benchmark GCM 9274 (tablet marking 77HA891). Conversions to other benchmarks and to GNSS observations yield slightly different conversions that reflect the inconsistent local benchmark elevations.

GCM 9274 was selected for this study because its monument – 77HA891 – is of the same series (and therefore likely the same datum) that was used to develop the river models, which in turn establish the boundary conditions for future dike breach simulations. For consistency, all FCLs that rely on this report must all be established relative to GCM 9274 (as opposed to using a different benchmark or GNSS observations).

The appropriate datum to transpose or convert any FCL is the datum assumed by the QP during its derivation. Design water levels cited in previous studies may have been developed using datum adjustments that are superceded by the revised value of -3.06 m. These elevations must be adjusted to support any direct comparisons.

Climate Change Allowances for Sea Level Rise

The IPCC AR5 report (2013) predicts likely SLR of between 0.26 m and 0.98 m by the late 21st century, depending on the assumed Representative Concentration Pathway (GHG emissions scenario). In all IPCC scenarios, and in all studies, SLR is expected to continue well past the year 2100 horizon.

In this regard, the provincial guidance of 1 m SLR from Year 2000 to Year 2100 is considered appropriate for IFHMP planning purposes. This value is recommended by Ausenco Sandwell (2011c) and incorporated in the draft amendment to the Flood Hazard Area Land Use Management Guidelines (BC MFLNRO, 2013b).

While 1 m of SLR may not ultimately coincide with the year 2100 timeline, the timeline is also reasonable for planning purposes. This allowance has been adopted by Canada's Atlantic Provinces and many US jurisdictions. The authors of BC's guideline document recommend reviewing and updating the SLR guidance every five years, with the first update due in 2015 (Ausenco Sandwell, 2011a).

KWL notes that the 1 m SLR allowance is applied in the draft amendment (MFLNRO, 2013b) as a constant 10 mm/year from Year 2000 to Year 2100. The SLR allowance at Year 2015 is therefore 0.15 m, with the remainder of the 1 m attributed to the period from Year 2015 to Year 2100.

The guidelines (MFLNRO, 2013b) indicate that the constant SLR assumption will be initially conservative, but will become less so as SLR accelerates. This is supported by recent observations of global SLR; for example, a recent Australian report concluded that global sea levels have been rising at an average rate of 3.2 mm/year for the past two decades. This represents nearly double the average rate of 1.7 mm/yr observed for the 20th century (CSIRO and ABoM, 2014).

Selecting an AEP for the Design Flood Level

The draft amendment to the Flood Hazard Area Land Use Management Guidelines (BC MFLNRO, 2013b) recommends a still-water level corresponding to a 200-year return period combination of tide and storm surge. The Ausenco Sandwell (2011b) guidelines recommend a 4,000 to 10,000-year return period combination of total water level that reflects emerging international standards for coastal flood protection (e.g., Delta commissee, 2008).

The District may wish to consider planning for a water level higher than the minimum 200-year return period recommended in the BC MFLNRO draft amendment, particularly for any perimeter coastal flood defences. The following criteria should be considered in any decision process:

- Evidence suggests SLR is accelerating and will continue past year 2100.
- Variation in external surge levels is small relative to overall uncertainties.
- Unlike river dikes, some wave and spray overtopping is expected during the design event for coastal flood protection works.

For comparison purposes, the tables below present 200-year return period and 4,000-year return period still-water coastal flood levels for both the joint probability approach (using RWLs from Point Atkinson) and the combined approach (using RWLs from Tofino).

Potential DFLs for four combinations of return period and calculation approach are shown in Table 5-7 and Table 5-8 below, with the recommended DFL shaded in yellow. Water levels determined using the joint probability approach incorporate RWLs from Point Atkinson. Water levels determined using the combined approach (Ausenco Sandwell, 2011a) incorporate RWLs from Tofino. These values do not account for wave effects (including wave setup and runup), site-specific wind setup, or freeboard. Wave effects are discussed in Section 5.5.

Table 5-7: Summary of Joint Probability Coastal Water Levels for Tide + Surge

Component	1 in 200 AEP	1 in 4,000 AEP
Hourly Water Level for Squamish, CD[1]	5.75 m	5.95 m
Conversion to Geodetic Datum[2]	-3.06 m	-3.06 m
Allowance for Local Effects[3,4]	+0.3 m	+0.3 m
Assumed SLR to Year 2015[5]	+0.15 m	+0.15 m
Present Day Designated Flood Level[6]	**3.14 m**	**3.34 m**
Additional SLR to Year 2100[5]	+0.85 m	+0.85 m
Year 2100 Designated Flood Level[6]	**3.99 m**	**4.19 m**

Notes:

1. Values in Chart Datum based on incremental joint probability analysis using the best available data provided to KWL by Canadian Hydrographic Services in August 2014 (A. Ballantyne, pers. comm.). Tide values based on predicted tides at Squamish. External storm surge values based on peaks-over-threshold frequency analysis of residual water levels at Point Atkinson.
2. Based on 2014 spirit levelling from GCM 9274 (77HA891) to CHS monuments M07C9001 and 4-1973 completed by Bunbury Associates for District of Squamish. All geodetic coastal elevations should be established relative to published elevation of GCM 9274.
3. Combined allowance for wind setup, local surge effects, unexplained residuals, sub-hourly tidal peaking and subsidence to Year 2100.
4. Wave setup and site-specific wind setup are not included and require site-specific assessments.
5. Assumed constant rate of 10 mm/yr from Year 2000 to Year 2100 is based on draft amendment to Flood Hazard Area Land Use Management Guidelines (BC MFLNRO, 2013b).
6. The coastal Designated Flood Level (DFL) represents a static water level for design and planning purposes that is generally applicable along the District's coastal margins (subject to site-specific assessment of wave setup and localized wind setup). Further allowances for Wave Effects and Freeboard must be added to obtain the Flood Construction Level.

Table 5-8: Summary of Combined Approach Coastal Water Levels for Tide + Surge

Component	1 in 200 AEP	1 in 4,000 AEP
Squamish HHWLT[1]	5.00	5.00
External Storm Surge[2]	+0.9 m	+1.25 m
Conversion to Geodetic Datum[3]	-3.06 m	-3.06 m
Allowance for Local Effects[4,5]	+0.3 m	+0.3 m
Assumed SLR to Year 2015[6]	+0.15 m	+0.15 m
Present Day Designated Flood Level[7]	**3.29 m**	**3.64 m**
Additional SLR to Year 2100[6]	+0.85 m	+0.85 m
Year 2100 Designated Flood Level[7]	**up to 4.14 m**	**up to 4.49 m**

Notes:

1. Based on updated information provided to KWL by CHS in August 2014 (A. Ballantyne, pers.comm.), confirmed by CHS to represent a significant change from the value of 5.15 m CD published in the most recent version of the tide tables (FOC, 2014).
2. Based on RWL frequency analysis results for Tofino, BC as shown in Ausenco Sandwell (2011a). Probability combines with 1 in 20 AEP of concurrent RWL + HHWLT from Appendix D of Ausenco Sandwell (2011a) to give AEP for DFL.
3. Based on 2014 spirit levelling from GCM 9274 (77HA891) to CHS monuments M07C9001 and 4-1973 completed by Bunbury Associates for District of Squamish. All geodetic coastal elevations should be established relative to published elevation of GCM 9274.
4. Combined allowance for wind setup, local surge effects, unexplained residuals, sub-hourly tidal peaking and subsidence to Year 2100.
5. Wave setup and site-specific wind setup are not included and require site-specific assessments.
6. Assumed constant rate of 10 mm/yr from Year 2000 to Year 2100 is based on draft amendment to Flood Hazard Area Land Use Management Guidelines (BC MFLNRO, 2013b.
7. The coastal Designated Flood Level (DFL) represents a static water level for design and planning purposes that is generally applicable along the District's coastal margins (subject to site-specific assessment of wave setup and localized wind setup). Further allowances for Wave Effects and Freeboard must be added to obtain the Flood Construction Level.

The coastal water levels being considered in the IFHMP represent a significant increase over those recommended in the 1994 FHMP. Understandably, the District will face significant challenges in adapting to meet even the minimum provincial recommendations. In August 2014, District council confirmed the IFHMP should assume a 200-year return period DFL to support its continuing analyses.

Summary

KWL has outlined the process for developing a Design Flood Level (still water flood level) for Howe Sound based on a combination of tide, external storm surge, subsidence, local effects, and allowances for Sea Level Rise. A number of the components are established or based on standard industry practice. Examples include relying on the latest available predicted tides and CD to GSC datum adjustment from CHS, and the adoption of 1 m SLR allowance based on the provincial guidelines.

Other key decision points are open to the discretion of the local authority. While KWL has provided recommendations, the District may wish to consider its alternatives. These issues are identified in the following list:

- External surge assessment: based on CHS data from Point Atkinson or Tofino
    - The IFHMP uses CHS data from Point Atkinson
- Approach to combining tide + surge: Joint Probability Analysis or Combined Method
    - The IFHMP adopts results based on Joint Probability Analysis
- Subsidence: include or exclude effects pending collection of better data
    - The IFHMP incorporates subsidence into the allowance for local effects below
- Allowance for local effects: take worst case for all factors or apply a combined allowance
    - The IFHMP provides combined allowance 0.3 m and recommends further data collection
- Return period for the Designated Flood Level (DFL)
    - Based on input from District Council, the IFHMP adopted a 200-year return period based on achieving acceptable risk for the total water level, including concurrent 200-year return period wave effects (discussed in Section 5.5).

5.5 Wave Modelling Update

SNC-Lavalin carried out an updated wave modelling assessment based on their internal wind and wave model for Howe Sound. The work involved updating the model to incorporate the following information:

- improved definition of the overwater wind field in the north reaches of Howe Sound, based on wind measurements made at Squamish Terminals and on the Squamish Spit;
- relatively recent hydrographic soundings made over the foreshore delta slopes of the Squamish River estuary by the Canadian Hydrographic Service;
- intertidal elevations from the District's extensive 2013 LiDAR surface;
- future ground contours for the Squamish Oceanfront Development site;
- field assessment of the present state of inter-tidal vegetation within the estuary; and
- a short record of preliminary District water level measurements at the 3rd Avenue tide gate.

Details of SNC-Lavalin's coastal modelling update are provided in Appendix C.

Coastal Model Bathymetry

The hydrographic soundings and the intertidal LiDAR were used to produce a series of nested bathymetry models of the Squamish Estuary. The models were then added to an existing wave simulation model for Howe Sound. The resulting model provides high-resolution intertidal bathymetry covering the Squamish River estuary, Cattermole Slough, and Mamquam Blind Channel areas of the District as shown in Figure 5-2 of Appendix C.

Figure 5-5 of Appendix C shows the location of detailed wave model reporting locations designated S1 through S27. These are located throughout the coastal margin of the downtown area. Detailed wave modelling was not extended to Woodfibre or south of the Stawamus River estuary.

The wave model was run using 4,000-year return period still-water depths determined by the combined approach plus an allowance of 0.35 m for local effects. This represents the highest still-water scenario considered for the IFHMP, and provides a conservative basis for estimating wave heights.

Marine Structures

Based on the detailed elevation data used in the model, the combined-approach 4,000-year return period DFL (still-water level) would inundate large areas of the Squamish River estuary. The inundated areas would include the southern ends of the Squamish Spit (Squamish River South Training Berm) and the landfill at Squamish Terminals. The lower 200-year return period DFL defined using joint probability analysis may not inundate the Squamish Spit but the LiDAR data suggest it could still inundate lower-lying parts of Squamish Terminals. Areas not inundated may still be awash. SLR will cause inundation to occur more frequently in the future unless these structures are raised to address the increased hazard.

For the purpose of the IFHMP, the IFHMP project team and the District have agreed on the following key assumptions regarding these structures:

- The structures remain in place at Year 2100 and are maintained at their current elevations without regard for sea level rise.
- Any damage from severe storms will be repaired so that the structures provide at least the same degree of sheltering to more inland areas as they do at present.
- The existing railway embankment leading to Squamish Terminals defines the inward (onshore) limit of reliability for the wave model results.
- Wave propagation was allowed over any portion of the structures that becomes submerged.

Wind and Wave Analysis

Wind data recorded at Environment Canada’s Pam Rocks station show that the Howe Sound area regularly experiences strong to gale force inflow wind conditions. Wind data collected by Squamish Terminals show that wind direction at the estuary boundary is consistently in line with the exposed southwest fetch during strong to gale force conditions. The Squamish Terminals data also suggest that wind speeds at Squamish are essentially the same as wind speeds at Pam Rocks during strong inflow conditions. Other sources have reached different conclusions, and additional data should be collected to confirm this relationship.

Wind speeds for the 200-year return period storm were defined based on a peaks-over-threshold analysis of wind data recorded at Pam Rocks. SNCL estimates a 200-year return period wind speed of 54 knots (27.8 m/s) for inflow conditions. An analysis of climate change effects relating to inflow winds on Howe Sound is beyond the scope of the IFHMP.

Seastates expected around the District’s coastal margins during the Designated Storm are shown in Figure 5-3 of Appendix C for a “Present Day” scenario (DFL = 3.67 m) and in Figure 5-4 of Appendix C for a “Year 2100” scenario (DFL = 4.67 m).

Site-specific seastate results are provided in Table 5-5 based on the following limitations:

- Wave diffraction effects around the flooded portions of the Squamish River Training Berm and Squamish Terminals are approximate only.
- Wave breaking effects over the flooded portions of the Training Berm and Squamish Terminals are approximate only.

- Vegetation within the estuary provides only marginal attenuation of the incident wave energy.

Wave heights reported in Appendix C for the 200-year return period storm range from a minimum of about 0.6 m for the present-day scenario to a maximum of about 2.2 m for the Year 2100 scenario. Predictably, the smallest waves occur in the most sheltered locations, specifically Cattermole Slough near the outlet of Bridge Pond and Mamquam Blind Channel near the CN Rail bridge. The largest waves occur at the most exposed locations, specifically a short distance offshore from Squamish Terminals and the tip of the Squamish Spit. The wave heights represent sea state conditions at the prediction point and do not include allowances for local wave set-up.

Validation of Wave Modelling Results

Thomson (1981) comments that greatest local wave heights of 1.5 m are generally produced over the longer fetches available to inflow winds, although waves up to 2.5 m have been reported for storm-forced conditions. Golder Associates (2008) observed 1 to 1.5 m breaking wave heights at the Nexen property during a December 2007 site reconnaissance that coincided with a southerly storm. This information provides a degree of qualitative validation for the results found in Appendix C at the most offshore locations.

Comparing wave heights between Appendix C and previous studies accepted by the District is inexact and subject to considerable uncertainty; however, the wave climate presented by Tetra Tech EBA (2014) for Upper Mamquam Blind Channel appears generally consistent with the results of Appendix C. In contrast, there are significant differences between the wave climate presented by EBA (2010) for the SODC area and corresponding results from Appendix C.

A detailed comparison of methodology and results between this study and previous coastal modelling (EBA, 2010; Tetra Tech EBA, 2014) is beyond the scope of the IFHMP. A separate comparison study would be required to resolve any discrepancies or directly compare past and present wave modelling results.

Recommended Sensitivity Analyses

The seastate results confirm that the Squamish Spit and Squamish Terminals provide a high degree of protection to the inland coastal margin of the District. Seastate estimates for Year 2100 are expected to be sensitive to assumptions about the future status of these structures.

Model results also indicate that seastates around the coastal margin are influenced but not controlled by the total depth of water during the Designated Storm. Inundation of vegetated inter-tidal estuary lands could affect assumptions about how vegetation and waves will interact in the future, which could in turn affect incident wave energy at the coastal margin.

Where appropriate, sensitivity to these issues should be explored prior to undertaking preliminary design of any coastal flood protection works or updating the IFHMP.

Combining Wave Effects with the Design Flood Level

Ausenco Sandwell (2011c) recommends that storm surge and wave components be derived based on a common Designated Storm. This implies that waves and external storm surge will be fully correlated.

The draft amendment to the province’s 2004 Flood Hazard Area Land Use Management Guidelines (BC MFLNRO, 2013b) proposes a slightly different approach based on combining a 200-year return period DFL (tide + external surge) with the 200-year return period wave climate. The implied relationship between waves and surge is statistically complex; however, wave climate and storm surge components cannot be fully correlated because the surge component of the DFL is not exclusively a product of the 200-year return period surge event.

Appendix D of the provincial Sea Dike Guidelines (Ausenco Sandwell, 2011a) presents preliminary evidence that maximum wave heights are not well correlated with the most extreme external surge events. This is supported by a comparison of storms at Pam Rocks and surge events at Point Atkinson carried out for this IFHMP (SNC-Lavalin, 2014). A concurrent unpublished hindcasting assessment by KWL using wind, tide and surge data from southern Vancouver Island confirmed a partial correlation relationship.

Calculating an overall probability for the case of partial wave-surge correlation becomes very complex. The resulting process must consider three dimensions of joint probability: surge and tide, surge and waves, and waves and tide. It is possible to address this challenge by applying a computationally-intensive hindcasting model that simulates all components over a multi-decadal timescale. Flood Construction Levels (FCLs) or Minimum Building Elevations (MBEs) could be estimated directly from hindcasting model output. This approach would provide the most accurate picture of total water levels for the District.

The resources required to support a hindcasting approach for Squamish are well beyond the scope of the IFHMP. Even the City of Vancouver's recent hindcasting study still adopted a simplified approach to correlation between waves and the DFL (CoV, 2014). More importantly, there is insufficient data available to support a hindcasting study for Squamish.

Without recourse to a hindcasting analysis, the District must consider the issue of surge-wave correlation on a qualitative basis. Other coastal flood hazard assessment studies (e.g., KWL, 2011c) have accounted for wave-surge correlation by adopting the upper envelope wave heights observed during significant storm surge events. Wind speed has been used a proxy for wave height in protected waters where the effects of swell – i.e., waves originating a long distance away – are negligible (e.g., KWL, 2014c). Studies by others have adopted average wind speed or wave height values (rather than upper bound values). All such analyses should be cross-checked to determine whether combinations of lower static water level and larger sea state produce higher total water levels, or vice versa.

SNC-Lavalin's wind-surge comparison found that only 6 of the top 20 inflow wind events recorded at Pam Rocks had a concurrent storm surge greater than 0.5 m (SNC-Lavalin, 2014). The upper-envelope wind speed for these six events was 47 knots (24 m/s), about 13% less than the estimated 200-year return period inflow wind condition.

The six data points identified by SNC-Lavalin are too few to support a conclusive analysis at this time. Data from the Pam Rocks station covers only the past ±20 years, and the correlation of wind speed data from Pam Rocks to Squamish Harbour must be confirmed. It may be possible to revisit the question of wave height-storm surge correlation once more data is available. Until then, the application of the 200-year return period wind speed remains appropriately conservative in keeping with the draft provincial guidelines.

Wind Setup and Wave Setup

The above discussion of wave correlation with DFL applies equally to wind setup and wave setup. Although wind setup and wave setup are often incorporated into the DFL, they are wind-driven processes and follow the timing and magnitude of the onshore wind rather than the external storm surge. Adding these components to a 200-year return period combination of tide and RWL can result in a more conservative DFL than a static water level hindcasting assessment.

Summary

Appendix C provides wave modelling results for 27 prediction points along the District's downtown coastal margin. Corresponding wave heights for a 200-year return period storm range from 0.6 m to 2.2 m, depending on location. These wave heights are validated by independent information, but are significantly greater than previous estimates used to establish provisional FCLs at SODC and along the west Mamquam Blind Channel (KWL, 2012b; KWL, 2013c). All prediction points are located a short distance offshore to exclude shoaling effects, since these effects must reflect the geometry and alignment of the future foreshore.

Adding the lowest wave height from Appendix C (0.6 m) and freeboard (0.6 m) to the recommended DFL of 3.99 m gives a result of 5.19 m. This value is almost 2 m greater than the 3.3 m FCL recommended in the 1994 FHMP and does not include additional allowances for:

- waves reaching the shoreline at heights greater than the minimum reported in Appendix C;
- conversion from significant wave height to the 2% exceedance wave height;
- wave runup;
- wave setup; or
- site-specific wind setup.

Of the exclusions noted above, wave runup alone can account for several times the wave height. This example calculation is provided to help the District anticipate and mitigate the potential implementation challenges that will undoubtedly be associated with adopting the forthcoming IFHMP FCLs.

Estimated wave heights are specific to the still-water depths assumed in Appendix C, which represent the most conservative (highest) present-day and future DFLs of all those considered herein. The sensitivity of results to water depth, the Squamish Spit, Squamish Terminals, and the vegetated inter-tidal estuary lands should be reviewed prior to the next IFHMP update. Wave interactions with CN's railway embankment result in unreliable model predictions within the Bridge Pond area; if necessary, this should also be resolved prior to the next IFHMP update. Additional local wind data should be collected in Squamish Harbour to support future wave modelling.

Wind waves and external storm surge are not fully correlated as assumed by some methods for combining still-water DFL and wave effects. Additional work is required to confirm a more realistic degree of correlation at Squamish prior to the next IFHMP update. Until this information is available, the IFHMP combines wave effects with a DFL based on joint probability methods according to the procedure laid out in the draft amendment to the provincial Flood Hazard Area Land Use Management Guidelines (BC MFLNRO, 2013b).

Combining the 200-year return period DFL with 200-year return period wave effects would almost certainly result in a total water level with a frequency of occurrence less than the intended 200-year threshold. The implied level of protection could easily exceed the 500-year level recently adopted by the City of Vancouver (CoV, 2014). It is possible that the final probability for this scenario could approach the 4,000-year return period range recommended by Ausenco Sandwell (2011c); however, such calculations would require additional data and a resource-intensive hindcasting procedure that is beyond the scope of the IFHMP.

5.6 Geohazards Review

The IFHMP study included a desktop review of local geohazards undertaken by Dr. Oldrich Hungr, P.Eng., P.Geo.of the University of British Columbia with support from Thurber Engineering, SNC-Lavalin, and KWL. A summary of the findings of the geohazards review and related work (e.g., Thurber, 2002; KWL, 2003; Cordilleran Geoscience, 2008; van Zeyl, 2009; KWL, 2010b; EBA, 2012; Baumann, 2012; LaCas Consultants, 2012; Knight Piésold 2015; Clague, 2015; NHC, 2017) is provided in the table below, with conclusions colour-coded based on their impact for the IFHMP as follows:

- Green items need not be considered further until the next IFHMP update.
- Yellow items should be studied prior to the next IFHMP update.
- Red items were investigated further as part of, or in parallel with, development of the IFHMP.

Note that a designation of green means only that further investigation would not be a cost-effective use of IFHMP funding at this time. Green designations do not necessarily mean that a given hazard is negligible.

The full text of Dr. Hungr's assessment of landslide-related flooding hazards is included as Appendix E. A separate discussion of tsunami hazards is provided in Appendix F.

Table 5-9: Summary of IFHMP Geohazards Review

Geohazard	Description	Comments	Recommendation
Squamish River Landslide Dam Breach	Landslide blocks Squamish River at Mt. Cayley complex; landslide dam fills, overtops and fails.	Low probability relative to other flood hazards; magnitudes less than Q200 at Brackendale.	Review conclusions and new literature at next IFHMP update.
Dam Failure (BC Hydro Daisy Lake Dam)	BC Hydro dam fails resulting in catastrophic release of water from Daisy Lake.	BCH dam safety requirements based on very low-probability events.	Co-ordinate emergency response planning with BC Hydro; exclude from IFHMP analysis.
Daisy Lake Displacement Wave	Rock avalanche from the Barrier generates a debris flow on Rubble Creek that runs out into Daisy Lake.	Limited consequence expected within District boundary unless wave initiates dam failure.	Review conclusions and new literature at next IFHMP update.
Cheakamus River Landslide Dam Breach	Rock avalanche from the Barrier and/or tributary debris flow blocks Cheakamus River, then overtops and fails.	Low probability (≤1 in 5,000), limited (if any) incremental increase in consequence within District boundary due to significant upstream attenuation, potentially Higher consequences for nearby areas.	Review conclusions and new literature at next IFHMP update.
Barrier Collapse – Loss of Garibaldi Lake	Massive and catastrophic collapse of the Barrier releases water from Garibaldi Lake.	Very low probability (<1 in 10,000), scenario not considered in engineering reports.	Review conclusions and new literature at next IFHMP update.
Mamquam River Glacial Outburst Flood	Landslide, ice, or glacial dam retains water then fails rapidly.	Possible, but no record of past events.	Review conclusions and new literature at next IFHMP update.

Geohazard	Description	Comments	Recommendation
IPP Dam Failure	IPP intake structure fails and results in a catastrophic release of the headpond.	Small headpond storage volumes result in limited failure consequences for larger rivers like Mamquam River and Squamish River (KWL, 2013f).	Review potential significance of single or multiple failures based on IPP developments planed or operating at next IFHMP update.
Cheekeye River Debris Flow	Major debris flow with potential for avulsion; minor events with local channel consequences including Cheakamus River displacement flood.	Potential threat to development on fan and Cheakamus I.R. No. 11 requires detailed consideration.	Detailed consideration required for fan zone will be completed in separate but parallel District process. Assess secondary consequences (e.g., landslide dam breach hazard on Cheakamus River) prior to next IFHMP update.
Debris Flows on Local Creeks	Debris flows initiated on steep local creeks have the potential to run out within District lands.	1994 FHMP provides a screening-level qualitative assessment.	Little merit to updating previous screening assessment – site-specific analysis would still be required.
Stawamus River Debris Flood	Landslide blocks Stawamus River, then overtops and fails.	Recent reports have identified new hazards closer to developed areas.	Add debris flood bulking factor of 1.5 to 2.0 to clear-water peak flow estimates at and above 200-yr return period.
Landslides and Rockfall	Steep slopes have the potential to initiate landslides that could originate or run out in District areas.	Landslides and geotechnical stability are outside the scope of the IFHMP.	Prepare a consolidated database of landslide risks and integrate into natural hazards mitigation policies.
Local Tsunami – Sub-aerial Slide	Large slide into Howe Sound produces large waves	No known signs of slope instability surrounding Howe Sound. Van Zeyl (2009) found that hazard in Howe Sound is considerably less than Knight Inlet. Knight Piésold (2015) estimates the annual likelihood of a landslide-induced tsunami affecting Woodfibre to be less than 1 in 2,500.NHC (2017) suggests hazard is negligible.	Review conclusions and new literature at next IFHMP update

Geohazard	Description	Comments	Recommendation
Local Tsunami – Submarine Slide	Large submarine slide produces large waves	Knight Piésold (2015) found a very low annual likelihood that a submarine landslide-induced tsunami could affect Woodfibre. NHC (2017) cites a lack of evidence for tsunamis induced by local seismic events. However, loose materials (e.g., in Squamish River delta) may be subject to liquefaction and flow slides during an earthquake.	Use existing data to prepare a preliminary opinion on the potential magnitude of liquefaction-induced flow slides on the Squamish Delta front and compare to the events assessed in the 2015 study.
Regional or Far-Field Tsunami	Offshore seismic event generates tsunami	EMBC (2008) recommends regional tsunami planning levels but does not consider higher wave height at Howe Sound entrance during Cascadia Event, resonance, or shoaling and convergence within Howe Sound.	Assume regional tsunami hazard is comparable to coastal flood hazard at similar probability levels. Confirm tsunami design event for next IFHMP update.

Tsunami Hazards

Given the significant coastal flood protection decisions made as part of the IFHMP, additional discussion of tsunami hazards is appropriate. A more detailed summary of the regional and local tsunami risk is provided in Appendix F. Subsequent to the preparation of Appendix F, a separate assessment and peer review of local tsunami hazards was undertaken for the Woodfibre Liquefied Natural Gas (LNG) project (Knight Piésold, 2015; J.J. Clague, 2015) and for the Newport Beach Development at SODC (NHC, 2017).

As described in Appendix F, the maximum expected tsunami wave height at the entrance of Howe Sound resulting from an offshore earthquake is less than 1 m. Emergency Management BC (2008) provides recommended tsunami planning levels (including wave height, run-up allowance, and factor of safety) for the BC coast. The recommended tsunami planning level for Zone E, which includes the Strait of Georgia and Howe Sound, is 2 m above normal highest tide. Applying EMBC’s recommended tsunami planning level of 2 m at Squamish yields peak water levels comparable to an extreme combination of high tide, external storm surge, wind setup, and wave effects.

EMBC (2008) notes that inundation could exceed the recommended tsunami planning levels at the head of inlets or when a tsunami is generated by a local landslide, and considered a maximum wave height of 0.5 m for Zone E that neglected a major earthquake at the Cascadia Subduction Zone off Vancouver Island. All of these factors suggest that the tsunami hazard in Squamish could exceed the generic Zone E planning levels. Detailed analysis of far-field tsunami amplification due to shoaling, convergence and resonance effects within Howe Sound would require data and modelling beyond the scope of the IFHMP.

As indicated in Table 5-9, local tsunamis could also be generated from sub-aerial or submarine landslides along Howe Sound. The local tsunami hazard can be proximity-dependent; one of the most notable landslide hazards is the submarine slope of the Squamish River delta front. Regular small slides demonstrate the static instability of the slope (Clarke et al., 2012) while previous work by Thurber Engineering and others has concluded that the submarine sediments are likely liquefiable when subjected to seismic loads.

Appendix F provides preliminary findings that a slide on the Squamish River delta front (e.g., due to liquefaction effects) could produce a tsunami with height from 0.6 m to 7 m. A 2015 study by Knight Piésold and a corresponding peer review by John Clague, PhD, P.Geo. of Simon Fraser University concluded that available information on historic submarine mass movements in Howe Sound and at the Fraser River Delta indicate a very low probability of initiating a local tsunami. While the Knight Piésold and Clague assessments do not specifically comment on the potential for a major seismic event to generate a liquefaction-induced flow slide; this probability is also assumed to be very low but should be confirmed prior to the next IFHMP update.

Based on the information available, the IFHMP assumes that the runup hazard for regional or far-field tsunamis approximately corresponds to the coastal design flood water level. The magnitude and frequency of potential tsunami hazards resulting from liquefaction of submarine sediments, particularly the Squamish River delta front, should be explored further prior to the next IFHMP update.

6. Conclusions and Recommendations

The Squamish community faces an unusually broad range of flood-related hazards. As it grew, the District developed a detailed flood hazard management program that provided the community with policy, planning, and structural protection tools. However, the last comprehensive Flood Hazard Management Plan was completed in 1994. New tools, changing hazards, and continued development over the 20 years since the 1994 FHMP have made the guidance provided by that document obsolete.

This section draws conclusions about the state of the District's pre-existing flood hazard management program by identifying strategic gaps between the pre-existing program and the increased knowledge of flood hazards. These gaps are presented in the context of the guiding principles outlined in Section 3, which represent some of the most significant guidance available at regional, provincial, national and international levels.

The conclusions reached in this report provide a high-level review of significant planning and policy gaps as well as structural mitigation gaps, and are not intended to provide a detailed and exhaustive review of all deficiencies.

6.1 Planning and Policy Conclusions

Risk Management Strategy

- Prior to the IFHMP, the District's approach to flood hazard management, including climate change, focused on a strategy of Protect, maintaining current lines of flood defence. Other strategies, including measures incorporated in the OCP, had limited implementation due to logistical challenges, high costs, and potential legal obstacles.
- The District has not yet formally adopted a strategy to address anticipated sea level rise and related climate change impacts (this study). Staff are applying Provincial and APEGBC guidelines in the interim on a case-by-case basis.
- The 200-year return period flood protection standards accepted for District flood protection works (OCP Policy 25-11) may or may not meet current needs in different areas.
- Unlike river floodplains in Squamish, the level of acceptable risk in Downtown Squamish and other areas subject to sea level rise and storm surges is not specified in the OCP (OCP Policies 25-3, 25-5, 25-12).
- The District does not have an official position on the balance of risk between protecting against coastal floods and mitigating the consequences of high-consequence, low-probability upstream dike breach events. A similar situation exists for the southern part of Garibaldi Estates, municipal works yard, and Squamish Nation Kowtain I.R. No. 17.
- The OCP does not advocate for the opportunistic managed retreat of critical flood response or "lifeline" facilities to areas outside the floodplain (as opposed to redeveloping at their current locations).
- A comprehensive hazard risk mitigation strategy, including area-specific standards of protection and risk tolerance, is required for the Cheekeye Fan.
- The alignment of private property interests with the District's need to mitigate risk is weak.

Risk Analysis

- The IFHMP geohazards review indicates that debris floods are possible on the Stawamus River. The potential impacts of this hazard have not been assessed in detail.
- Past coastal engineering studies do not appear to have assessed or made allowance for subsidence in determining future flood levels.
- Wind setup and design wave heights have a significant impact on estimates of future extreme coastal water levels. Currently there is limited local data to support engineering analysis.
- Existing structures at Squamish Spit and Squamish Terminals currently provide significant wave protection for much of the District's coastal margin. The future status and geometry of these structures may be subject to change as part of a long-term planning process.
- Existing flood hazard documentation is outdated and does not incorporate updated LiDAR mapping.
- The current reliance on a site-specific report by a Qualified Professional has inherent limitations due to the limited scope of such reports relative to the complexities of the hazards.

Regulation - Planning

- The Official Community Plan identifies flood hazards and debris flow hazards areas (Schedule D1) but lacks a development permit area for the protection of development from natural hazards (Section 488(1)(b) of the *Local Government Act).*
- A floodplain bylaw pursuant to Section 524 of the *Local Government Act* has not been adopted, and the potential conflict of such a bylaw with eligibility criteria for Disaster Financial Assistance has not been resolved.
- The zoning bylaw has minimal regulation of flood and debris flow hazards.
- The zoning bylaw allows all facilities excluded from the Gross Floor Area of a building to be located below the Flood Construction Level, some of which are highly vulnerable to flood hazards.
- The application of setbacks from flood protection works has not been consistent and has created conflicting precedents.

Regulation - Flood Construction Levels

- Flood Construction Levels provided in the 1994 Flood Hazard Management Plan are out of date and do not reflect current Provincial Guidelines or climate science studies.
- Existing risk mitigation does not address non-residential uses in areas subject to flood and debris flow hazards.
- Existing risk mitigation does not address vulnerable building features for residential and non-residential uses that are located below Flood Construction Levels.

Public Education

- There is a need to inform Squamish residents about the implications of flood and debris flow hazards, sea level rise, and related climate change impacts on the community.

6.2 Structural Flood Protection Conclusions

The "gaps" identified below for the District's structural flood protection system do not necessarily represent physical gaps in the flood defenses. In this context, a "gap" indicates that the structural flood protection works are in some way not meeting their desired level of function. Like the policy gaps identified above, structural flood protection gaps have been grouped by type and are described individually below.

Design Standards

- Updated modelling suggests that the District's existing dikes may not achieve their intended level of protection, defined in the OCP as the 200-year return period design flood on the local rivers. This includes, but is not limited to, known low points such as road and rail crossings that should be addressed in the District's Emergency Plan.
- The District does not have a comprehensive system of dedicated coastal flood defenses. Existing works are a combination of non-standard structures and *de facto* barriers such as the CN tracks at Bridge Pond.
- Some dike reaches do not meet the provincial and local design standards for cross-section geometry, or show evidence of undesirable seepage and piping. Conflicts between development and potential flood protection alignments create challenges for implementing significant upgrades at some locations.
- Many District dikes may not meet the province's recent seismic design guidelines. Seismic performance issues should be given appropriate consideration where risks and resources permit. Geotechnical studies will likely be required before undertaking any significant upgrades.
- Existing erosion protection revetments on the Stawamus River dike may not have sufficient height or size to provide full protection against the potential for debris floods identified by Baumann (1994).
- Overland flooding is expected in undiked areas of the Cheakamus River, Cheekeye River and Stawamus River. This flooding may affect development at flows less than the 200-year design flood stated in the OCP.
- A number of bridges, particularly on the Stawamus River and Cheekeye River, do not have sufficient hydraulic capacity to pass the corresponding design flood event. The CN Rail Bridge over the Mamquam River may also be backwatered during very high flows. Debris blockage is a possibility for some structures and could significantly exacerbate the situation. Loss of these structures could exacerbate flooding and hinder emergency response.

Jurisdiction and Access

- The District does not have a comprehensive suite of SROW and access agreements for the dike system. SROWs are important for operation and maintenance as well as to accommodate future upgrades.
- Private property owners have been allowed to permanently fence off areas of the dike crest, even where an SROW agreement exists. These obstructions hinder inspections and maintenance, and could inhibit emergency detection and response.
- Maintenance responsibility for some structures seems unclear. Challenges are exacerbated by historic inconsistencies in the public database maintained by provincial Inspector of Dikes.

- The legal status of dikes on First Nations land is unclear. Persistent on-reserve dike deficiencies serve as reminders of bipartisan challenges shared by the District and Squamish Nation.
- The ownership of sediment excavated from the local rivers has been a past point of contention between the District and the Squamish Nation. This and other dike-related issues touch on First Nations rights, traditional territory, and other matters beyond District jurisdiction.

Inspection, Reporting and Compliance

- The District's O&M manual is now approaching 20 years old and is in need of a comprehensive update to reflect new information on the dike system as well as new inspection and reporting requirements.
- The District's last two comprehensive dike inspections were completed in 2007 and 2015. Comprehensive inspections must be completed at a reasonable interval to identify new issues, keep track of evolving challenges, and facilitate the transfer of knowledge to the "next generation" of caretakers.
- The District has a high-level GIS base layer of flood protection works but lacks a comprehensive GIS database. An easily-accessible record of works, deficiencies and historical problems (e.g., 2004 and 2013 sinkholes) can be a valuable tool during a flood situation.
- Fills placed against the dike years ago without any compaction, quality control, or authorization from the Inspector of Dikes remain in place today. These fills have now revegetated and may be visually indistinguishable from proper dike fills.

Environment and Community

- The District lacks a formal strategy for comprehensive vegetation management on local flood protection structures.
- The District does not presently have a long-term multi-stakeholder sediment management strategy to identify and achieve appropriate flood protection goals, if any, with minimal environmental impact.

6.3 Recommendations

The recommendations outlined in this section are intended to maximize the effectiveness and efficiency of this IFHMP and future flood hazard management initiatives. Where appropriate, recommendations to address gaps in the District's flood protection program as outlined in Section 6.1 and 6.2 will be incorporated into the final IFHMP report.

KWL recommends the following to support this IFHMP and future flood hazard management studies:

Short-Term Recommendations (supporting this IFHMP)

1. Endorse a suite of processes and assumptions for the estimation of coastal flood hazard water levels based on the recommendations of this report or other factors the District deems appropriate. Specific decision items include:
    a. Source of external storm surge data (IFHMP recommendation: Point Atkinson);
    b. Approach to combining high tide and surge (IFHMP recommendation: joint probability);
    c. Allowance for subsidence (IFHMP recommendation: incorporate into local effects);

   d. Allowance for local effects (IFHMP recommendation: allow 0.3 m); and
   e. Approach for combining waves and DFL (IFHMP recommendation: combine 200-year return period DFL with 200-year return period seastate as per 2013 draft amendment to BC MFLNRO guidelines).

2. Continue to collect quality-controlled wind and water level to provide better data for an analysis of local coastal flood effects, possibly through partnerships with CHS (water level) and Squamish Terminals (wind).
3. Liaise with CHS to confirm the relationship between Chart Datum and local geodetic benchmarks.
4. Adopt a preliminary design debris flood “bulking factor” of 1.5 to 2.0 times the 200-year return period clear-water instantaneous peak flow for IFHMP hydraulic modelling of the Stawamus River. Carry out a detailed debris flood hazard study (e.g., KWL, 2010a) as resources permit.
5. Complete a comprehensive engineering inspection of the District’s dike system at the earliest opportunity so that the IFHMP can incorporate any key findings.

Mid-Term Recommendations (supporting potential outcomes of this IFHMP)

6. Confirm SROW gaps and begin compiling documentation on current land ownership, SROW application requirements and consultation procedures.
7. Conclusively determine whether, and to what extent, the District’s coastal margins are subsiding over time, and their vulnerability to subsidence during a major seismic event.
8. Collaborate with the Squamish Nation, the provincial Ministry of Transportation and Infrastructure, and/or CN Rail to determine whether interest and funding is available to pursue two-dimensional debris flood modelling of the lower Stawamus River in parallel with the IFHMP.
9. Consult with the Inspector of Dikes regarding the acceptability of IFHMP Stawamus River peak flow assumptions for future dike design and maintenance. Update Schedule D-1 of the OCP to reflect a Stawamus River debris flood hazard as part of comprehensive IFHMP updates to the OCP.
10. Complete the “periodic review” of the potential for lateral erosion on the Cheekeye River to breach Cat Lake that was recommended by engineering studies in the early 1990s. The review should be incorporated into ongoing debris flow hazard discussions for the Cheekeye Fan, since sufficient information may already be available to confirm the earlier conclusions of Bland (1992b) and Thurber & Golder (1993).
11. Consolidate a database of known landslide and rockfall hazard areas to support coordinated natural hazard mitigation policies in the next OCP update.
12. Build an understanding of expected seismic performance and related mitigation measures for high consequence dikes by carrying out pre-feasibility assessments for representative dike sections on an as-needed basis.

Longer-Term Recommendations (supporting the next IFHMP update)

13. Confirm that the potential for tsunami due to a submarine landslide induced by seismic liquefaction is commensurate with the other tsunami hazards and assumptions herein.
14. Consult with appropriate community groups and businesses regarding long-term plans for the Squamish Spit and Squamish Terminals. Update wave modelling results to ensure that

assumptions regarding future conditions are compatible with long-term plans, and explore sensitivity to these assumptions.

15. Request that the provincial government update the provincial Sea Level Rise guidelines as recommended by Ausenco Sandwell (2011a).
16. Explore opportunities to cost-effectively obtain concurrent wind and wave measurements prior to the next IFHMP update.
17. Complete seismic performance and mitigation analyses so that the next IFHMP can incorporate results into options assessment and project prioritization.

7. Report Submission

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Revision History

Revision #	Date	Status	Revision	Author
0	September 12, 2017	FINAL	Updated and issued with final IFHMP.	DR
E	February 24, 2015	FINAL DRAFT	Final draft for public release. Finalization of report withheld pending additional information that may become available prior to completion of IFHMP	DR

OQM | Organizational Quality Management Program

Appendix A

Report to Council for August 19, 2014 Meeting of District of Squamish Committee of the Whole (Excluding RTC Attachment 1)

REPORT TO: Council FOR: Regular Council
REPORT FROM: Engineering
PRESENTED: August 19, 2014 FILE:
SUBJECT: Integrated Flood Hazard Management Plan – Council Update #1

Recommendation:

That Council approves the following resolutions:

> **THAT** the District of Squamish receive the draft Background Report for the Integrated Flood Hazard Management Plan, and
>
> **THAT** the District of Squamish authorize staff to finalize the Background Report based on Council feedback.

---

1. Purpose:

The purpose of this report is to update and gain Council feedback on the findings of the Background Report for the Integrated Flood Hazard Management Plan (IFHMP). This presentation is designated "Council Update #1" in the IFHMP work program.

2. Background:

The District of Squamish is set in a spectacular natural environment surrounded by steep mountain slopes, pristine rivers and one of BC's most beautiful fjords. These surroundings expose Squamish to a wide variety of natural hazards including:

- flooding from the Squamish, Mamquam, Cheakamus, and Stawamus Rivers,
- debris flows from the Cheekeye River,
- outburst flooding associated with potential collapse of the Barrier at Garibaldi or a Mount Cayley landslide blocking the Squamish River,
- outburst flooding from a dam breach at the Daisy Lake Dam, and
- coastal flooding and tsunami (including landslide-generated waves in Howe Sound).

The District is the local diking authority and is responsible for providing the community with an adequate level of flood protection. The District is also responsible for managing community development in floodplain areas. In 1994, the District completed a Flood Hazard Management Plan (FHMP) to help achieve an appropriate balance between these two key District mandates.

As a result of the extensive level of floodplain development since 1994, new Provincial design standards, improved land use management policies and advances in flood analysis technology, the 1994 FHMP has become largely obsolete. This creates challenges for the District in its review of ongoing land development applications. On January 21, 2014 Council authorized staff to award the project to a multi-disciplinary consulting team led by Kerr Wood Leidal Associates Ltd. (KWL) and initiate work immediately to update the IFHMP to support continued growth within Squamish while prudently managing flood risk.

The first phase of the IFHMP was completion of a Flood Mitigation Gap Analysis in order to provide an overview of current and future flood hazards and document key areas where the current District flood mitigation program is underperforming. The deliverable from this phase of the project is a comprehensive Background Report (Attachment 1) which lays the technical foundation for the project and summarizes the existing state of knowledge around:

- history and inventory of known flood-related hazards within the District of Squamish, including climate change assumptions and timelines (Section 2);
- existing policy tools for flood hazard management and guiding principles for the IFHMP (Section 3);
- District-wide inventory of existing structural flood protection works (Section 4);
- Updated local hazard analyses (Section 5); and
- Conclusions regarding current gaps in both policy and structural flood protection aspects of the District flood hazard management program (Section 6).

The intent of Council Update #1 is to discuss the findings of the Background Report, obtain feedback on several key items and receive any Council direction required to finalize the report for continuation with the next phases of the project.

3. Project Information:

Scope of Work

Effective implementation of the updated IFHMP depends on public support and, accordingly, public engagement will be an essential part of the update process. Broad public consultation has been planned including two bi-lateral meetings with the Squamish Nation, six meetings with a Technical Working Group of stakeholders, three public open houses and presentation at five District Council meetings.

The scope of work for the IFHMP is summarized at a high level as follows:

1. Flood Mitigation Gap Analysis (this phase): providing an overview of current and future flood hazards and documenting key areas where the current District flood mitigation program is underperforming with regard to the District's intent and objectives.
2. Coastal Flood Hazard Mitigation Options: identifying a preferred alignment and concept for comprehensive coastal flood defenses to protect downtown Squamish, Dentville, the CN North Yards and the Squamish Industrial Park.
    a. Phase includes Technical Working Group Meetings #2/3, Public Consultation Session #1, District Council Meeting #2

3. Squamish and Mamquam River Risk Assessment: producing flood risk maps for the highly-developed Squamish River floodplain based on a coupled 1D/2D river/floodplain dike breach model.
4. Squamish and Mamquam River Flood Mitigation Options: defining the potential range of appropriate structural and non-structural aspects of the Districts flood mitigation program.
5. Cheakamus, Cheekeye, and Stawamus River Risk Assessment: documenting the interaction of development and flood/debris flow hazards for at-risk areas beyond the main Squamish River floodplain.
6. Risk Analysis Consultation: consulting with the public about the future direction, costs and benefits of the flood mitigation program.
    a. Phase includes Technical Working Group Meeting #4, Public Consultation #2, District Council Meeting #3, Technical Working Group Meeting #5
7. Integrated Flood Hazard Management Plan: creating a document that provides direction for balancing responsible flood hazard management with continued community development within the District of Squamish.
    a. Phase includes Council Meeting #4 (present draft plan), Technical Working Group Meeting #6 (reviewing draft plan), Public Consultation Session #3 (presenting IFHMP, soliciting feedback) and Council Meeting #5 (sharing public feedback, seeking authorization to finalize plan)

Project Status

To date the IFHMP consulting team, led by KWL, has completed extensive work in the initial 'Flood Mitigation Gap Analysis', culminating in the draft Background Report. Their work included a comprehensive review of flood related studies and papers in and surrounding the District of Squamish as well as a review of flood policy provincially, nationally and internationally. In addition, the team updated hazard assessments for all known flood and geohazards within the District including river and coastal hazards, and tsunami hazard. Independently, the District has also received a rezoning application for an area within the Cheekeye Fan debris flow hazard area. The developer has provided an expert panel review report which has contributed to updating knowledge of the Cheekeye Fan debris flow hazard.

Overview of Hazard Assessments

The goal of the IFHMP is to help the District better understand and mitigate flood risk. Risk is the product of a possible hazard (e.g., the 200-year return period flood) and the consequences of that hazard impacting vulnerable people, the environment and infrastructure. A high-risk situation may result from a fairly common hazard with relatively low consequence, or a very infrequent hazard with extreme consequence. The historic approach to flood protection throughout BC has involved protecting against a specified hazard with only limited and qualitative consideration of consequence.

The emerging standard of engineering practice is to move away from consideration of a specified hazard or return period (e.g., the 200-year return period flood) and toward consideration of a range of flood risks defined by their potential impact on a community. Decisions regarding flood mitigation are then based on the risk associated with each source of hazard. Applying a risk-based framework for flood protection promotes consistent decision-making and cost-effective resource management over the long term.

One of the main objectives of the IFHMP is to understand the District's portfolio of flood-related risks and move the District towards an acceptable level of risk for the community. In order to do this, the District will need to define a level of residual (or unmitigated) risk that would be "acceptable" to the community as a whole and to the individuals most affected.

Once defined, the District's flood protection objective is to reduce risk down to or beyond this acceptable limit. Risk reduction can be achieved either by mitigating hazards or by reducing potential consequences. The process of defining "acceptable risk" will require both public and Council input.

For the current phase of work only hazard assessments have been completed, however the current IFHMP work program includes risk assessments in later phases of the project.

River Hazard

As part of the initial phase of the project, KWL has updated all river hazard assessments. This required updating river peak flow hydrology based on additional data collected since the last updates. In many cases, the additional analysis allowed for a reduction in peak river discharges. However, the Association of Professional Engineers and Geoscientists of British Columbia (APEGBC) has recently issued climate change guidelines recommending that peak flow estimates for design and planning purposes be increased to account for climate change. The net effect of combining updated peak flows with climate change allowances for each river is summarized in Table 5-5 of the Background Report.

Based on the updated river hydrology, KWL updated and analyzed all river models. Several areas do not provide the intended level of protection defined in the OCP as protection to provincial standards against a flood hazard with an Annual Exceedance Probability (AEP) of 1 in 200 (the 200 year return period flood). These areas are described in Section 5 of the Background Report but can be summarized as follows:

- Squamish River Dike at Judd Slough, Eagle Run and North Yards,
- Mamquam River Dike at Hwy 99 & CN Rail crossings,
- Most areas along Paradise Valley and the lower Cheakamus River,
- Stawamus River dike at the Forest Service Road bridge and near Plateau Drive.

Over and above these "hydraulic" deficiencies, many of the dikes have not been constructed to current seepage or seismic guidelines and are considered sub-standard relative to current standards and best practices. In addition, many of the District's dikes lack continuous Statutory Right of Ways (SROWs). This can lead to challenges with maintenance access and land tenure for future upgrades. Finally, KWL's review of dike infrastructure in the District has identified gaps in the maintenance responsibility for some of the local dikes.

Staff notes that the District has been proactive in addressing the noted dike deficiencies. Between work completed in 2013 and planned work in 2015, approximately 2.5km of dike will have been raised in the North Yards and Judd Slough. An additional project is being developed to mitigate seepage and piping hazards at the south end of Eagle Run. The noted deficiencies will be considered in later stages of the project in order to prioritize required improvements to the District's diking system.

Coastal Hazards

In addition to river hazards, KWL and coastal sub-consultant SNC-Lavalin have completed a detailed coastal flood hazard assessment. This included the background analyses necessary to define coastal Flood Construction Levels (FCLs) in the next phase of the project (Coastal Flood Hazard Mitigation Options).

Determining coastal FCL's can be complex, involving many variables and different methods. However, the components that make up the FCL remain the same. They include:

- Astronomic tide – predicted by the Canadian Hydrographic Service (CHS) based on a mathematical relationship calibrated to short term data collected within Squamish Harbour.
- Storm surge – based on the measured difference (or "residual") between predicted tides and observed water surface elevations at CHS tide stations. Storm surge is caused by atmospheric conditions during storm events.
- Allowance for sea level rise – Provincial guidelines recommend planning for 1m of sea level rise by the year 2100
- Allowance for regional uplift or subsidence – Where a regional trend for net uplift or subsidence is identified from local geographical and geological data), it should be taken into account in coastal FCL's. Even rates of less than 1mm/year can have a significant effect over long time periods.
- Local effects – Local atmospheric and ocean conditions also affect design water levels. The main factors include local wind conditions ("wind setup") and local surge effects.

The combination of the components above produces what is commonly referred to as a 'still water level'. However, allowances for wave effects (discussed below) must be added on top of the still water levels to produce the final coastal FCL.

- Wave/wind effects – A local wave model is required to understand and estimate design wave heights and their interactions with present and future shorelines. A typical wave model requires local bathymetry, wind speed and direction analyses and a defined still-water level.
- Freeboard – normally 0.6m for a standard dike, this item is added to the other coastal flood level components to account for uncertainty and to preserve some latitude for unexpected events or performance conditions.

There are several approaches for determining coastal FCL's based on the components listed above. The differences between the methods are a result of:

- Selection of methodology for combining astronomic tide/storm surge
- Selection of approach for combining tide/surge with wave effects; and
- Selection of an appropriate Annual Exceedance Probability (AEP) for the resulting water levels

These are discussed below.

Combining Tide/Storm Surge

Provincial guidelines define two primary methods for combining the tide and storm surge components, namely the ‘combined’ approach and the ‘joint probability’ approach. These are described in detail in Section 5-4 of the Background Report. Generally, the combined approach adds the average annual maximum tide prediction (Higher High Water Large Tide, HHWLT) to a specified storm surge (often 1:200 AEP). AEPs are assigned to the resulting summation based on a number of simplifying assumptions.

By contrast, the joint probability method uses more complex statistical methods to combine tide and surge to determine the level for a desired Annual Exceedance Probability (AEP). Generally, the joint probability method is applied where resources permit as it typically results in a less conservative coastal flood elevation.

Selecting an Appropriate Annual Exceedance Probability for Still Water Levels

There are several conflicting Provincial guidelines and standards for the selection of an appropriate coastal AEP.

- BCMFLNRO – *Flood Hazard Area Land Use Management Guidelines* – a draft amendment of the document recommends using 1:200 AEP combination of tide and storm surge (determined using either joint probability or combined methods) together with a 1:200 AEP allowance for wave effects.
- The City of Vancouver recently adopted flood construction levels corresponding to the 1:500 AEP total water level (tide + surge + wave effects) based on a very rigorous modeling study.
- Ausenco Sandwell for BCMOE - *Guidelines for Management of Coastal Flood Hazard Land Use* - recommends using between 1:4,000 to 1:10,000 AEP combination of high tide and storm surge using the combined method.

An AEP of 1:4,000 to 1:10,000 for total water level is in line with other international standards for coastal flood protection. The above methods all take different approaches to estimating and applying AEP values and comparisons of AEP results between approaches is not straightforward.

There are several reasons for considering a more extreme AEP for coastal flooding as compared with river flooding. For example, due to wave interactions with the coastal perimeter (e.g., sea dike), it’s not realistic to completely eliminate overtopping from waves and spray. In order to completely eliminate any water from breaching, most sea dikes would need to be raised beyond the limit of economic feasibility. By contrast, river dikes do not usually have significant wave effects and are not intended to be breached in a design event.

When considering an appropriate design standard, it is important to understand the future application and impacts of coastal FCL's determined at this stage. The coastal FCL's will be used to determine the height of the sea dike protecting coastal areas. It will also affect building FCL's for future development within coastal areas which includes most low-lying areas south of the Mamquam River. For most of these areas, adopting overly conservative FCLs can pose implementation challenges (i.e costs associated with requiring buildings to rise significantly during redevelopment, inability to have habitable space at ground level, one property significantly higher than neighbor/road frontage, etc). Conversely, given the large area of Squamish influenced by coastal flooding, the density of development in those areas, the significance of commercial activity to the local economy and critical infrastructure in the downtown, it is important to establish a prudent level of protection.

As part of this process, the IFHMP suggests that the District begin to consider prudent and opportunistic relocation of critical facilities from floodplain areas to higher ground as the redevelopment cycle permits.

Local Uplift or Subsidence

CHS is currently the best source of information on local subsidence. Their data suggests that Squamish is subsiding; IFHMP inquiries have led CHS to initiate their own internal data review.

Comparison of published elevations for a Geodetic Survey of Canada benchmark near the intersection of Victoria and Cleveland suggest a rate of 1.6mm per year. Using this rate and projecting the level of subsidence to the year 2100 results in an allowance of 0.14m.

Local Effects

In addition to the components of coastal FCL discussed above, it is necessary to provide an allowance for local differences in external storm surge and wind setup experienced at Squamish relative to and the CHS tide station at Point Atkinson. Preliminary water levels have been collected at the 3rd Avenue tide gates and compared with the CHS data from Point Atkinson to explore local differences. Preliminary findings suggest that a local allowance of up to 0.35 m may be required. However, this is based on uncalibrated, poor-quality, single-event data. In addition, wind data has been collected from the Squamish Terminals and quality control issues have been observed that require resolution prior to relying on the data. Finally, the wave model produced by SNC-Lavalin is based on several assumptions. Further improvement in the model would require concurrent wind and wave height measurements in Squamish Harbour.

Based on the above, KWL recommends improving quality control and continuing data collection at the 3rd Avenue tide gates and to partner with Squamish Terminals to improve their wind data collection. These improvements can be made cost effectively and will assist in confirming the final local effects. Wave measurement is significantly more costly and does not fall within the scope or timelines of the IFHMP. Staff recommends evaluating the need for wave measurements at the conclusion of the IFHMP, and if necessary, collecting wave data prior to the next IFHMP update.

Wave Effects

To obtain a coastal FCL, wave effects must be added to the 'still water' levels discussed above. Provincial guidelines recommend combining wave heights from a 'Designated Storm' (e.g., 1:200 AEP) to the still water levels discussed above. However, preliminary review suggests that wave heights from the designated storm would not be strongly correlated with design still water levels. The combined approach for estimating FCLs is noted to be particularly conservative in this regard, as might be expected for a simplified approach: it assumes full correlation between external storm surge and wind speed (wave height).

The City of Vancouver elected to undertake a complex computer analysis to determine the most appropriate wave height to combine with design still water levels, however, the level of effort required is well beyond the scope of the IFHMP.

Recommendation

Staff proposes using the method proposed in the draft amendment of the *Flood Hazard Area Land Use Management Guidelines* which applies the 1:200 AEP for still water levels using the joint probability method. Wave effects for the 'Designated Storm' are added on top of these levels to determine the final FCL. While this guideline is still in draft form and will provide less conservative results than the combined approach and higher AEPs recommended in the Ausenco Sandwell guidelines, a few points should be noted:

- The draft amendment to the 2004 guidelines were prepared by the flood safety section of the BC Ministry of Forests, Lands and Natural Resource Operations in 2013 with full knowledge of the content and recommendations of the 2011 Ausenco Sandwell guidelines;
- The results of the approach are likely to prove more conservative than the 1 in 500 AEP total water level results adopted by the City of Vancouver in their recent coastal FCL bylaw;
- When correlations between surge, tide and wave effects are properly considered, the AEP (or return period) of the total water level is expected to remain relatively consistent with emerging international standards; and
- The change in FCL from the 1994 FHMP looks to be fairly severe. Adopting a more conservative FCL would exacerbate challenges arising during implementation.

Staff is confident that using this method will provide an appropriate level of protection that is in compliance with the most recent Provincial guidance.

Geohazards

Included in the scope of the IFHMP is a high-level review of geohazards. A range of geohazards were identified; however, the analysis concludes that many of the identified geohazards are either too unlikely (e.g., BC Hydro dam failure), too remote (e.g., Squamish River landslide dam breach at Mount Cayley), or too site-specific (e.g., local creek debris flow hazards) to be included in the IFHMP. Geohazards flagged as relevant for the IFHMP include Cheekeye Fan debris flows, landslide-generated tsunamis in Squamish harbor, and Stawamus River debris floods.

The IFHMP work program currently proposes to give some high-level consideration to options for the Cheekeye Fan zone. Given the recent rezoning application, it is anticipated that the scope of the IFHMP will be expanded to include an analysis of mitigation options (protect vs retreat vs accommodate vs do nothing). This analysis will assist the District in understanding preferred options for land use management in the Cheekeye Fan zone.

SNC-Lavalin completed a preliminary assessment of the potential for a local tsunami generated by movement of the submarine slopes located in Howe Sound. Similar events have occurred both provincially (Kitimat Inlet) and globally (Alaska, Norway), sometimes with fatal consequences. SNC-Lavalin's analysis suggests that landslides from the Squamish River 'delta front' (the leading edge of sediment deposited by the Squamish River) could result in local tsunamis ranging in height from 0.6 m to 7 m. SNC-Lavalin does not provide commentary on the potential probability of these events. The Background Report recommends undertaking a more detailed analysis to either validate or eliminate the potential risk to the Squamish waterfront due to a seismic or landslide generated tsunami.

Given that it is not currently practical to mitigate against a high magnitude/low frequency locally-generated tsunami, the limited scope of the IFHMP, and the significant upgrades already required to address more conventional coastal flood hazards, staff recommend that further study of this hazard be deferred and completed once the IFHMP is complete.

Current Flood Hazard Management in Squamish

The District's current flood hazard management program has three main components as follows:

1) Maintain 200 year protection along river dikes and maintain sea dikes surrounding downtown Squamish.

2) Document areas prone to flood and debris flow hazards in OCP.

3) Avoid permitting development in areas subject to unacceptable flood and debris flow hazards and require a report by a qualified engineer establishing suitability of the land for development as well as any mitigation measures.

Section 6 of the Background Report provides a high-level review of significant planning and policy gaps as well as structural gaps for consideration as the project continues. From a staff perspective, the most significant gaps in the District's current flood hazard management practices are:

- The District lacks a Development Permit Area (DPA) for hazard lands. This poses significant difficulties for regulating development within these lands. A DPA allows a local government to specify site-specific solutions such as required floodproofing measures and setbacks from dikes which would facilitate development reviews.
- The District also lacks a Floodplain Bylaw. As a result, all development within the floodplain requires a Qualified Professional, retained by the developer, to review

developments on a site by site basis in order to certify that the lands may be used 'safely for the intended use' and to specify floodproofing conditions such as FCL.

These policy gaps pose challenges for both developers and the District and are an area that is anticipated to be improved as a recommendation of the IFHMP. Other key gaps (e.g., lack of SROW, incomplete coastal flood defences, etc) have been discussed throughout this report.

Integrated Flood Hazard Management Plan - Technical Working Group

The District has formed a technical working group consisting of regulators and stakeholders with an interest in floodplain protection within Squamish. The Squamish Nation is a key partner in this project given their shared interest in floodplain protection for the reserves that lie within the District boundary. Other TWG stakeholders include:

- Ministry of Forests, Lands and Natural Resource Operations (MFLNRO), Inspector of Dikes
- MFLNRO, Ecosystems
- MFLNRO Hydrologist
- Ministry of Transportation and Infrastructure
- Navigable Waters
- Emergency Management BC
- CN Rail
- BC Hydro
- Vancouver Coastal Health

The Technical Working Group has convened its first meeting in order for the Project Team to present the draft Background Report, discuss key findings and receive initial feedback. The background report has also been distributed to the group for comments and feedback received will be considered prior to report finalization.

4. **Department Comments**

Considerable work has been completed in the first phase of the IFHMP. The Background Report provides a strong foundation for setting the direction and scope of the project moving forward. There are several key gaps noted in the Background Report and discussed in this report that staff recommends pursuing as part of the IFHMP as well as key items that the project team would like to confirm with Council prior to proceeding.

5. **Implications:**

a) **Budget:**

There are some minor recommended additions to the scope of the IFHMP including improved collection of wind/ocean data to confirm local effects. At present, it is recommended to absorb these costs into the project budget and pursue other opportunities to reduce scope and maintain the current project budget.

b) **Policy:**

The IFHMP will make recommendations for new flood hazard management policy in the final stage of the project.

c) **Environmental**

6. Attachments:

1) Background Report

7. Alternatives to Staff Recommendation:

Staff Recommendation:

THAT the District of Squamish not authorize staff to finalize the Background Report based on Council feedback.

____

David Roulston, P.Eng

Municipal Engineer

________________________________	________________________________
Rod MacLeod	Robin Arthurs
Director of Engineering	GM, Corporate Services
________________________________	________________________________
Linda Glenday, MBA	Joanne Greenlees
GM, Development Services & Public Works	GM, Financial Services

CAO Recommendation:

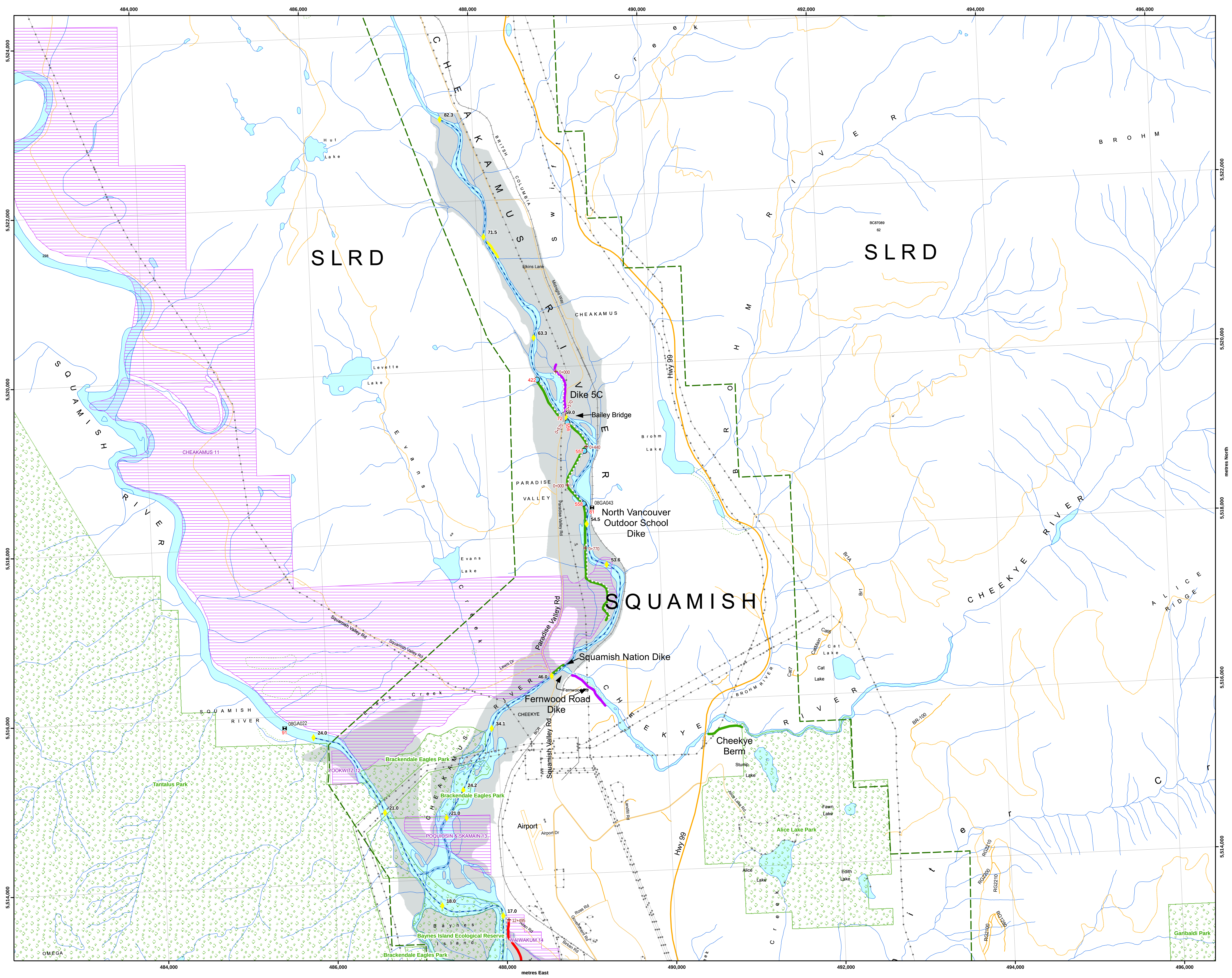
That the recommendation of Engineering be approved.

____

C. Speaker, CAO

Appendix B

BC Ministry of Environment Dike Inventory Maps



Squamish North

squamish_n_31

Local Diking Authorities

District of Squamish
Other Flood Control Works
(Fernwood Rd. & Dike 5c)
North Vancouver Outdoor School
Squamish Nation

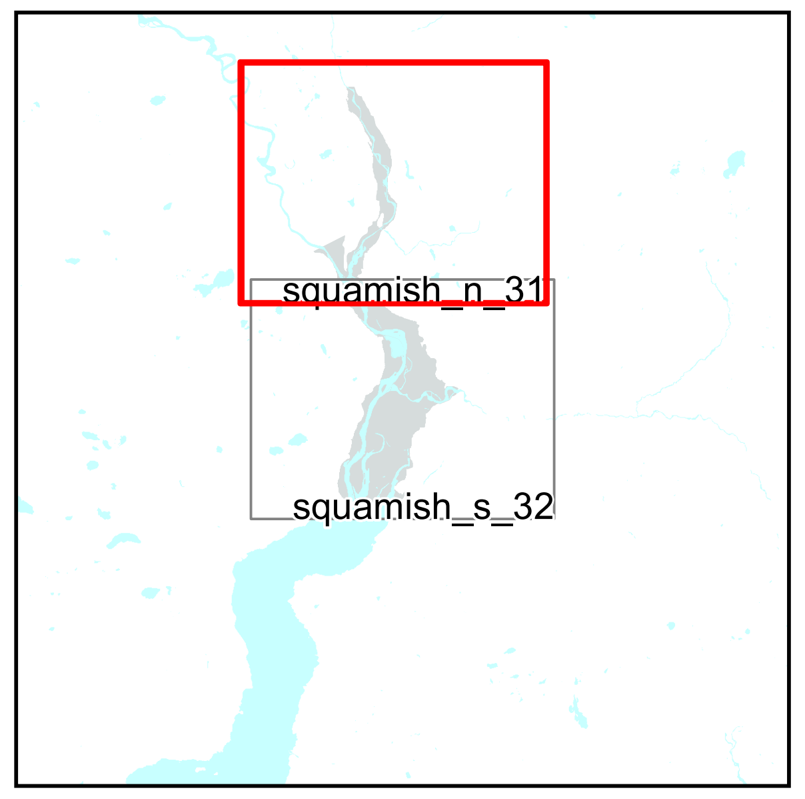
Legend

- ● Pumpstation / Floodbox
- ● Pumpstation
- ● Floodbox
- ○ Open Culvert
- Staff Gauge
- Dike Crest Gauge
- Water Survey Canada (WSC) Real Time Gauge
- Relief Well
- Low Dike
- ▲ Special Concern
- + Metric Stationing 0+000
- + Imperial Stationing 0+00
- ◆ Flood Profile Points Incl. Freeboard
- Flood Profile Line
- ○○○○○ RipRap
- Local Authority Standard Dike §
- Local Authority Non-Standard Dike §§
- Other Flood Control Works
- Fish and Wildlife Water Related Structure
- Dikes Outside Local Area (See Note 1)
- Floodplain
- Municipal Boundary
- Indian Reserves
- Provincial Park
- Regional District Park
- Water Pipeline
- Sewer Pipeline
- Gas Pipeline
- Energy Pipeline
- Oil
- Electrical transmission line
- Pipeline
- Railway

Note 1: Dikes are shown for reference purposes and are outside local diking authority area.

Notes Specific to Local Diking Authorities

Index Map



Squamish North

squamish_n_31

Map produced for Ministry of Environment,
Lower Mainland Region.

Printed from Digital Files by
the Integrated Land Management Bureau

Map Projection: Albers, NAD83

Grid Projection: UTM Zone 10N, NAD 83

Revised Date: April 23, 2007

File: squamish_n_31

Integrated Land Management Bureau

SQUAMISH NORTH

1:20,000

0 0.5 1 2 3 4 5 Kilometers

0 0.25 0.5 1 1.5 Miles

IMPORTANT NOTICE & DISCLAIMER

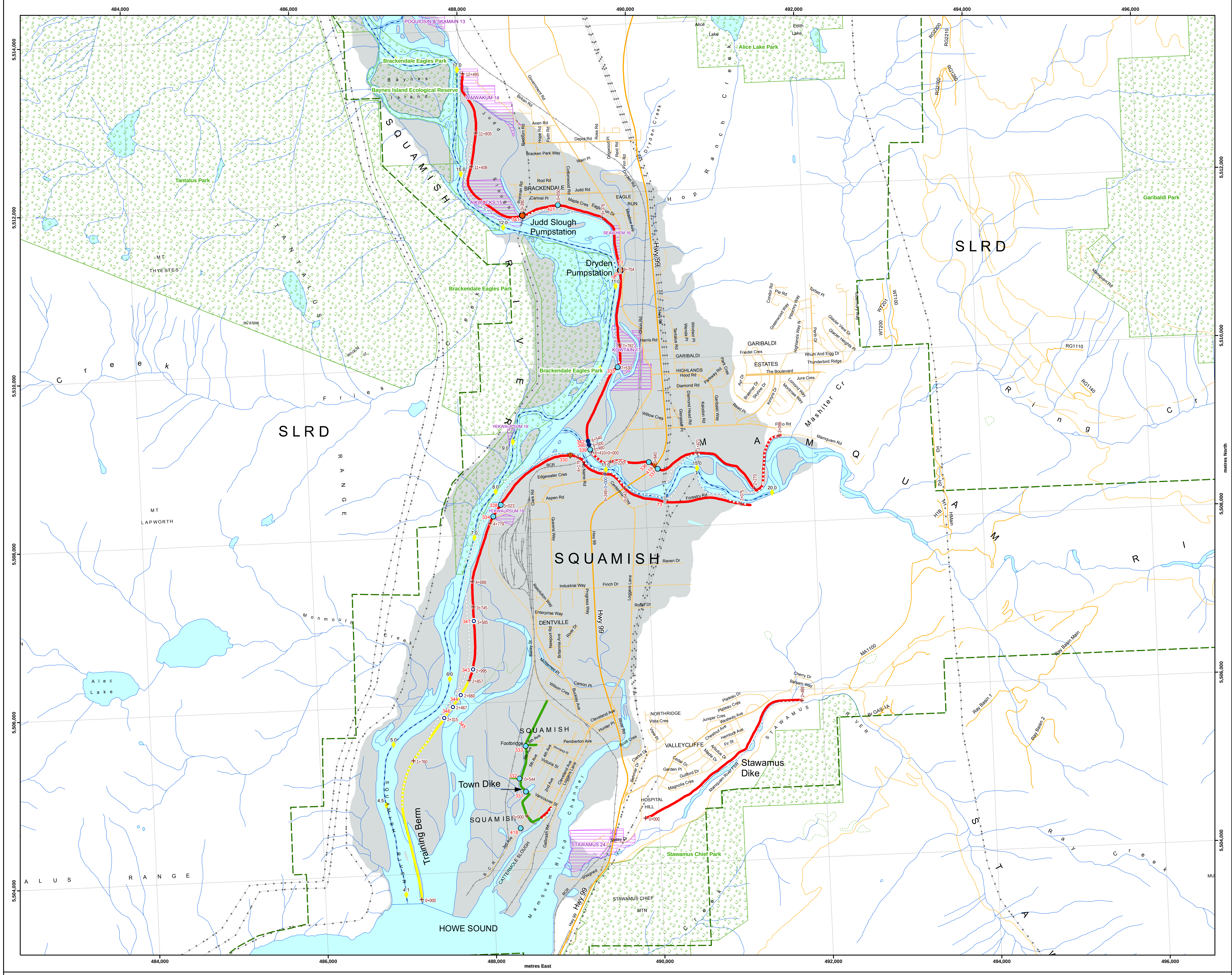
The floodplain boundaries and related flood protection infrastructure shown are provided to support flood emergency preparedness, planning & response; broad-based floodplain management, planning & reviews; and other related activities. It is NOT intended to replace detailed floodplain maps designated under the 1987 Canada/BC Floodplain Mapping Agreement.

FLOODING MAY OCCUR OUTSIDE OF THE FLOODPLAIN AREAS SHOWN.

The data was compiled from various sources; it is not warranted as to its accuracy or sufficiency by the Ministry of Environment, and is not intended for legal purposes.

§ Standard dike - a flood protection structure that meets, or has met, provincial dike standards that are regulated by the Inspector of Dikes under the *Dike Maintenance Act*.
Due to morphological, hydrological, and other changes in or about river systems, such a dike shown on the map may not continue to meet current standards.
IMPORTANT: To verify a standard dike's current status, the Inspector of Dikes office should be contacted.

§§ Non-standard dike - a flood protection structure that has a lower level of protection than that provided by a standard dike. Flood protection works that conform to this classification often protect rural agricultural lands and are sometimes referred to as agricultural dikes.



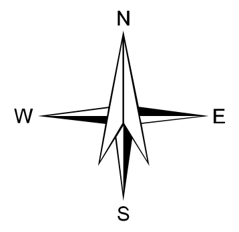
Squamish South

squamish_s_32

Local Diking Authority

District of Squamish

Legend



- ● Pumpstation / Floodbox
- ● Pumpstation
- ● Floodbox
- ○ Open Culvert
- ◑ Staff Gauge
- ▯ Dike Crest Gauge
- ⊠ Water Survey Canada (WSC) Real Time Gauge
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- ━ Fish and Wildlife Water Related Structure
- ━ Dikes Outside Local Area (See Note 1)
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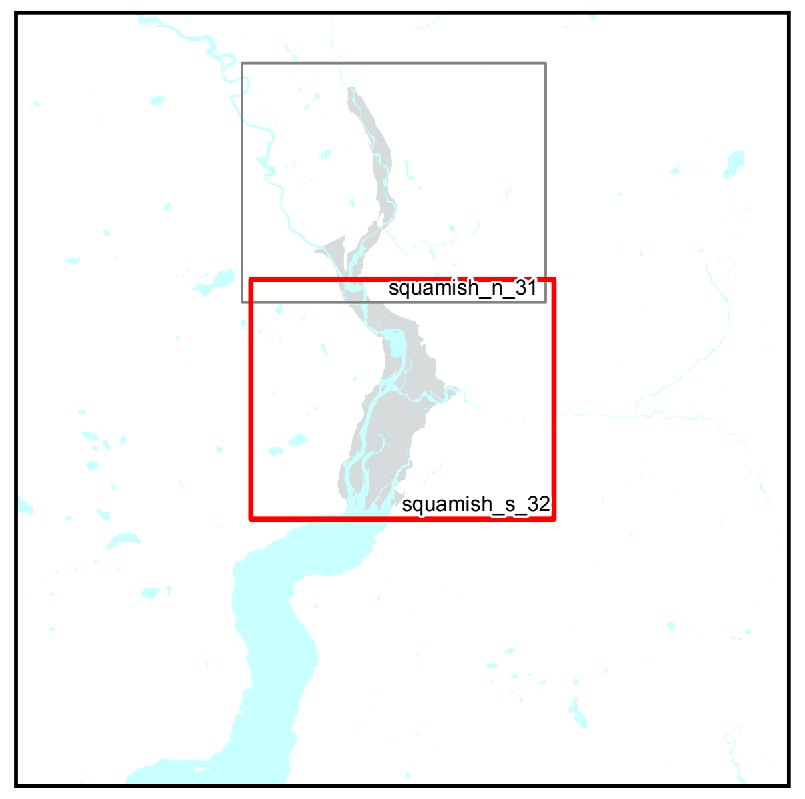
- ▨ Indian Reserves
- ▨ Provincial Park
- ▨ Regional District Park
- ‒ ‒ ‒ Water Pipeline
- ‒ ‒ ‒ Sewer Pipeline
- ‒ ‒ ‒ Gas Pipeline
- ‒ ‒ ‒ Energy Pipeline
- ‒ ‒ ‒ Oil
- ‒▪‒▪ Electrical transmission line
- ===== Pipeline
- ‒+‒+ Railway

Note 1: Dikes are shown for reference purposes and are outside local diking authority area.

Notes Specific to Local Diking Authorities

Index Map



Squamish South

squamish_s_32

Map produced for Ministry of Environment,
Lower Mainland Region.

Printed from Digital Files by
the Integrated Land Management Bureau

Map Projection: Albers, NAD83

Grid Projection: UTM Zone 10N, NAD 83

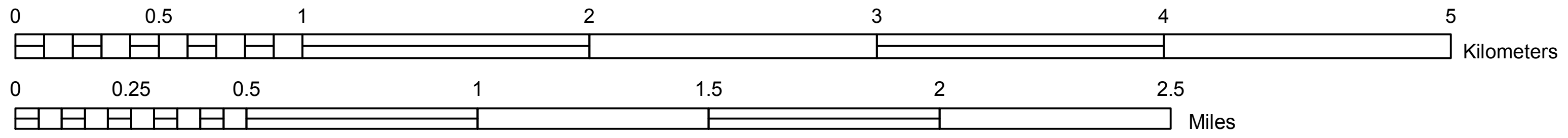
Revised Date: April 12, 2007

File: squamish_s_32

Integrated Land Management Bureau

SQUAMISH SOUTH

1:20,000



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Appendix C

Assessment of Coastal Flood Hazard

SNC·LAVALIN

District of Squamish Integrated Flood Hazard Management Plan

Client: **Kerr Wood Leidal**

Assessment of Coastal Flood Hazard

Contributors:	J. Wilson, S. Ang, EIT	
Reviewed by:	J. Readshaw, P. Eng	
Received by Client:	D. Roche, P. Eng	
	Name	**Signature**

PROFESSIONAL ENGINEER
PROVINCE OF BRITISH COLUMBIA
JOHN S. READSHAW
24/2/2015

Document No.	**618897- 3000 - 41EB - 0001**	Rev. No.	**0**

2015/02/12

REVISION INDEX

Issue Code	Revision					Revision Details
	No.	By	Rev'd.	App.	Date	
RI	0	multi	JSR	GV	12 Feb 2015	Issued for Information

Issue Codes: RC = Released for Construction, RD = Released for Design, RF = Released for Fabrication, RI = Released for Information, RP = Released for Purchase, RQ = Released for Quotation, RR = Released for Review and Comments

NOTICE

This document contains the expression of the professional opinion of SNC-Lavalin Inc. ("SLI") as to the matters set out herein, using its professional judgment and reasonable care. It is to be read in the context of the Agreement, and the methodology, procedures and techniques used, SLI's assumptions, and the circumstances and constrains under which its mandate was performed. This document is written solely for the purpose stated in the Agreement, and for the sole and exclusive benefit of the Client, whose remedies are limited to those set out in the Agreement. This document is meant to be read as a whole, and sections or parts thereof should thus not be read or relied upon out of context.

SLI has, in preparing any cost estimates, followed methodology and procedures, and exercised due care consistent with the intended level of accuracy, using its professional judgment and reasonable care, and is thus of the opinion that there is a high probability that actual costs will fall within the specified error margin. However, no warranty should be implied as to the accuracy of any estimates contained herein. Unless expressly stated otherwise, assumptions, data and information supplied by, or gathered from other sources (including the Client, other consultants, testing laboratories and equipment suppliers, etc.) upon which SLI's opinion as set out herein is based has not been verified by SLI; SLI makes no representation as to its accuracy and disclaims all liability with respect thereto.

SLI disclaims any liability to the Client and to third parties in respect of the publication, reference, quoting, or distribution of this report or any of its contents to and reliance thereon by any third party.

Contents

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1. SUMMARY

This document summarizes the assessment of the coastal flood related hazards undertaken for the IFHMP for the District of Squamish.

2. SCOPE

The scope of work for this assessment was defined in the proposal presented to the District of Squamish by Kerr Wood Leidal. In summary form, the scope of this assessment of the coastal flood hazard was:

- Update the definition of the wave climate around the perimeter of the coastal boundary of the District of Squamish that includes:
    - Latest hydrographic sounding information available from CHS for the Squamish River delta front
    - Recent LiDAR mapping data for the Squamish River estuary obtained by the District of Squamish
    - Anticipated re-grading and proposed inter-tidal and sub tidal modification of the SODC lands and adjacent waters.
    - Review and assessment of local wind effects in for inflow wind conditions in the north end of Howe Sound (Squamish Harbour)
    - Review and assessment of potential influence of rising sea levels on the existing vegetation in the Squamish estuary and the potential effect on the wave climate over this area
- Provide coastal water levels (tide and storm surge effects) expected to be concurrent with major river flooding events

The results of the Coastal Flood Model update will be used by the IFHMP team to develop integrated flood hazard mitigation options which are documented separately from this Design Brief document.

3. REFERENCE DOCUMENS

The following documents are used as primary reference documents for this assessment:

RD [1]: "**Guidelines for Management of Coastal Flood Hazard Land Use** – Climate Change Adaptation Guidelines for Sea Dikes and Coastal Flood Hazard Land Use", BC Ministry of Environment, 27 January 2011.

RD [2]: "**Sea Dike Guidelines** – Climate Change Adaptation Guidelines for Sea Dikes and Coastal Flood Hazard Land Use", BC Ministry of Environment, 27 January 2011.

RD [3]: Tide & Current Tables 2011 – "Canadian Tide and Current Tables – Volume 5 – Juan de Fuca Strait and Strait of Georgia", Canadian Hydrographic Services, Fisheries and Oceans Canada, 2014.

4. SITE SPECIFIC CRITERIA

4.1.1 Datum

The vertical datum used for this assignment is Canadian Geodetic Datum (CGVD28), unless noted otherwise. At Squamish, the 0 m (CGVD) contour varies between 3.08 m and 3.21 m above CHS chart datum (CD), depending on the relevant date of the required conversion.

The horizontal datum used for this assignment is UTM Zone 10.

4.1.2 Sea Level Rise

A mean sea level rise of 1.0 m was used to define the sea level rise expected due to the influence of climate change by or before 2100. As the available data for the Squamish area indicates there is no recorded local ground uplift or subsidence in the area, the mean sea level rise of 1.0 m was taken to be the local sea level rise.

Local subsidence or uplift rates may vary over the Squamish estuary area; however, no specific data is available to reliably further quantify this potential effect.

4.1.3 Tidal Water Levels

The tidal water levels are based on Canadian Hydrographic Services (CHS) data for Squamish, as published in Volume 5, Canadian Tide and Current Tables for Squamish, which is a Secondary Port station and for Point Atkinson, the designated Primary Port reference station. The predicted tidal levels are summarized in Table 4-1.

Table 4-1: Summary of Tidal Water Levels for Squamish

Tidal Level	Water Level (m, CD)		Water Level (m, CGVD28)
	Reference Port	Secondary Port	Squamish
	Point Atkinson	Squamish	
Higher High Water, Large Tide (HHWLT)	5.06	+0.09	+2.07
Higher High Water, Mean Tide (HHWMT)	4.39	+0.06	+1.37
Mean Water Level (MWL	3.08	+0.06	+0.06
Lower Low Water, Mean Tide (LLWMT)	1.16	0.00	-1.92
Lower Low Water, Large Tide (LLWLT)	-0.03	0.00	-3.11
Note: Conversion of tidal water levels (CD) to water levels relative to CGVD28 based on 3.08 m. Water Levels assumed constant across Squamish Estuary, including Mamquam Channel. No change in tidal water levels assumed with a sea level rise of 1.0 m.			

4.1.4 External Storm Surge

The expected magnitude of the external storm surge related water levels in the Strait of Georgia, at the entrance to Howe Sound, are provided in Section 3.2.5 of the “Sea Dike Guidelines“, issued by the Province of British Columbia. The recommended values are summarized below in Table 4-2.

Table 4-2: Expected Magnitude of External Storm Surge, Georgia Strait Above Predicted Tide (Reference: RD[2] "Sea Dike Guidelines")

AEP (per cent chance of being equalled or exceeded in any year)	**AEP** (1/average recurrence interval – expressed in years)	**Strait of Georgia Entrance to Howe Sound (m)**
50 %	Annual	0.73
20 %	1/5	0.83
10 %	1/10	0.9
4 %	1/25	1.0
2 %	1/50	1.1
1 %	1/100	1.2
0.2 %	1/500	1.3
0.1 %	1/1000	1.4

The external storm surge magnitudes, as defined at the entrance to Howe Sound in Table 4-2, can be expected to change as the external surge wave propagates up Howe Sound, both as a result of the bathymetry in the Sound, which may result in convergence of flows, especially towards the head of the Sound but also due to local wind setup as strong inflow winds at the north end of the Sound start to affect the surge processes as they approach the Squamish Estuary. The local wind effects especially will vary over the estuary due to the influence of the extensive shallow water. The effects of inter-tidal and submerged vegetation, especially as sea level rises, will also influence the magnitude of the local effects.

4.1.5 Local Storm Surge Effects

For the purpose of this assessment, a preliminary estimate of the total local effects for storm surges within Howe Sound was developed by analysis of the recorded water level data from the external water level monitor at the 3rd Avenue tide gate located at the inner end of Cattermole Slough.

The raw tide gate data was available at approximately 4 minute intervals during the period January through May 2014. After adjustment of the calibration factor for the raw data, based on comparison with CHS predicted tide data for Point Atkinson, also available at 5 minute intervals, and validation against periods of time when total water levels were within 0.1 m of the predicted water levels, the resulting dataset suggests that during a storm on 11 January 2014, the residual water levels at the 3rd Avenue tide gate are approximately 0.2 to 0.35 m higher than the residual water levels at the Point Atkinson water level station.

The peak residual water level at Point Atkinson during the 11 January 2014 event was 0.55 m above CHS predicted tides. The direction (from) and wind speed at Pam Rocks during this event was approximately South 25 knots.

For the purpose of his assessment, a preliminary allowance of 0.35 m for local effects during a severe storm and related storm surge was adopted for the Squamish Estuary. This allowance is an interim allowance that should be further reviewed during the IFHMP process.

4.1.6 Currents

Measured current data within the Squamish area are not available for this assessment. For the purpose of this assessment no effect of current on sea state was considered.

4.1.7 Tsunami

A summary of potential tsunami effects at Squamish is described in SLI Document 618897-3000-41EN-0001 provided separately in the IFHMP main report.

Tsunami wave events and related effects are considered to be separate and independent events from a coastal storm event.

4.1.8 Landslide Generated Waves

A summary of potential landslide generated wave events from submarine slides on the delta front of the Squamish estuary described in SLI Document 618897-3000-41EN-0001 provided separately in the IFHMP main report.

Landslide generated wave events and related effects are considered to be separate and independent events from a coastal storm event.

5. COASTAL FLOOD HAZARD MODEL UPDATE

5.1 Wind Model

5.1.1 Definition of the Howe Sound Wind Environment

The calculation of the sea state (and associated wind set-up) at the Squamish estuary requires a reliable estimate of the overwater winds both within Howe Sound in general but especially within the upper (north) reaches of Howe Sound.

There are various references in the technical literature that suggest inflow winds tend to accelerate as they approach the estuary. J. Buckley (1977) stated that Southerly (from) winds in Howe Sound are expected to be stronger in the Squamish area than they are in the Southern end of the Sound. Richard Thomson (1981) stated that strong Southeasterly (from) winds are often “funneled into strong up-channel winds in Howe Sound”. Furthermore, he remarked that this phenomenon was most prominent at the head end of the Sound, near Squamish.

Twenty years of historical wind data within Howe Sound are available at the Environment Canada weather recording station at Pam Rocks:

• Station Name:	Howe Sound Pam Rocks
• Station ID:	10459NN
• Location:	49° 29’ 16.009” N, 123° 17’ 58.030” W
• Duration of Record:	11 Feb 1994 – present (including gaps and missing data)
• Years of available record:	20 years (4.6 % of data missing)

The Pam Rocks station data indicate that during observed inflow conditions winds over the period of record the winds in this area of Howe Sound are typically less than 45 knots with one observation of a 57 knot wind speed that appears to be a data spike.

Historical wind data is also available at several locations within the Squamish area at the following locations:

Table 5-1: Summary of Squamish Area wind data locations

Station Identifier	Station Name	Source	Location		Elevation (m)	Type of Data	Time Interval		
			Latitude (N)	Longitude (W)			Start	End	Total (yrs)
1047660	Squamish	EC	49.700000	123.133333	31.1	Daily	1965	1966	1
1047661	Squamish EPS	EC	49.700000	123.15	2.1	Hourly	1979/03/01	1983/12/14	4+
1047662	Squamish FMC Chemicals	EC	49.683333	123.166667	3	Hourly	1971/04/01	1976/05/31	5
10476F0	Squamish Airport	EC	49.783057	123.160835	53.7	Hourly	1982/05/17	Present	32
1047FF0	Squamish Airport	EC	49.781667	123.161944	52.1	Hourly	2010/01/26	2010/04/02	<1
AIS	Squamish Terminal	Squamish Terminals		S warehouse	Roof top	Hourly	2009/11/18	2014/05/27	4+

Notes:
AIS: weather data received from anemometer operated by Squamish Terminal and broadcast over VHF AIS system.

Preliminary assessment of the local area stations, and in particular, of the Squamish FMC Chemicals station, indicated that wind speeds of up to 50 knots, during inflow (southerly) conditions, were measured on a relatively frequent basis during the 5 year period of record. No concurrent data was available for Pam Rocks, Squamish Airport or at Point Atkinson, to assess the basis of these relatively high wind speeds.

Over the 32 years of record from Squamish Airport and over the 4+ years of record from the Squamish EPS station, there are occasional records of inflow (southerly winds) between 50 and 70 knots.

Preliminary assessment of the AIS data set obtained during this study from Squamish Terminals, which does overlap the period of record at Pam Rocks, and which can be considered to be representative of overwater winds, indicated that winds at the Terminal, especially during inflow (southerly) conditions are consistent (± 5 knots, occasionally 10 knots lower) with Pam Rocks. However, it should be noted that data is missing in the AIS file during many strong storms - as defined at Pam Rocks.

It is recommended that acquisition of additional representative wind data on the waterfront of Squamish should be undertaken by the District, prior to more detailed design stages of the IFHMP process.

For the purpose of this assessment, the recorded wind speeds at Pam Rocks are considered to be representative.

5.1.2 Designated Storm Assessment

For the purpose of this assessment for the IFHMP, a target probability of approximately 1/4000 was adopted for the Annual Exceedance Probability (AEP) of the total water level of combined tide and storm surge. In the absence of a full quantitative risk analysis, this level of AEP for the combination of tide and storm related water levels is consistent with the recommendations in the Provincial Government guideline documents for a community such as Squamish. A detailed quantitative risk analysis, specific to the District of Squamish, might result in a different choice for the target AEP for the combination of tide and storm related effects.

As tides and storms (including the characteristics of winds, surge and waves during the storm) are totally independent events, the AEP for the total water level can be decoupled, based on standard statistical procedures, for example, Devore (1995), as follows:

P(tide and storm surge) = P(storm surge) x P(of a storm occurring at high tide).

The probability of a winter storm occurring at the same time as a high (spring tide) tide has been estimated to be approximately 1/20 during the typical winter storm interval (approximately mid-October to mid-January). As the processes driving tidal water levels and the processes driving severe storms are independent, the selected target AEP of 1/4000 for total water levels leads to the definition of a Designated Storm with an annual exceedance probability of 1/200 for definition of the storm related contributions to the water levels around the coastal perimeter of the District of Squamish, as per the guidelines in the Provincial Guideline documents.

The external storm surge expected during a Designated Storm with an AEP of 1/200 can be determined from Table 4-2 in Section 4.1.4.

A preliminary analysis of the site exposure around the coastal perimeter of the Squamish Estuary, undertaken for this assignment, determined that wave conditions around the waterfront areas will be largely defined by the strength of the winds in the northern reaches of Howe Sound, and particularly in Squamish Harbour, and by the relatively short fetch extending in a general NE direction from Watts Point. Some wave action will also be diffracted around Watts Point and will be augmented by the wind stress across the relatively short fetch to the Squamish Estuary. In this situation, the most important element defining the wave climate in the Estuary will be the peak wind speed, over the duration of approximately one hour that should be expected during the Designated Storm.

For the purpose of this assessment, a peak over threshold analysis of the wind record from Pam Rocks was undertaken. The analysis was confined to winds at Pam Rocks from the southern sector only and a screening requirement that more than 72 hours was required between events was imposed to assist in ensuring that individual events were independent. Events that lasted only 1 hour were also eliminated as short duration events that might not be capable of generating appropriate sea states.

The resulting inflow wind events from the Pam Rocks record are summarized in Table 5-2. Although the data record from Pam Rocks is relatively short (20 years), reasonable estimates of low probability events can be made provided that reliable statistical methods are employed that reflect the uncertainties related to a sample drawn from a 20 year record. An assessment of methods for defining the sample, including selecting one or more events per year, all events over various thresholds or sufficient events so that at least one storm per season was included in the sample, showed that the results were relatively insensitive to sampling method. The available record length is also too short to determine if any trends are present in the dataset.

The statistics of the samples showed that the underlying parent distribution of the wind events was consistently most likely a Type 1 Extreme Value Distribution, also known as the Gumbel distribution, a Fischer Tippett Type 1 distribution or the General Extreme Value (GEV) distribution with a shape parameter of zero (0). Parameters of the distribution fitted to the samples from the Pam Rocks dataset were estimated with Maximum Likelihood methods.

Table 5-2: Summary of Inflow Events at Squamish

Rank	Date				Peak Wind Speed
	yyyy	mm	dd	hr PST	knots
16	1994	2	12	18	37.7
35	1994	3	21	2	34.0
32	1994	12	19	10	35.0
17	1995	3	9	18	37.7
2	1995	11	17	21	44.7
36	1996	2	5	8	34.0
12	1996	4	23	18	38.8
37	1996	11	30	18	34.0
8	1997	1	1	6	43.1
4	1997	3	30	19	44.2
38	1997	10	9	22	34.0
28	1998	11	15	23	36.1
5	1998	11	24	2	44.2
3	1999	1	28	23	44.7
20	1999	2	5	17	37.2
13	2000	2	22	9	38.8
29	2001	11	15	2	36.1
9	2001	11	20	1	42.0
21	2001	12	16	15	37.2
30	2002	11	16	16	36.1
31	2002	12	12	11	36.1
33	2002	12	15	20	35.0
39	2002	12	25	20	34.0
11	2003	1	2	8	39.9
40	2003	3	13	9	34.0
18	2003	12	5	22	37.7
34	2006	1	1	18	35.0
6	2006	11	15	12	44.2
22	2006	12	11	14	37.2
23	2006	12	21	0	37.2
24	2007	1	9	11	37.2
10	2007	11	11	23	41.0
25	2007	12	3	13	37.2
26	2008	1	4	20	37.2
7	2009	11	9	7	44.2
1	2010	1	18	5	46.9
19	2011	2	12	17	37.7
27	2011	11	22	3	37.2
14	2012	3	12	10	38.8
15	2012	11	17	10	38.8

The results of the extreme value analysis are summarized in Table 5-3.

Table 5-3: Extreme Value Analysis of Inflow Wind Speeds for Squamish Harbour

Annual Exceedance Probability (1/yr)	Peak Wind Speed (knots) 10 m ASL	Standard Error of Estimate (knots)
Expected Annual	41	± 0.8
1/5	43	± 1.2
1/10	45	± 1.5
1/25	48	± 2.0
1/100	52	± 2.6
1/200	54	± 3.0
1/500	56	± 3.4
Based on Pam Rocks recorded wind data. Direction from 215° T at the estuary, based on observations		

5.2 Wave Model

5.2.1 Introduction

The wave climate during the Designated Storm (AEP = 1/200) was determined using a nested series of SWAN based wave generation and propagation models for Howe Sound and the Squamish area estuary. SWAN (Simulating WAves Nearshore) is a third-generation numerical wave model, developed jointly by Delft University of Technology, Netherlands and the Office of Naval Research, USA, that computes the generation and propagation of random, short-crested wind-generated waves in coastal regions and inland waters. In order to realistically reproduce wave conditions resulting from historical storms at any location in the coastal waters of British Columbia, a numerical tool for the spatial interpolation of Environment Canada wind observations, independently developed by SNC-Lavalin was used. The resulting computed spatial or time-varying wind field is provided as input to the SWAN model.

The nested model layout is shown in Figure 5-1 and the model was run with a stationary wind field based on the winds estimated from Pam Rock over the southern half of the model and with repeater wind stations in the reaches north of Anvil Island that echoed the wind speed at Pam Rocks but constrained the wind direction to follow the main axis of the channels between Anvil Island and Watts Point and to a direction from 215° T across Squamish Harbour.

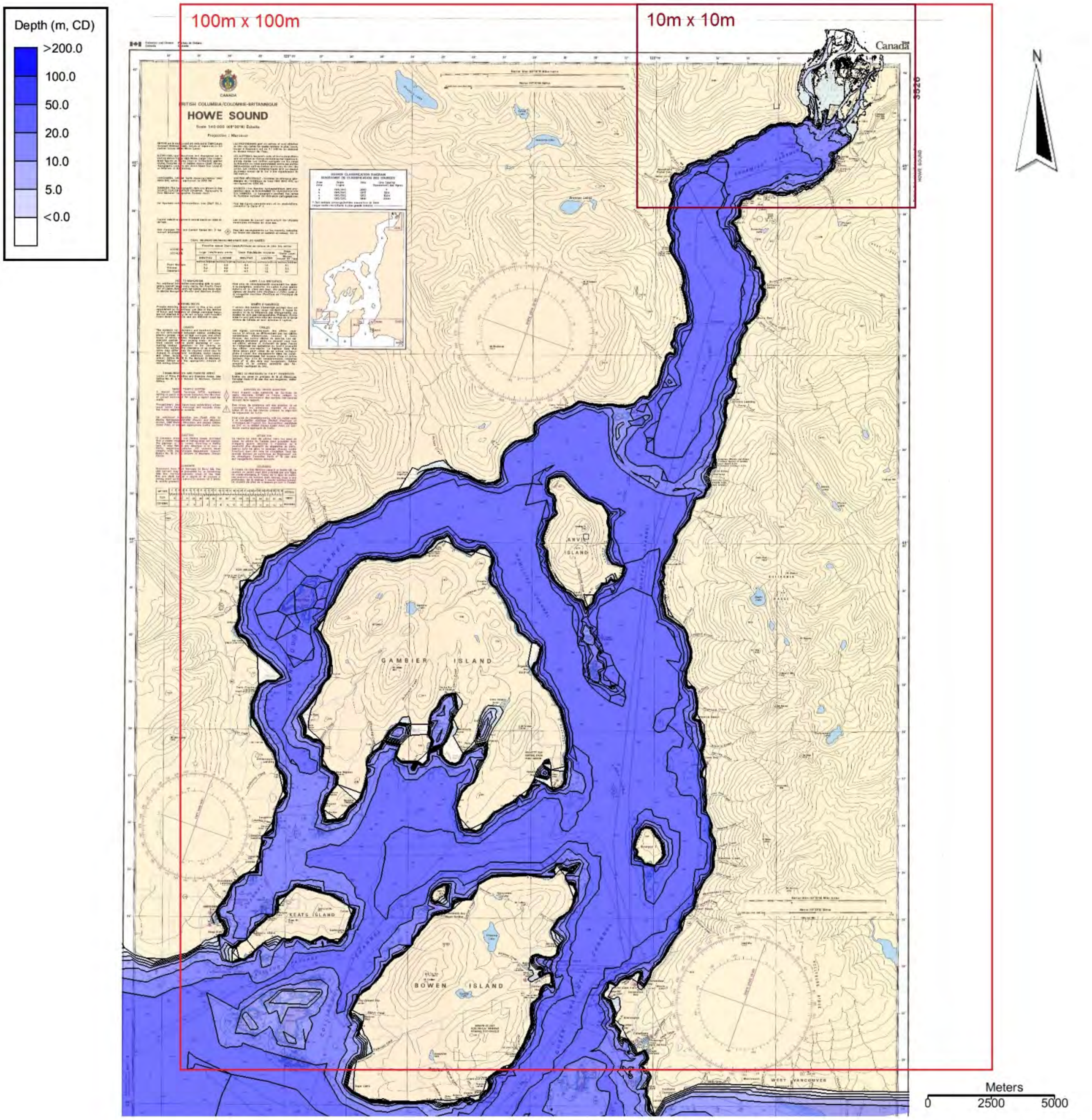


Figure 5-1: SWAN Grid

5.2.2 Bathymetery

The bathymetry for the coarse resolution Howe Sound model grid is based on a blend of the CHS digital coastal 500 m x 500 m model for coastal British Columbia and digitized chart based contours close to the shorelines of Howe Sound and the various islands in the sound. The bathymetry for the fine grid model is based on a blend of the following data sources:

- CHS digital coastal 500 m x 500 m model for coastal British Columbia
- digitized chart based contours close to the shorelines
- latest CHS Field Sheet data for the Squamish Estuary delta front and low tide areas of the waterbodies (Squamish River, Squmish Terminals and Cresent Slough, Cattermole Slough and Manquam Blind Channel) and the low tide regions on the Squamish Estuary inter-tidal areas.
- LiDAR data, obtained by the District of Squamish in 2009 for the mid to upper tidal and supra-tidal regions of the estuary.
- Gridded design elevations for the proposed SODC modifications were also used for the wave model used to estimate the wave climate corresponding to a 1 m rise in sea level.
- The existing LiDAR based elevations of the Squamish River West Training dike and the fill embankment at Squamish Terminals were also retained for the wave model used to estimate the wave climate corresponding to a 1 m rise in sea level.

All data was corrected to the same datum as noted in Section 4.1.1. The resulting bathymetry model was field checked based on the LiDAR ground elevation at several locations around Squamish Terminals and determined to be accurate within 0.05 m.

A compiled view of the bathymetry ensemble over the Squamish Estuary is shown in Figure 5-2.

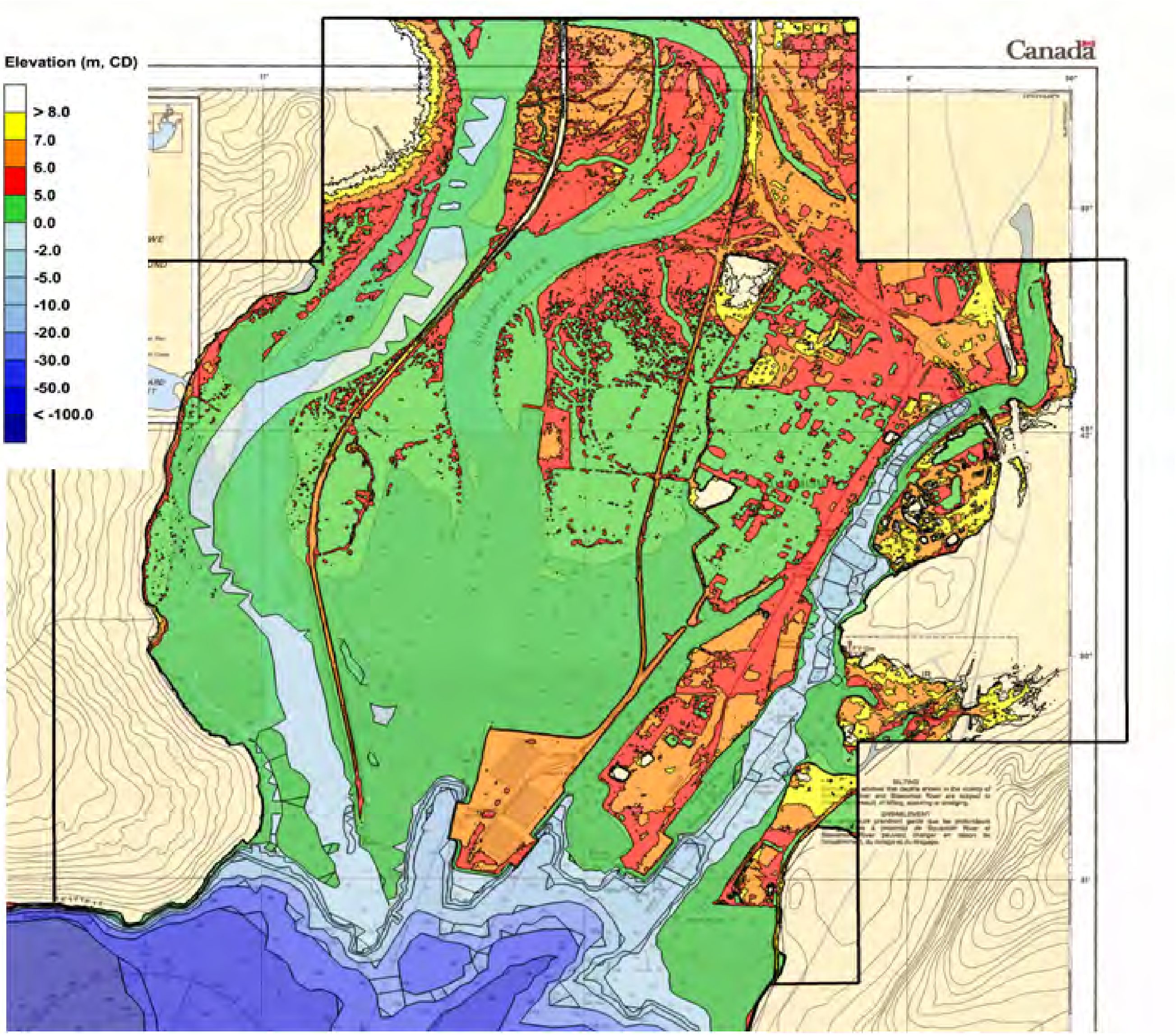


Figure 5-2: Ensemble Bathymetry for the Squamish Estuary Nested Model Area
(modifications for future SODC lands not shown)

5.2.3 Model Setup Parameters

The SWAN model contains a number of modules to account for various wind energy input and wave dissipation processes during the propagation of the wave climate into the shoreline boundaries of the model. This analysis was undertaken with the following selection options and settings:

- Version: 40.91AB
- Bottom Friction: JONSWAP model : 0.067 (sensitivity showed insignificant effect)
- Wave Setup Off: (wave setup was assessed on a reach by reach basis outside of SWAN)
- Wave Breaking: Rate of Dissipation model: 0.73 (sensitivity showed insignificant effect)

- White capping: Koman model: Dissipation 0.00236 Steepness 0.00302
- Triad wave-wave iteration: Off
- Quadruplets: Default
- Directional Resolution: 50 (7.3 degrees)
- Diffraction: Off (sensitivity analysis indicated only minor effects if on)
- Reflection: Off

The following water level components were used based on the background materials summarized above, to define the total water levels expected during the Designated Storm.

Table 5-4: Summary of Water Levels during Designated Coastal Flood (AEP = 1/200)

Component	**Present-Day (2014) Water Level No Storm**	**Present-Day (2014) Water Levels during 1/200 AEP Storm**	**1 m SLR (estimated 2100) during 1/200 AEP Storm**
HHWLT (Squamish - CGVD 1928)	2.07 m	2.07 m	2.07 m
Allowance for Sea Level Rise	0.0 m	0.0 m	1.0 m
External Storm Surge (1/200 AEP)	-	1.25 m	1.25 m
Local Effects on Storm Surge[a]	-	*0.35 m*	*0.35 m*
Designated Flood Level (CGVD28) (Not Including Wave Effects)	**2.07 m**	**3.67 m**	**4.67 m**
Designated Flood Level (CD) (For comparison with Figure 5-2) (Not Including Wave Effects)	5.17 m	6.77 m	7.77 m

Notes:

[a]: interim value recommended pending resolution of the local effects in Howe Sound and the spatial variation across the Squamish Estuary

Detailed review of the DFLs in Table 5-4 and the ensemble bathymetry (Figure 5-2) for the Estuary indicates that depending on the sea level rise scenario, various components of the existing waterfront of Squamish may play important roles in dissipating wave energy during the Designated Storm. For instance:

- The south end of the Squamish River West Training dike will likely be submerged during the Designated Storm, if it were to occur today.
- The dike will definitely be submerged after a 1 m SLR unless the dike was raised.

- The embankment fill at Squamish Terminal may be awash during the Designated Storm, if it were to occur today.
- The fill will definitely be submerged after a 1 m SLR unless the fill was raised or diked.
- The railway embankment, including the portion that parallels 3rd Avenue, will likely be submerged during the Designated Storm, if it were to occur today.
- The railway embankment will be submerged after a 1 m SLR unless the embankment was raised.
- The existing elevations of the SODC lands are also presently below the DFL during the Designated Storm. As these lands are expected to be raised as part of the proposed SODC project, it was assumed they would provide a corresponding degree of protection to the eastern portions of the Squamish Estuary.
- It is also clear that as sea level rises, large areas of the central portions of the estuary, including areas that are presently heavily wooded, in the northern portions of the central area, west of the existing railway embankment, will be exposed to more frequent inundation during ordinary high tides in the future. Frequent inundation will likely lead to a significant change in vegetation and in the resulting energy dissipation caused by the vegetation.

For the purpose of all wave model runs for a 1 m SLR, it was assumed that the present elevations of the Squamish River West Training dike, including the existing vertical timber pile supported wall at the end of the spit, and the Squamish Terminal embankment fill, were maintained at their present elevations. It was also assumed that the wooded areas in the central portion of the estuary would be extensively modified by natural processes and therefore would be unlikely to provide the potential wave energy dissipation that a wooded area might provide.

For the purpose of the IFHMP process, the wave model results were defined only on the west side of the railway embankment, as wave energy dissipation over a submerged structure can only be approximately estimated in the SWAN model. As the wave model results are already affected by the submergence of the south end of the Squamish River West Training dike, it was felt this was a necessary constraint on the area of validity for the model results.

More detailed assessment of the effects of these outer structures and of the wooded areas should be incorporated into the next update of the IFHMP.

5.3 Results

5.3.1 Existing Water Levels

The coastal model results, if the Designated Storm were to occur in 2014, are shown in Figure 5-3.

The sharp gradient in sea state (H_s) in the vicinity of the Squamish River West Training dike can be seen. It should be noted that wave breaking on the existing dike is modelled; however, overtopping and continuing propagation of the overtopping wave energy in the lee of the dike are not included. Expected diffraction effects around the dike and the existing vertical piled wall are approximated as are the diffraction effects around the Squamish Terminals embankment fill.

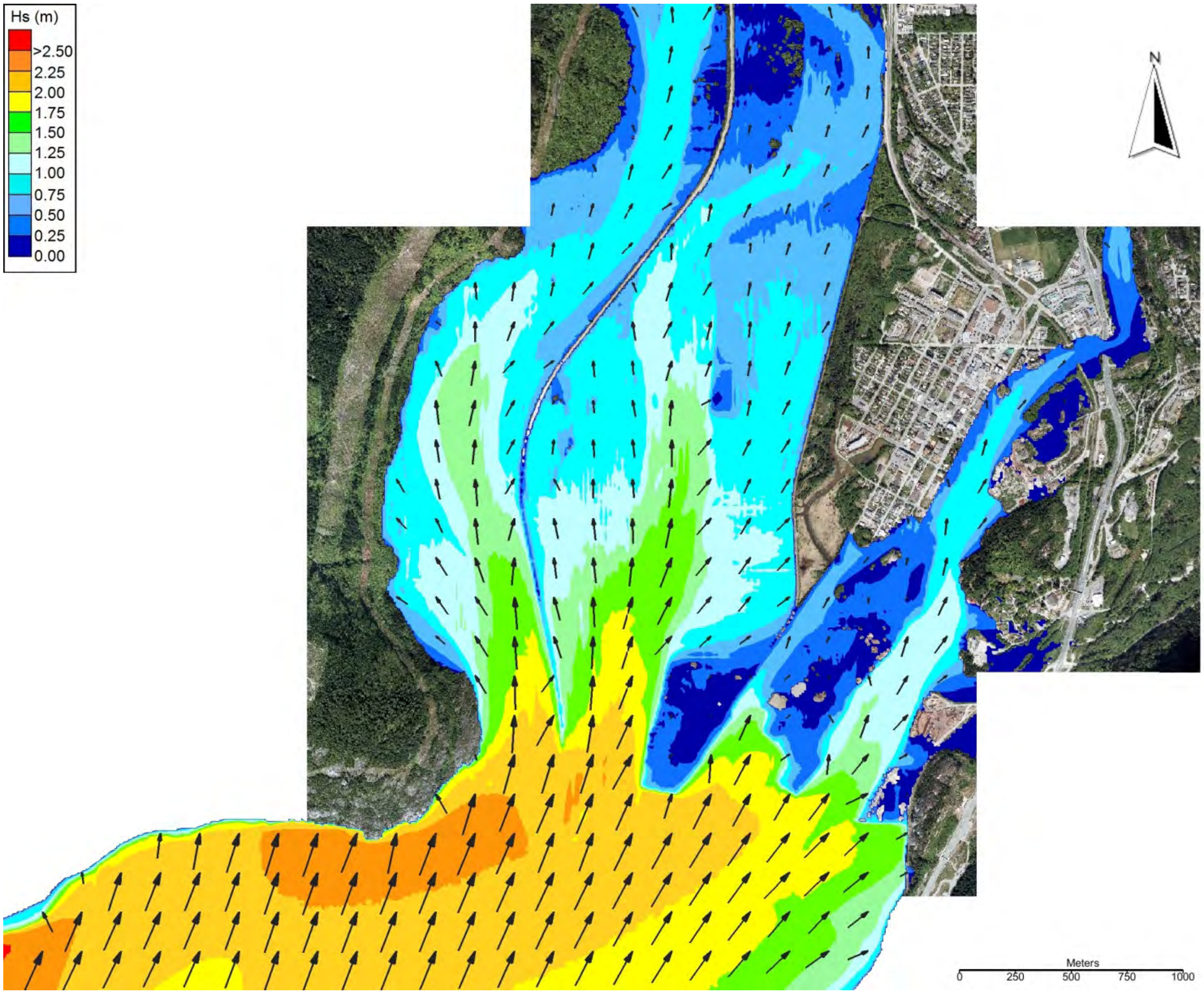


Figure 5-3: Seastate During Designated Storm in 2014 (0 m SLR)

5.3.2 One Metre Sea Level Rise

The coastal model results if the Designated Storm were to occur after a 1 m rise in sea level, are shown in Figure 5-4.

The effect of the Squamish River West Training dike can still be seen. It should be noted that wave breaking on the existing but now submerged dike is modelled; however, overtopping and continuing propagation of the overtopping wave energy in the lee of the dike are not included. Expected diffraction effects around the dike and the existing vertical piled wall are approximated as are the diffraction effects around the Squamish Terminals embankment fill. However, in this scenario it is likely that the results in the lee of Squamish Terminals are only approximate along the southernmost 500 m of the existing railway embankment.

It should also be noted that no geomorphologic changes to the estuary have been estimated due to ongoing effects while sea level rises. These changes might include sedimentation or erosion in the central portion of the estuary, changes at the delta front of the Squamish River, or changes in the Cattermole or Mamquam Blind Channel, other than the proposed changes for the SODC lands.

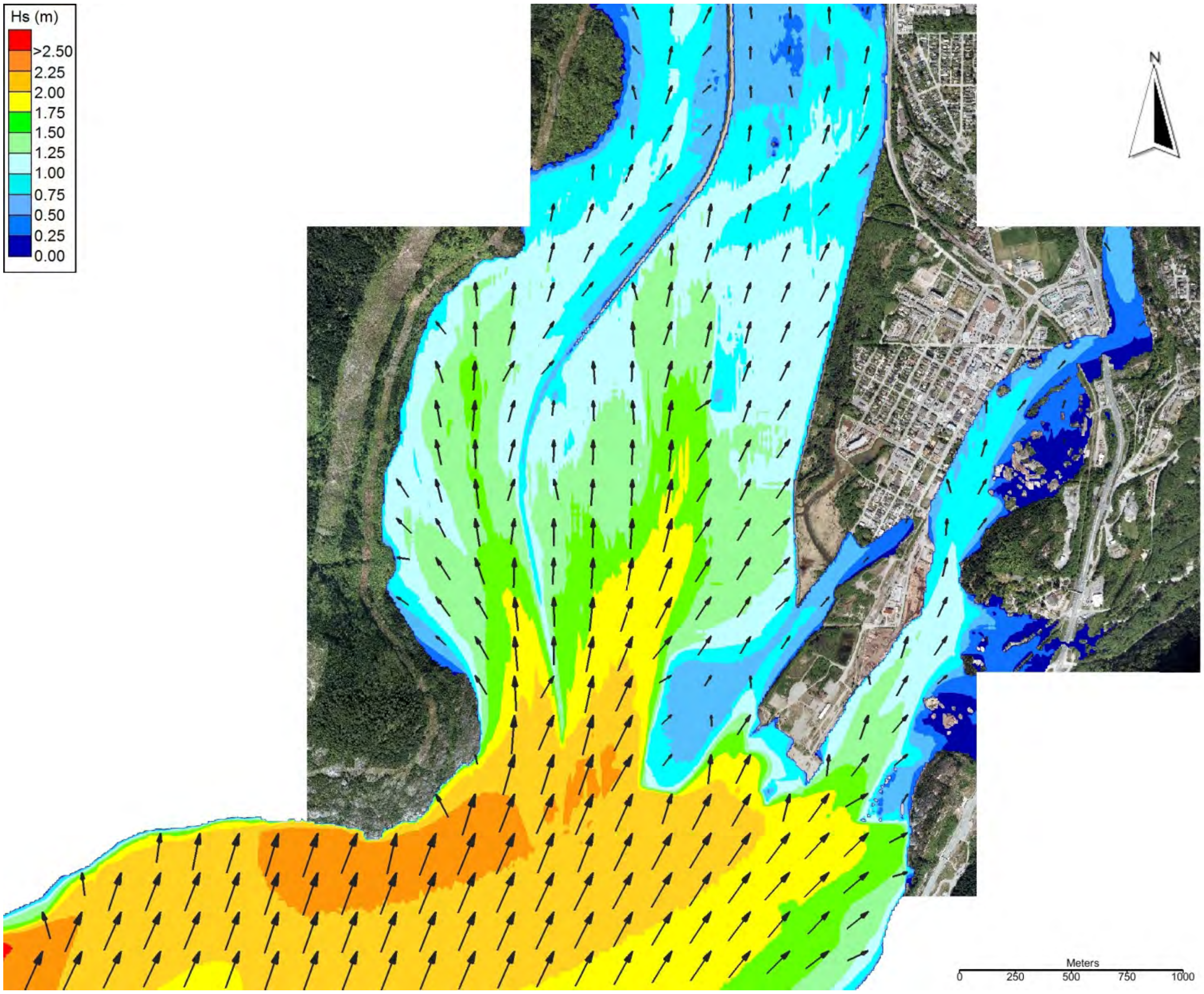


Figure 5-4: Seastate During Designated Storm after 1 m of SLR (estimated 2100)

5.3.3 Site Specific Summary Results

Site specific, more detailed, sea state results for specific locations indicated in Figure 5-5 are provided below in Table 5-5.

Examination of the ratio of the depth of water at each site, for each sea level rise scenario, indicates that the sea states around the coastal perimeter are not limited in height by the depth of water. This result implies that the decisions made throughout this assessment regarding; the wind climate in Squamish Harbour, compared to Pam Rocks, the shelter provided by the Squamish River West Training Dike and the embankment fill at Squamish Terminals, are more important to the sea state around the coastal perimeter of Squamish than is the total depth of water at the same locations.

The presence and condition of the submerged vegetation within the estuary will also be important. The present results assume that vegetation throughout the estuary is mainly inter-tidal marine vegetation.

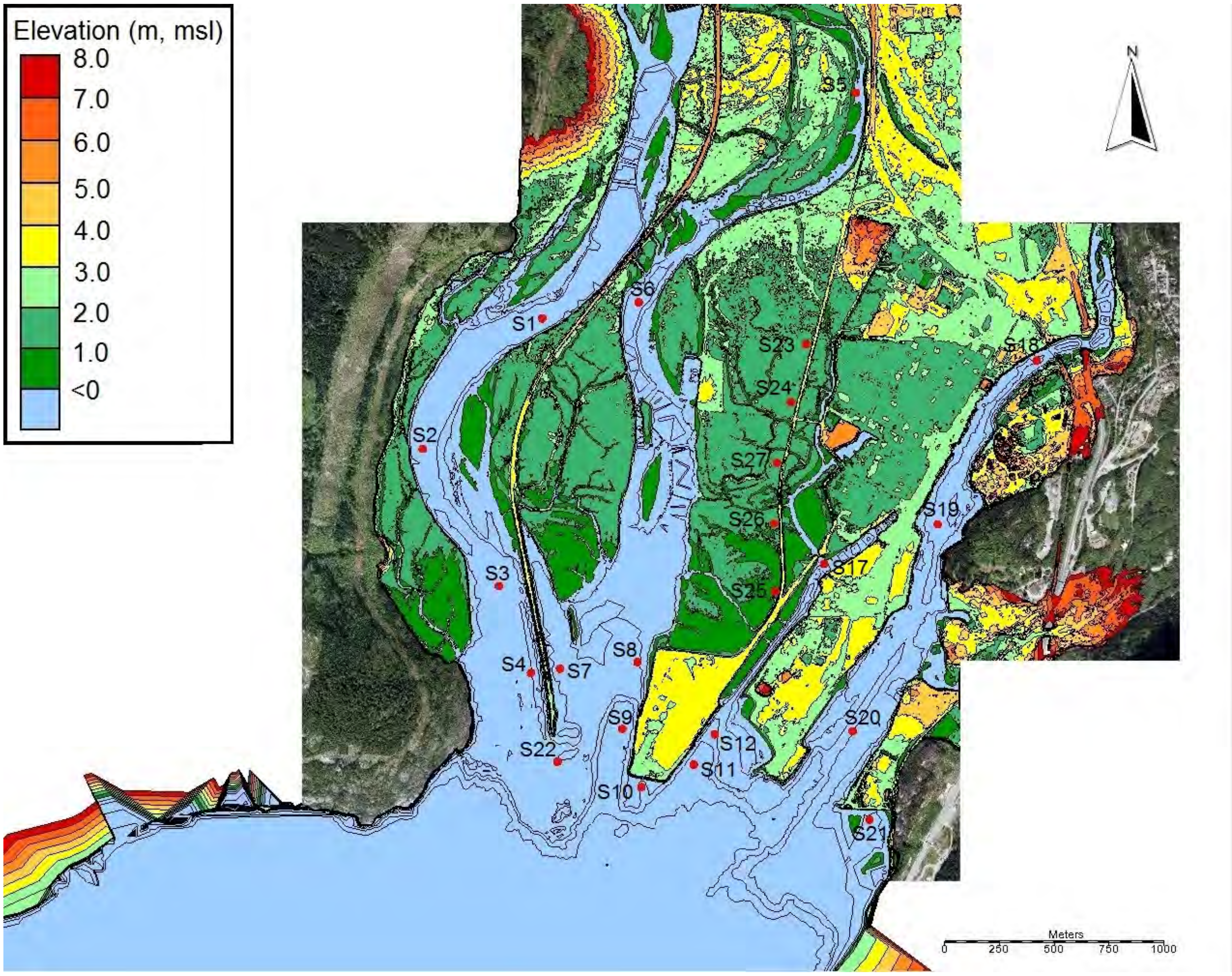


Figure 5-5: Locations of Site Specific Sea State Results

Table 5-5: Summary of Site Specific Sea State Parameters during Designated Storm

Water Level	Present Day (2014)				1 m SLR (2100)			
Observational Point	**Depth (m)**	**H_s (m)**	**T_p (s)**	**Dir (^{o}T)**	**Depth (m)**	**H_s (m)**	**T_p (s)**	**Dir (^{o}T)**
S1	7.8	0.8	2.9	217	8.8	1.0	3.3	211
S2	7.9	1.1	3.3	169	8.9	1.2	3.3	165
S3	7.2	1.7	4.3	172	8.2	1.8	4.3	171
S4	8.6	1.9	4.3	191	9.6	2.0	4.8	189
S5	3.8	0.7	2.6	195	4.8	1.0	3.3	202
S6	5.5	1.2	3.3	183	6.5	1.4	3.8	184
S7	6.6	1.4	4.3	174	7.6	1.7	4.3	187
S8	6.0	1.7	4.8	210	7.0	1.9	4.8	212
S9	18.5	2	4.8	209	19.5	2.1	4.8	210
S10	9.2	2.1	4.3	204	10.2	2.2	4.3	204
S11	18.6	1.9	4.3	199	19.6	1.9	4.3	199
S12	9.6	1.7	4.3	197	10.6	1.7	4.3	198
S17	5.1	0.6	2.3	209	6.1	0.6	2.6	213
S18	9.3	0.6	2.6	221	10.3	0.6	2.6	220
S19	9.8	0.9	3.3	195	10.8	1.0	3.3	194
S20	8.9	1.3	3.8	214	9.9	1.4	3.8	212
S21	5.0	1.6	4.8	228	6.0	1.7	4.8	228
S22	6.2	2.2	4.8	203	7.2	2.2	4.8	203
S23	2.1	0.8	3.3	212	3.1	1.1	3.8	216
S24	2.1	0.8	3.3	213	3.1	1.1	3.8	216
S25	2.9	0.8	2.6	236	3.9	1.0	4.8	229
S26	2.3	1	3.3	220	3.3	1.3	4.3	219
S27	2.1	0.8	3.3	212	3.1	1.2	3.8	215

Note:

1: These sea state estimates do not include the effect of local wave set-up, which should be considered if the sea states are translated further into shallower waters.

2: These estimates are only representative of the sea state at the indicated location. Reference should be made to Figure 5-3 or Figure 5-4 for information on the likely variation with position in the immediate area.

6. JOINT COASTAL FLOODING AND STREAMFLOW ASSESSMENT

6.1 Background

Assessment of the flooding hazard due to river discharge in the study area requires the specification of a coastal boundary condition, which reflects the joint probability of high river flows and concurrent expected external and local storm surge effects. For the purpose of this assessment, the relationship between the external storm surges observed at Point Atkinson and the peak flows combined flows from the Squamish and Mamquam Rivers was examined to determine the likely storm surge that should be expected when the two rivers were at peak flow.

While it is theoretically possible that a maximum river flow could occur at the same time as the Designated Storm it was considered this would be a conservative combination of probabilities. It was however considered possible and likely that a maximum river flow could occur at the same time as a high spring tide.

6.2 Relationship Between Peak Combined River Flow and Storm Surge

For the purpose of this assessment the magnitude and time of maximum observed river flows was provided by KWL. The relationship between the combined maximum flows and the concurrent external surge at Point Atkinson during the overlapping period of record is shown in Figure 6-1 for the three main seasons of the year when high combined river flows are generally experienced at Squamish.

The results suggest that during summer and fall seasons there is very little related storm surge, which is consistent with the meteorological processes resulting in formation of external storm surge in the North Pacific basin.

Figure 6-1 also indicates that the concurrent external storm surge is also relatively low and an upper bound concurrent storm surge of approximately 0.6 m is still less than the external storm surge expected during the average annual storm, as defined in Table 4-2.

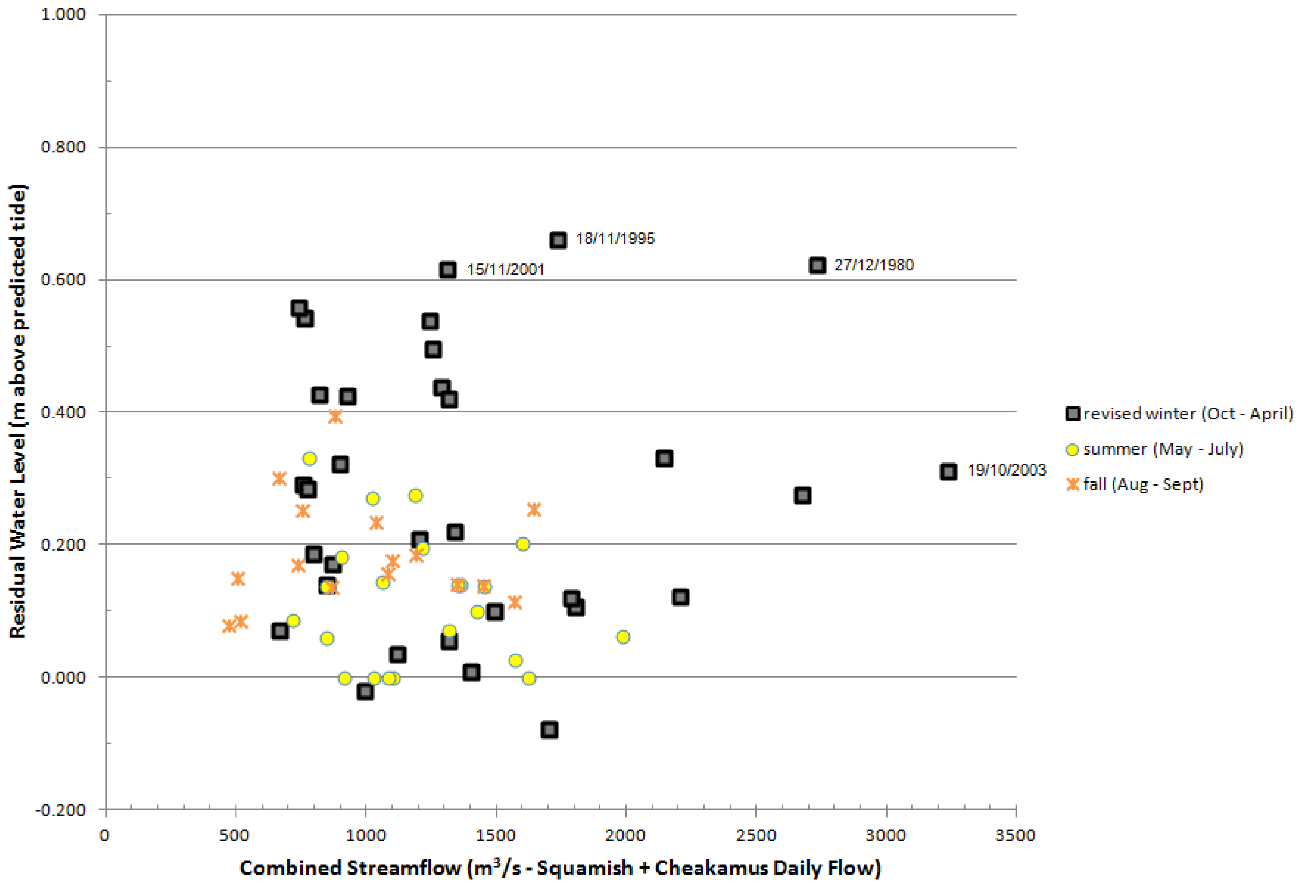


Figure 6-1: External Storm Surge and Concurrent Combined Streamflow

For the purpose of this assessment it is recommended that an additional 0.3 to 0.35 m should be added to account for the expected local effects of the influence of Howe Sound, including wind forcing and flow convergence up the Sound.

6.3 Times Series of Concurrent Storm Surges

The time series for the storm surges expected to be concurrent with either a 1/200 AEP flood, or during a 1/200 AEP storm, were estimated based on a review of the actual time series of recorded external storm surges during the 4 events identified in Figure 6-1 or during the largest storm surge recorded at Point Atkinson. These events indicated that the duration of an external storm surge (as defined by the departure of the residual water level above predicted tide in the Strait of Georgia) varied significantly. In one case, for the events identified in Figure 6-1, the external surge lasted approximately 36 hours, while the longest event lasted 7 days; however, during the 7 day period, there were three peak surge events.

During the largest storm surge recorded at Point Atkinson on 27 January 1983, the external storm surge built up slowly over a 6 day period, peaked during the 7th day and then slowly decayed over an additional 5 days.

For this phase of the IFHMP, two time series, as indicated in Figure 2, were developed to describe the ocean boundary condition at the mouth of the Squamish River during a flood with an AEP of 1/200 and for a flood that peaked during a coastal storm with an AEP of 1/200.

The time series shown in Figure 2 should be combined with the corresponding predicted tide for the event under consideration.

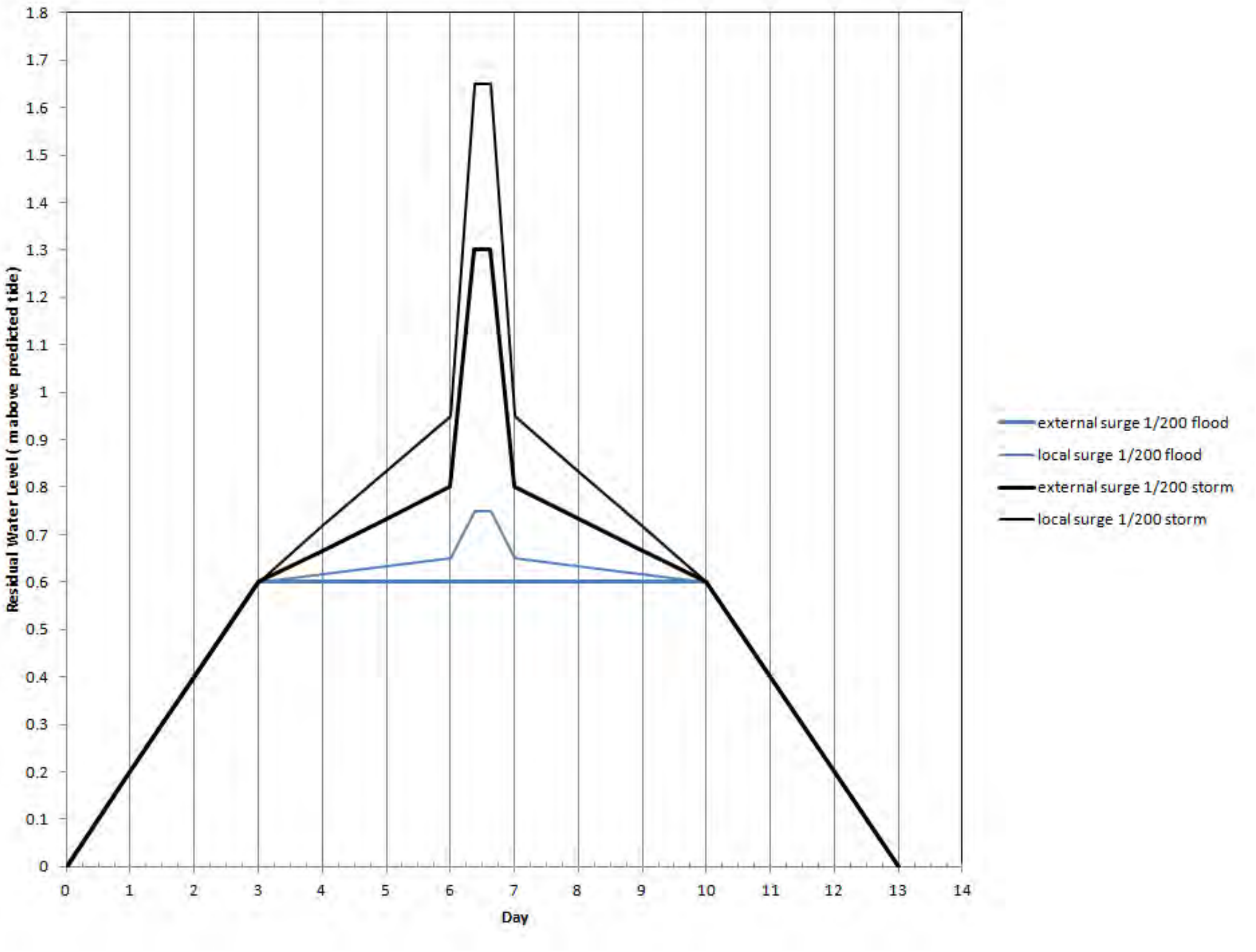


Figure 2: Synthetic Time Series for 1/200 AEP Surges

7. SUMMARY / CONCLUSIONS

7.1 Water Levels and Seastate During the Designated Storm

The results of this assessment have found that the sea state around the coastal perimeter of the District of Squamish during the Designated Storm, which has an annual exceedance probability (AEP) of 1/200, is very sensitive to assumptions made regarding the future condition of the Squamish River West Training dike and the embankment at Squamish Terminals. For the purpose of this IFHMP it is assumed that:

- The structures will remain in place in the future and will be maintained at present elevations without regard to future sea level rise
- Any storm related damage that might occur in the future, in any storm event, will be repaired so that the structures provide at least the same degree of sheltering as they do at present
- The existing railway embankment leading to Squamish Terminals defines the present limit of reliability of the results of this assessment.

These assumptions should be reviewed at all stages of implementation of the IFHMP.

It should also be noted that the predicted magnitude of the sea state during the Designated Storm is very dependent on the relationship defined in this study for inflow wind conditions between winds at Pam Rocks and winds in Squamish Harbour and at the entrance to the Squamish Estuary. For the purpose of this assessment it has been assumed that the winds are the same as recorded at Pam Rocks and are constant over the duration of the storm peak. This relationship should be further investigated during all stages of implementation of the IFHMP.

While sensitivity studies of the potential effects of wave diffraction or wave propagation around or over the offshore structures identified above were undertaken and suggest that wave diffraction effects around the structures or the regeneration of waves in the lee of the structures when they are awash are relatively minor, the SWAN model is not the most suitable model for definition and assessment of these effects. Detailed modelling of the potential effects of these structures and of the implications to their long-term influences should be undertaken.

7.2 Concurrent Streamflow and Metocean Conditions

The assessment of the concurrent values of streamflow and metocean conditions defined in this study is based on a relatively small number of events during the winter season. Further investigation of the mutual relationships both during severe ocean storms and during severe river flow events should continue to be undertaken.

8. REFERENCES

1] Buckley, J. R. (1977). *The Currents, Winds, and Tides of Northern Howe Sound*. PhD thesis submitted to the Department of Physics and Institute of Oceanography, University of British Columbia.

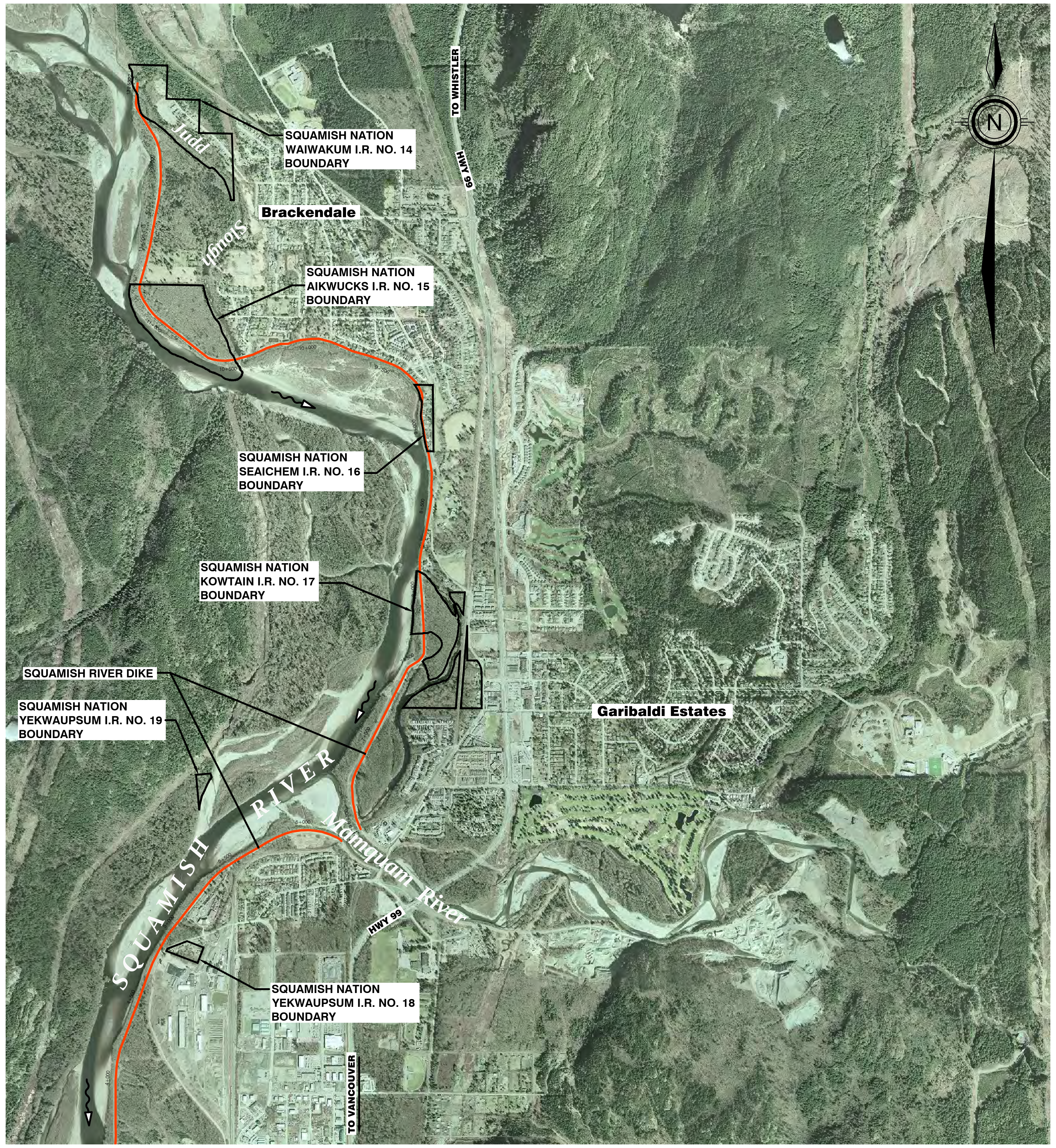
2] Thomson, R. E. (1981). *Oceanography of the British Columbia Coast*. Ottawa: Dept. of Fisheries and Oceans.

3] Devore, J.L. (1995). *Probability and Statistics for Engineering and the Sciences.* International Thomson Publishing, Inc.

Appendix D

Updated Squamish River Dike Profile Drawings

Paper Size = ANSI D
At Full Size, this border measures 520 mm x 800 mm



ORTHOPHOTO SOURCE: GEOBC, APRIL 6, 2009

SITE PLAN

Scale: 1:20,000

DISTRICT OF SQUAMISH
INTEGRATED FLOOD HAZARD MGMT PLAN
SQUAMISH RIVER DIKE CREST
& WATER SURFACE PROFILES

LOCATION PLAN

N.T.S.

PRELIMINARY
DO NOT USE FOR DESIGN

LEGEND

DESIGN FLOOD PROFILES

— —	MODELLED YEAR 2100 Q1000 FLOOD EL. + 0.6 m FREEBOARD
▬	MODELLED YEAR 2100 Q1000 FLOOD ELEVATION
— —	MODELLED YEAR 2100 Q200 FLOOD EL. + 0.6 m FREEBOARD
▬	MODELLED YEAR 2100 Q200 FLOOD ELEVATION

DIKE CREST PROFILES

BEST DATA	OTHER DATA	SOURCE
▬	—	2013 LIDAR
▬	N/A	2013 SURVEY
■ ■ ■ ■	N/A	2012 SURVEY
▬ ▪ ▬	N/A	2010 SURVEY
▬ ▪ ▪ ▬	N/A	2009 SURVEY
■ ■ ■ ■	N/A	2008 SURVEY
■ ▬ ■	– · · — · · –	2003 SURVEY
▬	—	2006 AERIAL
▮▮▮▮▮▮▮▮	- - - - - - - -	2005 AERIAL

"BEST DATA" REFERS TO THE MOST RECENT AND RELIABLE DIKE CREST ELEVATION PROFILE FOR ANY GIVEN PORTION OF THE SQUAMISH RIVER DIKE CREST. THE "BEST DATA" SYMBOL IS USED TO HIGHLIGHT A SOURCE WHEN IT IS THE GOVERNING DIKE CREST ELEVATION PROFILE.

DRAWING LIST

DRAWING No.	TITLE
G1	SITE PLAN, LOCATION PLAN AND DRAWING LIST
G2	KEY PLAN
SW1	JUDD SLOUGH (STA. 11+000 TO 12+500)
SW2	BRACKENDALE (STA. 9+500 TO 11+000)
SW3	EAGLE RUN (STA. 8+000 TO 9+500)
SW4	HARRIS SLOUGH (STA. 6+500 TO 8+000)
SW5	MAMQUAM CONFLUENCE (STA. 4+800 TO 6+300)
SW6	NORTH YARDS (STA. 3+300 TO 4+800)

KERR WOOD LEIDAL
consulting engineers

Seal:

Rev	Date	Des	Dwn	Chk	Description of Revision	Rev	Date	Des	Dwn	Chk	Description of Revision
0	2012-01-23	EE	SC	DR	DRAFT FOR DISCUSSION						
1	2012-05-03	DR	SC	DR	UPDATED PROFILE & LABELING						
2	2014-06-13	SC	SC	DR	UPDATED W.S. PROFILES & LABELING FOR IFHMP						
3	2014-06-18	SC	SC	DR	UPDATED W.S. PROFILES FOR IFHMP						
4	2015-02-25	ABS	PAC		ADDED 2013 LIDAR + Q1000						

DISTRICT OF SQUAMISH
INTEGRATED FLOOD HAZARD MGMT PLAN
DIKE CREST & WATER SURFACE PROFILES
YEAR 2100 Q200 & Q1000
SITE PLAN, LOCATION PLAN & DRAWING LIST

Project No. 463-278
Group GENERAL
Drawing No. G1
Rev. 4

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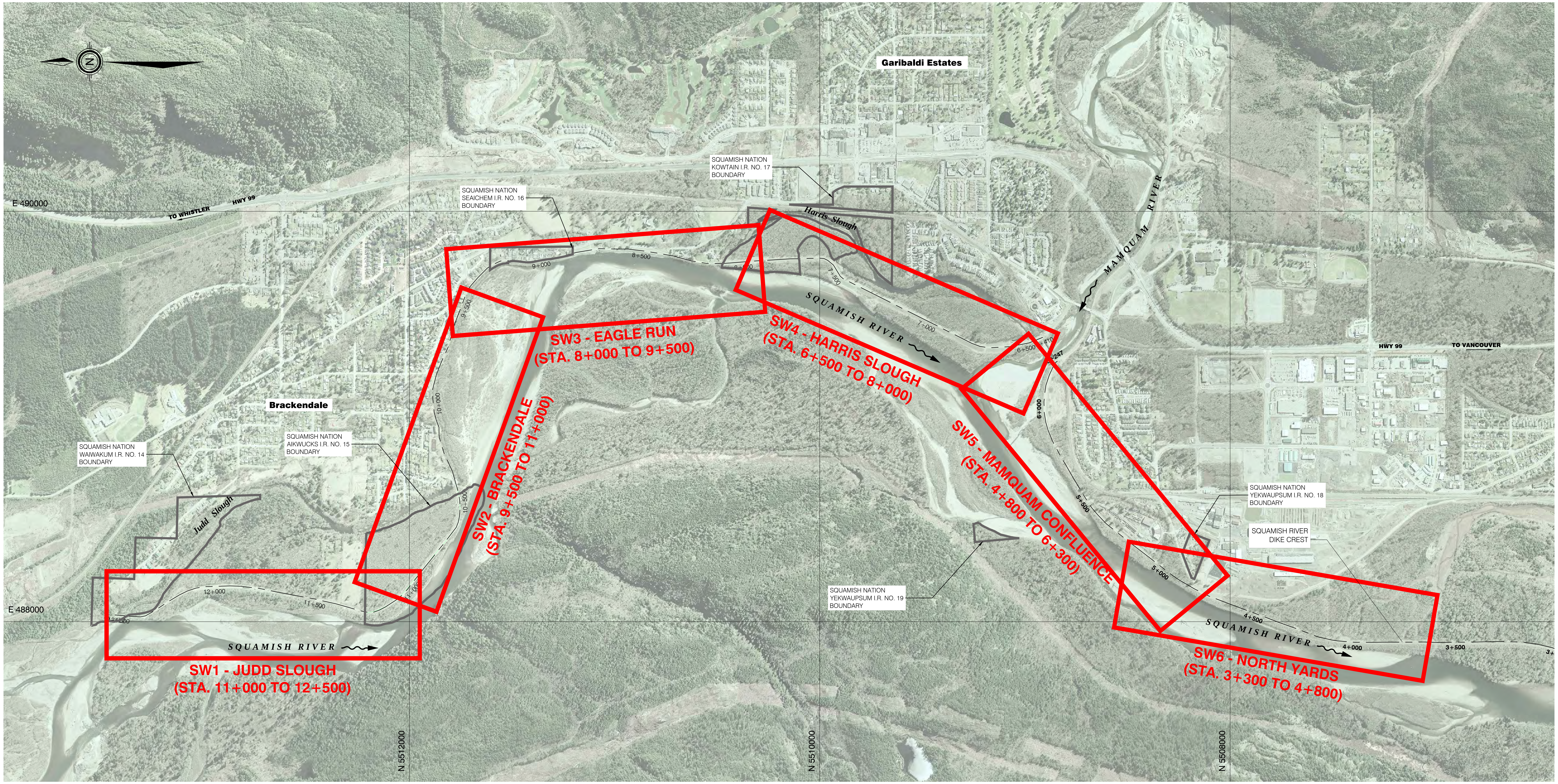

ORTHOPHOTO SOURCE: GEOBC, APRIL 6, 2009

KEY PLAN

SCALE 1:10,000

PRELIMINARY
DO NOT USE FOR DESIGN

KERR WOOD LEIDAL
consulting engineers

Seal:

Rev	Date	Des	Dwn	Chk	Description of Revision
0	2012-01-23	EE	SC	DR	DRAFT FOR DISCUSSION
1	2012-05-03	DR	SC	DR	UPDATED PROFILE & LABELING
2	2014-06-13	SC	SC	DR	UPDATED W.S. PROFILES & LABELING FOR IFHMP
3	2014-06-18	SC	SC	DR	UPDATED W.S. PROFILES FOR IFHMP
4	2015-02-25	ABS	PAC		ADDED 2013 LIDAR + Q1000

Rev	Date	Des	Dwn	Chk	Description of Revision

DISTRICT OF SQUAMISH
INTEGRATED FLOOD HAZARD MGMT PLAN

DIKE CREST & WATER SURFACE PROFILES
YEAR 2100 Q200 & Q1000
KEY PLAN

Project No. 463-278
Group GENERAL
Drawing No. G2
Rev. 4

ORTHOPHOTO SOURCE: GEOBC, APRIL 6, 2009

PLAN

Scale: 1:2000

PROFILE

Scale: H 1:2000, V 1:50

REFERENCE FLOWS AND INSTANTANEOUS PEAK DISCHARGE ESTIMATES FOR SQUAMISH, CHEAKAMUS, AND MAMQUAM RIVERS					
RIVER	WSC STATION	WSC STATION NAME	APRIL 6, 2009 AVERAGE FLOW	YEAR 2100 Q200	YEAR 2100 Q1000
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MAMQUAM	08GA075	MAMQUAM RIVER ABOVE RING CREEK	7.07 m³/s	1000 m³/s (AT MOUTH)	1,390 m³/s (AT MOUTH)

Year 2100 200-yr and 1,000-yr return Period Discharges from District of Squamish Integrated Flood Hazard Management Plan (KWL, 2014)
Flows from April 6, 2009 are daily average flows from WSC records and are representative of conditions shown in the orthophotos

PRELIMINARY
DO NOT USE FOR DESIGN

LEGEND	
🟩	EXISTING DIKE CREST ABOVE YEAR 2100 Q200+0.6m
🟨	EXISTING DIKE CREST WITHIN YEAR 2100 Q200 0.6m FREEBOARD
🟥	EXISTING DIKE CREST BELOW YEAR 2100 Q200

NOTES:
1.KWL CHAINAGE ESTABLISHED FOR PROJECT 463.134 BASED ON MWLAP DIKE INVENTORY
2. MODELED DESIGN FLOOD ELEVATION FROM DISTRICT OF SQUAMISH INTEGRATED FLOOD HAZARD MANAGEMENT PLAN (KWL, 2015)

KERR WOOD LEIDAL
consulting engineers

Seal:

Rev	Date	Des	Dwn	Chk	Description of Revision	Rev	Date	Des	Dwn	Chk	Description of Revision
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3	2014-06-18	SC	SC	DR	UPDATED W.S. PROFILES FOR IFHMP						
4	2015-02-25	ABS	PAC		ADDED 2013 LIDAR + Q1000						

DISTRICT OF SQUAMISH
INTEGRATED FLOOD HAZARD MGMT PLAN

DIKE CREST & WATER SURFACE PROFILES
YEAR 2100 Q200 & Q1000
JUDD SLOUGH STA. 11+000 TO 12+500

Project No. 463-278
Group SITE WORKS
Drawing No. SW1
Rev. 4

ORTHOPHOTO SOURCE: GEOBC, APRIL 6, 2009

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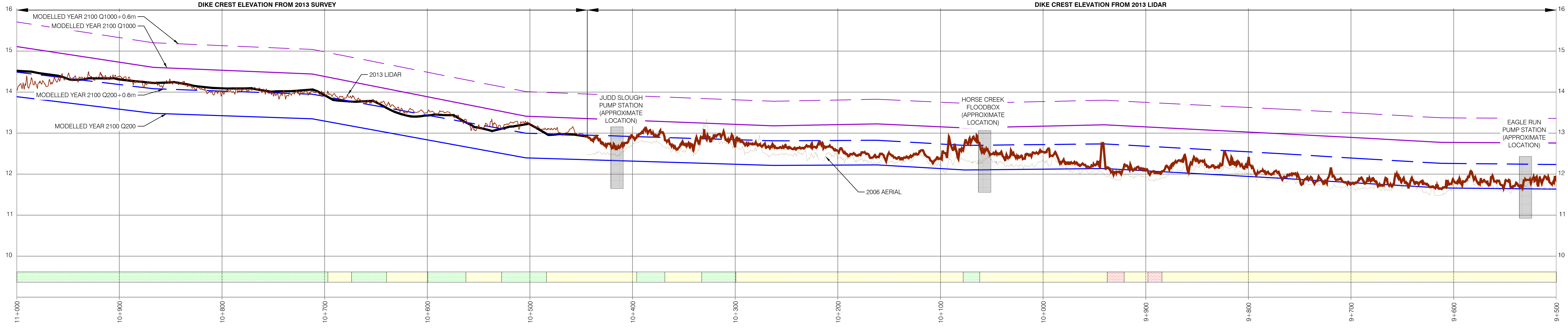

PROFILE
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PRELIMINARY
DO NOT USE FOR DESIGN

REFERENCE FLOWS AND INSTANTANEOUS PEAK DISCHARGE ESTIMATES FOR SQUAMISH, CHEAKAMUS, AND MAMQUAM RIVERS					
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LEGEND	
🟩	EXISTING DIKE CREST ABOVE YEAR 2100 Q200+0.6m
🟨	EXISTING DIKE CREST WITHIN YEAR 2100 Q200 0.6m FREEBOARD
🟥	EXISTING DIKE CREST BELOW YEAR 2100 Q200

NOTES:
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KERR WOOD LEIDAL
consulting engineers

Seal:

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3	2014-06-18	SC	SC	DR	UPDATED W.S. PROFILES FOR IFHMP
4	2015-02-25	ABS	PAC		ADDED 2013 LIDAR + Q1000

DISTRICT OF SQUAMISH
INTEGRATED FLOOD HAZARD MGMT PLAN

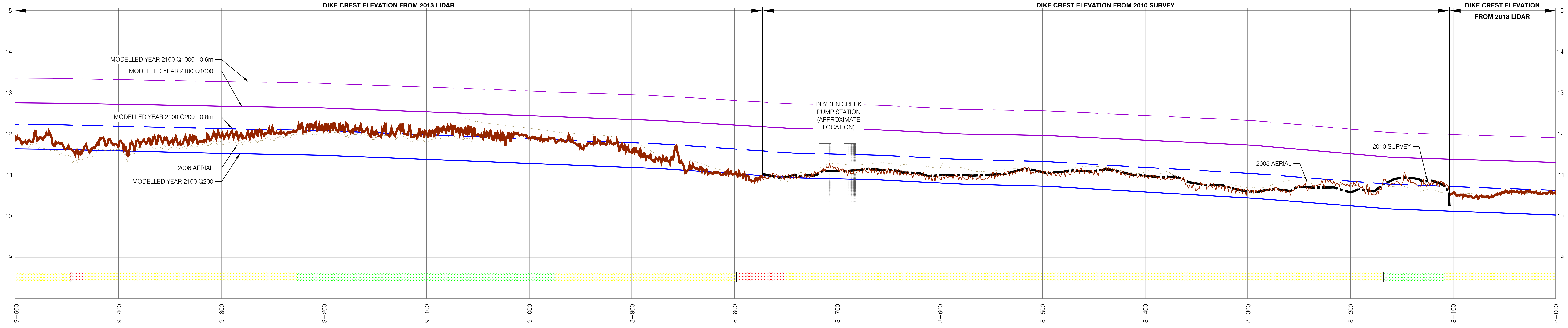
DIKE CREST & WATER SURFACE PROFILES
YEAR 2100 Q200 & Q1000
BRACKENDALE STA. 9+500 TO 11+000

Project No. 463-278
Group SITE WORKS
Drawing No. SW2
Rev. 4

ORTHOPHOTO SOURCE: GEOBC, APRIL 6, 2009

PLAN

Scale: 1:2000



PROFILE

Scale: H 1:2000, V 1:50

PRELIMINARY
DO NOT USE FOR DESIGN

REFERENCE FLOWS AND INSTANTANEOUS PEAK DISCHARGE ESTIMATES FOR SQUAMISH, CHEAKAMUS, AND MAMQUAM RIVERS					
RIVER	WSC STATION	WSC STATION NAME	APRIL 6, 2009 AVERAGE FLOW	YEAR 2100 Q200	YEAR 2100 Q1000
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Year 2100 200-yr and 1,000-yr return Period Discharges from District of Squamish Integrated Flood Hazard Management Plan (KWL, 2014)
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LEGEND	
🟩	EXISTING DIKE CREST ABOVE YEAR 2100 Q200+0.6m
🟨	EXISTING DIKE CREST WITHIN YEAR 2100 Q200 0.6m FREEBOARD
🟥	EXISTING DIKE CREST BELOW YEAR 2100 Q200

NOTES:
1.KWL CHAINAGE ESTABLISHED FOR PROJECT 463.134 BASED ON MWLAP DIKE INVENTORY
2. MODELED DESIGN FLOOD ELEVATION FROM DISTRICT OF SQUAMISH INTEGRATED FLOOD HAZARD MANAGEMENT PLAN (KWL, 2015)

KERR WOOD LEIDAL
consulting engineers

Seal:

Rev	Date	Des	Dwn	Chk	Description of Revision
0	2012-01-23	EE	SC	DR	DRAFT FOR DISCUSSION
1	2012-05-03	DR	SC	DR	UPDATED PROFILE & LABELING
2	2014-06-13	SC	SC	DR	UPDATED W.S. PROFILES & LABELING FOR IFHMP
3	2014-06-18	SC	SC	DR	UPDATED W.S. PROFILES FOR IFHMP
4	2015-02-25	ABS	PAC		ADDED 2013 LIDAR + Q1000

Rev	Date	Des	Dwn	Chk	Description of Revision

DISTRICT OF SQUAMISH
INTEGRATED FLOOD HAZARD MGMT PLAN

DIKE CREST & WATER SURFACE PROFILES
YEAR 2100 Q200 & Q1000
EAGLE RUN STA. 8+000 TO 9+500

Project No. 463-278
Group SITE WORKS
Drawing No. SW3
Rev. 4

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ORTHOPHOTO SOURCE: GEOBC, APRIL 6, 2009

PLAN

Scale: 1:2000

PROFILE

Scale: H 1:2000, V 1:50

REFERENCE FLOWS AND INSTANTANEOUS PEAK DISCHARGE ESTIMATES FOR SQUAMISH, CHEAKAMUS, AND MAMQUAM RIVERS					
RIVER	WSC STATION	WSC STATION NAME	APRIL 6, 2009 AVERAGE FLOW	YEAR 2100 Q200	YEAR 2100 Q1000
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Year 2100 200-yr and 1,000-yr return Period Discharges from District of Squamish Integrated Flood Hazard Management Plan (KWL, 2014)
Flows from April 6, 2009 are daily average flows from WSC records and are representative of conditions shown in the orthophotos

PRELIMINARY
DO NOT USE FOR DESIGN

LEGEND	
🟩	EXISTING DIKE CREST ABOVE YEAR 2100 Q200+0.6m
🟨	EXISTING DIKE CREST WITHIN YEAR 2100 Q200 0.6m FREEBOARD
🟥	EXISTING DIKE CREST BELOW YEAR 2100 Q200

NOTES:
1.KWL CHAINAGE ESTABLISHED FOR PROJECT 463.134 BASED ON MWLAP DIKE INVENTORY
2. MODELED DESIGN FLOOD ELEVATION FROM DISTRICT OF SQUAMISH INTEGRATED FLOOD HAZARD MANAGEMENT PLAN (KWL, 2015)

KERR WOOD LEIDAL
consulting engineers

Seal:

Rev	Date	Des	Dwn	Chk	Description of Revision
0	2012-01-23	EE	SC	DR	DRAFT FOR DISCUSSION
1	2012-05-03	DR	SC	DR	UPDATED PROFILE & LABELING
2	2014-06-13	SC	SC	DR	UPDATED W.S. PROFILES & LABELING FOR IFHMP
3	2014-06-18	SC	SC	DR	UPDATED W.S. PROFILES FOR IFHMP
4	2015-02-25	ABS	PAC		ADDED 2013 LIDAR + Q1000

DISTRICT OF SQUAMISH
INTEGRATED FLOOD HAZARD MGMT PLAN

DIKE CREST & WATER SURFACE PROFILES
YEAR 2100 Q200 & Q1000
HARRIS SLOUGH STA. 6+500 TO 8+000

Project No. 463-278
Group SITE WORKS
Drawing No. SW4
Rev. 4

ORTHOPHOTO SOURCE: GEOBC, APRIL 6, 2009

PLAN

Scale: 1:2000

PROFILE

Scale: H 1:2000, V 1:50

NOTES:
1.KWL CHAINAGE ESTABLISHED FOR PROJECT 463.134 BASED ON MWLAP DIKE INVENTORY
2. MODELED DESIGN FLOOD ELEVATION FROM DISTRICT OF SQUAMISH INTEGRATED FLOOD HAZARD MANAGEMENT PLAN (KWL, 2015)

REFERENCE FLOWS AND INSTANTANEOUS PEAK DISCHARGE ESTIMATES FOR SQUAMISH, CHEAKAMUS, AND MAMQUAM RIVERS					
RIVER	WSC STATION	WSC STATION NAME	APRIL 6, 2009 AVERAGE FLOW	YEAR 2100 Q200	YEAR 2100 Q1000
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Flows from April 6, 2009 are daily average flows from WSC records and are representative of conditions shown in the orthophotos

PRELIMINARY
DO NOT USE FOR DESIGN

LEGEND	
🟩	EXISTING DIKE CREST ABOVE YEAR 2100 Q200+0.6m
🟨	EXISTING DIKE CREST WITHIN YEAR 2100 Q200 0.6m FREEBOARD
🟥	EXISTING DIKE CREST BELOW YEAR 2100 Q200

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consulting engineers

Seal:

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2	2014-06-13	SC	SC	DR	UPDATED W.S. PROFILES & LABELING FOR IFHMP
3	2014-06-18	SC	SC	DR	UPDATED W.S. PROFILES FOR IFHMP
4	2015-02-25	ABS	PAC		ADDED 2013 LIDAR + Q1000

Rev	Date	Des	Dwn	Chk	Description of Revision

DISTRICT OF SQUAMISH
INTEGRATED FLOOD HAZARD MGMT PLAN
DIKE CREST & WATER SURFACE PROFILES
YEAR 2100 Q200 & Q1000
MAMQUAM CONFLUENCE STA. 4+800 TO 6+300

Project No. 463-278
Group SITE WORKS
Drawing No. SW5
Rev. 4

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ORTHOPHOTO SOURCE: GEOBC, APRIL 6, 2009

PLAN

Scale: 1:2000

PROFILE

Scale: H 1:2000, V 1:50

REFERENCE FLOWS AND INSTANTANEOUS PEAK DISCHARGE ESTIMATES FOR SQUAMISH, CHEAKAMUS, AND MAMQUAM RIVERS					
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Flows from April 6, 2009 are daily average flows from WSC records and are representative of conditions shown in the orthophotos

PRELIMINARY
DO NOT USE FOR DESIGN

LEGEND	
🟩	EXISTING DIKE CREST ABOVE YEAR 2100 Q200+0.6m
🟨	EXISTING DIKE CREST WITHIN YEAR 2100 Q200 0.6m FREEBOARD
🟥	EXISTING DIKE CREST BELOW YEAR 2100 Q200

NOTES:
1.KWL CHAINAGE ESTABLISHED FOR PROJECT 463.134 BASED ON MWLAP DIKE INVENTORY
2. MODELED DESIGN FLOOD ELEVATION FROM DISTRICT OF SQUAMISH INTEGRATED FLOOD HAZARD MANAGEMENT PLAN (KWL, 2015)

KERR WOOD LEIDAL
consulting engineers

Seal:

Rev	Date	Des	Dwn	Chk	Description of Revision	Rev	Date	Des	Dwn	Chk	Description of Revision
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3	2014-06-18	SC	SC	DR	UPDATED W.S. PROFILES FOR IFHMP						
4	2015-02-25	ABS	PAC	DR	ADDED 2013 LIDAR + Q1000						

DISTRICT OF SQUAMISH
INTEGRATED FLOOD HAZARD MGMT PLAN

DIKE CREST & WATER SURFACE PROFILES
YEAR 2100 Q200 & Q1000
NORTH YARDS STA. 3+300 TO 4+800

Project No. **463-278**
Group **SITE WORKS**
Drawing No. **SW6**
Rev. **5**

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Appendix E

Assessment of Landslide-Related Flooding Hazards

O. Hungr Geotechnical Research Inc.
4195 Almondel Rd., West Vancouver, B.C., V7V 3L6, CANADA, Tel.: (604)926-9129 E-mail: ohungr@eos.ubc.ca

April 24, 2014

Thurber Engineering,
Suite 900 - 1281 West Georgia Street
Vancouver, BC V6E 3J7

Attention, Mr. David Hill, P.Eng.

A Preliminary Overview Assessment of Landslide-Related Flooding Hazards, Squamish, B.C.

Dear Sirs/Ladies:

Following a request by Mr. David Hill, we carried out a preliminary review of the potential for flooding related to landslide activity. The study area is the District of Squamish. The study is concerned only with possible flooding caused by damming or diversion of streams by major landslides or displacement waves in the ocean due to landslides. The scope of the study is very limited, due to its preliminary nature and it is expected that the issues discussed in this report will be studied further in greater detail in the future. Given the limited scope of the assignment, the range of hazards identified in this report may not be complete.

1. Work Completed

A literature review of landslide hazards in the region surrounding Howe Sound and its main tributaries was completed using references available to us as well as our project files and information provided by TEL and found using Web searches. The list of references selected as being relevant to the study is attached.

2. Hazard Scenarios

2.1 Landslides Along Rivers and Glacier Hazards

Most of Squamish is built on the floodplains of the Squamish, Cheakamus, Mamquam and Stawamus rivers and on the fans and delta of the same. All of these rivers drain mountainous terrain and major landslides could cause damming of the streams. Breach of the natural dams could cause flooding downstream. The potential peak discharge from such an event in this region is reduced by the fact that all of these rivers flow in glacier-eroded, U-shaped valleys with relatively wide bottom. For example, the 48 million m^3 Capricorn rock avalanche of 2010, one of the largest historic landslides in Canada, increased the discharge of the Lillooett River by only 200 m^3/s in Pemberton, 64 km downstream (Guthrie et al., 2013). The 1853 Rubble Creek rock avalanche on Cheakamus River had a volume of some 40 million m^3, but there is no evidence of catastrophic flooding at Squamish, 30 km downstream (Moore and Matthews, 1978) (although the historical record is not complete).

The Squamish River is approximately 80 km long and drains a mountainous and heavily glaciated watershed of 3,328 square kilometres. The closest point with history of large-scale landsliding is Mt. Cayley, a Quaternary volcano situated 47 km upstream of Squamish. Major rock avalanches occurred here in 1963 and 1985, but no significant flooding was registered downstream (Evans et al., 2001, Woods, 1986). The upper reaches of the Squamish and its tributaries have very steep slopes and numerous glaciers. There are signs of mountain slope deformations at Blanca Mountain and elsewhere. As mentioned above, a very major landslide would be required to produce significant flooding as far as Squamish and the probability of such an occurrence is considered low.

The Cheakamus River drains a steep glacier-cut valley between the Whistler divide and the Cheekye fan, with several glacier-deepened tributary hanging valleys. Three large lakes exist in this drainage: Garibaldi Lake, Cheakamus Lake and Daisy Lake. As mentioned above, the 1853 Barrier rock avalanche dammed the Cheakamus channel by relatively shallow landslide deposits and created Daisy Lake, which was more recently enlarged by the construction of a B.C. Hydro dam, founded on the landslide deposits. There is a possibility of a new landslide in the Rubble Creek valley (Garibaldi Advisory Panel, 1978). We believe that B.C. Hydro maintains a reduced water level behind Daisy Dam, in order to reduce the potential for a displacement wave and flood (although this is to be confirmed).

Displacement of water from either the Cheakamus or Garibaldi Lake as a result of a rockslide or a glacier failure from the surrounding slopes impacting the lake cannot be ruled out. But there is no record of past events or signs of potential instability in these locations.

The Mamquam River flows alongside the Opal Cone lava flow and there appears to be no significant probability of major landslide damming. Glacier meltwater outbursts from Mamquam Glacier or other glaciers in the drainages that flow towards Squamish are possible. But there is no record of such events in the past.

The Cheekye River has a history of producing large-scale debris flows, resulting from landslides in the steep headwaters eroded in volcanic rocks, overlying weathered basement metamorphics (Baumann, 1991a). The most significant positively-identified event occurred approximately 11,000 years B.P. and had a volume of 2.8 million m^3. Debris flows of various sizes from the Cheekye have periodically caused flooding on the Cheakamus River and damage to communities near the Cheakamus/Squamish confluence (Friele and Clague, 2005, KWL, 2008). A major potential debris flow on the Cheekye could endanger large parts of the Cheekye Fan (Thurber and Golder, 1995). However, such deposits would be relatively shallow and significant flooding on the lower Squamish River is not likely.

The Stawamus River drains a glacial valley north of the Sky Pilot-Stawamus Chief Massif. The valley contains steep intrusive rock slopes mantled by glacial and colluvial soils. The lower reaches of the valley slopes contain glacial drift and outwash (kame) terraces. The valley presents rock fall and debris avalanche hazards common to valleys of this type. According to Baumann (1994), the hazards have been aggravated by the poor state of logging roads in the drainage and by the possibility of landslides associated with the construction of a gas pipeline in glacio-fluvial deposits. We do not know whether these issues have been addressed subsequent to the 1994 Baumann report.

To our knowledge, no major potential slope stability issues have so far been identified along the Mashiter Creek. (We have not been able to review a report by Baumann, 1995).

In a summary, landslide-related flooding on rivers flowing into Squamish cannot be ruled out. However, apart from identified hazards on Cheekye Fan, at Rubble Creek and on Stawamus River, no specific imminent hazards can presently be pointed out.

2.2 Howe Sound – Waves Caused by Sub-aerial Landslides

Waves in fjords caused by the impact of landslides from steep, glacier-excavated slopes, have occurred in many locations around the world. Notable examples with fatal consequences were recorded in Norway (e.g. Bjerrum and Jorstad, 1968).

This subject was studied in detail in a high-quality Masters thesis at the Simon Fraser University by VanZeyl (2009), who made a detailed comparison of conditions in Howe Sound and in Knight Inlet. The latter locality has evidence of several large rock slides from steep bedrock slopes, including one that is believed to have raised a wave which destroyed the Kwalate native village with a loss of several tens of lives (Bornhold et al., 2007). A detailed review of slope morphology and lithology bordering Howe Sound and submarine deposits led VanZeyl (2009) to conclude that the potential for wave-producing rock slide here is considerably less than at Knight Inlet. The reasons for this conclusion include relative absence of steep slopes situated close to the shoreline and lack of evidence of landslide deposits on the bottom of the fjord.

A detailed review of slope hazards on the eastern slopes of Howe Sound was completed by Blais Stevens (2008) and Blais-Stevens and Septer (2008). There are periodic occurrences of debris flows and rock fall, at magnitudes that do not have the potential to raise substantial waves. The largest historical landslide is a fatal rockslide in Jane Basin, in the headwaters of Britannia Creek (with no impact on Howe Sound).

On the south side of Jane Basin, there is an extensive area of rock disturbed by mining subsidence, which could create a rock slide in Britannia Creek drainage (Irvine, 1944, Baumann, 1991b, O.Hungr Geotechnical and S.G. Evans, 2002). This potential landslide would not cause a wave in Howe Sound.

A very detailed study of submarine morphology using sonar equipment has been carried out by the Geological Survey of Canada (Jackson et al, 2008). This produced no evidence of major subaerial landslide deposits, except on the west side of Bowen Island, below deformed slopes of Mt. Gardner. The age of these features is unknown and they are distant from the District of Squamish.

Apart from the above-mentioned cases, to our knowledge, there are no reports of major slope deformation features, or other signs of past or incipient large-scale slope instability surrounding Howe Sound. It should be noted, however, that there is only very limited aerial Lidar coverage on these slopes. Slope deformation and instability features could be concealed by the heavy vegetation of the slopes surrounding Howe Sound. For example, significant undocumented rock deformation was noted during past work near Elevation 900 m, just north of the M-Creek channel.

2.3 Howe Sound – Waves Caused by Submarine Landslides

Waves caused by submarine landslides are a relatively frequent hazard in fjords (Bjerrum, 1971). The most serious historical example of such waves occurred in Port Valdez during the 1964 Alaska Earthquake, when both a failure of the river delta at the head of the fjord and major landslides in glacial deposits bordering the shoreline caused very large and destructive waves (Lee et al., 2007). However, this example is probably not applicable as a precedent for Howe Sound, because the 1964 subduction earthquake epicentre was only a few km from Valdez. More relevant are the submarine landslides of 1974 and 1975 in Kitimat Inlet where failure of clay slopes along the shoreline raised waves possibly as high as 8 m (Prior et al., 1983, Johns et al., 1984). Both events occurred at low tide, with no earthquake shaking involved. In one case, construction activity along the shore may have triggered the slope failure.

A summary of recorded submarine landslides, compiled by Bornhold et al., 2001, is shown in Figure 1. Not all of these created substantial waves. In particular, neither the Fraser Delta failure of 1985, nor the Howe Sound landslide of 1955 formed waves.

The 1955 landslide was a failure of the front of a small, coarse-grained delta modified by fill at the Woodfibre mill site. As described by Terzaghi (1956) this was a relatively slow failure, without much evidence of liquefaction, although recent sonar surveys did show some landslide deposits on the bottom of the fjord (Prior et al., 1981). A larger landslide involving an accumulation of mine waste at the front of the Britannia Creek delta occurred in the nineteen fifties (Blais-Stevens and Septer, 2008). This severed the B.C. Rail line, but did not appear to have raised a substantial wave. Deposits of mobile sediment flows radiate from the Britannia Creek delta and are probably connected partly to the disposal of mine waste and tailings from the Britannia Mine (Prior and Bornhold, 1984b).

The inventory of side scan sonar records compiled by Jackson et al. (2008) shows few signs of submarine landslides other than those mentioned, although portions of the east bank slopes north of Furry Creek show possible signs of large-scale slumping within glacial drift lining the side of the fjord. The date and scale of these submarine processes is unknown and the slide deposits on the bottom of the fjord cannot be identified in the sonar record.

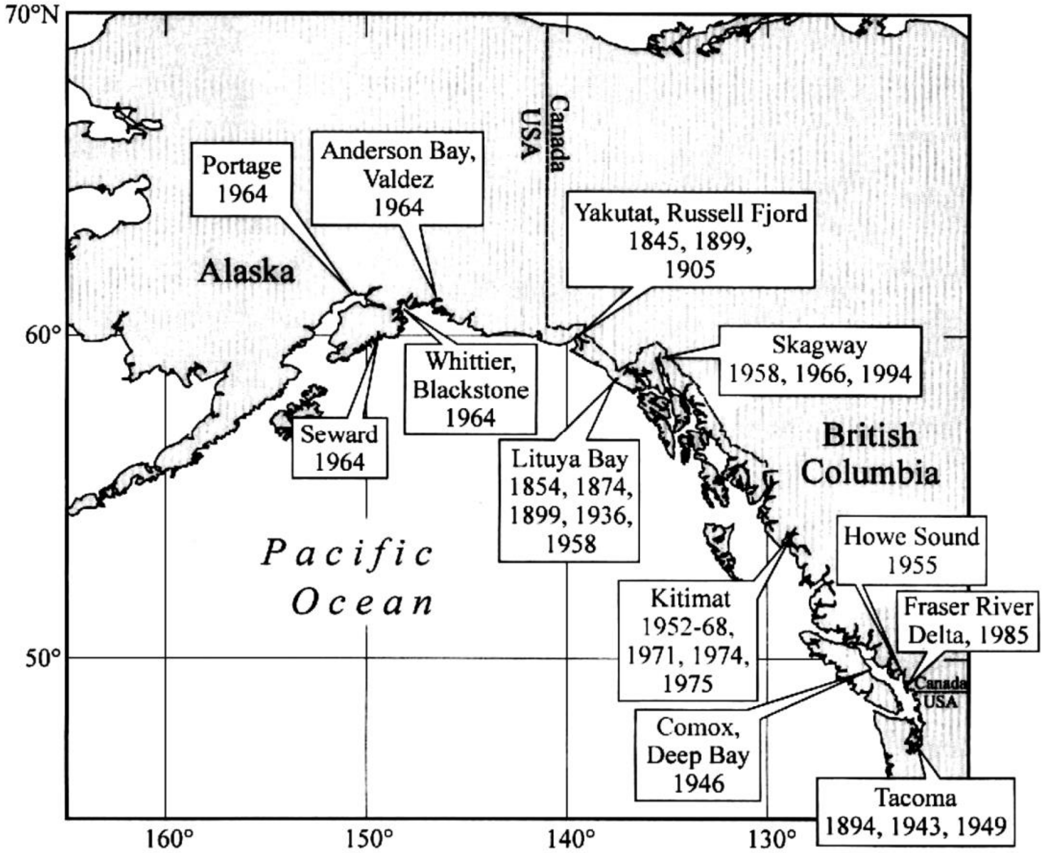

Figure 1
Submarine landslides in fjords of the Pacific Coast (Bornhold et al., 2001).

The front of the Squamish delta is being rapidly extended by deposition of sand and silt from the Squamish River. The delta front is subject to periodic slumping and generation of density currents, which are shown in the changing morphology of the delta front (Prior and Bornhold, 1984a). Periodic sliding of recent sediments on the delta front and the occurrence of density currents have been documented recently by systematic bathymetric surveys, conducted by a research group from the University of New Brunswick (Hughes Clarke et al., 2012). These processes are typical of coarse-grained elongated deltas that receive large sediment discharges and do not, usually form waves. Similar processes operate also on the Fraser delta in Vancouver (McKenna et al., 1992). However, the Squamish delta contains deep deposits of loose sand, silt and clay, which are susceptible to earthquake liquefaction to depths of several tens of metres (Klohn Crippen, 2005).

3. Conclusions and Recommendations

Three possible sources of landslide-related flooding that could affect the District of Squamish have been briefly considered: flooding due to landslides along tributary rivers, due to landslides impacting Howe Sound or submarine landslides occurring in the fjord. Given the spectacular, rugged topography and diverse geology surrounding Squamish, such hazards can never be ruled out and a certain degree of risk from them will always need to be tolerated by any developments in this region. There is no recorded historical evidence that this type of flooding has occurred in recent past within the study area.

The most evident and urgent potential hazards of this type emerging from this preliminary review include debris flows on Cheekye Fan and a potential earthquake liquefaction failure of a part of the Squamish Delta, or other parts of the Howe Sound shoreline. Studies should be carried out to further delineate these hazards.

It would be advisable to compile an inventory of geotechnical borehole data, to help characterize the soil deposits forming the shorelines of Howe Sound and the Squamish and Britannia deltas, so that their response to a potential major seismic event could be evaluated. We assume that a detailed seismic stability analysis of the Squamish Delta and the dyking system will be carried out in due course, as development of the central part of Squamish proceeds.

Given the continuing development pressures and increasing population of this rugged region, an aerial Lidar image of the slopes and summits surrounding the District and Howe Sound should be obtained, in order to ensure that state-of-the–art surveillance of these slopes is in place. Once the Lidar image is obtained, the hazard overview contained in this report should be updated

Identified landslide hazards along the Stawamus River should be monitored or mitigated, as recommended by previous reports (e.g. Baumann, 1994).

If you have any questions concerning this report, please contact us.

Yours very truly,

O.Hungr Geotechnical Research, Inc.
Per O.Hungr, P.Eng./P.Geo., Pres.

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Appendix F

Review of Tsunami and Landslide Wave Hazards

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TECHNICAL MEMO

TO:	File	**DATE:**	12/02/2015
C.C.:	John Readshaw	**FROM:**	Philippe St-Germain
PROJECT:	District of Squamish Integrated Flood Hazard Management Plan	**MEMO NO:**	0001
SUBJECT:	Review of Tsunami and Landslide Wave Hazards	**DOCUMENT NO:**	618897-3000-41EN-0001-Rev.0

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Reviewed and Approved by:	John Readshaw, P. Eng.	

1. INTRODUCTION

This document summarizes a preliminary assessment of the risk to the District of Squamish from seismic and landslide generated tsunami waves. The assessment was made as part of the initial phase on the ongoing Integrated Flood Hazard Management Plan (IFHMP) process.

The water bodies that form the coastal perimeter of the District of Squamish are exposed to the risk of tsunamis generated either by seismic events or landslide events in various locations both near and far from the Squamish River estuary. This review is a preliminary assessment of the risk as outlined further below.

The behaviour of a tsunami wave train in Howe Sound and at the District of Squamish waterfront, from either source, will depend on the characteristics of the tsunami wave train and it's interaction with the bathymetry and coastal topography of Howe Sound. A preliminary assessment of the potential for tsunami amplification due to resonance within Howe Sound is also summarized below.

2. DEFINITIONS

The following terms, used throughout this document, have the following meaning, unless noted otherwise in context:

• Tsunami Reference Plane:	Taken to be the mean water level over the length of the tsunami wave train (which will include the tide and atmospheric affected sea surface)
• Tsunami wave train	A seismic or landslide event will generate a series of waves which travel away from the generation source. The exact character of the wave train (ie: the number of wave crests, the interval between waves and the total duration of the tsunami) will vary greatly depending the details of the forcing event.
• Tsunami wave height:	Elevation difference between the crest and the trough of a tsunami wave (tsunami wave crest amplitude + tsunami wave trough amplitude)
• Tsunami wave runup	The highest elevation, reached by a tsunami wave, above a defined reference plane, which be different from the Tsunami Reference Plane.
• Tsunami wave crest amplitude:	Elevation difference between the crest of a tsunami wave and the Tsunami Reference Plane
• Tsunami wave trough amplitude:	Elevation difference between the trough of a tsunami wave and the Tsunami Reference Plane

3. TSUNAMI HAZARD SCENARIOS

A tsunami is a series of waves, typically with an interval between waves measured in minutes, generated in a body of water by an impulsive disturbance that displaces the water column in the vertical direction. They are generally generated by seismic events or both sub-aerial or submarine landslides, but also, more rarely, by volcanic eruptions, explosions, and the impact of cosmic bodies, such as meteorites. Over the last decades, several potential tsunami sources have been identified on the Pacific Coast of Canada. Tsunami sources with the potential to affect the District of Squamish are described in the following sections.

3.1 Subduction Zone Earthquakes

A *subduction zone* is a location where tectonic plates come together, one riding over the other. A subduction zone has the potential to generate large earthquakes resulting in vertical motion of the seabed and the formation of tsunami waves.

3.1.1 Cascadia Subduction Zone

The west coast of Canada is particularly susceptible to large tsunami waves due to the proximity of the *Cascadia Subduction Zone* (CSZ), which stretches from mid-Vancouver Island to Northern California and forms the boundary region between the Juan de Fuca and North America plates. Because of the large fault area, the CSZ has the potential to produce large subduction earthquakes and therefore large tsunamis.

Geological studies along the West Coast, in conjunction with historical Japanese records, have found that a large, tsunami was generated by a subduction earthquake in the CSZ, magnitude M_w 9.0, in the year of 1700 [1]. Various investigations have estimated that the average recurrence interval for this large event is between 400 and 600 years, with a further range of uncertainty in the order of hundreds of years [2].

The Institute of Ocean Science (IOS) has modelled the propagation of a similar CSZ related tsunami together with detailed assessment of the tsunami effects in Victoria and Esquimalt harbours [3]. The online graphical outputs of the coarse version of this model, although qualified as preliminary, suggests tsunami wave heights of about 5-10m on the outer coast [4], but only ~0.75 m at the entrance of Howe Sound, Figure 1. The spatial grid resolution of the model is not reported nor is the boundary condition at the northern end of the Strait of Georgia and therefore the influence of these model parameters on the predictions at the entrance of Howe Sound is unknown. An earlier study [5] suggested that the CSZ tsunami wave crest amplitudes in the Strait of Georgia would be ~20% (1-2 m) of those on the outer coast.

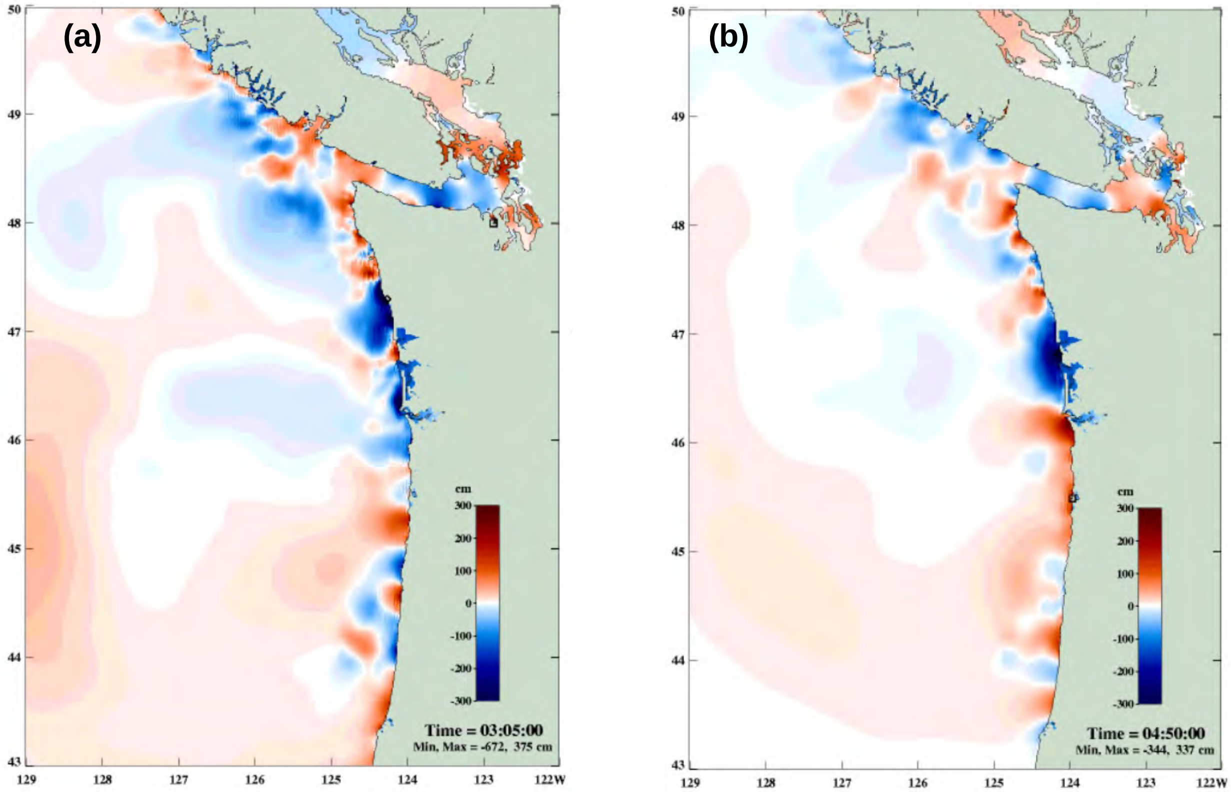


Figure 1: Computed Wave Height for CSZ Tsunami near Howe Sound

(a) first wave crest (~0.50 m above reference plane)
(b) subsequent wave trough (~0.25 m below reference plane)

Tsunami generation occurs at time = 00:00:00.
Source:[3].

3.1.2 Other Pacific Subduction Zones

As tsunami waves can travel great distances from their generating source, any tsunamigenic earthquake along the subduction zones surrounding the Pacific Ocean, Figure 2, can potentially affect the west coast of Canada. However, the height of the tsunami waves reaching the coast will depend on the orientation of the fault line, which governs the predominant direction of wave propagation.

Figure 2: Subduction Zones in the Pacific Ocean Basin
(adapted from [1])

The best example of a tsunami affecting the British Columbia coastal from a distant subduction zone is the 28 March 1964 tsunami that partially damaged Port Alberni, British-Columbia. This tsunami, generated by a M_w 9.2 subduction earthquake south of the Alaskan coast, reached Vancouver Island within approximately 4 hours, with a maximum wave height of 2.4 m at Tofino [6]. However, due to resonant amplification in Alberni Inlet, the waves of the tsunami exceeded 6 m at the City of Port Alberni. The resulting flooding and property damage were made worse because the tsunami also arrived around the time of high tide [6].

The amplification that occurred in Alberni Inlet is generally considered to be related to the relatively long (~ 40 km) and narrow (~ 1-2 km) character of the Inlet. The Inlet is also characterized by relatively shallow approaches (~ 100 m) at the entrance in Barkley Sound and deeper depths (> 250 m) in the narrower portions of the Inlet.

Although there are some similarities between Alberni Inlet and Howe Sound, a tsunami generated at a subduction zone other than the CSZ is not expected to significantly influence water levels in Howe Sound because of the attenuating topography of the Gulf Islands archipelago at the southern end of the Strait of Georgia. The maximum wave height recorded at Point Atkinson for the 1964 tsunami event was approximately 0.25 m [7].

3.2 Shallow Local Earthquakes

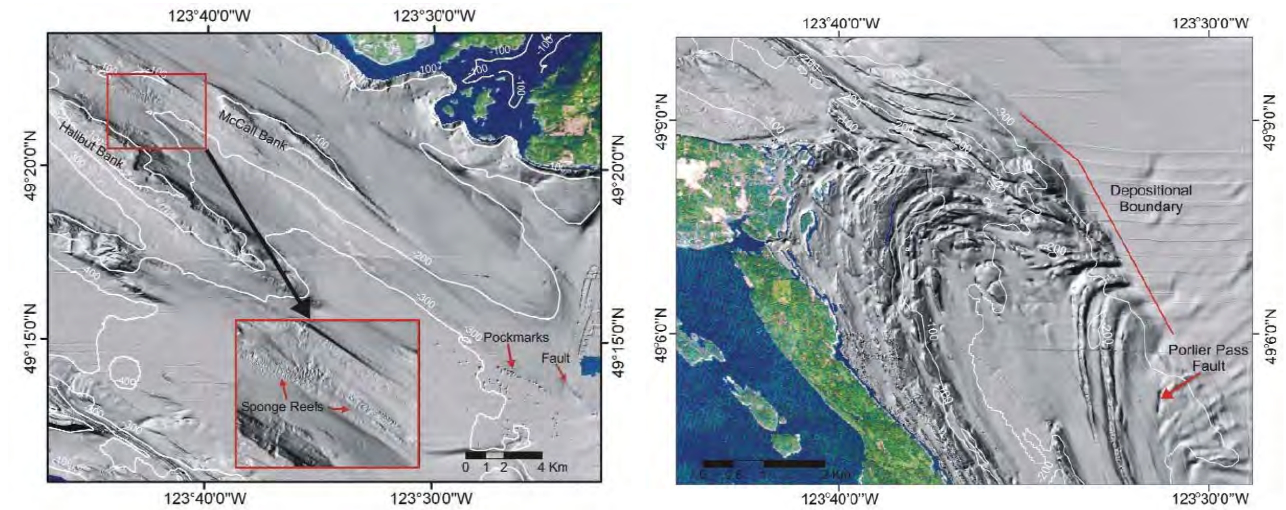
Earthquakes with epicentres located closer to the ground surface (crustal earthquakes) can also generate tsunamis, if they cause vertical seafloor displacement.

A number of features on the seafloor of the Strait of Georgia may be fault-controlled and have tsunami generation potential; however, the status of these faults remained unknown as of 2005 [4]. If any of these faults are active, and vertical displacement of the seafloor occurs during an earthquake, then the ensuing tsunami may represent a hazard to coastal areas located adjacent and parallel to the fault zone [4].

A multibeam bathymetric mapping program of the Strait of Georgia [8] has identified two areas of seabed disturbance that have been interpreted as active faults:

- the easterly fault zone in the vicinity of English Bay (Fraser Delta Fault, Figure 3a) and
- the western fault zone in the vicinity of Valdes Island (Porlier Pass Fault, Figure 3b).

However, it is not specifically stated that these faults have the potential to generate tsunamis. The Fraser Delta Fault, Figure 3a, is close to the entrance to Howe Sound.



(a) (b)

Figure 3: Active Faults in the Strait of Georgia:
(a) Fraser Delta Fault (west of Point Grey –RHS of image)
(b) Porlier Pass Fault

Source [8]

Vertical offsets in the seafloor are also observed on active faults in eastern Juan de Fuca Strait, south of the Gulf Islands. However, because of the attenuation provided by the Gulf Islands archipelago, it is considered unlikely, [4], that tsunamis generated by seismic events centered in Juan de Fuca Strait or Puget Sound would result in any significant tsunami waves in Howe Sound.

3.3 Submarine Landslides

Three areas were identified in the waters in or adjacent to Howe Sound where submarine landslides could occur and potentially result in a tsunami that might affect the District of Squamish waterfront. Submarine landslides generally occur due to either seismic loading or due to local processes such as gradual but sustained sediment loading from rivers. The magnitude of a landslide-generated tsunami largely depends on the volume of material displaced and the rate of displacement.

3.3.1 Squamish Delta

A brief review of submarine slides on the Squamish Delta is reported in [9], which states that the Delta contains deep deposits of loose sand, silt, and clay, which are susceptible to earthquake induced liquefaction to depths of several tens of meters [12]. It is likely that a related submarine landslide would have the potential to generate a tsunami, as summarized below.

A comparable situation exists in the Kitimat River delta, where two tsunamis occurred in October 1974 and April 1975 as the result of submarine landslides [13]. In these cases, no earthquakes were involved. The maximum wave heights were estimated to be between 6 and 7 m. These submarine landslides have been assessed by AMEC [14] and the reported material volume associated with these events was on the order of 10 to 25 x 10^6 m^3 of material.

In the Squamish River delta, in October 2006, it was reported [16], that one of the navigation buoys marking the approach to the Squamish Terminals had moved a considerable distance seaward. The buoy was recovered and repositioned. Two multibeam surveys of the area (March 2006 and November 2006) provided a detailed map of a likely related underwater landslide. The slide occurred on the steep slope of the delta front - an area with initial water depths of 0-50 m (CD). After the slide, the water depths in this area increased by 10-20 m. The debris field was clearly visible in the surveys, flowing down-slope from the slide site in a southwest direction for a distance of about 1 km and ending in a water depth of ~ 120 m. The debris field had a height of 5-10 m along its length.

Subsequent surveys of the area indicate that the delta front immediately in front of the river mouth is slowly growing and may become unstable again in the future [16].

Recent research by the University of New Brunswick's Ocean Mapping Group [17] has found that relatively small submarine landslides periodically occur on the delta front. A survey program established to identify the timing and style of slide events on the delta-fore slope found that three major active channels are present, Figure 4. During a monitoring period over the 2011 summer freshet period, 103 discrete slide events were identified. Five of these events were clearly associated with a considerable (>20,000 m^3) collapse of the delta face. The first two events occurred before the main freshet and are associated with low water spring tides. The later three events were clearly correlated with peaks in river discharge (increasing from ~ 400 m^3/s to > 800 m^3/s).

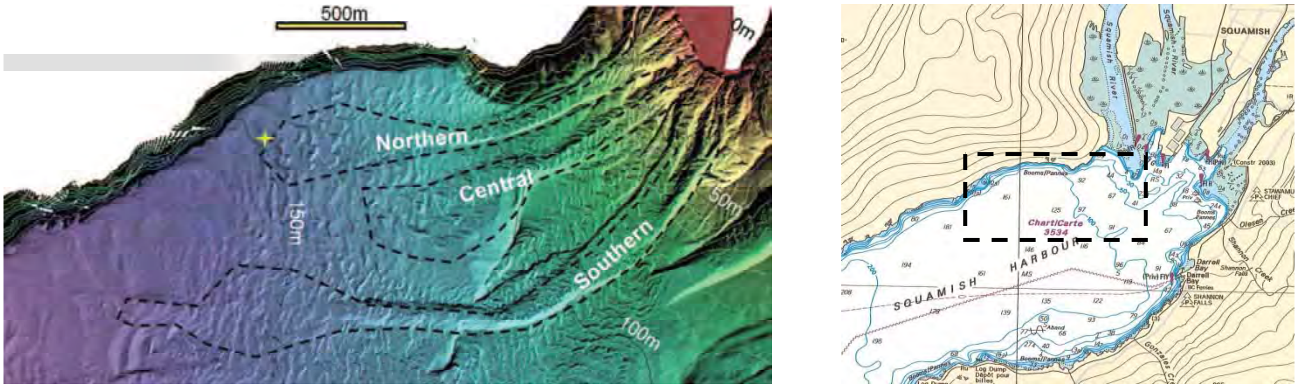


Figure 4: Squamish Delta bathymetric survey (left) illustrating the three major channels of slides [17] - Approximate survey coverage area (right)

Although slumping of the fore-slope of a delta is not uncommon in river deltas that receive high sediment loads, and does not usually generate waves [9], the history of slumping on the Squamish River delta has been assessed further to quantify any potential that might exist. In this case the differences between two historical CHS surveys were investigated to develop some insights on the potential for landslide generated waves on the Squamish delta.

Two surveys were available from CHS for January 1990 and June 2004 respectively. By 2004, which is prior to the event described above in 2006, it is clear that significant accretion had occurred at the top seaward edge of the delta, directly south of the training jetty, Figure 5. It is likely that the accretion is largely the result of the deposition of upstream sediments eroded from the banks of the Squamish River or tributaries, during the storm of October 2003. Information available in [16] on the 2006 event, and from the volume of accretion indicated in Figure 5, together suggest that the volume of slumping in 2006 may have consisted of approximately 3.8 x 10^6 m^3 of material. Desktop procedures [18], for estimating landslide generated tsunami potential, indicates that a tsunami wave train, with a 0.6 to 1.8 m maximum wave height may have been generated local to the slide area.

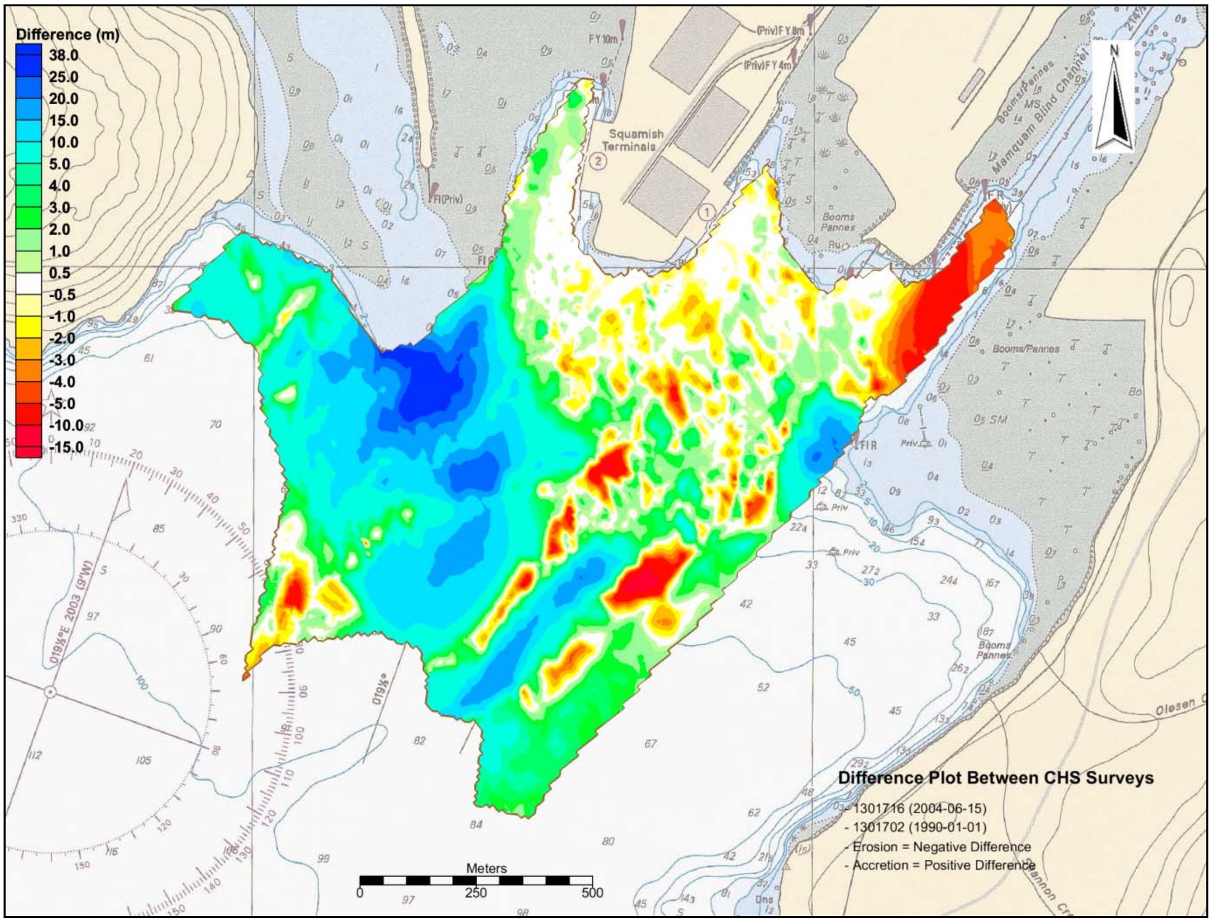


Figure 5: Difference Plot between June 2004 and January 1990 CHS Surveys

Note:
positive difference = deposition
negative difference = erosion

The same procedures, for a hypothetical slide with twice the volume of the 2006 slide, suggest an upper bound tsunami wave height between 3.0 m and 7.0 m. The variability in the prediction lies in the uncertainty associated to the assumed the geometry of the slide. More analysis would be required to refine and validate such slide from a geotechnical standpoint.

A submarine slide on the foreshore of the Squamish River delta would generate a wave train travelling in the same direction as the slide (i.e., oriented offshore); however, lateral wave radiation should be expected and some waves could also propagate landward. Numerical modeling would be required to define the propagation of the tsunami waves and their interaction with the surrounding coastlines. There is a possibility that waves propagating radially away from the source could be reflected towards Squamish from the steep rocky coastline between Darrell Bay and Watts Point.

3.3.2 Howe Sound Sources

A review of waves generated by submarine slides in Howe Sound is provided in [9]. It is reported that the inventory of side scan sonar records compiled by [19] shows very few signs of past submarine landslides in Howe Sound, other than two human-induced slides at the Woodfibre mill site and the Britannia Creek delta in the 1950s. Neither of these events are known to have formed tsunami waves. However, portions of the east bank slopes of north Furry Creek delta show possible signs of large-scale slumping within glacial drift lining the side of the fjord. No further assessment of the tsunami potential of a Furry Creek slide was undertaken for this assessment.

3.3.3 Fraser River Delta

The southwest front of the Fraser River delta has been the focus of several studies as it is considered to be at risk of underwater slope failure. The largest submarine landslide known to have occurred in historical times at the

Fraser River delta was in 1985 [9]. The volume of the slope failure, which did not induce a tsunami, was estimated to between 1.4 x 10^6 m^3 and 3.0 x 10^6 m^3 of material[10].

The tsunami potential of a catastrophic slope failure of the Fraser River delta, irrespective of causal mechanism, has also been assessed by researchers from IOS [11], who modeled the water column response to various hypothetical slides. The volumes of these slides varied from 230 x 10^6 m^3 to 750 x 10^6 m^3 of material and the modelling exercise resulted in tsunami wave crest amplitudes between 4 and 18 m, which crossed the Strait of Georgia and reached the Gulf Islands of Mayne Island and Galiano Island within 6 minutes. Wave heights in the vicinity of Howe Sound were not reported. The likelihood of such a large slope failure; however, does not have a consensus within the geological community, even under seismic loading [phone communication with Dr. J. Clague – 30/05/2014].

3.1 Sub-aerial Landslides

A sudden landslide from a steep mountain slope bordering Howe Sound could potentially trigger a tsunami that could reach Squamish. However, the probability of a sub-aerial landslide-generated tsunami in Howe Sound is low, although not negligible, as no slopes bordering the Sound are known to be unstable [4]. Nevertheless, it is believed that a large (> 10 x 10^6 m^3) landslide in southern Howe Sound might produce tsunami waves several metres high in Sunset Beach, Horseshoe Bay, or Deep Cove [4].

Apart from various cases of periodic occurrences of debris flow and rock fall at magnitudes that do not have the potential to raise substantial tsunami waves, there are no reports of major slope deformation features, or other signs of past or incipient large-scale slope instabilities surrounding Howe Sound [9]. However, there is only very limited aerial LiDAR coverage of the slopes surrounding Howe Sound and more coverage might identify slope deformation and instability features that could be concealed by the heavy vegetation present on these shorelines.

4. RESONANCE AND AMPLIFICATION IN TIDAL INLET

Long period oscillations are a long wave phenomenon that occur in harbours, tidal inlets and partially enclosed basins that are connected through one or more openings to the sea [20]. Resonance is the tendency of such a water body to oscillate with greater amplitude at some frequencies than others. Resonant properties of a particular basin depend solely on the basin’s geometry and are independent of the external mechanism forcing the oscillations. Resonance occurs when the dominant frequencies of the external forcing match the resonant frequencies of the basin. In the case of a tsunami, considerable amplification may occur when the dominant frequencies of the tsunami waves match the resonant frequencies of the basin.

One of the best examples of strong tsunami amplification due to resonance is the case of Port Alberni following the 1964 Alaskan tsunami; discussed earlier in Section 2.2. Spectral analysis of two months of background oscillations recorded at the Port Alberni and Bamfield tide gauges was performed by oceanographers at IOS to establish resonant frequencies for the Barkley Sound - Alberni Inlet system [6]. It was found that the resonant frequencies of the system were similar to the spectrum of the 1964 tsunami, which likely explains the wave amplification that occurred.

No information was found on the resonant properties of Howe Sound. As a preliminary estimate, using an analytical approach [20] and assuming a 40 km long basin with a uniform depth of 250 m, the resonant frequencies, or periods, of the Sound were estimated to be 54, 18, 11, 8, 6, and 5 minutes for the 0th, 1st, 2nd, 3rd, 4th, and 5th resonant modes, respectively. Analysis of IOS modelling results for a CSZ earthquake [3] suggests a typical wave period of ~2.5 hours at the entrance of Howe Sound. As this period is longer than the estimated Howe Sound resonant periods, resonant amplification is not expected to occur for scenario CSV related tsunami. This estimate should be verified as the IOS model was developed to assess tsunami effects in Victoria and Esquimalt harbours and its accuracy in the vicinity of Howe Sound or the Strait of Georgia was not available for this assessment.

Although periods of tsunami waves generated by subduction earthquakes tend to be long, periods associated to landslide-generated tsunami waves are generally smaller (<10 min), meaning that they could match some of the higher resonant periods estimated for Howe Sound. However, the duration of any landslide generated wave train is not likely to last long enough to setup resonance in the Sound.

5. CONCLUSION AND RECOMMENDATIONS

Known sources for tsunamis that could adversely affect the District of Squamish have been reviewed and for those sources likely to pose the most risk to the District, a preliminary estimate has been made of the potential height of the largest wave in the tsunami wave train. The most likely source is a submarine landside on the fore slope of the Squamish River delta and desktop procedures suggest an upper bound largest wave height of 3 - 7 m is possible. The actual maximum expected runup elevation for a potential tsunami event around the shorelines of Squamish requires more detailed analysis.

A tsunami generated by a Cascadia Subduction Zone earthquake offshore of the Pacific Northwest coastline of North America is likely to be significantly attenuated before it reaches the entrance of Howe Sound. The expected maximum tsunami wave height at the entrance to the Sound is <2 m.

A tsunami generated at a subduction zone elsewhere on the Pacific Rim is not expected to significantly affect Howe Sound.

A preliminary estimate of the resonance potential of Howe Sound suggests that tsunami waves resulting from a Cascadia Subduction Zone earthquake will likely not be amplified in Howe Sound, due to resonance. Because the duration of a wave train from a landslide-generated tsunami would generally be short in duration, waves generated from this type of source are also not expected to experience resonance effects in the Sound.

Due to several limitations of the available information, as summarized above, it is recommended that a more detailed analysis of tsunami generation and of resulting tsunami runup, should be undertaken to either validate and quantify or to eliminate the potential risk to the District of Squamish waterfront due to a seismic or a landslide generated tsunami.

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