Photo source: all photos from NHC, November 15, 2021

Chemainus River Flood Mapping Program
Part 1 – Floodplain Mapping

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DISCLAIMER

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- Rachel Hay — Hydrologist, NHC

We respectfully acknowledge that the Chemainus River, its tributaries, watershed, and estuary lie within the traditional, unceded territories of the Coast Salish Peoples.

The study area falls within the territory of the Hul’qumi’num Treaty speaking First Nations peoples, including Cowichan, Halalt, Stz’Uminus, Penelakut, Lyackson, and Tsuubaa-asatz Nations.

EXECUTIVE SUMMARY

The Chemainus floodplain, located on Vancouver Island, BC, is at risk to flood hazards. The mountainous and coastal geography of the region has resulted in communities located along the broad low lying coastal plain and delta, where they are vulnerable to flooding and fluvial geomorphic hazards. The Chemainus River has experienced the two largest floods on record during the past two years. The Cowichan Valley Regional District (CVRD), with its partners, is actively working towards reducing the flood risk within the region. One of the primary steps is improving the understanding of the hazards through floodplain mapping. Northwest Hydraulic Consultants Ltd. (NHC) was retained by the CVRD with support from the Nation Disaster Mitigation Fund (NDMP) to prepare updated floodplain maps for a 7.5 km long reach of the Chemainus River and portions of its two main tributaries, from where it exits the canyon upstream of Highway 1 to the estuary. The primary mapping products include:

- Floodplain maps showing flood construction levels (FCL) for a designated flood of 200-years adjusted to account for future climate change and sea level rise.
- Depth and velocity maps for the designated flood condition.
- Geomorphic hazard maps and accompanying geomorphic atlas.

Regional hydrometric gauges and existing studies were reviewed to determine a suitable approach for calculating the design flood. The 20- and 200-year instantaneous peak flood flows derived from a frequency analysis of data from Water Survey of Canada gauges 08HA001 *Chemainus River Near Westholme* and 08HA016 *Bings Creek near the mouth* were selected as the design events. In the lower reaches of the Chemainus and Bonsall floodplains, the water levels are governed by the interaction of river flows, the astronomical tide level and the magnitude of any storm surge. A joint probability assessment of discharge and tides suggested a 200-year riverine discharge combined with a moderately high ocean level (20-year event) were appropriate to represent designated flood scenarios. By the end of this century the 200-year event can be substantially different as the magnitude, and frequency of flood events may be influenced by changes in climate (i.e., global climate change) or changes in vegetation and landcover within the watershed. In attempt to account for the projected changes, the calculated 200-year flows were increased by 20% to establish the flow for the design flood events.

Geomorphic changes can occur over time (multiple events) or suddenly (single flood event) that can alter the coarse or condition of the river. The Chemainus River is prone to channel migration processes, which could alter the conveyance pattern, depth, and velocity of floodwater across the floodplain. A geomorphic assessment was carried out to assess the dominant fluvial and coastal processes that operate on the floodplain and delineate areas that are susceptible to channel and shoreline migration hazards. A geomorphic atlas is included in Appendix C, which summarizes the field investigations, desktop review and analyses carried out for the study, and provides more detail on these geomorphic processes. The geomorphic assessment guided the development of a geomorphic hazard map.

LiDAR data and orthophotos of the channel and floodplain, collected in 2019 and 2021, were acquired and combined with channel survey collected by NHC in 2021. This data was used to develop a digital elevation model that supported analysis and mapping. A 2D numerical hydraulic model was developed (HEC-RAS) using the DEM. The model was calibrated and validated using survey measurements and photographs of high water from the 2021 flood. The model was then used to simulate the 20-year and 200-year design flood events.

A coastal assessment was completed to review the tide levels and completed wave modelling of the estuary. The design flood levels for the estuary were determined using an extreme event analysis of the tides and joint probability analysis to determine the joint occurrence of tides and storm surge. A regional estimate for sea level rise by year 2100 was applied. The design water levels were used in combination with select design winds to create waves and assess coastal runup through the estuary.

Flood construction levels (FCL), the minimum recommended level for habitation or commercial activities, was calculated by adding a 0.6 m freeboard above the simulated 200-year design flood level. The 200-year design flood level is a composite of both 200-year return period riverine conditions and 200-year return period coastal conditions. The freeboard is to account for local variations in water level as well as uncertainty in the data and analysis. FCLs were plotted as isolines along the study reach on the floodplain maps (in CGVD2013a vertical datum). The FCLs were projected outwards to high ground to determine the design flood extents. Flood hazard maps were developed for the design flood showing the flood depths (without freeboard added) with velocity magnitude shown as arrows overlayed. Geomorphic hazard maps were also created which delineate several hazards including historical migration zones, channel erosion zones, avulsion zones, potential geotechnical hazards, estuary distributary channel zones and coastal erosion zones. The mapped FCL, flood hazard and geomorphic hazard maps provide information to support flood mitigation including land use regulation, emergency preparedness, and emergency response.

The hazards mapped within the current study are limited to flood hazards associated with the Chemainus River within the study extents. Other sources, as well as more extreme flood events, may result in a magnitude or spatial distribution of flooding different than that mapped. It is recommended that the entire report and appendices are read and understood prior to applying the maps and study findings.

A second component of the project builds on the floodplain mapping investigations to identify and assess alternative strategies for mitigating flood and erosion hazards. This second phase is described separately.

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APPENDIX SECTIONS

1 PROJECT SNAPSHOT

Name: Chemainus River Flood Mapping Program – Part 1: Floodplain Mapping

Study Area: Chemainus River including Bonsall Creek and Whitehouse Creek that are part of the Chemainus floodplain on Vancouver Island, British Columbia (Figure 1.1)

Agency: Cowichan Valley Regional District (CVRD)

Funding: National Disaster Mitigation Program (NDMP) and Emergency Management BC (EMBC)

Goals: Develop up-to-date flood maps and channel migration zone maps.
Understand and guide watershed management planning using a science based approach.
Develop technical tools for use in future flood management.

Objectives:

1. Develop an official 200-year Designated Floodplain Map for the Chemainus River system.
2. Develop geomorphic hazard mapping of the potential channel and shoreline migration zones on the Chemainus River floodplain.
3. Develop a comprehensive hydraulic modelling tool and geomorphic atlas that can be used to evaluate flood mitigation measures.

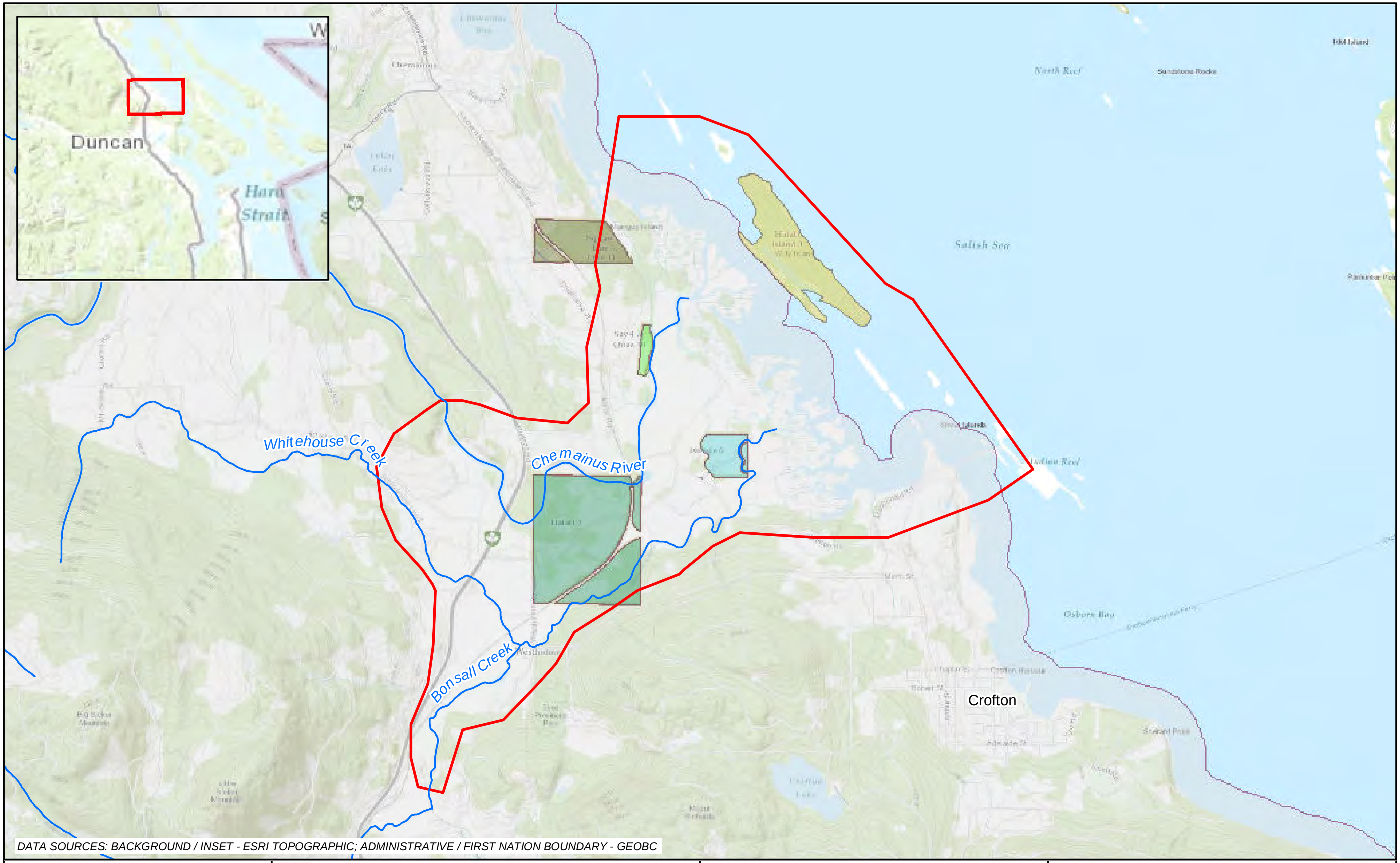
Approach: Collaborative, including stakeholder and public consultation.

Timeline: May 25, 2021 – March 15, 2023

This Report: The summary report is part 1 of the 2-part series of reports to develop floodplain maps and strategic flood management options for the Chemainus floodplain. This report provides a high-level overview of the technical tools developed for part 2 and the methods undertaken to complete flood and geomorphic hazard mapping for the Chemainus Basin. Report sections include: Chemainus watershed overview, surveys, hydrology, geomorphology, hydraulic modelling, coastal assessment and wave modelling, flood maps, geomorphic hazard, and recommended next steps. Additional technical information describing the detailed hydrological, hydraulic, and geomorphic investigations that have been carried out is summarized in the following appendices.

- Appendix A: Surveys
- Appendix B: Hydrology
- Appendix C: Geomorphic Atlas
- Appendix D: Hydraulic Modelling
- Appendix E: Coastal Modelling
- Appendix F: Flood Mapping Methodology
- Appendix G: Flood Depth and Velocity Hazard Maps
- Appendix H: Designated Floodplain Map
- Appendix I: Geomorphic Hazard Map

These appendices should be consulted and reviewed prior to using the flood and geomorphic hazard maps.



STUDY AREA

ADMINISTRATIVE BOUNDARY

DISTRICT OF NORTH COWICHAN

FIRST NATION BOUNDARY

HALALT 2

HALALT ISLAND 1

SAY-LA-QUAS 10

SQUAW-HAY-ONE 11

TSUSSIE 6

SCALE - 1:50,000

0 0.5 1 1.5 2 KM

N

Coordinate System: NAD 1983 UTM ZONE 10N
Units: METRES

Job:3006373

Date: 07-OCT-2021

CVRD

nhc northwest hydraulic consultants

CHEMAINUS RIVER FLOOD MAPPING PROGRAM

OVERVIEW OF ADMINISTRATIVE BOUNDARIES

FIGURE 1.1

SWM, \\mainfile-nan\Projects\Active\3006373 Chemainus IFMP\95 GIS\3006373_SWM_BoundaryMemo_AdminBoundaries.mxd

2 FLOOD MAPPING GUIDELINES AND STANDARDS

NHC has completed floodplain maps for the Chemainus River using the best practises and guidelines. The specific guidelines that were consulted are listed below:

- EGBC (2018). *Legislated Flood Assessments in a Changing Climate in BC, Version 2.1*. Engineers & Geoscientists British Columbia, Burnaby, BC. 192 pp.
- MFLNRORD (2018). *Flood Hazard Area Land Use Management Guidelines*. Ministry of Forests, Lands, Natural Resource Operations and Rural Development. Update Section 3.5 and 3.6 of 2004 report.
- APEGBC (2017). *Flood Mapping in BC, APEGBC Professional Practice Guidelines, V1.0*. The Association of Professional Engineers and Geoscientists of British Columbia, Burnaby, BC. 54 pp.
- MFLNRO (2011). *Coastal Floodplain Mapping - Guidelines and Specifications*. Ministry of Forests, Lands and Natural Resource Operations (MFLNRO). 91 pp.

Several earlier documents have also been reviewed. However, these reports have been largely superseded or incorporated into the later guidelines, including Ausenco-Sandwell (2011a, 2011b, 2011c) which serves as the basis for the 2018 MFLNRORD amendment. Additionally, the framework for determining geomorphic hazard zones for this project was adapted and modified from approaches used in Washington state, listed in Section 0.

Flood maps are a major component of flood management and non-structural flood mitigation. Local authorities are granted general powers to regulate development in floodplains (such as FCLs) where they act in the interest of the public safety through the provincial *Local Government Act*. The role of floodplain mapping as part of developing a comprehensive flood management strategy is discussed in Part 2 of this study.

NHC has completed designated floodplain maps with flood construction levels and inundation extents, depth and velocity hazard maps and erosion hazard maps. The designated floodplain maps produced in this study supersede previously developed floodplain maps for the study area.

For the riverine flood mapping, the EGBC guidelines were followed which stipulated the minimum designated flood level should have an annual exceedance probability (AEP) of 0.5%, corresponding to a return period of 200 years. Climate change out to the year 2100 was considered and included in the development of the designated flood as per the guidelines.

The EGBC guidelines also stipulate that a minimum 200 year (0.5% AEP) probability of occurrence be used for coastal flood mapping. Changes to water levels and storm events due to future climate change must consider up to the year 2100 or farther. This was included in the new floodplain maps. NHC used the probabilistic approach for this study where the designated event is determined by a probabilistic analysis of tides and storm surge with a joint 200 year probability of occurrence. The probabilistic method considers the joint probability of storm surge and high tide occurring simultaneously.

Following the probabilistic approach, the coastal FCL may be calculated as the sum of the following components (MFLNRORD, 2018):

- 200 year water level as determined by probabilistic analyses of tides and storm surge
- Wind set-up
- Allowance for local relative sea level rise to the year 2100
- Estimated wave effects associated with the 200 year storm
- Freeboard

Designated Flood Level (DFL)

Flood Construction Reference Plane (FCRP)

Flood Construction Level (FCL)

3 THE CHEMAINUS RIVER WATERSHED

Physical Setting

The Chemainus River drains 355 km^2 of mainly forested uplands and mountains on the southeastern slopes of Vancouver Island. The watershed has an overall length of approximately 45 km and a width of between 5 km to 10 km. The headwaters are located north of Cowichan Lake, with the highest point reaching an elevation of 1,534 m on the peak of Mount Whymper. The river generally flows in a south-easterly direction in a structurally controlled valley until it turns northward near Mount Sicker.

The average gradient of the channel is ~0.9% (~0.5°), steepening to 17% (~10°) in the upper 4 km. Tributary channels that feed into the mainstem are often steeper. Approximately 27% of the Chemainus River watershed slopes are greater than 15° and 18% is greater than 25°. Hillslope gradients that exceed 25° are considered to have a potential for instabilities (Sidle et. al, 1985); channels with an average slope equal to or greater than 15° are considered to have a potential for debris flows (APEGBC, 2017). Watershed morphometrics (e.g., watershed area and length, relief ratio, and the ratio between basin relief and the square root of the basin area) are typically used to conduct a preliminary assessment whether a watershed is dominated by clearwater floods, debris floods or debris flows (Church and Jakob, 2020; Wilford et al., 2004). The morphometric analysis indicates clearwater floods are likely to be the dominant hydrogeomorphic processes on the mainstem channel of the lower Chemainus River, though smaller tributary sub-basins in the upper watershed may be prone debris flows and debris floods.

Near Mount Sicker, the river turns northward and flows across the Nanaimo Lowlands and onto a broad unconfined alluvial plain near Westholme. During large floods the river spills upstream of the Highway 1 bridge along the right (south) bank and flow is diverted out of the Chemainus River into Whitehouse Creek and eventually Bonsall Creek. These spills occurred in November 2022 and January 2020 as well as in several earlier flood events.

The lower 5 km of river has an irregular meandering channel pattern, with recent channel scars or sloughs that indicate former positions of the river channel. The lower river has constructed a large delta consisting of sandy tidal flats that are prograding into Stuart Channel.

Bonsall Creek also flows into the Chemainus River estuary tidal flats, just south of the Chemainus River. The Bonsall Creek watershed is 35.8 km^2, with an overall length of approximately 10 km. Bonsall Creek drains the southern and eastern slopes of Sicker Mountain (maximum watershed elevation of 721 m), the Somenos Lake Lowlands, and a small upland north of Crofton. The floodplain mapping reach of

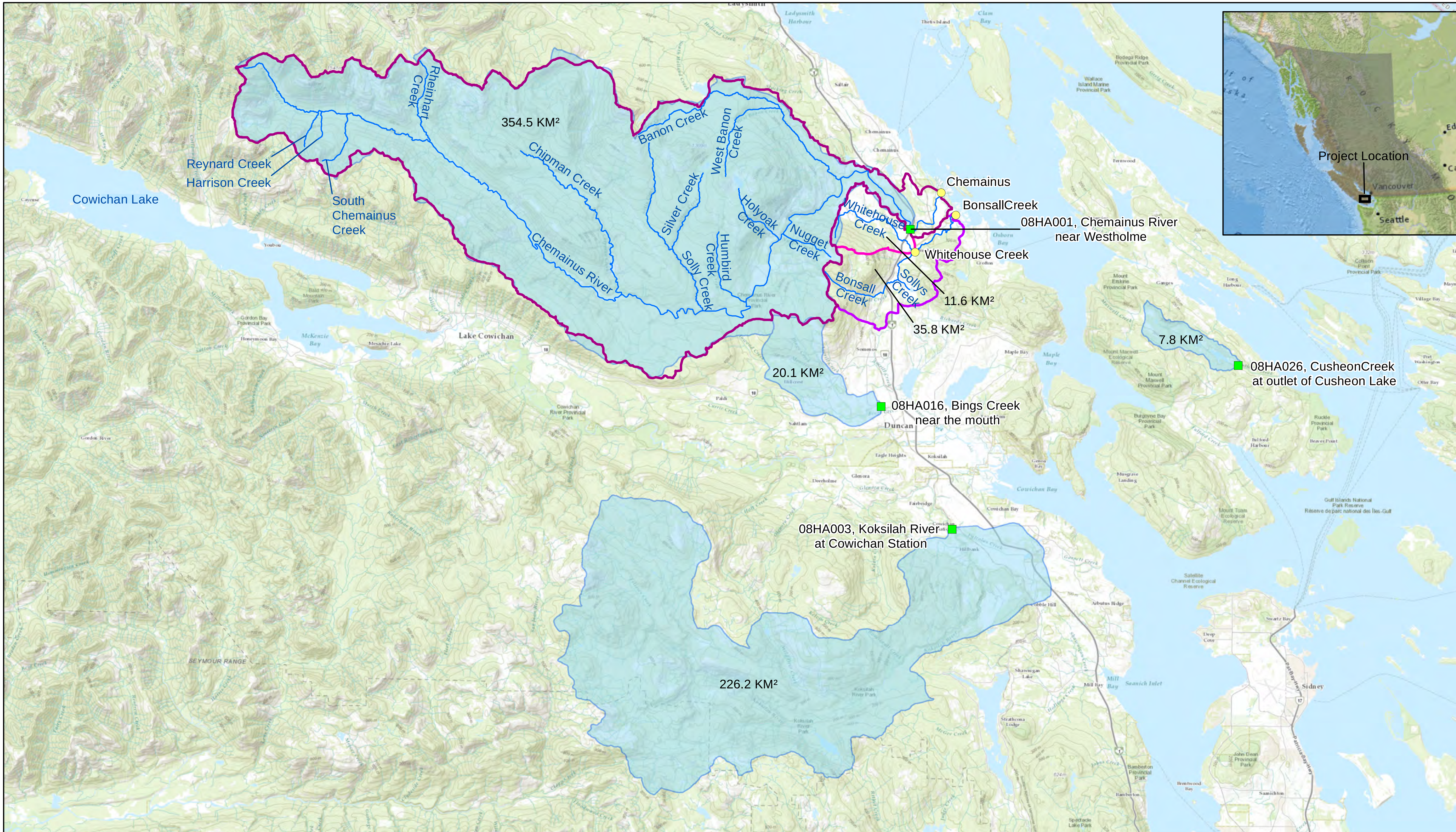
Bonsall Creek is on the alluvial plain in an incised, irregular meandering channel. Whitehouse Creek is a main tributary for Bonsall Creek, comprising 11.6 km^2 of the Bonsall Creek watershed. Whitehouse Creek drains a portion of the Chemainus valley and the eastern slopes of Big Sicker Mountain.

Figure 3.1 shows the main rivers contributing to the study area, as well as watershed outlines for these rivers and select nearby Water Survey of Canada (WSC) stations.

People and Settlements

The Chemainus River floodplain, its watershed, estuary, and surrounding islands have been used since time immemorial by First Nation peoples for village sites, hunting, fishing, trapping, harvesting, and other cultural and sacred purposes (Rozen DL, 1985; Arthur Jim, Stz'Uminus First Nation Band Council member and cultural consultant, pers. comm. 18 March 2022). Halalt No. 2 (Halalt First Nation), Say-La Quas No. 10 (Stz'uminus First Nation), and Tussie No 6 (Penelakut Tribe) federal administrative boundaries are all located within the floodplain.

In 1849, colonization of the region began under the Hudson's Bay Company (L.M. Bell and R.J. Kallman, 1976), after which the landscape started to drastically change. The Trans-Canada Highway, Chemainus Road-Crofton Road, and Island Corridor Foundation (ICF) Rail line also cross the floodplain in the study area. Today the Chemainus River floodplain includes variety of land-uses, with agriculture being an important component. Portions of the floodplain lie within the boundaries of the Municipality of North Cowichan and the Cowichan Valley Regional District.



Watershed Pour Points
WSC Gauges
Streams
Chemainus Ruver Watershed
Bonsall Creek Watershed
Whitehouse Creek Watershed
WSC Gauges Watersheds

DATA SOURCES: BACKGROUND – ESRI WORLD TOPO, INSET – NATIONAL GEOGRAPHIC, WATERSHEDS AND STREAMS - BC FWA, GAUGES - WSC

SCALE - 1:200,000

0 1 2 3 4 5 6 7 8 KM

N

Coordinate System: NAD 1983 CSRS UTM ZONE 10N
Units: METERS

Job: 3006373 | Date: 20-MAY-2022

CHEMAINUS RIVER FLOOD MAPPING PROGRAM
REGIONAL WATERSHED OVERVIEW

FIGURE 3.1

4 FLOOD HISTORY

Floods on the Chemainus river typically occurs from November to March. Multiple days of heavy rain and rain-on-snow events are the primary driving mechanisms of riverine flooding. These intense winter storms are called atmospheric rivers. The extent of flooding brought on by these winter storms depends on the antecedent conditions of the Chemainus watershed during the month leading up to the storm. There have been many floods through history in this area. A complete list of the flood history is included in Appendix B, however, the top four floods recorded are listed below with three of them having occurred in the last 4 years.

Table 4.1 Description of largest four floods recorded on Chemainus River

Date	Chemainus River Flow (08HA001) (m^3/s)	Reported Flooding from (Septer, 2006) until 2006, thereafter local and NHC reports.
February 11, 1983	537	Following this flood event, in September 1984 a petition was signed by 24 residents and land owners to express concern over frequent flood damage and disruption of the road access along the lower Chemainus River (NHC, 1990).
January 3, 2019	512 (QPI)	The Chemainus River spilled its banks. Pinson's Corner flooded.
February 1, 2020	729 (QPI)	Flooding closed Highway 1 and Pinson's Corner. Russel's Farm was flooded.
November 15, 2021	652 (QPI)	Historic rainfall records were broken as an atmospheric river storm event impacted British Columbia. Flooding closed Highway 1 and Pinson's Corner. Russel's Farm was flooded. Residents in the lower floodplain were evacuated. See Photo 4.1.

Photo 4.1 Photos taken by NHC during the peak of the November 15, 2021 flood. Top left is Crofton Rd looking south from Hwy1a bridge, top right is Russel Farms Market, bottom left is corner of Chemainus Rd and Westholme Rd through Halalt First Nation and bottom right is Hwy 1 facing south where the flood overtopped the highway.

5 FIELD INVESTIGATIONS AND SURVEYS

NHC undertook a series of surveys to gather information about the Chemainus River. The survey information forms the basis of data inputs for the hydraulic models used in this project. Bathymetric and terrestrial surveys were completed and compiled into a Digital Elevation Model (DEM). A brief overview of the types of information collected is outlined below. Further technical information is in Appendix A.

Datum:

Several vertical datums are in use in the Chemainus study area. The Canadian survey and cartography industry has adopted the Canadian Geographic Vertical Datum 2013 (CGVD2013); the Province of British Columbia is migrating to this datum as new projects come online. As such, CGVD2013 was selected for the project.

- Horizontal Datum: North American Datum 83 (NAD83) CSRS 3.0.0.BC.1.NVI
- Projection: UTM Zone 10 North
- Vertical Datum: CGVD2013
- Geoid Model: CGG2013a

Figure 4.1 NHC completing surveys in the Chemainus Estuary

River and Chemainus Estuary surveys:

- Bathymetric surveys are measurements of ground elevations that are underwater. Data was collected with traditional land survey equipment.
- Bathymetric surveys were completed for the Chemainus River, Bonsall and Whitehouse Creek and transects in Chemainus Estuary.
- Geomorphic field investigations were carried out between October 2021 and March 2022, including knowledge sharing with First Nations, visual observations, sediment sampling, and field measurements.

Terrestrial surveys:

- Terrestrial surveying, also called land surveying, collects elevation and distance information for points on the surface of the Earth. Various terrestrial surveys were completed for this project.
- Bridges in the study area were surveyed so they could be represented in the hydraulic model. A series of hydrometric benchmarks were surveyed to shift WSC water levels into CGVD2013 datum.

LiDAR and DEM:

LiDAR (Light detection and ranging) data was used for general terrestrial topography over the study area. 2019 LiDAR was provided by GeoBC for the Chemainus floodplain and newer 2021 LiDAR for the Chemainus River only was provided by the Watershed Board. The DEM used the 2019 as the base topography data with the 2021 Chemainus River lidar overlaying and superseding the 2019 data where they overlap. The intersection between these two lidars and the survey data was carefully reviewed to ensure seamless stitching between the three datasets.

6 HYDROLOGY

A hydrologic analysis was completed for the Chemainus floodplain. The hydrologic analysis provides the required discharge and water level data for input to the flood models. A brief overview of the hydrologic assessment is provided below. Further technical information can be found in Appendix B.

Review of extreme flood events:

- Extreme flooding in Chemainus floodplain typically occurs from a series of Pacific low-pressure frontal systems generated off the West Coast of Vancouver Island. These storms, referred to as atmospheric rivers, bring large precipitation cells to the region that can lead to flooding.
- The Chemainus River has experienced the two largest floods on record during the past two years: the flood on February 1, 2020 peaked at 3 am, measuring 722 m^3/s, corresponding to a 15-year return period. The flood on November 15, 2021 peaked at 11am, measuring 648 m^3/s, corresponding to a 10-year return period.

Figure 5.1 Chemainus River looking upstream from Hwy 1 at peak of Nov 15, 2021 flood.

- Statistical frequency analysis was completed on Water Survey of Canada gauges to estimate the likelihood of extreme floods. The 200-year flood was estimated and was used to generate final flood mapping.

Timing of River and Coastal Flood Events

- In the lower reaches of the Chemainus and Bonsall floodplains, the water levels are governed by the interaction of river flows, the astronomical tide level and the magnitude of any storm surge. The highest water levels at any location do not necessarily correspond to the highest inflow discharge or highest ocean level.
- A joint probability assessment of discharge and tides suggested a 200-year riverine discharge combined with a moderately high ocean level (20-year event) were appropriate to represent designated flood scenarios.

Climate Change:

- Climate change science was reviewed to estimate how future flows on the Chemainus River may change by the year 2100[1].

[1] PCIC (2019). PCIC Regional Analysis Tool: https://www.pacificclimate.org/analysis-tools/pcic-climate-explorer

- Under warmer winters a greater portion of precipitation may fall as rain instead of snow. It was assumed that under climate change, the Chemainus discharge may increase up to 20 percent by the year 2100.

7 GEOMORPHOLOGY

The Chemainus River floodplain is prone to hydrogeomorphic channel hazards associated with channel avulsion, lateral channel instabilities and shoreline erosion. A geomorphic assessment was completed for the study area to assess the geomorphic processes and potential for channel migration on the floodplain and delineate areas that are susceptible to shoreline and channel migration hazards. The information has been used to prepare Geomorphic Hazard Maps. Channel stability and sediment deposition are also important considerations in flood mapping as they influence the accuracy of mapping and the recommended freeboard requirements. Further technical information can be found in Appendix C.

At the upstream end of the study area, the Chemainus River flows onto an alluvial fan. The fan is characterized by a radial topographic pattern emanating from valley confinement onto the floodplain. **Figure 6.1** shows sediment accumulations and a log jam that formed on the southern (right) bank of the river during the November 2021 flood event, near the upstream end of the floodplain.

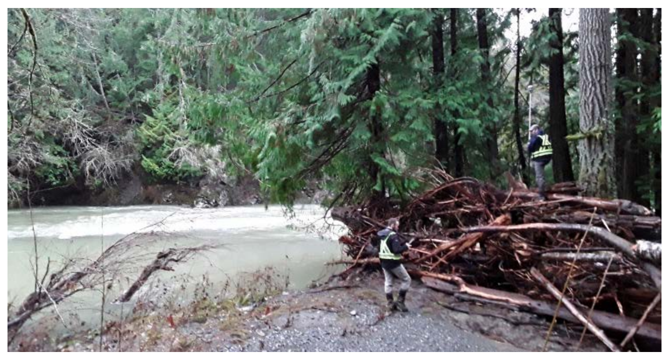


Figure 6.1 Log Jam on Chemainus River at upstream end of the floodplain

The floodplain includes areas that are potentially susceptible to coastal erosion and active channel processes, including lateral channel shifting and channel avulsion. A channel avulsion is a process whereby a channel is diverted from an established channel to a new channel path (First-order avulsion) or pre-existing path (Second-order avulsion) on the floodplain. Channel processes that can trigger an avulsion include the formation of log jams or other blockages and accumulation of sediment in depositional zones. Past and present-day depositional zones along the river, and relic channel patterns on the floodplain were identified using available imagery, DEM data, mapping information, and WSC rating curve gauge records. Results of model simulations were interpreted to evaluate river and wave hydraulics and shear stresses and infer erosion and sedimentation potential.

Historical channel positions were determined by delineating bank lines based on an assessment of eight years of imagery, including georeferenced historic air photos, Google Earth imagery, orthophotos, and federal historical survey information from the 1880s. Erosion hazard zones were estimated by computing historical bank migration rates, assessing valley and reach-scale channel planform constraints, evaluating surficial geology and bank material characteristics and historical channel evolution patterns. Wave model results, based on anticipated typical conditions with 1 m SLR were used to assess coastal erosion hazard potential.

Avulsion hazard zones were determined through a multi pronged approach. Valley and channel slope ratios and channel superelevation calculations were compared to established 'threshold' criteria at several potential avulsion nodes. Historical avulsion pathways, presence of relic channels, and post-flood field observations were accounted for; log and sediment deposition patterns were evaluated along with historical channel survey comparisons of the 1986 and 2021 channel bed profile to assess for trends of aggradation or degradation.

8 HYDRAULIC MODELLING OF RIVERS

Hydraulic river modelling was completed for three areas in the Chemainus Watershed (Figure 8.1):

1. The Chemainus River and estuary
2. Bonsall Creek
3. Whitehouse Creek and Butcher's Slough

The Hydraulic model was developed using the bathymetric survey, LiDAR, and landcover. Boundary conditions were determined in hydrologic analysis and coastal assessment. The hydraulic model was calibrated to the November 15, 2021 high water event using NHCs surveyed high water marks (Appendix D). The model was able to simulate 2021 water levels within 0.21 m of observed values on average. While the calibration doesn't seem tight, the confidence in the HWMs collected during the peak of the flood and the spread of them across the floodplain means this model is a much better representation of the floodplain than most models. The model was used to simulate present day flows as well as future climate change conditions. The results of the hydraulic model were used to make flood maps. Further technical information on the hydraulic modelling portion of this project can be found in Appendix D.

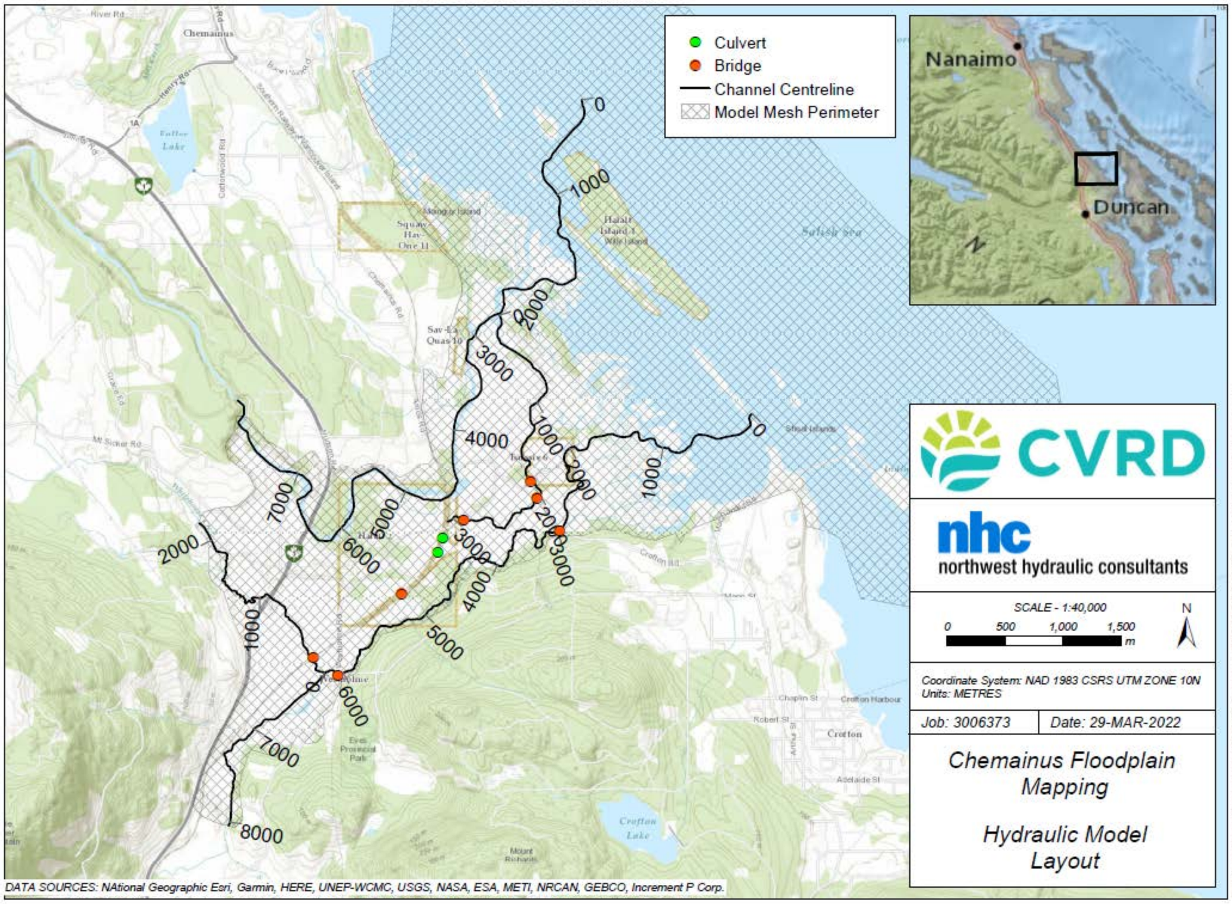


Figure 8.1 Hydraulic model layout; numbers along reaches identify model stationing.

9 COASTAL ASSESSMENT AND WAVE MODELLING

The coastal assessment portion of this study included review of tide levels for the Chemainus Estuary, and wave modelling for the Strait of Georgia, Stuart Channel and Chemainus Estuary. The 2D hydraulic model developed for this study requires tide data to simulate flood levels in the lower portion of the Chemainus floodplain. Wave analysis is required to complete flood mapping around shorelines. A brief overview of key coastal and wave modelling results is provided below. Further technical information regarding the coastal assessment can be found in Appendix E.

Coastal flood level assessment and climate change:

- An extreme event analysis was conducted using tide levels for the Chemainus Estuary.
- A joint probability analysis was completed to determine the joint occurrence of tides and storm surge.

- Climate change science and the BC Flood Mapping Guidelines (APEGBC, 2017) were reviewed to estimate regional sea level rise for the Chemainus Estuary by the year 2100.
- Estimations indicate that regional sea level rise for the Chemainus Estuary by the year 2100 is 1.0 m.

Wave modelling:

- Wind data was analyzed and used as inputs for the wave model (SWAN, model version 41.30, Figure 8.1).
- The potential damage generated by waves depends on the slope and characteristics of the shoreline (riprap versus grassy slope versus beach slope). Shoreline characteristics of the estuary and surrounding area were documented, and corresponding wave effects for defined shoreline reaches were calculated (Figure 8.2).
- The results of the wave modelling were incorporated into the flood mapping for the shoreline in the study area.

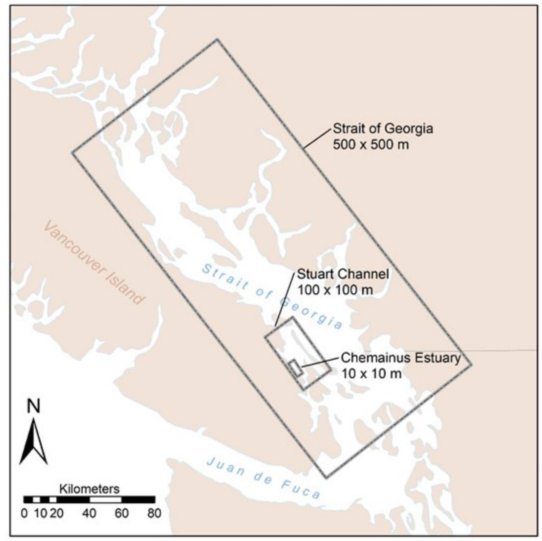


Figure 8.1 Wave model grid extents

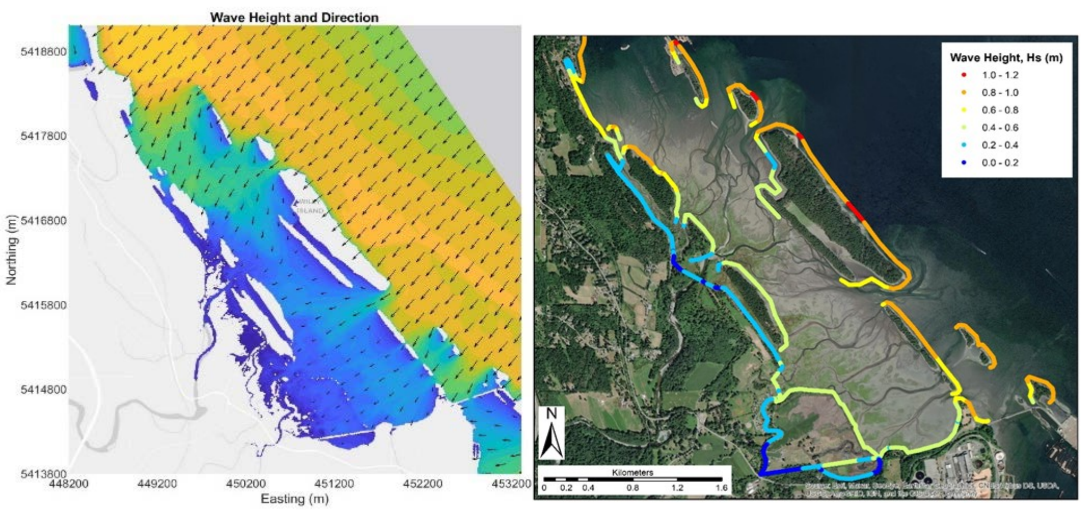


Figure 8.2 Wave model results and shoreline exposure

10 FLOOD AND GEOMORPHIC MAPS

A floodplain map delineates the area that can be expected to flood, on average, once every 200 years. There is a 0.5 % chance of the flood event happening in any given year. This 200-year flood is selected based on Provincial guidance (APEGBC, 2017). Two types of floodplain mapping products were produced as part of this study: flood depth and velocity hazard maps and designated floodplain maps. The methodology for developing the maps is explained in Appendix F. They are both created using the design flood; a 200-year flow on the river that was increased to account for climate change impacts and a 200-year still water ocean level that was increased to account for sea level rise (SLR) in the year 2100. Geomorphic hazard maps prepared for this study delineate areas that are susceptible to shoreline and channel migration hazards. The methodology for developing the maps is explained in Appendix C.

Flood depth and velocity hazard maps:

Flood depth and velocity hazard maps show the flood depths, extents, and associated velocities under a defined flood event. The maps were developed using the same scenario as the designated floodplain maps. The flood depth and velocity hazard maps are informational only and are intended for providing input for high level planning. They are not to be used for designating floodplains, establishing flood construction levels, designing dikes or any other structures. Freeboard and wave effects is not included in any of the flood depth and velocity maps. Flood depth maps are located in Appendix G.

Designated Floodplain maps:

Designated floodplain maps show the estimated flood boundary and associated flood construction levels under a defined flood event. A flood construction level is the minimum elevation for habitable buildings in a floodplain. In British Columbia, the standard flood event for which designated flood maps are developed is the 200-year flood with the addition of a climate change factor. For this study the designated floodplain map adopts conditions used for the 2100 timeframe. Flood construction zones along the shorelines incorporate wave effects. Flood construction levels also include a freeboard of 0.6 meters and elevations are in CGVD2013 datum. Designated flood maps are displayed at a 1:5000 scale; there are 4 map sheets for the floodplain that cover the study area. Designated flood maps are located in Appendix H.

Geomorphic hazard map:

Geomorphic hazard mapping prepared for this study delineate areas that are susceptible to channel migration hazards, including channel avulsion, lateral channel instabilities and shoreline erosion. The geomorphic hazard map is intended to help reduce risk by providing guiding information for land use planning. Geomorphic hazard mapping shows the estimated geomorphic hazard boundary over a 60-year planning horizon. This time horizon was selected based on the long -life design service life category defined in the BC Housing Design Guidelines and Construction Standard (BC Housing, 2019). The framework for determining geomorphic hazard zones for this project was adapted and modified from approaches used in Washington state. The following guidelines from other jurisdictions have been considered in the undertaking of this study:

- A Framework for Delineating Channel Migration Zones. Washington State Department of Transportation.(Rapp and Abbe, 2003).
- Channel Migration Processes and Patterns in Western Washington. A Synthesis for Floodplain Management and Restoration. State of Washington Department of Ecology14 (Legg and Olsen, 2014).
- Forest Practices Board Manual. Technical supplement to Washington State forest practice rules.(Forest Practices Board, 2004).

The maps show the following boundaries, according to their susceptibility to a particular geomorphic process. A Qualified Professional must be consulted for site-specific geomorphic analysis.

The geomorphic hazard mapping (Appendix I) includes the following mapping boundaries

- Modern Valley Bottom (MVB): Area where channel migration has likely occurred in the past several thousand years and is susceptible to occurring under the present-day hydroclimate regime.
- Historical Migration Zone (HMZ): Area that the channel occupied in the historical record, based on available imagery and survey data. This area is also susceptible to erosion and avulsion hazards.
- Channel Erosion Hazard Zone (EHZ): Area susceptible to bank erosion by stream flow over a 60-year planning horizon. This area is also susceptible to avulsion hazards. In addition to channel avulsion, the Chemainus River floodplain is prone to lateral channel instabilities and shoreline erosion.
- Avulsion Hazard Zone (AHZ): Area that is susceptible to avulsion. This area may also be susceptible to estuary distributary channel hazards in tidally influenced areas. The AHZ is classified into two categories (after(Nanson and A. David Knighton, 1996):
    - First-order avulsion: sudden and major shift to a new part of the floodplain
    - Second-order avulsion: sudden reoccupation of an old channel on the floodplain. Second-order avulsion zones may also be subject to first-order avulsions.
- Potential Geotechnical Hazard (Unrated): Area with steep slopes within the channel erosion hazard zone, which may become geotechnically unstable due to inundation or erosion of the toe of the slope. A geotechnical assessment is required to determine an appropriate geotechnical setback for land that may potentially be subject to any potential geotechnical hazards. Only steep slopes within 10 m of the erosion hazard zone boundary were flagged as potential geotechnical hazards. Additional steep slope hazards not flagged may exist outside areas identified as potential geotechnical hazard.
- Estuary Distributary Channel Hazard Zone (DHZ): Relatively lower gradient area influenced by tidal processes and susceptible to the formation of distributary channels. This area is also susceptible to channel erosion and avulsion hazards.
- Coastal Erosion Hazard Zone (CHZ): Landward extent of area likely to be at risk of erosion from tidal currents and waves generated during coastal storms, with 1 m sea level rise. This area is also susceptible to channel erosion, avulsion, and estuary distributary channel hazards.

11 DISCUSSION

Summary of Results

For the mapped 200-year design flood event, overbank flooding is observed through almost the entire study reach. The inundated areas consist of Halalt First Nation, Penelakut Tribe Tsussie Reserve, agricultural homes and fields, several roads, and the E&N Railway. The progress and movement of the flood is described below:

- Chemainus River floods over its right bank as it enters the valley where its flood waters pass through several fields, flood over Mt Sicker Rd, and impact several homes and properties in that region including Russel Farm Market, the Chevron Gas Station and Red Rooster Diner. This location is considered to be a potential first-order avulsion node, where the channel could be diverted from its established channel to a new channel path on the floodplain.
- Some of the water is diverted back into the Chemainus river but the majority of it continues south toward the Trans Canada Hwy (Hwy 1) where it ponds behind the highway next to the southwest valley wall. It eventually overtops the highway in this location spilling into the fields between Whitehouse and Bonsall Creek.
- The floodwater in the fields around Bonsall creek slowly moves downstream following Bonsall Creek. Some of the water is caught by the E&N Railway and stays on the upstream side of the railway and floods toward Chemainus River. The rest follows Bonsall Creek to the estuary.
- Downstream of Hwy 1 Bridge on Chemainus River (Green Bridge), the flood waters come over the banks move along several old side channels on the right bank. The flood passes through Halalt First Nation toward the estuary until it reaches the E&N Railway. From there the water backs up and reroutes toward the Chemainus River. Some water passes through culverts in the E&N Railway, some water overtops the Railway near Bonsall Creek. This location is considered to be a potential second-order avulsion node, where the channel could be diverted from its established channel into a pre-existing path on the floodplain.
- Downstream of the rail bridge, water floods over Pinsen's corner. Some of the floodwater is directed over Chemainus Rd toward Bonsall Creek, some over Crofton Rd toward the estuary and the rest follows Chemainus River to the estuary.
- Downstream of Crofton Rd there are several flow paths to the estuary which are all heavily inundated with fast moving water as the flood attempts to drain to the ocean. Access to Tsussie is cut off with swift water and inundated roads in all directions.

The flood construction level, geomorphic hazards and flood depth and velocity maps together illustrate the potential flood hazard in the Chemainus floodplain. They can be used to assess the region, areas within the study area, or particular properties. However, localized hazards should be reviewed for local and current conditions before relying on the result of the maps for assessment of a particular property.

Limitations

Industry best practices were followed to develop the floodplain maps and geomorphic hazards. However, actual flood levels and extents may vary from those shown. Local channel obstructions (such as log jams), local storm water inflows, the presence of unidentified culverts, the condition and capacity of existing culverts, tributary flow, groundwater, or other land drainage can cause flood levels to exceed those indicated on the map. Furthermore, erosion, degradation, aggradation, channel migration, avulsion, or channel blockages, may occur before or during a flood event and alter the expected flood levels and extents.

The model geometry was kept fixed to that surveyed in 2021. Variations of channel geometry from that surveyed in 2021 can alter the expected flood levels and extents. The maps do not provide information on site-specific hazards such as land erosion or sudden shifts in the water courses. Despite potentially being at risk to flood hazards; erosion protection structures, dikes, banks, bridges, and other infrastructure within the floodplain were not inspected or evaluated during this study for their ability to protect or withstand flood events.

The study area is limited to the Chemainus River including Bonsall and Whitehouse Creek where they are part of the Chemainus floodplain. Further upstream, the creeks narrow and become too small to be represented with the Chemainus flood model or on the regional-scale floodplain maps and are outside of the study limits and the influence of the Chemainus River. Therefore, these types of local flooding issues are outside the scope of this present study.

Floodplain maps are an administrative tool that indicates the flood elevations and floodplain boundaries for the designated design flood. Similarly, geomorphic hazard maps are an administrative tool that depict the extent of geomorphic hazards for a given planning horizon. A Qualified Professional must be consulted for site-specific engineering analysis to determine the specific hazard associated with a particular development. It is recommended that development within flood hazard or geomorphic hazard areas be guided by the EGBC (2018) Professional Practice Guidelines, Legislated Flood Assessments in a Changing Climate in BC to account for the specifics of a particular development and any changes since the development of these floodplain maps.

The geomorphic hazard zones identified by this study are based on recent observations, historical information, as well as interpretation of specific model simulations for river flood and wave design events considered to be reflective of channel and shoreline forming processes. Projected changes with SLR and altered peak flows to the year 2100 have been considered. However, this study does not account for other, uncertain future changes that could alter the landscape and may induce a geomorphic response resulting in an altered geomorphic hazard potential. The geomorphic assessment carried out for this study does not include an evaluation of sediment sources, terrain assessment, or assessment of the potential or frequency of slope instabilities, debris flow, debris flood, potential for channel jamming and outburst flooding, or hyper-concentrated flow

There is a residual risk that more extreme events may occur with greater flood depth and velocity. Changes in climate, land use, river form, or societies' risk tolerance may limit the usefulness of this work in time. Historically, floodplain maps in British Columbia are expected to need replacement every 25 to 30 years. Climate change is expected to increase the rate of change in the future; therefore, these maps may need to be reviewed, re-assessed, or replaced more frequently or following occurrence of a large flood event.

12 RECOMMENDATIONS AND NEXT STEPS

Floodplain and geomorphic hazard maps have been prepared for the Chemainus floodplain. The floodplain maps represent the 200-year flood adjusted for climate change and sea level rise conditions in year 2100. The floodplain and geomorphic hazard maps represent hazards from the river, creeks and coastline (in the form of waves). The maps do not represent effects of a tsunami. The produced maps can help guide identification and prioritization of mitigation measures, development or modification to emergency response planning, development of flood management strategies as well as inform regulators and property owners of the potential risks for land use within the floodplain.

The following are recommendations of this study:

- The new designated floodplain maps (Appendix H) should be adopted for flood planning purposes, including establishing flood construction levels, and enforced with a flood by-law. The new designated floodplain maps supersede the Province of BC maps from 1990 which are outdated and did not consider sea level rise or climate change.
- The flood depth and velocity maps (Appendix G) are informational only and intended for providing input for planning personnel. They are not to be used for designating floodplains, establishing flood construction levels, designing dikes or any other structures.
- The geomorphic hazard map (Appendix I) should be adopted for flood planning purposes and used in conjunction with the floodplain maps.
- The new floodplain maps and geomorphic hazard maps should be reviewed after a period of 10-15 years, or after the occurrence of any extreme flood event. Floodplain maps need to be updated periodically to account for topographic changes, new developments which affect hydraulic conditions, and new information related to future climate change.
- It is recommended that the CVRD, North Cowichan, and Halalt Nation continue to communicate the project findings with agencies and organizations that have flood management roles and responsibilities.
- Mitigation for flooding in the Chemainus floodplain will be further investigated however, the most obvious mitigation measure, due to relatively minor cost and effectiveness at reducing flood risk, is updating the regulatory controls on development within the floodplain (such as flood by-laws). Although such measures do not help existing structures and infrastructure, they do limit potential threats for future development.

Next Steps:

A next step in flood management planning for the Chemainus floodplain would be to complete the flood management strategy options. The options would include multiple strategies for dealing with / mitigating floods that might potentially suit the communities in the area. It would include a flood risk assessment, suggest mitigation measures for the area.

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APPENDIX A

SURVEYS

APPENDIX A

SURVEYS AND WATER LEVEL MEASUREMENTS

TABLE OF CONTENTS

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1 BACKGROUND

This section describes the data used to support the hydraulic modelling components of the project. Ground elevation data was drawn from a series of surveys carried out for this project. The acquisition of topographic, bathymetric, and hydrographic information forms the basis of data inputs for the hydraulic modelling component. The topographic data was mainly LiDAR, and NHC surveys. Bathymetric data included NHC bathymetric surveys in Chemainus River and Bonsall and White creeks. For the coastal component, bathymetry data included CHS Non-Navigational 10m Gridded Bathymetry Data (NONNA-10), contours interpreted from CHS charts, Canadian Digital Elevation Model (CDEM), for the Chemainus Estuary and Stuart Channel and National Oceanic and Atmospheric Administration (NOAA) data for Strait of Georgia.

2 DATUM AND COORDINATE SYSTEM DETAILS

Several vertical datums are in use for current and historic data in the study area. The Canadian survey and cartography industry has adopted the Canadian Geographic Vertical Datum 2013 (CGVD2013), and the province of British Columbia is migrating to this datum as new projects come online. As such, CGVD2013 was selected for the project.

In summary, specific coordinate system details are:

1. Horizontal Datum: North American Datum 83 (NAD83) CSRS 3.0.0.BC.1.NVI
2. Projection: UTM Zone 10 North
3. Vertical Datum: CGVD2013
4. Geoid Model: CGG2013a

3 DATA PROVIDED TO NHC

3.1 LiDAR

LiDAR surveys provide detailed topographic mapping over the dry portions of channels and floodplain. LiDAR data is necessary both for representing the conveyance of the floodplain in the hydraulic model and for mapping the extent and depth of flooding in the final floodplain maps. The details of the LiDAR used in this study are summarized in Table 3.1.

Table 3.1 Reported specifications of available LiDAR data

	2019 GeoBC	2021 Cowichan Watershed Board
Acquisition Date	October 14, 2018 – October 1, 2019	March 27, 2021
Tide Level	Low	Low
Project Coverage	Full Coverage	Partial, Chemainus River Only
Non-vegetated Vertical Accuracy (NVA) – Vertical Root Mean Square Error ($RMSE_Z$)	0.029 m	Mean = 0.112 m, RMSE = 0.161 m
Horizontal Root Mean Square Error ($RMSE_r$)	**information not available*	**information not available* 1 control point difference - dX = 0.17 m; dY = 0.000 m
Aggregate nominal point density (ANPD) for DSM (first return) and DEM (last return)	DSM: 8-10 pts/m^2 DEM: information not available	DSM: 36 pts/m^2 DEM: ~ 70 pts/m^2
Datum	CGVD2013	CGVD2013

The 2019 LiDAR covers the entire floodplain while the 2021 LiDAR only covers Chemainus River channel and banks. However, 2021 LiDAR is most recent and will cover any changes that occurred on the Chemainus river due to the 2020 flood. Therefore, it was included in the DEM with the 2019 LiDAR.

The LiDAR data was put through a QA/QC procedure which involved conducting field check surveys using a Real Time Kinematic receiver and base station and then comparing the surveyed ground elevations to elevations from the topographic grid derived from the LiDAR data. The check survey points were evenly dispersed around the study area (Figure 3.1) to ensure the full extent of the mapped floodplain was assessed. Details of the survey equipment and methods are described in Section Accuracy Considerations. The accuracy of the check surveys was 0.05 m. Results of the comparison are summarized in Table 3.2. The differences in elevations were used to estimate the Root Mean Square Error (RMSE) for the LiDAR dataset to independently verify that the RMSE value reported by the LiDAR provider adheres to the Federal Flood Mapping Framework (Natural Resources Canada and Public Safety Canada, 2018b) and the Federal LiDAR Acquisition Guidelines (Natural Resources Canada and Public Safety Canada, 2018a). As is shown in Table 3.2, the RMSE of the 2019 LiDAR was checked but 2021 LiDAR has limited data provided. The 2021 LiDAR was provided after the LiDAR check points were laid out and covers very little of the floodplain, so overlap was limited to only 1 point.

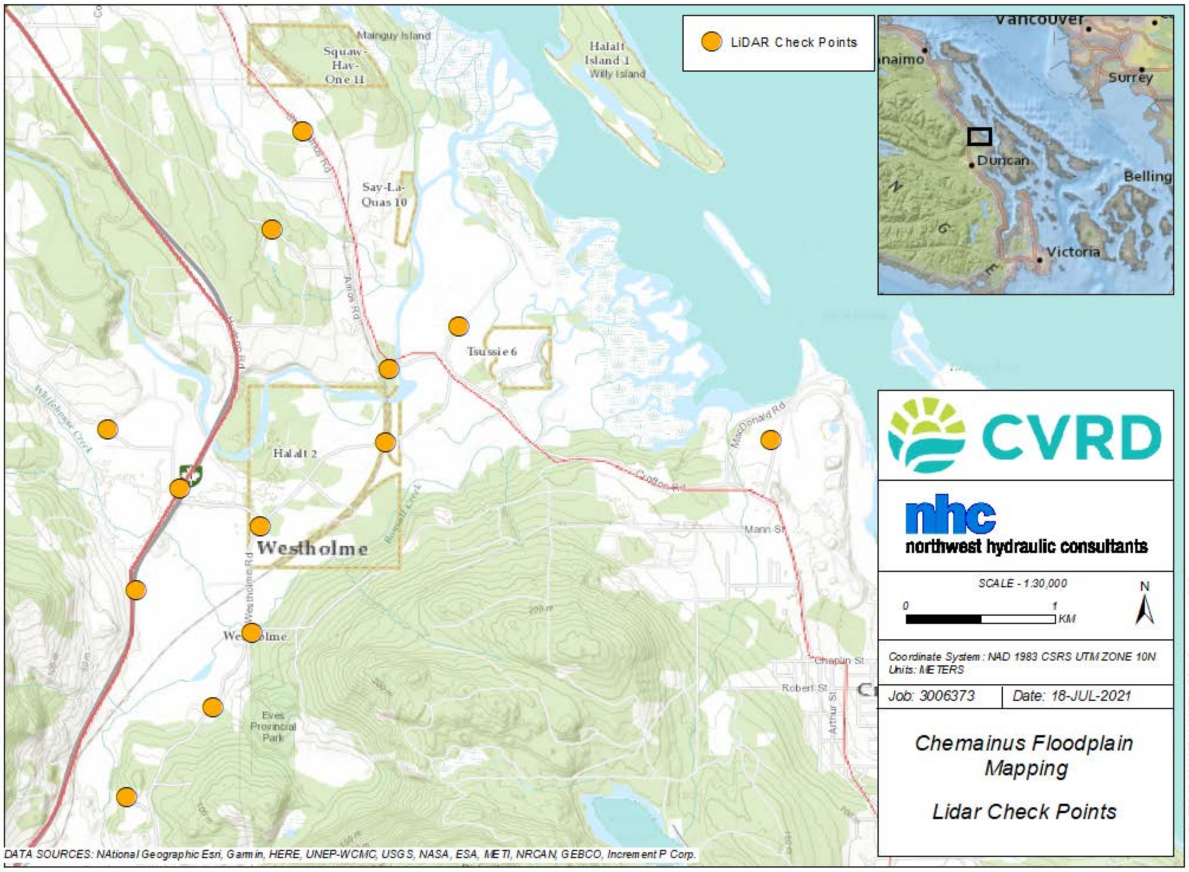

Figure 3.1 LiDAR check points for Chemainus Floodplain

Table 3.2 LiDAR Checkpoint Calculations

Point	NHC Survey Elevations (CGVD2013)	2019 LiDAR Elevations (CGVD2013)	2021 LiDAR Elevations (CGVD2013)	Difference (m)	
				2019 LiDAR	2021 LiDAR
1	8.04	8.07		-0.03	
2	10.88	10.92		-0.05	
3	10.85	10.87		-0.03	
4	28.91	28.90		0.01	
5	9.02	9.04		-0.02	
6	7.94	7.98		-0.04	
7	8.55	8.61		-0.06	
8	3.22	3.26		-0.04	
9	21.80	21.86		-0.06	
10	7.13	7.12	7.14	0.01	-0.01
11	40.42	40.45		-0.03	

12	32.03	32.03		0.00	
13	7.69	7.86		-0.17	
Root Mean Square Error (RMSE)				0.06	-

A comparison with the federal guidelines and the chosen LiDAR sources for this project is summarized in Table 3.3. After review of the LiDAR data and meta data, we have determined we do not have enough information to independently confirm that it meets the federal guidelines for horizontal accuracy. However, it does meet the federal guidelines in all other aspects and through NHCs own check (for 2019 LiDAR only). There is one control point information provided for the 2021 LiDAR showed a very small horizontal difference. NHC will rely on the reported RMSE provided by the 2021 LiDAR.

Table 3.3 LiDAR data accuracy and density for floodplain mapping applications for available LiDAR

Data accuracy	Flood Risk Category			2019 GeoBC LiDAR	2021 Cowichan Watershed Board LiDAR
	High	Medium	Low		
Vertical Accuracy (open, level, hard surfaces)					
Non-vegetated Vertical Accuracy (NVA) – Vertical Root Mean Square Error ($RMSE_Z$)	≤ 5.0-7.5 cm	7.5-10.0 cm	15 cm	2.9 cm	16.1 cm
Non-vegetated Vertical Accuracy (NVA) – 95% confidence level (≈ 1.96 * $RMSE_Z$)	≤ ±10-15 cm	±15-20 cm	±30 cm	6.7 cm	31.5 cm (calculated by NHC)
Horizontal Accuracy (open, level, hard surfaces)					
Horizontal Root Mean Square Error ($RMSE_r$)	≤ 11-15 cm	30-45 cm	60 cm	Not found in metadata	Not found in metadata
Horizontal Accuracy – 95% confidence level (≈ 1.7308 * $RMSE_r$)	≤ ±20-25 cm	±50-75 cm	±100 cm	Not found in metadata	Not found in metadata
Data density					
Aggregate nominal point density (ANPD) for DSM (first return) and DEM (last return)	≥ 4-10 pts/m^2	2-4 pts/m^2	1-2 pts/m^2	DSM: 8-10 pts/m^2 DEM: information not available	DSM: 36 pts/m^2 DEM: ~ 70 pts/m^2

A comparison of the 2021 and the 2019 LiDAR was conducted to see where major differences are occurring (Figure 3.2). The differences observed mostly occur along the banks and the bars of the river. This was expected since Chemainus River saw a large flood in 2020 which was expected to have moved sediment in the river (moved the gravel bars) and to have eroded banks. No systematic difference has been observed. Please note that the channel is showing orange (0.1-0.5 m difference) because the one set of LiDAR was hydro-flattened, and the river was likely at a different level when flown.

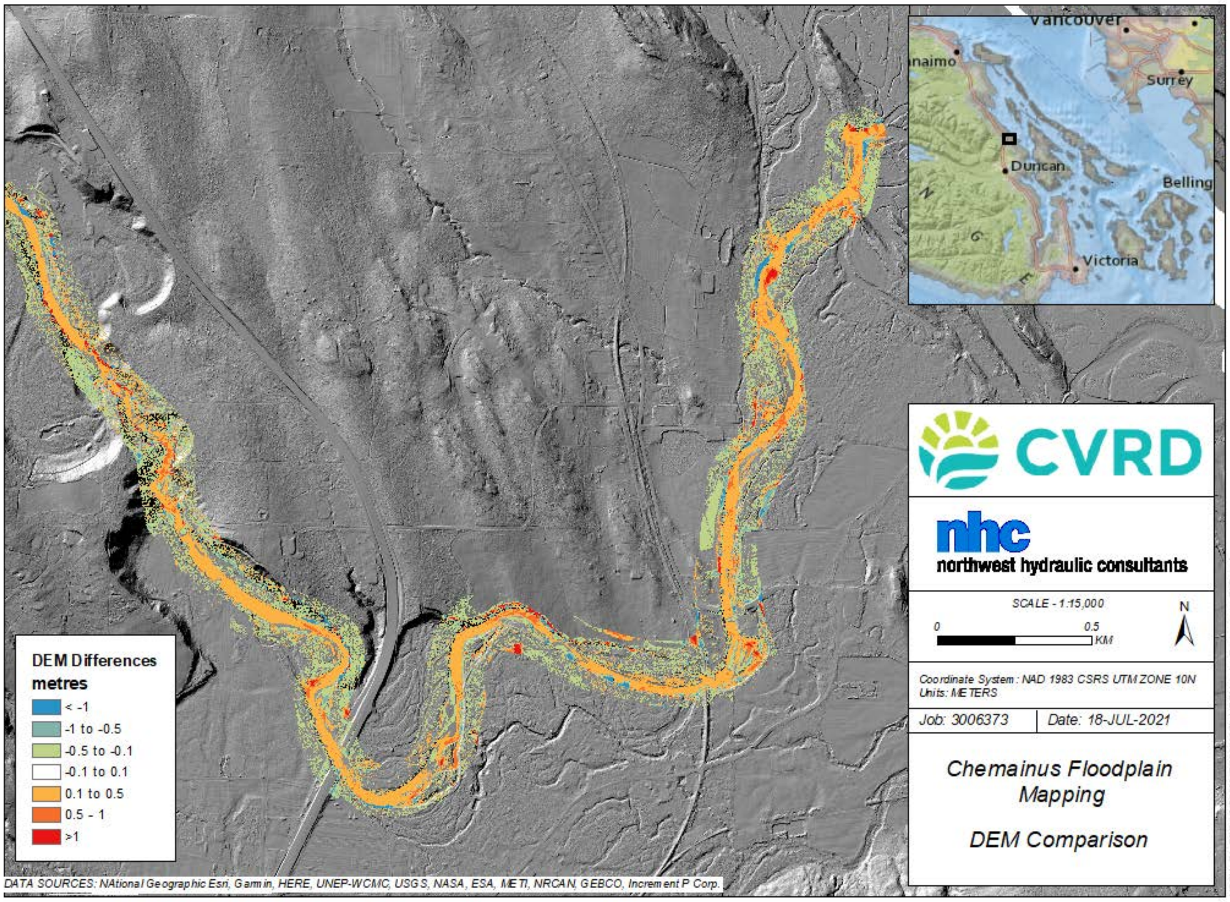

Figure 3.2 2019 LiDAR and 2021 LiDAR comparison

The differences in the banks due to the erosion and depositional changes and is the reason why NHC would prefer to use this more recent LiDAR in the Chemainus River even though it did not have as low of a RMSE as the 2019 LiDAR. The RMSE for the 2021 LiDAR is based on GPS control points for both the Koksilah and the Chemainus River flights combined so it is unclear how accurately this reflects the Chemainus River data alone. Additionally, the RMSE is reportedly based on points taken at the edge of road, tall grass, and shrub. The vegetation points can vary significantly and NHC only intends to use the Bare earth points for this study. This would likely reduce the RMSE if only edge of road points were included. The 2021 LiDAR is also of higher resolution which is useful to see banks and bars. This LiDAR was also more likely to tie in better to the current survey as there was little change in the river between the dates when the LiDAR was flown, and the survey was conducted.

After careful review, the 2019 GeoBC in combination with the 2021 Cowichan Watershed Board LiDAR is suitable for use in this project and for floodplain mapping. The additional 2021 LiDAR data, when combined with the 2021 bathymetric provides an excellent basis for developing a high-quality DEM of the channel and floodplain.

3.2 Bathymetric Charts

For modelling tidal and wave effects, bathymetric elevations were compiled for the Strait of Georgia, Stuart Channel, and Chemainus Estuary from multiple sources. Topographic elevations in the vicinity of the project site (within the Chemainus Estuary wave model and hydraulic model grid extents) were obtained from GeoBC 2019 LiDAR and processed by NHC GIS analysts (in the project vertical datum: CGVD2013). Table 3.4 provides a summary of elevation data used for the tidal and wave modelling.

Table 3.4 Bathymetric data sources

<table>
<tr><th>Wave Computational Grid</th><th>Data Source</th></tr>
<tr><td>Strait of Georgia
(500 x 500 m)</td><td>• CHS Non-Navigational 10 m Gridded Bathymetric Data (NONNA-10)
• Digitized CHS Charts
• NOAA 3 arc-second resolution dataset</td></tr>
<tr><td>Stuart Channel
(100 x 100 m)</td><td rowspan="2">• NHC Bathymetric Survey data
• GeoBC 2019 LiDAR
• CHS Non-Navigational 10 m Gridded Bathymetric Data (NONNA-10)
• Contours interpreted from CHS Charts
• Canadian Digital Elevation Model</td></tr>
<tr><td>Chemainus Estuary
(10 x 10 m)</td></tr>
</table>

4 NHC SURVEYS

4.1 Survey Equipment

NHC carried out a series of surveys that included setting up a control network, and collecting ground, bridge, bathymetric and hydrographic surveys. The following equipment was used to complete the survey work:

- Trimble R12 GNSS RTK GPS rover receiver
- Trimble S7 Robotic Total Station
- Trimble R12 GNSS RTK GPS base receiver w/ Pacific Crest 35-watt radio
- Trimble TSC3 controller w/ Trimble Access field software
- Trimble Business Center desktop software
- Takacat boat

4.2 Accuracy Considerations

The following are equipment accuracies in ideal field conditions:

- Trimble R12 GPS RTK receivers: +/-0.05 m
- Nikon NPL 332 Total Station: +/- 0.02 m

Typically, the overall bathymetry survey accuracy is 0.10 to 0.15 m for the multi-sensor kinematic (moving collection) setup applied. Ground surveys using GPS have a normal accuracy of +/- 0.05 m. Total station surveys, such as of the bridge structures, have +/- 0.05 m accuracy.

4.3 Control Surveys

A static survey was completed to establish the control network for the project. A base receiver was set up in the morning each day at a central location and left to log static data for 8+ hours. Three occupations of the receiver's static data were submitted to National Resources Canada Precise Point Positioning (NRCAN PPP) post processing service and averaged to determine the coordinates of the RTK base point. The resulting coordinates were checked to British Columbia Provincial survey monument GCM 754630 and tied to within GPS tolerance. Daily occupations on control points were loaded into Trimble Business Center and processed with the dual frequency baseline processor to ensure accuracy through the project area.

4.4 River Bathymetry Surveys

Figure 4.1 shows the layout and extent of the bathymetric survey. The survey was conducted by NHC staff members from May 25 to June 4, 2021, with an additional day on June 14, 2021. The terrestrial and bathymetric survey was completed using Real Time Kinematic (RTK) Global Positioning System (GPS). Trimble R12 receivers, a Pacific Crest 35-watt external radio, and Trimble TSC3 data collector were used to collect the data. Where RTK GPS environments were poor, the survey crew used a Trimble S7 Robotic Total Station.

Additional cross sections were gathered at key locations defined by the senior modeller to better capture river bathymetry. Cross sections on Bonsall Creek were captured in key locations as thick vegetation did not allow for the planned sections to be surveyed. The estuary check points and profiles were gathered during the low tide and were accessed by walking or by boat. Ten bridges across the floodplain were surveyed to be incorporated into the two-dimensional model. LiDAR check points were gathered to ensure merging of multiple data sets is within acceptable tolerances. The WSC gauge 08HA001 was surveyed to convert gauge data to the updated vertical datum.

The survey captured all but one of the historical cross sections from the 1990 flood plain study of the Chemainus River. While not all of the original cross sections were collected on Bonsall Creek, key cross sections were collected to ensure the channel could be appropriately represented in the DEM and subsequent flood modelling.

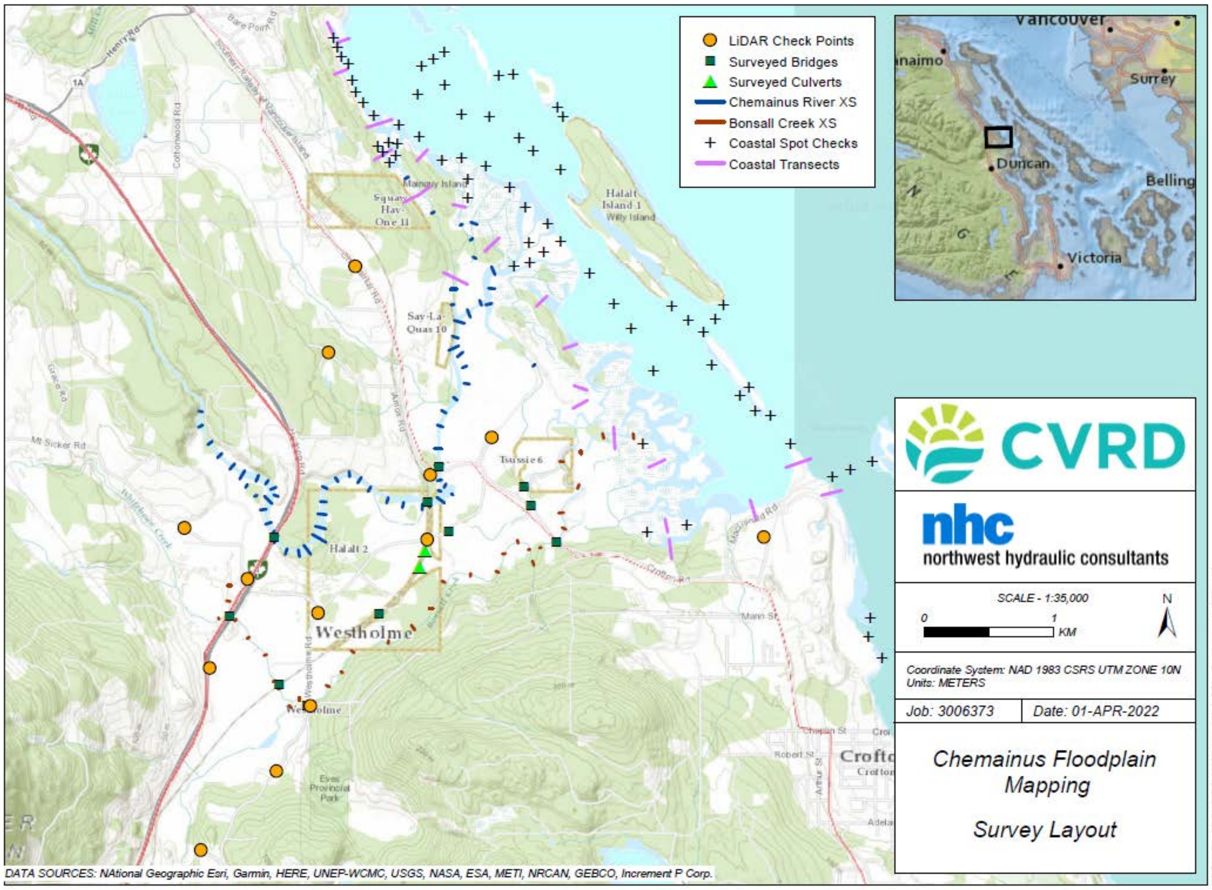

Figure 4.1 Survey Layout for Chemainus Floodplain

4.5 Bridge Surveys

Ten Bridges were surveyed as part of the study. At each location the following items were recorded:

- Top of bridge deck
- Span length
- Span width
- Top elevation (top of curb or solid guardrail – upstream and downstream)
- Low Chord elevation
- Any constricting factors of the river at the bridge locations upstream and downstream
- Piers
  - Number
  - Location
  - Width
  - Type (e.g., concrete, pile bent, etc.)

- Shape (e.g., round nose, wedge shape, etc.)

The bridges that were surveyed for this project are shown in Table 4.1.

Table 4.1 List of bridges surveyed for this study.

No.	Bridge/Road	Watercourse	Station (m)	Piers or Abutments?
1	Highway 1 (Green Bridge)	Chemainus River	6,400	No
2	E&N Railway	Chemainus River	4,625	No
3	Highway 1A (Chemainus Road)	Chemainus River	4,345	Yes - 1
4	Highway 1A (Chemainus Road)	Butcher's Slough	2,885	No
5	Tsussie Road	Butcher's Slough	1,835	No
6	Crofton Road	Butcher's Slough	2,035	No
7	Highway 1	Whitehouse Creek	895	No
8	Railway bridge	Whitehouse Creek	200	No
9	Westholme Road	Bonsall Creek	6,052	No
10	Crofton Road	Bonsall Creek	2,980	No

4.6 High Water Marks

High water marks were collected during the Nov 15, 2021, flood event to use for calibration of the hydraulic model. The highwater marks were surveyed using the same method described above for the river and topography surveys. A collection of the high-water marks collected can be seen in Figure 4.2.

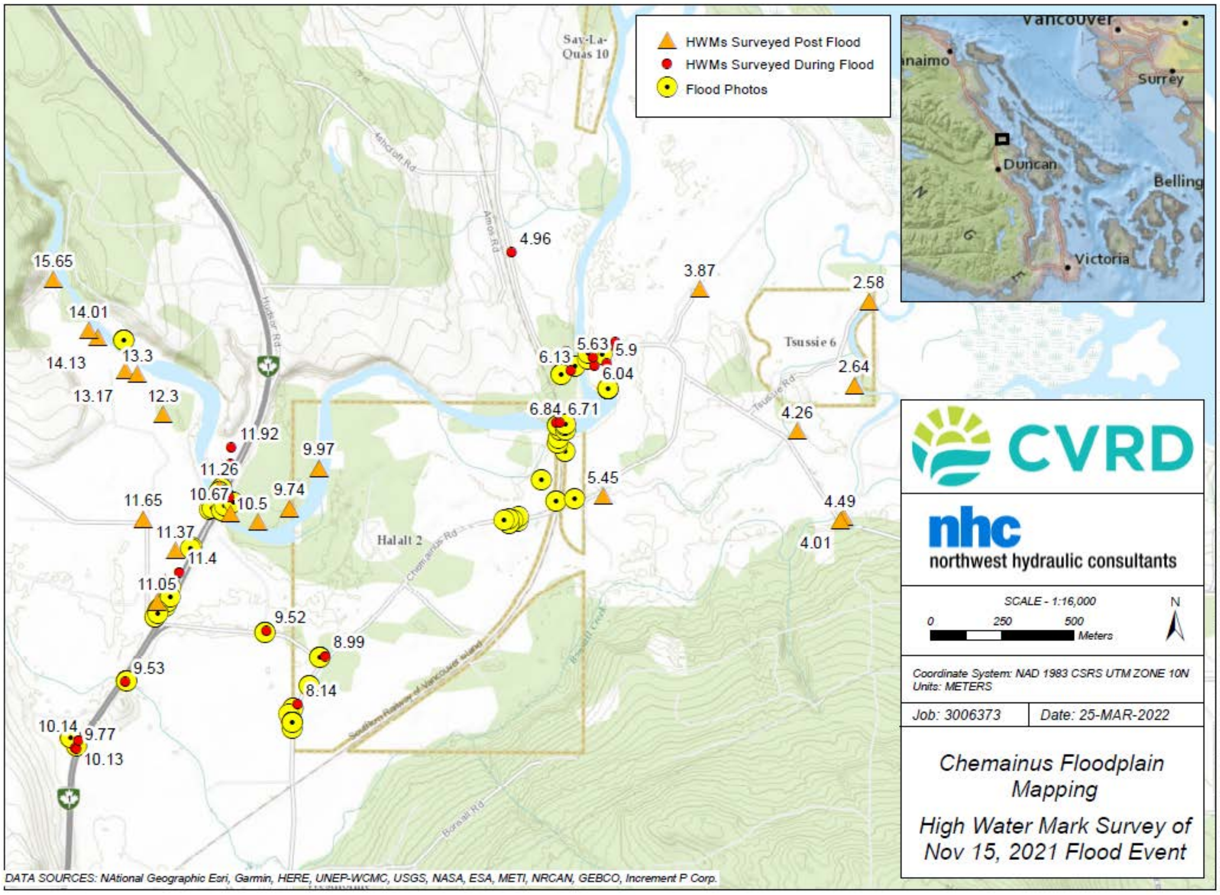

Figure 4.2 HWM locations surveyed during Nov 15, 2021, flood.

5 CONCLUSIONS

After careful review, the 2019 GeoBC in combination with the 2021 Cowichan Watershed Board LiDAR is suitable for use in this project and for developing floodplain mapping products that are consistent with present guidelines and standards.

The NHC bathymetric surveys combined with the two LiDAR data sets provides an excellent basis for hydraulic modelling and preparing updated flood maps of the Chemainus River floodplain.

6 REFERENCES

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APPENDIX B

HYDROLOGY

APPENDIX B
HYDROLOGY

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1 THE CHEMAINUS RIVER FLOODPLAIN AND BONSALL CREEK

The Chemainus River watershed is 355 km^2, with an overall length of approximately 45 km and width typically between 5 km to 10 km (Figure 1-1). The headwaters are located north of Cowichan Lake, with the watershed's highest point at the peak of Mount Whymper (maximum watershed elevation of 1,534 m). The river generally flows in a south-easterly direction in a structurally controlled valley until it turns northward near Mount Sicker and begins flowing over the Nanaimo Lowlands. It then continues to a broad alluvial plain near Westholme and enters the Chemainus River Estuary tidal flats draining into Stuart Channel. The floodplain mapping reach includes the lowest 5 km of river on the alluvial plain, which has an irregular meandering channel pattern, with recent channel scars or sloughs that indicate former positions of the river channel.

Bonsall Creek also flows into the Chemainus River Estuary tidal flats, just south of the Chemainus River. The Bonsall Creek watershed is 35.8 km^2, with an overall length of approximately 10 km. Bonsall Creek drains the southern and eastern slopes of Sicker Mountain (maximum watershed elevation of 721 m), the Somenos Lake Lowlands, and a small upland north of Crofton. The floodplain mapping reach of Bonsall Creek is on the alluvial plain in an incised, irregular meandering channel. Whitehouse Creek is a main tributary for Bonsall Creek, comprising 11.6 km^2 of the Bonsall Creek watershed. Whitehouse Creek drains a portion of the Chemainus valley and the eastern slopes of Big Sicker Mountain.

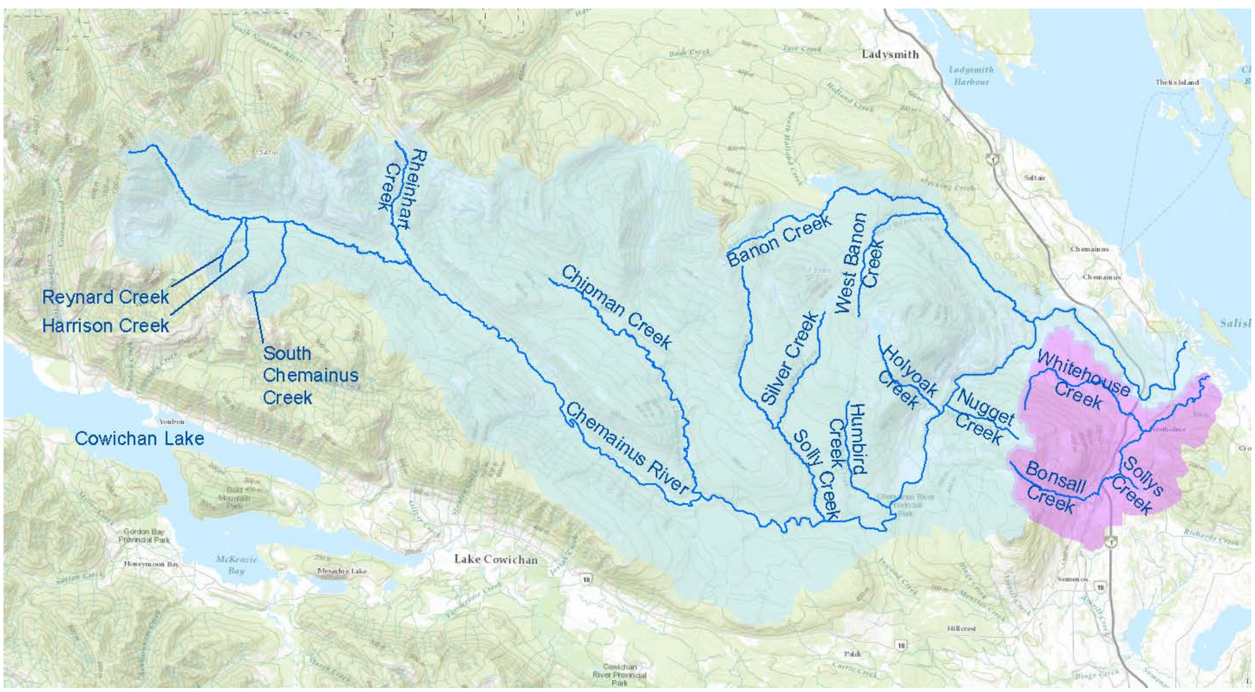

Figure 1-1 Overview of Chemainus River and Bonsall Creek watersheds.

2 STUDY APPROACH

To simulate various flood modelling scenarios for the Chemainus River and Bonsall Creek floodplains, inflow points and associated drainage areas were defined as shown in Figure 2-1 and Table 2-1. Water Survey of Canada (WSC) gauges were reviewed to determine appropriate gauges to inform flood frequency analysis. A climate change factor was applied to frequency analysis estimates which were then scaled to model inflow points. Inflow hydrographs were developed for various calibration and design scenarios using hydrograph shapes from past events.

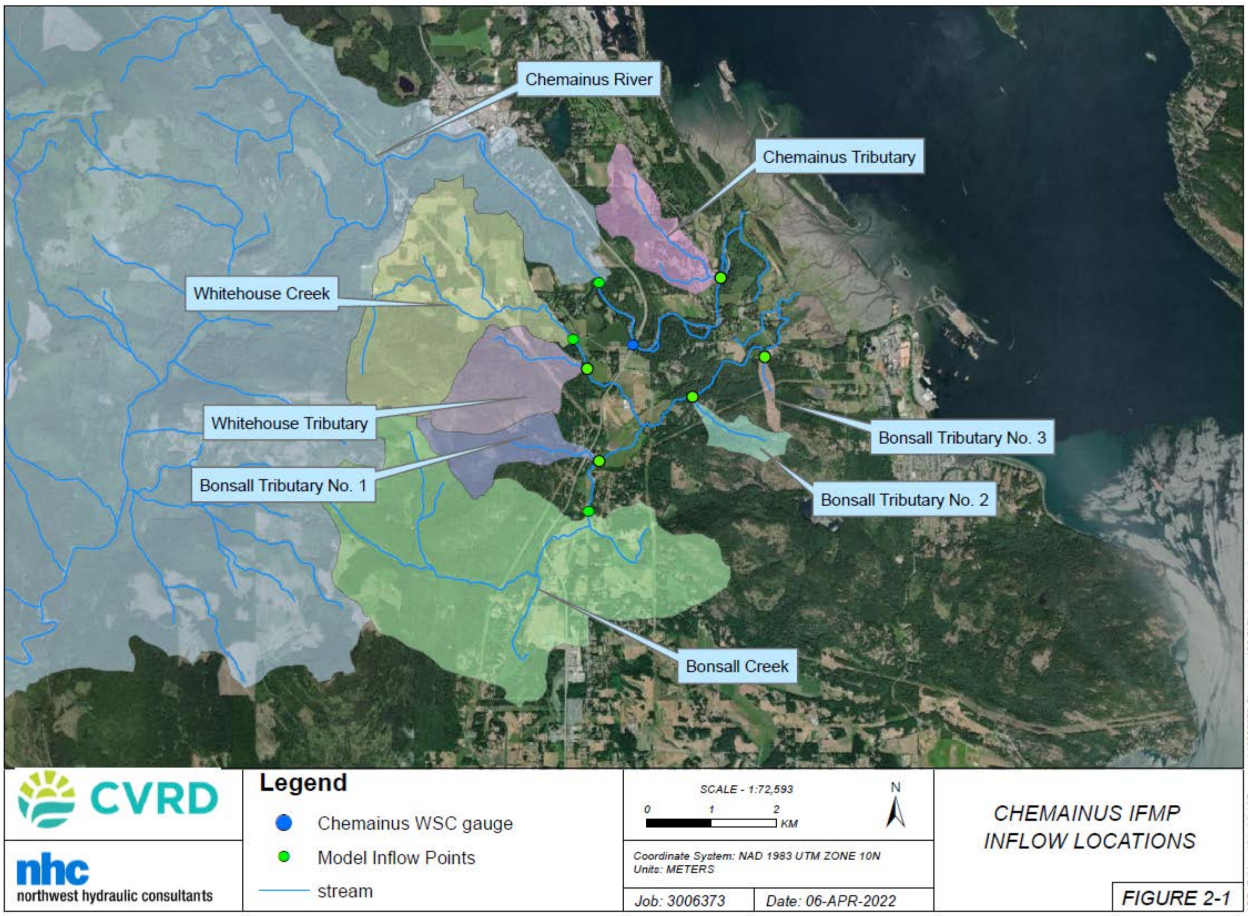

Figure 2-1 Overview of model inflow points.

Table 2-1 Summary of drainage areas for model inflow points.

Watershed	Chemainus River	Bonsall Creek	Whitehouse Creek	Unnamed Chemainus Tributary	Unnamed Whitehouse Tributary	Unnamed Bonsall Tributary1	Unnamed Bonsall Tributary2	Unnamed Bonsall Tributary3
Area (km^2)	349	14.4	6.8	1.8	2.5	1.6	0.64	0.2

3 OVERVIEW OF WSC GAUGES USED

Design flows for this study were based primarily on 2 WSC gauges as shown in Table 3-1. The gauges were selected based upon the inflow requirements of the hydraulic model. The Chemainus River WSC gauge (08HA001) was used to develop inflows for the Chemainus River. A proxy basin analysis was completed and the Bings Creek WSC gauge was selected as the most appropriate proxy gauge to develop inflows for Whitehouse and Bonsall Creek.

Data records for both stations were accessed via the Environment Canada Data Explorer (version 2.1.8) HYDAT (version date October 19, 2021). For years 2018-2020 provisional WSC data was accessed through a data request.

Once gauges were selected the drainage areas and data records were reviewed. Drainage areas were reviewed using Esri ArcGIS software and spatial layers from the BC Freshwater Atlas and basin shapefiles from WSC. Data records were assessed for completeness and years with instantaneous peaks (QPI) and maximum daily peaks (QPD) were noted. WSC site description sheets were reviewed for additional meta data.

Table 3-1 Overview of WSC gauges used for this study.

River	WSC gauge	Record	Regulated	QPI Record	QPD Record	Basin Area (km^2)
Chemainus River near Westholme	08HA001	1914-1914, 1952-present	N	1988-2020	1915-1916, 1953-2020	355
Bings Creek near the mouth	08HA016	1961-present	N	1994-present	1962-present	15.5

4 HISTORIC FLOOD EVENTS

Flooding on eastern Vancouver Island generally occurs in the late fall and winter from atmospheric river storms. When the Chemainus River exceeds bankfull stage upstream of the Highway 1 bridge, flows may concentrate in an overflow channel on the right bank and get directed into Whitehouse Creek.

Table 4-1 Overview of historic floods on the Chemainus River. When available, instantaneous annual peak flow (QPI) values are presented.

Date	Chemainus River Flow (08HA001) (m^3/s)	Reported Flooding from (Septer, 2006) until 2006, thereafter local and NHC reports.
December 22-23, 1947	No data	The Island Highway near Westholme was under water for over a mile (1.6 km) after Chemainus River overflowed its banks. In the Westholme district, dozens of homes were surrounded by water. Between Victoria-Chemainus, hundreds of acres of low-lying pasture land were inundated
January 20-25, 1951	No data	A combination of continuous heavy rain for four days, melting snow and high water tides, backed up water in the Chemainus, Koksilah and Cowichan rivers. Low-lying areas at

		their mouths were flooded, peaking late on January 25. On January 25, Native Indian settlements at Cowichan Bay, Chemainus, Crofton, Westholme and Somenos were seriously threatened. On January 25 at Chemainus, one of the seven bridges was temporarily afloat
December 22-23, 1963	241 (estimated)	The Cowichan, Chemainus and Koksilah rivers all spilled their banks Large areas were flooded after almost 2 in. (50 mm) of rain fell in 30 hours. Worst hit area was Westholme where the Chemainus River broke its banks and flooded hundreds of acres, completely isolating Pinson's Corner, a small settlement between Crofton-Chemainus. At Pinson's Corner, a garage, restaurant and several homes were completely flooded with 4 ft. (1.2 m) of muddy water. Just south of Westholme, the rail line also flooded. Water was across the road between the Pimbury bridge and the Klemklemaetz bridge. On the Cowichan Indian Reserve some homes were cut off, forcing some families to evacuate.
December 25-26, 1972	382 (estimated)	A high tide on Christmas night caused flooding in North Cowichan and Chemainus. In the Chemainus area, about 10 more homes also flooded. The oil tanks ruptured in two of these houses, covering everything inside with 0.5 in. (1.25 cm) of oil. The local mayors wanted their communities declared disaster areas. Heather Street in North Chemainus also flooded. Road conditions on the Island Highway were poor. Floodwaters up to 5 ft. (1.5 m) deep cut the Chemainus to Crofton road
February 11, 1983	537	Following this flood event, in September 1984 a petition was signed by 24 residents and land owners to express concern over frequent flood damage and disruption of the road access along the lower Chemainus River (NHC, 1990).
March 18, 1997	382 (QPI)	In a 24-hour period from March 17-18, the Chemainus weather office recorded 86.2 mm of rain, breaking the previous 24-hour record for March of 79 mm. The Chemainus River overflowed its banks at the intersection of Crofton and Chemainus roads, the regular rain trouble spot in the Crofton area.
January 3, 2019	512 (QPI)	The Chemainus River spilled its banks. Pinson's Corner flooded.
February 1, 2020	729 (QPI)	Flooding closed Highway 1 and Pinson's Corner. Russel's Farm was flooded.
November 15, 2021	652 (QPI)	Historic rainfall records were broken as an atmospheric river storm event impacted British Columbia. Flooding closed Highway 1 and Pinson's Corner. Russel's Farm was flooded. Residents in the lower floodplain were evacuated.

5 FLOOD FREQUENCY ANALYSIS

Flood frequency analysis requires that data be independent, homogeneous and stationary over time. The independence requirement means that floods from one year do not affect the following year (the river returns to base flow between the 2 events. “Homogeneous” means the annual floods are all from a single population of flood generating events. An example of non-homogeneity is when some floods are generated by winter precipitation while others occur in the spring due to snowmelt. “Stationarity” means the statistical properties of the floods does not change over time (no trend of increasing or decreasing flows). In a time of climate change this assumption is often violated. Statistical tests can be carried out to verify each of these assumptions.

5.1 08HA001 Chemainus River near Westholme

5.1.1 Frequency Analysis on QPI records

Frequency curves were derived for 08HA001 Chemainus River near Westholme using QPI values, including the 31 published observations between 1988 and 2018 and preliminary values for 2019 and 2020. Prior to 1988 all the stage measurements on the Chemainus River were collected manually each day using a wire weight gauge. As a result, the published annual maximum daily discharges are not strictly averages or instantaneous peaks. The readings are simply instantaneous observations at a fixed time.

The data was independent (Wald-Wolfowitz test) and did not exhibit significant increasing or decreasing trends (Mann-Kendall stationarity test). The Generalized Extreme Value Maximum Likelihood, Method of Moments, and Method of Weighted Moments distributions as well as the Log Pearson III Sundry Averages Method, Method of Moments base 10, and Water Resources Council distributions were compared. The fit of each distribution was visually assessed, and each fit was considered poor, particularly for high return intervals where the preliminary value for the February 1, 2020 event consistently appears as an outlier. This suggests the current peak instantaneous discharge record does not contain a sufficient number of very high flow events to appropriately estimate high return period (e.g. greater than 20-year) floods.

5.1.2 Frequency Analysis on QPD records

The record of QPD values for 08HA001 is longer than the available QPI record and includes several very high flow events. Daily values over 400 m^3/s were recorded in 1968, 1979, 1980, 1981, 1982, 1983, 1986, and 2020. However, prior to 1988, all data are based on daily manual gauge readings, which do not strictly represent daily average values.

Frequency curves were derived for 08HA001 based on annual maximum daily discharge record, including the 65 published observations between 1915 and 2018 and preliminary values for 2019 and 2020. The data was independent (Wald-Wolfowitz test). The data had an increasing trend at the 5 percent significance level but passed the Mann-Kendall test at the 1 percent significant level. The Generalized Extreme Value Maximum Likelihood, Method of Moments, and Method of Weighted Moments distributions as well as the Log Pearson III Sundry Averages Method, Method of Moments base 10, and Water Resources Council distributions were compared. The fit of each distribution was visually assessed, and each fit was considered reasonable up to return intervals of 200 years. The frequency curve that was adopted was the GEV distribution using method of weighted moments (Figure 5-1, Table 5-1).

Frequency analysis estimates based on daily values were then adjusted to instantaneous values using a multiplier (QPI:QPD ratio). To establish an appropriate multiplier, the ratio of the peak instantaneous value to the peak daily value was determined for each year when both values were available, including preliminary values for 2019 and 2020. Ratio values ranged from 1.08 to 1.94, with an average value of 1.44. The 90th percentile value was selected as an appropriate multiplier, with a value of 1.7 (Table 5-2). The rationale for adopting this approach is described below:

During the November 15, 2021 flood event, NHC field staff observed flood water spilling from the right (south) bank immediately upstream of the WSC gauge. The overbank spill flowed southward across the floodplain, through the Russell Farm Market and eventually passed under the Highway 1 crossing into Whitehouse Creek. Bank overflow occurred when discharges at the gauge exceeded approximately 350-400 m^3/s (Figure 5-2). The hydraulic model was calibrated to high water marks and flood inundation extents from the November 15 ,2021 event. Results from the hydraulic model indicated flow losses up to 30 percent occur over the right bank prior to passing the WSC gauge. It is assumed that over the Chemainus WSC gauge history, flow losses have become progressively worse. Correspondence with WSC staff indicated they have not been able to account for these flow losses in their measurements for this site. To account for flow losses at higher return periods, the 90th percentile multiplier was adopted. This value is consistent with the multiplier used in NHC (1990).

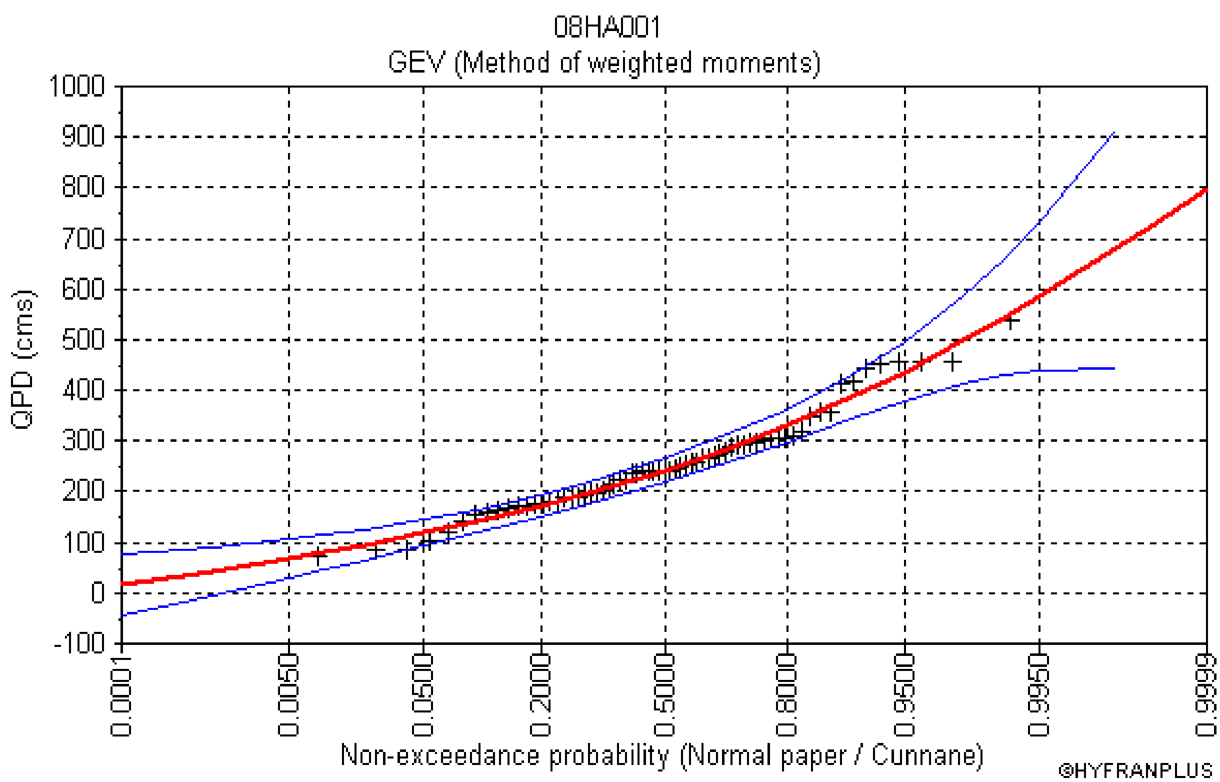

Figure 5-1 GEV frequency distribution for the Chemainus River near Westholme (08HA001) based upon QPD values.

Table 5-1 Flood frequency estimates for the Chemainus River near Westholme. Frequency estimates are based upon QPD values.

RP	Chemainus River 08HA001 (1915-1916, 1953-2020) GEV (method of weighted moments)
200	587
100	544
50	499
20	436
10	386
5	330
2	242

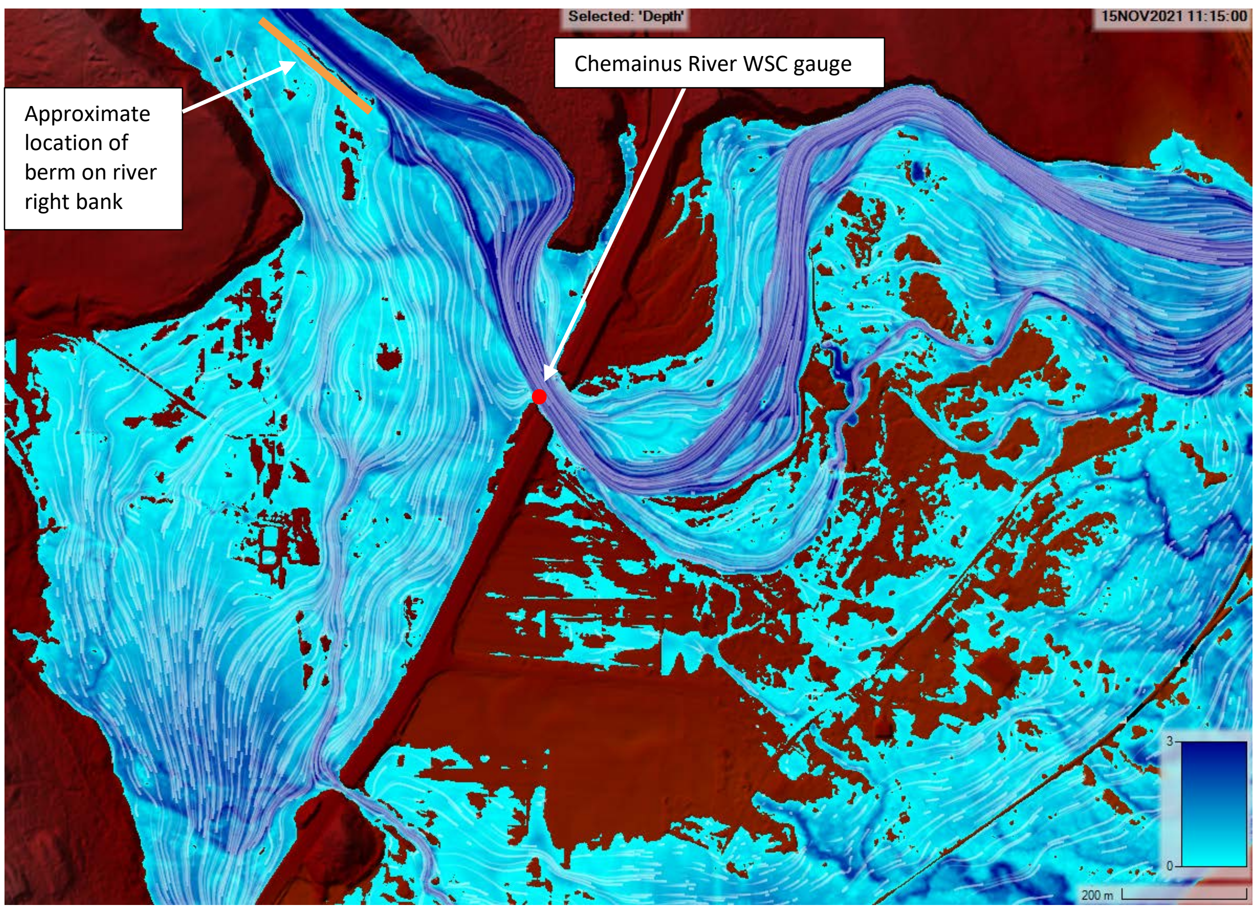

Figure 5-2 Plan view of the Chemainus River at Highway 1. Inundation extents represent November 15, 2021 flood event.

Table 5-2 Flood frequency estimates based on 1.4 and 1.7 peaking ratio for the Chemainus River near Westholme. The peaking ratio of 1.7 was adopted for this study.

	Chemainus River 08HA001 (1915-1916, 1953-2020) GEV (method of weighted moments)	
RP	1.4 QPD:QPI	1.7 QPD:QPI
200	845	998
100	783	925
50	719	848
20	628	741
10	556	656
5	475	561
2	348	411

5.2 08HA016 Bings Creek near the mouth

Frequency curves were derived for 08HA016 Bings Creek near the mouth using QPI values from 1994-2020. The data was independent (Wald-Wolfowitz test) and did not exhibit significant increasing or decreasing trends (Mann-Kendall stationarity test). Frequency analysis was completed using the: log-Pearson type III, the generalized extreme value, the gumbel and log-normal3 probability distributions. The GEV distribution was adopted (Figure 5-3, Table 5-3).

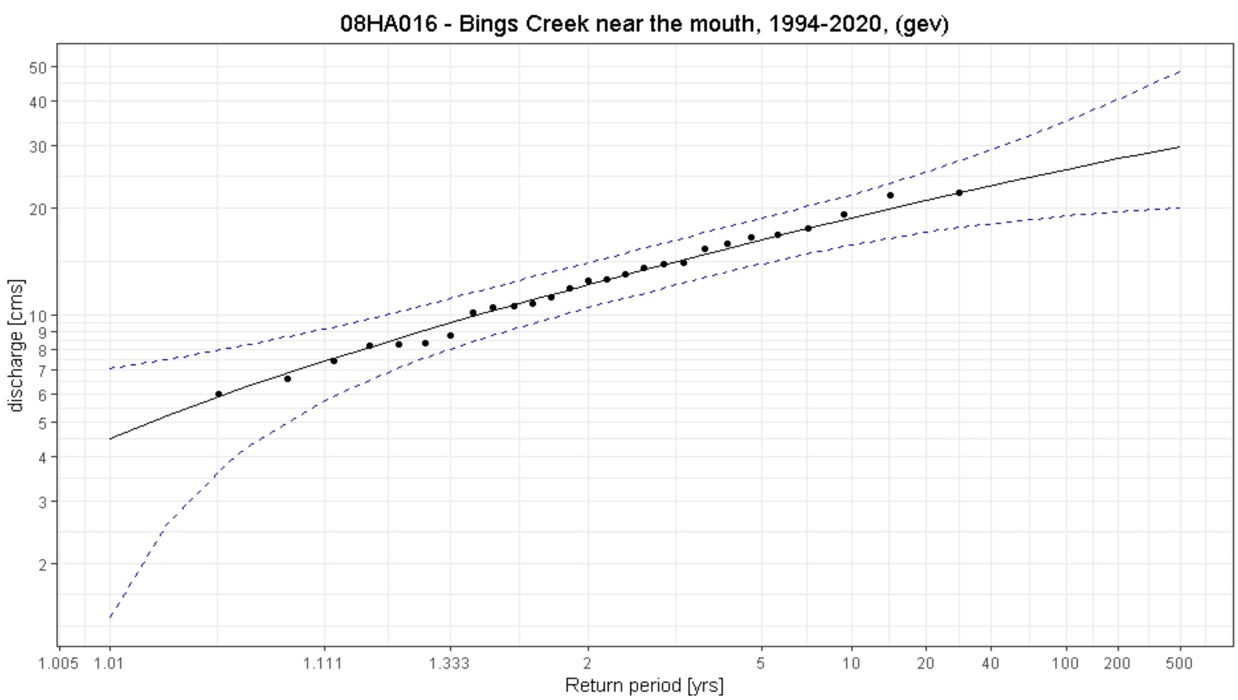

Figure 5-3: Flood frequency results using the generalized extreme value probability distribution for Bings Creek near the mouth.

Table 5-3: Flood frequency estimates for Bings Creek near the mouth.

08HA016-Bings Creek near the mouth (1994-2020)	
Return Period	**Estimate (gev)**
500	30
200	27
100	26
50	24
20	21
10	19
5	16
2	12

6 CLIMATE CHANGE

In the fall of 2021, NHC submitted a memo to the CVRD that reviewed available guidelines and best management practices for incorporating climate change to boundary conditions for the Cowichan Watershed (NHC, 2021b). Climate change projections from PCIC for the Cowichan watershed were reviewed along with EGBC guidance (CVRD, 2017; EGBC, 2018). NHC recommended and the CVRD approved of a 20 percent increase in peak flows be adopted for this study for regulatory floodplain maps to account for climate change.

7 BOUNDARY CONDITIONS

7.1 Gauged Points of Inflow

The resulting frequency analysis values adopted for model inflows on the Chemainus River are presented in Table 7-1. The 08HA001 Chemainus River near Westholme gauge is very close to the model boundary location, with only a 0.33 km^2 difference in drainage area between the two locations, so area scaling did not affect frequency analysis results.

Table 7-1 Summary of adopted model inflows for the Chemainus River.

Return Period (years)	Chemainus River 08HA001 (1915-1916, 1953-2020)	
	GEV (method of weighted moments)	
	Present Day	Climate Change
	1.7 QPD:QPI	20 percent climate change increase
200	998	1,197
100	925	1,110
50	848	1,018
20	741	889
10	656	787
5	561	673
2	411	494

7.2 Ungauged Points of Inflow

The frequency analysis results for Bings Creek were transferred to Whitehouse Creek, Bonsall Creek and tributary points of inflow using area-based scaling. Area based scaling is a common approach to estimating flood flows in ungauged basins and has been tested by Eaton et al. (2002) and (NHC, 2021a). Area based scaling can be estimated according to the following equation:

$$Q_2 = Q_1 \left(\frac{A_2}{A_1}\right)^b \qquad \text{Equation 1}$$

where Q_1 is the known peak discharge, Q_2 is the unknown peak discharge, A_1 is the known basin area, A_2 is the basin area for the unknown discharge and b is the scaling factor. Eaton et al. (2002) analyzed non-regulated WSC stations across British Columbia and found that a scaling factor of 0.75 provides an approximate estimate that is realistic for BC watersheds. NHC (2021a) examined hydrologically homogenous regions across BC and found that a scaling factor of 1.0 was appropriate for the region.

A scaling factor of 1.0 was adopted for design inflow estimates for Bonsall Creek, Whitehouse Creek and tributaries as shown in Table 7-2. Inflows were increased by 20 percent for climate change. These estimates are expected to have a high level of uncertainty since correlation or validation with site data is not possible. Additionally, changes in flow generating processes due to climate change or land use change may affect the frequency of conditions leading to peak flows.

Table 7-2 Adopted model inflows for Bonsall Creek, Whitehouse Creek and tributary reaches.

Return Period (years)	Bonsall Creek (m^3/s)	Whitehouse Creek (m^3/s)	Unnamed Chemainus Trib (m^3/s)	Unnamed Whitehouse Trib (m^3/s)	Unnamed Bonsall Trib1 (m^3/s)	Unnamed Bonsall Trib2 (m^3/s)	Unnamed Bonsall Trib3 (m^3/s)
200	19.80	9.35	2.48	3.44	2.20	0.88	0.28
200 + 20% CC	23.76	11.22	2.97	4.13	2.64	1.06	0.33

7.3 Previous Flood Frequency Estimates

Table 7-3 compares the adopted peak flood flows derived in previous flood studies to those adopted in the current study. The accuracy of previous flood frequency estimates was limited by the short record of instantaneous peak discharges on the Chemainus River and Bings Creek that was available at the time. The longer data record at the WSC gauges has allowed refinement of the frequency analysis. Values compared in Table 7-3 do not include climate change factors.

Table 7-3 Comparison of peak flows adopted in previous studies to those used in the current study.

Stream	Return Period (years)	Ministry of Environment (NHC, 1990)	NHC (1990)	Current Study
Chemainus River	20 (D)	465	465	436
	20 (I)	860	790	741

Stream	Return Period (years)	Ministry of Environment (NHC, 1990)	NHC (1990)	Current Study
	200 (D) 200 (I)	706 1300	706 1200	587 998
Bonsall Creek	20 (D) 20 (I)	40 85	15.4 26.2	-- --
	200 (D) 200 (I)	45 117	22.1 37.6	-- --

Notes:

1. 200 (D) indicates 200-year discharge (daily mean value)
2. 200 (I) indicates 200-year discharge (instantaneous value)
3. NHC (1990) Bonsall Creek watershed area = 19km^2, compared to present study Bonsall Creek watershed area = 14 km^2, therefore flow values not compared.

8 INFLOW HYDROGRAPHS

Hourly inflow hydrographs are required for model development and design scenarios.

8.1 Calibration Events

For calibration, hourly discharge data for the Chemainus gauge was obtained from WSC for the November 15, 2021 flood event. Unsteady inflow hydrographs for Bonsall Creek, Whitehouse Creek and tributary reaches were scaled based upon Bings Creek hourly discharge for the February 1, 2020 event. The Bings WSC gauge went offline during the 2021 flood event therefore hydrographs were not available.

8.2 Design Scenarios

For model simulations of design scenarios, synthetic flood hydrographs were developed with the assumption that the flood hydrograph shape follows that of a recorded WSC hydrograph shape. The February 2020 flood hydrograph for the Chemainus WSC gauge was scaled up for the 200-year design flow events. The 2020 flood hydrograph was selected as it represents a larger flood event for the watershed and the hydrograph shape is that of a single peak (versus double peak hydrograph).

The February 2020 flood hydrograph for Bings Creek was used to develop synthetic design hydrographs for Bonsall Creek, Whitehouse Creek and tributaries.

For design simulations it was assumed that all inflows peaked at the same time.

9 JOINT PROBABILITY OF DISCHARGE AND TIDES

9.1 Timing of River and Coastal Flood Events

In the lower reaches of the Chemainus and Bonsall floodplains, the water levels are governed by the interaction of river flows, the astronomical tide level and the magnitude of any storm surge. The highest water levels at any location do not necessarily correspond to the highest inflow discharge or highest ocean level. The available guidelines for floodplain mapping in British Columbia do not provide guidance on how to quantify the risk of flooding in tidally-affected rivers and estuaries. Until recently, it has been common practice in BC to assume the 200-year river flood discharge coincides with the 200-year maximum ocean level (including astronomical tide, surge and local wind set-up). However, in many cases the probability of these two events occurring simultaneously may be very low. For example, a significant flood occurred during February 2020 (Figure 9-1). Peak ocean levels did not coincide with the peak discharge for the Chemainus River. The flow of the Chemainus River was approximately a 10-15 year flood while the ocean level return period was less than a 1.5-year event.

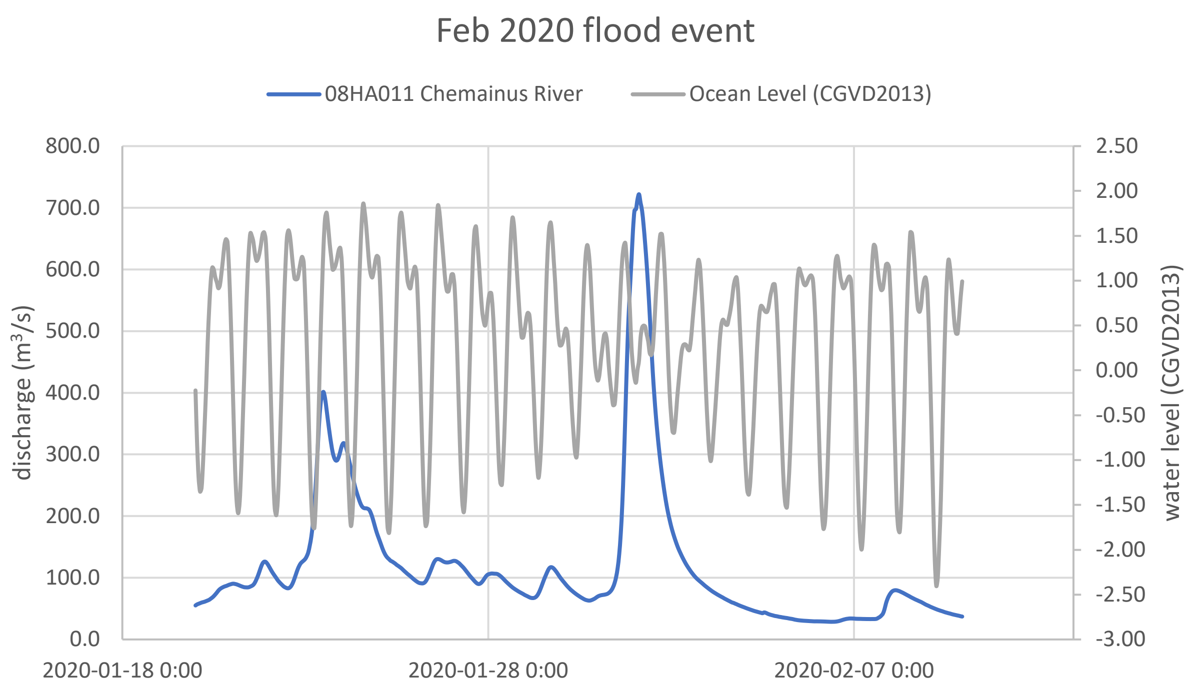

Figure 9-1 Observed discharge and ocean levels during the February 2020 flood event.

9.2 Joint occurrence of River and Coastal Flooding

To determine the appropriate combination of ocean levels and river discharges for the designated flood scenarios NHC undertook a joint probability analysis adopting methods as outlined in (White, 2007). This involved a statistical analysis of daily maximum ocean levels and the corresponding daily discharges using coincident records between 1952-1971, 1972-1974 and 1975-2021. Figure 9-2 is a scatter plot illustrating that there is only a weak dependence between high river flows and high ocean levels. The level of dependence was quantified in terms of defining the probability that if the river inflows exceeded a given threshold (say a 1% exceedance), the ocean level would also exceed a corresponding threshold (Table 9-1).

The results of this analysis confirmed that extreme river inflows and ocean levels have a low probability of occurring simultaneously. Based on the 85% threshold and 0.33 dependence factor it was decided to represent the designated 200-year river inflow and ocean level scenarios as shown in Table 9-2. The first scenario represents an extreme river discharge (200-year event) combined with a moderately high ocean level (20-year event). The second scenario represents a moderately high river discharge (20-year flood) combined with an extreme ocean level (200-year event). The corresponding ocean levels in Table 9-2 are based on the analysis presented in Appendix D – Coastal Modelling. The hydraulic model results from each scenario were run and then the highest of the two values at each location on the floodplain were selected to represent the final adopted 200-year water level.

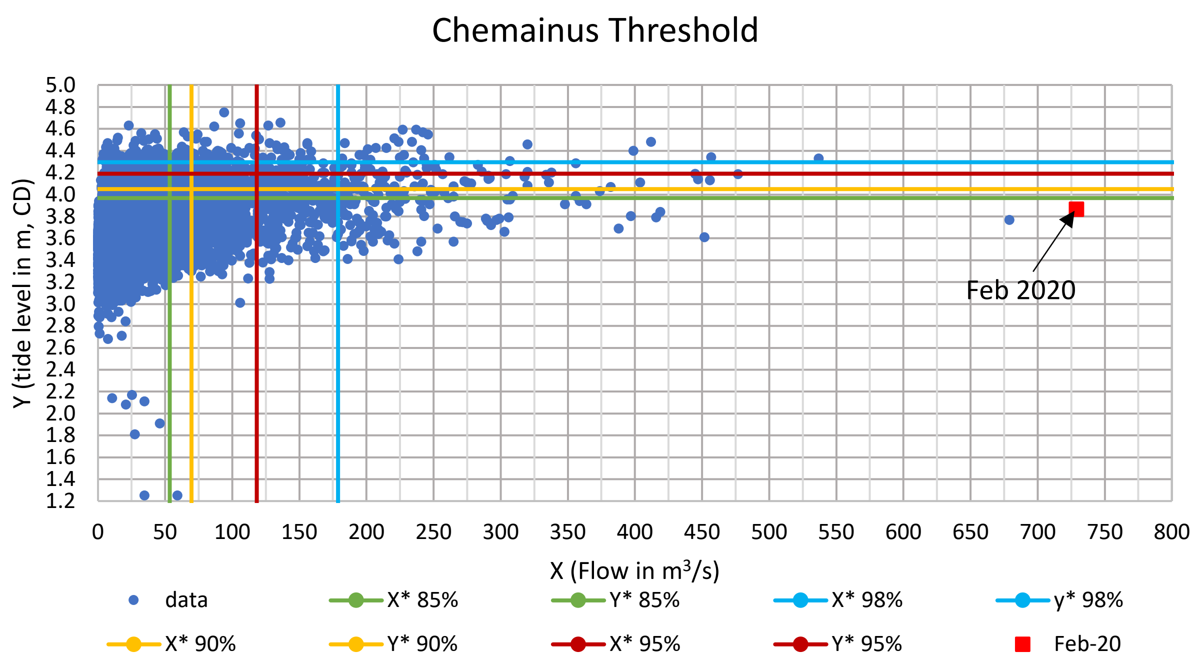

Figure 9-2 Joint occurrence of ocean levels and river discharges on the Chemainus River.

Table 9-1 Thresholds and associated dependence factor.

Threshold	Dependence
	Chemainus River and Ocean Levels
85%	**0.33**
90%	**0.30**
95%	**0.21**
98%	**0.14**

Table 9-2 Adopted flood scenarios for joint occurrence of river floods and ocean levels.

Scenario	River Inflows		Ocean Levels	
	Return Period (years)	Chemainus River discharge (m^3/s)	Return Period (years)	Elevation (m, CGVD2013)
Present Day	200	998	20	2.34
	20	741	200	2.47
Year 2100 climate change	200	1,197	20	3.34
	20	889	200	3.47

10 SUMMARY

Table 10-1 lists the key scenarios that were used to develop flood mapping for the study area. The two scenarios were enveloped and the highest water surface elevation was adopted for the regulatory map.

Table 10-1: Scenario adopted resulting from the joint probability analysis.

Scenario	Riverine		Ocean Levels		Mapping product produced with associated boundary conditions
	Return period	% change in flood discharge for climate change	Return Period	Climate Change	
Design Event	1:20-year	0	1:200-year	1 m SLR	Regulatory floodplain map
	1:200-year	20	1:20-year	0 M SLR	

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APPENDIX C

GEOMORPHOLOGY

Image credit: CVRD (aerial-based imagery) and NHC

Chemainus River Geomorphic Atlas

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Chemainus River Flood Mapping Program

Geomorphic Atlas

October 2022
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northwest hydraulic consultants

Document Tracking

Date	Revision No.	Reviewer	Issued for
2022-10-20	0	W. Hilsen	Final

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INTRODUCTION

NHC has prepared this document for the Cowichan Valley Regional District (CVRD) to support geomorphic hazard mapping of the potential channel and shoreline migration zones on the Chemainus River floodplain. The geomorphic atlas provides a conceptual framework that can be used to evaluate flood mitigation options.

This atlas provides a summary of NHC's investigation into the geomorphic processes that were used to inform and define the geomorphic hazard mapping, and to provide important context on channel stability and potential future conditions that may affect the geomorphic hazard potential.

SCOPE OF WORK

The study focus is on the geomorphic channel and shoreline migration potential on the Chemainus floodplain and lower approximately 8 km of the Chemainus River. The scope of work does not include an evaluation of sediment sources, terrain assessment, or assessment of the potential or frequency of slope instabilities, debris flow, debris flood, potential for channel jamming and outburst flooding, or hyper-concentrated flow.

ACKNOWLEDGEMENT

We respectfully acknowledge that the Chemainus River, its tributaries, watershed, and estuary lie within the traditional, unceded territories of the Coast Salish Peoples.

The study area falls within the territory of the Hul'qumi'num speaking First Nations peoples, which includes Cowichan Tribes, Halalt, Stz'uminus, Penelakut, Lyackson, and Tsuubaa-asatz Nations .

The following NHC personnel participated in the study:

- Ryan McQueen — Analysis and lead author
- Ilana Klinghoffer — Analysis, co-author, and hazard mapping
- Wil Hilsen — Field investigations, editor, and reviewer

TABLE OF CONTENTS

1 DATA SOURCES

Field Data

- Estuary, river channel, and terrestrial survey data (NHC, May to June 2021)
- Topographic surveys of bank positions and highwater marks (NHC October to November 2021).
- Field photographs (NHC August 2021 to March 2022)
- Mesohabitat spatial data (Cowichan Watershed Board 2021)
- Historical river cross section data (1986 BC Surveys Section, Water Management Branch, BC Ministry of Environment)

Personal Communication and Knowledge Sharing

- Chief James Thomas, Halalt First Nation (7 October 2021)
- Tim Thomas, Halalt First Nation fisheries technician (8 October 2021)
- Halalt First Nation Spill Response Coordinator Geoffrey Backman (9 December 2021)
- Halalt First Nation Band Manager (30 November 2021)
- Penelakut First Nation Band Manager Josh James (30 November 2021)
- Stz'uminus First Nation Council Member and cultural consultant Arthur Jim (18 February 2022) and accompanied by Terry Gibson Stz'uminus First Nation local guide on 18 March 2022).
- Ken Epps, Mosaic Forest Management (17 September 2021)
- Sean Wong, Sr. Biologist. BC Ministry of Transportation and Infrastructure (20 October 2021).
- Jeff Anderson, Geomorphic Consulting (for Cowichan Watershed Board BCSRIF Twin Watersheds Project, 7 March, 2022)
- Dave Clough, DR Clough Consulting (26 October 2021)

Geospatial Data

Imagery

- Historical air photos (1950, 1957, 1968, 1975, 1987, 1992; courtesy of the UBC Geographic Information Centre)
- Google Earth (2005)
- 2019 (MNC) and 2021 (FLNRORD) orthophotos

LiDAR (light detection and ranging) data

- 2019 LiDAR of the Chemainus floodplain (GeoBC)
- 2021 LiDAR of the Chemainus River (Cowichan Watershed Board)

Canadian Hydrographic Service (CHS) Non-Navigational (NONNA) Bathymetric Data

- 10 m grid depth data converted to CGVD2013 elevation data
- Supplemented with CHS Chart3310 data

Basin-scale data sets

- Topography (CDEM)
- ESRI imagery (2019)
- Bedrock geology (BCGS)
- Surface geology (TRIM)
- BC 1:20,000 scale Freshwater Atlas (FWA)

2 APPLICABLE GUIDELINES

The following BC guidelines are applicable:

- Legislated Flood Assessments in a Changing Climate in BC – Professional Practice Guidelines (EGBC, 2018)
- Flood Hazard Area Land Use Management Guidelines (MFLNRORD, 2018)
- Flood Mapping in BC – Professional Practice Guidelines (APEGBC, 2017)

The following guidelines from other jurisdictions have been considered in the undertaking of this study:

- A Framework for Delineating Channel Migration Zones. Washington State Department of Transportation. Rapp et. al., November 2003.
- Channel Migration Processes and Patterns in Western Washington. A Synthesis for Floodplain Management and Restoration. State of Washington Department of Ecology. Legg et. al., August 2014
- Forest Practices Board Manual. Technical supplement to Washington State forest practice rules. dnr.wa.gov. 2000.

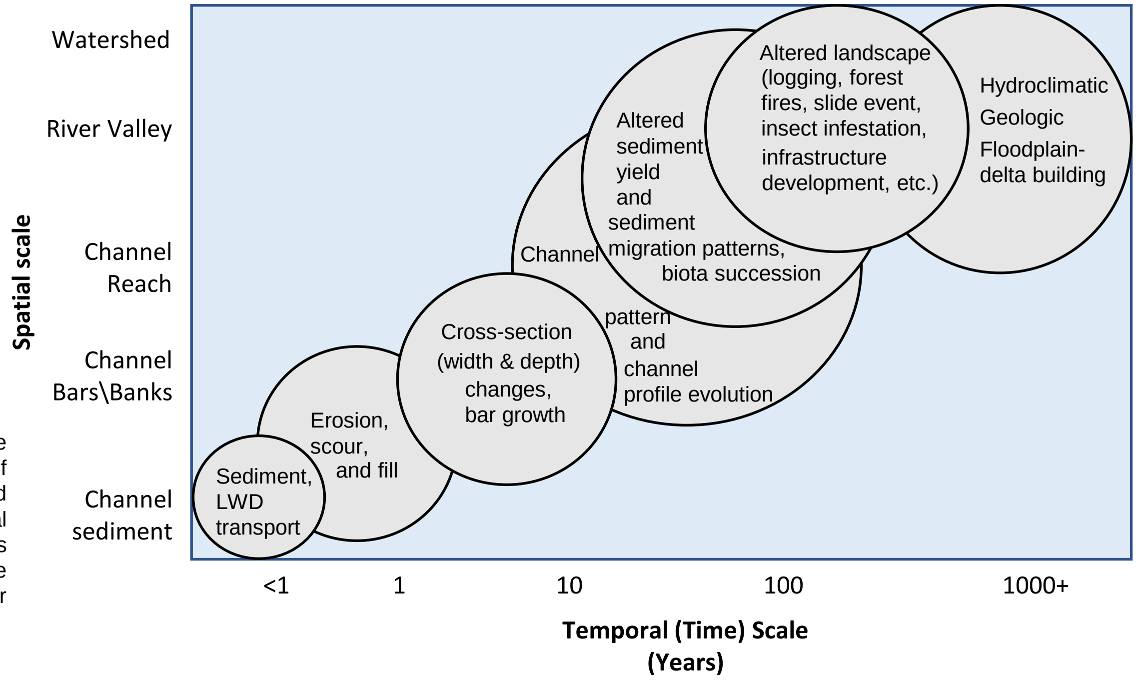
3 CONCEPTUAL FRAMEWORK

The Chemainus River floodplain is prone to hazards associated with channel avulsion, lateral channel instabilities and shoreline erosion. The goal of the hazard mapping conducted for this project is to delineate areas that are susceptible to channel and shoreline migration hazards (Rapp, C.F., Abbe, T.B. 2003). The mapping, referred to herein as a Geomorphic Hazard Map, is intended to help reduce risk by providing guiding information for land use planning.

The following fluvial and coastal processes have been considered in the assessment. These geomorphic processes operate on the landscape at a range of spatial and temporal scales.

- Channel hydraulics associated with floods
- Supply of sediment and large woody debris (LWD) from the watershed and upper channel reaches.
- Channel erosion, scour, and infilling associated with fluvial processes
- Lateral channel instability and channel avulsion potential
- Distributary channel processes and tidal effects
- Shoreline recession associated with wave erosion and sediment transport

▸ Conceptual representation of the different scale of physical influences and fluvial and coastal geomorphic processes operating on the landscape (after Richards et. al. 2002).



The Geomorphic Atlas provides a summary of the field investigations, desktop review and analyses carried out for the study. The document is structured to provide a multi-scaled perspective on the dominant geomorphic processes used to define the mapping units shown in the geomorphic hazard map. These processes are presented in Sections 4 to 9 as summarized below, and Section 10 describes the analysis undertaken for the geomorphic hazard mapping.

- SECTION 4 WATERSHED-SCALE PROCESSES: Describes the present-day hydroclimatic and geologic characteristics of the watershed. Presents an overview level description of the hillslope hazard potential and sediment supply.
- SECTION 5 LAND-USE AND IMPACTS OF EUROPEAN SETTLERS: Identifies major influences and disturbances to the watershed, river system and shoreline. Describes the physical changes that occurred and anticipated longer-term geomorphic response.
- SECTION 6 MODERN VALLEY BOTTOM AND ACTIVE CHANNEL PROCESSES: Defines the modern valley bottom and describes the active channel processes on the Chemainus River floodplain.
- SECTION 7 REACH-SCALE CHANNEL CHARACTERISTICS & DOMINANT PROCESSES: Includes an overview level description of the reach characteristics, and a detailed reach-by-reach summary of key observations, characteristics, and processes.
- SECTION 8 SEDIMENT MOBILITY AND THE CHANNEL PROFILE: Presents study reach-scale longitudinal profile plots of bed elevation and channel changes between 1986 and 2021, based on a comparison of survey data. Includes longitudinal profile plots of sediment grain size characteristics, and sediment mobility potential.
- SECTION 9 FUTURE CONDITIONS: Description of potential future conditions and geomorphic response:
  - Watershed-scale or river valley-scale changes that may physically change the landscape and induce a longer-term geomorphic response under present-day or future hydroclimatic conditions. The geomorphic response to some historical watershed-scale changes (e.g., logging, road and rail development, historical mining) are ongoing.
  - Altered flow regime and reach-scale and channel-form adjustments.
  - Base level changes, landward migration of tidal and coastal effects, and adjustments to the channel profile.

4 WATERSHED SCALE PROCESSES

Physiography and Watershed Morphometrics

The Chemainus River Watershed is located on the east coast of Vancouver Island, draining an area of 385 km^2. At 1,500 m above sea level, Mount Whymper is the highest point in the watershed.

In the upper watershed, the river flows southeast and turns northeast near Mount Sicker, parallel to a fault line, and onto the Nanaimo Lowlands (Yorath and Nasmith, 1995). The channel was originally formed by glaciofluvial processes, and the present-day channel is underfit and is confined by tall channel banks. As the river erodes the toe of these banks, steeper sections become prone to failures and provide an important source of sediment to downstream reaches.

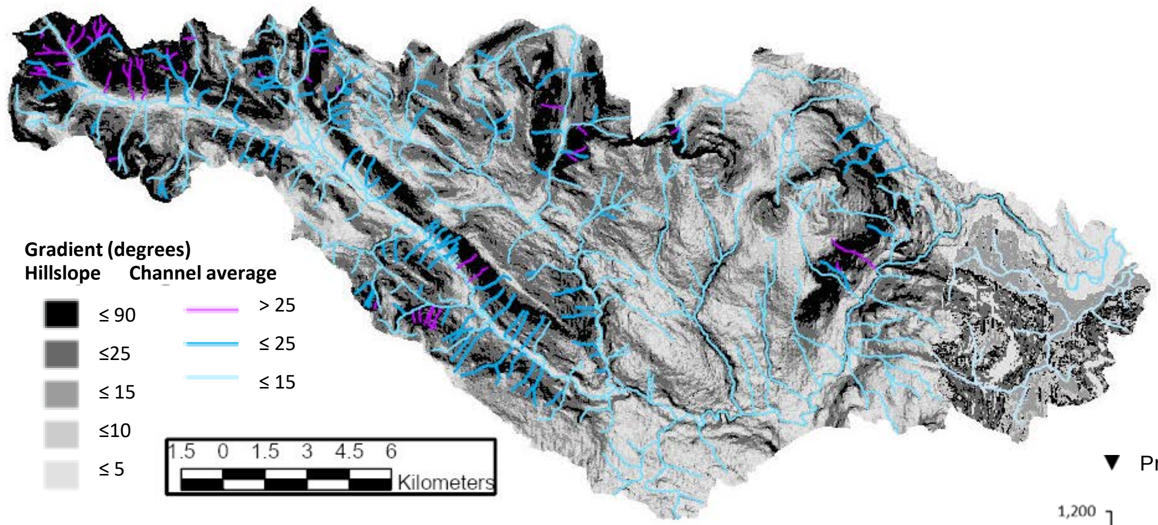
About 8 km from the mouth, the Chemainus River exits confinement and continues onto a broad alluvial plain. Here, the channel exhibits an irregularly sinuous meandering planform, whereby the position of meander bends are confined by bedrock outcrops, bridge constrictions and rock armoured banks.

The morphometric analysis indicates clearwater floods are likely to be the dominant hydrogeomorphic processes on the mainstem channel of the lower Chemainus River, though smaller tributary sub-basins in the upper watershed may be prone debris flows and debris floods.

Watershed morphometrics are typically used to conduct a preliminary assessment whether a watershed is dominated by clearwater floods, debris floods or debris flows (Church and Jakob, 2020; Wilford et al., 2004).

Morphometric parameters evaluated for this study include watershed area and length, relief ratio, and the Melton ratio (the ratio between basin relief and the square root of the basin area).

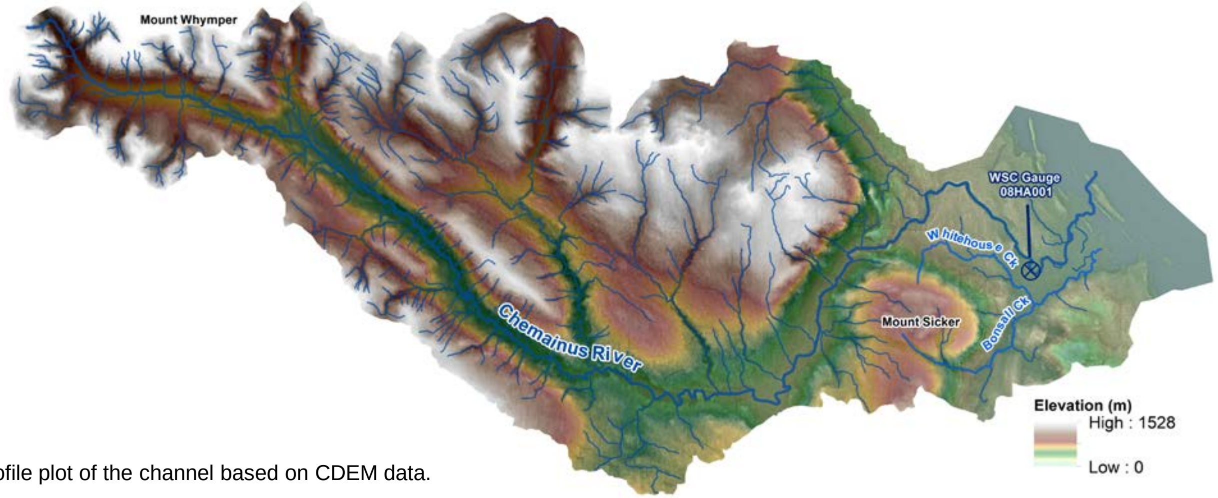
Watershed Morphometrics	
Watershed Area (km^2)	384.6
Watershed Length (km)	38.0
Melton Ratio	0.08
Relief Ratio	0.04



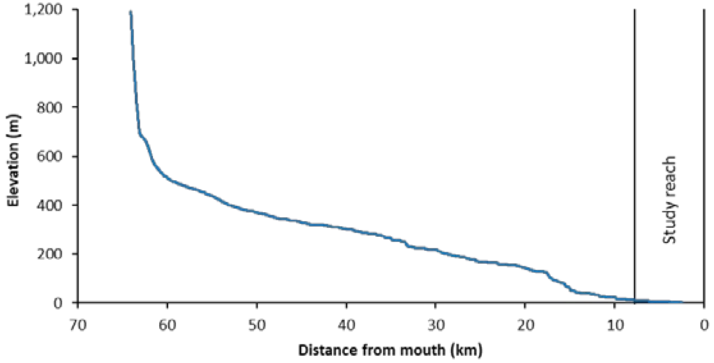
▲ Channel average and hillslope gradients (CDEM and FWA data).

High energy hydrogeomorphic hazards – debris flows and debris floods – can entrain substantial volumes of sediment and woody debris, producing a peak discharge much larger than a typical flood event; debris flows may occur in channels that have an average slope ≥15 degrees (APEGBC, 2017). Hillslope gradients ≥25 degrees are considered to have a potential for instabilities (Sidle et. al, 1985).

Based on the CDEM data, approximately 27% of the Chemainus River watershed is >15 degrees and 18% is >25 degrees (shown in the grey and black shading above). Dark blue and purple channels show tributary channels prone to debris flows.



▼ Profile plot of the channel based on CDEM data.



▲ Watershed basin plot developed using CDEM and FWA data.

The channel profile upstream of the study reach becomes steeper and includes several falls.

- Between 20 km to 60 km upstream of the mouth the average mainstem channel gradient is approximately 0.9% (~0.5°)
- In the upper 4 km it steepens to approximately 17% gradient (~9.7°).

4 WATERSHED SCALE PROCESSES

Climate and Hydrology

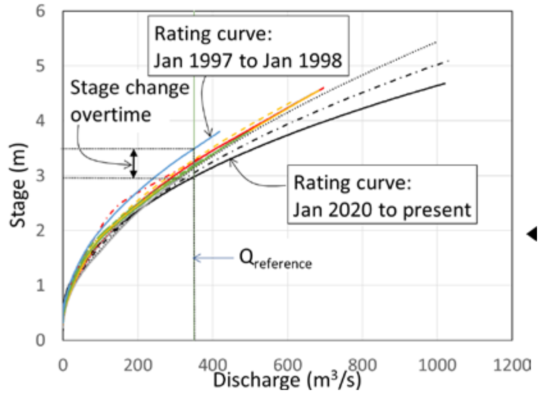
- The Chemainus River Watershed resides within the Eastern Vancouver Island hydrologic zone (Obedkoff, 2003).
- The discharge regime closely follows the precipitation regime. Most rainfall occurs in the winter, with November being the wettest month, and July the driest.

Based on studies in northeast Vancouver Island and the Sunshine Coast, rain dominated zones extend up to 300 m elevation and the transient snow zone is between 300 to 800 m, with the snowpack zone above 800 m. (Babakaiff, 2000). Based on a hypsometric analysis, the proportion of the watershed within each zone is presented below:

- Rain dominated : approximately 13%
- Transient snow zone: approximately 59%
- Snowpack zone: approximately 28%

The Water Survey of Canada (WSC) gauge 08HA001 is installed near Highway 1 along the lower reach of the river (see Page 3 for gauge location).

- Hydraulic model results conducted for this study indicate that up to 30% of the river's flow spills overbank upstream of the gauging station during flood events, and therefore peak flood discharges reported by WSC may be under-estimated.
- Observations indicate relative water levels (i.e., stage) associated with the $Q_{reference}$ have fluctuated by more than 0. 5 m between 1995 and present. This relative change in stage infers a correspondingly similar magnitude of channel bed fluctuation.



◀ Stage-discharge relationship for WSC hydrometric station Chemainus River near Westholme (08HA001) since 1995

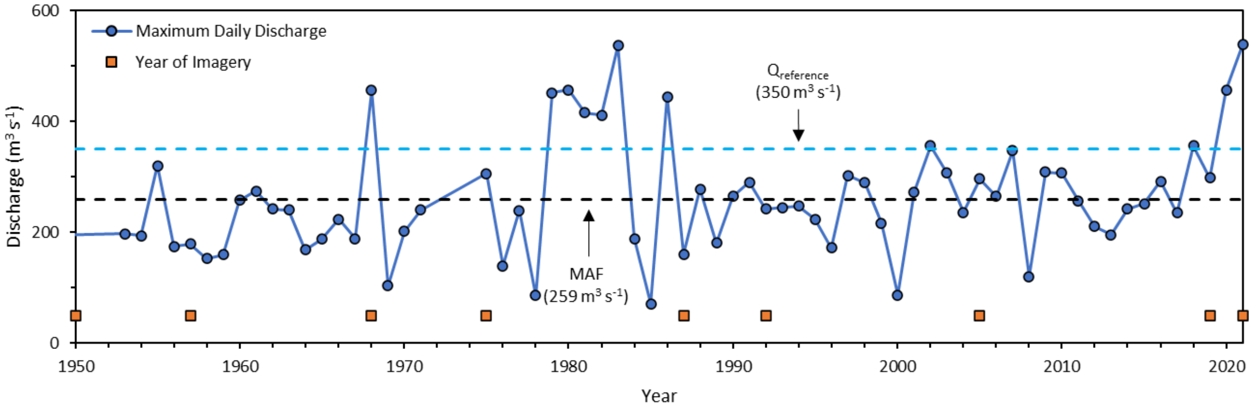
This study analyzes geomorphic processes using a reference discharge ($Q_{reference}$) of 350 $m^3 s^{-1}$. This value approximates the bankfull discharge, the flood condition at which the active channel width is inundated with water and coarse bed sediment is likely to be mobilized. This value has been applied to estimate sediment transport potential and sediment transport processes at a broad reach-scale, and more detailed analysis could help refine the critical discharge value for sediment entrainment.

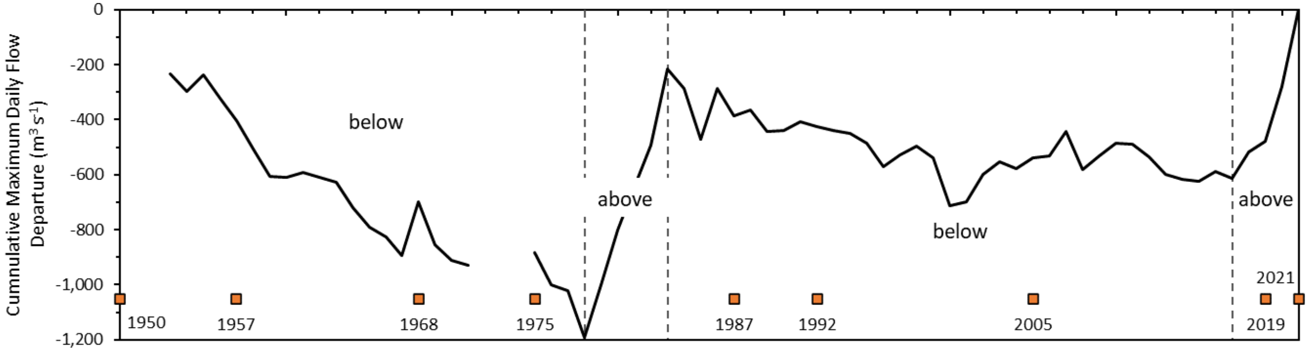
The largest floods within the period of record (1950 to 2021) occurred in 2021, 1983, 2020, 1980, and 1968 (in rank order from largest event).

Recognizable periods of above average floods occurred from 1978 to 1983 and from 2017 to 2021. Below average floods dominated other time periods with occasional years that experienced a large flood event.

The record of cumulative maximum daily flows notably plots below the cumulative long-term average, whereas a system in equilibrium would tend to vary above and below the average.

The reason for this is that high flows occurring from 2018 to 2021 are substantially greater than in prior years, which skews the long-term average towards these more recent events. This may imply that the system is shifting to a new equilibrium state in which higher magnitude floods occur more frequently.





▲ Upper graph: Historical annual maximum daily flow sequence from the WSC gauge 08HA001 on the Chemainus River. MAF = mean annual flood.

Lower graph: Cumulative flood flow departures showing trends in peak daily flows relative to the long-term average (i.e., where the cumulative maximum daily flow departure equals 0).

A rising trend indicates a time period with floods that are persistently above the average annual, whilst a falling trend indicates a time period with floods that are persistently below average. Orange squares represent years of available air photos or orthophotos that were used to interpret channel changes over time.

4 WATERSHED SCALE PROCESSES

Bedrock Geology

The Chemainus River Watershed lies within the Wrangellia terrane, which on Vancouver Island comprises three volcano-sedimentary cycles (Paleozoic Sicker Group, Upper Triassic Vancouver Group and Jurassic Bonanza Group) overlapped by Upper Cretaceous sediments of the Nanaimo Group (Massey and Friday, 1987).

Rocks of the Island Plutonic Suite are relatively stable and resistant to weathering processes leading to relatively lower landslide rates than other lithologies (Guthrie, 2005). This may not hold true for areas where logging is involved. Conversely, rocks of the Sicker group are more vulnerable to landslides (Guthrie, 2005).

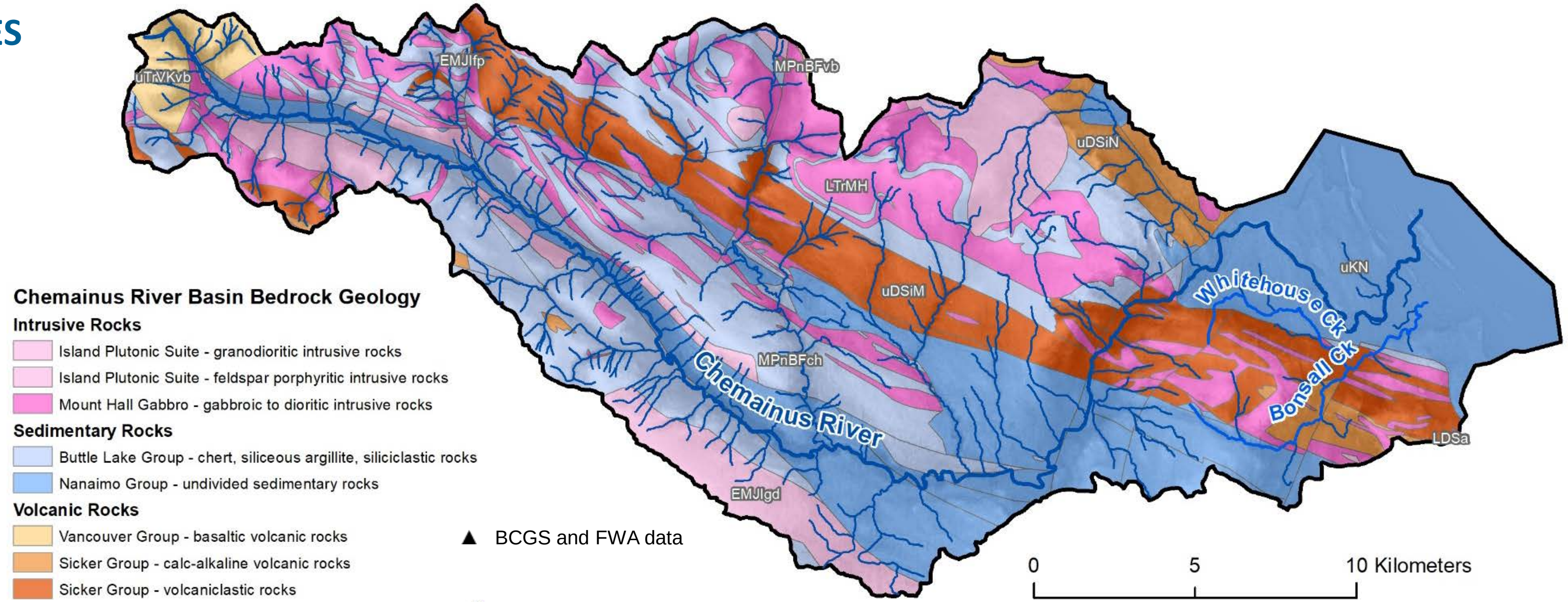
Surficial Geology

The watershed is covered by a blanket of till, with colluvial deposits accumulating on steep hillslopes.

Striae, flutings, and stoss and lee topography indicate that ice moved in a south to southeast direction during the last major sheet that occupied Vancouver Island (Halstead, 1966).

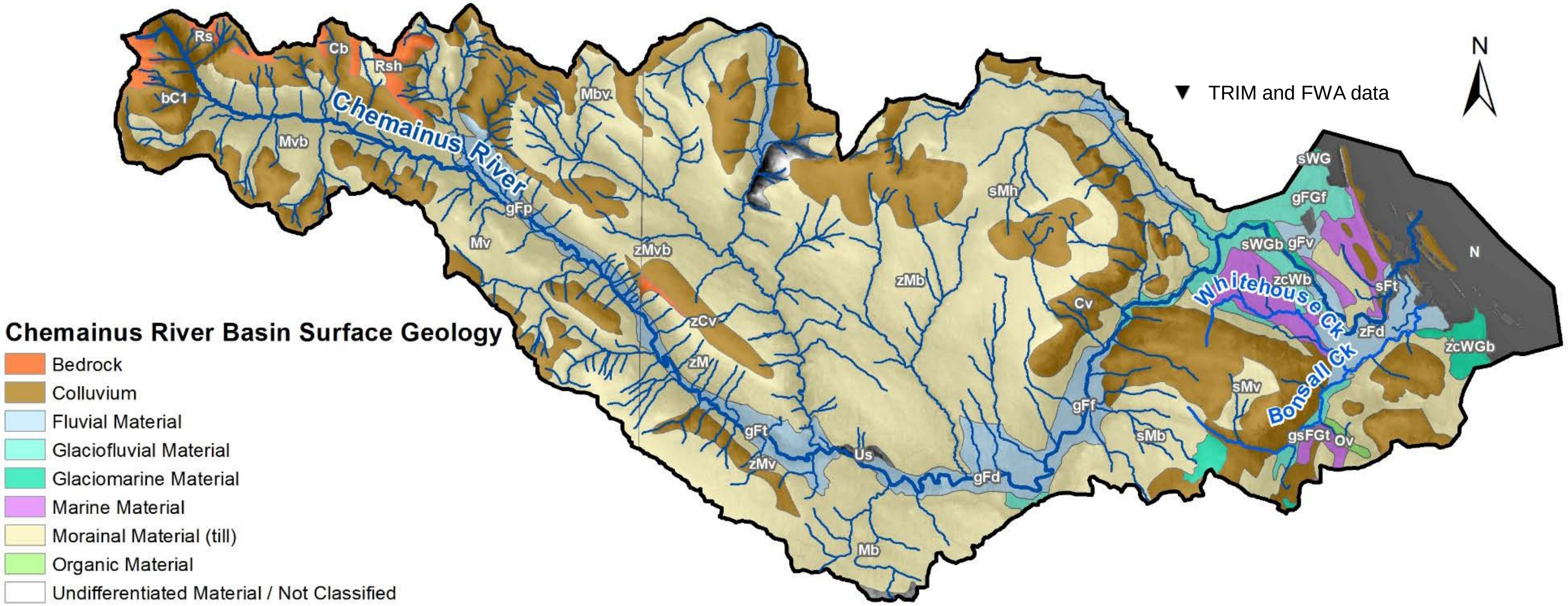
In the lower watershed, the modern-day channel is underfit and incises into glaciofluvial deposits. The lower 10 km or so of the river is bordered by marine and glaciomarine deposits that form high terrace bluffs, partially constraining the position of the modern-day channel.

▲ Terrace bluffs in the lower watershed composed of compact glaciomarine sediment.



▲ BCGS and FWA data

0 5 10 Kilometers



▼ TRIM and FWA data

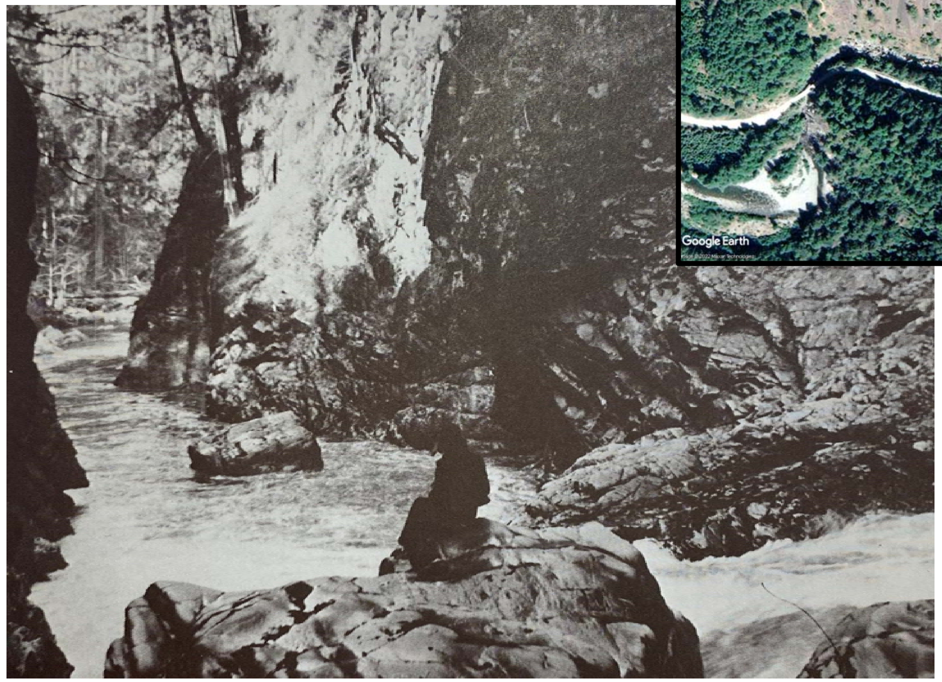
4 WATERSHED SCALE PROCESSES

Sediment Supply Potential

Sediment supply The rate of sediment supply to the lower reach partly depends on hillslope erosion processes that deliver sediment to the channel system farther up in the watershed. There is a recognized potential for instabilities in the watershed (described in more detail on Page 3).

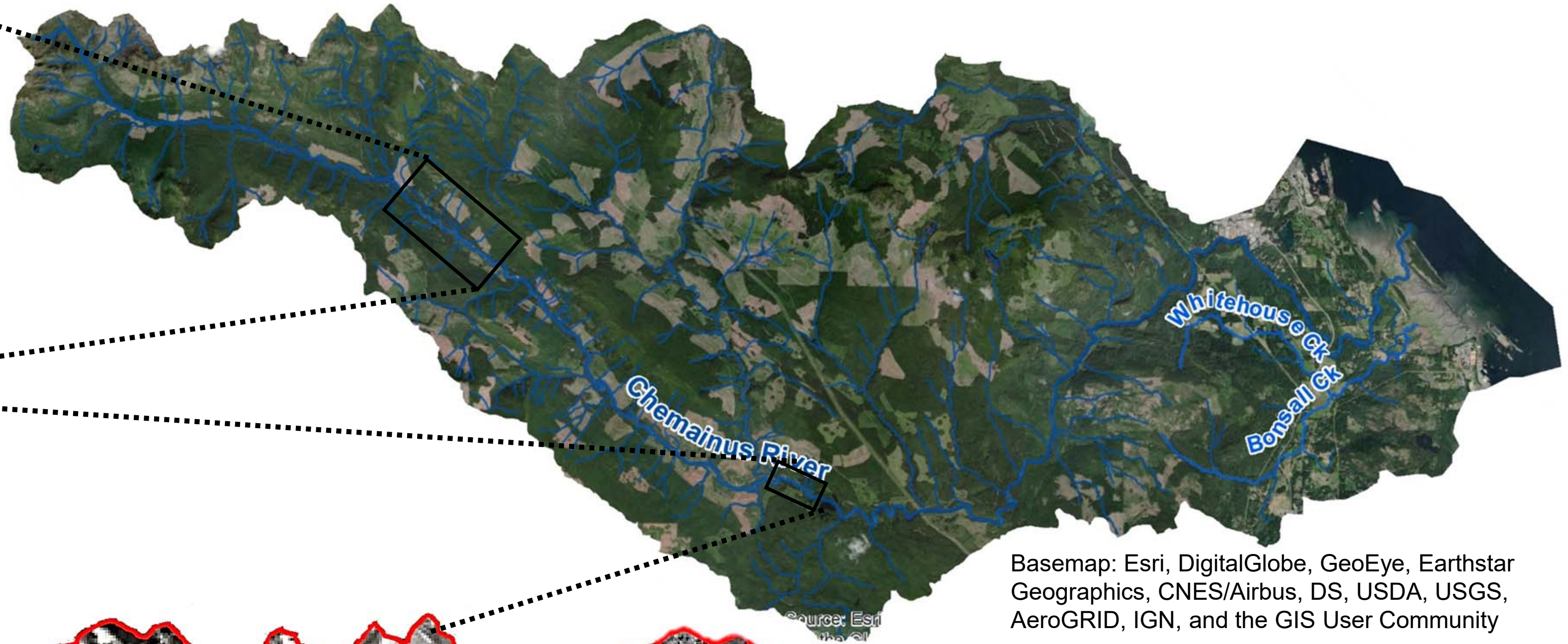
Bank erosion and slope failures along the channel banks supply sediment to the mainstem.

Altered forest cover affects snow accumulation, and melting, interception and transpiration of precipitation during storms (Pike et. al. 2010). Hydrologic recovery occurs with forest regeneration; however, the geomorphic response to logging is a more complex and longer-term process (see Page 34).

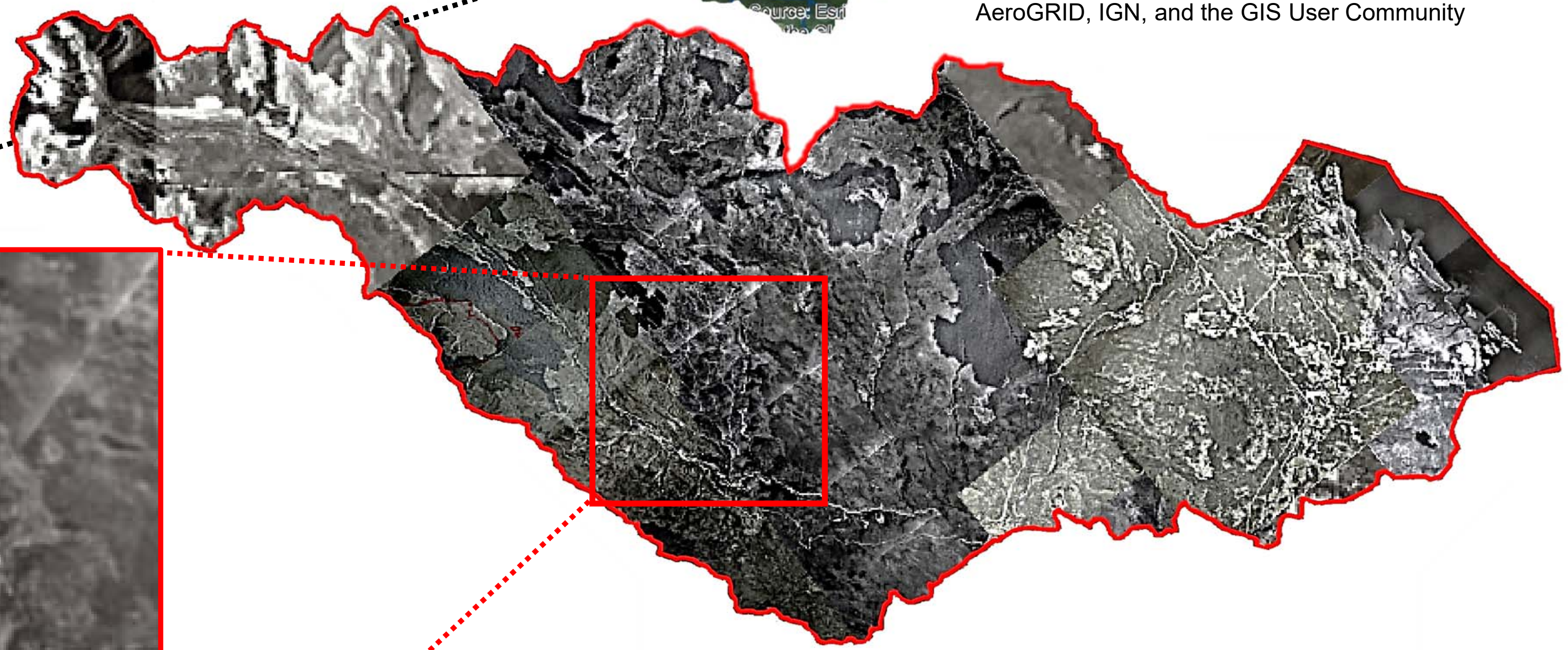


▲ Copper Canyon at the falls (Olsen, W.H., 1981), reportedly the narrowest location on the Chemainus River. Steep, narrow canyons in the upper watershed create a potential for channel blockages.

▼ Recent image of the watershed forest cover area. Inset image at the top left illustrates an unstable channel reach in the upper watershed that is a sediment supply source. The image at bottom left shows slope failures along a steep stream bank located within a confined channel reach, also a noticeable source of sediment.



Basemap: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus, DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community



▲ Overtime, logging has occurred in much of the watershed. The image above is compiled from historical air photo (primarily circa 1962 with supplemental, lower resolution 1987 imagery to infill gaps in the photo record). Large cut blocks are visible on relatively steep terrain areas. Visible slide paths lead into the channel in the historical photo records.

5 LAND USE AND INFLUENCE OF EUROPEAN SETTLERS

▲ Top photo: Historical logging operations in the Chemainus River watershed. Bottom photo: First bridge over Chemainus River. (Copper Canyon Commemorative Committee, 1990).

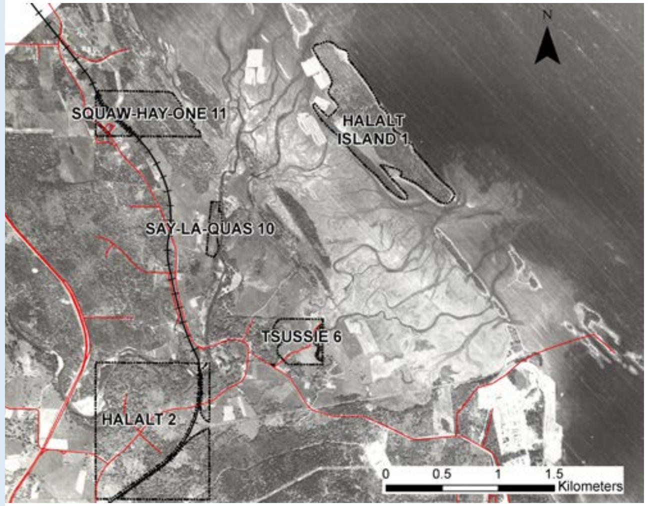
The Chemainus River, its watershed, estuary, and surrounding islands have been used since time immemorial by First Nation peoples for village sites, hunting, fishing, trapping, harvesting, and other cultural and sacred purposes (Rozen DL, 1985; Arthur Jim, Stz'uminus First Nation Band Council member and cultural consultant, pers. comm. 18 March 2022).

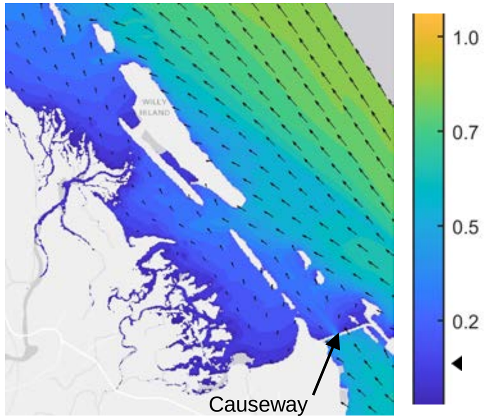
Geomorphic response to European settlers

European settlement has dramatically altered the Chemainus River, and its watershed, floodplain, estuary, and coastline. This includes:

- Altered sediment yield and timing and frequency of peak flood events associated with historical mining activities and legacy forestry.
- Altered drainage patterns and potential for hillslope instabilities and sedimentation associated with the legacy road deactivation practices and development of cutblocks and road and rail networks in the watershed. Ongoing forestry practices in the watershed have not been evaluated for this study.
- Altered sediment deposition patterns, and channel planform and profile changes associated with channel hydraulics at road and railway bridge crossings.
- Encroachment into historical channel migration zones.
- Concentration of channel flow during food events associated with the earthen berm constructed along the southern bank of the floodplain upstream of Highway 1.
- Altered channel flow pathways and floodplain flow resistance associated with land clearing and landscaping in support of agriculture and other intensive land uses on the floodplain.
- Altered rates and patterns of deposition of sediment and LWD in the low gradient channel reaches, in the distributary channel zone and in the estuary (Chief James Thomas, pers. comm. 7 October 2021).
- Altered tidal and wave processes in the estuary associated with the construction of the causeway to the pulp and paper mill.

▼ 1962 air photo overlain with road and railway networks that bisect the Chemainus River floodplain, interrupting natural drainage patterns, and cutting off former distributary channels and occasionally active fluvial zones.





◀ SWaN model simulations for an easterly storm, showing simulated wave height (m) and wave direction. The results show a pronounced influence of the pulp mill causeway on wave propagation into and out of the estuary.

▲ Google Earth image showing two water wells (white circles) located within the active channel corridor.

- In 1862, J.D. Pemberton, Surveyor-General reported that, *"the river has cut perpendicular passes through clay hills. High on the brink stand pines weighing 10 to 40 tons, which with every fresh landslip are swept with great velocity down the stream. Below these hills the river could not well be bridged"* (Olsen, W.H., 1981).
- Industrial development reportedly had started as early as 1866 and expanded with establishment of the Esquimalt and Nanaimo Railway in 1886. Harvest cut blocks and other development associated with logging has altered sediment supply rates into the Chemainus River and estuary, compared to pre-disturbance conditions. Development of the Crofton pulp mill in 1958 has closed off the southern opening to the estuary between Vancouver Island and Shoal Island (Bell, L.M., Kallman, R.J., 1976).
- By the 1900s the Chemainus River was spanned by a concrete and steel bridge to replace a wooden truss structure (Turner R.D. 1973).
- The Federal Government enacted fish licensing regulations is 1888, and by 1913 the Department of Fisheries and Oceans forcibly removed all First Nations fishing weirs from the Cowichan and Chemainus Rivers. (Hodding, B.A 1998).
- In the 1930s and 1940s, development of the Copper Canyon mine and the growing logging industry was supported by the construction of a 63 km long railway line by the Victoria Lumber Company Ltd.

6 MODERN VALLEY BOTTOM AND ACTIVE CHANNEL PROCESSES

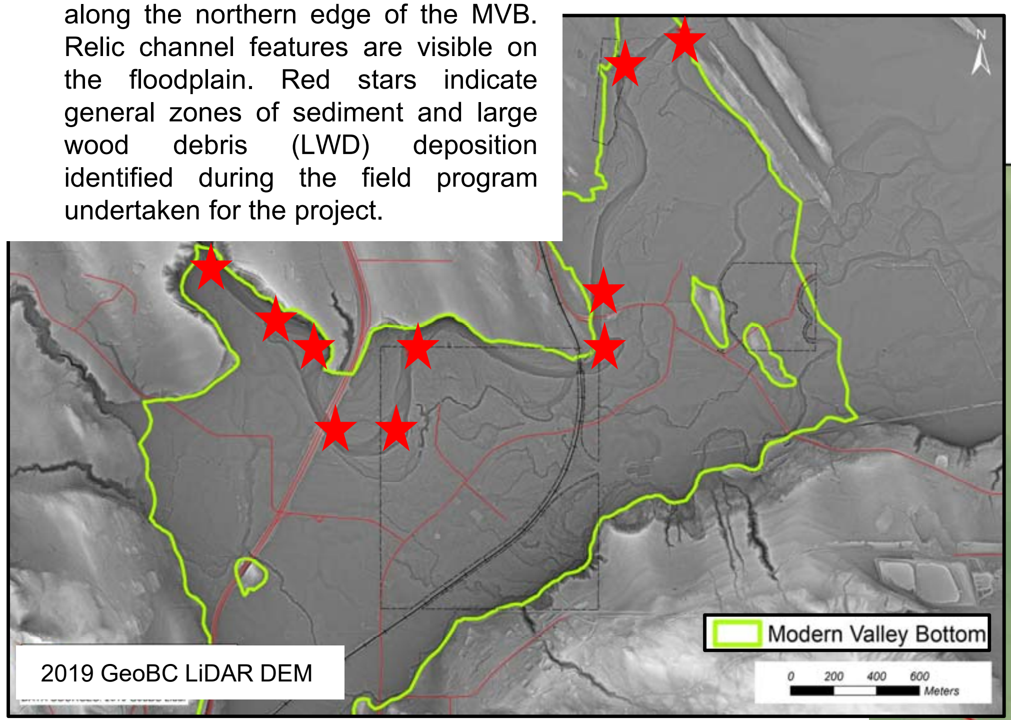
The Modern Valley Bottom (MVB) is the portion of the landscape that has been affected by channel processes under the contemporary hydroclimatic regime (Olsen et al. 2014).

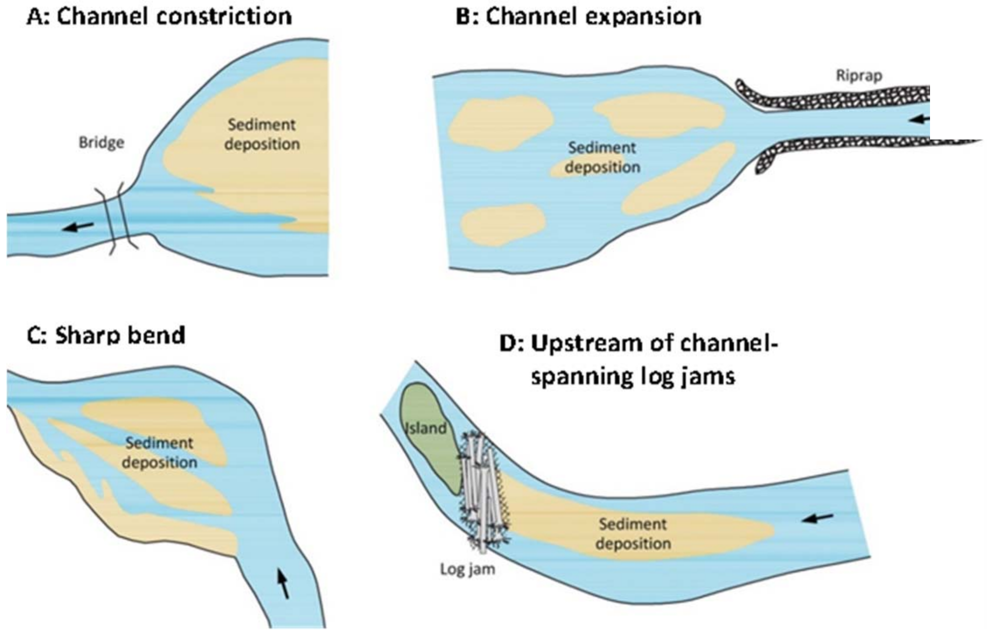
The MVB is a defined region that is based on interpretation of relict fluvial features, bedrock and surficial geology, and relative elevations on the valley landscape.

The Chemainus River MVB includes areas that are potentially susceptible to active channel processes, including lateral channel shifting and channel avulsion. A channel avulsion is a process whereby a channel is diverted from an established channel to a new channel path (First-order Avulsion) or pre-existing path (Second-order Avulsion) on the floodplain.

Channel processes that can trigger an avulsion include the formation of log jams or other blockages and accumulation of sediment in depositional zones.

▼ The texturized DEM of the floodplain. The present-day active channel flows along the northern edge of the MVB. Relic channel features are visible on the floodplain. Red stars indicate general zones of sediment and large wood debris (LWD) deposition identified during the field program undertaken for the project.



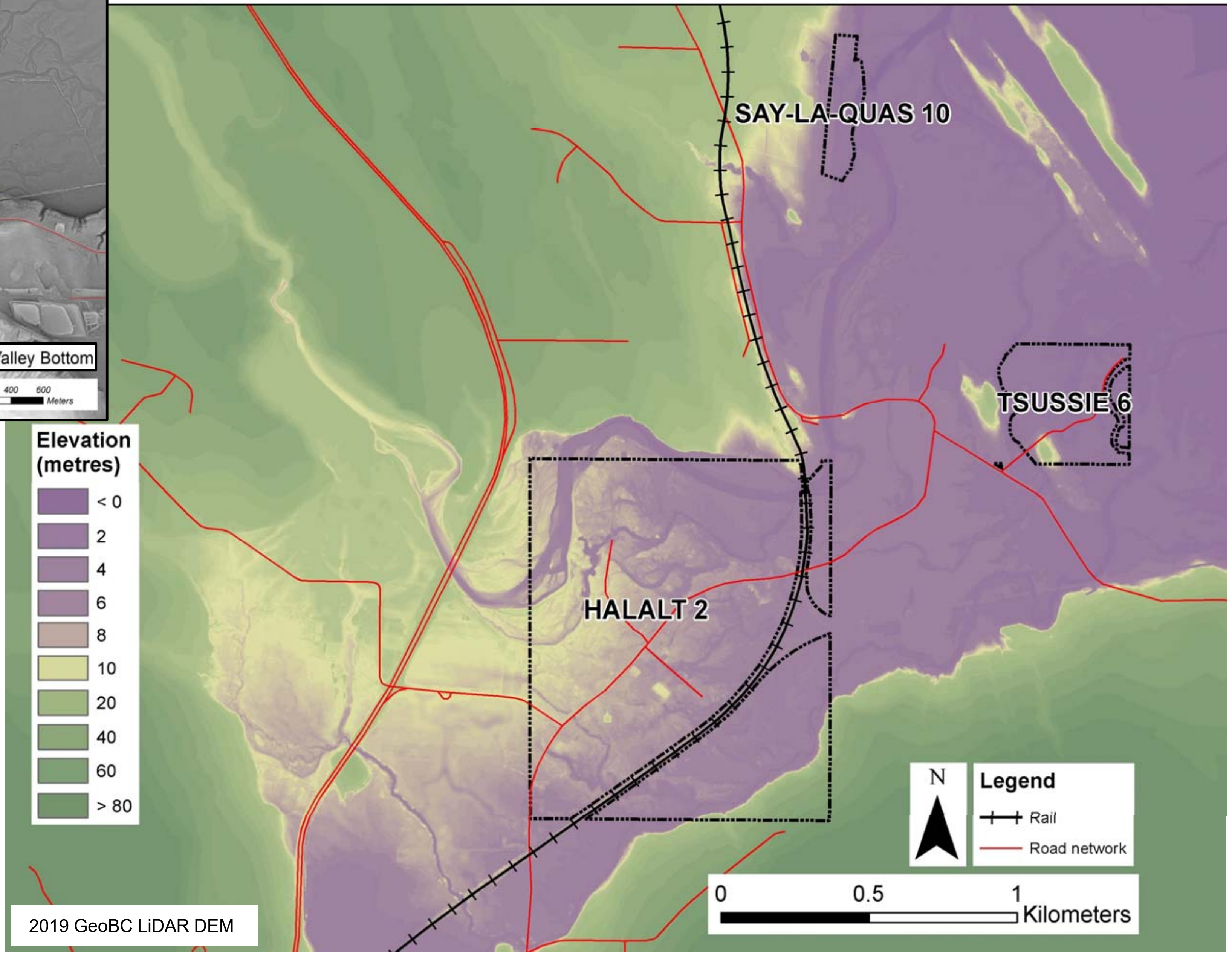


◄ The schematic at left (after NHC, 2015a) illustrates discrete locations where sediment conceptually is more prone to depositing along a stream channel.

In general, sediment tends to deposit along the Chemainus River channel at specific locations.

- Upstream or downstream of channel constrictions (A, B).
- Along the outside of meander bends (C).
- Upstream of backwatered areas that can form as a result of channel obstructions such as log jams (D) or in tidally influenced areas.

▼ At the upstream end of the MVB floodplain, the Chemainus River flows onto an alluvial fan. The fan is characterized by a radial topographic pattern emanating from valley confinement onto the floodplain. Distributary channels are common on fan formations (Rapp et. al. November 2003). The MVB is defined by the steep sided valley walls (illustrated by the relatively dark green colour shades in the figure below). The alluvial fan is illustrated by the transitional light green, yellow and light purple colours between the valley walls and floodplain.



7 REACH-SCALE CHANNEL CHARACTERISTICS AND DOMINANT PROCESSES

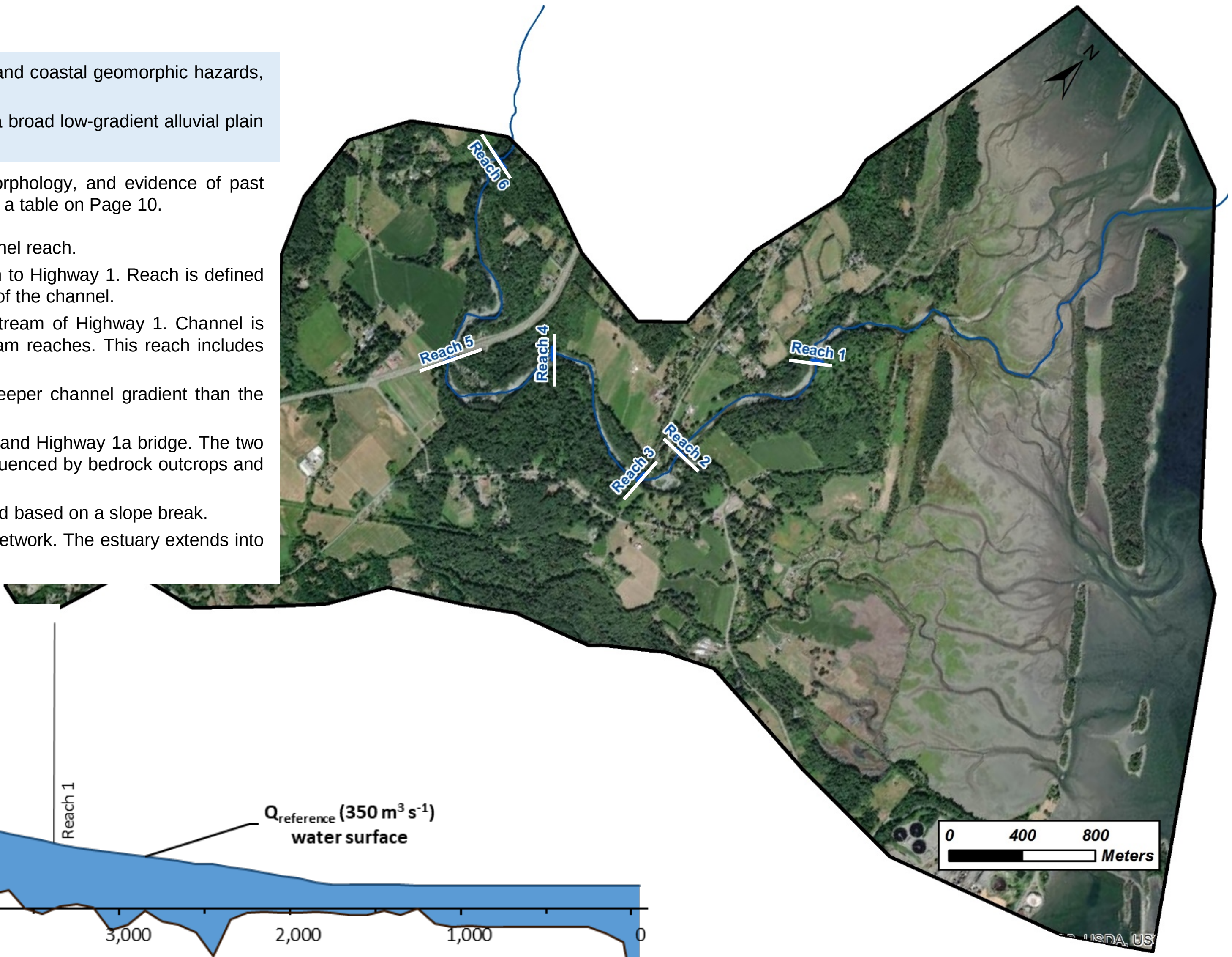
Study Extent

The lower approximately 8 kilometers of the Chemainus River were mapped for channel migration and coastal geomorphic hazards, matching the approximate extent of hydraulic modeling used to define flood hazard maps.

Within the mapped area, the Chemainus river exits a confined canyon reach and spreads out onto a broad low-gradient alluvial plain upstream of an estuarine environment where the Chemainus River meets the ocean.

The study area was subdivided into reaches based on differences in channel hydraulics and morphology, and evidence of past channel migration and lateral instability. Criteria used to discretize channel reaches are summarized in a table on Page 10.

- **Reach 7:** (upstream of the hydraulic model extents) encompasses a steep, confined channel reach.
- **Reach 6:** extends from the transition from a confined to unconfined channel downstream to Highway 1. Reach is defined by a relatively stable channel planform constrained by a high terrace along the north side of the channel.
- **Reach 5:** a zone of hydraulic expansion (and a depositional zone) immediately downstream of Highway 1. Channel is laterally unstable and has a lower degree of confinement than upstream and downstream reaches. This reach includes numerous intermittent flood channels.
- **Reach 4:** confined by a terrace on the north side of the channel. This reach has a steeper channel gradient than the upstream and downstream reaches.
- **Reach 3:** sediment and log debris depositional zone located between the railroad bridge and Highway 1a bridge. The two crossings form a distinctive hydraulic control on the system. This reach is also heavily influenced by bedrock outcrops and a rock armoured southeastern embankment.
- **Reach 2:** located downstream of the Highway 1a bridge. The downstream extent is defined based on a slope break.
- **Reach 1:** encompasses the relatively flat reach, characterized by a distributary channel network. The estuary extends into the Stuart Channel.



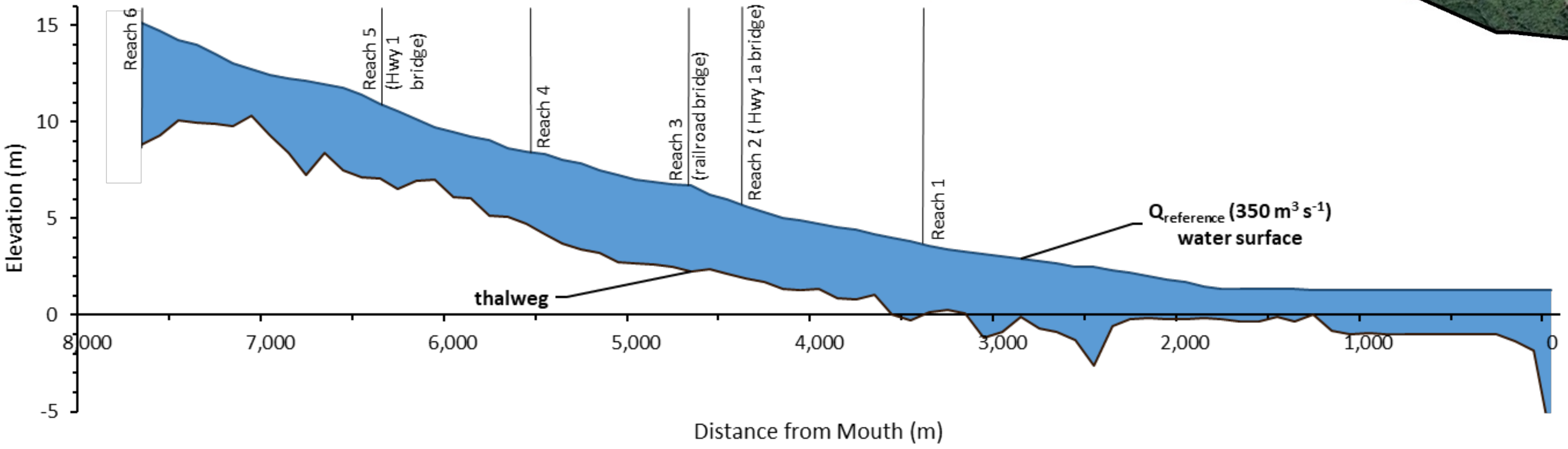


Image source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus, DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community)

7 REACH-SCALE CHANNEL CHARACTERISTICS AND DOMINANT PROCESSES

Reach-Scale Channel Characteristics

Parameter	Description	Units	Reach 7	Reach 6	Reach 5	Reach 4	Reach 3	Reach 2	Reach 1
Streamwise Length	Streamwise length of the reach	m	1,217	1,415	813	937	296	996	3,327
Straight-Line Length	Straight-line length of the reach	m	1,133	1,132	570	827	264	895	2,327
Sinuosity Ratio	Ratio of stream length to straight-line length	$m\ m^{-1}$	1.07	1.25	1.43	1.13	1.12	1.11	1.43
Channel Type	Channel type as defined by the sinuosity ratio	-	straight	sinuous	sinuous	sinuous	sinuous	sinuous	sinuous
Down-valley slope to channel slope ratio	Valley slope divided by streamwise channel slope	$m\ m^{-1}$	1.06	1.15	1.84	2.11	1.32	2.32	4.73
Bankfull Width	Reach-average channel width (2021)	m	37	80	114	43	65	44	65
Bankfull Width to Depth Ratio	Wetted width to depth ratio at bankfull conditions	$m\ m^{-1}$	-	22.1	34.2	9.9	16.9	12.1	18.8
$Q_{reference}$ - Average Shear Stress	Reach-averaged shear stress from 2D modeling of the approximate bankfull discharge (i.e., $Q_{reference}$)	Pa	-	82	87	64	95	46	18
$Q_{reference}$ - Maximum Shear Stress	Maximum shear stress from 2D modeling of the approximate bankfull discharge (i.e., $Q_{reference}$)	Pa	-	177	135	109	124	68	41
Grain Size - D_{50}	Median size of surface sediment	mm	-	51	38	34	33	-	16
Grain Size - D_{84}	84th percentile size of surface sediment	mm	-	86	68	58	59	-	28
Unvegetated Bar Area	Unvegetated bar area mapped from 2021 orthophoto	m^2	5,502	18,284	17,462	3,685	5,888	9,523	14,613
Vegetated Bar and Island Area	Vegetated bar and island area mapped from 2021 orthophoto	m^2	-	17,176	27,146	6,215	4,559	6,285	5,316
Average Erosion Rate	Reach-average erosion rate from 1950 to 2021, based on bankline delineation interpreted from available imagery (2021 imagery taken prior to flood)	$m\ yr^{-1}$	-	0.4	0.9	0.7	0.7	0.8	-
Maximum Erosion Rate	Maximum erosion rate from 1950 to 2021, based on bankline delineation interpreted from available imagery (2021 imagery taken prior to flood)	$m\ yr^{-1}$	-	1.3	7.1[1]	1.4	4.5	2.0	-
Number of Log Jams	Number of log jams identified by Cowichan Watershed Board (2021)	-	4	13	14	7	6	10	33
Identified Historical Avulsions	The number of avulsion events identified from 1950 to 2021 aerial imagery and historical maps from the 1800s.	-	0	0	1	1	0	1	Many

Notes:

1. In Reach 5, the Maximum Erosion Rate was calculated in two different ways based on the location within the reach and available information. Along the left bank and along the downstream portion of the right bank, the Maximum Erosion Rate of 0.9 $m\ yr^{-1}$ was calculated using the same procedure used for the other reaches, based on air photo bankline delineation from 1950 to 2021. Along the upstream portion of the right bank, from RKM 5.9 to 6.4, recent survey data showing evidence of erosion associated with the November 2021 flood was available. This additional survey information was used in calculating a Maximum Erosion Rate of 7.1 $m\ yr^{-1}$ for the right bank along this segment of the channel.

Channel Assessment Meso-habitat Spatial Data (Cowichan Watershed Board 2021)

As part of a detailed channel assessment carried out in the summer of 2021 (Cowichan Watershed Board, 2021), spatial meso-habitat data was made available for this project. This dataset included: bankfull width to depth ratio, channel entrenchment, complexity, disturbance, floodplain availability, geomorphic condition, mesohabitat, spawning gravels, stream cover, stream incision, stream substrates, wetted width to depth ratio, and log jams.

Reach breaks (RBs) within the study area, as defined by the Cowichan Watershed Board (2021) data, are also illustrated in the map to the right and summarized below. These reach breaks extend upstream through the entire 64 km length of the channel, and so the study area is more broadly divided into three reaches, based on differences in channel morphology/confinement and tidal influence.

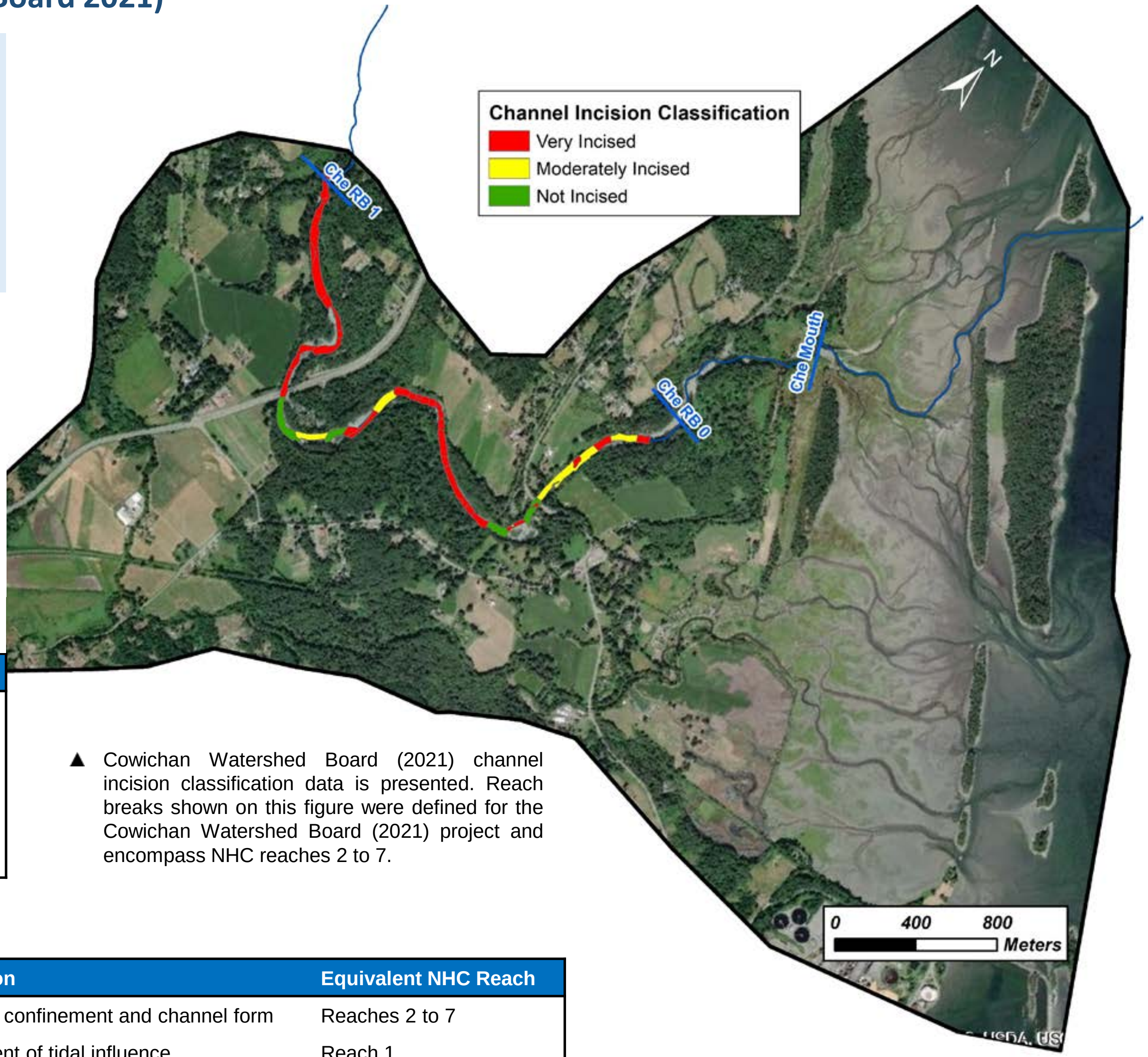
Channel Sinuosity and Avulsion Potential

Cowichan Watershed Board (2021) Reach 1 (RB 1) encompasses NHC's reaches 2 to 7 and broadly incorporates the Chemainus River reach between the confined valley and tidally influenced zone.

This reach has a sinuosity ratio of 2.0 which is reflective of a 'meandering' channel type and indicative of a channel that has a higher propensity to avulse during a high-discharge event. Typically, avulsions occur when the channel sinuosity is greater than 1.5, assuming the discharge exceeds the threshold needed for an avulsion (Forest Practices Board, 2004).

This sinuosity computed based on the Cowichan Watershed Board (2021) reach is higher than the shorter reaches that NHC used for the erosion rate classification calculations. This highlights the scale-dependent nature of this parameter. Application of the Watershed Board (2021) reach evaluates channel and floodplain morphology at the valley-scale, which is considered appropriate for evaluating channel avulsion potential.

Parameter	Description	Units	RB 1	RB 0	Che Mouth
Streamwise Length	Streamwise length of the reach	m	4,260	984	2,470
Straight-Line Length	Straight-line length of the reach	m	2,127	792	1,750
Sinuosity Ratio	Ratio of stream length to straight-line length	$m\ m^{-1}$	2.00	1.24	1.41
Channel Type	Channel type as defined by the sinuosity ratio	-	meandering	sinuous	sinuous
Channel Slope	Reach-average slope along the thalweg	$m\ m^{-1}$	0.0020	0.0023	0.0017



▲ Cowichan Watershed Board (2021) channel incision classification data is presented. Reach breaks shown on this figure were defined for the Cowichan Watershed Board (2021) project and encompass NHC reaches 2 to 7.

Image source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus, DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community)

Channel Incision

Channel incision is a metric used to describe the degree of connectivity between the stream and adjacent floodplain. Very incised areas are considered relatively more disconnected from the floodplain, whereas areas that are classified as not incised are relatively more connected to the floodplain.

Note: thalweg refers to the line connecting the deepest part of the channel profile

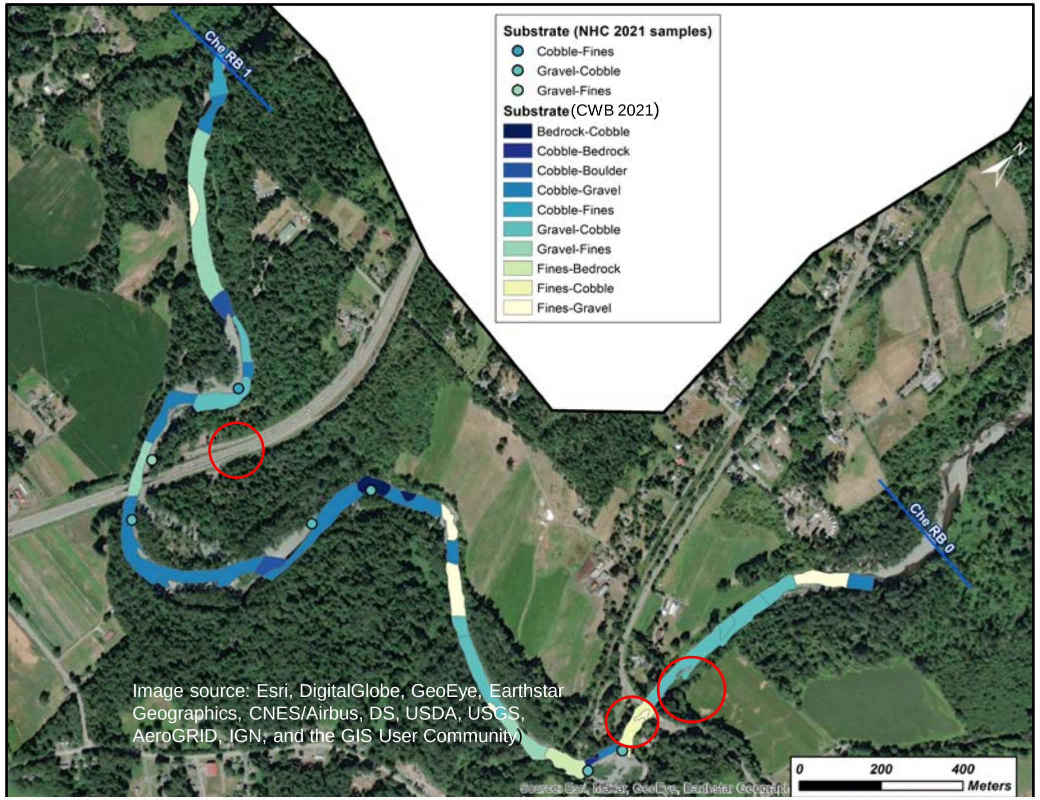
RB Name	Description	Equivalent NHC Reach
RB 1	Change of confinement and channel form	Reaches 2 to 7
RB 0	Upper extent of tidal influence	Reach 1
Che Mouth	Mouth of Chemainus main channel	Reach 1

Channel Assessment Meso-habitat Spatial Data (Cowichan Watershed Board 2021)

Stream Substrate

A detailed classification of stream substrate is presented in the left panel below. The data is derived from low-flow Wolman pebble counts collected during the summer of 2021 (Cowichan Water Board, 2021).

- The river-bed is dominated by cobble to gravel sized sediment with localized bedrock outcrops and deposition of fines.
- Upstream of the three bridges – Highway 1, the railroad bridge, Highway 1a bridge (circled in red) – the stream substrate is locally finer than upstream and downstream locations. This localized fining of sediment caliber is likely produced by backwatering effects during high flows. The bridges impose an artificial constraint on channel width, which reduces the amount of flow that can be conveyed at a given time. This causes the flow of water to slow down and leads to upstream sediment deposition.
- NHC pebble counts (2021) were collected at a relatively higher flow than the CWB (2021) data, which reduced the sample area coverage.

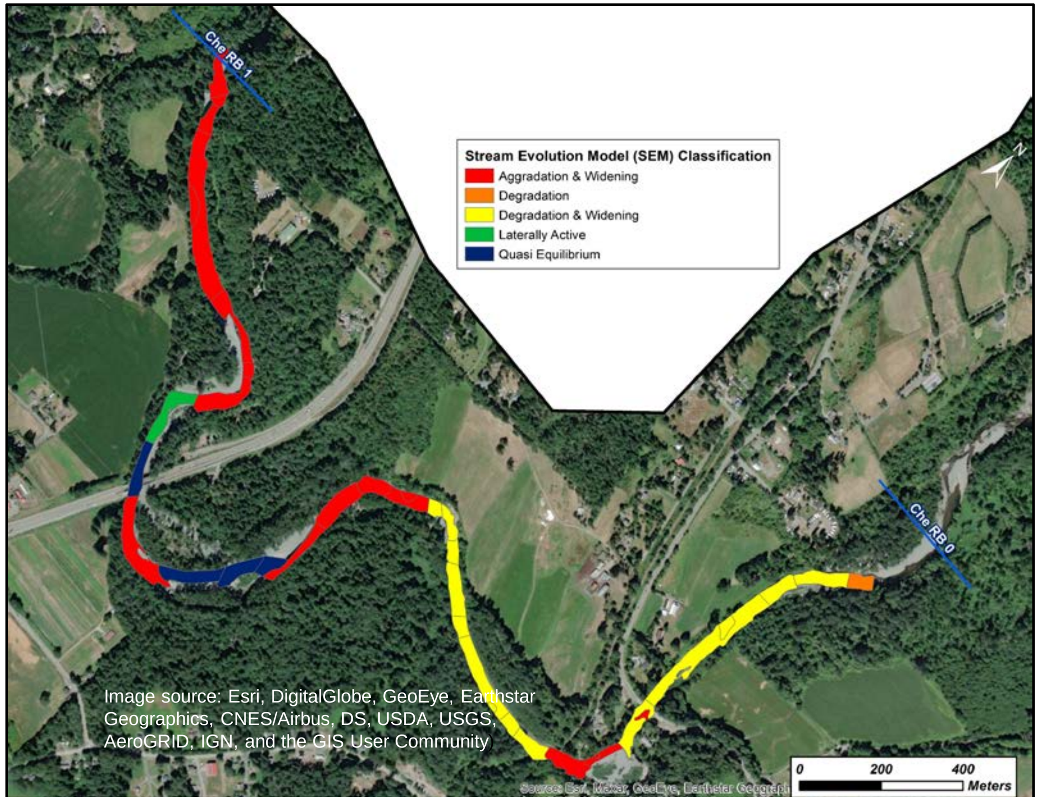


▲ Stream substrate classification. Red circles highlight localized sediment fining upstream of bridges.

Stream Evolution Model

The geomorphic condition of the channel, as expressed by the Stream Evolution Model (SEM) classification (Cluer and Thorn, 2004) is presented in the right panel below. Data provided by the Cowichan Water Board (2021).

- Upstream of Highway 1, most of the channel is in a state of aggradation and widening. The channel is laterally active locally downstream of a vegetated island, whereby a back-channel rejoins the mainstem.
- The lower half of the reach is defined to be mostly in a state of degradation and widening. Between the railroad bridge and Highway 1a bridge, the channel is in a state of aggradation and widening (described on Page 31).
- These results agree with NHC's measurements of vertical bed elevation changes from 1986 to 2021 (Page 31).

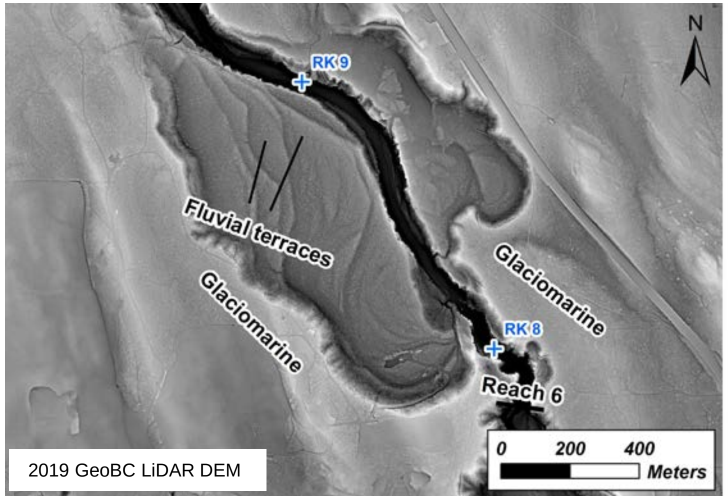


▲ Stream Evolution Model (SEM) classification of the channel's geomorphic condition.

Reach 7 (RK 9 to RK 7.8) : Confined Channel Reach

- Through Reach 7, the Chemainus River flows southeast within a roughly 40 m wide channel with a steeper gradient (0.0064 m m^{-1}) than downstream reaches.
- Near the downstream extent of Reach 7 (around RK 8) the channel is confined on either side by valley walls approximately 40 m high, composed of resistant glaciomarine sediment.
- Upstream of RK 8, the channel is bordered on either side by terraces that sit 20 m to 25 m above river level. During a period of sea-level lowering, the stream likely cut these terraces in older deposits (Halstead, 1966). The modern-day channel appears to be underfit and no longer erodes the terrace surfaces.
- Channel banks are well-vegetated, contributing to high bank stability in Reach 7.
- Reach 7 is just upstream of the hydraulic model extent, so information on shear stress and flood levels was not available for this study.

The lack of major in-channel storage sites through this reach is indicative of a transport-dominated regime. Sediment and large woody debris (LWD) are typically conveyed farther downstream with only transient gravel bars forming and deforming year to year within this reach.

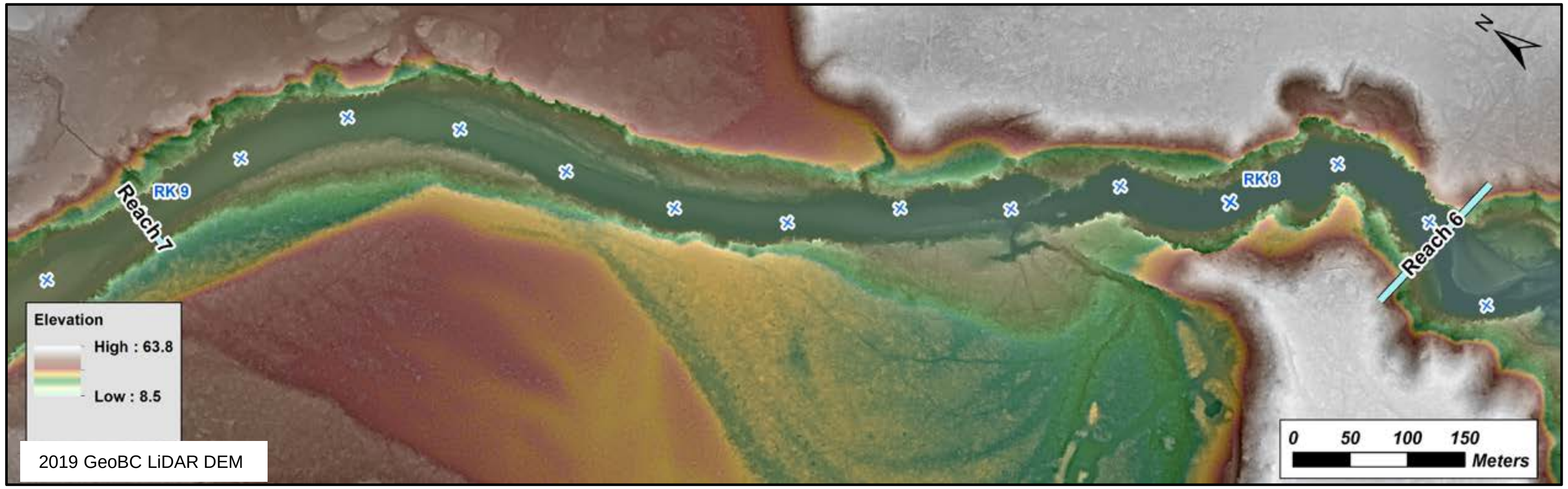


2019 GeoBC LiDAR DEM

Reach 7	
Reach Length (m)	1,217
Average Slope (m m^{-1})	0.0064
D_{50} (mm)	-
Mean Erosion Rate (m yr^{-1})	-

Note: D_{50} refers to the median sediment grain size diameter, measured from bar surface photos.

2021 FLNRORD orthophoto



2019 GeoBC LiDAR DEM

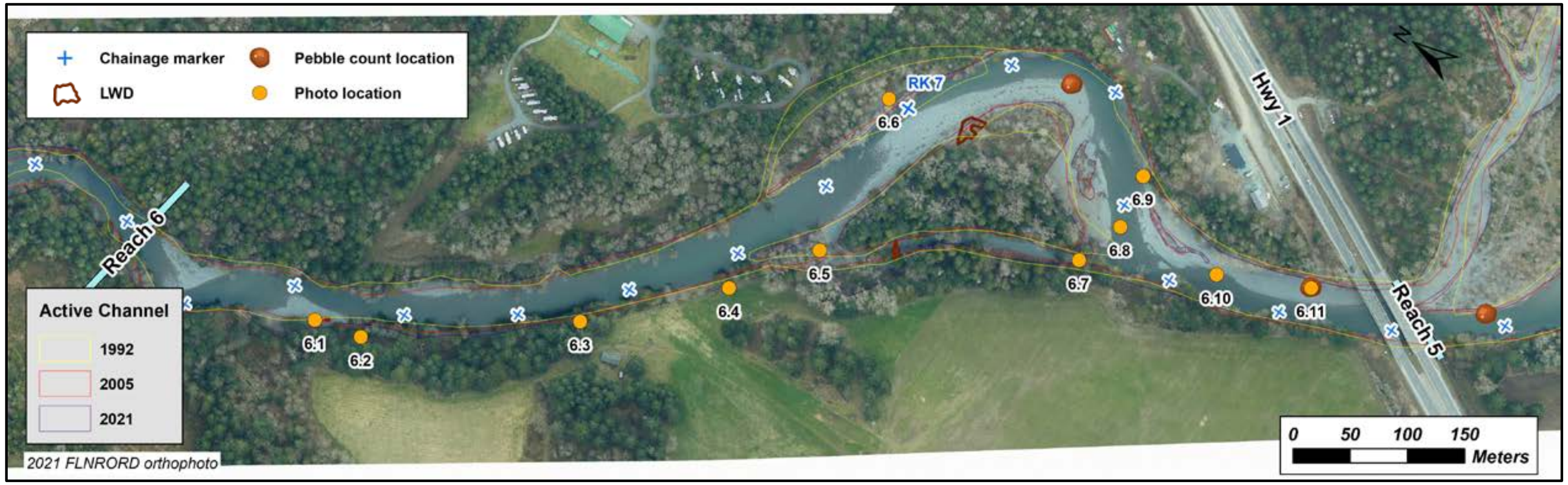
Note: RK refers to the River Kilometer distance measured along the channel thalweg, upstream of the approximate seaward extents of the estuary (northeast of the northern Willy Island passage). Each 100 m channel distance is marked with an 'X' and every RK is labelled.

Reach 6 (RK 7.8 to RK 6.4): Reach Morphology

- In Reach 6 the river exits a confined canyon and flows onto a broad alluvial plain.
- At the upstream end of the reach, the channel flows through a straight channel, roughly 40 m wide. Small lateral bars at the top of the reach consist of boulders and cobbles, often with LWD accumulations, indicative of a high-energy environment.
- In the upstream end of the reach bedrock outcrops and tall terraced banks constrain the channel position to the north. Along the southern channel boundary, a discontinuous earthen berm runs parallel to the river, which reduces overbank flow onto the floodplain during flooding.

▼ Photo 6.1 Boulders and coarse cobble on the bar surface.

▼ Photo 6.2 Bedrock outcrop along the left (north) bank of the channel.



▲ Photo 6.3 Earthen berm reduces the amount of flow that spills out onto the floodplain during peak flood events.

Reach 6	
Reach Length (m)	1,415
Average Slope (m m^{-1})	0.0014
D_{50} (mm)	51
Mean Erosion Rate (m yr^{-1})	0.4

- Near RK 7, the Chemainus river splits into two channels around a vegetated island and bar complex. The island formed prior to 1950, and appears stable over time, increasing in extent as vegetation establishes and matures.
- Near RK7, the main channel is bounded to the north by terrace bluffs. Opposite the bluffs, sediment has accumulated along the margin of the island, ranging from coarse cobbles near the head, to finer gravels at the tail.
- A secondary channel, 10 km to 15 m wide, flows south of the island. This channel is shorter and straighter than the main channel, and potentially offers a more energy-efficient path to convey flow. A review of historical air photos suggests that the channel has become increasingly active over time.

Note: Left and right channel descriptors refer to a downstream facing view of the channel.

▶ Photo 6.4 Overbank sand deposits 0.1 to 0.2 m deep.

Reach 6 (RK 7.8 to RK 6.4): Partially Confined Channel Reach

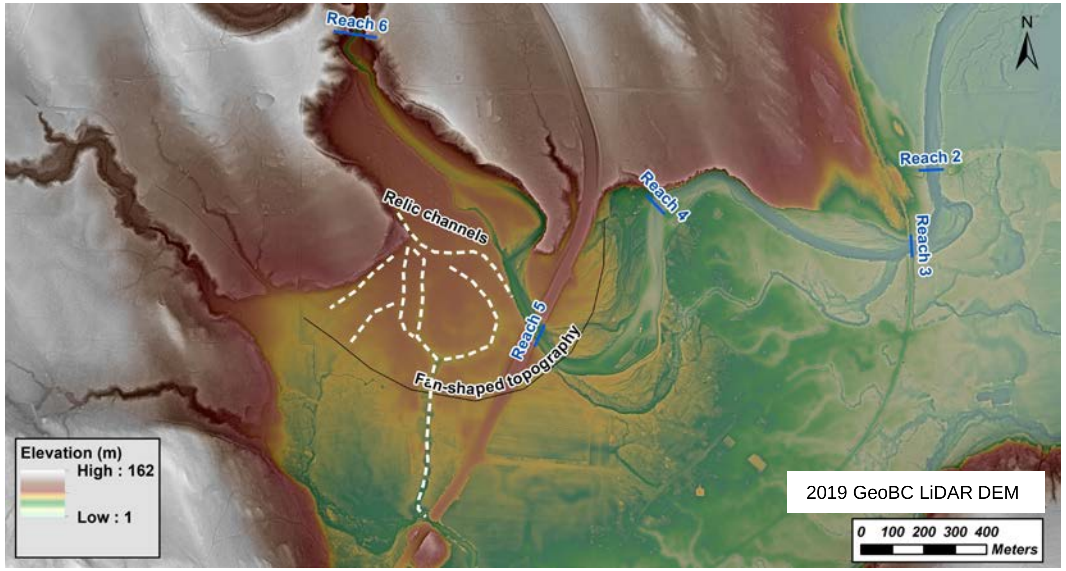
As the river exits confinement from the steep terraced banks it becomes increasingly more coupled with the adjacent floodplain area. During large floods, overbank flow spills out onto the floodplain depositing fine sediment carried in suspension and over time produces the fan-shaped depositional pattern observed in the DEM.

Relic channels in the floodplain south of the modern-day channel, reveal insights into historical channel positions. Should the earthen berm that runs along the southern channel bank fail or be removed, these old channels are potential primary pathways for overbank flow.

Analysis of a simulated 200-yr flood event shows that at this stage, roughly 70% of the discharge is conveyed within the Reach 6 channel banks, and 30% of the discharge flows south, overbank across the floodplain. Log jams or sediment accumulations could alter the channel conveyance capacity over time.

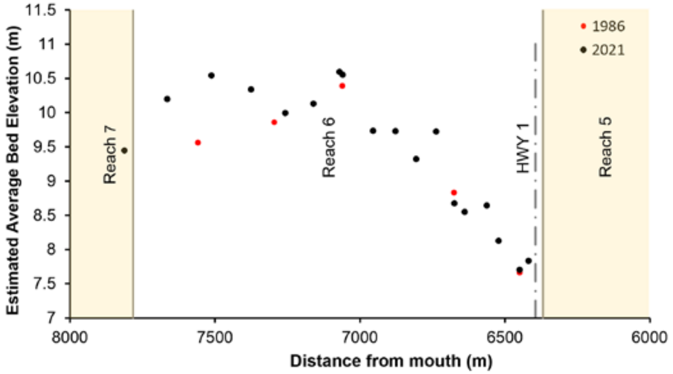
▶ Photo 6.5 LWD accumulation and sediment lobes on the island.

▼ Photo 6.6 A steep riffle at the head of the bar. Surface sediment at the bar head is primarily cobbles.



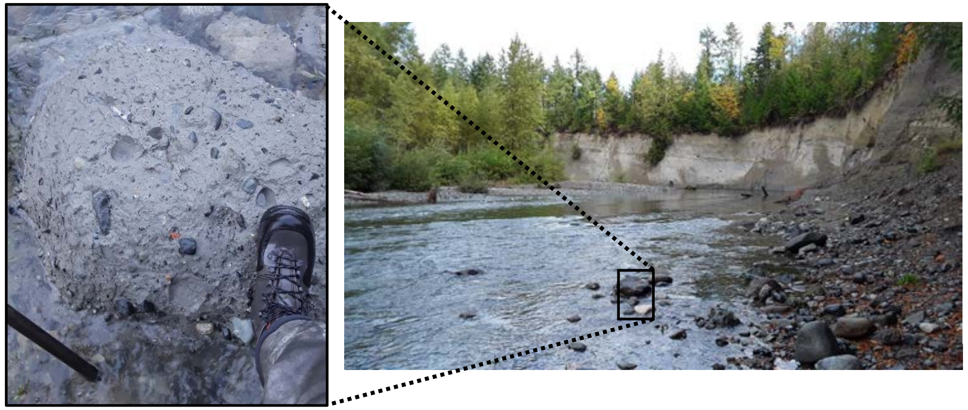
▲ DEM illustrating the fan-shaped topography across the Chemainus River floodplain.

▼ Plot of average bed elevation in 1986 and 2021 in Reach 6 indicating apparent channel aggradation (see Page 31 for more details).



▼ Photo 6.7 (Upstream view) Back-channel has multiple downed trees spanning the channel width.

▶ Photo 6.8 Fine to medium gravels on the tail of the bar opposite the bluff. This is much finer sediment than found along the toe of the bluff and head of the next bar downstream highlighting the within-channel spatial variation in shear stress and stream energy.



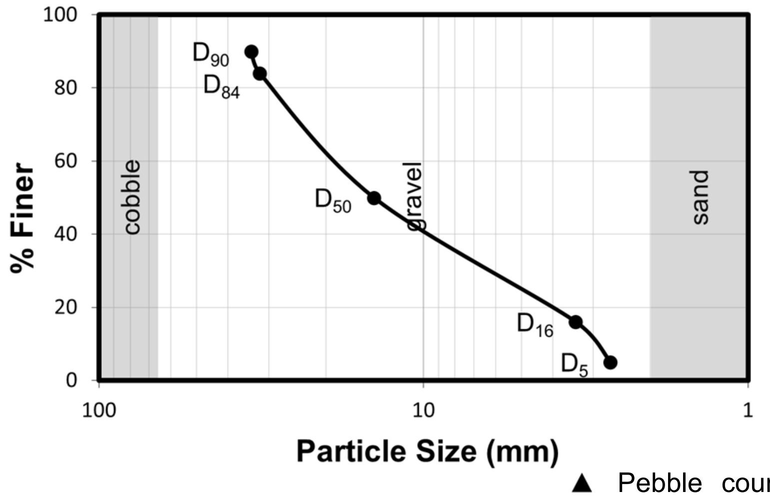
◀ Photo 6.9 Glaciomarine deposits composed of silt, clay, stony clay, and till-like mixtures up to 20 m thick provide resistant banks to the channel through this reach. This feature has kept the position of the contemporary channel position relatively stable since deglaciation (Halstead, 1966).

Reach 6 (RK 7.8 to RK 6.4): Upstream of Highway 1

The November 2021 flood caused erosion at the toe of the right (southern) bank, which is composed of compact sands and gravels. While this area has historically been relatively laterally stable with little to no bank retreat observed since 1950, the right bank is directly exposed to flow forces where the mainstem channel and back channel rejoin at the downstream end of the island.

An increase in the proportion of flow directed into the southern channel would have direct implications for the dynamics of downstream-reaches. Specifically, it may change the direction in which flow attacks channel banks in Reach 5.

- Downstream of the vegetated island, the two channels rejoin into a single mainstem. Here, sediment has accumulated along the left side of the channel, while the channel thalweg flows close to the right (south) bank.
- The artificial constraint on channel width imposed by the Highway 1 bridge creates upstream backwatering during high flows and creates a localized fining of surface sediment caliber along the left bank deposit. The median size of sediment upstream of the bridge is in the range of 15 mm to 30 mm, while further downstream pebble counts indicate a median size of surface sediment in the range of 40 mm to 50 mm.

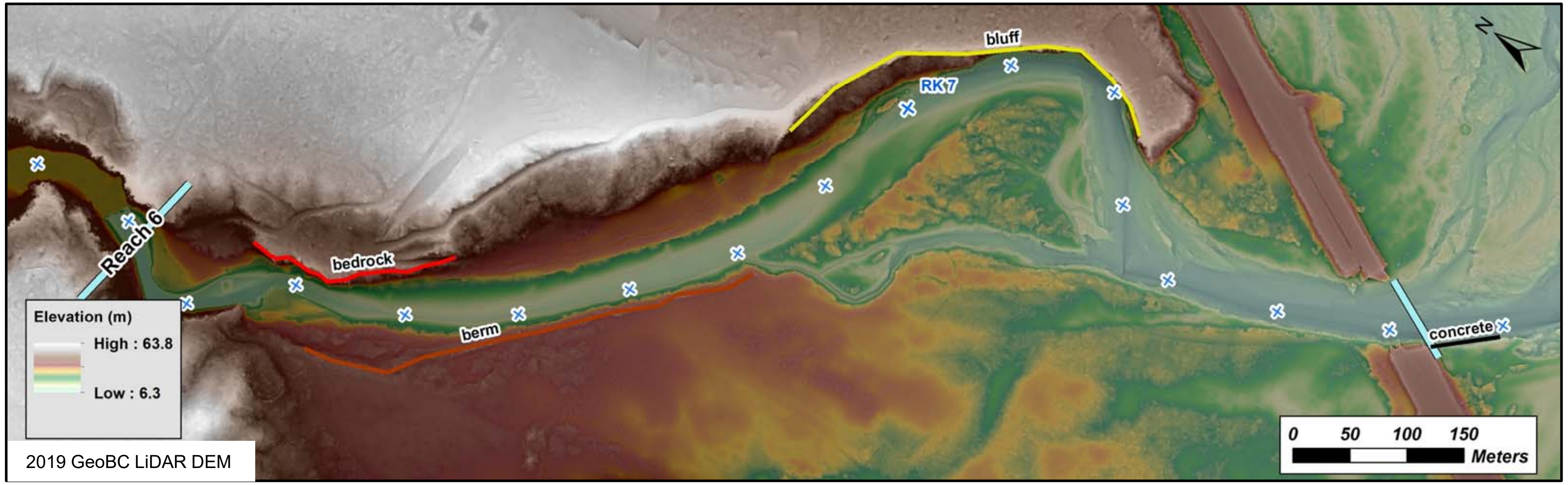


▲ Pebble count taken at RK 6.45, just upstream of the Highway 1 bridge. D_{90} refers to the sediment grain size diameter that is not exceeded 90% of the time in the sample dataset.

◄ Photo 6.11 Gravel-sand mix on the bar tail upstream of the Highway 1 bridge.

▲ Photo 6.10 At the mid-channel bar the substrate is much coarser than that seen on the tail.

▲ Photo 6.7 (Downstream view). Toe erosion along the right (southern) bank. This bank line has been relatively stable historically.



Reach 5 (RK 6.4 to RK 5.5): Reach Morphology

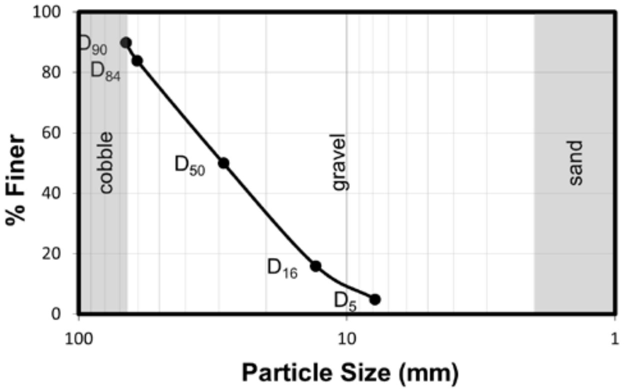
Reach 5 of the Chemainus River falls partially within the boundary of the Halalt First Nation administrative boundary. Reach 5 is a primary depositional zone and is laterally unstable.

- The confinement imposed by the Highway 1 bridge plays a large role in the stability and morphology of Reach 5.
- Downstream of the bridge, the river enters a zone of hydraulic expansion and is a prominent depositional zone. At higher flows, water and sediment is conveyed through multiple channels around islands and over bar tops, re-working existing sediment deposits.
- LWD jams on islands have been modified and anchored using heavy cable and ballast. These anchored jams help control local channel hydraulics and habitat conditions by altering the spatial patterns of scour and deposition (Abbe and Montgomery, 1996).
- At present, the ability for the river to laterally migrate across the valley bottom is limited in places by rock armouring along the right (southern) bank. There is evidence in the DEM of past channels flowing through the floodplain south of the modern-day channel.

Photo credit: CVRD

◄ Chemainus River downstream of the Highway 1 bridge. Photo shows high-flow channel on the inside of the bar, and log jams on the vegetated island.

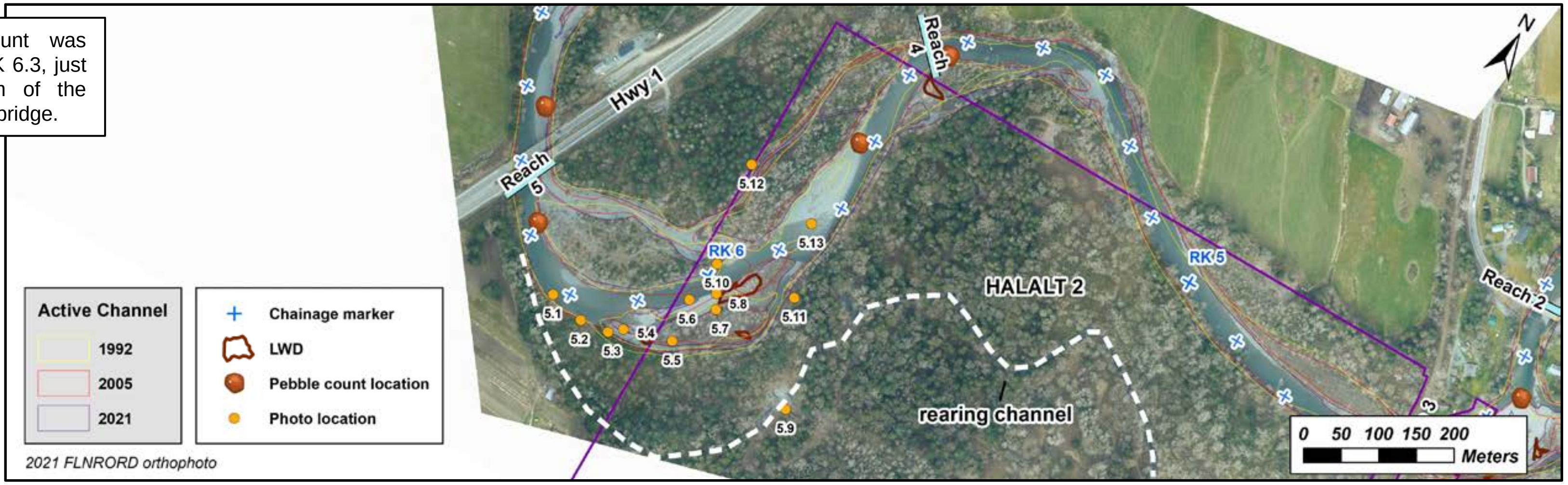
▼ Photo 5.8 Upstream log jam on the vegetated island.



◄ Pebble count was taken at RK 6.3, just downstream of the Highway 1 bridge.

Reach 5	
Reach Length (m)	813
Average Slope (m m^{-1})	0.0029
D_{50} (mm)	38
Mean Erosion Rate* (m yr^{-1})	0.9

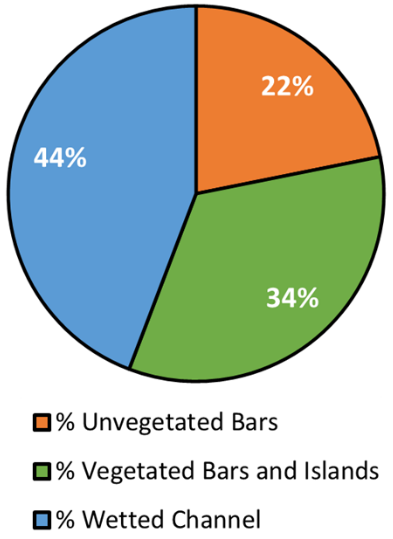
* Mean erosion rate calculated from changes in bankline position from 1950 to 2021 but does not include the substantial erosion produced in the November 2021 flood event. This is discussed in more detail on Page 19.



Reach 5 (RK 6.4 to RK 5.5): Point Bar

Since 1975, vegetation has established and matured on the bar downstream of Highway 1 providing increased flow resistance locally. The distribution of vegetated surfaces (on islands and vegetated bars) appears to be an important control on the morphodynamics of Reach 5.

- Peak flood events overtop and carve channels into the bar surface, producing variations in sediment caliber across the bar. Sand and fine gravel is transported along back channels and high-elevation surfaces, while areas closer to the main low-flow channel exhibit a coarser texture.
- A municipal water well is located on the interior of the bar and has been reinforced with heavy rock armour to provide protection from scour. The area is in the vicinity of a high-flow channel and is potentially exposed to erosion from annual flood events.
- In 2021, sediment was removed from the bar tail adjacent to the wetted channel to allow flow through the area and to lessen the force of flow against the bank opposite of the bar (DR Clough, 2007).

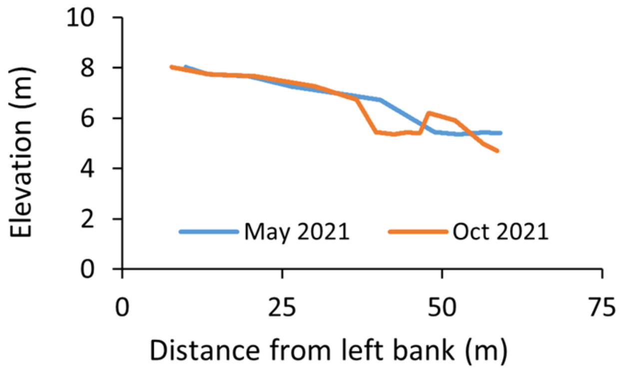


▲ Proportion of unvegetated bars, vegetated bars and islands, and wetted channel in Reach 5 in 2021.

▲ Photo 5.10 High-flow channel on the bar surface. Sandy lobes are left behind during the falling limb of the flood as water levels drop and the finer sediment falls out of suspension. The boulders at the right of the photo armour the water well installed on the bar.

▼ Photo 5.12 Fine to medium gravel and sand is transported through a back-channel along the inside of the point bar. The channel is about 2.5 m wide and incised approximately 0.3 m into the floodplain.

▶ Bed lowering along the left side of the channel at RK 5.8, resulting from sediment removal in 2021.



▶ Photo 5.13 Sediment was removed from the bar tail (2021) to create a wider wetted channel and to reduce flow towards the opposite bank.

Reach 5 (RK 6.4 to RK 5.5): Bank Erosion

Opposite the point bar, the right (southern) channel bank is on the outside of a meander bend and is susceptible to erosion from upstream flows. This section of bank line is highly significant because of its proximity to the Halalt First Nation band office and community facilities, and because roads and houses in the vicinity would be threatened should the banks erode in this direction.

- Approximately the first 40 m of right bank downstream of the Highway 1 bridge is reinforced with concrete blocks and has shown little to no erosion since 1950. Field visits (in 2021) indicate some of the concrete blocks are absent along the toe but are visible higher up on the bank.
- Downstream of the concrete, the channel bank is composed of loosely consolidated layers of cobble, gravel and sand with varying degrees of root-strength provided by riparian vegetation. Coarse gravel and cobble deposits in the bank stratigraphy are deposited by relatively high energy flood events, whilst finer-grained sand deposits reflect deposition during more moderate flow conditions.
- Mapping of historical bank line positions shows that from 1950 to 2021, the outer bank has retreated at an average rate of 0.9 m per year with year-to-year variations based on the flow regime.
- In November 2021, the atmospheric river that hit the Pacific Northwest produced a substantial flood on the Chemainus River. Topographic survey measurements collected pre- and post-flood indicate that this event caused the outer bank to retreat by 2.5 to 6.3 m. This magnitude of bank retreat is 2.7 to 7 times higher than the historical erosion rate.
- The largest magnitude of bank retreat in Reach 5 (in 2021) was observed in the downstream most section of bank line, just upstream of the island. This area is most directly exposed to high-velocity flows from upstream and has a very shallow root network offering little to no stabilization.

▲ The November 2021 flood eroded a 200 m section of bank line downstream of Highway 1. As a result, the bank retreated away from the channel by up to seven metres. 2021 FLNRORD orthophoto.

▲ Photo 5.1 Exposed roots offer relatively more resistance to erosion than farther downstream. However, the silty bank material is relatively more erodible than the composition downstream.

▲ Photo 5.2 Exposure at the downstream end of the eroding bank line. The sandy layer near the toe is easily eroded. Coarser material is loose and uncompacted. The roots through upper horizon offer minimal stabilizing benefit.

Reach 5 (RK 6.4 to RK 5.5): Avulsion Potential

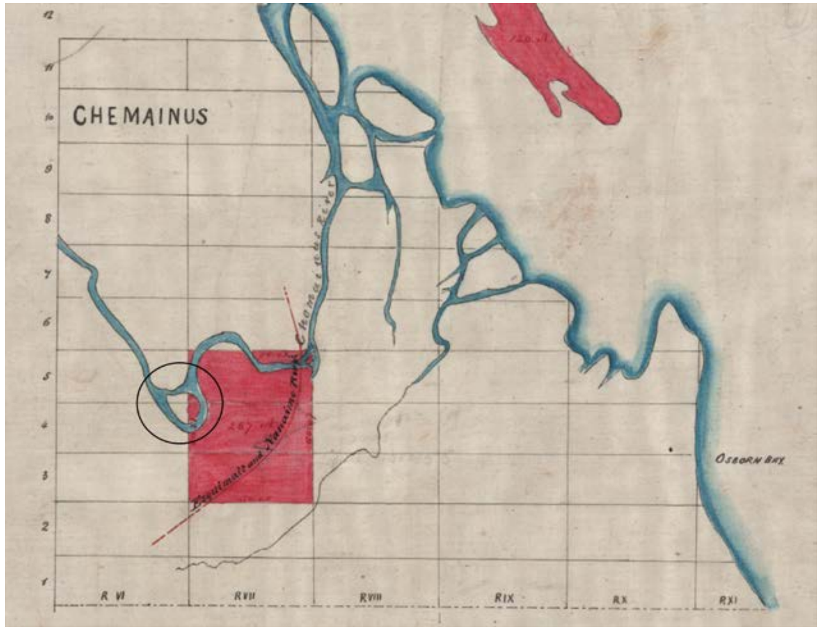
A historical side channel, approximately 6 m to 8 m wide, has been deepened and is used by the Halalt Fisheries for juvenile fish rearing (Chief Thomas, pers. comm. 3 August 2022). A relic channel located on the right (south) bank of the Chemainus River connects to the Halalt Fisheries channel, and if a triggering mechanism produces a breach of the channel banks near the relic channel, it will provide a preferential pathway to convey overbank flow downstream along a similar hydraulic gradient to the contemporary main channel.

This location is prone to channel avulsion.

- The risk of avulsion into the relic channel would be exacerbated by LWD accumulations or sediment aggradation near the entrance to the channel.
- A map produced in 1877 suggests that historically flow was conveyed across two channels through Reach 5, where the southern channel appears to overlap the position of the Halalt Fisheries rearing channel. This provides supporting evidence for the possibility of an avulsion in this reach to return to a similar multi-channel configuration as occurred in the past.

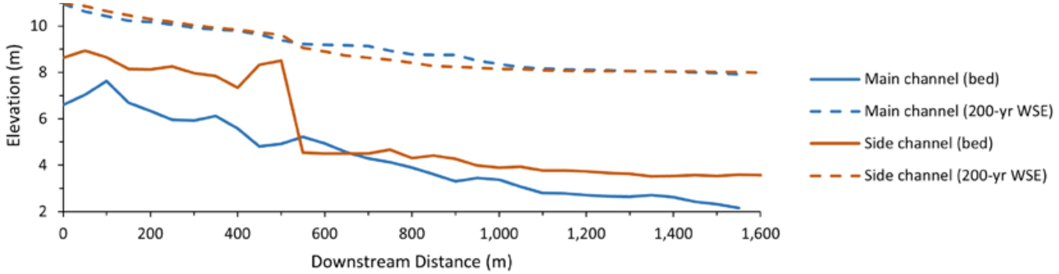
▲ Photo 5.9 The floodplain channel and pond system is used for rearing juvenile fish by Halalt Fisheries. Photo at left shows a floodplain channel in August 2021. Photo at right shows the facility following the November 2021 flood event.

▼ Map of the Chemainus River from 1877 (Indian Affairs Survey Records No. BC 220) shows Reach 5 historically was split into multiple channels. Shaded red areas represent Halalt First Nation administrative boundary.

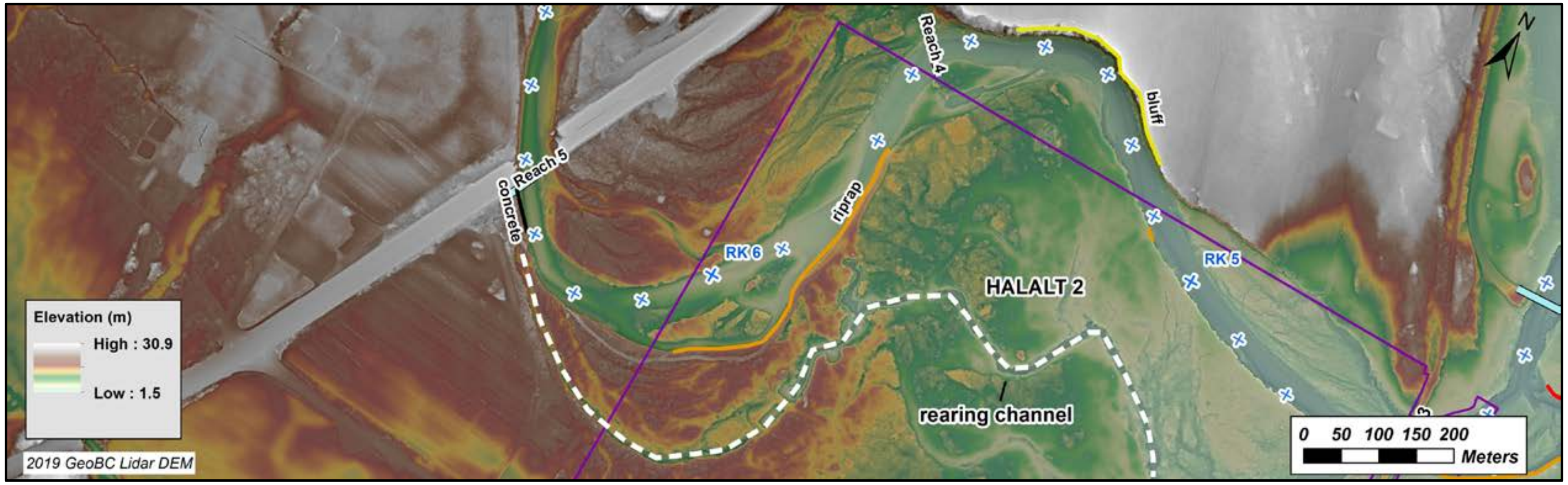


▶ Comparison of channel bed and water surface profiles in the mainstem and relic side channel.

Main channel	
Length (m)	1,620
Average Gradient (m m^{-1})	0.0029
Side channel	
Length (m)	1,736
Average Gradient (m m^{-1})	0.0031



▼ DEM showing a visible relic channel path.



Reach 5 (RK 6.4 to RK 5.5): Island and Side Channel Erosion

Given the angle of exposure from upstream flows, and the deposition of sediment on the opposite side of the channel, the southern channel bank and island is threatened by erosion during future flood events.

- Near the right (south) bank of Reach 5, an approximately 10 m wide side-channel flows around an elongate vegetated island. The island and secondary channel bank lines are exposed to high-velocity flows, and as such have been the focus of ongoing river management works.
- Upstream of the island, the southern channel bank is armoured with riprap and is connected to the head of the island via placed LWD and boulders.
- The secondary channel flowing behind the island is also reinforced with riprap along its outer bank. In spot areas where riprap is absent, the banks are composed of uncompacted sand and gravel at the upstream end and soft fine-grained loamy material downstream where the back-channel rejoins the mainstem.
- The island bank adjacent to the main channel experiences high-velocity flows during peak floods and has been reinforced with piled gravel and placed LWD.

▲ Photo 5.5 Riprap along the right channel bank behind the island.

▲ Photo 5.4 Wattle fencing at the head of the island installed in 2021.

▲ Photo 5.11 Soft, loamy material along the bank is easily eroded.

▲ Photo 5.7 Gravel pile-up along island bank is reinforced with LWD.

▲ Photo 5.6 Coarse cobble and boulder substrate on the vegetated island is indicative of a high energy environment. The river mobilizes smaller particles downstream.

▼ Photo 5.3 LWD was placed at the entrance to the side channel to reduce flow into this area. The LWD connects riprap armour along the upstream bank to the log jam at the head of the island.

Reach 4 (RK 5.5 to RK 4.6): Channel Confinement

Reach 4 of the Chemainus River resides partially within the Halalt First Nation administrative boundary.

From RK 5.5 to RK 4.6, the river flows within a 30 m to 40 m wide bedrock channel with little sediment covering the bed. The lack of sediment cover means that the channel slope through this reach is primarily controlled by the bedrock over which it flows.

- The channel is confined to the north by terrace bluffs that extend 15 m to 20 m above the river bottom elevation. These bluffs are composed of compact fine-grained sediment of marine/glaciomarine origin, the same unit described in Reach 6.
- The bluffs are more resistant to erosion than other alluvial banks within the channel and have remained relatively stable in the air photo record dating back to 1950. However, undercutting of the toe of the bluff was observed during the November 2021 atmospheric river flood. Given the height of the bluffs, continued undercutting by fluvial erosion has the potential to trigger a mass wasting event which could block the river. For this reason, these banks were flagged as geotechnical hazards in the geomorphic hazard maps.
- Opposite the bluffs, sediment has accumulated on the inside of a channel bend forming a point bar. This site has historically been a sediment sink and has been the focus of past sediment excavation efforts.

◄ Photo taken at low-flow, exposing the bedrock channel bed at the top of reach 4. This provides an important control on the channel gradient in this reach.

▲ Photo 4.1 from August 2021 prior to the winter storm season.

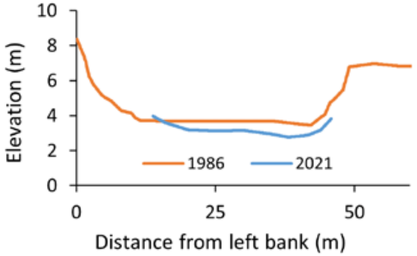
▲ Photo 4.1 Erosion at the toe of the bluff from the November 2021 flood.

Reach 4	
Reach Length (m)	937
Average Slope (m m^{-1})	0.0022
D_{50} (mm)	34
Mean Erosion Rate (m yr^{-1})	0.7

Reach 4 (RK 5.5 to RK 4.6): Upstream of the Railroad Bridge

Downstream of the point bar, Reach 4 has few sediment storage sites, and is characterized by a transport-dominated regime. Sediment appears to be flushed through this reach and accumulates downstream of the railroad bridge in Reach 3.

- The right (south) bank of the channel shows signs of undercutting and has been reinforced locally with log spurs and riprap. Despite this, the historical mean rate of erosion (0.7 m yr^{-1}) through Reach 4 is low compared to other mapped reaches.
- Between RK 5.5 and RK 5.1, where the channel is confined to the north by the bluffs, there has been limited lateral migration over the air photo period of record. However, repeat surveys at approx. RK 5.1 indicate that scour (-0.30 m vertical change) occurred between 1986 and 2021.



◄ Plot showing scour at RM 5.1 between 1986 and 2021 based on repeat surveys.

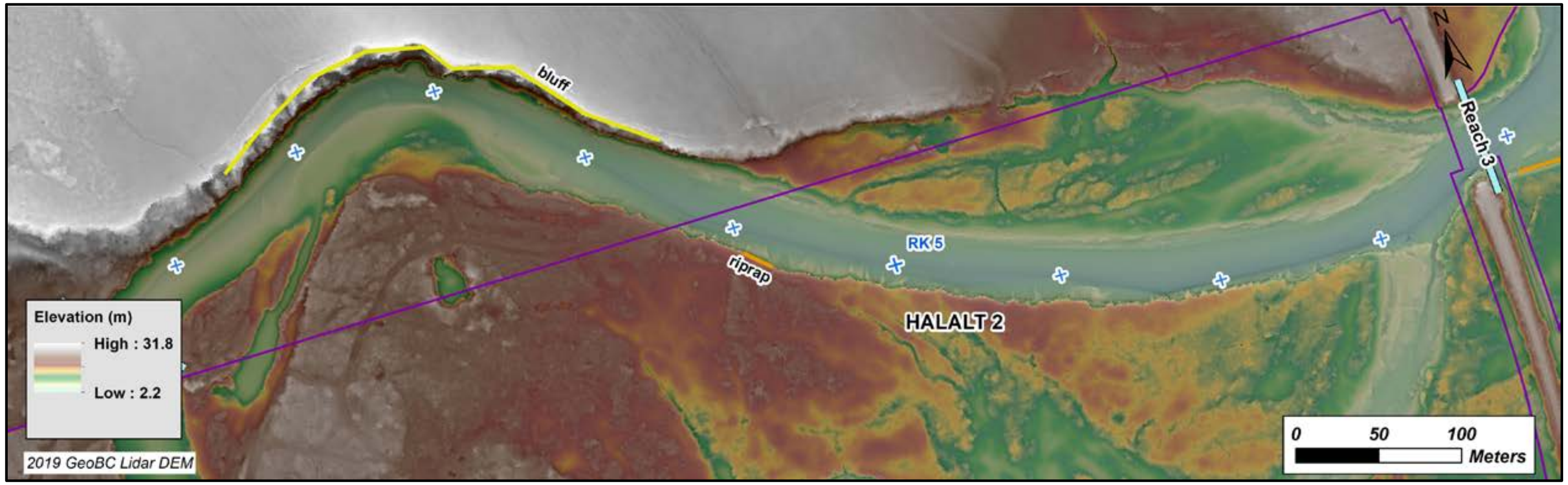
- Upstream of the railroad bridge, mature vegetation has increasingly established on an old gravel bar on the left (north) side of the channel since 1950. This has produced a straighter channel planform over time.
- Backwatering produced by the channel constriction at the railroad bridge likely contributes toward the localized deposition of fine sediment along the left margin of the channel.

► Photo 4.3 Log spurs along the right bank of the channel designed to deflect flow and mitigate against erosion. Rocks placed along bank to supplement the armouring.

► Photo 4.4 The Halalt Fisheries rearing channel rejoins the Chemainus River just upstream of the railroad bridge.

▲ Photo taken from the railroad bridge during low-flow conditions, looking upstream at the exposed sand and gravel bar and vegetated area on the inside of the bar.

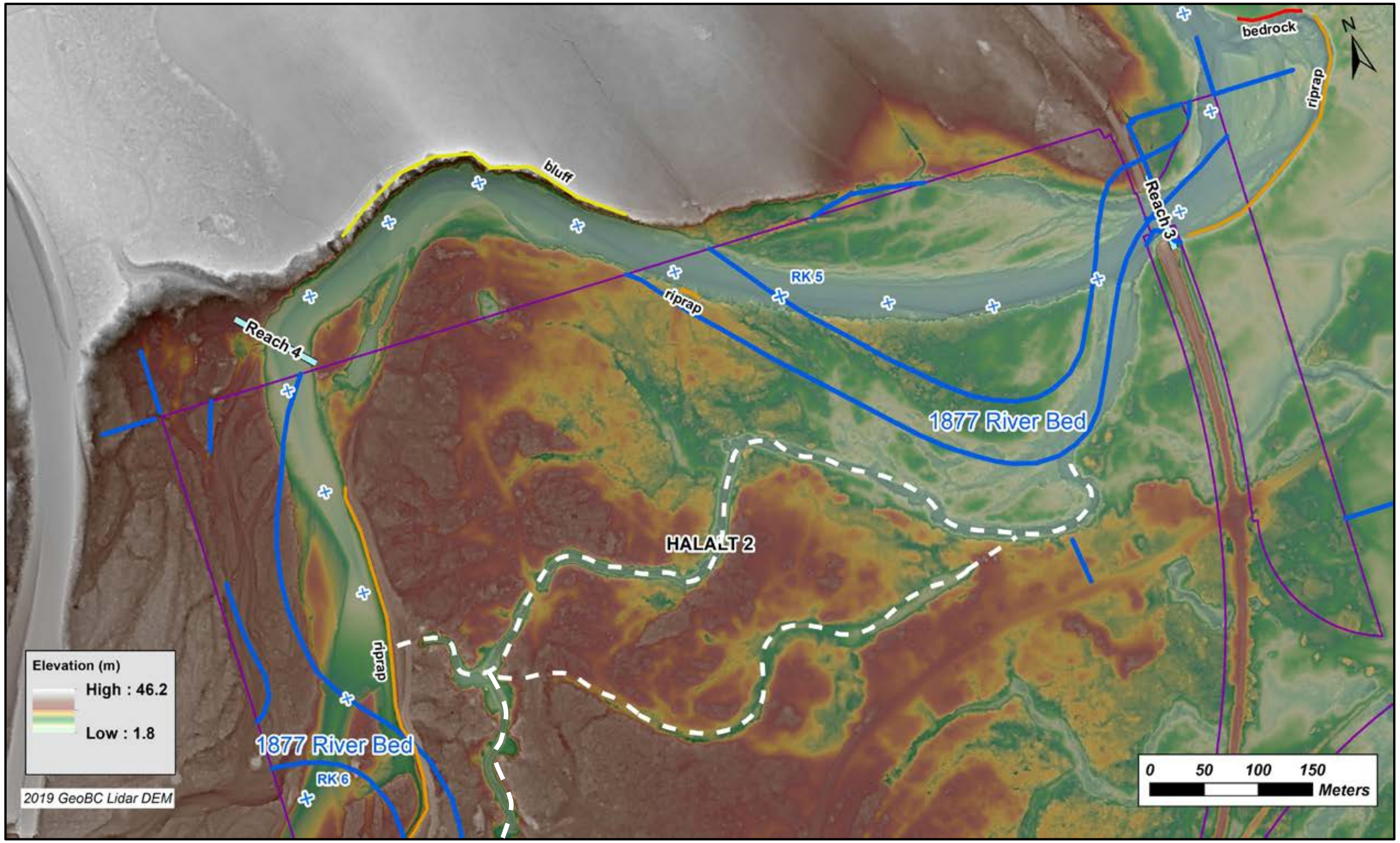
▼ Photo 4.2 Undercutting and exposed root structure along the right bank of the channel.



Reach 4 (RK 5.5 to RK 4.6): Relic Channel

There is a risk of avulsion into the relic channel if a triggering mechanism produces a breach of the channel banks near the upstream entrance to this historic channel in Reach 5.

- A Canada Lands 1877 survey of the area indicates the presence of an approx. 55 m wide old river-bed south of the present-day channel from approximately RK 5.1 to RK4.7.
- This southern relic channel comprises part of the historic channel migration zone and occurs within the Halalt First Nation lands.
- If the log spurs and riprap at RK 5.1 (described on Page 23) do not control the local undercutting along the right bank, and if further erosion occurs at RK 5.1 to RK 5.2, it is possible that the Chemainus River may re-occupy the relic channel at RK 5.1 to RK 4.7.
- South of the approx. 55 m wide old river-bed is another, narrower (approximately 15 m wide) relic channel that runs south of the present-day Chemainus River channel from approximately RK 5.9 to RK 4.8 (shown with the white dashed line on the figure at right).



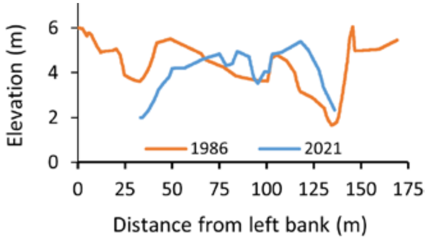
▲ DEM showing historical channel and visible relict channel paths.

▲ Historical map of the Chemainus River from the 1800's (Map of Chemainus District. Undated; traced by R. Cridge at the Land Title Office Victoria. Scale 4 Inches = 1 Mile or 20 Chains = 7 Inches, Surveyor General's Vault, Land Title and Survey Authority of British Columbia. 35 Tray 1 Vancouver Island) overlaid by the Canada Lands 1877 river-bed survey (blue outline) and the 2021 Chemainus River location (yellow transparent shading).

Reach 3 (RK 4.6 to RK 4.3): Depositional Zone

The railroad and Highway 1A bridges form a distinctive hydraulic control on the system and form a zone of sediment and LWD deposition in between them.

- A 10,000 m^2 partially-vegetated gravel bar occupies 80% to 90% of the active channel width in the middle of Reach 4. In 1975, this bar was attached to the left (east) bank but has since been re-worked and re-shaped such that the 2021 bar is closer to the right bank and the primary low-flow channel is located west of the bar.
- Stands of vegetation on the bar surface tend to trap logs floating downstream, often forming jams. Between the patches of vegetation, high-flow channels have been carved across the bar top.
- The outer (east) bank of Reach 4 is armoured with riprap, which has maintained the position of this bank line since 1992. Downstream of the riprap, a bedrock outcrop is exposed along the channel bank, also maintaining the position of the bank line historically. The hardened bank line exerts a primary control on reach-scale hydraulics and patterns of scour and fill.



◄ Surveyed bed elevations at the mid-channel bar at RK 4.5. Between 1986 and 2021, the left channel deepened and widened. Accretion occurred along the right margin of the mid-channel bar and within the right channel.

▼ Coarse to very coarse gravel deposits along the bar edge.

▲ The bedrock outcrop along the right channel bank provides increased resistance to erosion, acting as an important control on channel stability and patterns of scour and deposition in this reach.

◄ 3.1 Small log jam spanning the back channel flowing behind the gravel bar.

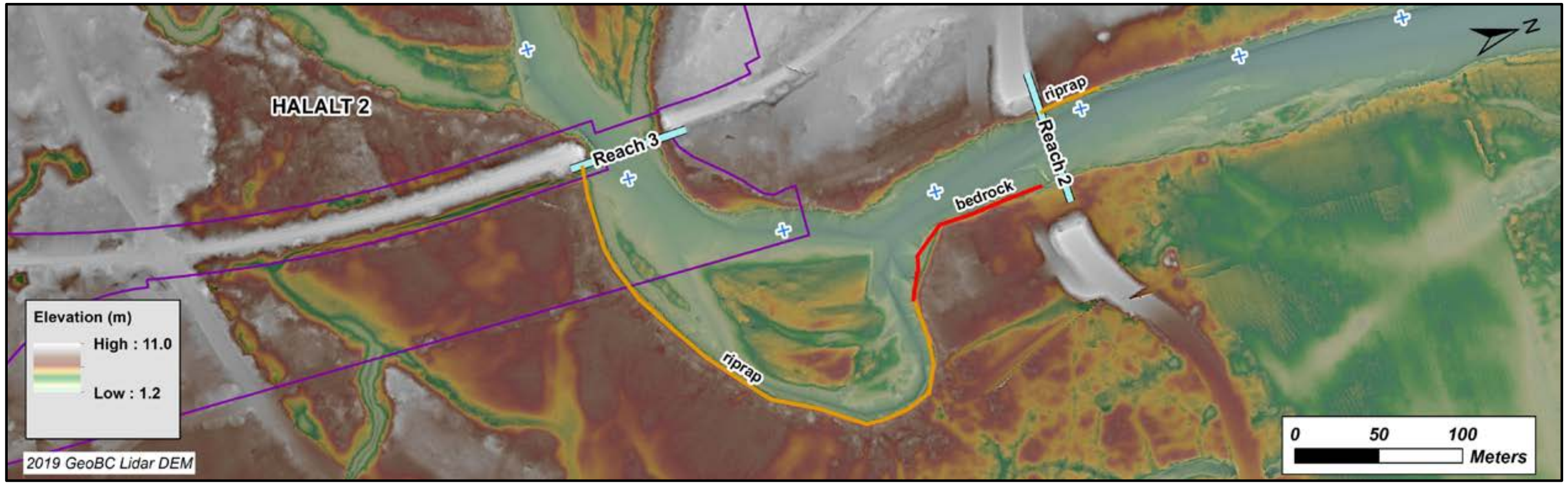
◄ Photo 3.2 Back-channel bank is armoured by riprap, which shows signs of scour along the toe.

Reach 3 (RK 4.6 to RK 4.3): LWD Accumulation

▲ Massive pile up of LWD at the Highway 1A bridge from January 2022.

Reach 3	
Reach Length (m)	296
Average Slope (m m^{-1})	0.0018
D_{50} (mm)	33
Mean Erosion Rate (m yr^{-1})	0.7

▲ Photo 3.3 Multiple logs, floated downstream by a 2021 flood, caught on the foundation structures of the Highway 1A bridge.



Reach 2 (RK 4.3 to RK 3.3): Downstream of Highway 1A

Downstream of the Highway 1A bridge, the river flows north along a 40 m to 50 m wide channel with gravels deposits along the right channel margin.

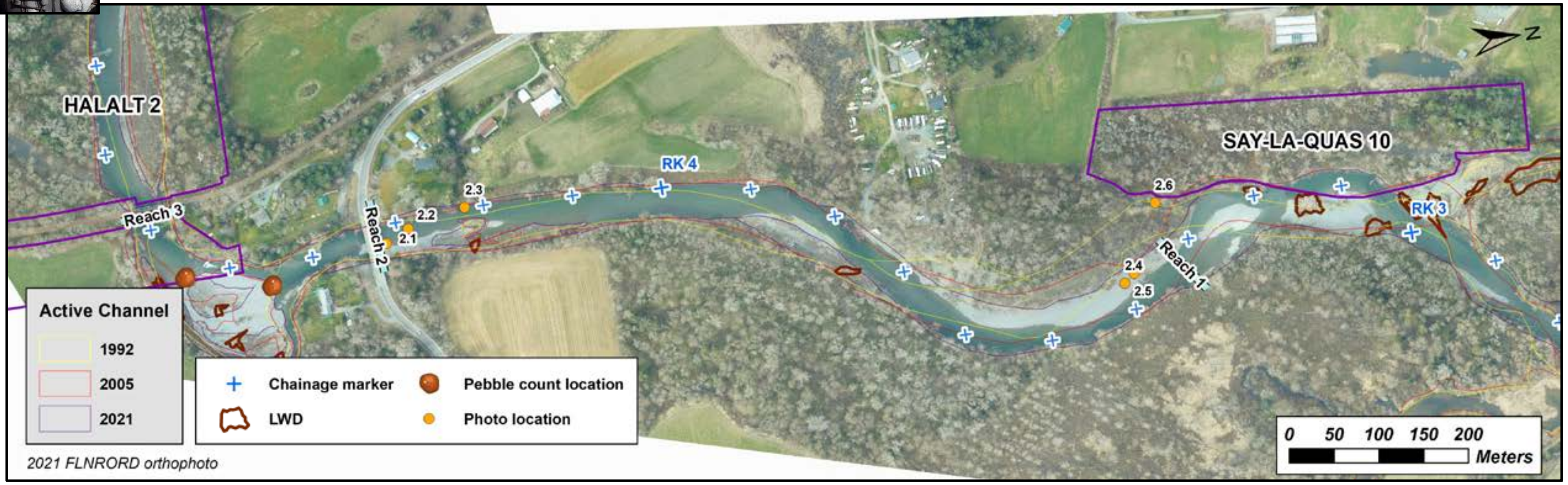
- Deposition in this area is largely influenced by hydraulic expansion effects downstream of the bridge, and localized dynamics associated with LWD trapping patterns on the upstream side of the bridge.
- Bedrock along the right (east) bank at the downstream end of Reach 3 provides increased flow resistance locally and may help deflect some portion of the flow towards the left (west) side of the channel.
- Riprap armouring has been installed along an approximately 40 m section of the right bank line downstream of the bridge. The channel has widened in this area since 1992, likely prior to riprap installation.

▶ Photo 2.3 Downstream of the riprap, the bank is composed of silty material with clay and fine sand. The toe of the bank is a gravel-sand mix.

▼ Photo 2.2 Riprap along the left bank of the channel prevents scour.

▲ Photo 2.1 Sediment accumulation along the right side of the channel downstream of the Highway 1A bridge.

Reach 2	
Reach Length (m)	996
Average Slope (m m^{-1})	0.0015
D_{50} (mm)	-
Mean Erosion Rate (m yr^{-1})	0.8



Reach 2 (RK 4.3 to RK 3.3): Gravel bar

At RK 3.5, a gravel bar attached to the left (west) channel bank borders the Stz'uminus First Nation's Say-La-Quas 10 administrative boundary to the north. Remnants of a historical village site were identified by Stz'uminus First Nation Band Council member and cultural consultant Arthur Jim (18 February 2022).

- Bar texture is finer than observed in upstream reaches, with gravel deposits along the bar head and bar margin, and a high proportion of sand deposited on the mid-bar and bar tail.
- During high-flows, water is conveyed across bar-top channels and a back-channel that flows behind the bar.
- As the bar has developed and migrated downstream since 1992, the outer bank across from the bar has been eroded to accommodate the space occupied by new bar area.
- Across from the bar, riprap armouring limits the channel's ability to erode an approximately 100 m long section of its banks. The erosive force focused on this area is likely transferred downstream, affecting patterns of downstream erosion.

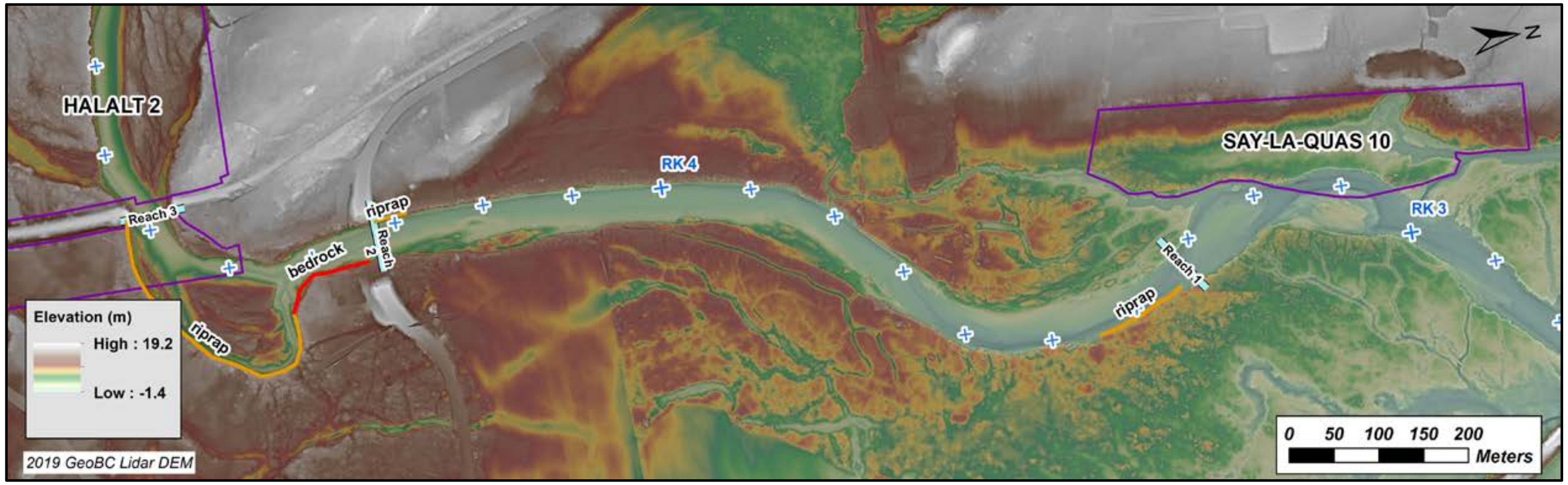
▲ Photo 2.5 The bar tail has a high proportion of sand. The bank opposite the bar has been stabilized with riprap.

▲ Photo 2.6 Channel flowing behind the bar-island complex.

▲ Photo 2.4 LWD deposited across the tail of the bar.

Comparison of cross sections surveyed in 1986 and 2021 show slight degradation in the middle and downstream portions of Reach 2, with unit vertical change of -0.3 m at RK 3.7 and RK 3.9. Slight aggradation (unit vertical change of 0.1 m) was observed at RK 4.3, just downstream of the Highway 1A bridge.

▲ A channel avulsion occurred between 1950 and 1968.Since then, the gravel bar has become increasingly stable as vegetation has established on the bar interior. The bar and meander bend have migrated downstream since 1992 as sediment is eroded from the bar head area and deposition occurs on the bar tail.



7 REACH-SCALE CHANNEL CHARACTERISTICS AND DOMINANT PROCESSES

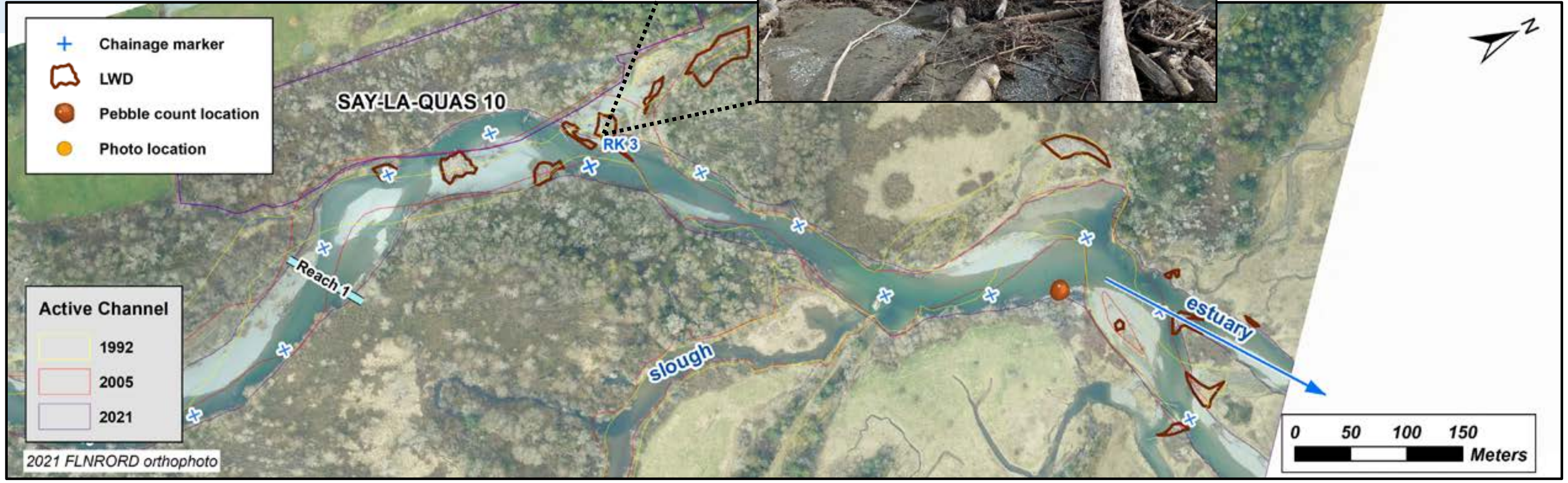
Reach 1 (RK 3.3 to RK 0): Distributary Channel Network

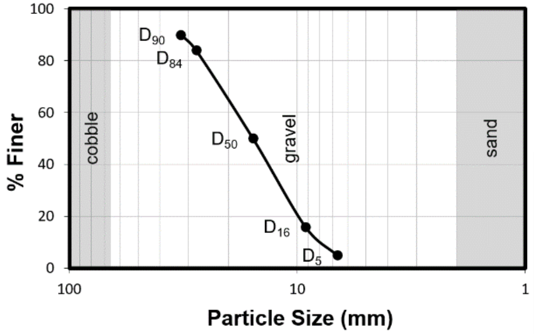
The distributary channel network shifts and evolves through time based on complex interactions between fluvial and coastal processes. Specific channels may become activated or abandoned based on rates of sediment aggradation, LWD jams, and re-working of sediment by tidal currents and wave action.

The upstream end of Reach 1 is bordered to the west by the boundary of the Say-La-Quas 10 administrative boundary. The lower Chemainus River distributary channel network located near RK 3 was identified as sacred and a former fishing, harvesting, trapping, hunting and village site for the Stz'uminus First Nation peoples (Arthur Jim, pers. comm. 18 March 2022).

◀ LWD and sediment accumulation at the head of a distributary channel, viewed downstream toward the mainstem.

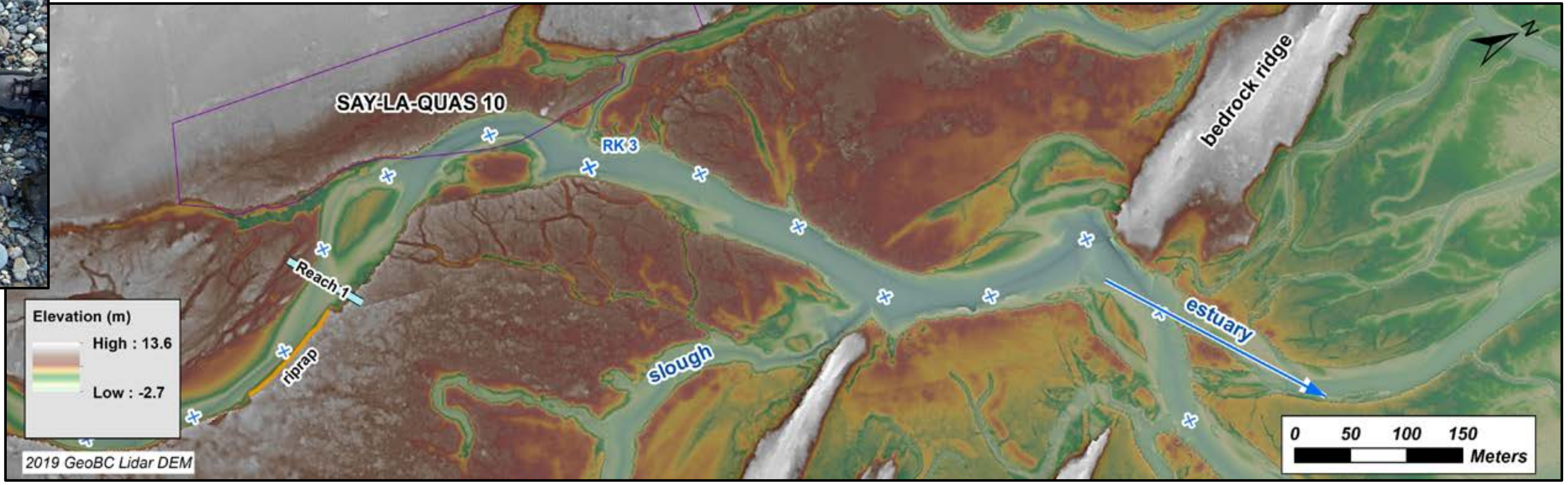
- The primary flow path for the Chemainus River used to flow farther north and has been blocked by sediment and LWD accumulating at the entrance over the past decade or so. The lower reach of this channel borders the boundary of the Stz'uminus First Nation Squaw-Hay-One administrative boundary located approximately 800 m to 1,000 m downstream, to the northwest.
- Hydraulic effects of this blockage on mainstem channel overbank flooding and erosion potential is uncertain and has not been verified.
- The Reach 1 slope (0.0005 m m^{-1}) is much flatter than upstream resulting in a finer bed texture, and increased deposition of sediment and LWD.
- The position of the channel network is constrained at several locations by the presence of northwest to southeast oriented bedrock ridges in the estuary.





▶ Example of the fine to medium gravels deposited on the bar surface at the pebble count location.

Reach 1	
Reach Length (m)	3,327
Average Slope (m m^{-1})	0.0005
D_{50} (mm)	16
Mean Erosion Rate (m yr^{-1})	-

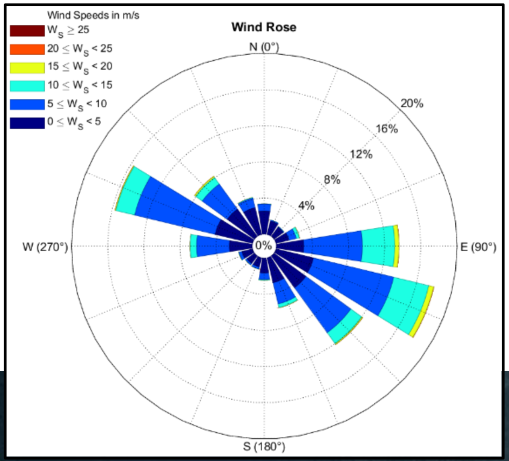


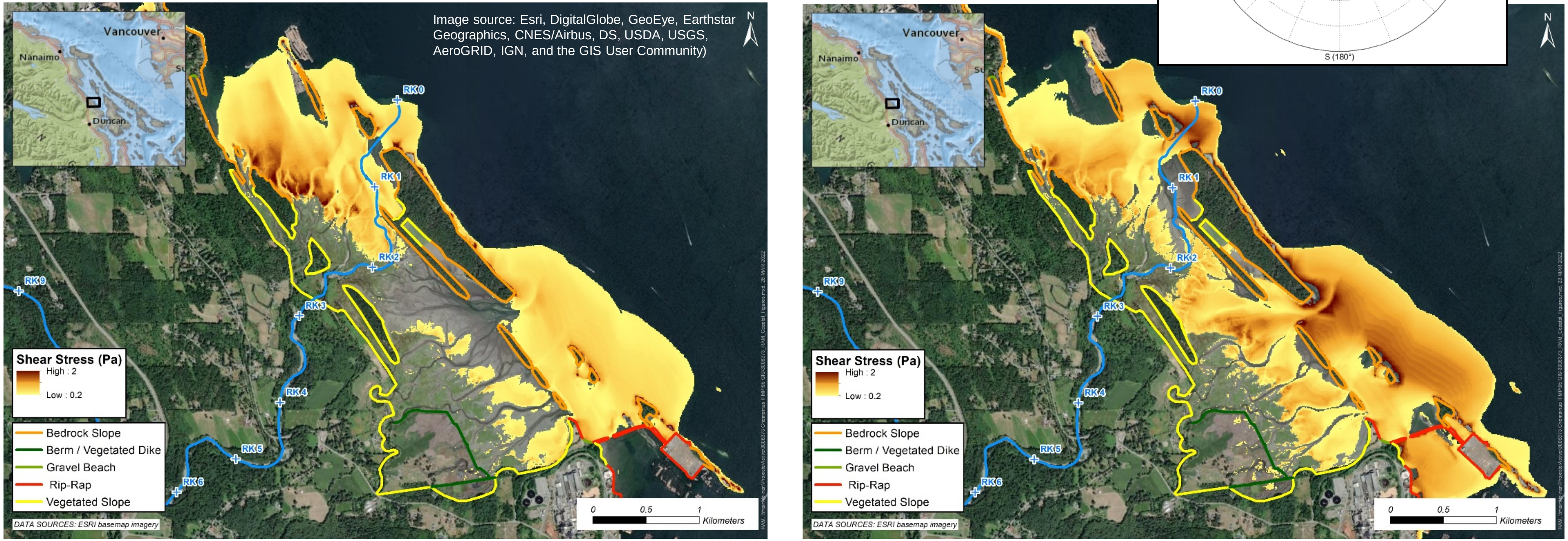
Reach 1 (RK 3.3 to RK 0): The Chemainus River Estuary

The Chemainus River estuary is characterized by a complex channel network distributed across a relatively flat gradient. The low gradient provides an environment whereby avulsions are common, and the channel network is continuously shifting. Combined with tidal influences and riverine processes, wave erosion plays an important role on the dynamics of the Chemainus River estuary.

- The estuary is largely protected from severe winter storms blowing across the Strait of Georgia due to the presence of the Gulf Islands (including Valdes, Thetis, Galiano, and Saltspring Islands). However, significant wind-generated waves are still generated through the Stuart Channel (between the Gulf Islands and Vancouver Island).
- Wind-generated waves produce shear stresses strong enough to mobilize and re-distribute sediment between periods of flooding in the estuary.

▶ Wind rose for Halibut Bank in the Strait of Georgia shows that the region experiences winds oriented largely in the northwest to southeast direction.





▲ Wave shear stress from SWaN model simulations of northerly (left panel) and east-southeasterly (right panel) annual wind events. The northerly wind event produces higher magnitudes of shear stress near the main channel of the Chemainus River, while the east-southeasterly event produces shear stress across a wider area of the estuary. The bedrock and rip-rap shorelines are likely to be resistant to erosion, while the gravel beaches and vegetated slopes are more likely to erode at a higher rate.

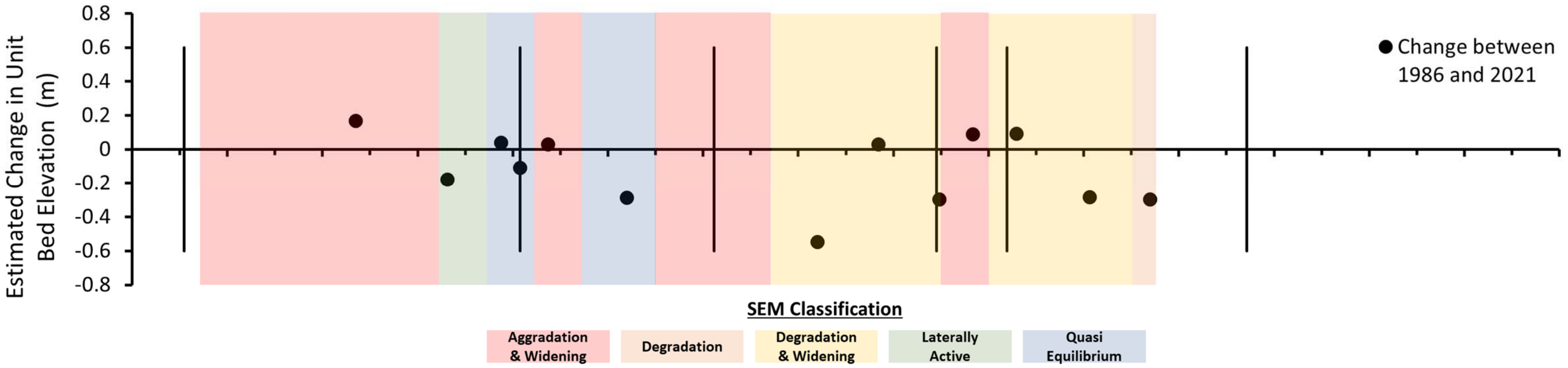
Sediment Accumulation and Channel Profile Changes

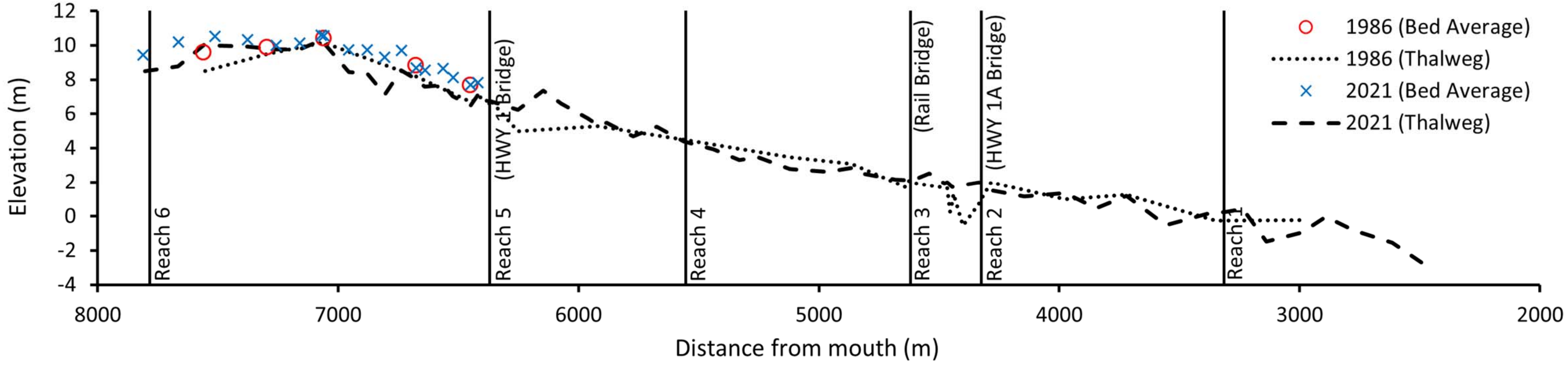
There are several depositional zones along the study reach where sediment and LWD is prone to accumulating. These zones are typically associated with hydraulic controls at bridge crossings, bedrock outcrops, and valley confinement. Sediment accumulation is associated with changes in channel width and bed elevation along the channel profile.

- Reach 6:
  - Aggradation since 1986 is apparent, particularly at RK 7.1.
  - The dominant SEM class (provided by the Cowichan Water Board, 2022) for Reach 6 is aggradation and widening.
- Reach 5:
  - The 1986 to 2021 channel surveys show the thalweg elevation has increased overtime, particularly within a few hundred metres downstream of the Highway 1 bridge. Average bed elevation changes over time within this channel reach are difficult to interpret because of the high degree of lateral instability exhibited over time.
  - The SEM classes for Reach 5 indicate a state of aggradation and widening near the upstream and downstream ends of the reach and a quasi-equilibrium state mid-reach.
- Reach 4:
  - An overall degrading trend is apparent. At RK 5.1, cross-section surveys reveal bed lowering of approximately 0.55 m. This location coincides with the entrance to an old river-bed position south of the modern-day channel, which could be re-opened should the channel erode into its banks (see Page 24 for more details).
  - The SEM classes for this reach shows a transition from aggradation and widening at the upstream end to degradation & widening in the lower 700 m of the reach.
- Reach 3:
  - Aggradation is apparent across the reach, and vertical changes in the thalweg elevation is in the order of 2 m in the reach upstream of the Highway 1A bridge.
  - The dominant SEM class is a state of aggradation and widening.
- Reach 2:
  - Bed lowering is apparent across the reach.
  - The dominant SEM class is a state of degradation and widening.

▼ Plot showing the estimated change in bed elevation between 1986 and 2021 cross-section surveys, overlaid with SEM classes (SEM data provided by the Cowichan Water Board, 2022).

SEM classes reflect the geomorphic condition of the channel. The SEM classes consider the cyclical nature of channel evolution, whereby the channel transitions between periods of aggradation, degradation and quasi-equilibrium.





▲ Plot showing average bed elevation and thalweg elevation data from 1986 and 2021 survey data. Average bed elevation represents the average elevation at each cross section, including the deepest parts of the channel, top of exposed channel bars and all points in between.

Sediment Mobility

- Plots represent the maximum values for each parameter over the course of an unsteady hydraulic model run of a 350 $m^3 s^{-1}$ discharge flood event ($Q_{reference}$). This reference discharge approximates bankfull flow, the flood condition that forms and maintains the morphology of the current-day channel.
- These plots show hydraulic and sediment mobility parameters extracted from NHC's 2D HEC-RAS model of the river. See accompanying reports for details of hydraulic model development.
- The plotted values represent positions along the channel thalweg. They do not reflect the complex spatial variations across the channel laterally.
- The distribution of grain sizes along the river channel was interpolated from a small sample of surface pebble counts collected by NHC in 2021.
- Sediment grain size data collected by KWL (2021) and CWB (2021) are also presented in the middle plot to the right but were not used to interpolate the downstream trend of grain size along the longitudinal profile. No information on subsurface samples was collected.
- Due to these limitations, inferences on sediment mobility are limited to general trends.

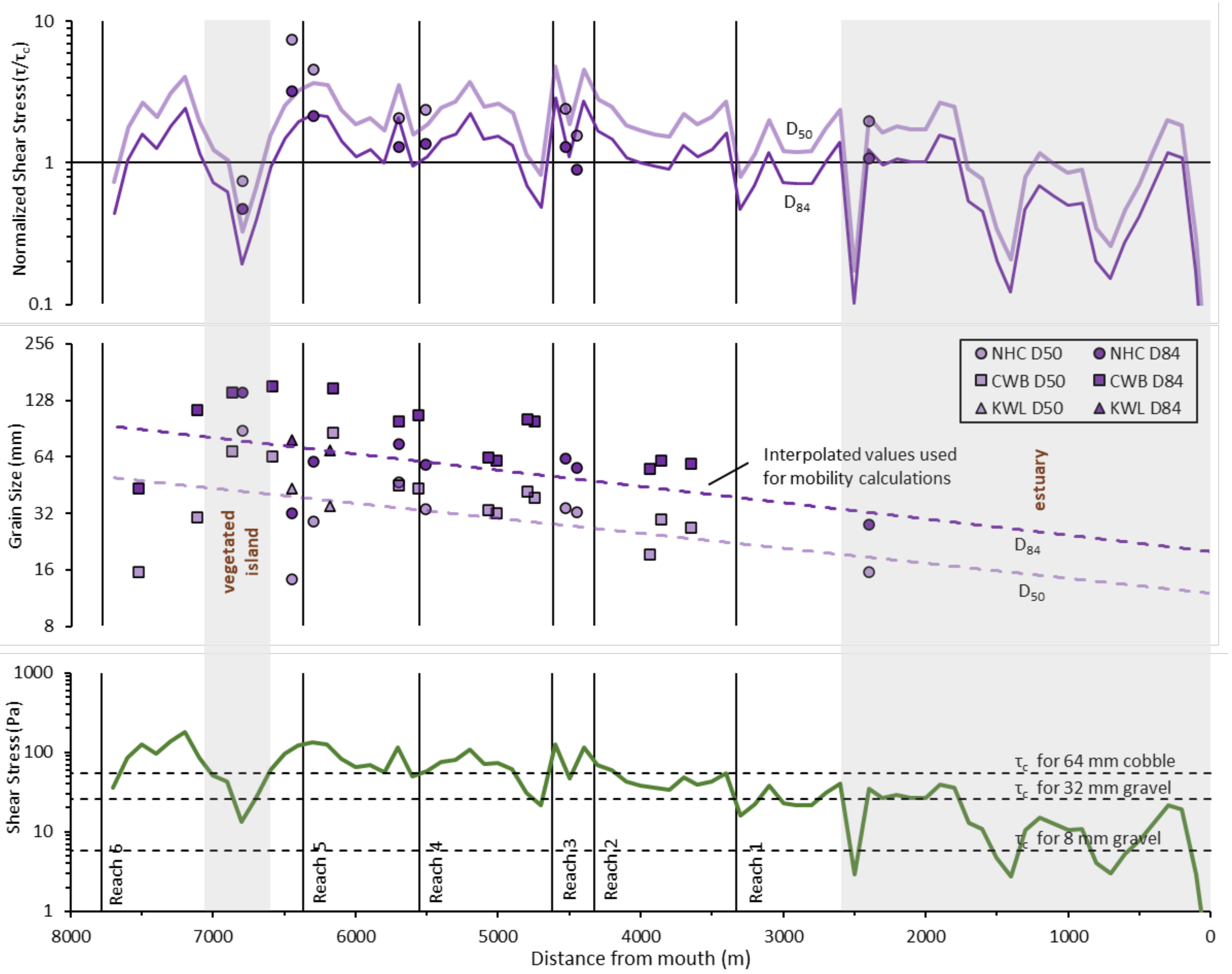
Sediment Transport Parameters

Shear stress (τ): The strength of flow available to move sediment, proportional to flow depth times flow slope.

Critical Shear Stress (τ_c): The shear stress required to move a given size of sediment as bedload.

Shields Parameter (τ^*_c): The ratio of fluid forces tending to initiate particle motion to the gravity force tending to keep the particle at rest. Dependent upon the size of the individual particle, but also the arrangement, shape, and size distribution of the surrounding material. A value of 0.045 is typically used, but values from 0.02 to 0.25 are possible. Larger amounts of sand and finer subsurface material promote lower values of τ^*_c.

- Based on the simulated flood event, the Chemainus River is capable of transporting cobble-sized sediment through Reaches 6 to 3, downstream of which the shear stress drops below the threshold required to move this caliber of sediment.
- Medium to coarse gravel may be transported to the top of the estuary (around RK 1.7), downstream of which only finer sediment is mobile.
- At approximately RK 6.7 to RK 7.1, there is a dip in shear stress. This coincides with the location of a large vegetated island in Reach 6, where flow splits into two channels. The variation of shear stress across the two channels is shown below at RK 6.9.



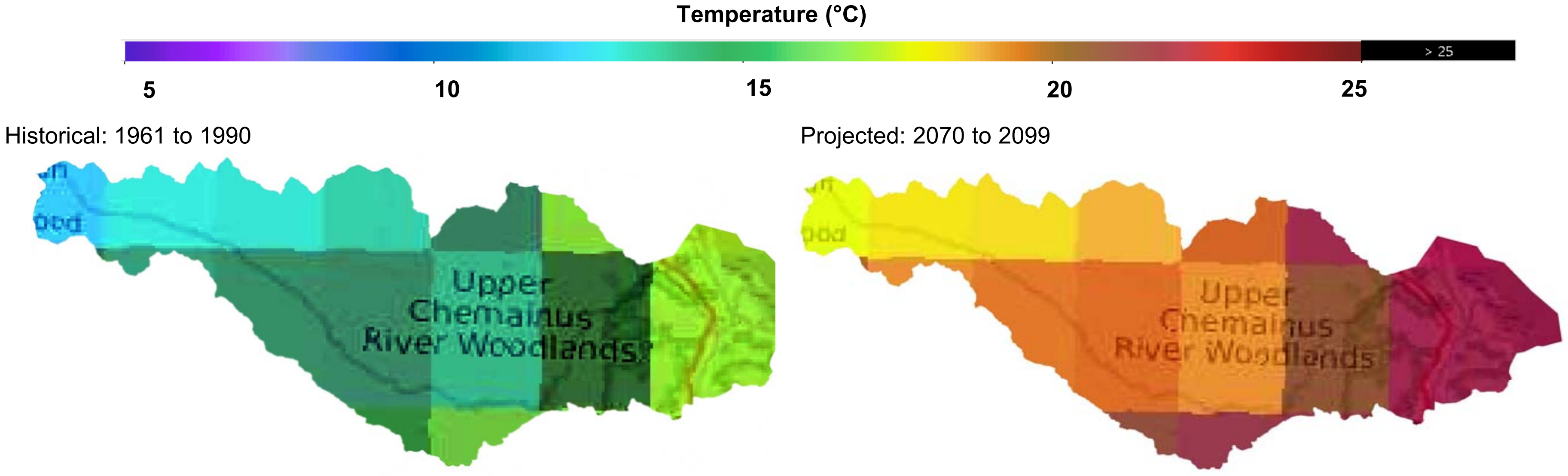
9 ALTERED CONDITIONS

Hydroclimate

In the context of ongoing climate change in British Columbia, we can expect to see changes in environmental conditions (APEGBC, 2017). Under existing or altered hydroclimatic conditions, physical changes may occur to the landscape that induce a longer-term geomorphic response that will alter how the watershed and floodplain responds to floods.

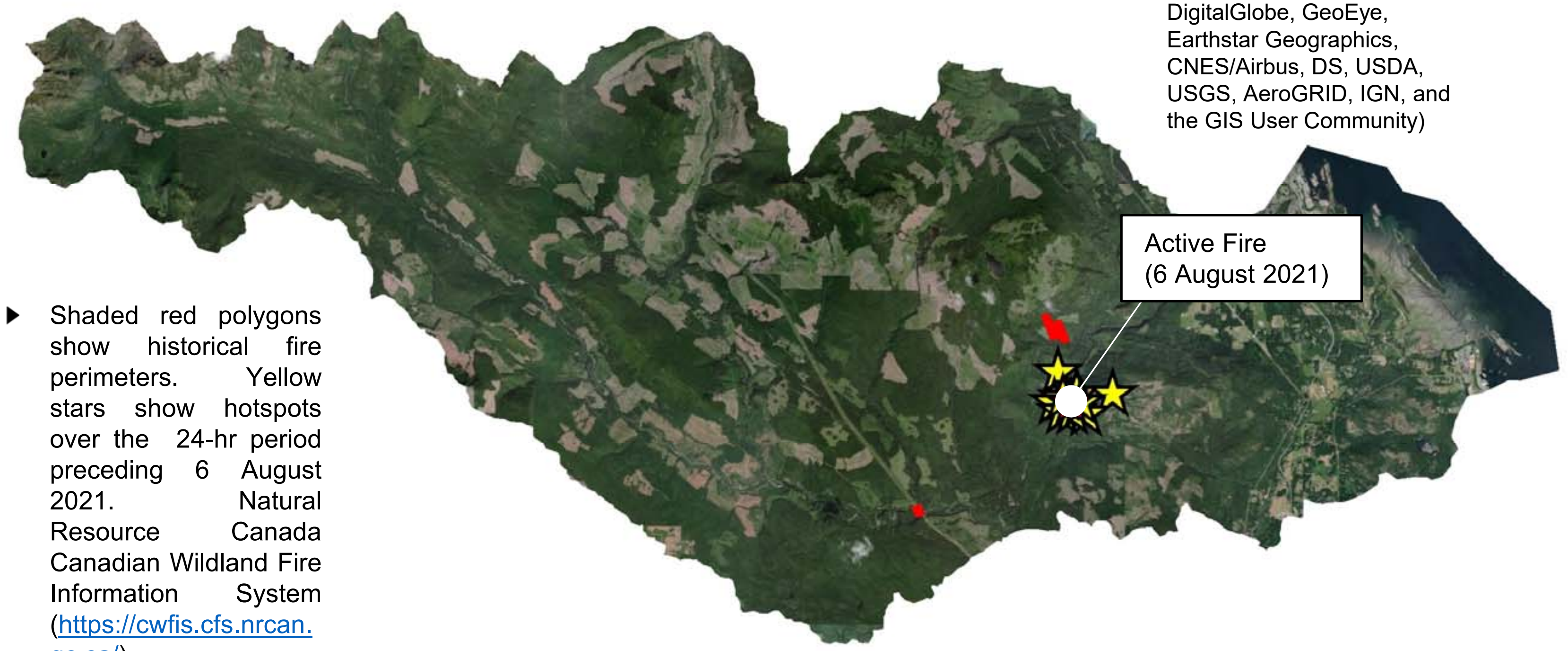
Altered hydroclimatic conditions may induce the following geomorphic responses:

- Sea level rise (SLR) will alter the upstream extent that the stream channels are influenced by tides, alter the pattern and position of estuary distributary channel formation, and will expose areas farther inland to coastal processes (see Page 36).
- Increasing summertime temperatures could result in more frequent and larger fires. Increasing winter temperatures could result in adverse conditions for forest health, such as insect infestation:
    - Fires can have both immediate and long-term hydrologic effects. Disturbance effects include relatively short-term soil hydrophobicity, which increases runoff rates (Winkler et al 2010); longer-term effects to runoff patterns as a result of altered tree canopy. Similarly, altered rates of transpiration and interception of precipitation by the tree canopy as a result of insect infestation may lead to altered soil moisture conditions, snowmelt patterns, and streamflow patterns (Pike et. al. 2010).
    - The post-event landscape can have an altered effective erodibility of the landscape. Over time, deadfall and debris accumulation on steep slopes, gullies, and stream channels may increase the potential for high energy hydrogeomorphic events such as debris floods or debris flows and channel sedimentation (Pike et. al 2020).
    - Depending on the spatial extensiveness of the event, the effects may be relatively localized or at a watershed-scale. Accumulation of debris and sediment can sometimes continue for several years, with a geomorphic response that persists for longer than the immediate hydrologic impacts.
    - Riparian vegetation succession patterns could influence channel resistance to bank erosion, LWD recruitment patterns and potential for channel form changes.



▲ Projected Summer Temperatures (for June, July, and August, from Pacific Climate Impacts Consortium, PCIC). The PCIC Plan2Apapt tool generates maps describing projected future climate conditions for regions throughout BC based on a standard set of climate model projections (https://services.pacificclimate.org/plan2adapt/app/).

Image source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus, DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community)



▶ Shaded red polygons show historical fire perimeters. Yellow stars show hotspots over the 24-hr period preceding 6 August 2021. Natural Resource Canada Canadian Wildland Fire Information System (https://cwfis.cfs.nrcan.gc.ca/).

9 ALTERED CONDITIONS

Sediment Supply

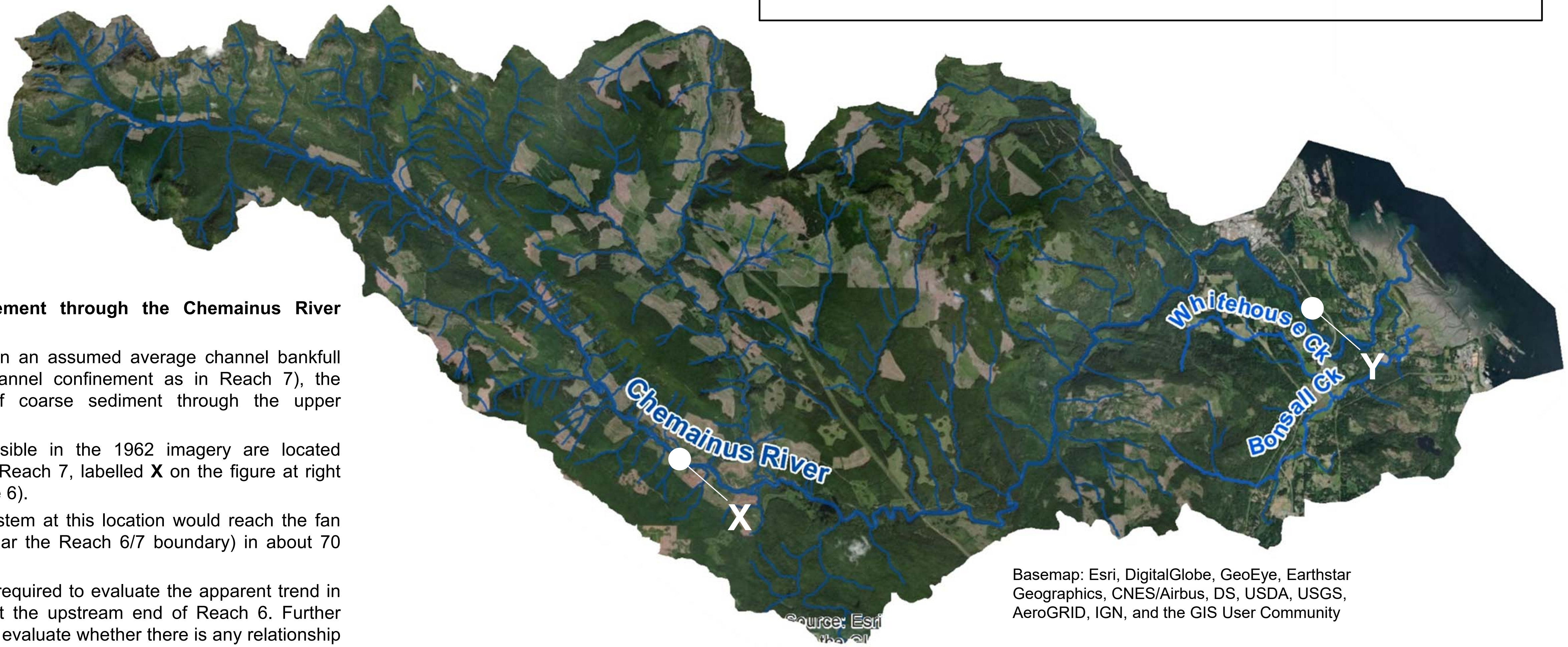
Over a time-scale of decades to centuries, sedimentation rates and patterns at the alluvial fan are a function of the supply of sediment from the watershed slopes to the mainstem and tributary channels, degree of lateral channel stability, and relative rate of sediment transport and storage within the active channel.

Altered sedimentation patterns and rates on the alluvial fan may induce channel geometry and profile changes. Altered conditions on the fan could increase the geomorphic hazard potential on the MVB.

Legacy effects of historical forestry activities that started in the 1800s has altered the pattern of coarse sediment supply to the alluvial fan on the floodplain.

- Once introduced into the mainstem channel, coarse sediment can take many decades to reach the alluvial fan.
- The movement of coarse sediment through the system can be modelled following Beechie (2001) based on an annual travel distance (L_b) as a function of bankfull channel width w_{bf}:

$$L_b = -32 + 21 \times w_{bf}$$



Basemap: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus, DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Example concept: sediment movement through the Chemainus River watershed:

By applying Beechie (2001), based on an assumed average channel bankfull width of 37 m (assuming similar channel confinement as in Reach 7), the estimated annual travel distance of coarse sediment through the upper watershed is 745 m/year.

- Slide pathways and cutblocks visible in the 1962 imagery are located approximately 50 km upstream of Reach 7, labelled **X** on the figure at right (The 1962 image is shown on Page 6).
- Sediment entering the channel system at this location would reach the fan apex (labelled **Y** on the figure, near the Reach 6/7 boundary) in about 70 years.
- More survey monitoring would be required to evaluate the apparent trend in average bed elevation changes at the upstream end of Reach 6. Further investigations would be required to evaluate whether there is any relationship between the apparent aggrading trend at this location and legacy effects of historical forestry activities (plotted bed elevation changes at this location are shown and discussed on Pages 15 and 31).

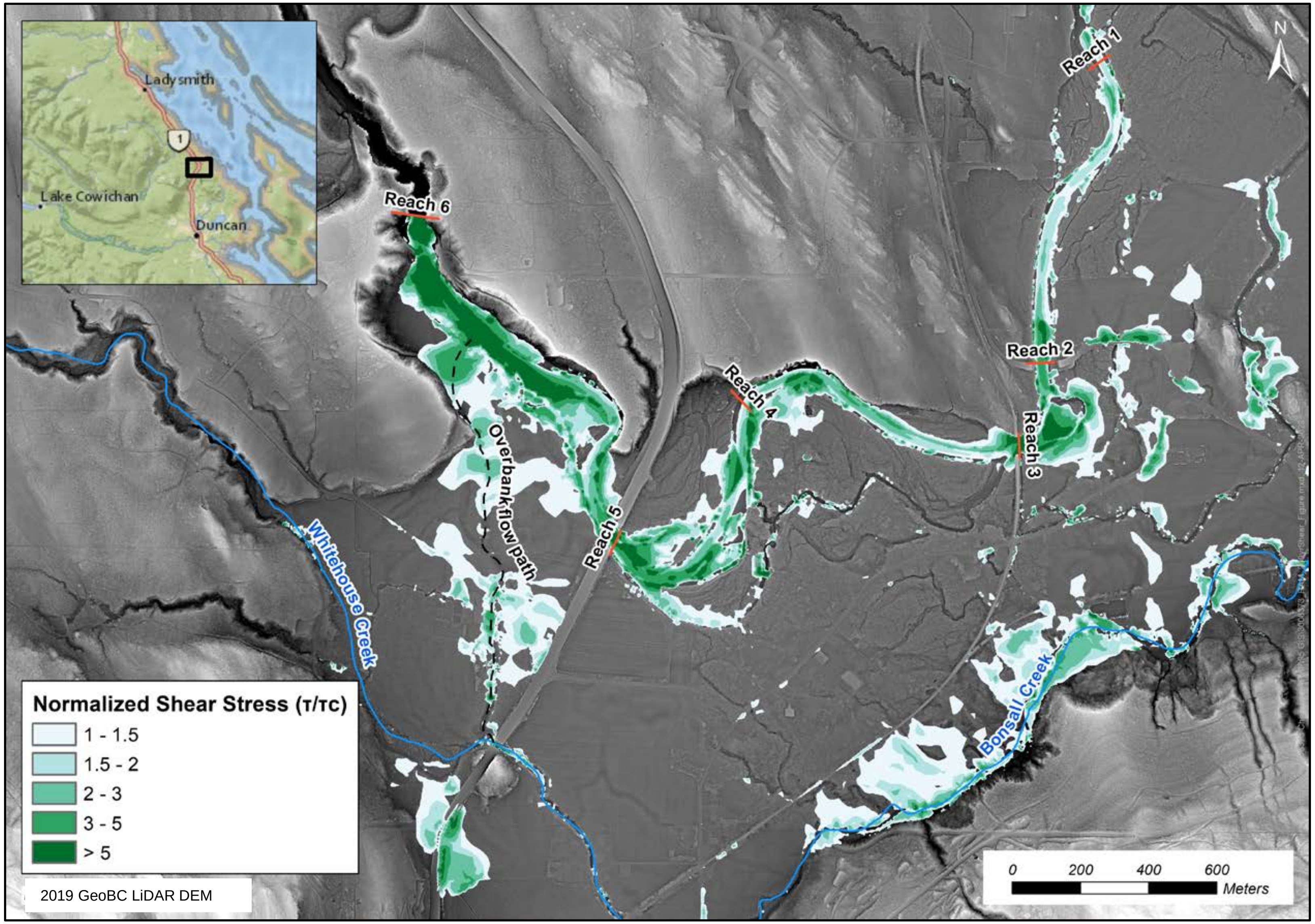
Flow Regime

In the context of ongoing climate change in British Columbia, the morphology of the Chemainus River will evolve and adapt to the altered hydroclimatic regime. Therefore, changes in the magnitude and recurrence of peak flood events may lead to adjustments in channel form.

- The map panel to the right illustrates the spatial pattern of shear stresses produced by a 2D HEC-RAS hydraulic model simulation of a 0.5% annual exceedance probability flood (i.e., 200-year recurrence interval flood), with a 20% increase in discharge to account for climate change. The darker shades of green represent areas of higher normalized shear stress and, thus, higher potential for sediment transport.
- For in-channel areas, a normalized shear stress value around 1 implies incipient motion of sedimentary particles on the bed. As the normalized stress increases to around two or more, we expect to see full transport of bed material.
- Outside the channel, the floodplain may scour in areas experiencing high shear stress values during the simulated 0.5% annual exceedance probability (AEP) flood. The patterns in floodplain shear stress reveal preliminary insights into preferential overbank flow paths and potential locations where channels may form during an extreme flood event.
- In Reach 6, a low-lying area on the floodplain south of the present-day channel experiences high shear stress during the modeled event. This channel ultimately delivers flow south into Whitehouse and Bonsall Creeks. Hence, an increase in the amount of flow through this area has direct implications for the stability of these creeks.
- Overbank flow spilling out from Reach 6 may also drain towards the upstream edge of Highway 1, inducing the potential for scouring along the road prism. In the absence of relief structures that allow flow to drain downstream of Highway 1, water may be carried parallel to the road and lead to sediment deposition and aggradation.

This section summarizes some of the potential responses of the channel to an extreme flood event. However, an important driver of morphological changes over time and channel form are the more moderate and more frequent events, such as the bankfull discharge (Wolman and Miller, 1960).

Changes in the channel width and pattern in response to climate change is described in more detail on Page 42.



▲ The normalized shear stress produced during a 2D HEC-RAS hydraulic model simulation of a 0.5% AEP flood with a 20% increase in discharge to account for climate change. Normalized shear stress is calculated as the ratio of shear stress (τ) to critical shear stress (τ_c) for sediment entrainment. Here, a critical shear stress of 25 Pa was used, an approximate threshold for mobility of coarse gravels (USGS, 2013).

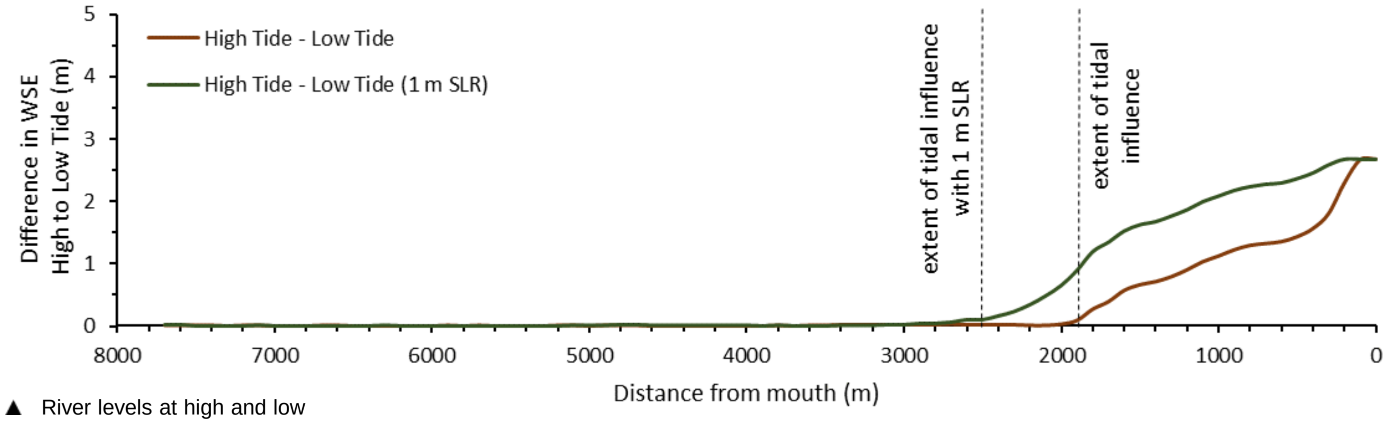
9 ALTERED CONDITIONS

Base Level Changes

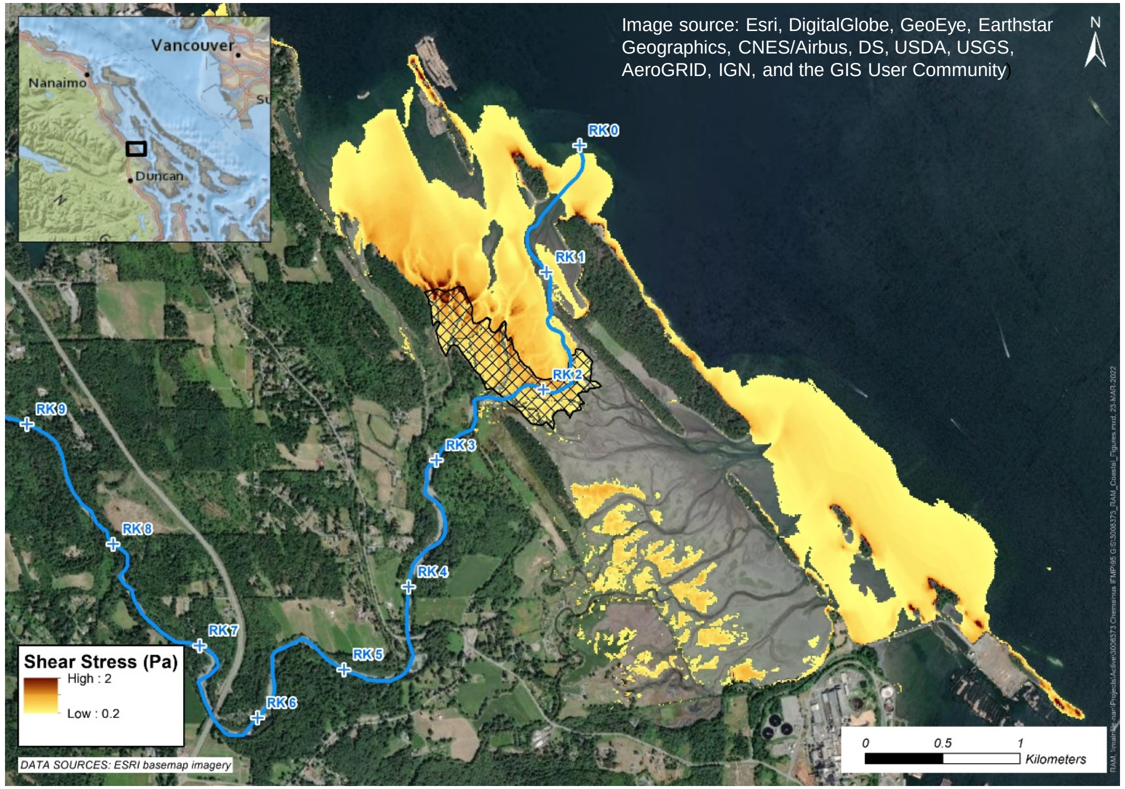
The base level is defined as the limit below which a stream cannot erode. For the Chemainus River, this occurs as the river enters the ocean, whereby the stream's velocity is reduced losing its erosive power, and sediment is deposited.

- Climate-change induced SLR will produce a change in the base level of the Chemainus River. Rivers may respond in many ways to a higher future base level, including aggradation and adjustments to the channel profile, altered sediment mobility patterns and sediment grain sizes, changes in channel planform, increasing bed roughness, or a combination of these (Schumm, 1993).
- The morphological response of the Chemainus River to SLR may take place over a long period of time (multi-decadal-scale). A 1 m SLR will cause the extent of tidal influence to migrate approximately 600 m upstream, based on hydraulic simulations with bankfull ($Q_{reference}$) riverine flow combined with a mean tide. Tidal effects with SLR may extend farther upstream under different tide and river flow conditions. As the tidal influence extends farther upstream, an increased potential for channel aggradation may induce more frequent channel avulsions (Jerolmack, 2009).
- SLR affects the spatial pattern of shear stress produced by waves such that patterns of erosion and deposition along the coastal fringe zone will be altered.
- Salt-water intrusion may alter the shoreline and lowland biota, which would influence channel resistance to bank erosion and potential for channel form changes.

▲ Photo looking north over the Chemainus River Estuary (CVRD photo).



▲ River levels at high and low tide based on the mean annual tide and bankfull flow conditions ($Q_{reference}$). WSE = water surface elevation.



▶ Simulating Waves Nearshore (SWaN) model simulations of wave shear stress for a northerly wind event with 1 m SLR and Higher High Water Meant Tide. Only shear stress values greater than or equal to 0.2 Pa are presented, representing an approximate threshold required to mobilize sand-sized sediment.

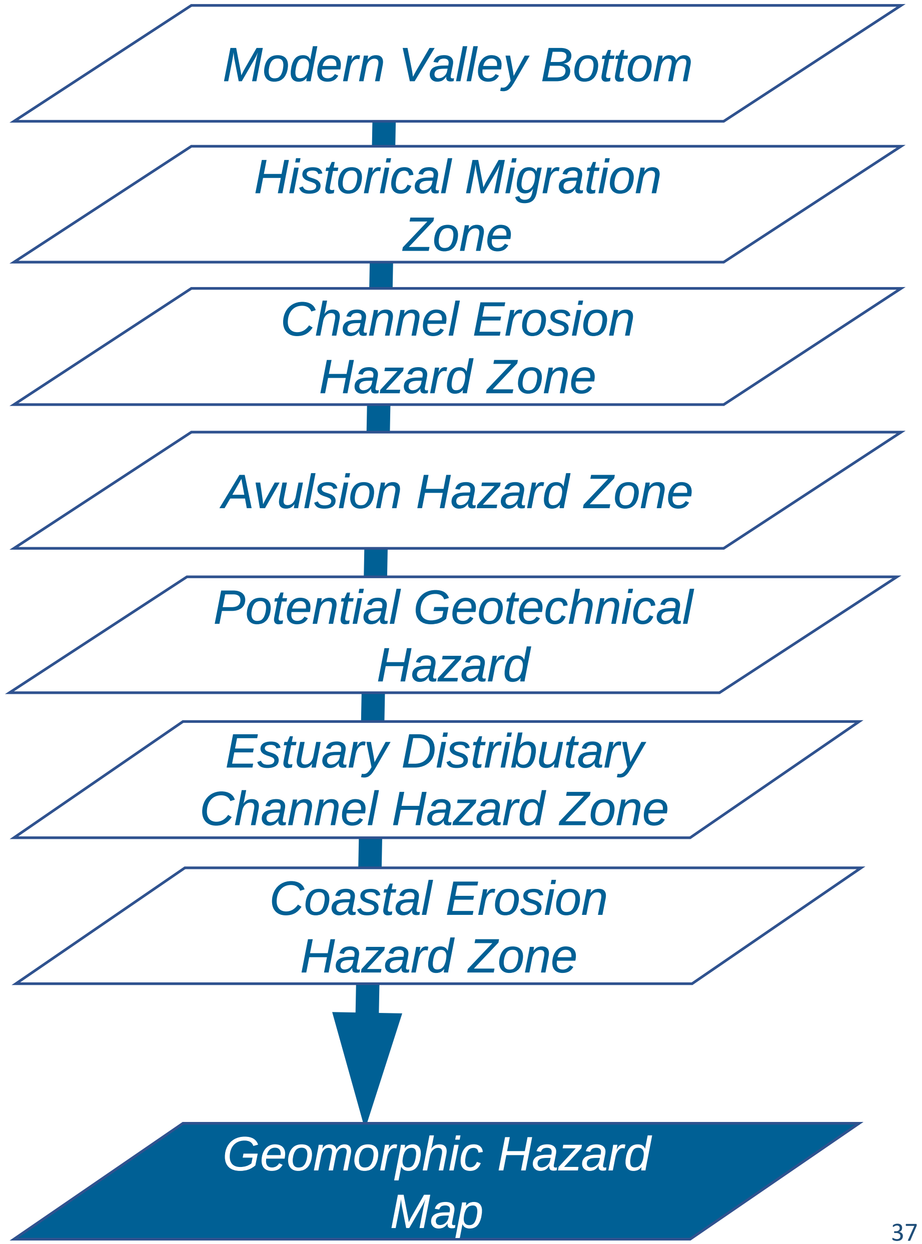
The black cross-hatched polygon represents the primary area where shear stress is high enough to mobilize sand in the 1 m SLR scenario, but not during present-day conditions. This highlights the potential for the area affected by wave erosion to migrate upstream under a climate change scenario.

10 GEOMORPHIC HAZARD MAPPING

Geomorphic Hazard Map Elements

The framework for defining geomorphic hazard zones for this project was adapted and modified from approaches used in Washington state (see Page 1). A 60-year planning horizon was selected based on the long -life design service life category defined in the BC Housing Design Guidelines and Construction Standard (BC Housing 2019).

ZONE	HAZARD DEFINITION
Modern Valley Bottom (MVB)	Area where channel migration has likely occurred in the past several thousand years and is susceptible to occurring under the present-day hydroclimate regime.
Historical Migration Zone (HMZ)	Area that the channel occupied in the historical record, based on available imagery and survey data. This area is also susceptible to erosion and avulsion hazards.
Channel Erosion Hazard Zone (EHZ)	Area at risk to bank erosion by stream flow over a 60-year planning horizon. This area is also susceptible to avulsion hazards.
Avulsion Hazard Zone (AHZ)	Area that is at risk to avulsion over a 60-year planning horizon. This area may also be susceptible to estuary distributary channel hazards in tidally influenced areas. The AHZ is classified into two categories (after Nanson and Knighton 1996): • First-order avulsion: sudden and major shift to a new part of the floodplain • Second-order avulsion: sudden reoccupation of an old channel on the floodplain. Second-order avulsion zones may also be subject to First-order avulsions.
Potential Geotechnical Hazard (Unrated)	Area with steep slopes within the erosion hazard zone or avulsion hazard zone, which may become geotechnically unstable due to inundation or erosion of the toe of the slope. A geotechnical assessment is required to determine an appropriate geotechnical setback for land that may potentially be subject to any potential geotechnical hazards. Only steep slopes within 10 m of the erosion hazard zone boundary were flagged as potential geotechnical hazards. Additional steep slope hazards not flagged may exist outside of the erosion hazard zone.
Estuary Distributary Channel Hazard Zone (DHZ)	Relatively lower gradient area influenced by tidal processes and susceptible to the formation of distributary channels. This area is also at risk to channel erosion and avulsion hazards.
Coastal Erosion Hazard Zone (CHZ)	Landward extent of area likely to be susceptible to erosion from tidal currents and waves generated during coastal storms, with 1 m sea level rise. This area is also susceptible to erosion, avulsion, and estuary distributary channel hazards.



10 GEOMORPHIC HAZARD MAPPING

Geomorphic Hazard Mapping Criteria

The framework for determining geomorphic hazard zones for this project was adapted and modified from approaches used in Washington state (see Page 1).

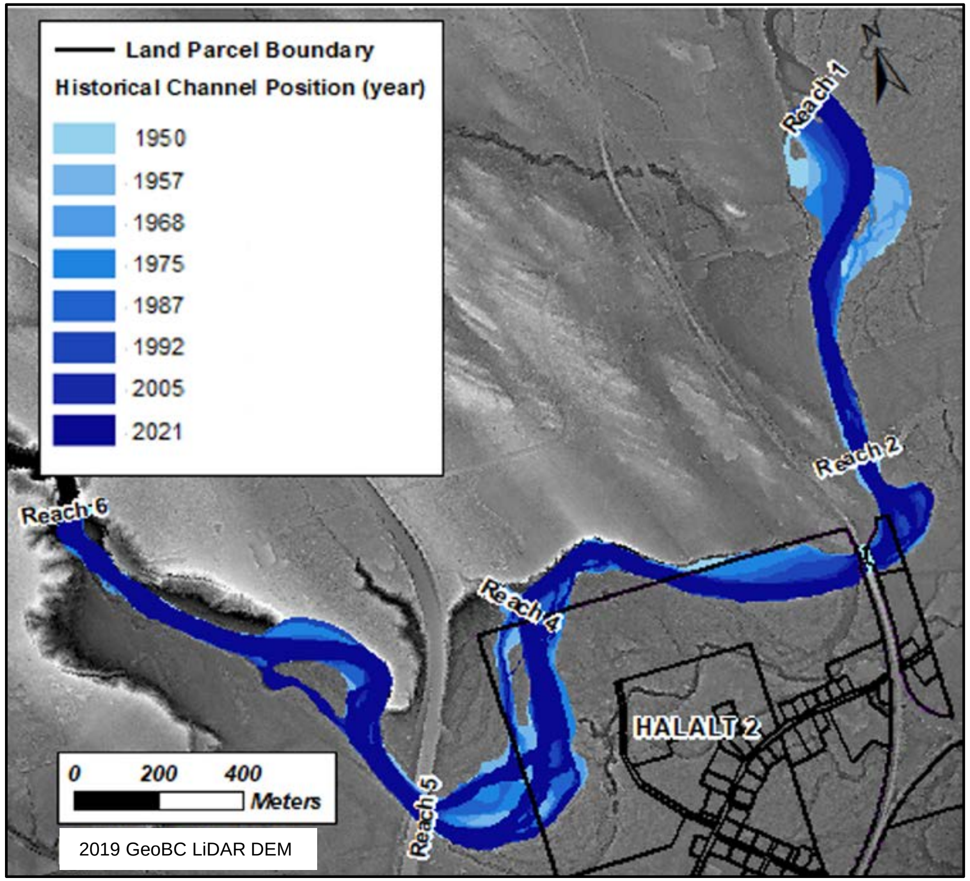
ZONE	METHOD OF DETERMINATION
Modern Valley Bottom (MVB)	Interpretation of local geology information; and DEM topography and terrain information.
Historical Migration Zone (HMZ)	Interpretation of historical imagery (air photos, Google Earth imagery, and orthophotos) spanning a 71-year time period (1950 to 2021) and an 1877 survey of riverbed locations within the Halalt First Nation administrative boundary (see Pages 39 and 40).
Channel Erosion Hazard Zone (EHZ)	Calculated reach-averaged erosion rates and maximum measured erosion rates on a reach-by-reach basis. Application of maximum versus reach-averaged erosion rates were applied according to the rules outlined in Erosion Buffer Rules table on Page 41. Regime channel width changes associated with climate change effects have been incorporated according to the approach outlined on Page 42.
Avulsion Hazard Zone (AHZ)	Post-2021 flood channel assessment, documented evidence of historical avulsions, interpreted 2D HEC-RAS hydraulic model simulation results, calculated channel superelevation and slope ratio between potential avulsion paths and the existing channel (see Page 43).
Potential Geotechnical Hazard Zone (Unrated)	Interpreted from existing terrain, but not mapped or assessed in detail; a geotechnical study is recommended to refine the assessment of geotechnical hazards.
Estuary Distributary Channel Hazard Zone (DHZ)	Interpreted historical imagery (air photos, Google Earth imagery, and orthophotos) spanning a 71-year time period (1950 to 2021) and interpreted observations of tidal influence and 2D HEC-RAS hydraulic model simulations of tidal influence with 1 m sea level rise.
Coastal Erosion Hazard Zone (CHZ)	Interpreted area exposed to wave induced shear stresses, from SWaN model simulations of annual northerly and east-southeasterly wind events, based on 1 m sea level rise.

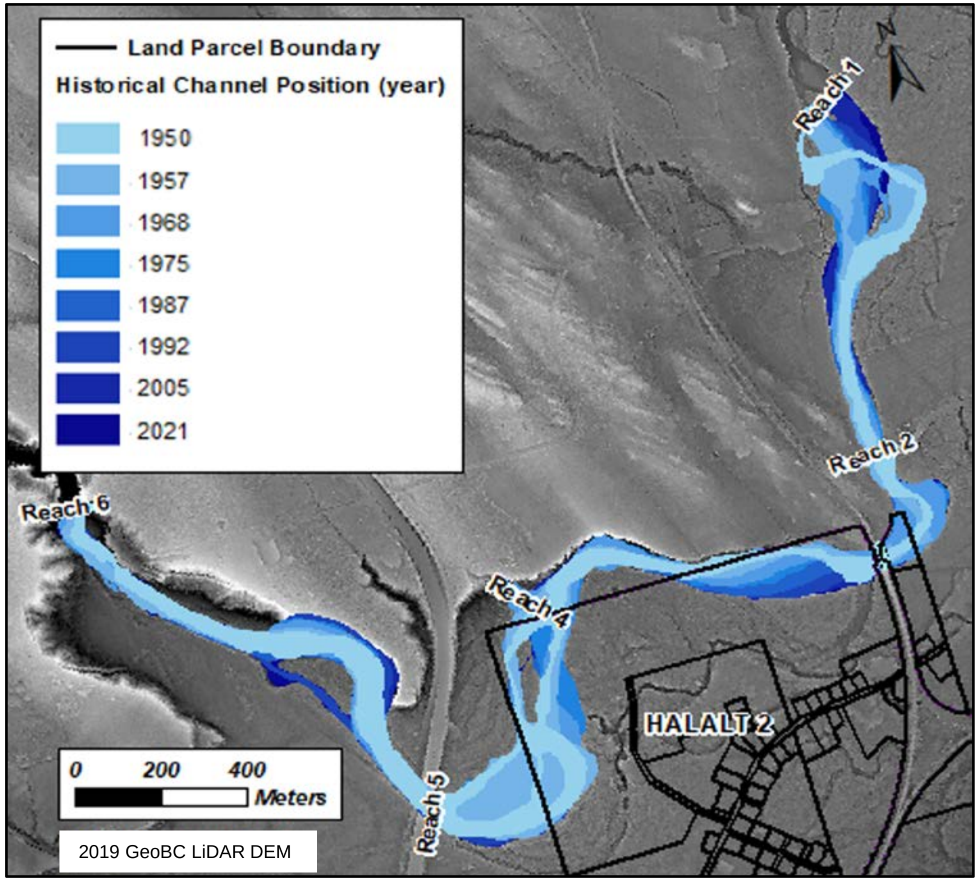
Historical Channel Migration Zone (HMZ) Mapping: Channel Position

Historical Channel Migration Mapping

- Historical channel positions were determined by delineating bank lines based on an assessment of georeferenced historic imagery.
- Historical air photos were available and analyzed for 6 years between 1950 and 1992.
- Two additional years of historical imagery were also analyzed: Google Earth imagery from 2005 and orthophotos from 2021.
- In total, bank lines were delineated based on 8 years of historic imagery spanning a 71-year period (1950 to 2021).

- The southern channel that flows along the island in Reach 6 has become more prominent over time, with flow being primarily directed along the northern main channel in 1950 (light blue) and flow splitting across the northern and southern channels in more recent years (dark blue).
- Near the downstream end of Reach 4, the channel has progressively migrated southwards throughout the air photo period of record (1950 to 2021).
- Outward migration of the meander bend at Reach 3 is apparent from the historical channel mapping. A bedrock outcrop along the downstream end of the outer bend provides increased resistance to erosion. At the upstream end of the outer bend, riprap is present, although there are signs of scour along the toe.
- At the downstream end of Reach 2, the channel avulsed westward between 1950 and 1957. Since 1975, the channel has been progressively migrated eastward along the at channel bend at this location.

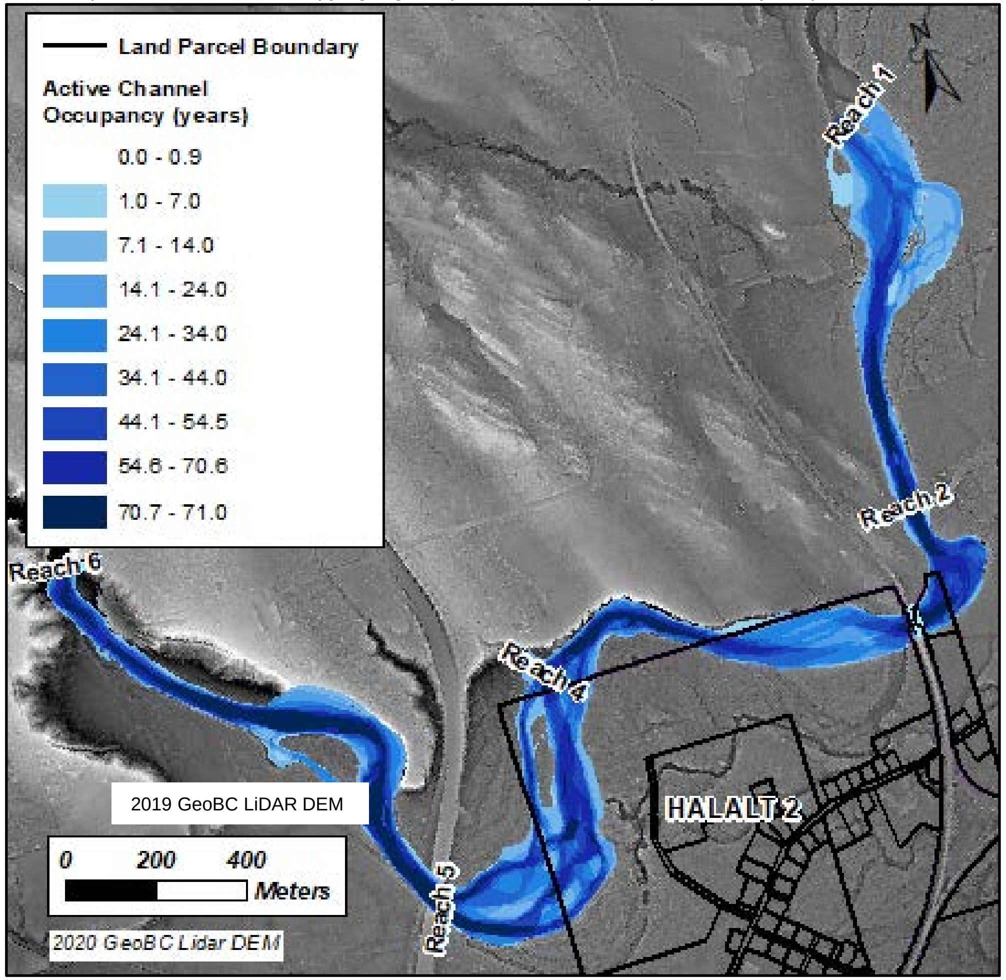




- Historical channel position based on analysis of historical imagery, with the channel positions overlaid from oldest to most recent (left) and most recent to oldest (right).

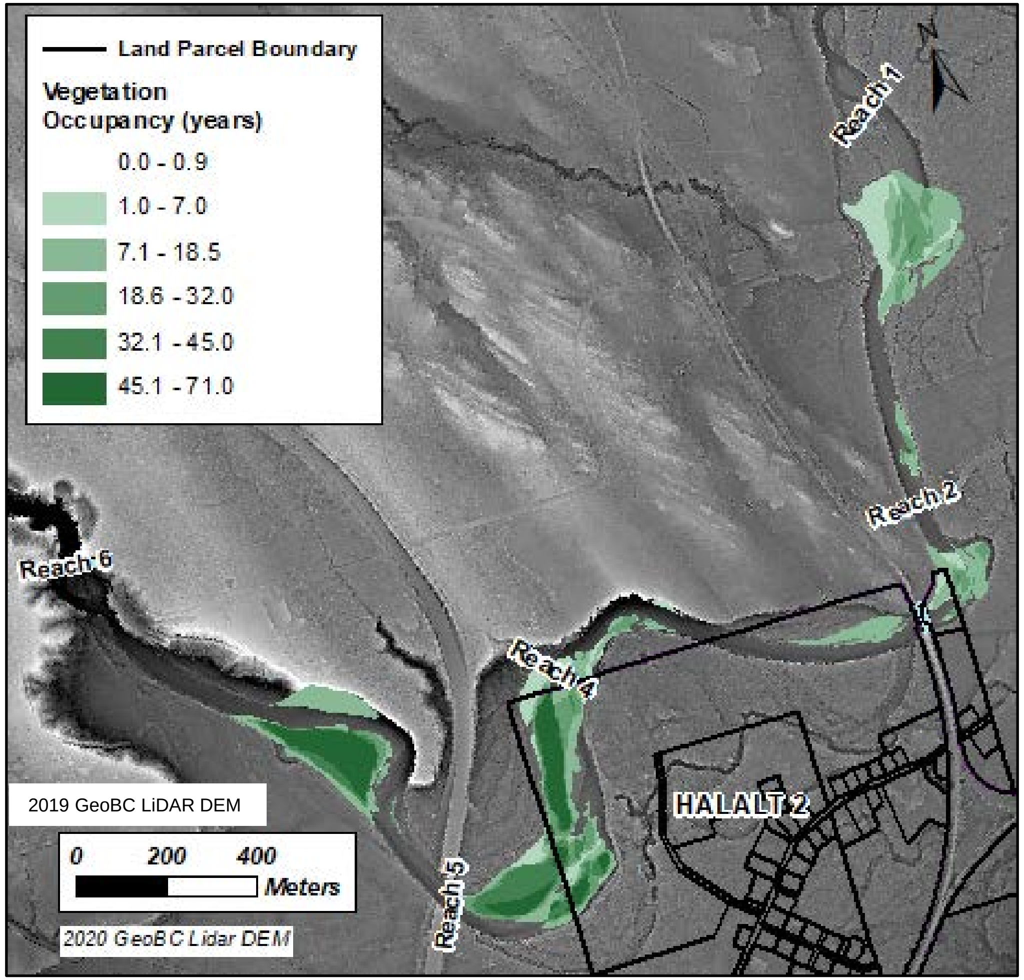
Historical Channel Migration Zone (HMZ) Mapping: Channel Occupancy

- Greater lateral stability (darker shades of blue) is observed in the straighter portions of Reach 2 and Reach 6, and along the erosion-resistant bluffs in Reach 4. At these locations, the channel has occupied the same path for much (55 to 71 years) of the air photo period of record.
- At the outer channel bends in Reach 5, Reach 3, and Reach 2 there has been more lateral instability (lighter shades of blue), with the channel occupying a given path for fewer years (ex. 1 to 14 years).



▲ Map of historical channel occupancy based on analysis of historic air photos.

- Prominent vegetated features have been present for much (45 to 71 years) of the air photo period of record in Reach 6 (upstream of the HWY 1 bridge) and in Reach 5 (downstream of the HWY 1 bridge).
- At channel bends in Reach 3 and Reach 2 there are more dynamic vegetated features. At these locations loss and regrowth of vegetation has occurred, corresponding to lateral instability of the channel.



▲ Map of historical occupancy of vegetated bars and islands based on analysis of historic air photos.

Erosion Hazard Zone (EHZ) Mapping: Buffer Rules

The Erosion hazard buffer width was based on the maximum erosion buffer and reach-averaged buffer as described in the table below. Estimated regime channel changes associated with climate change induced increased peak flows have been incorporated into the EHZ (described on Page 42).

Interpreted Channel Bank Material	Susceptibility to Erosion Historically (1950 – 2021)	Channel Geomorphology	Erosion Hazard Buffer
Alluvium	High	Some combination of: - Highly erodible bank material - History of channel instability observed in air photo record; -Evidence of geomorphic processes that suggest potential future instability	Maximum erosion buffer *or* probability-based maximum erosion buffer
	Low	Some combination of: - Somewhat erosion-resistant bank material; - History of channel stability observed in air photo record; - Evidence of geomorphic processes that suggest decreased risk of instability	Reach-averaged buffer increased by erosion-resistant percentage of the reach
Bedrock	Low	-	Reach-averaged Buffer
Riprap or concrete	-	-	Either reach-averaged buffer increased by erosion-resistant % of Reach *or* maximum erosion buffer, *or* probability-based maximum erosion buffer depending on channel geomorphology (refer to rules described for alluvium)
Bluffs (till/glacio-marine clay)	Low	Channel directly impinges on bluffs	Reach-averaged buffer
		Channel is offset from bluffs; bank material is alluvium	Reach-averaged buffer increased by erosion-resistant percentage of the reach

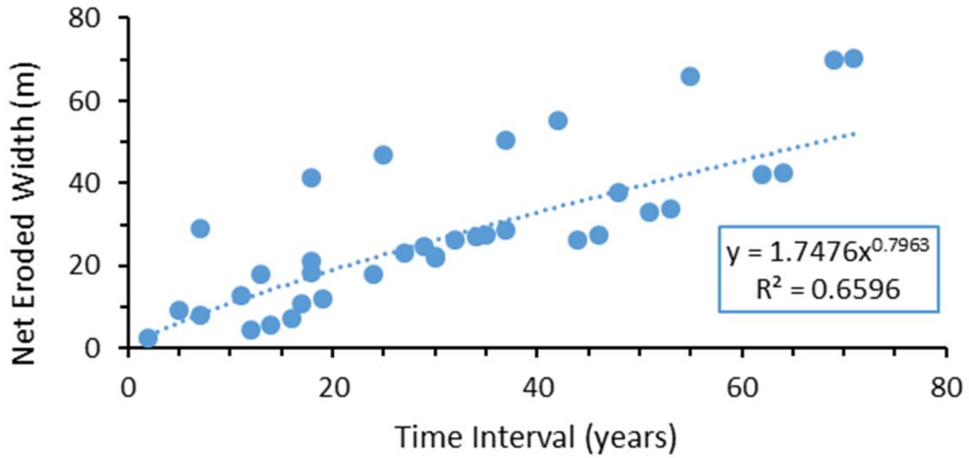
Erosion Hazard Buffer Metrics

Maximum erosion buffer: width is derived from the maximum erosion rate over the air photo period of record, applied over a 60-year time interval

Reach-averaged buffer: width is calculated by interpolating the average eroded width for a 60-year time interval. Average eroded widths were calculated based on an analysis of areal change over the 71-year air photo period of record

Probability-based maximum erosion buffer: width is derived from a probability-based approach incorporating survey data. The probability-based approach was only applied along the right bank in the upstream portion of Reach 5, and survey data collected before and after the November 2021 flood was used. A probability analysis, performed based on the historic flood record, indicated a 92% chance of an event of that magnitude occurring no more than 6 times over a 60-year interval. The eroded width associated with the November 2021 flood and the calculated annual average erosion rates were proportionally applied over a 60-year time horizon to project the erosion buffer.

▶ Graph of average eroded width for Reach 2 over the 71-year air photo period of record calculated based on areal changes in the active channel. The rate of change fits a power function, in which the magnitude of change decreases with increasing duration. Over a given flood event, the active channel may erode floodplain that was previously unoccupied over the period of record. However, over time, the channel re-erodes areas historically occupied by the channel.



10 GEOMORPHIC HAZARD MAPPING

Regime Modelling

Rational regime theory for alluvial rivers is based on the concept that the width, depth, and gradient of a river channel are determined by the range of flows to which it is subject and by the grain-sizes and supply of channel bed-sediment from the watershed. The bankfull discharge is often viewed as a flow condition that has a strong influence on the channel form. Adjustments in the magnitude of this channel-forming discharge are anticipated to induce changes in the river geometry (i.e., an increase or decrease in channel width, depth, or gradient).

The erosion hazard boundary delineated for the geomorphic hazard map accounts for the potential for morphological changes in response to the anticipated increase in the magnitude of peak flows associated with climate change in British Columbia. For this study, a regime modeling approach was adopted using the physics-based UBC Regime Model (UBCRM), and the bankfull discharge has been approximated using a reference discharge, $Q_{reference}$, of 350 m^3 s^{-1}.

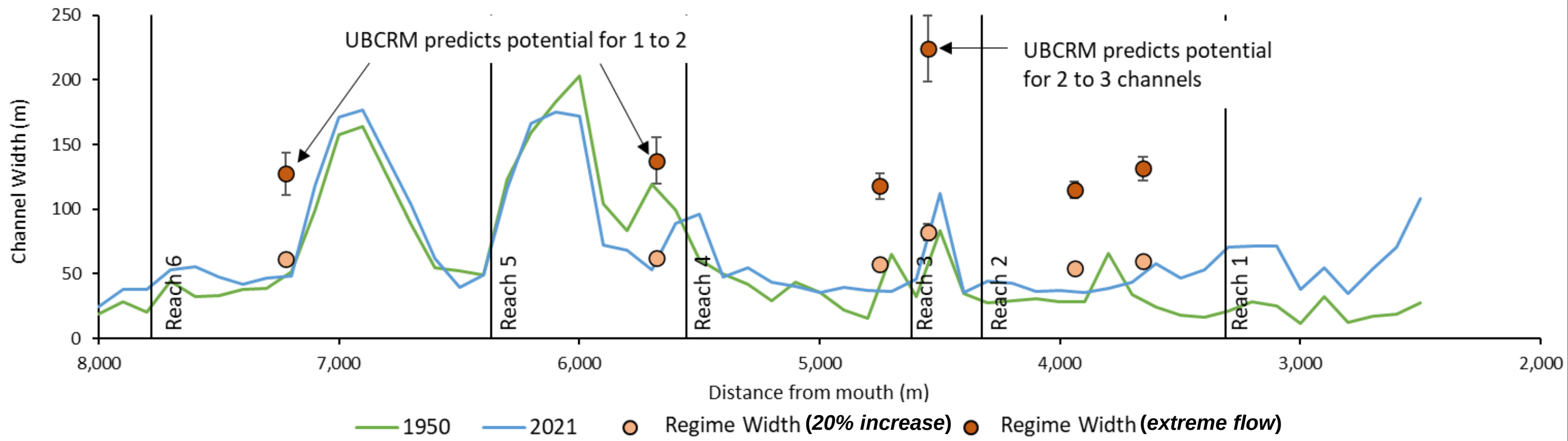
The UBCRM predicts channel form as controlled by the following input parameters: channel-forming discharge, energy gradient slope, bed material grain size distribution, and strength of the channel banks. The model builds on a long history of previous work focused on developing 'regime curves' that relate channel geometry to the channel-forming discharge (U.S. Army Corps of Engineers, 1994).

The UBCRM was calibrated to the 2019 DEM channel geometry by applying the channel forming discharge ($Q_{reference}$) and estimating the distribution of bed sediment from NHC's 2021 pebble counts and data provided by KWL (2021) and CWB (2021).

After the model was calibrated, it was run a second time to determine the regime channel dimensions associated with a 20% increase in the channel-forming discharge, accounting for climate change projections (laballed as *20% increase*). A final iteration of the UBCRM was run using a 0.5% AEP flood event with a 20% increase in discharge to account for climate change to assess the potential channel geometry produced from this extreme flow event (labelled as *extreme flow*).

- Longitudinal profile plot of the UBCMRM results showing predicted channel width and number of channels for two flow scenarios.

  Channel widths measured from 1950 air photos and 2021 orthophotos are shown for reference.



The UBCRM predicts that the river will widen by 6 to 11 m in response to an increase of 20% in the channel forming discharge ($Q_{reference}$). This falls within the projected erosion hazard area buffers, as depicted in the geomorphic hazard map (Page 44).

Channel widening near areas adjacent to low-lying floodplain channels (e.g., the Halalt rearing channel in Reach 6) may increase the potential for a future channel avulsion should these channels become more directly exposed to high velocity flows.

The future conditions 0.5% AEP flood event is likely to fundamentally alter the morphology of the lower Chemainus River. The UBCRM predicts increases in channel width ranging from 50 to 150 m, with multi-thread channel configurations becoming the preferred channel geometry within Reaches 3, 5, and 6. These predictions also provide supporting evidence for the high susceptibility of the Chemainus River floodplain to channel avulsions during extreme flows.

Assumptions and Limitations

The UBCRM assumes, rather conservatively, that the regime flood event is sustained for a sufficient time period to allow the channel to adjust its geometry accordingly. However, extreme flows may be briefer than the duration needed to produce significant morphological adjustments, and changes in channel width may be less than predicted.

The UBCRM also relies on the assumption that channel form is a product of fluvial processes. This assumption cannot be applied to the lower portion of the channel, where tidal backwatering affects upstream channel hydraulics, sediment transport, and channel form. In consideration of this, regime channel analysis focused upstream of Reach 1.

10 GEOMORPHIC HAZARD MAPPING

Avulsion Hazard Zone (AHZ) Mapping

- Several potential avulsion nodes (i.e., channel locations where an avulsion could occur) were identified based on the following criteria:
  - Analysis of historical avulsions
  - Interpreted 2D HEC-RAS hydraulic model results (water surface elevation, shear stress, depth, velocity, and overbank flow paths)
  - DEM analysis and interpretation of relic channel pathways
  - Assessment of the post-2021 flood channel assessment
  - Identified historical sediment and LWD accumulation zones, and evaluation of the potential for reduce hydraulic conveyance or channel-blockage
- Avulsion hazard metrics, including super-elevation, normalized super-elevation, and slope ratio (see avulsion hazard metrics box on right), were calculated for several selected potential avulsion paths using an approach adapted from NHC (2015b).

The avulsion hazard zone is classified into two broad categories, as presented on Page 44):

- First-order avulsion: sudden and major shift to a new part of the floodplain
- Second-order avulsion: sudden reoccupation of an old channel on the floodplain.

▼ Table of Avulsion Hazard Metrics for six selected paths for which avulsion hazard metrics were calculated. Cells shaded in yellow suggest that an avulsion may occur at those locations. A broader assessment of the area indicates that potential avulsion paths are not limited to these four paths and avulsion hazards exist throughout much of the floodplain.

Avulsion Node	River Kilometer (Km)	Normalized Super-elevation (m)	Slope Ratio (Bed elevation, m)
A	7.4	0.3	3.9
B	6.2	0.6	2.5
C	5.9	1.3	0.0
D	5.5	0.1	2.0
E	4.5	0.2	3.5
F	4.2	0.3	5.4

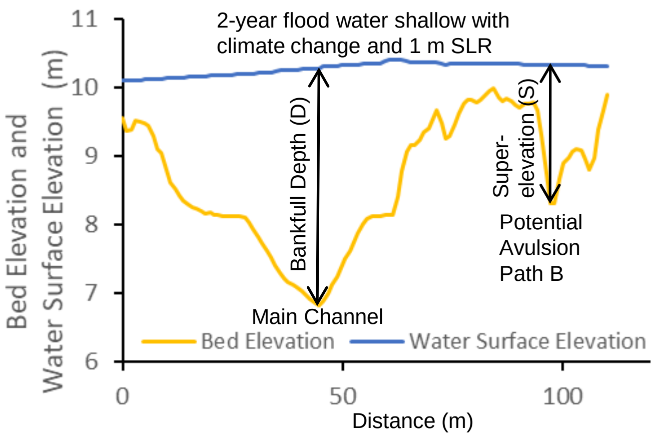
Avulsion Hazard Metrics

Super-elevation: describes the degree to which a channel is perched above the floodplain (see graph on right)

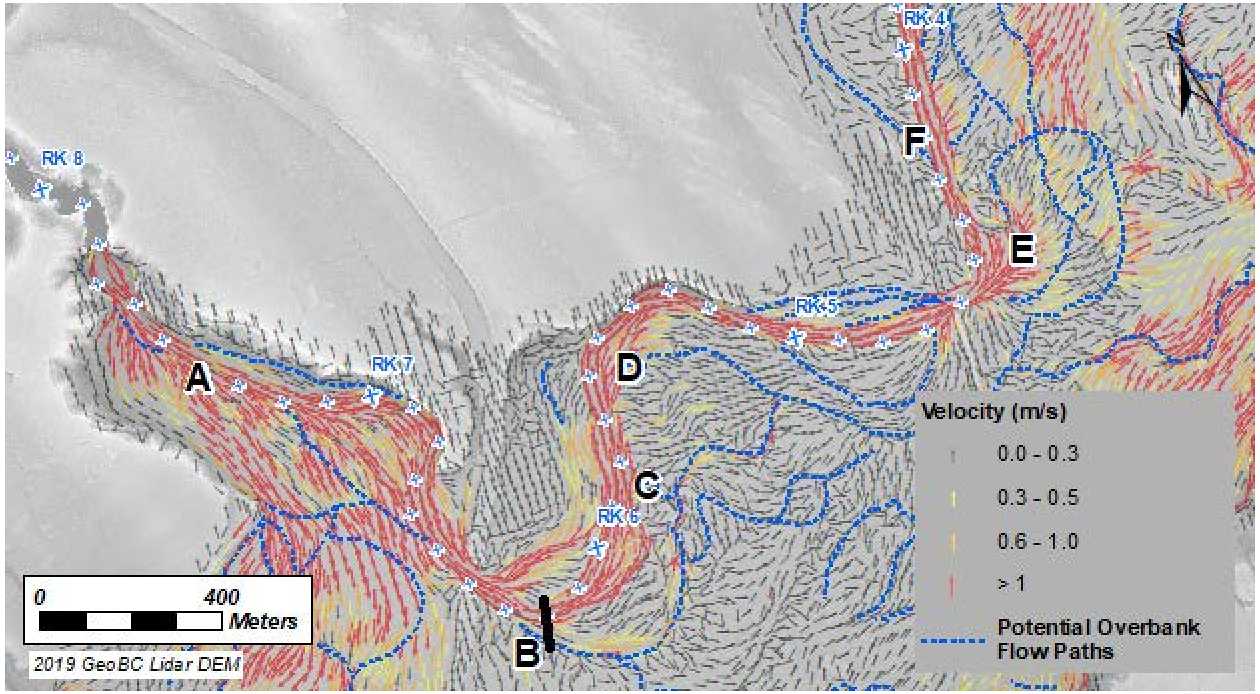
Normalized super-elevation: ratio of super-elevation to channel depth

Slope ratio: ratio of the slope of a possible avulsion path to the existing main channel slope

Example cross section plot showing super-elevation (S), bankfull depth (D), bed elevation, and water surface elevation for the 2-year flood with climate change and 1 m SLR. Cross section plot taken at avulsion node B (see map below for location). ▼



▶ Map showing select potential avulsion nodes (labelled A to E). 2D HEC-RAS hydraulic mode simulations of velocity vectors and rates (metres per second) for the design flood event and interpreted overbank flow paths are shown for context (blue paths).



10 GEOMORPHIC HAZARD MAPPING

Overview Level Mapping Information

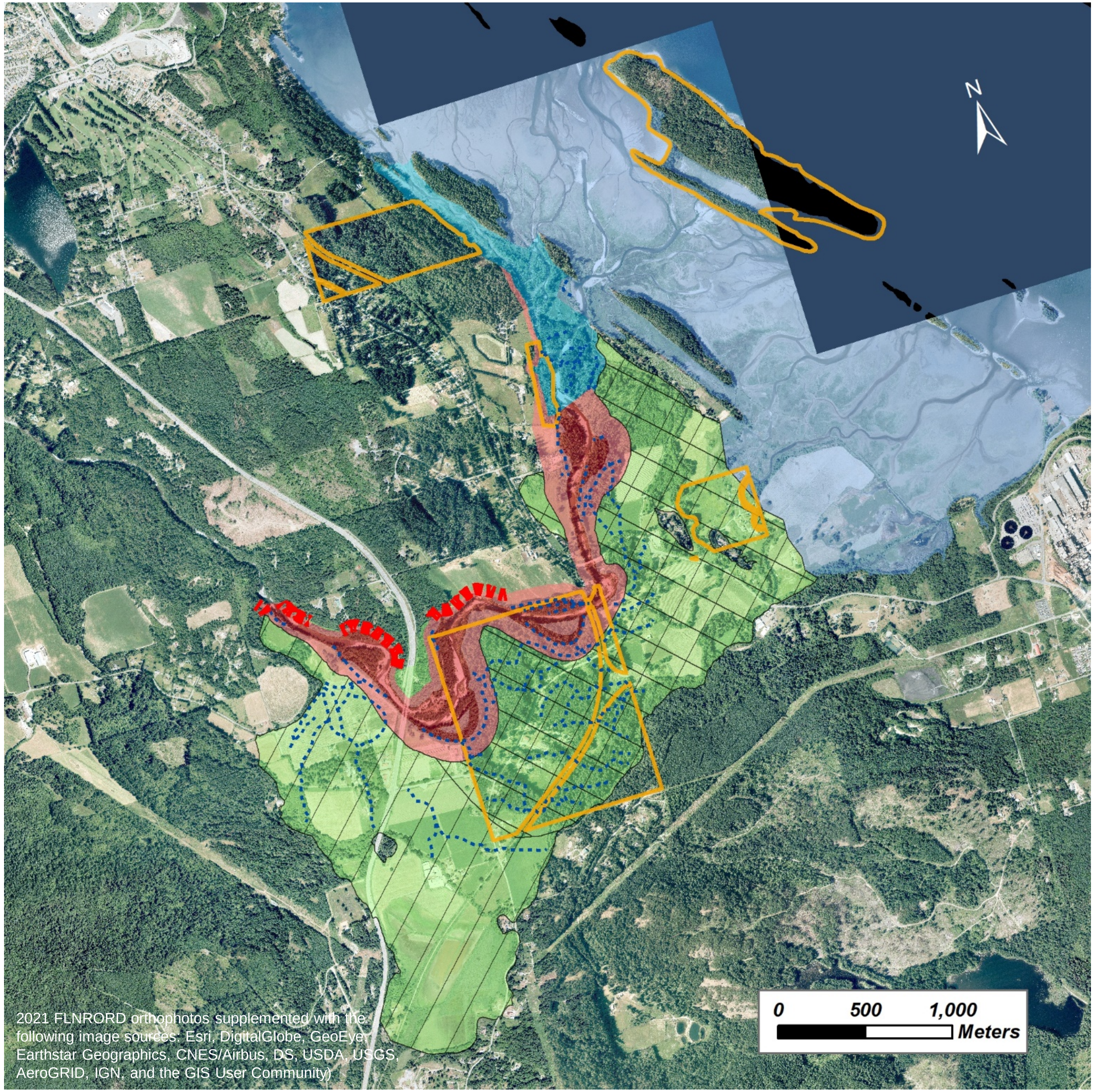
Legend

- First Nation Administrative Boundary
- Detected Relic Channel Paths
- Potential Geotechnical Hazard
- First Order Avulsion Hazard Zone
- Second Order Avulsion Hazard Zone
- Modern Valley Bottom
- Historical Migration Zone
- Erosion Hazard Area
- Distributary Hazard Zone
- Coastal Hazard Zone

The definitions for the hazard zones delineated in the geomorphic hazard map are provided on Page 37 and mapping criteria is described on Pages 38 to 43.

Potential geotechnical hazard defines an area with steep slopes within the erosion hazard zone or avulsion hazard zone, which may become geotechnically unstable due to inundation or erosion of the toe of the slope.

A geotechnical assessment is required to determine an appropriate geotechnical setback for land that may potentially be subject to any potential geotechnical hazards. Only steep slopes within 10 m of the erosion hazard zone boundary were flagged as potential geotechnical hazards. Additional steep slope hazards not flagged may exist outside of the erosion hazard zone.



▶ Geomorphic hazard map at the study area scale, showing the full extent of hazard mapping

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APPENDIX D

HYDRAULIC MODELLING

APPENDIX D

HYDRAULIC MODELLING

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1 INTRODUCTION

A hydraulic model of the Chemainus floodplain and estuary was developed to simulate the design events and subsequently determine the expected flood level and extent of flooding during the events. The area was modelled using a two-dimensional model, which calculates varying water depths and velocities as well as allows flow to move in multiple directions across the floodplain. The following sections present the data used to develop the model, the development and calibration of the model, the model results, and the limitations.

2 DATA SOURCES

2.1 Survey Data

NHC collected channel survey data of the Chemainus River, Bonsall Creek and a small portion of Whitehouse Creek as part of the study. The details of the survey and the extents are listed in Appendix A. All NHC survey data was collected with in Universal Transverse Mercator (UTM) Zone 10, North American Datum of 1983 (NAD83) CSRS. Vertical coordinates are based on the Canadian Geodetic Vertical Datum of 2013 (CGVD2013).

Observations supported the definition of modelling parameters to represent the crossings as shown in Photo 2.1.

Photo 2.1 Survey of main channel and side channels with boat upstream of Highway 1 Bridge to complete detailed observations and measurements for hydraulic model input.

Cross sections were collected upstream and downstream of each crossing within the study reach pertinent to model development. Ten bridges were surveyed for the study and are summarized in Appendix A. Six bridges were included in the Chemainus River 2D model are summarized in Section 3.3.

Flood control structures, such as embankments or berms, were not captured by the ground survey and were only captured as part of the LiDAR. Complete survey and assessment of flood control structures was not conducted as part of this study.

2.2 Digital Elevation Model (DEM)

For modelling and mapping purposes, a digital elevation model (DEM) of the floodplain and mainstem channel was derived from bare earth LiDAR. It constitutes a seamless representation of the Chemainus River floodplain and channel topography suitable for 2D numerical modelling. The details of the LiDAR can be found in Appendix A. In addition to the Chemainus River channel, the DEM includes bathymetry for Bonsall Creek. Bridges and culverts are removed from the DEM, so that the DEM approximately represents the channel under the bridge. The DEM has a 1.0 m cell size.

The DEM was created using the data sources summarized in Table 2.1.

Table 2.1 DEM data sources.

Data Type	Source	Location	Acquisition Date	Datum + Projection
Bathymetry point data	NHC	Chemainus River and Bonsall Creek	25 May 2021	NAD 83(CSRS) UTM Zone10, CGVD2013
Terrestrial LiDAR	GeoBC/FLNRORD	Entire project area (Vancouver Island and the Sunshine Coast).	14 Oct 2018 to 1 Oct 2019	NAD 83(CSRS) UTM Zone10, CGVD2013
Terrestrial LiDAR	Terra Remote Sensing Inc.	Project area: 3 km^2 of Chemainus	27 Mar 2021	NAD 83(CSRS) UTM Zone10, CGVD2013

Bathymetry data for the Chemainus Rivers and Bonsall Creek were obtained from NHC bathymetry points. 3D polyline breaklines were used to interpolate a continuous bathymetric surface of the Chemainus River and Bonsall Creek from NHC bathymetric survey data. Topography survey points were added for bridge abutments.

To join river bathymetry with the topographic surface, the riverine surface created in GIS was converted to raster format, then pasted onto the LiDAR surface. Checks were done to ensure that no vertical steps existed between the bathymetric and topographic data.

2.3 Orthophotos

Colour orthophotos were provided by the CVRD that corresponded with the 2019 GeoBC LiDAR. Additional ortho photos of just Chemainus River were provided by Cowichan Watershed Board which were collected with the 2021 LiDAR. The orthophotos were used to interpret features on the floodplain, help assess channel and floodplain roughness, supplement field survey information, and provide context in the interpretation of the model results.

2.4 Hydrometric Data

Hydrometric data was described in detail in the hydrology appendix for this report. Flow records from WSC station Chemainus River near Westholme (08HA011), located at Highway 1 bridge on Chemainus River in the study reach, was used to estimate historic flood flows and design flood flows for hydraulic modelling. Bonsall and Whitehouse Creek, which flow across the Chemainus floodplain were estimated using a regional analysis based on WSC gauge Bings Creek near the mouth (08HA016). The following flood flows have been modeled:

- For calibration:
  - 2020 QPI estimate – 722 m^3/s
  - November 15, 2021 QPI (preliminary estimate) – 652 m^3/s
- For flood mapping:
  - 20-year QPI with increase for climate change – 889 m^3/s
  - 200-year QPI with increase for climate change – 1197 m^3/s

Water Survey of Canada's discharge data for the November 15, 2021 event were still designated as "preliminary" at the time of this study. Therefore, the Nov 15, 2021 flows were estimated from the real-time discharge and water level records posted on their official WSC hydrometric station:

(https://wateroffice.ec.gc.ca/mainmenu/real_time_data_index_e.html)

During high flood events the Chemainus River spills out of bank upstream of Highway 1, causing flow to be diverted across the highway into Whitehouse and Bonsall Creek. Since the gauge is situated downstream of this spill, observed discharge measurements during high spilling flows will underestimates the total inflow.

Without knowing the correction WSC applies for this at Chemainus River gauge, the November 15, 2021 calibration flow was increased to be similar to the 2020 event. This was based on the water levels observed at the gauge (very similar for both years, 11.27 m in 2020 vs 11.23 m in 2021), the reports of similar extents and heights observed in the field for 2020.

2.5 High Water Marks

The largest flood of record occurred on the Chemainus River in February of 2020 and then a similar but slightly smaller sized flood occurs on Nov 15, 2021. During and following the 2021 flood, high water marks (HWM) were surveyed throughout the floodplain by NHC. The survey included 44 points within the study area, as shown in the Figure 2.1. These points are associated with the estimated 2021 QPI of 652 m^3/s through the study reach.

In addition, photos of the flood taken by NHC were used to help identify flood extents (Photo 2.2). The photos were taken on Nov 15, 2021 during the peak of the flood.

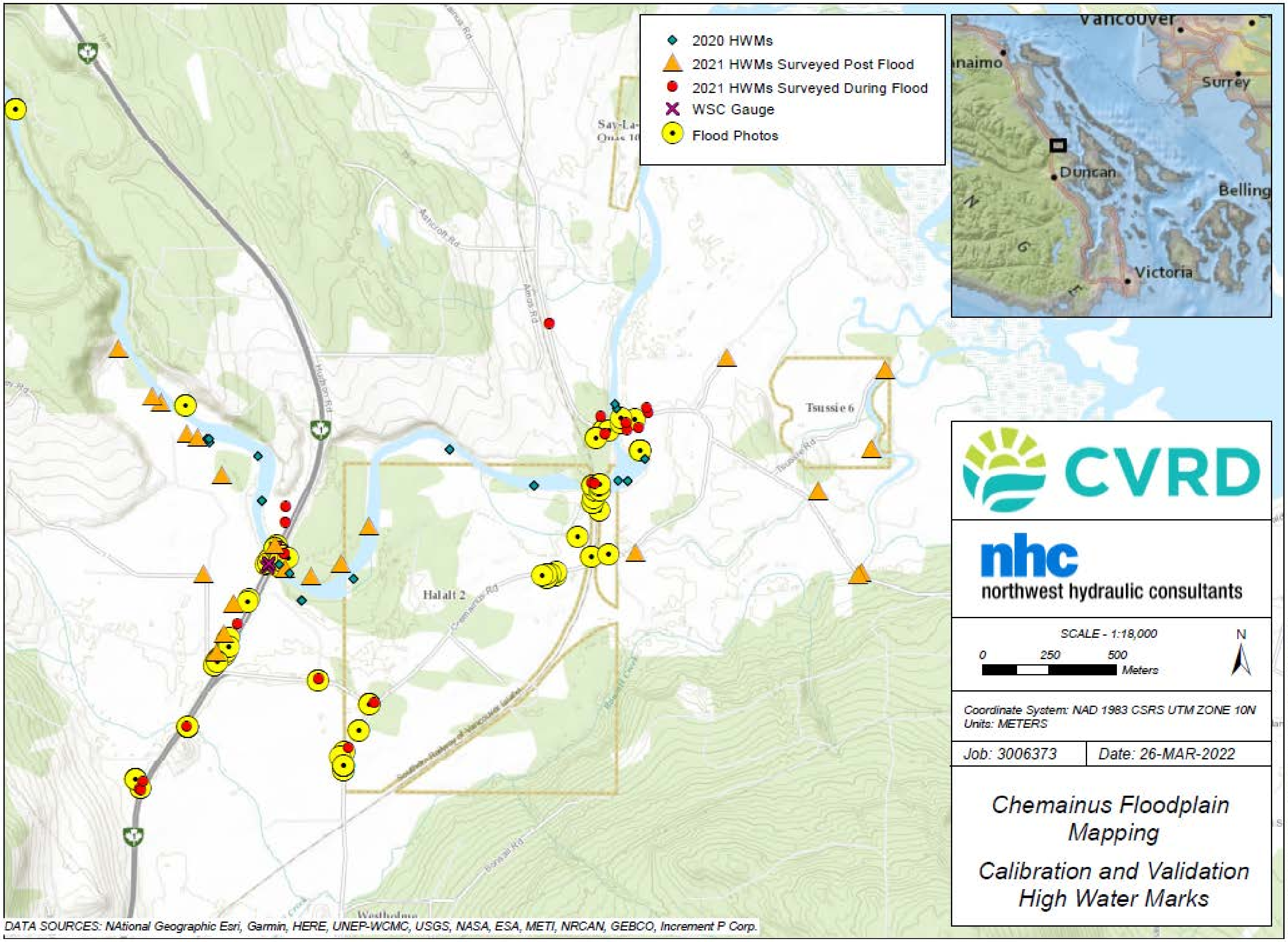


Figure 2.1 Overview of HWMs used for calibration of the hydraulic model. Red points indicate HWMs surveyed during the peak of the 2021 flood event. Orange Triangles indicate HWMs surveyed 5 days after the peak of the flood had passed. Yellow circles indicate flood photos taken and green dots indicated 2020 estimated HWMs.

Photo 2.2 Flooding in Chemainus on Nov 15, 2021 at peak of flood. Photo on top left is looking south at water overtopping Hwy 1 just south of Russel Farms. Photo on top right is just off Hwy 1a or Chemainus Rd Bridge looking east towards Pinson's Corner. Photo on bottom left is Russel Farms Market as seen from Hwy 1. Photo on bottom right is corner of Chemainus Rd and Westholme Rd looking northeast through Halalt First Nation.

3 HYDRAULIC MODEL DEVELOPMENT

Riverine floodplain mapping is generally based on flood profiles calculated from a one-dimensional (1D) model; that is where flow is simulated as moving in one direction, downstream. Two-dimensional (2D) and three-dimensional (3D) models are used for calculating hydraulic conditions where cross flow and vertical currents are of interest, such as: localized scour, effluent mixing, or flow splits. For many locations 1D modelling is still appropriate for floodplain mapping. However, where there are multiple flow paths, either overbank or secondary channels, 2D modelling may be more appropriate to guide or form the basis for floodplain mapping. For this project, the Chemainus River was simulated in 2D.

The hydraulic model includes an 8 km reach of the Chemainus River, from the estuary to approximately 700m upstream of the Chemainus River Campground. Approximately 200 m of Whitehouse Creek is included upstream of the confluence with Bonsall Creek and approximately 8 km of Bonsall Creek is included in the model, from the estuary to approximately 200 m upstream of Emerald Place (road) (Figure 3.1). The river channel through the study reach is mostly singular and well defined with gravel bars and cut banks. It has a wide floodplain on the right bank that accommodates overbank flooding. Details of the geomorphic features of the floodplain can be found in the Geomorphic Atlas in Appendix C.

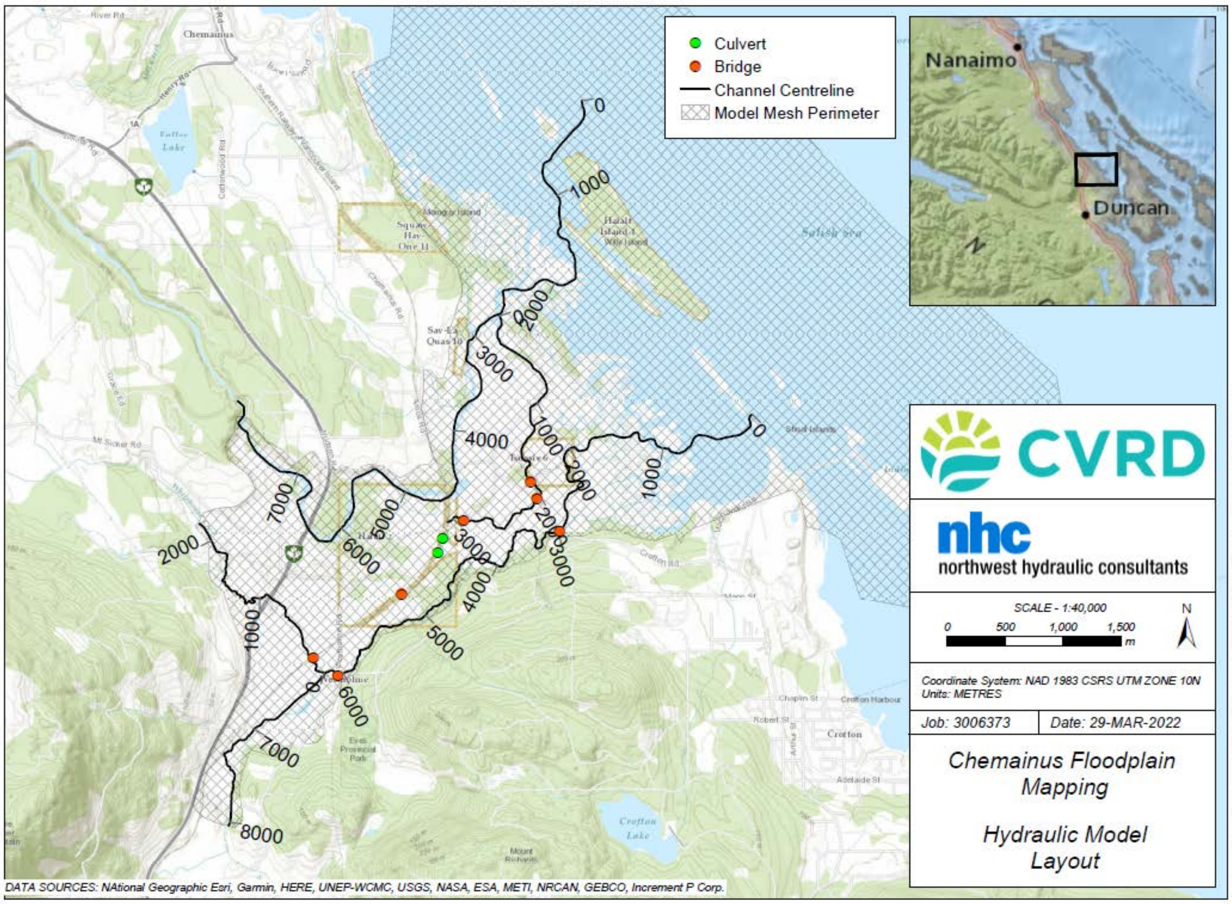


Figure 3.1 Hydraulic Model Layout

Active side channels have been captured by the LiDAR and are included in the 2D model as possible flow paths. The variability in channel form along the Chemainus River, such as channel sinuosity, varying channel width, point and mid-channel bars, wood debris, and bank vegetation are represented in the model through the assigned Manning's n roughness factor.

3.1 HEC-RAS Software

HEC-RAS (River Analysis System), a computer program developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC), was used to simulate the flood conditions, and calculate the flood profile. HEC-RAS has been approved for floodplain mapping projects by major agencies such as FEMA and has been used historically here in BC on many floodplain mapping studies. Version 6.1 was released in September of 2021 and was used for this study. The program is designed to perform one-dimensional (1D), two-dimensional (2D), or combined 1D and 2D hydraulic calculations for a full network of channels. The model includes routines for the hydraulic structures (bridges) of most relevance to this study. Furthermore, the model can simulate both steady and unsteady flow conditions. For this project a 2D unsteady flow model was used to calculate the flood profile for the study reach.

For the 2D unsteady flow computations, the 2D computational cells were pre-processed in order to develop detailed hydraulic property tables based on the underlying terrain (this allowed for larger cells to be partially wet with the correct water volume based on the modelled water surface and DEM resolution). Although RAS2D is a sophisticated modelling tool, it has several basic assumptions and limitations:

- The model assumes a fixed geometry for the channel and floodplain in spite of bank erosion, scour, deposition and potential avulsions taking place during high flows.
- The absence of blockages, such as debris jams at bridge crossings and debris plugs at floodplain openings, is assumed.
- Dike or embankment breaches are assumed not to occur.
- The model is as accurate as its calibration. The 2021 flood is a large flood and therefore the calibrated roughness coefficients should be representative, and the high-water marks were collected by NHC during the peak of the flood. The calibration data used was very strong with engineers on site for firsthand exposure. There is uncertainty in the flow estimates due to the nature of the floodplain which makes confidence more difficult.
- At the start of a flood simulation, the model floodplain is assumed to be dry although there may already be water in the form of localized ponding and runoff from precipitation. Also, a multi-peaked hydrograph may cause more severe flooding than the event simulated.

3.2 Mesh Development and Extents

The 2D model geometry consists of variable mesh sizes including of 30 m by 30 m mesh on the floodplain, a 5 by 5 refinement area mesh Chemainus River and a 3 m by 3 m mesh on the tributaries. Raised roadways and berms were identified in satellite imagery and the DEM and breaklines were used to force the mesh cells to align along the features to capture the raised profiles.

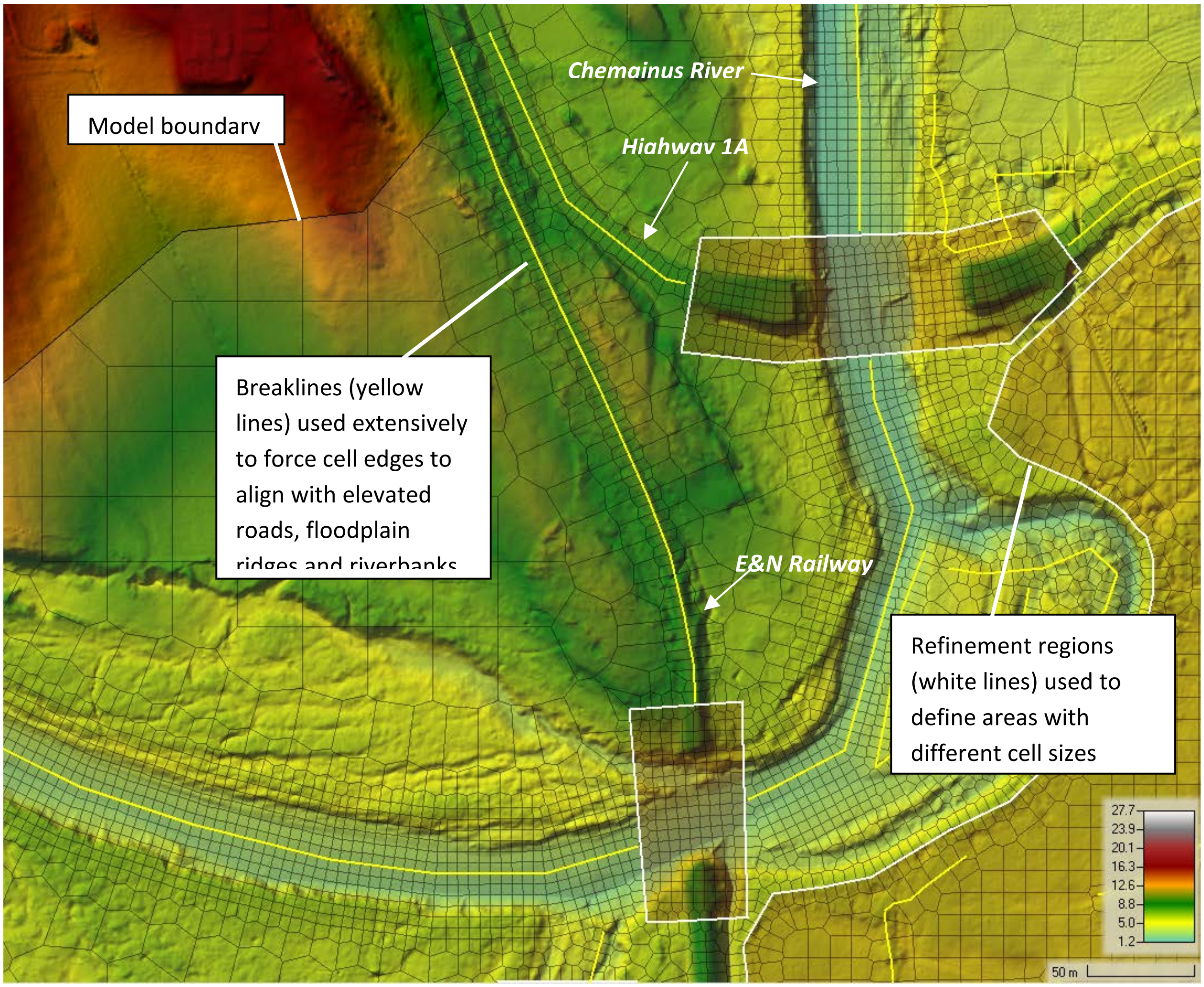


Figure 3.2 Example model mesh at the Highway 1A and Railway bridges over Chemainus River. Example mesh sizes for Chemainus River and floodplain, use of breaklines and Refinement regions, and underlying DEM

The model boundaries are set outside of the mapping extent. As the flood model can be expected to maintain a strictly subcritical flow regime, the river hydraulics are controlled by downstream conditions; the location of the boundaries ensure no boundary effects impact the model results within the mapping extents.

3.3 Hydraulic Structures

Hydraulic Structures represented in the model include bridges, specific culverts and road and railway embankments in the floodplain.

Culverts

Two culverts were included in the Chemainus River 2D model (Table 3). NHC survey data was used to create the model culvert.

Table 3.1 Culverts in the Chemainus 2D model

No.	Dike	Watercourse	Length (m)
1	370m south of Chemainus River, underneath the E&N Railway	Chemainus River floodplain	23.3
2	502m south of Chemainus River, underneath the E&N Railway	Chemainus River floodplain	20.9

Bridges

Bridges were reflected as 'bridge' elements. A number of locations became submerged and requiring the modelling pressurized flow conditions and overtopping flow over bridge decks. For consistency, all bridges were modelled as 'bridge' elements, except for the bridges crossing the Chemainus River. These bridges were removed from the model due to causing model instabilities and artificial flow results because the model performed and matched calibration better without the bridge structures in place. Since the modelled Additionally, since the modelled flows did not reach Chemainus bridge low chords, and the abutments were captured in the DEM, the structures were not needed in the model.

The bridge geometry was based on survey data collected as part of this work. The six bridges included in the Chemainus River 2D model are summarized in Table 3.2. None of the bridges that overtop during the CC 2100 scenario are on the Chemainus River, which limits the hydraulic impact of the bridges on the overall flooding extent.

Table 3.2 List of bridges in Chemainus River 2D Model

No.	Bridge/Road	Watercourse	Station (km)	Piers or Abutments?	Overtopping during CC 2100 flow conditions?
1	Highway 1A (Chemainus Road)	Butcher's Slough	2,885	No	Yes
2	Tsussie Road	Butcher's Slough	1,835	No	Partially. WSE above downstream high chord.
3	Crofton Road	Butcher's Slough	2,035	No	Yes
4	Westholme Road	Bonsall Creek	6,052	No	Yes
5	Crofton Road	Bonsall Creek	2,980	No	No. Crofton Road flooding on left bank north of bridge.
6	Railway bridge	Whitehouse Creek	200	No	Yes

Road and Railway Embankments

Breaklines were used extensively in the Chemainus River 2D model to capture the effects of all major raised roads and railroad embankments, natural high ground, and other topographic controls that could obstruct and direct overbank flows across the floodplain. Elevation data was extracted from the model DEM. Breaklines were also used extensively in the channels and flow paths to capture the low points. Orienting the mesh cell faces to be perpendicular to the flow path using breaklines provides a greater accuracy for the modelled 2D velocity.

3.4 Boundary Conditions

Model boundary conditions consist of inflows entering the model for the upstream boundary and water levels at in the estuary for the downstream boundary. Both sets of boundaries are dynamic; all major inflows were represented by flood hydrographs and ocean levels by tidal cycles. A detailed description of the hydrologic analyses is provided in the Hydrology appendix.

Boundary condition locations are shown in Figure 3.1 and summarized in Table 3.3. All inflows are based upon instantaneous daily flows (QPI).

Table 3.3 Summary of Chemainus River 2D model boundary conditions

No.	Boundary Condition	Data Source	Type	Data format
1	Chemainus River	WSC station Chemainus River near Westholme (08HA011)	Inflow (Upstream)	Flow hydrograph
2	Bonsall Creek	Regression Analysis	Inflow (Upstream)	Flow hydrograph
3	Whitehouse Creek	Regression Analysis	Inflow (Upstream)	Flow hydrograph
4	Unnamed Chemainus R. Tributary	Regression Analysis	Inflow (Upstream)	Flow hydrograph
5	Unnamed Whitehouse Creek. Tributary	Regression Analysis	Inflow (Upstream)	Flow hydrograph
6	Unnamed Bonsall Creek. Tributary 1	Regression Analysis	Inflow (Upstream)	Flow hydrograph
7	Unnamed Bonsall Creek. Tributary 2	Regression Analysis	Inflow (Upstream)	Flow hydrograph
8	Unnamed Bonsall Creek. Tributary 3	Regression Analysis	Inflow (Upstream)	Flow hydrograph
9	Estuary	DFO Fulford Harbour (7330) and Patricia Bay (7277)	Stage (Downstream)	Stage hydrograph

The downstream boundary condition was based on water levels obtained from the Fisheries and Oceans Canada (DFO) Fulford Harbour (7330) and Patricia Bay (7277) tide gauges. Tidal boundary conditions were created by extracting observed tidal sequences, then shifting the data both in time and stage to match the required return period estimate. The tidal sequence used for the runs was based on the observed values in 2014 at Patricia Bay. This time series was shifted up and timed so that the peak ocean level coincided with the peak of the freshet hydrographs. The ocean boundary conditions were applied at the edge of the model mesh shown in Figure 3.1.

A detailed description of the coastal analyses is provided in the Coastal Assessment and Wave Modelling appendix.

4 MODEL CALIBRATION AND VALIDATION

Model calibration typically forms an important step of hydraulic model development. It involves gradual refinement of model parameters to ensure simulated water levels match observed levels for a particular flood event. Adjusted model parameters often include channel roughness and floodplain roughness, but can also include approximation of channel blockage, scour, or degradation that may have occurred during a particular event. Once variables have been fine-tuned, the model is typically used for simulating a second independent flood event with known flows and observed water levels to validate that the calibrated model is suitable for events other than just the calibrated event. Ideally, information exists for flow conditions similar to that being simulated; that is the model is calibrated and validated for high flows for models to be used to simulate flood flows.

The amount, spatial extent, and accuracy of flow and level data from past floods limits the ability for model calibration and validation. For the current study, the 2021 flood was used for model calibration and the 2020 event was used for validation.

4.1 Roughness Coefficients

Hydraulic roughness coefficients, represented by Manning's n values, strongly influence the computed profile. Care must be exercised to assign appropriate values based on observed highwater marks, technical literature, and professional judgement. Roughness factors account for friction losses resulting from surface roughness, vegetation, channel irregularities (variations in cross section size and shape), obstructions (stumps, roots, logs, isolated boulders) and channel alignment (degree of meandering).

The Chemainus River, Bonsall Creek and Whitehouse Creek were divided into reaches with similar channel bed material, sectional geometry, slope, and plan form. Each reach was then assigned an initial roughness value for the in-channel portion of the reach. These initial roughness values were assigned based on field observations of channel bed composition and verified with values referenced in the literature (A Strickler, 1923; Chow, 1959; Cowan, W.L., 1956; Limerinous, 1970; Wong and Parker, 2006).

The floodplain was assigned varied roughness values based on satellite imagery. The Manning's n roughness coefficients (summarized in Table 4.1) were defined based on land type (Figure 4.1).

Table 4.1 Floodplain Manning's n roughness coefficients with respect to land use type.

Land Use Type	Manning's Roughness Coefficient (n)
Forest	0.065
Agricultural	0.036
Rural	0.065
Urban	0.072
Lake or ponded water	0.024
Wetlands	0.032
Road	0.013

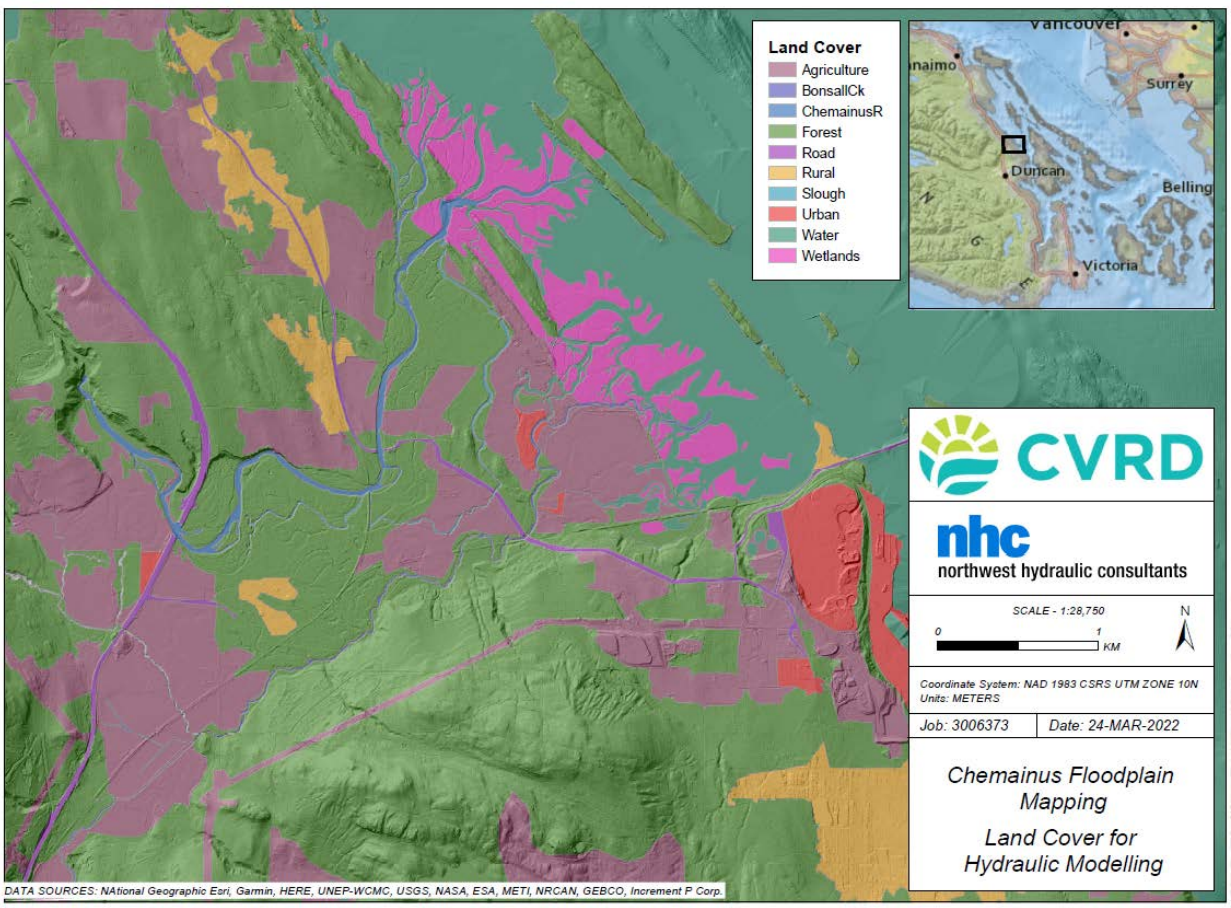


Figure 4.1 Land cover mapping for hydraulic modelling.

4.2 2021 Calibration

Under high-flow conditions channel bars and banks are overtopped, and effective channel roughness can change compared to low-flow conditions. To ensure accurate modeling of the 200-year design flood for floodplain mapping, the hydraulic model was calibrated to the 2021 flood.

The 2021 flood was simulated with the model, and the water surface elevations were compared to the observed HWMs from the 2021 flood survey (Figure 2.1). The channel roughness values were modified until the simulated water surface was found to adequately represent the observed water surface during the 2021 flood.

The final calibrated model's roughness coefficients for each channel is listed in Table 4.2. The agreement between the observed and the simulated water levels at the HWM points has an overall mean absolute error (MAE) of 0.21 m and root mean square error (RMSE) of 0.25m. The median value for calibration was -0.05 m and the average was -0.04 m. A comparison of the observed and simulated WSEs for the 2021 flood is plotted in Figure 4.2 and Figure 4.3.

Table 4.2 Final calibrated in-channel roughness coefficients in the Chemainus River 2D model

Channel	Manning's Roughness Coefficient (n)
Chemainus River	0.035
Bonsall Creek	0.04
Butcher's Slough	0.035
Whitehouse Creek	0.04

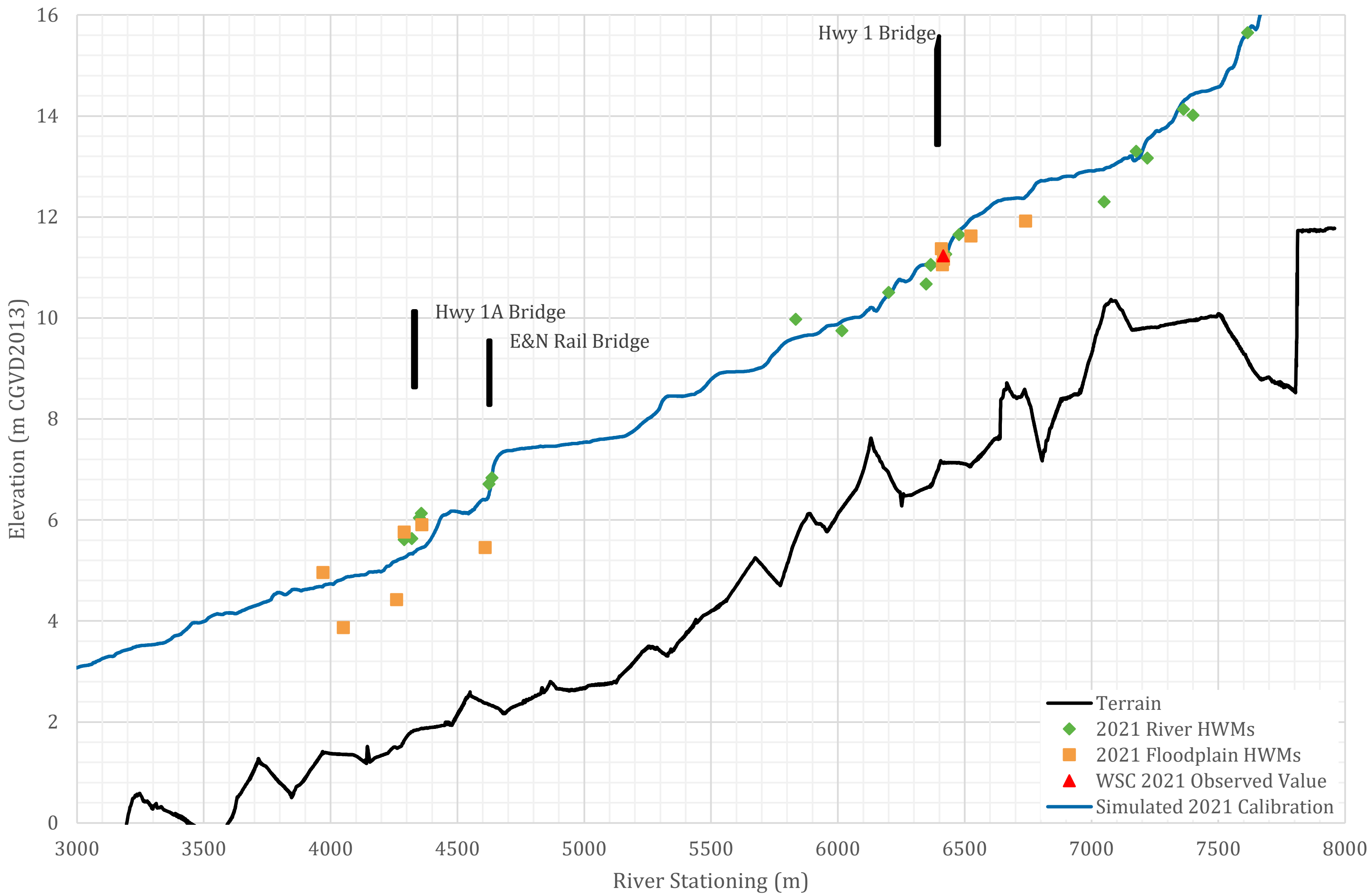
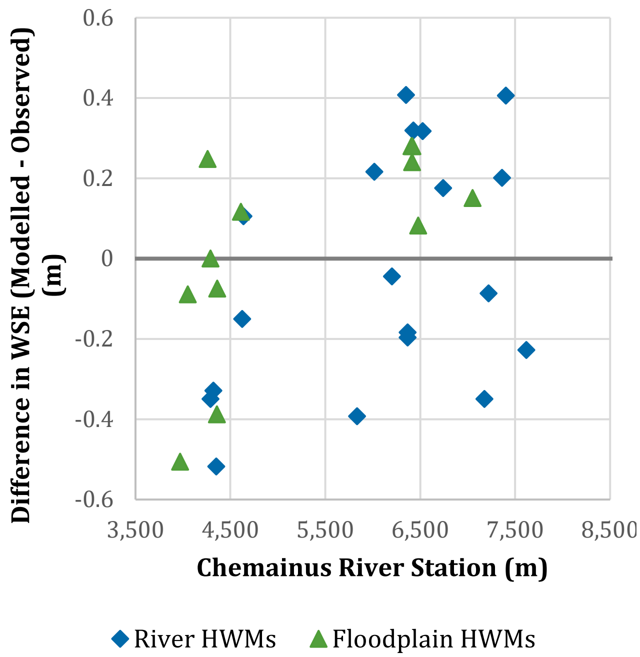


Figure 4.2 Chemainus River calibration profile.



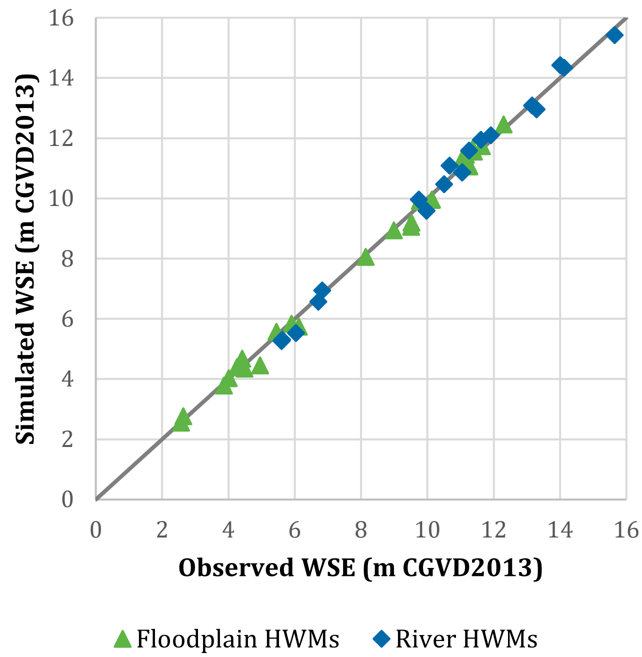


Figure 4.3 A comparison of the observed and simulated WSEs for the 2021 flood. The left plot shows the difference between the observed and modelled along the Chemainus River and the right plot shows the simulated vs the observed for the entire floodplain and river. The diagonal line represents WSEs that are equal or a perfect calibration.

Figure 4.2 and Figure 4.3 illustrate that the model in general shows good agreement with the observed flood. There are points in both the river and floodplain that over and underpredict the water level with no visible pattern or bias. The channel roughness appears to be representative and was not further modified - roughness values selected are appropriate for the flow, channel form, bed texture, and channel slope based on referenced literature and past modelling experience.

Figure 4.2 is also slightly misleading for some HWMs as the water surface varies across the river (superelevation of water surface or local variations) and the profile drawn is on the thalweg of the river. Therefor the water surface elevation at the edge of the river and the middle of the river may not be the same at the same stationing. Figure 4.3 and Table 4.3 show the calculated difference between the observed and the modelled WSE.

Table 4.3 Summary of 2021 flood peak modelled and observed water surface elevations

Location	Channel	Station (m)	Observed WSE (m)	Modelled WSE (m)	Difference (Modelled - Observed) (m)
WSC Gauge - U/S Hwy 1 Bridge, RB	Chemainus	6415	11.23	11.06	-0.17

Location	Channel	Station (m)	Observed WSE (m)	Modelled WSE (m)	Difference (Modelled - Observed) (m)
U/S Hwy 1 Bridge, LB	Chemainus	6525	11.62	11.94	0.32
U/S Hwy 1 Bridge, LB	Chemainus	6740	11.92	12.09	0.18
D/S Hwy 1 Bridge, RB	Chemainus	6366	11.06	10.86	-0.20
D/S Hwy 1 Bridge, RB	Chemainus	6366	11.04	10.86	-0.18
Russel Farms	Floodplain, Chemainus RB	n/a	11.40	11.55	0.15
Hwy 1 Overflow	Floodplain, Whitehouse RB	n/a	10.13	9.94	-0.19
Hwy 1 Overflow	Floodplain, Whitehouse RB	n/a	9.77	9.91	0.14
Hwy 1 Overflow	Floodplain, Whitehouse RB	n/a	10.14	9.96	-0.18
Hwy 1 Whitehouse Bridge	Floodplain, Whitehouse LB	n/a	9.53	9.19	-0.34
Chemainus Rd	Floodplain, Chemainus RB	n/a	9.52	9.05	-0.47
Chemainus Rd Intersection with Westholme Rd	Floodplain	n/a	8.99	8.93	-0.06
Westholme Rd	Floodplain	n/a	8.14	8.05	-0.09
Hwy 1A / Crofton Rd	Floodplain, Chemainus LB	3970	4.96	4.45	-0.51
D/S Hwy 1A Bridge, LB	Chemainus	4290	5.61	5.26	-0.35
U/S Hwy 1A Bridge / Graveyard, LB	Chemainus	4358	6.13	5.74	-0.39
U/S Hwy 1A Bridge – Driveway, RB	Chemainus	4360	5.91	5.83	-0.08
U/S Hwy 1A Bridge, RB	Chemainus	4350	6.04	5.52	-0.52
Crofton Rd, RB	Chemainus	4290	5.76	5.76	0.00
Hwy 1A / Crofton Rd	Floodplain, Chemainus RB	4260	4.42	4.67	0.25
D/S Hwy 1A Bridge, RB	Chemainus	4320	5.63	5.30	-0.33

Location	Channel	Station (m)	Observed WSE (m)	Modelled WSE (m)	Difference (Modelled - Observed) (m)
U/S Rail Bridge, LB	Chemainus	4636	6.84	6.94	0.11
D/S Rail Bridge, LB	Chemainus	4624	6.71	6.56	-0.15
Hwy 1 Overflow, 250m from river	Floodplain, Chemainus RB	6478	11.65	11.73	0.08
RB, close to river	Chemainus	7220	13.17	13.08	-0.09
RB, close to river	Chemainus	7176	13.30	12.95	-0.35
RB, close to river	Chemainus	7362	14.13	14.33	0.20
RB, close to river	Chemainus	7400	14.01	14.42	0.41
RB, close to river	Chemainus	7615	15.65	15.42	-0.23
RB, side channel/avulsion u/s of Hwy1 Bridge	Chemainus	7050	12.30	12.45	0.15
Hwy 1 Overflow, 220m from river	Floodplain, Chemainus RB	6408	11.37	11.65	0.28
U/S at Hwy1 Bridge, LB	Chemainus	6425	11.26	11.58	0.32
D/S at Hwy1 Bridge, LB	Chemainus	6348	10.67	11.08	0.41
D/S Hwy1 Bridge, LB	Chemainus	6200	10.51	10.46	-0.04
D/S Hwy1 Bridge, LB	Chemainus	6016	9.74	9.96	0.22
LB, close to river	Chemainus	5834	9.97	9.58	-0.39
Hwy 1 Overflow, 320m from river	Floodplain, Chemainus RB	6416	11.16	11.44	0.28
Hwy 1 Overflow, 400m from river	Floodplain, Chemainus RB	6412	11.05	11.29	0.24
Field, 430m from river	Floodplain, Chemainus RB	4050	3.87	3.78	-0.09
RB, close to channel	Butcher's Slough	1990	4.27	4.40	0.14
RB, close to channel	Bonsall	2970	4.02	4.03	0.02
RB, close to channel	Bonsall	2985	4.49	4.34	-0.15

Location	Channel	Station (m)	Observed WSE (m)	Modelled WSE (m)	Difference (Modelled - Observed) (m)
LB, close to channel	Bonsall	1976	2.58	2.55	-0.03
LB, close to channel	Bonsall	2294	2.64	2.76	0.12
right side (looking downstream) of Chemainus Rd, RB close to channel	Butcher's Slough	2875	5.45	5.57	0.12
			Root Mean Square Error (RMSE)		0.25 m
			Mean Absolute Error (MAE)		0.21 m

Log Jam at Hwy 1A

While the calibration is good in general, there is poor agreement between the HWMs surveyed at Hwy 1A bridge and the hydraulic model. The model underpredicts the points right at the bridge on the upstream and downstream side (roughly 0.35 m). During the 2021 flood, a log jam was observed to pile up under the bridge on the right bank caught on the historical bridge abutment. It is possible this log jam backs up the river locally at this location. The model was unable to replicate these conditions. Several attempts were made to apply blockages at the bridge to simulate the log jam and while the model was able to get good agreement with the upstream bridge points, it underpredicted the downstream bridge points (upwards of 0.7 m). It was determined that simulating with no blockage and no bridge deck (no 1D bridge routines used at this location) produced the best results at Hwy 1A bridge.

Photo 4.1 Log jam under Hwy 1A bridge on right bank during Nov 15, 2021 flood as seen from bridge looking upstream.

Photo 4.2 Log jam under Hwy 1A bridge on right bank during Nov 15, 2021 flood as seen from right bank looking under bridge from upstream (left) and downstream (right) side.

Rating Curve

From the WSC gauge within the study reach, the reported rating curve was compared with a similar curved developed from the hydraulic model. It is unknown exactly where WSC collects the data points at low flow when they are able to cross the river and at high flows the discharge measurements are collected from the bridge. At high flows, the bridge is at a slight skew to the flow. The rating curve from the model was exacted perpendicular to the flow under Hwy 1 bridge. Therefore, comparisons with the gauge data were reviewed, but not directly used for model calibration or validation. Figure 4.4 illustrates its reasonable comparison for moderate flows, but divergence for the more extreme flows, which are likely to have less physical flow measurements used for curve development.

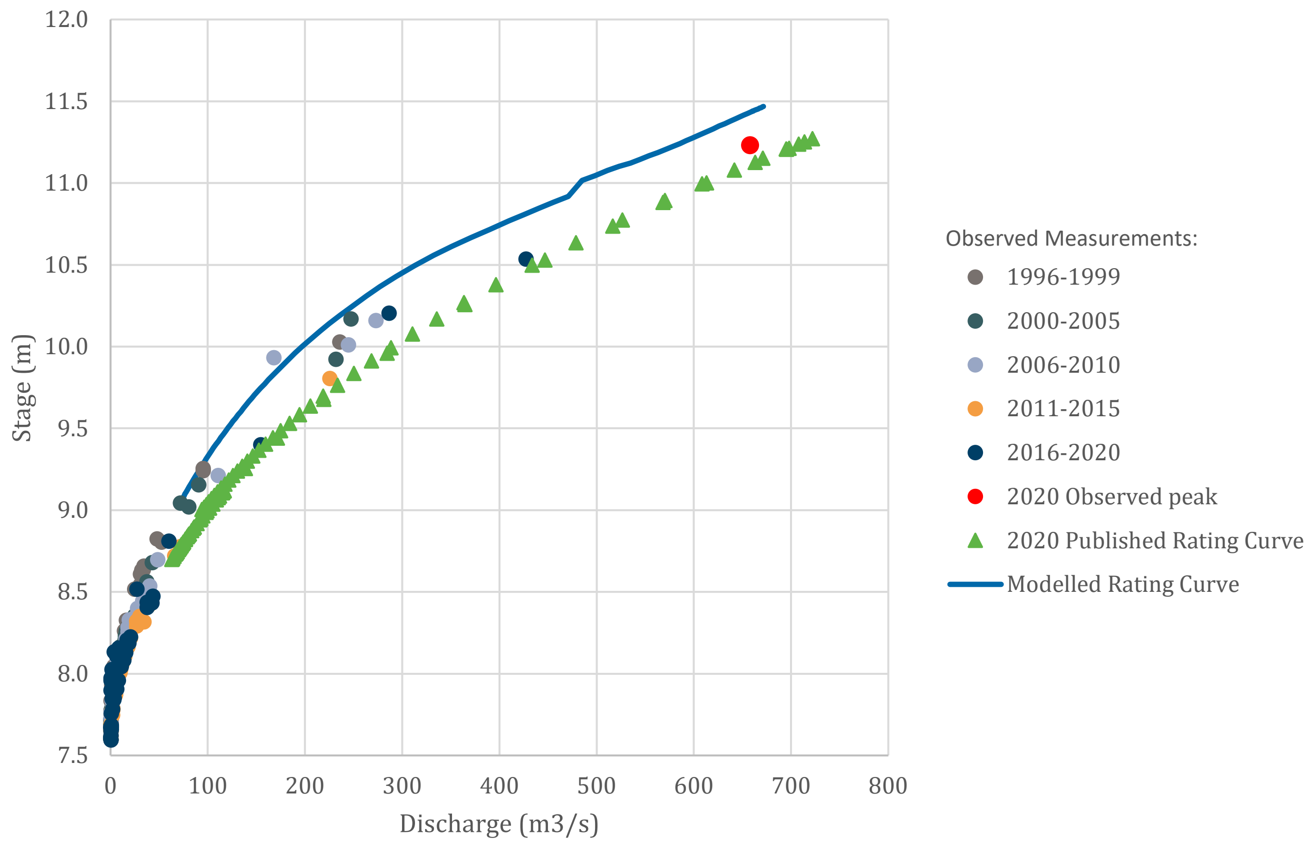


Figure 4.4 Observed measurement points, published 2020 rating curve and simulated rating curve for 08HA001 – Chemainus River Near Westholme WSC gauge.

4.3 2020 Validation

The calibrated model was also run with the boundary conditions from the 2020 flood to validate the model against the HWMs that were collected in the field during the initial surveys. There is higher uncertainty with HWMs that are collected over a year and a half after a flood event. Any intermediate flood events or storms can wipe out past evidence of a flood. The profile of the validation is shown in Figure 4.5. While many of the points are well below the modelled profile, we still have high confidence in the hydraulic model. The 2021 event was very similar in size to the 2020 event and the HWMs collected in the field during the 2021 event support the higher profile compared to many of the 2020 HWMs. The WSE reported at the WSC gauge supports the validation profile modelled, and there are several points collected that agree well with the profile. It is possible that many of the lower HWMs were from a lower event that occurred after February 2020 or from the receding limb of the flood event when the water was dropping. Without observing or having real time measurements, we can not be certain of the HWMs and place less credibility on them as a result.

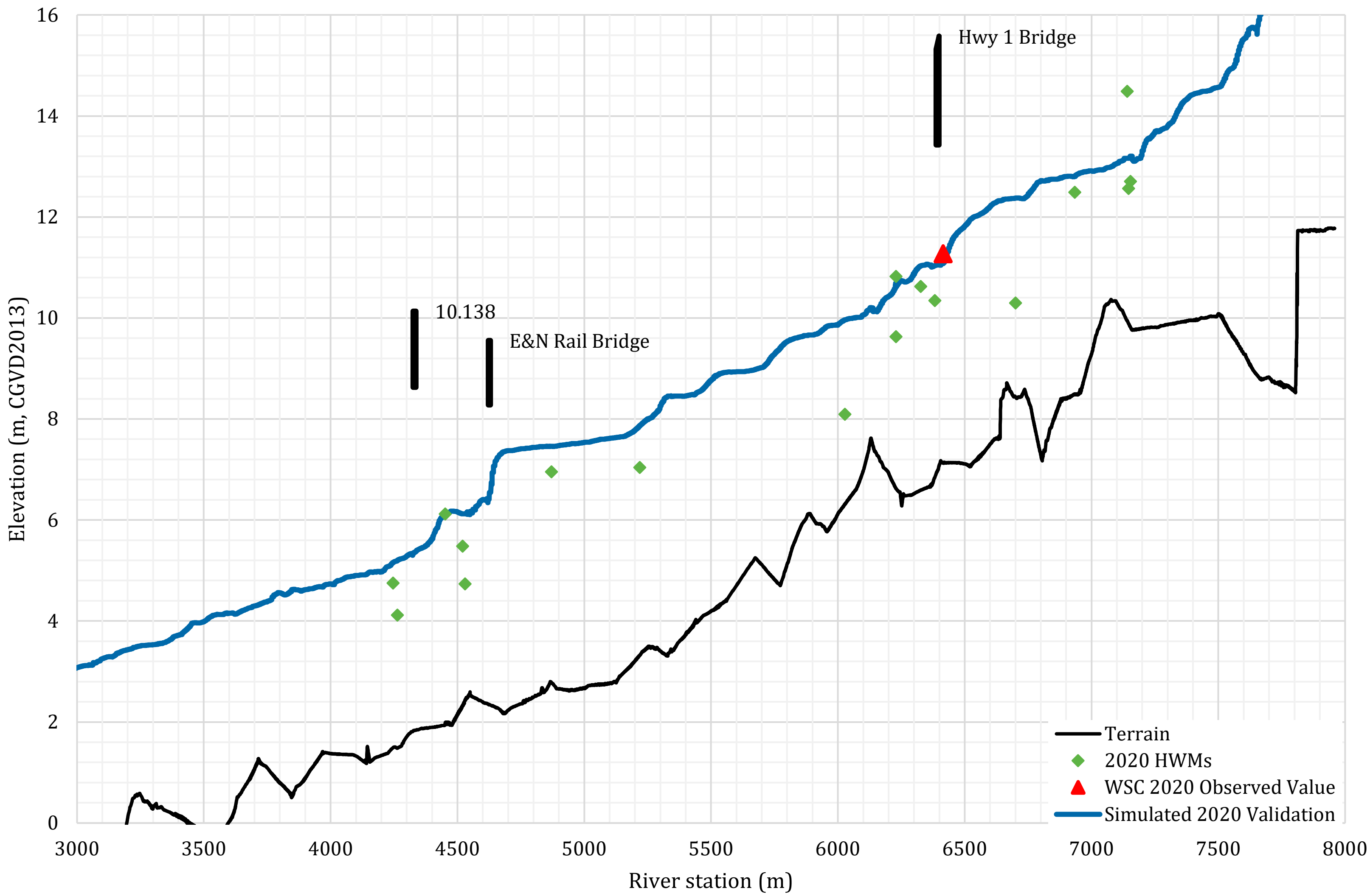


Figure 4.5 Chemainus River validation profile.

4.4 Model Calibration Summary

The collection of HWM data during the 2021 flood was invaluable to the calibration of the Chemainus River hydraulic model. The flood was the second largest on record and the data was collected by NHC using best survey practises for flood conditions during the peak of the flood. Photos and videos were also taken to support the calibration process. The high confidence in the survey values and the distribution of HWMs across the floodplain created some of the best conditions possible for model calibration. The Chemainus River hydraulic model calibrated very well over all to the observations and will be an essential flood management tool.

5 MODEL SUMMARY AND RESULTS

Present day design flow as well as future climate change conditions were simulated. Design flows correspond to the 200-year return period flow for each watercourse, with a 20-year ocean level. A 20% flow increase was added to approximate climate change (CC) in the year 2100. For the tidal boundary, a sea level rise allowance of 1.0 m was added to the climate change 2100 ocean level. A design run of a 200-year ocean level with a 20-year river level for the year 2100 was also completed, since this event was determined to have approximately the same return period as the former. The greater WSE of the two runs was used for the flood mapping. Additional information is provided in the hydrology and coastal appendices.

These two design runs were repeated for modelled railway breaches, which were constructed in November 2021. Results from these design runs are preliminary, as final construction for these breaches has not been completed. It is anticipated that culverts will be placed at these locations however, the configuration is unknown at this time. These locations were modelled as open breaches, which would provide the more extreme conveyance of flood waters and therefore yield more conservative estimates for WSE west/downstream of the railway.

The dike-like structures, namely the railway, within the Chemainus River 2D model were assumed to remain intact throughout the entire simulation period in all the run scenarios. No dike failure simulations were conducted. Flood depths and extents simulated by the base runs may differ from actual conditions significantly if a dike or similar were to fail. Table 5.1 summarizes design runs used for the Chemainus hydraulic model. The design profiles associated with the following design flows is shown in Figure 5.1. As is seen in the profile, the area impacted by the Rail breach is limited to the backwater area immediately upstream of the rail bridge. The breaches reduce the flood profile in the river in this location up to 0.1 m.

Table 5.1 Design flood inflows for the Chemainus floodplain.

Flow Conditions	No.	Scenario	Upstream boundary conditions – Peak Flow				Downstream boundary conditions – Peak Ocean Level	
			Return Period	Chemainus River (m^3/s)	Bonsall Creek (m^3/s)	Whitehouse Creek (m^3/s)	Return Period	Ocean level (m CGVD2013)
CC 2100	1	Q200 | 20-yr SWL	200-yr+CC	1197	23.8	11.2	20-yr + 1.0 m SLR	3.35
	2	Q20 | 200-yr SWL[1]	200-yr+CC	889	17.8	8.4	200-yr + 1.0 m SLR	3.48
CC 2100	3	Q200 | 20-yr SWL | Rail breach	200-yr+CC	1197	23.8	11.2	20-yr + 1.0 m SLR	3.35
	4	Q20 | 200-yr SWL[1]| Rail breach	200-yr+CC	889	17.8	8.4	200-yr + 1.0 m SLR	3.48

Notes:
1. SWL is Still Water Level. See Appendix D: Coastal Modelling for description of how ocean level was calculated.
2. SLR is Sea Level Rise.

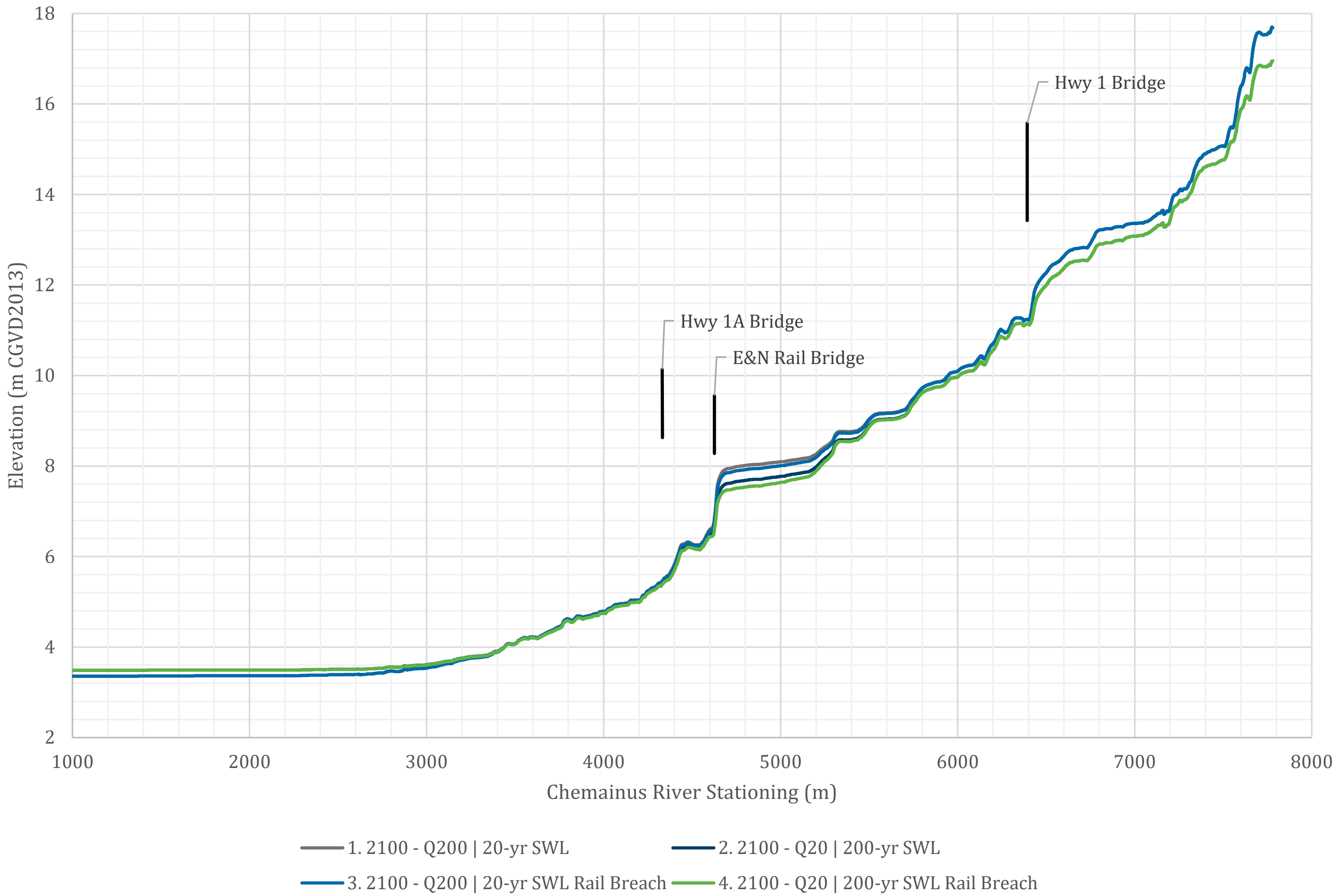


Figure 5.1 Chemainus River design water surface profiles.

6 MODEL SENSITIVITY

The simulated model results (i.e. the flood level) are primarily dependent on the channel geometry and flow. Other model parameters can however also influence the results, such as:

- Inflow,
- Downstream boundary condition, and
- Channel roughness values.

Values for these parameters were varied within a reasonable range to assess the model's sensitivity to certain inputs.

The 200-year design flood inflow was simulated with and without climate change impacts (20%). The resulting water level profiles were compared with the design water level profile to determine which areas of the river are sensitive to discharge. The water levels varied on average by 0.1 m, with a couple of isolated variations up to 0.2 m in backwater areas near the bridges (Figure 6.1). It was observed that the more water supplied to the river, the more water diverted to the floodplain. The right bank upstream of Hwy 1 is low enough that larger volumes of water just pass over it onto the floodplain. Therefore, it appears the river itself is relatively insensitive to discharge increases with little changes in the profile. However, this means that greater discharges (including increases predicted for the future) will spill more water to the floodplain, potentially impacting more people.

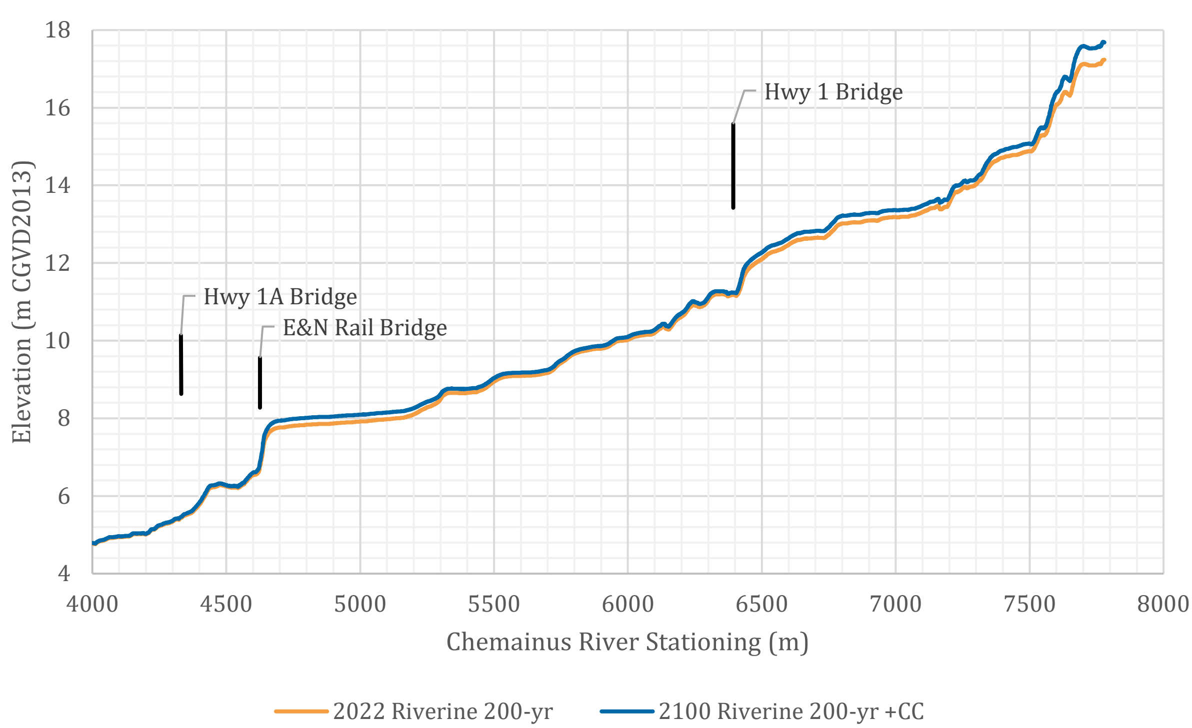


Figure 6.1 Sensitivity of hydraulic model to changes in inflow

The tidal boundary condition in the estuary was simulated with and without the impacts of sea level rise (SLR)under flood conditions to see how far upstream the effects of estuary can be seen (Figure 6.2). Results show that the tidal influence during a flood can be seen up to 2.4 km under regular tides in flood conditions and up to 3.7 km when 1 m SLR is applied. Therefore, under future conditions tides will be seen further upstream in regular yearly flows and will have more impact to properties in and near the estuary.

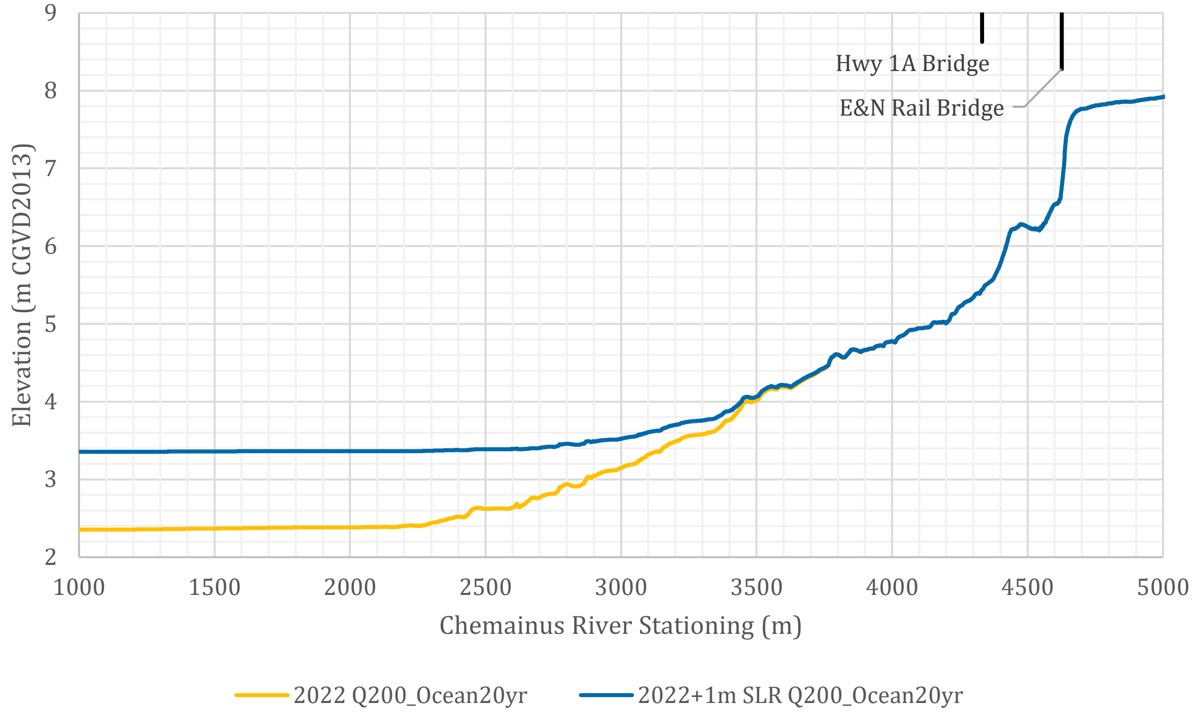


Figure 6.2 Sensitivity of hydraulic model to increase in ocean conditions

The channel roughness values were varied by +/- 25%. The results demonstrated that uncertainties in defining channel roughness could typically result in changes in design water level of less than or equal to 0.05 m and no more than 0.3 m. The Chemainus River downstream of KM 7 is insensitive to the roughness coefficients because so much of the flow is conveyed on the floodplain. If the channel roughness is increased, more water is pushed onto the floodplain and the water surface elevation in the channel doesn't really change. The floodplain acts as a regulator for the channel. Upstream of KM 7 however, more sensitivity can be observed (water is confined) and changes in the 0.2 – 0.3 m can be observed (Figure 6.3).

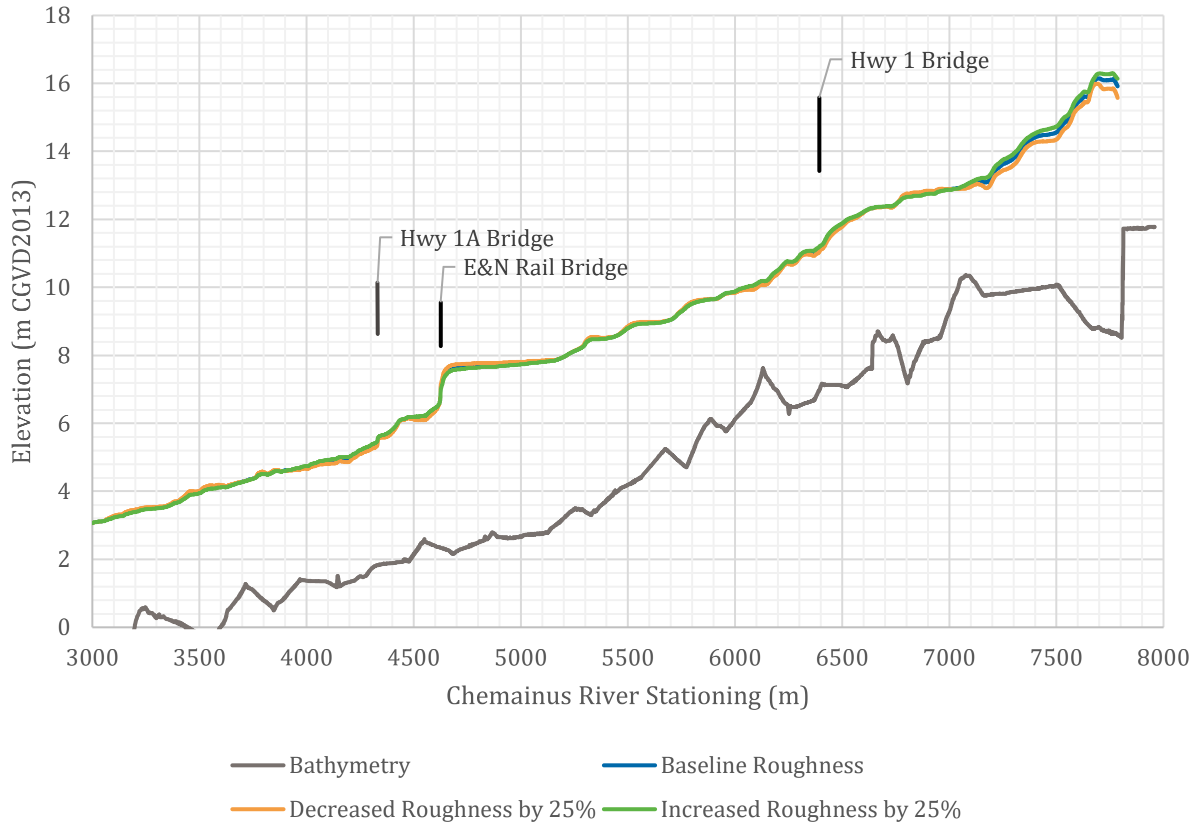


Figure 6.3 Sensitivity of hydraulic model to change in roughness coefficients

7 MODEL LIMITATIONS

The hydraulic model developed is based on mathematical equations that attempt to simulate complicated real-world hydraulics. Naturally, there is a difference between the simulations and real-world dynamics. Some inherent limitations of the Chemainus River 2D model are discussed below.

1. The basic assumptions and limitations of Hec-Ras are described in Section 3.1.
2. Uncertainties in survey data for bathymetric, topographic and lidar data are discussed in Appendix A.
3. Although specified to contain bare-earth data, the LiDAR used for developing the DEM may contain some artificial high points, especially in areas where vegetation is dense, creating unrealistic “dry spots” for some floodplain simulations.
4. There is limited or no bathymetry available in some tributaries and small channels (e.g. Butcher’s Slough, Whitehouse Creek, etc.), which thereby underestimates the conveyance capacity of these water bodies.

5. The models do not account for seepage, local drainage from small creeks and ditches, direct precipitation behind dike-like structures, groundwater draining from upslope areas, or springs. Therefore flood extents may be different than those modelled.
6. There are inherent uncertainties associated to the calibration and validation data. For example, due to data availability limitations, the validation event selected for the 2D model had a high degree of uncertainty for the HWM locations and elevations, which caused a poor model agreement to “observed” results.
7. The models represent channel and floodplain conditions at the time of LiDAR and survey collection. This has significant implications in model use for two reasons:
    a. A significant change in the railway line occurred in November of 2021 when two breaches of the berm-like structure were created. The railway acts to retain flood flows on the east/upstream side. Breaching this feature caused flood risk to be transferred downstream. This occurred following model calibration / validation.
    b. Topographic changes in the channel and floodplain will occur over time either due to natural ongoing changes (floods etc.) or as a result of activities like gravel removal, building of dikes or new bridges, etc. Such changes will lead to water level differences and updating of the model will be required.
8. While attempts were made to model future climate conditions, a high degree of uncertainty surrounds present predictions. Projected precipitation increases were translated directly into a discharge increase and no detailed climate change projections were undertaken. See the Hydrology appendix for details.
9. The model was developed with HEC-RAS software v.6.1. Future versions may affect the model results to some degree. An updated version would have some coding optimizations that may change the results, particularly for this 2D model. However, the differences, if any, would be expected to be minor.

Despite the above limitations, the model developed is considered robust for its intended use and forms a useful tool for modelling various flow conditions in the Chemainus River and floodplain.

8 CONCLUSION

The Chemainus River experienced its second flood of record and second big flood in two years in November 2021. This flood occurred within the timeframe of this study which allowed NHC to be in the relatively unique situation of being able to collect comprehensive observations of flooding over the entire floodplain region during the flood. This extremely recent and relevant observation data combined with current up to date topography (both lidar and bathymetry) provides a very strong basis for developing and calibrating a 2D hydraulic model. In the past, flood mapping investigations are forced to use data that is outdated or does not reflect current conditions which increases uncertainty in calibration. This limits the overall accuracy of the models for estimating more extreme design flood levels and flood extents. The hydraulic model developed for Chemainus River is very strong and the calibration values should be a reasonably good representation of the actual predictive accuracy of the model.

9 REFERENCES

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APPENDIX E

COASTAL MODELLING

APPENDIX E:
COASTAL MODELLING

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

CD	Chart Datum
CGVD2013	Canadian Geodetic Vertical Datum of 2013
CHS	Canadian Hydrographic Service
DFL	Design Flood Level
DFO	Fisheries and Oceans Canada
EC	Environment Canada
FCL	Flood Construction Level
FCRP	Flood Construction Reference Plane
FLNRORD	Ministry of Forests, Lands, Natural Resource Operations & Rural Development
HHWMT	Higher High Water Mean Tide
HHWLT	Higher High Water Large Tide
LLWMT	Lower Low Water Mean Tide
LLWLT	Lower Low Water Large Tide
MoE	Ministry of Environment
MWL	Mean Water Level
SLR	Sea Level Rise
SWAN	Numerical Wave model, Simulating WAves Nearshore

1 INTRODUCTION

The coastal flood level within the Chemainus Estuary may be assessed (along with the riverine flood level) and used to derive a minimum construction level for habitable floors, which is known as the Flood Construction Level (FCL). The FCL provides a mitigation measure to limit the likelihood of flooding for developments located within floodplains and along coastlines.

This Appendix summarizes the methodology used to calculate the coastal FCL for the Chemainus Estuary for the year 2100. Key guidelines and regulations referenced as part of this assessment are provided in Section 2. Our project approach to calculating coastal FCLs is discussed in Section 3, with reference to key guidelines and regulations. The meteorological and oceanographic (metocean) setting is defined in Section 4. Wave model methodology and results are provided in Section 5. FCL calculations, including calculation of wave run-up and discussion of freeboard allowance, are described in Section 6. Limitations of this assessment are discussed in Section 7. A full list of references are provided in Section 8.

2 REFERENCE GUIDELINES & REGULATIONS

The following key guidelines and regulations were reviewed and are referenced as part of this study:

- Flood Hazard Area Land Use Management Guidelines (MWLAP, 2004) and Amendment Section 3.5 and 3.6 (MFLNRORD, 2018)
- Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC (EGBC, 2018)
- Professional Practice Guidelines – Flood Mapping in BC (EGBC, 2017)
- Climate Change Adaptation Guidelines for Sea Dikes and Coastal Flood Hazard Land Use (BC MoE, 2011a,b,c)
- Coastal Floodplain Mapping Guidelines and Specifications (MFLNRORD & KWL, 2011)
- EurOtop Manual on Wave Overtopping (EurOtop, 2018)

3 APPROACH TO COASTAL FCL CALCULATIONS

For residential properties, the FCL is generally based on an event with a 1-in-200 year probability of occurrence. For more densely populated areas, it may be appropriate to use a less probably 1-in-500 year event. In addition, changes due to future climate change must consider up to the year 2100 (roughly 80 years from present) or farther.

The BC Ministry of Environment (MoE) guidelines (BC MoE, 2011b) and the BC Ministry of Forests, Lange, Natural Resource Operations and Rural Development's (FLNRORD) amendment of the Flood Hazard Area

Land Use Management Guidelines (MFLNRORD, 2018) present two approaches for determining the 1-in-200 year Coastal FCL using the (1) combined method and (2) probabilistic method:

- Combined: Designated event based on simultaneous occurrence of the Higher High Water Large Tide[1] (HHWLT) elevation and the estimated 1-in-200 year storm surge.
- Probabilistic: Designated event as determined by a probabilistic analysis of tides and storm surge with a joint 1-in-200 year probability of occurrence. The probabilistic method considers the joint probability of storm surge and high tide occurring simultaneously.

The combined method also tends to be more conservative than the probabilistic approach, and hence provincial guidelines (MFLNRORD, 2018) allow use of a reduced freeboard for mitigation based on this method. The difference in freeboard allowance applied to each method results in their determinations of FCL often having similar elevations. Regardless, the probabilistic approach is generally understood to result in a more precise estimation of the probability of extreme water levels than the combined method. NHC has utilized the probabilistic method for this study, which has the added benefit of maintaining consistency with other recent Flood Mapping studies, such as the nearby *Cowichan-Koksilah Flood Mapping Project* (NHC, 2021)

Following this approach, the coastal FCL may be calculated as the sum of the following components:

- 1-in-200 year water level as determined by probabilistic analyses of tides and storm surge
- Wind set-up
- Allowance for local relative sea level rise to the year 2100

Designated Flood Level (DFL)

- Estimated wave effects associated with the 1-in-200 year storm

Flood Construction Reference Plane (FCRP)

- Freeboard

Flood Construction Level (FCL)

4 METEOROLOGICAL AND OCEANOGRAPHIC SETTING

4.1 Vertical Datum

For the purpose of this report, elevations (including water levels) are referenced to the Canadian Geodetic Vertical Datum of 2013 (CGVD2013) unless stated otherwise. Note that the following formulas can be used to convert elevations between CGVD2013 and the Canadian Geodetic Vertical Datum of 1928 (CGVD28)[2] and Chart Datum[3] at the project site:

$$Elev_{CGVD2013} = Elev_{CGVD28} + 0.15 \text{ m}$$
$$Elev_{CGVD2013} = Elev_{CD} - 2.35 \text{ m}$$

[1] HHWLT values are defined in Canadian Hydrographic Services (CHS) tide tables.

[2] CGVD28 is based on HT2 hybrid geoid model, Epoch 1997 of NAD 83 (CSRS).

[3] Chart Datum references the lowest normal tide (0 m tide) meaning it will only rarely will the tide fall below this elevation.

4.2 Astronomical Tides

Astronomical tide elevations are published in the Canadian Hydrographic Service (CHS) Canadian Tide and Current Tables for various reference ports in Canada. Predicted tidal elevations[4] for the project site are provided in Table 1.

Table 1 Summary of tides at the project site (CHS, 2021)

Description	Tide Elevation (m, Chart Datum)	Tide Elevation (m, CGVD2013)
Higher High Water Large Tide (HHWLT)	4.05	1.70
Higher High Water Mean Tide (HHWMT)	3.65	1.30
Mean Water Level (MWL)	2.50	0.15
Lower Low Water Mean Tide (LLWMT)	1.00	-1.35
Lower Low Water Large Tide (LLWLT)	-0.10	-2.45

Notes:
1. HHWLT represents the average of the highest high waters, one from each of 19 years of predictions.
2. HHWMT represents the average of all the higher high water levels (i.e. daily high tides) in the same period.
3. MWL is the average hourly water level and corresponds approximately to CGVD28 or Mean Sea Level (MSL).

4.3 Joint Occurrence of Tides and Strom Surge

Storm surge is the rise in water level due to atmospheric effects (such as wind stress and reduced atmospheric pressure) above the normal tidal level. Storm systems (which produce storm surge) and tidal levels are independent events. NHC previously estimated the joint probability of storm surge and tides based on the nearby Patricia Bay water level observation station (where a long, continuous observation record is available) (NHC, 2021). The water level record includes both the astronomical tide cycle and non-astronomical effects (which are typically comparable to the storm surge level)[5]. A total of 45 years of data (1976 to 2020) was recorded at the station and analyzed. During this time, the highest recorded water level at Patricia Bay was 2.22 m CGVD2013 (0.68 m above HHWLT) on December 16, 1982.

As part of the previous work completed by NHC (2021), an extreme value analysis (EVA) was conducted on the Patricia Bay water level record considering several methods to determine a best fitting probability distribution; tested distributions included annual maxima (Gumbel and GEV distributions) and peak-over-threshold (GPD) methods. Water levels[6] were converted from Patricia Bay to the project site based on high-tide tidal conversions published by CHS[3].

[4] CHS publishes tidal elevations for the Fulford Harbour Primary Reference Port and tidal differences for the Secondary Ports of Chemainus and Crofton, which have been averaged and used to estimate the tidal elevations expected at the project site.

[5] Non-astronomical effects may be due to storm surge and wind/wave setup. At the Patricia Bay station it is expected that non-

[6] Based on extreme value analysis using the 95% Confidence Interval Annual Maxima (GEV).

Table 2 Joint occurrence of tides and surge in Chemainus

Return Period (Years)	Joint Tide and Surge Level (m, CGVD2013)
2	2.10
10	2.29
20	2.34
50	2.40
100	2.44
200	2.47
500	2.51

4.4 Sea Level Rise

Sea level rise (SLR) is the combined effect of global sea level changes and local land subsidence or uplift. Global sea level rise is the product of a changing climate, associated with increased global ice melt and ocean volumes (due to thermal expansion). Local changes in the land elevation are the result of isostatic rebound due to the historical retreat of glaciers, tectonic uplift, and sediment consolidation.

4.4.1 Global Sea Level Rise

Based on worldwide tide gauge records, global sea level has risen more than 0.2 m since the late 19th century (Thomson et al. 2008). However, since the early 1990's the rate of sea level rise has continuously increased beyond historical levels, from approximately 2.3 mm/yr in the 1990's to 4.6 mm/yr in the 2010's[7]. The rate of future SLR is expected to increase further in the later portion of the 21st century. Projections of the rate and overall magnitude of future sea level rise vary greatly depending on the considered emissions scenarios and the limitations of SLR models being used. Regardless, it is widely predicted that between 0.2 to 0.3 m of global SLR will occur by 2050 [8,9] (Oppenheimer et al., 2019). The variance in SLR predictions is significantly larger for the later half of the century, with estimates presently ranging between 0.5 to 1.8 m for year-2100[10] (Oppenheimer et al., 2019). In addition, more recent studies that include physical ice sheet processes (such as structural collapse and undercutting by warm ocean waters) predict significantly higher levels of SLR, far exceeding 2.0 m by year-2100 under certain scenarios (e.g. DeConto & Pollard, 2016; Hansen et al., 2016).

[7] Based on analysis completed by NHC using data available through the NASA portal (https://climate.nasa.gov/vital-signs/sea-level/) from Frederikse et al., 2020.

[8] Beyond the year 2000 reference levels

[9] Based on ensemble mean estimates, with the likely range (17 – 83 % Confidence Interval) for all RCP's between 0.2 – 0.4 m.

[10] Based on the ensemble mean estimates for emissions scenarios RCP 4.5 and RCP 8.5, which appear likely based on current sea level trends.

In 2011, the Province of British Columbia published guidance on the recommended allowance of global SLR for planning and design. The recommended allowance for global SLR was 0.5 m for year-2050 and 1.0 m for year-2100, based on year-2000 reference levels (BC MoE, 2011b). Based on the current available science, the recommendations appear to over-predict SLR in the short term (i.e. 0.5 m for year-2050) and potentially underpredict SLR in the long-term (i.e. year-2100 onward).

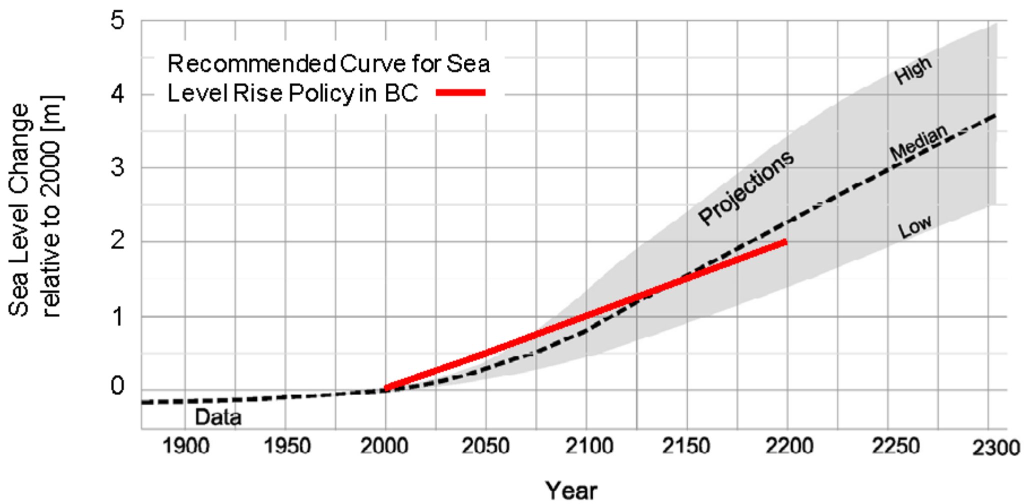

Figure 1 **Recommended allowance for sea level rise in BC Ministry of Environment Climate Change Adaptation Guidelines (BC MoE, 2011b)**

As the century progresses, global SLR projections and government guidance will continue to be adapted to reflect realized attempts to mitigate emissions, increased data collection, improved climate models, and improved scientific understanding. The provincial guidance has not yet been updated to address observations and updated predictions since 2011. Regardless, it seems that global SLR of between 1.0 to 2.0 m is almost certain, but the timing is still unclear. Future rates of climate change are partially influenced by future human behaviour, and thus the high levels of uncertainty with regards to timing.

For the purpose of this assessment, the recommended 1.0 m of global sea level rise by year-2100 has been considered (BC MoE, 2011b). Note, that the rate of SLR is projected to increase as the climate warms; therefore, any increase over the past 20 years (since the year-2000 reference levels) is expected to be minimal and was hence excluded.

4.4.2 Local Vertical Land Movement

The BC MoE (2011c) provides rates of uplift/subsidence at various stations across BC. The closest relevant station to the project site is located directly north of the Chemainus River Estuary on Bare Point (east side of Chemainus Bay):

- Chemainus GPS: +2.0 mm/year

These observation at the Chemainus GPS suggest that the region may experience 2 mm of uplift per year, or 0.20 m of uplift by year-2100[11]. However, there are large uncertainties surrounding the expected local vertical land movement within the Chemainus River Estuary, which is comprised of soft and recently deposited sediments often subject to consolidation and subsidence. For example, portions of the Fraser River Estuary are subsiding on the order of -2 mm/year BC MoE (2011c).

4.4.3 Local Relative Sea Level Rise Allowance

The local relative SLR allowance considered for this project is included in Table 3. Uplift has not included due to the uncertainties surrounding estimates of global SLR and potential subsidence of the Chemainus River Estuary.

Table 3 Local relative sea level rise allowances

Sea Level Rise Scenario	Year	Global SLR (m)	Uplift (m)	Local SLR (m)
1	2021	0.00	0.00	0.00
2	2100	1.00	0.00	1.00

4.5 Winds

The central Strait of Georgia is characterized by severe winds oriented in the NW-SE direction, corresponding to the orographic forcing in the Strait of Georgia (Thomson, 1981). Strong winter storm events result in frequent southerly and southeasterly winds blowing up the Strait of Georgia. Winter outflow conditions also result in severe, but generally less frequent, northerly and northwesterly winds blowing down the Strait.

Most of the region is not exposed to severe wind-generated waves due to the presence of the Gulf Islands (Including Valdes, Thetis, Galiano, and Saltspring Islands), which shelter the region from the larger waves generated in the Strait of Georgia. However, significant waves may still be generated throughout Stuart Channel. Fetch lengths (the distance which wind can blow unimpeded across water) are up to 25 km.

Winds capable of generating waves at the project site are explored and defined in this section.

4.5.1 Wind Data

Environment Canada (EC) and the Department of Fisheries and Oceans (DFO) operate several wind stations (anemometers) that help characterize the wind climate within the central Strait of Georgia. The local and regional wind climate were analyzed from eleven wind stations, as shown in Figure 2. Notably, there are no known anemometers within Stuart Channel, directly offshore of the project site. The closest

[11] Relative to the year 2000 reference levels as per MOE, 2011.

station – north Cowichan – is located too far inland to be an accurate proxy for winds that generate waves overwater, and was thus not included in the analysis. In addition, the nearby Georgia Strait and English Bay wave buoys were only installed in 2021 and do not yet have historical data available publicly online.

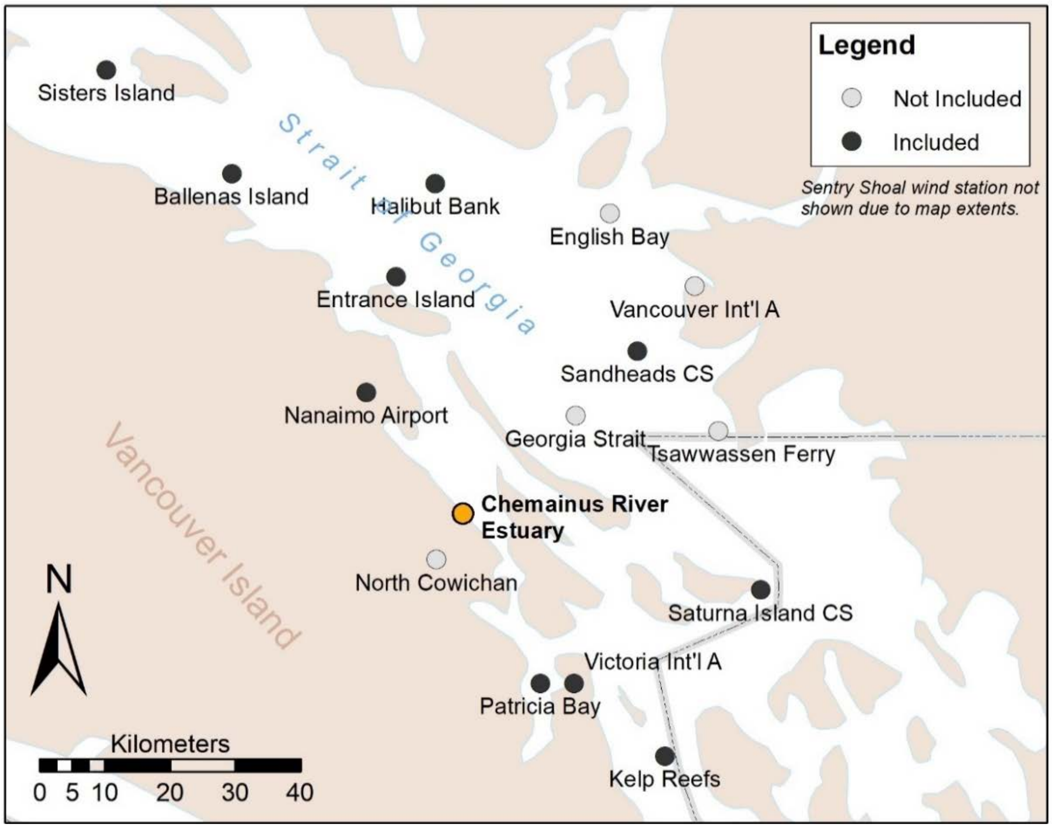

Figure 2 Local wind stations considered for this study. Black circles indicate nearby stations included in the wind analysis. Grey circles include nearby stations not included due to data quality, length, topography, or proximity concerns.

4.5.2 Wind Speeds and Directions

Observed wind speed magnitudes were transformed to the standard 10 m elevation wind speed (U_{10}), based on the common exponential wind profile assumption. To characterize wind events, a wind rose was developed for Halibut Bank (Figure 3), which has an extensive and continuous observation record. From the wind rose, it can be seen that the region experiences wind largely in a NW-SE direction.

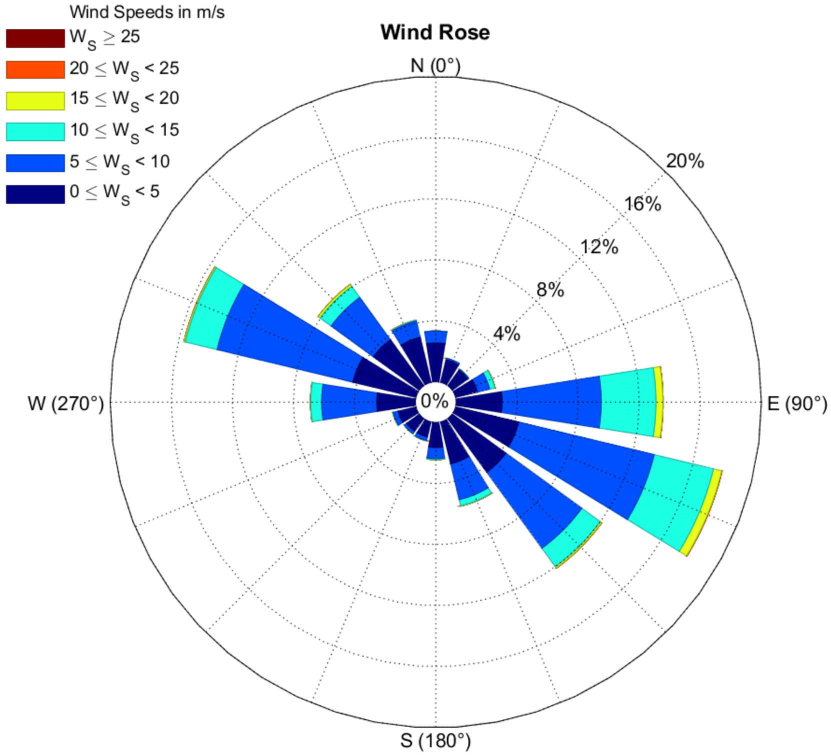

Figure 3 Wind rose for Halibut Bank

Return periods[12] for extreme wind events were also estimated (Table 4). As the Chemainus River Estuary has an easterly exposure, wind speed data was split into northerly, easterly, and southerly quadrants[13], and westerly winds were omitted from the analysis.

Climate change is expected to result in variations to global weather patterns (IPCC, 2013). In the Strait of Georgia, changes to the magnitude, frequency, and duration of storm events are possible as regional ocean, air, and land temperatures change in the future. Ausenco-Sandwell (BC MoE, 2011a) analysed local weather and wave data against a calibrated global and regional atmospheric-oceanographic model, and found that no significant changes to wind and waves were expected in coastal BC waters. Regardless, predicted changes are highly variable and no conclusive studies are available at the time of writing this report. There is presently little information available for this region to justify adaptations to the design wind characteristics to account for the rates and magnitudes of these changes. As such, no modification to the design wind speed or direction has been made to account for climate change.

Note that coastal FCL's must consider winds associated with a 1-in-200 year water level. However, based on extensive experience by NHC in the region, peak winds and peak water levels do not generally coincide. Because of this it is overly conservative to consider a 1-in-200 year wind speed occurring concurrently with a 1-in-200 year water level. In previous analyses (e.g. Lanarc and NHC, 2019) we have

[12] Based on the mean value, using a Weibull distribution with coefficient, k, between 1.0 – 1.4, to achieve a best fit.

[13] For the purpose of the wind analysis, northerly is defined as 315° – 45°, Easterly is defined as 45° – 135°, and Southerly is defined as 135° – 225°.

found that the governing scenario with a total 1-in-200 probability is actually closer to a 1-in-20 year wind speed corresponding with a 1-in-50 year water level, or vice versa. However, for this project site, there is significant uncertainty related to the coincidence of wind speeds and water levels due to a lack of locally available data. As such, the 1-in-50 year wind field is considered to occur simultaneously with the 1-in-200 year water level for this project (see Section 4.3 for further discussion).

Table 4 Wind speed return periods at Halibut Bank

Return Period (Years)	Quadrant		
	Northerly	Easterly	Southerly
2	17.3	20.7	18.1
10	20.1	22.4	20.0
20	21.5	23.2	20.7
50	**23.2**	**24.2**	**21.6**
100	24.5	25.0	22.2
200	25.8	25.7	22.8
500	27.4	26.7	23.5

4.5.3 Wind Fields

Severe historical storms with the dominant wind direction from each of the three considered quadrants were identified (see Table 5). These events were used as a basis to develop synthetic wind fields with the required return periods (scaled to match the return period at Halibut Bank) and realistic spatially varied wind field characteristics (based on the wind speeds and wind directions at the other nearby wind stations). Synthetic wind events with 1-in-50 year return period at Halibut Bank were developed for northerly, easterly, and southerly quadrants (see Figure 4 - Figure 6).

Table 5 Historical wind events as observed at Halibut Bank

Quadrant	Date	Wind Speed (m/s)	Wind Direction (o^{TN})	Return Period (Years)	Wind Speed Scaling Factor 1-in-50 year
North	2007-Jan-05	24.67	316	110	0.94
East	2010-Apr-02	24.43	118 [1]	60	0.99
South	2018-Dec-20	20.76	180	20	1.04

Notes:
1. Wind directions for easterly events were adjusted -30º to develop synthetic wind event more representative of strong easterly conditions.

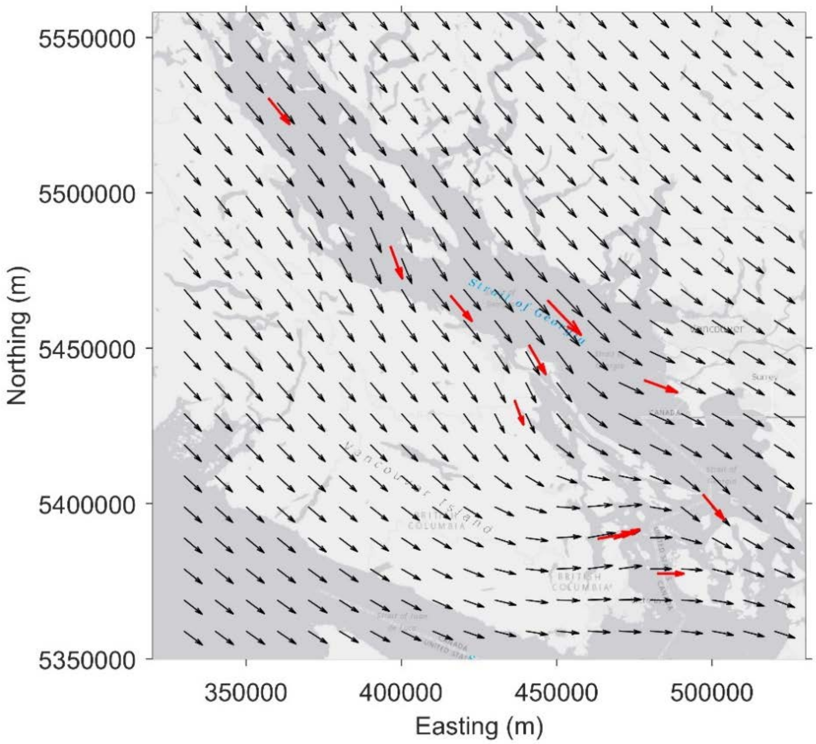

Figure 4 **Synthetic wind field during a northerly wind event (modelled after 2007-Jan-05 storm). Red arrows indicate local wind stations considered in analysis.**

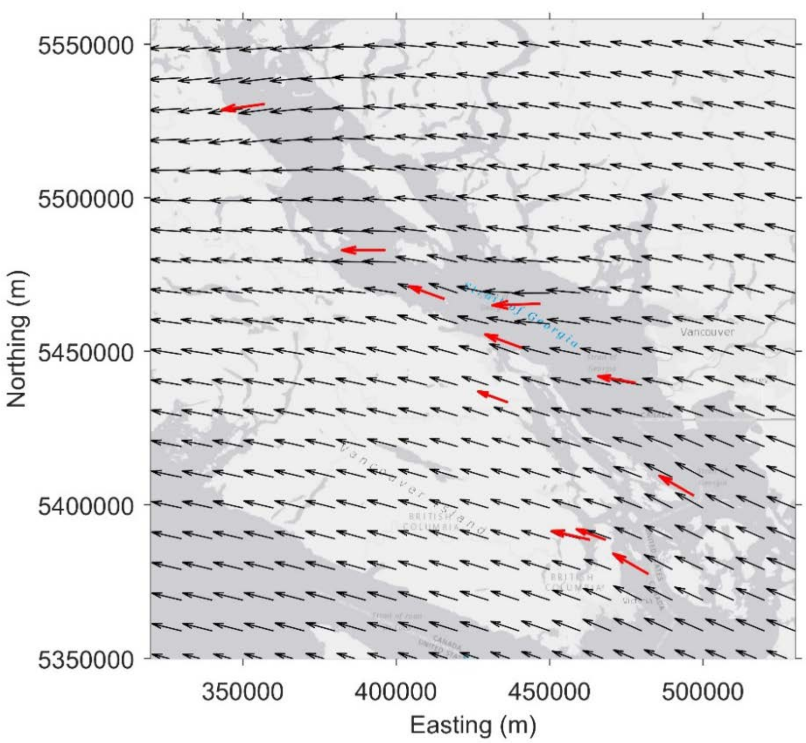

Figure 5 **Synthetic wind field during an easterly wind event (modelled after 2010-Apr-02 storm). Red arrows indicate local wind stations considered in analysis.**

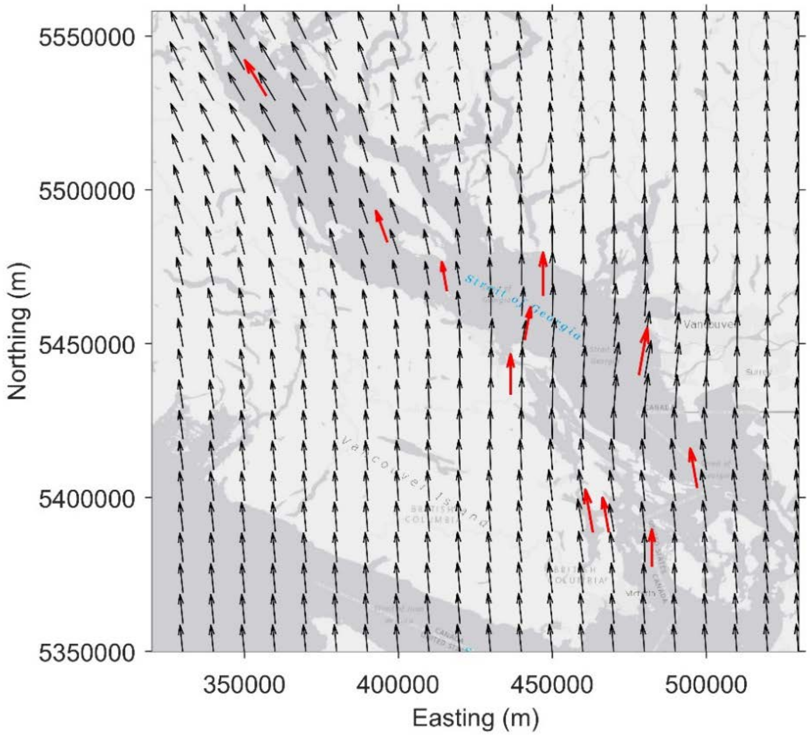

Figure 6 **Synthetic wind field during a southerly wind event (modelled after 2018-Dec-20 storm). Red arrows indicate local wind stations considered in analysis.**

4.6 Wind Set-Up

Wind set-up is the effect of wind blowing over a water surface, exerting a horizontal stress on the water surface and piling water up in the downwind direction. In long, enclosed, shallow bodies of water, wind setup can raise the still water level above the regular tide and surge levels. Conversely, along open stretches of shoreline and deep bodies of water, wind set-up is minimal and is not a governing factor in design. Within the estuary, the water depths are shallow, but the estuary itself is relatively ‘porous’ with numerous islands and channels, which does not permit water to ‘pile-up’. Wind set-up was estimated using a numerical wave model with a coarse grid resolution (see Section 4). Based on these simulations, the wind set-up is expected to be less than 0.01 m. As such, a specific allowance for wind set-up was not included in this assessment.

5 WAVE MODELLING

5.1 Model Documentation

SWAN (Simulating Waves Nearshore) is a numerical wave model used to simulate wave generation and propagation in deep water into coastal areas and shorelines. SWAN is a third-generation wave model, developed at Delft University of Technology in the Netherlands, that computes random, short-crested wind-generated waves in coastal regions and inland waters. SWAN incorporates physical processes such as wave propagation, wave generation by wind, white-capping, shoaling, wave breaking, bottom friction, sub-sea obstacles, wind and wave setup, and wave-wave interactions in its computations. For this project, SWAN version 41.20A was used.

NHC previously developed an in-house large-scale numerical wave model of the Strait of Georgia using SWAN. For this project, two additional models (Stuart Channel and Chemainus Estuary) were developed and 'nested' within the larger model (Figure 7). The 'nested' wave model grids have increasing resolution and their extents narrow in on the project site. Wave model grid parameters are provided in Table 6.

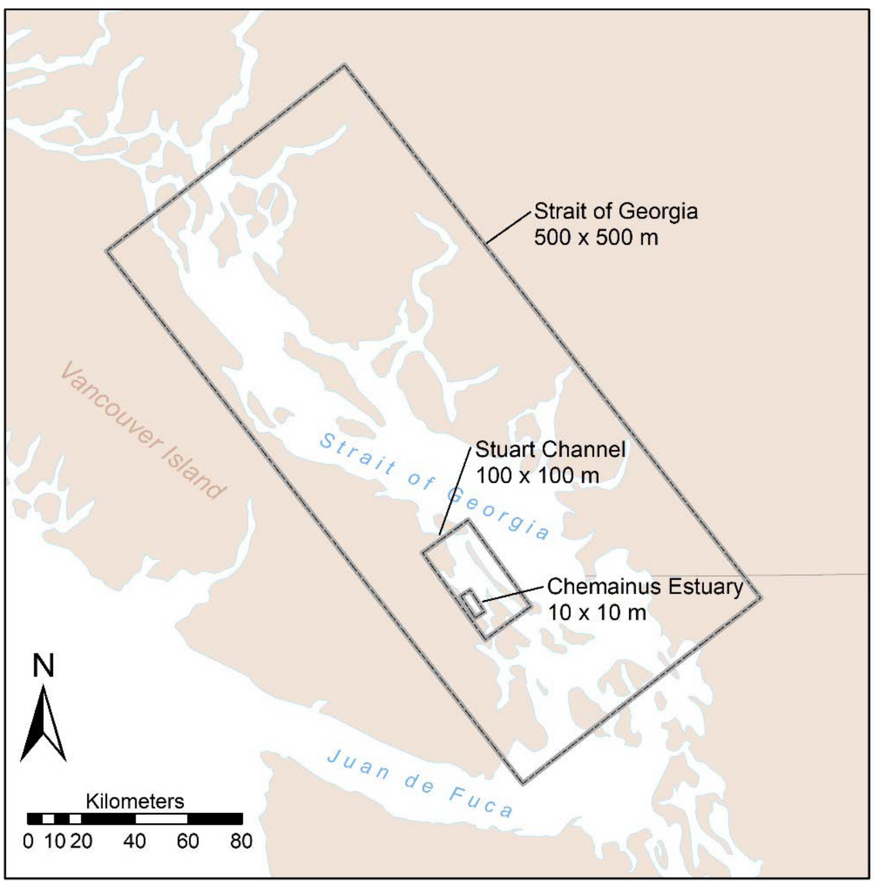

Figure 7 Wave model grid extents

Table 6 Wave model grid parameters

Computational Grid	Origin (UTM 10N, m)	Rotation (º CCW)	Grid Cells (#)	Grid Size (m)
Strait of Georgia	470,000E 5,349,000W	38	226 x 506	500m
Stuart Channel	456,000E 5,403,000W	36	210 x 400	100m
Chemainus Estuary	452,500E 5,411,400W	33	420 x 970	10m

5.2 Boundary Conditions & Bathymetry

Bathymetric elevations for the wave model were compiled for the Strait of Georgia, Stuart Channel, and Chemainus Estuary from multiple sources. Topographic elevations in the vicinity of the project site (within the Chemainus Estuary grid extents) were obtained from GeoBC 2019 LiDAR and processed by NHC GIS analysts (in the project vertical datum: CGVD2013). Table 7 provides a summary of elevation data used for the wave modelling. The wave model elevation model uses grid cell averaging and triangular interpolation to achieve a smooth surface.

Table 7 Bathymetric data sources

Computational Grid	Data Source
Strait of Georgia (500 x 500 m)	• CHS Non-Navigational 10 m Gridded Bathymetric Data (NONNA-10) • Digitized CHS Charts • NOAA 3 arc-second resolution dataset
Stuart Channel (100 x 100 m) Chemainus Estuary (10 x 10 m)	• NHC Bathymetric Survey data • GeoBC 2019 LiDAR • CHS Non-Navigational 10 m Gridded Bathymetric Data (NONNA-10) • Contours interpreted from CHS Charts • Canadian Digital Elevation Model

The 1-in-50 year spatially varying wind fields (as described in Section 3.5) are applied over the model domain to simulate the wind-generated component of waves within the model. The wind fields are interpolated and applied to the wave models on a 10 km grid.

The Strait of Georgia and Stuart Channel coarse wave models do not include additional wave damping due to vegetation or terrestrial roughness. However, at the project site it is important to incorporate the effects of terrestrial and intertidal vegetation such that wave penetration within the estuary is appropriately resolved. There are extensive agricultural lands in the region and brackish salt marsh vegetation is ubiquitous within the Chemainus Estuary. The Chemainus Estuary wave model includes a spatially varying wave damping factor based on the land and vegetation type, similar to that undertaken for the *Cowichan-Koksilah Floodplain Mapping project* (NHC, 2021). Based on land-use mapping, three typologies were defined for the coastal model: (1) no damping, (2) lightly vegetated with low damping, and (3) heavily vegetated or developed with high damping (Figure 8). River channels, mudflats, beaches, etc. have no additional damping imposed. Wetlands and agricultural lands are considered to have 'low damping'. Forests, rural areas, and urban areas are considered to have 'high damping'.[14]

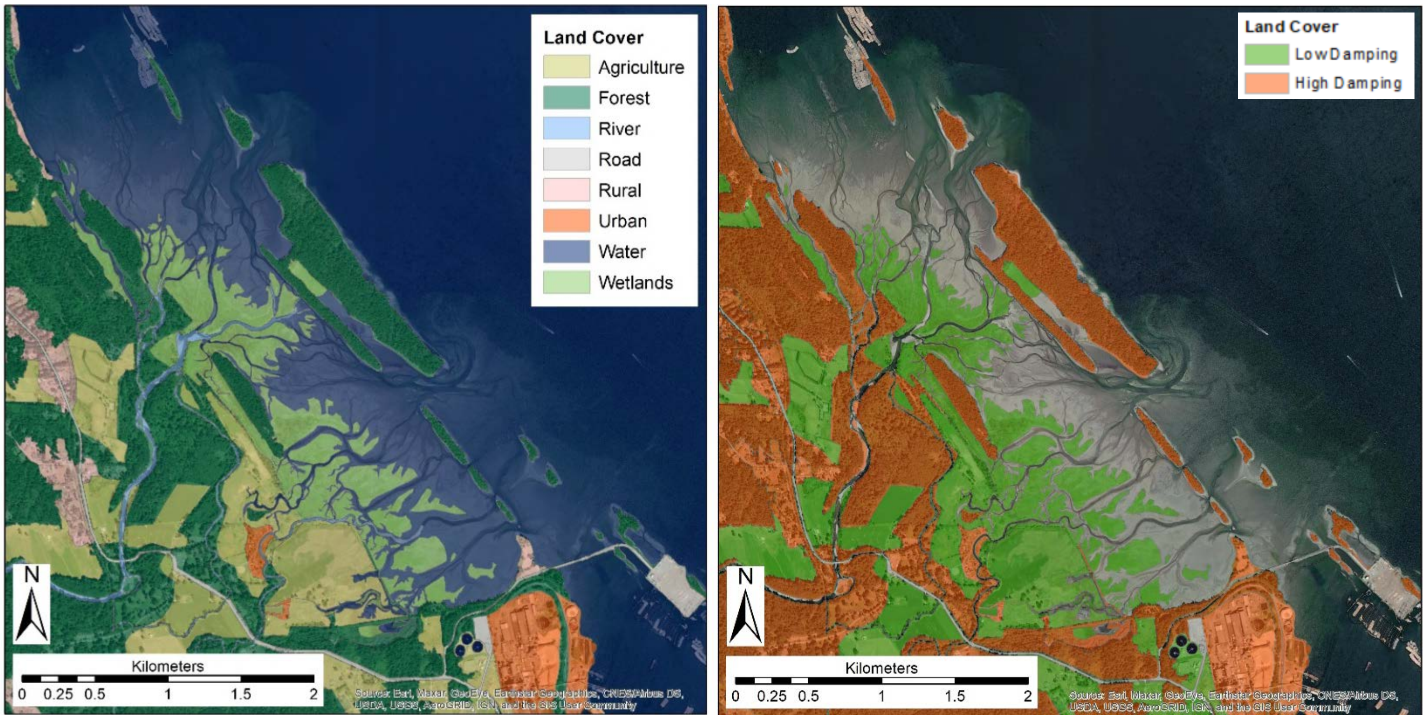

Figure 8 Vegetation typologies within the Chemainus Estuary wave model

5.3 Base Model Runs

As per Section 2, coastal FCL's must consider the 1-in-200 year total water level, year-2100 local relative SLR, wave effects associated with the designated storm, and a freeboard allowance. The base model runs used to establish wave effects are outlined in Table 8.

Note that because peak wind speeds and peak water levels often do not perfectly coincide, it is often appropriate to consider a high probability wind speed (e.g. 1-in-10 year) coinciding with a low probability water level (e.g. 1-in-200 year) to develop the wave effects during the designated storm. However, for this project site, there is significant uncertainty related to the coincidence of wind speeds and water

[14] Damping is simulated through SWANs vegetation module, where several parameters are static (i.e. vegetation high, diameter, and drag coefficient) and one parameter (i.e. drag coefficient) is varied spatially to approximate spatially varied wave damping. For the base scenario, the vegetation height is 0.326 m, vegetation diameter is 0.00463 m, and the drag coefficient is 0.5, as per NHC, 2021. The number of stems is set to 0 for areas with no additional damping, 500 for low damping, and 5000 for high damping.

levels due to a lack of locally available data. As such, the 1-in-50 year wind field is considered to occur simultaneously with the 1-in-200 year water level for this project to assess the potential coastal hazard.

In addition, following a sensitivity analysis (see Section 4.4), it was determined that portions of the site are particularly vulnerable to waves from the northeast. Although NE winds are not expected to be common and there are no large NE storms on nearby anemometer records, there is significant uncertainty around the wind speeds and directions in Stuart Channel. As such, an additional NE wind event[15] was included in the base model runs. The wave generation modelling scenario resulting in the highest waves for each reach was used for the wave effects analysis (see Section 5.1).

Table 8 Wave model base scenarios

Scenario	Wind Field Event	Water Level Event	Local SLR
A1	1-in-50 yr Northerly	1-in-200 yr	+0.0m
A2			+1.0m
D1	1-in-50 yr North-easterly	1-in-200 yr	+0.0m
D2			+1.0m
B1	1-in-50 yr Easterly	1-in-200 yr	+0.0m
B2			+1.0m
C1	1-in-50 yr Southerly	1-in-200 yr	+0.0m
C2			+1.0m

[15] The NE wind event uses non-spatially varying winds from 50^{oTN} with a wind speed equal to 75% of the 1-in-50 yr wind speed measured at halibut Bank for SE storms, as strong NE storm events are not likely to occur.

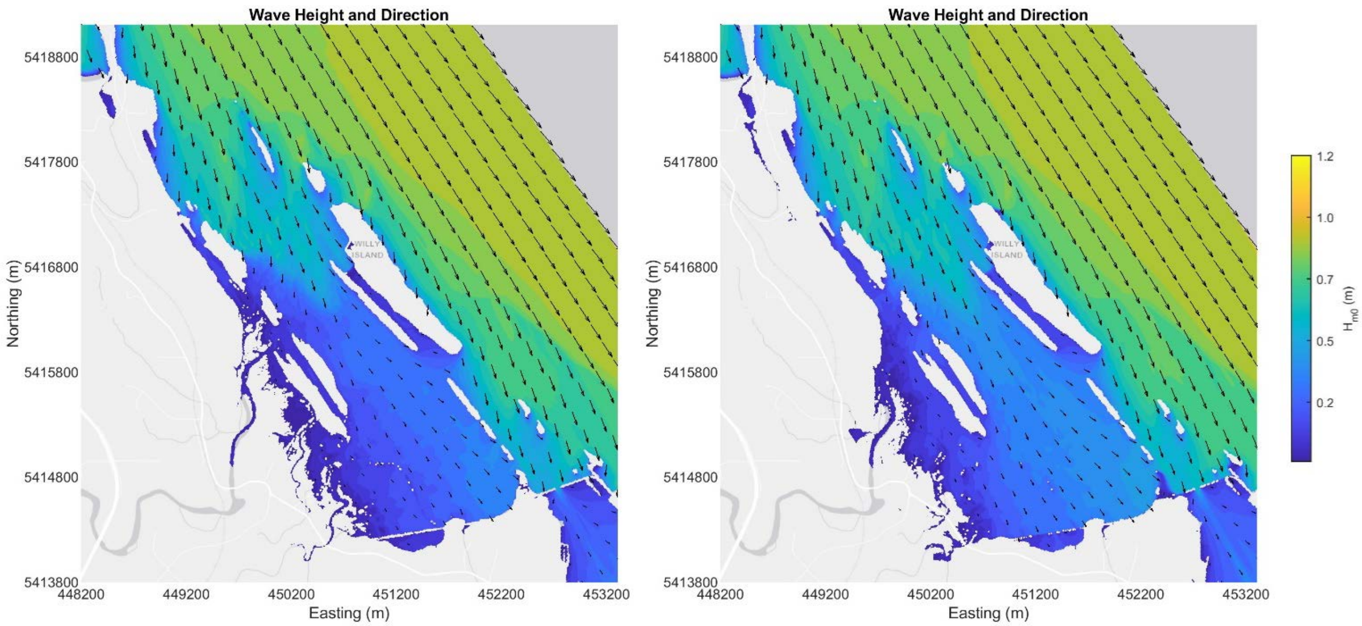

Figure 9 Northerly base run for (left) 0.0m of SLR and (right) 1.0m of SLR

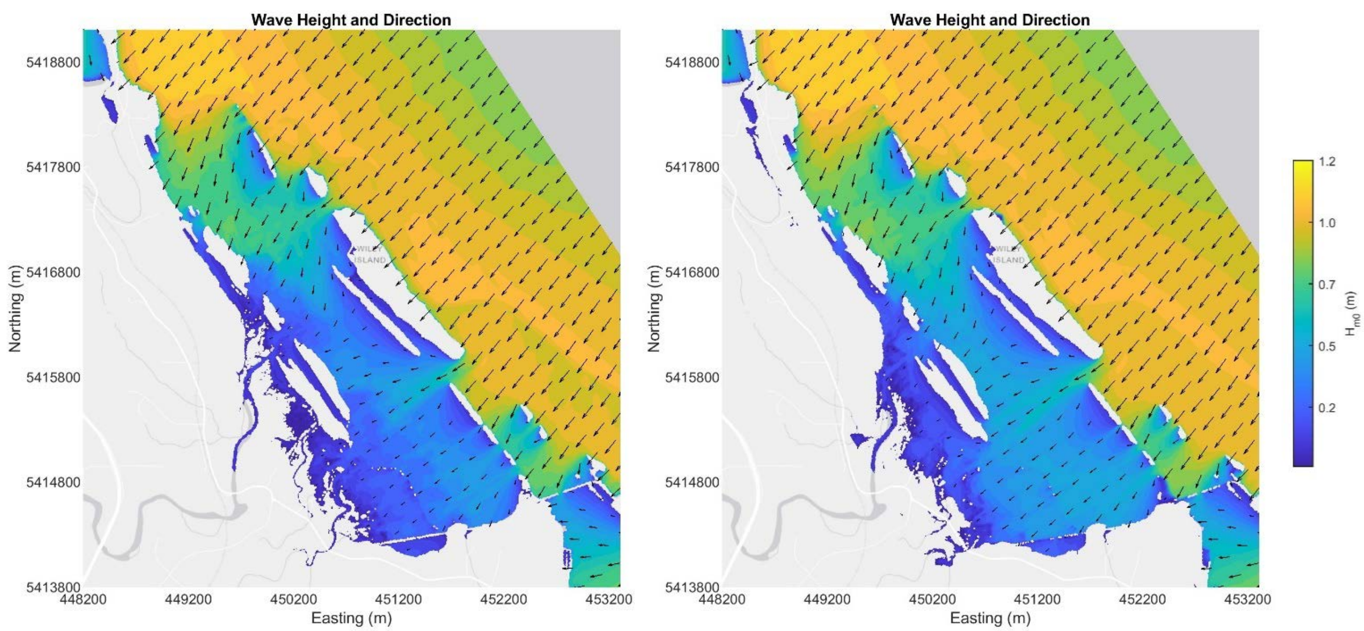

Figure 10 Northeasterly base run for (left) 0.0m of SLR and (right) 1.0m of SLR

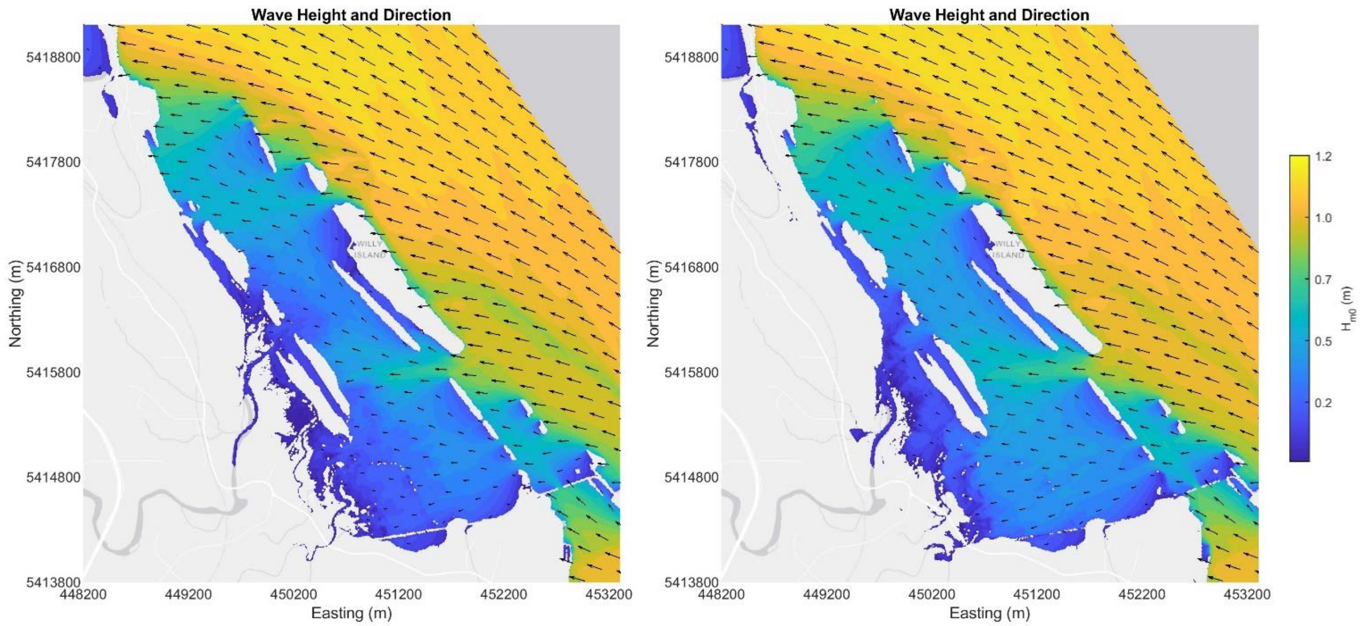

Figure 11 Easterly base run for (left) 0.0m of SLR and (right) 1.0m of SLR

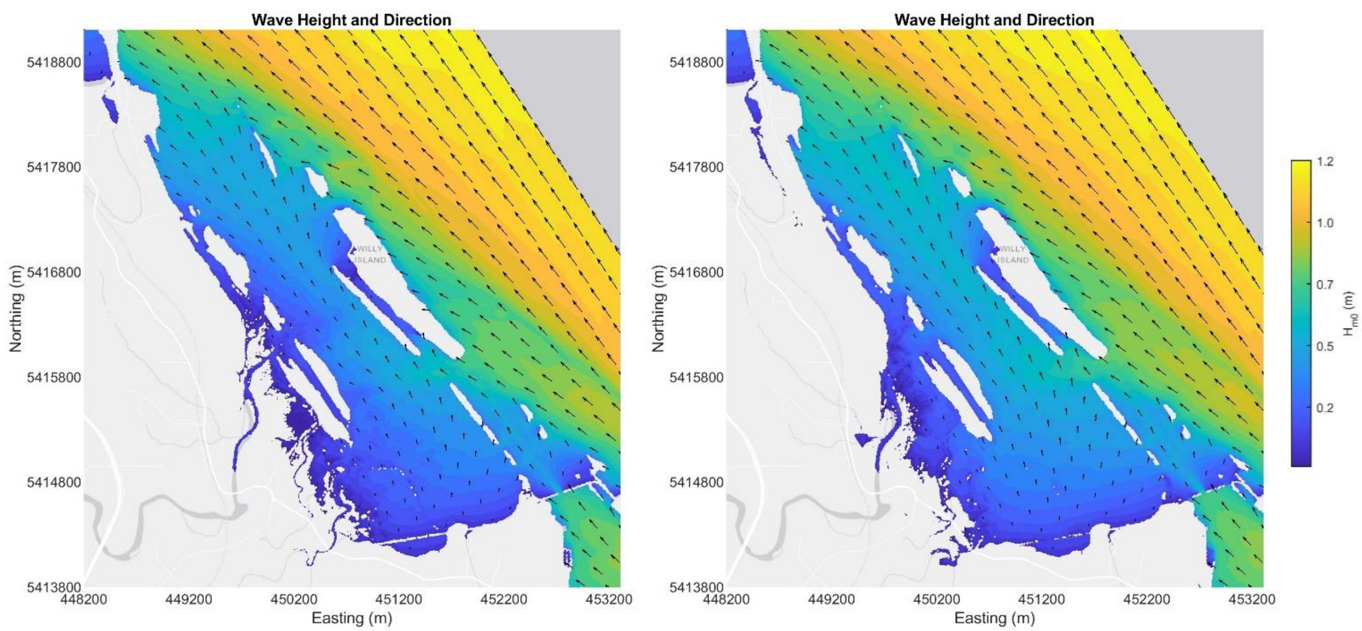

Figure 12 Southerly base run for (left) 0.0m of SLR and (right) 1.0m of SLR

5.4 Sensitivity

As part of the previous study by NHC for the Cowichan Bay area (NHC, 2021), NHC's Strait of Georgia SWAN model results were checked against the Halibut Bank wave buoy for a northwesterly and a southeasterly wind event. Because the model is stationary (i.e. not varying temporally) and measurements are not, direct calibration and validation of the wave model was not undertaken. Instead, the aim is to predict offshore wave heights and periods of similar magnitude as those observed for a given wind event, while erring on the conservative side. The Strait of Georgia model results are generally considered to predict offshore wave heights at Halibut Bank within +25%/-10% and wave periods within ±10%. A sensitivity analysis was also completed on several input parameters, including the grid size, wave generation method, and influence of diffraction.

There is no wave data available within Stuart Channel or the Chemainus Estuary to calibrate either of these SWAN models. The SWAN model input parameters were thereby determined based on professional judgement, literature review, and a sensitivity analysis. In addition, the incident wave climate has been checked against local knowledge as much as possible. Selected input parameters and sensitivity analyses are outlined in Table 9 below.

Table 9 SWAN model input and sensitivity parameters

Variable	Base Value	Values		
Grid Size [1]	10 m	5m	20 m	
Frequency Range and Resolution [1]	0.05 - 1.5 Hz (m_{sc}=30)	0.05 - 1.0 Hz (m_{sc}=30)	0.05 - 0.65 Hz (m_{sc}=40)	
Wave Gen Method	Komen	Janssen	ST6	
Breaker Index, ϒ	Default (0.73)	0.6	0.8	
Diffraction	On	Off	-	
Surface roughness [1]	Vegetation module with JONSWAP friction Eq. (Low damping areas: N_{stems} = 500; High damping areas: N_{stems} = 5000)	Vegetation module with JONSWAP friction Eq. (Entire model domain: N_{stems} = 500)	Vegetation module off, with spatially varied Madsen friction Eq.	Vegetation module off, with JONSWAP friction Eq. (default)
Wind Direction	N, E, S	NNE	NE [2]	SE
Sea Level Rise [1]	0.0 m, 1.0 m	2.0 m	-	

Notes:
1. Sensitivity run tested on the new, nested 'Chemainus' grid only.
2. NE winds are non-spatially varied.

Sensitivity tests were compared against the Easterly base run with 0.0 m of sea level rise. Results of the sensitivity tests are as follows:

- Grid size (Figure 13)
    - An increased grid size (i.e. 20 m) results in insufficient resolution of steep slopes where the water is relatively deep (e.g. the outer edge of Willy Island). It also does not sufficiently resolve narrow features, such as causeways and dike crests.
    - A small grid size (i.e. 5 m) results in similar results as the base case (i.e. 10 m resolution) across the model domain, with the exception of a small area within the agricultural dike in the SW corner of the Chemainus Estuary. In this area alone, the finer grid results in wave heights up to 0.2 m higher. This variation is within the margin of error for the model. For computational efficiency and balancing computer effort the 10 m resolution model was deemed suitable for final runs.
- Frequency range and resolution (Figure 14)
    - A frequency range of 0.05 – 1.0 Hz with the same m_{sc} (number of frequency bins) effectively increases the resolution across a narrower frequency range. This increased resolution with a lower high frequency (low period) cut-off, results in almost no changes to model results. This indicates that the base model run resolution sufficiently resolves frequencies.
    - A frequency range of 0.05 – 0.65 Hz with an increased frequency resolution to m_{sc} = 40 results in variations in wave heights of up to 0.2 m and wave periods of up approximately 0.2 s. Notably, this range cuts-off high frequency (low period) waves, resulting in under-estimates of wave heights in sheltered areas. These results are expected to be less reliable than the base run.
- Wave generation method
    - The coarse model using Janssen and ST6 wave generation methods were not stable and could therefore not be compared. Notably, the coarse Strait of Georgia model has been run using the base method (i.e. Komen) used and tested on numerous previous projects within the region. Further research is warranted into the correct parameters for ST6 for this region, but such effort was outside of the scope for this project.
- Breaker index, ϒ (Figure 15)
    - The breaker index is set to 0.73 by default in the SWAN model based on available literature and physical model simulations (Booij, N. et al., 2004).
    - A change in the wave breaker index, ϒ, from 0.73 to 0.6 or 0.8 results in very minor changes across the model domain. The default setting was deemed appropriate.
- Surface roughness (Figure 16)
    - The vegetation module turned on for the entire model domain (with N_{stems} = 500) results in slightly lower wave heights in areas where no vegetation exists, but results in similar levels of wave dissipation within the estuary (as expected).

- The use of the Madsen friction equation with a spatially varied roughness (instead of the vegetation module) results in similar levels of wave dissipation as the base run (within approximately 0.1 m).
- As expected, the use of the JONSWAP friction equation with the vegetation module off (the default setting) results in higher wave heights in shallow vegetated areas.

- Wind direction (Figure 17)
  - The ENE scenario results in larger waves on the deep northern edge of the estuary compared to the E base run, but similar results to the N base run. As such, this wind direction is not considered to be a governing scenario.
  - The NE scenario similarly results in larger waves on the deep northern edge of the estuary compared to the E base run. In addition, larger waves penetrate into the SW corner of the estuary. Because of the estuaries' vulnerability to waves from this direction, this scenario was added to selected base runs (see Section 4.3).
  - The SE scenario does not result in waves that are significantly different than the E or S base runs and is not considered to be a governing scenario.
- Sea level rise (Figure 18)
  - Increased sea level rise will result in increased flooding due to both an increase in the still water level (and its penetration inland) and a corresponding in wave penetration inland. The sensitivity runs clearly show that wave heights near the river inlet onto the estuary will increase significantly as sea levels rise. Note that only a 1.0 m sea level rise has been considered as part of the base runs (see Section 3.3 and 4.3)

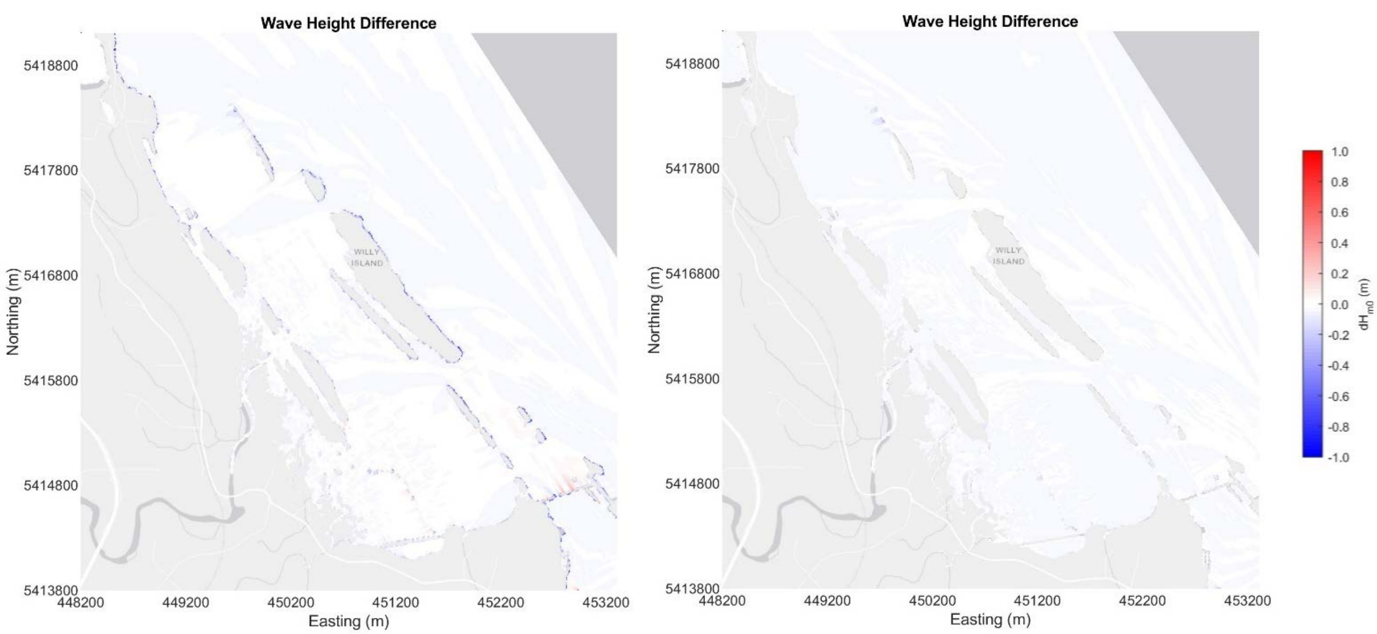

Figure 13 Difference in wave height (dH_{m0}) relative to the Easterly base case with 0m SLR due to variation in computational grid size: (left) 20 m grid and (right) 5 m grid

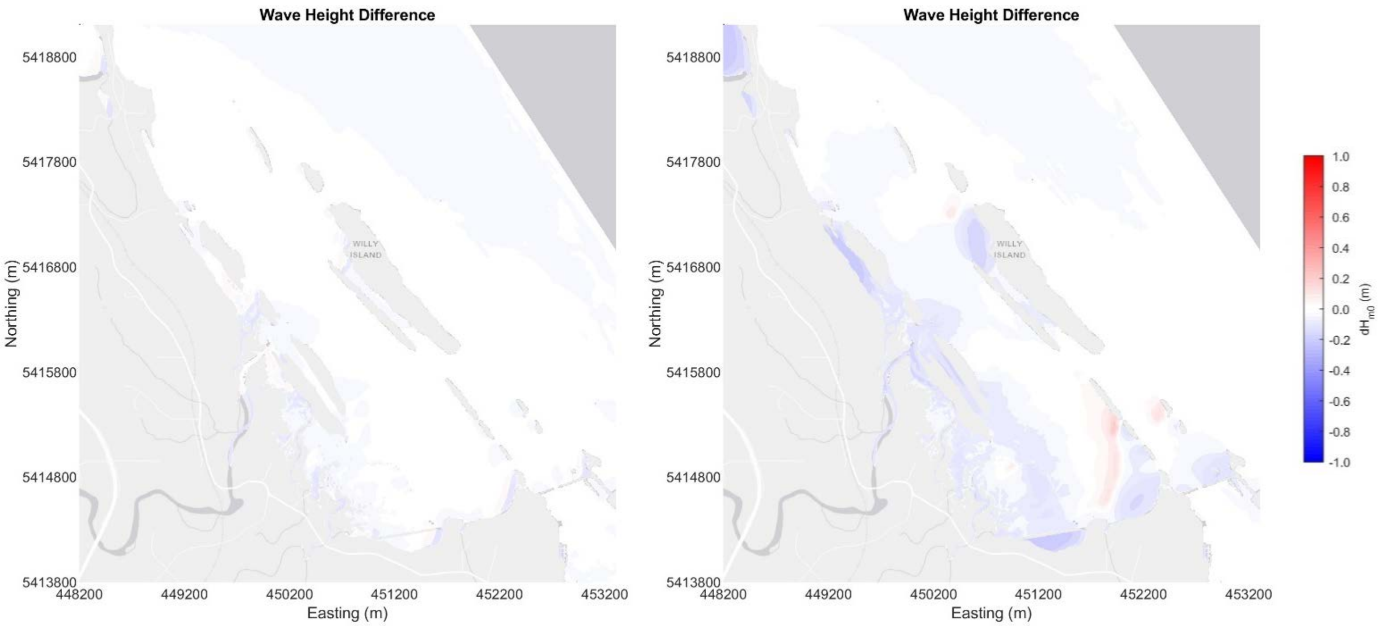

Figure 14 **Difference in wave height (dH_{m0}) relative to the Easterly base case with 0m SLR due to variation in the frequency range and frequency resolution across range: (left) Decreased range to *f* = 0.05 - 1.0 Hz and (right) Decreased range to *f* = 0.05 – 0.65 Hz and increased resolution to m_{sc} = 40**

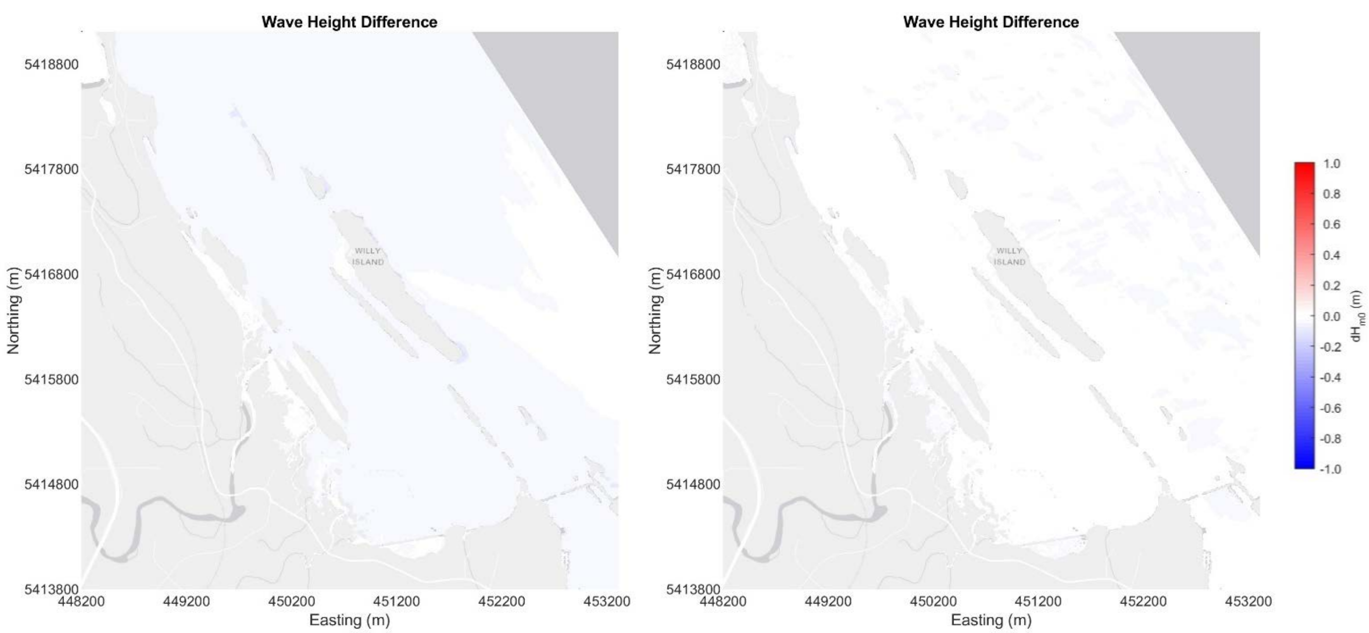

Figure 15 **Difference in wave height (dH_{m0}) relative to the Easterly base case with 0m SLR due to variation in the breaker index, ϒ: (left) ϒ = 0.6 and (right) ϒ = 0.8**

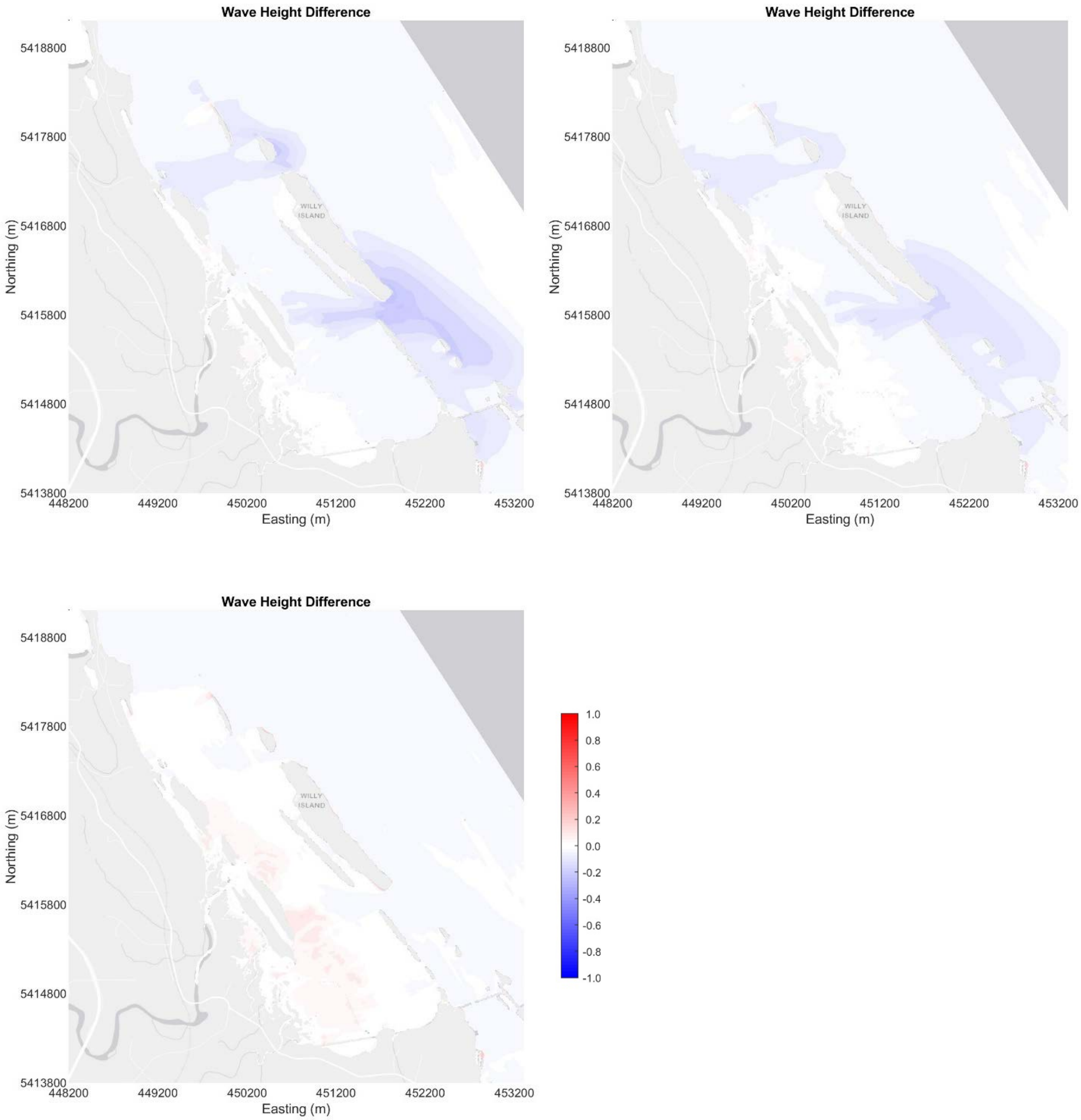

Figure 16 Difference in wave height (dH_{m0}) relative to the Easterly base case with 0m SLR due to variations in roughness: (top-left) vegetation module (N_{stems} = 500 across entire model domain) with JONSWAP friction Eq., (top-right) vegetation module off, with spatially varied Madsen Friction Eq., and (bottom left) vegetation module off, with JONSWAP friction Eq.

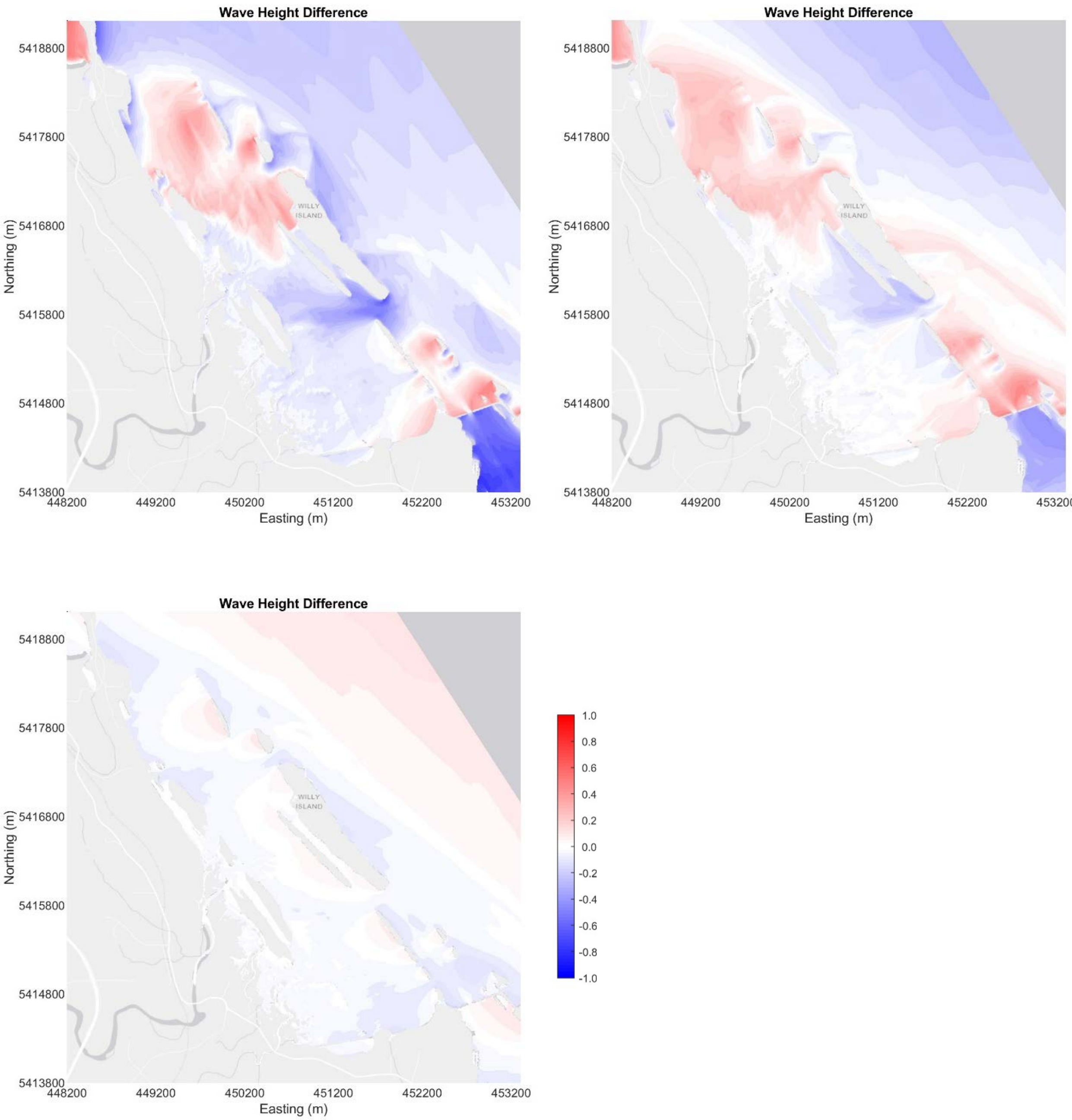

Figure 17 Difference in wave height (dH_{m0}) relative to the Easterly base case with 0m SLR due to variations in wind direction: (top-left) NNE spatially varied, (top-right) NE non-spatially varied, and (bottom left) SE spatially varied

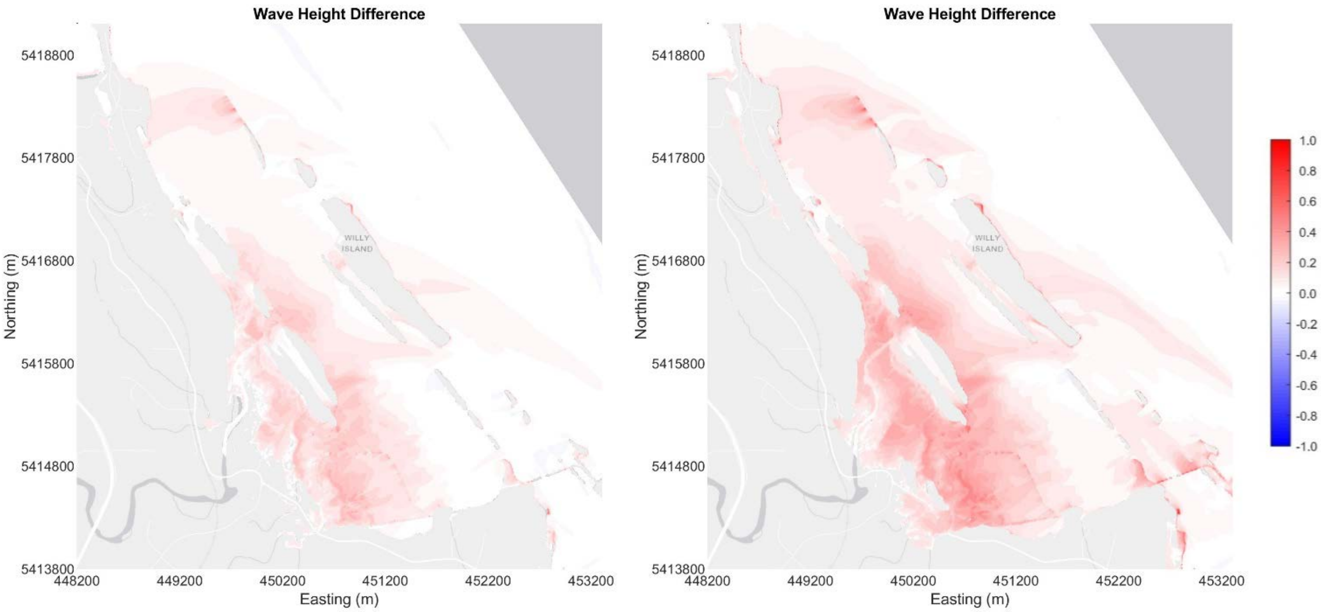

Figure 18 Difference in wave height (dH_{m0}) relative to the Easterly base case with 0m SLR due to an increase in sea level rise of: (left) 1.0 m and (right) 2.0 m. Note, the wave penetration extent up the river in the 2.0 m SLR scenario is limited by the computational grid extent.

6 FLOOD CONSTRUCTION LEVELS

6.1 Wave Effects

6.1.1 Background

Wave effects are loosely defined as the effect of waves interacting with the shoreline. The extent of wave effects can be described by two common metrics: (1) the level of wave overtopping or (2) the level of wave run-up at the shoreline. Wave overtopping it the volume or rate of water which overtops the crest of a structure, and is particularly useful when defining safe dike crest elevations, for example. Wave run-up is the maximum vertical extent of wave uprush on a beach or structure above the still water level. This metric is typically used for defining regional FCL's. As is standard coastal engineering practice for most applications (including flood hazard analyses), the level of wave run-up is generally characterized by the two percent exceedance value of wave run-up, $R_{2\%}$ (i.e. only two percent of the wave run-up values observed will reach or exceed $R_{2\%}$).

6.1.2 Shoreline Reach Characterization

The level of wave run-up depends greatly on the slope, orientation, and character (vegetation and roughness) of the shoreline. These aspects were characterized as follows:

Shoreline Character

The shoreline in the Chemainus River Estuary area was delineated into sections of shoreline with similar slope and character as shown in Figure 19. The area is largely dominated by steep bedrock slopes in the NW, natural mildly sloping shorelines within the estuary, and steeper rip-rap slopes surrounding the more industrial area in the SE.

Wave Exposure

The results of the wave analysis (see Section 4) were used to estimate the incident wave characteristics (wave height, period, and obliqueness) along the shoreline (Figure 20).

Shoreline Reaches

The shoreline was then broken up in 'reaches' used to calculate wave run-up (Figure 21). Reaches are defined as sections of shoreline with similar slope, orientation, character, and wave exposure.

Figure 19 Shoreline typologies within the Chemainus Estuary

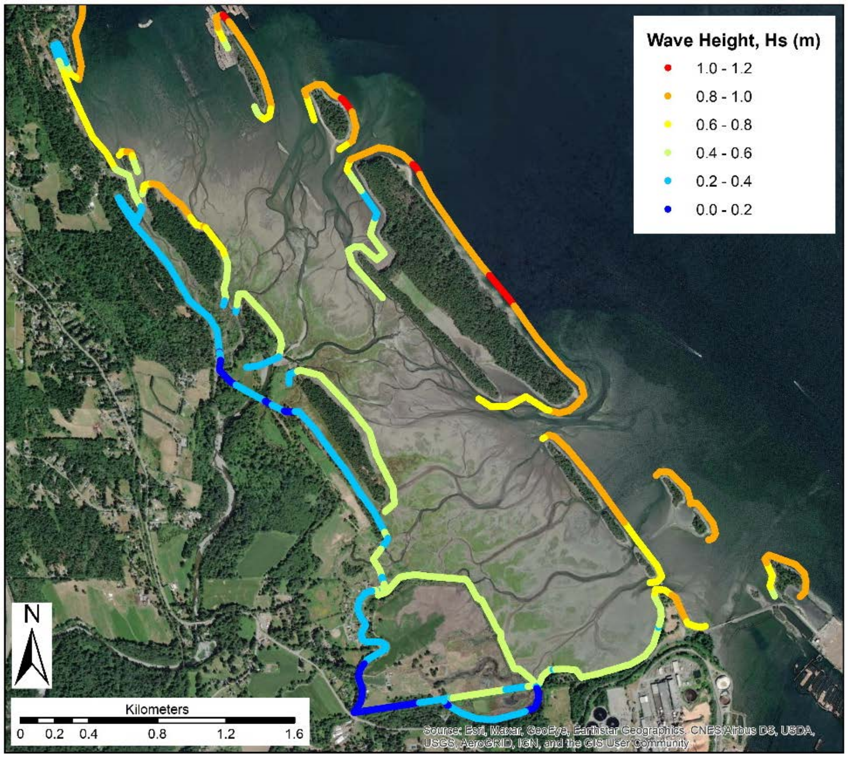

Figure 20 Maximum wave exposure for 1.0 m SLR

Figure 21 Shoreline reaches for calculation of wave run-up

6.1.3 Wave Run-Up Calculation

Wave run-up was estimated for each of the shoreline reaches shown in Figure 21. Run-up was calculated based on empirical equations and methodology outlined in the EurOtop '*manual on wave overtopping of sea defences and related structures*' (EurOtop, 2018). A reduction factor was applied to account for the roughness of various types of shorelines (see Table 10). An additional reduction factor (ranging from 0.7 – 0.9) was applied to shorelines that are exposed to predominantly oblique waves.

Table 10 Roughness reduction factor for wave run-up calculations

Variable	Reduction Factor for Roughness, *f*
Gravel Beach	~0.8 [1]
Vegetated Slope	0.8
Bedrock Slope	1.0
Berm / Vegetated Dike	0.8
Rip-Rap	0.6
Vertical Wall	1.0

Notes:
1. Roughness reduction factor for gravel beaches varies based on incident wave conditions, based on Arana (2017)

The estimated wave run-up for each reach is provided in Table 11 for the 1-in-200 year with 1.0 m of SLR. Note that the delineation of the shoreline into reaches was made to be conservative, such that the highest expected wave run-up across each reach is applied over the entire reach. It is acknowledged that this approach may result in conservative estimations of the FCL at individual properties and that a more detailed site-specific assessment for an individual property might yield a lower FCL. However, such site-specific analysis was not possible within the scope and scale of this study.

Table 11 Wave run-up and FCL estimates for 1.0 m of SLR

Reach	1.0 m SLR Run-Up, $R_{2\%}$ (m)	1.0 m SLR FCL (m, CGVD2013)
R1.1	1.8	5.9
R1.2	0.2	4.1
R1.3	1.0	5.1
R1.4	2.3	6.4
R1.5	1.7	5.8
R2.1	0.3	4.4
R2.2	0.6	4.7
R2.3	0.4	4.5
R2.4	0.1	4.1
R3.1	0.1	4.1
R3.2	0.0	4.1
R3.3	0.5	4.6
R4.1	0.8	4.9
R5.1	0.5	4.6
R6.1	0.4	4.5
R6.2	1.1	5.2
R6.3	0.5	4.6
R7.1	2.4	6.5
R7.2	1.8	5.9
R7.3	2.0	6.1
R7.4	2.3	6.4
R7.5	2.4	6.5
R7.6	1.6	5.7
R7.7	2.9	7.0
R7.8	2.8	6.9
R8.1	1.4	5.5
R8.2	1.2	5.3
R8.3	1.2	5.3
R8.4	2.0	6.1

6.2 Freeboard

Freeboard is an allowance applied to FCL calculations to accommodate temporal and spatial uncertainties, as well as the precision of the data and assessment. In coastal areas (where wave effects are significant), the freeboard is applied on top of the design flood level (DFL) and wave effects components. Notably, where wave effects are expected to be less than approximately 0.3 m, such as on rivers, small lakes, and very sheltered sections of coastline, it is generally appropriate to include the wave effects component within the freeboard.

According to EGBC (2017), there are no provincial standards for freeboard. However, typical freeboard values adopted in BC are between 0.3 – 0.6[16] m for coastal environments (EGBC, 2017; EGBC 2018). Larger freeboards are also appropriate for regional analyses where site specific characteristics cannot be fully incorporated and/or where there is the potential for other hard to predict phenomena (e.g. sedimentation, ice build-up, etc.) (EGBC, 2017).

Due to the regional scale of this study and following the FLNRORD (2018) guidance for freeboard when using a probabilistic approach, a freeboard of 0.6 m was adopted.

6.3 Flood Construction Levels

Coastal FCLs apply to Chemainus Estuary shorelines within the study limits that are exposed to coastal processes as described in Section 3. The FCL is the sum of design water level, future SLR allowance, subsidence/uplift allowance (if applicable), wave effects, and freeboard. The FCL for 1.0 m of SLR (future, approximately year 2100) are summarized Table 11.

7 LIMITATIONS AND UNCERTAINTIES

This assessment of Coastal FCLs has several limitations related to available data, modelling and calculations, and inherent environmental uncertainties. Key limitations and uncertainties are as follows:

- There is a notable lack of wind data available within Stuart Channel, which presents uncertainties when characterizing the designated storm event in the region. The study therefore assumes wind characteristics similar to those within the Strait of Georgia, as characterized by Halibut Bank, which is expected to lead to conservative wind speeds.
- Wave modelling requires accurate representations of the underlying bathymetry. The bathymetry used in this assessment represents the best data available at the time of the study; however, there were notable data gaps in the vicinity of: (1) steep and heavily vegetated shorelines which may not be accurately reflected in the available LiDAR data, (2) the Chemainus River distributary channels and mudflats which were inundated during the LiDAR flight, and (3) the delta slope break onshore of the limit of CHS data availability. In addition, bathymetry is subject to change due to erosional and depositional processes on numerous time scales; such changes create uncertainties in merging datasets from different years and in applying the wave model to future (year 2100) scenarios.
- The wave model set-up assumes the following:
    - Water level is static (i.e. not a function of time) and set to the offshore ocean level. River flows are not included in the model, which may increase water levels above those

[16] A value of 0.3 m is recommended when using an additive approach, and a value of 0.6 m is recommended when using a probabilistic approach (as is used for this project).

modelled in SWAN; however, these interactions are captured within the HEC-RAS model (see Appendix E).

- The model grid size is 10 m, meaning that features smaller than this size may not be fully defined (depending on their orientation). Diked coastal areas in particular should therefore be subject to site specific assessment.
- The extent of vegetation within the model is set to the year 2021 extent, and does not reflect changes in vegetation that may occur due to future anthropogenic activities or sea level rise.
- Offshore log booming activities may attenuate waves during a storm event beyond what is predicted by the model.

- Wave run-up calculations are based on empirical equations and relationships for idealized and uniform slopes. Individual waves may also produce wave run-up that is beyond the R2% value. Increased quantities of woody vegetation would also be expected to decrease wave run-up below what is predicted.
- The delineation of the shoreline into reaches for FCL calculation was made to be conservative, such that the highest expected wave run-up across each reach is applied over the entire reach. This approach may result in conservative estimations of the FCL at individual properties.

Despite the above limitations, the wave model and calculations used to derive the coastal FCLs are considered robust for their intended use. Notably, incorporation of a Freeboard Allowance in the helps to account for uncertainties and unknowns in the modelling and wave run-up calculations.

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APPENDIX F

FLOOD MAPPING METHODOLOGY

APPENDIX F

FLOOD MAPPING METHODOLOGY

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1 MAPPING OVERVIEW

Two mapping products were developed for this study:

1. Flood depth and velocity hazard maps for design flood.
2. Designated floodplain maps depicting the flood construction level (FCL) for the design flood.

The design flood shown in the mapping is a combination of:

- 200-year flow from Chemainus River and tributaries simulated with 20-year estuary water level;
- 200-year estuary water level simulated with 20-year flow on Chemainus River and tributaries.

Both simulations listed were run with the E&N Rail embankment in its original state (whole - at time of survey and start of study) and its modified (breached in two locations in emergency response to November floods) state. The maximum water surface elevation of all simulations is taken and combined in GIS to create the design flood event. Digital files for each of the mapping products, compatible with ArcGIS, are provided as part of the results of this study.

The sections below describe the approach take to transfer results from the riverine, lake and coastal modelling into mapping products.

2 FLOOD DEPTH AND VELOCITY MAPS

Flood depth rasters and velocity arrows were generated for the Chemainus Floodplain based on the 2D hydraulic model HEC-RAS 6.1. Flood depth rasters for the peak of the design flood were exported directly from the HEC-RAS 2D model in TIFF format. Flood depth values are in metres. The rasters match the model's DEM resolution of one metre.

Velocity vectors are extracted from the model mesh nodes in U and V directions and are translated into velocity arrows overlayed on the depth rasters. Velocity arrows show the magnitude and direction of water movement where each magnitude is a different colour and size (see example below). Table 2.1 describes the depth categories displayed on the flood depth maps. These categories were adapted from a Japanese national standard (EXCIMAP, 2007; MLIT, 2005), have been applied by NHC for numerous other projects across BC, and are presented in the provincial flood mapping guidelines (APEGBC 2017).

Table 2.1 Description of flood depth categories.

Depth (m)	Description of Typical Conditions	Legend Color
0 – 0.1	most buildings are dry; underground infrastructure may be flooded	

Depth (m)	Description of Typical Conditions	Legend Color
0.1 – 0.3	most buildings are dry; walking in moving water or driving is potentially dangerous; underground infrastructure may be flooded	
0.3 – 0.5	most buildings are dry; walking in moving or still water or driving is dangerous; underground infrastructure may be flooded	
0.5 – 1.0	water on ground floor; underground infrastructure flooded; electricity failed; vehicles are commonly carried off roadways	
1.0 – 2.0	ground floor flooded; residents and workers evacuate	
> 2.0	first floor and often higher levels covered by water; residents and workers evacuate	

3 DESIGNATED FLOODPLAIN MAPS

3.1 Riverine

The simulated design flood water surface was mapped at 1:5,000 scale on the 4 sheets (24”x36”) that are included in the map appendix. Freeboard, discussed in Section 3.1, was added to the simulated water level surface, and the combined surface was then mapped over the DEM and projected across the floodplain to delineate flood extents. The maps show flood extents with and without freeboard allowance. With freeboard included, the maps indicate the minimum level for construction at a certain point within the floodplain, referred to as the Flood Construction Level (FCL). The maps include isolines or lines corresponding to equal FCLs, generally in 0.3 m increments. There are occasions when the interval is larger 0.3 m and those occur when there is a large change in water surface elevation such as over a road or embankment.

3.1.1 Freeboard Requirements

Freeboard is added to provide a safety factor. The freeboard accounts for local variations in water level (such as standing waves, super-elevation at the outside of river bends, local turbulence, blockages) and uncertainty in the flood level simulations. Historically in British Columbia, the minimum freeboard allowance applied has been the greater of 0.3 m above the instantaneous (peak) flood event or 0.6 m above the daily flood event. For some rivers, freeboard should be increased to 1 m or more, to address greater uncertainty in the assessment or concerns regarding sediment deposition, debris blockages or ice jams (MWLAP, 2004).

In recent years, a minimum freeboard of 0.6 m has been frequently used with an instantaneous event[1], as suggested in recent provincial guidelines for sea dikes (MOE, 2011) and as discussed in the EGBC professional practice guideline for floodplain mapping (EGBC, 2017).

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[1] A brief set of examples of use of a minimum of 0.6 m freeboard above the instantaneous flood flow within BC include flood hazard study and mapping in Prince George, the lower Fraser River, Maple Ridge, Squamish, North Vancouver, City of Fernie,

Considering the potential for bed level changes in the Chemainus River, the amount of debris supplied in a flood, and the uncertainty of climate change on future flood flows, a minimum freeboard allowance of 0.6 m is recommended.

The CVRD, North Cowichan, Halalt First Nation and Penelakut Tribe, may wish to define a higher level of protection for certain infrastructure or facilities, such as major transportation routes, hospitals, emergency response centers, communications centers, residences for the elderly, or schools. Conversely, a reduced freeboard may be suitable for some land use, particularly land use with reduced design life or reduced vulnerability to flood exposure. The risk tolerance accepted for any site or area depends on societal norms (such as stated in existing provincial guidelines) as well as the potential consequence of the flood hazard for the infrastructure or facility in question. Direct and indirect threats to life, harm, economy, environment, social, and cultural values should be considered when altering freeboard or the design hazard.

3.1.2 Filtering of Inundation Extents

Filtering was used to remove isolated inundated areas and isolated elevated areas other than those manually flagged. This is typically done to improve the readability of the maps and to limit the reliance on slight variations in floodplain topography, which may change with time. Isolated inundation areas smaller than 100 m^2 and several manually flagged isolated inundation areas >100 m^2 were also removed; these were mapped as inundated to account for culverts or seepage that may be connected to these isolated wet areas.

3.2 Chemainus Estuary

Coastal flood mapping for the Chemainus estuary is based on water levels from the 2D hydraulic model results generated in HEC-RAS 6.1 for the 200-year return period ocean water level. The flood extent polygons are based on the outputs from the HEC-RAS model, and do not include wave effects.

Coastal FCLs (including wave effects and freeboard) are applicable within the delineated “Coastal Flood Construction Level (FCL) Zones.” The methodology for determining the landward extents of these zones is shown in Figure 3.1. The Coastal FCL Zone landward boundary is defined as being 30 m landwards from the HHWLT which is roughly where the natural boundary and typical shoreline is located. It was truncated less than 30 m in spots where the elevation of the topography was greater than the FCL. Gaps of < 100 m^2 in the coastal FCL zone were filled in. The Coastal FCL (defined and calculated by shoreline reach in Appendix D) is applicable in the Coastal Flood Construction Zone. Landwards of the Coastal Flood Construction Zone, the FCL is based on the still water elevation exported from the HEC-RAS model in Chemainus Estuary plus freeboard.

Regional District of East Kootenay, Pemberton, Okanagan, and Vernon (KWL, 2014, 2017; MFLNRORD and NHC, 2014; NHC, 2008, 2016, 2017, 2018, 2019, 2020b, 2020a, 2021).

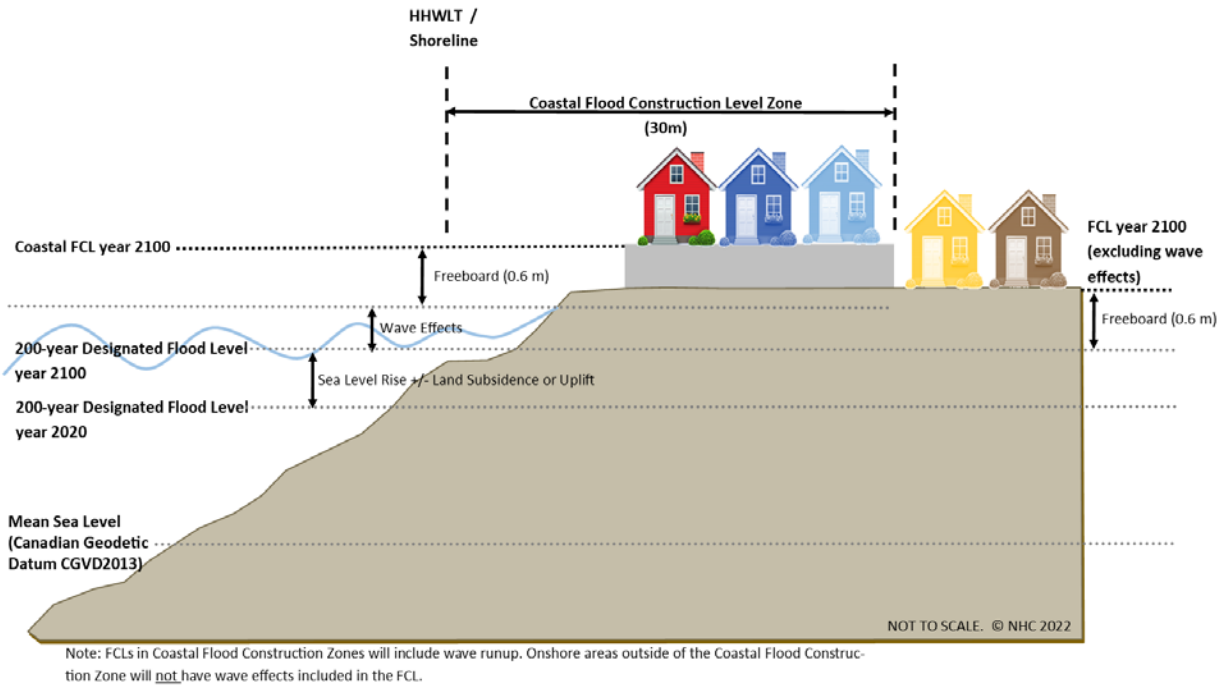

Figure 3.1 Methodology for determining the coastal flood construction level zone

3.3 Map Notes and Limitations

A series of notes and limitations are included on the maps. The following provides additional, more detailed information:

1) The flood depth and velocity hazard maps are informational only and intended for providing input for high level planning. They are not to be used for designating floodplains, establishing FCLs, designing dikes or any other structures.

2) LiDAR from 2019 and 2021 along with 2021 bathymetric survey data was used to create a Digital Elevation Model (DEM) of the study area. Major transportation corridors were captured in the DEM, but openings such as culverts within embankments were omitted.

3) The DEM was used to develop a HEC-RAS (version 6.1) 2D hydraulic model. The model geometry is fixed although variations from erosion, degradation or aggradation may occur over time (particularly during a flood event). Future updates of the DEM and hydraulic model are required. All river channels were assumed to be free of obstructions.

4) The HEC-RAS 2D model was calibrated to observed flows and water levels during the 2021 high flow event and validated to the 2020 flood event.

5) **Freeboard is not included** in any of the flood depth maps.

6) For the flood scenario mapping, all embankments were assumed to remain intact. If overtopped in the model, overflow will occur, but the embankment geometry remains unchanged, preventing a breach from forming. In reality, most overtopped embankments will fail. Additionally, embankments can possibly breach through other failure mechanisms well before they are overtopped.

Detailed embankment crest elevation data is critical for accurate simulation floods. The embankments in the DEM were represented using LiDAR. LiDAR accuracy in general is acceptable, it is unreliable where crests are covered by trees or flood walls are present.

3.4 Interpolating FCLs From the Flood Maps

FCLs are documented on the floodplain maps with labelled isolines. The FCL for a specific building or space is to be taken as the highest FCL applicable for that location which is considered the FCL at the upstream extent of the building or space. Where the building or space is located between isolines, two options exist for determining the applicable FCL:

- Approach 1: the FCL is taken as the value represented by the next upstream isoline, or
- Approach 2a: the FCL is calculated through linear interpolation between the two isolines in which the upstream face of the building or space is located.
- Approach 2b: the FCL is calculated through linear interpolation between the three isolines in which the upstream face of the building or space is located. Do the calculation as if there were only 2 isolines, then do it again using the result from the first calculation with the third isoline.

An example is presented below based on the red building and two mapped isolines shown in Figure 3.2:

- The upstream FCL line has an elevation of 12.9 m, with the downstream FCL having an elevation of 12.6 m. The distance between these lines is 190 m, and the upstream side of the building is 125 m upstream from the 12.3 m FCL isoline.
- The FCL for the labelled building can be calculated as follows:
    - Approach 1: $12.9\ \mathrm{m}$
    - Approach 2a: $12.6 + (12.9 - 12.6)\left(\frac{125}{190}\right) = 12.8\ \mathrm{m}$

A second example is presented below based on the orange building and mapped isolines shown in Figure 3.2:

- The two upstream FCL lines have an elevation of 12.0 m, with the downstream FCL having an elevation of 11.7 m. The distance between the right 12.0 isoline and 11.7 isoline is 260 m, and the intermediate point (red dot) is 125 m upstream from the 11.7 m FCL isoline.
- The FCL for the labelled building can be calculated as follows:
    - Approach 1: $12.0\ \mathrm{m}$

Approach 2b: Use linear interpolation for two of the isolines (setting an intermediate point (red dot)): $11.7 + (12.0 - 11.7)\left(\frac{125}{260}\right) = 11.84$ m. Then using the interpolated result (11.84) and the third isoline (12.0), use linear interpolation again to get the FCL.

Distance between the intermediate point and the left 12.0 isoline is 250 m, therefore

$$11.84 + (12.0 - 11.84)\left(\frac{50}{250}\right) = 11.87 \text{ m.}$$

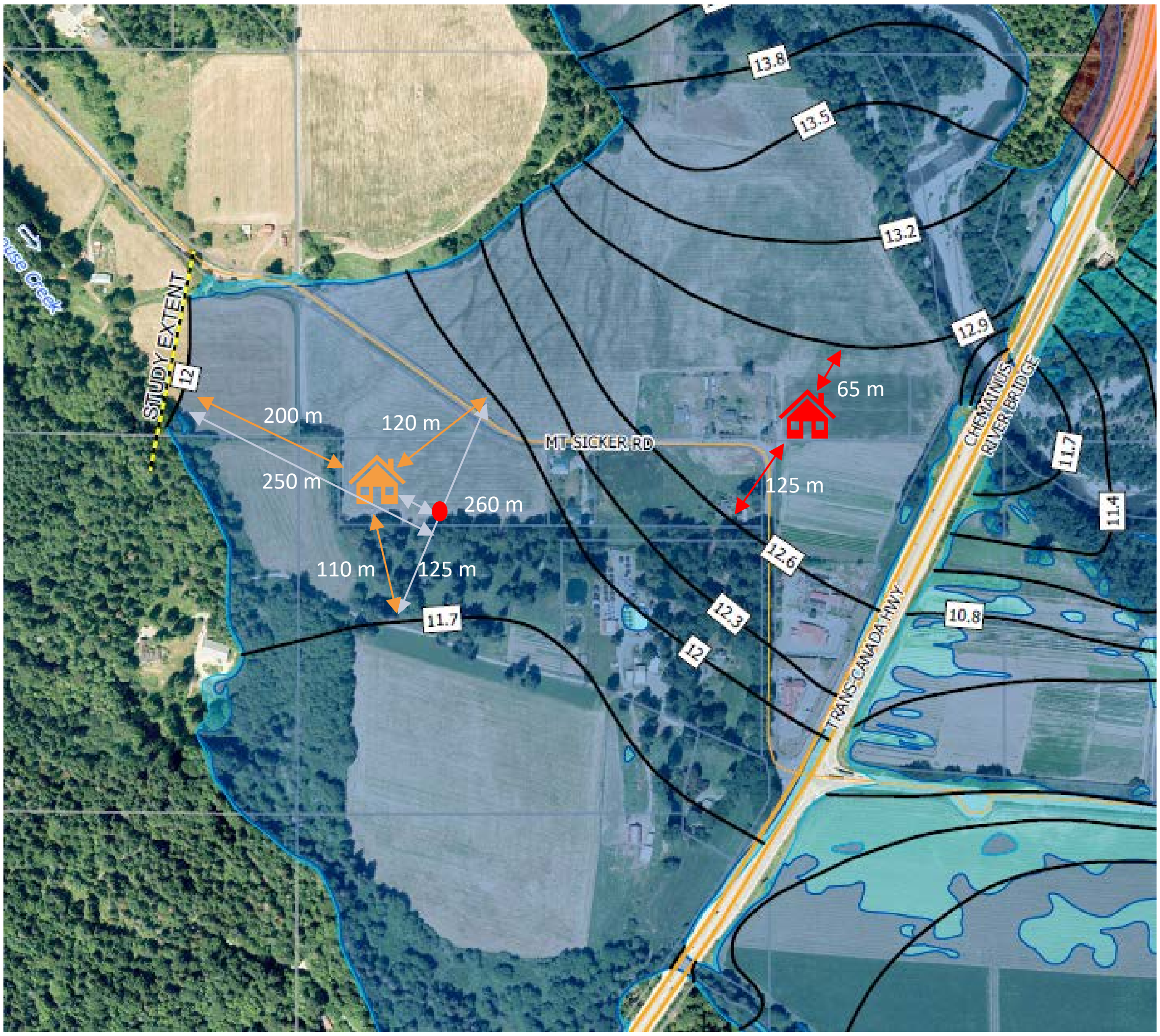

Figure 3.2 FCL calculation example

4 COMPARISON WITH PREVIOUS DESIGNATED FLOODPLAIN MAP

Floodplain maps for the Chemainus floodplain were prepared in 1990. The previous maps developed were based on a branched 1D hydraulic model of the Chemainus channel, main spill channels and Bonsall Creek. This approach was used in order to attempt to represent the overbank spills from the main channel of the Chemainus River. In general, 1D models calculate a single water surface elevation for every cross section and then project that elevation across the floodplain. This is different than a 2D model which calculates the water surface elevation for every cell in the floodplain and allows transfer of water across adjacent cells. This provides spatially varying water levels across channels and floodplains, and results in a more accurate representation of water levels on the floodplain.

The Flood Construction Levels in the 1990 study were derived from two different design floods conditions on the Chemainus River:

- 200-year instantaneous maximum discharge (1,200 m^3/s).
- 200-year mean daily discharge (706 m^3/s).

In 1990 Provincial floodplain mapping guidelines specified that the flood construction levels be determined at each cross section from the higher of two conditions:

- The 200-year instantaneous water level plus 0.3 m of freeboard
- The 200-year daily water level plus 0.6 m of freeboard.

The previous study did not account for future climate change or sea level rise and did not include wave runup effects along the coastal shoreline.

The current study used 0.6 m of freeboard on the instantaneous 200-year plus climate change. Since the adopted design discharges are very similar to the previous study, this means that changes in the FCL are largely due to different freeboard allowance, complex floodplain flow patterns that could not be represented in the 1D model, and morphological changes that have occurred in the river since 1990. Also, higher FCL values near the ocean reflect the effects of future sea level rise (+1 m) as well as wave runup effects.

Figure 4.1 compares the new and previous FCL values. It can be seen that there is a difference in layout of the FCL isolines and on average there is an increase in the FCL values. As explained above, the difference in FCL isoline layout is not surprising given the Chemainus floodplain involves a complicated flow split upstream of Hwy 1 Bridge. This change in pattern means that the increase in FCL is not constant or consistent. In fact, there is a portion of land in Halalt First Nation that's FCL has decreased as result of the updated analysis. The difference in FCL elevations at several point of interest is listed below (Table 4.1). All FCLs are reported in CGVD2013.

Table 4.1 Comparison of FCLs in floodplain for new and historical maps.

Location	Historic FCL (m CGVD2013)	New FCL (m CGVD2013)	Difference (m)
Pinson's Corner (corner of Crofton and Chemainus Rd)	5.65	6.15	0.5
Corner of Halalt Rd and Chemainus Rd	9.65	9	-0.65
Russel Farms	12.0	12.6	0.6
North Cowichan Monitoring Wells	11.15	11.25	0.1

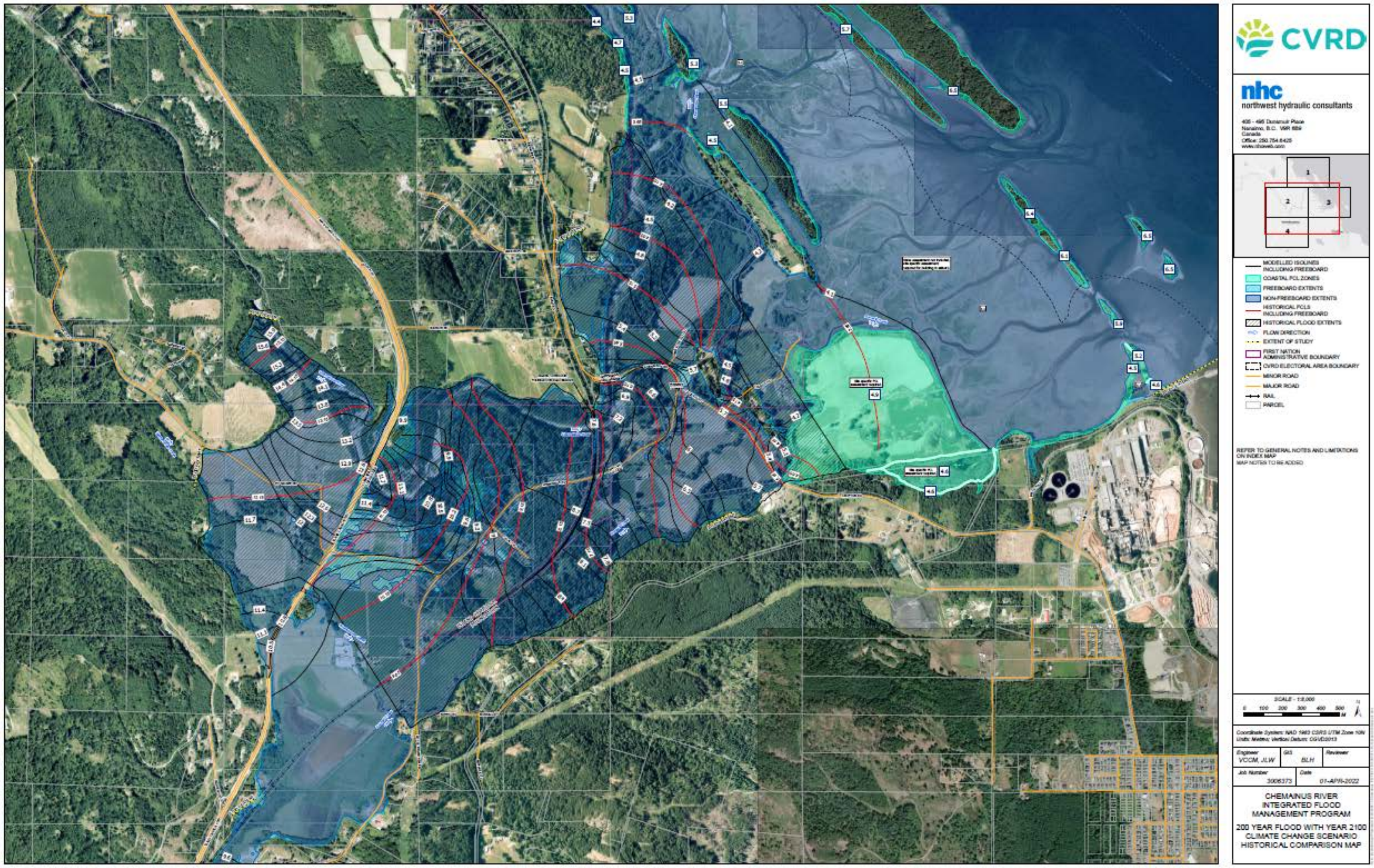

Figure 4.1 Historical floodplain maps comparison

5 CONCLUSIONS

Updated floodplain maps of the Chemainus River and Bonsall Creek were prepared using new surveys and state of the art 2D hydraulic models to represent both riverine and coastal flood construction levels and flood hazards. The adopted design flood conditions represent a 200-year flood event accounting for future climate change and sea level rise in the year 2100.

Important information on the limitations of the floodplain maps and methods for applying the maps to estimate FCL values on the floodplain are described in Section 3.3 and 3.4. This information should be reviewed prior to using the maps. Additional information from the main technical report should also be consulted.

The new flood maps replace and supersede the previously published maps that were issued by the province in 1990.

6 REFERENCES

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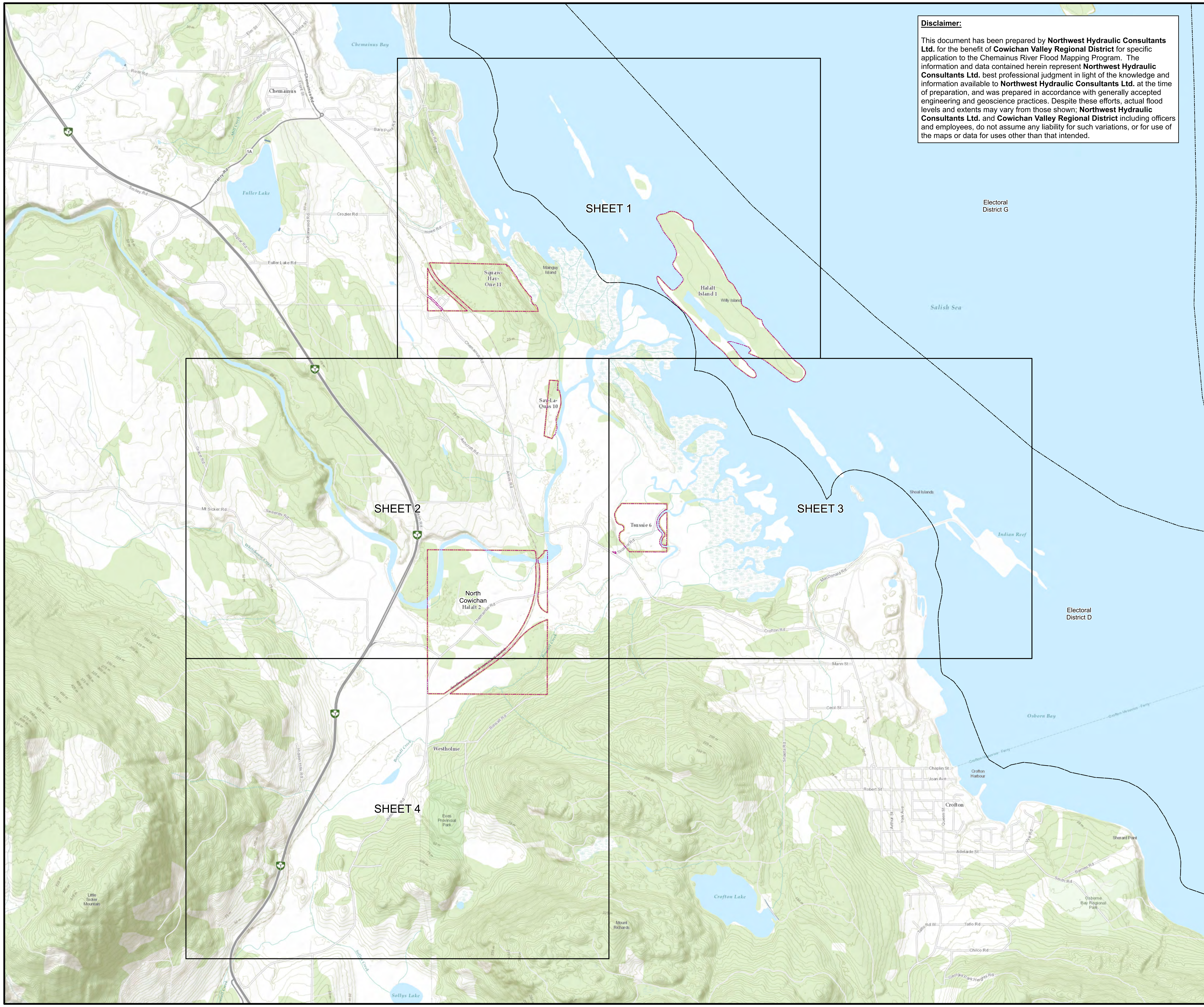
APPENDIX G

FLOOD VELOCITY AND DEPTH MAPS



Disclaimer:

This document has been prepared by **Northwest Hydraulic Consultants Ltd.** for the benefit of **Cowichan Valley Regional District** for specific application to the Chemainus River Flood Mapping Program. The information and data contained herein represent **Northwest Hydraulic Consultants Ltd.** best professional judgment in light of the knowledge and information available to **Northwest Hydraulic Consultants Ltd.** at the time of preparation, and was prepared in accordance with generally accepted engineering and geoscience practices. Despite these efforts, actual flood levels and extents may vary from those shown; **Northwest Hydraulic Consultants Ltd.** and **Cowichan Valley Regional District** including officers and employees, do not assume any liability for such variations, or for use of the maps or data for uses other than that intended.

General Depth - Velocity Map Notes:

1. Please Refer to the Disclaimer.
2. The flood depth and velocity maps were prepared under the Cowichan Valley Regional District's "Chemainus River Flood Mapping Program" by Northwest Hydraulic Consultants Ltd (NHC) in 2021-2022. This study's final report should be consulted prior to use of the flood maps.
3. The maps delineate potential flooding and velocities caused by a designated flood event. Two types of floods are assessed:

a. Riverine floods, having a 200-year return period event with a 20% climate change allowance

b. Coastal flood, having a 200-year return period event + 1 m global sea level rise (with an adjustment for local tectonics) and local wave effects.

4. The future climate change scenario represents plausible conditions in the year 2100. However, the actual time frame for the changes is uncertain.
5. The depths and velocities are based on the maximum values from the designated flood event. Depths do not include freeboard. All hazard layers were modelled with the same parameters and boundary conditions as the design flood.
6. Velocities shown on the map are depth-averaged values. Surface velocities may be higher. The velocities shown on the maps don't include local flow acceleration effects due to obstructions around structures, buildings or debris or local wave effects.

Data Sources:

1. Floodplain topography is based on Lidar flown by GeoBC between October 14, 2018 – October 1, 2019. Chemainus River and immediate overbank topography is based on Lidar acquisitioned by the Cowichan Watershed Board on March 27, 2021 and was provided to NHC by the CVRD.
2. River channel bathymetry on Chemainus River and Bonsall Creek were surveyed by NHC on various dates from May 2021 – June 2021. Offshore bathymetry in Stuart Channel was supplied by Canadian Hydrographic Service (CHS) Non-Navigational 10 m Gridded Bathymetric Data (NONNA-10).
3. Municipal boundaries, and cadastral information were provided by the CVRD and GeoBC.
4. High-resolution orthoimagery flown in June 2019 was provided by the CVRD and displayed on the maps where it exists. 2020 orthoimagery from Esri is displayed where the high-resolution data was not available.

Use and Limitations of Depth - Velocity Maps:

1. Floodplain maps are an administrative tool that depict the potential flood depth, extent, and velocity. They are not designated floodplain maps and should not be used for determining flood levels as they do not include freeboard. Please see the designated floodplain maps prepared for the same study (NHC, 2022) for flood construction levels (FCL).
2. The maps depict the flooding conditions at the time of surveys. Future changes to the river channels, floodplain, and future climate change/sea level rise will render the maps obsolete. The information on the maps should be reviewed after 5 years have elapsed since publication or after any extreme flood occurrence. .
3. Underlying hydraulic analysis assumes channel and shoreline geometry is stationary. Erosion, deposition, degradation, and aggradation are expected to occur and may alter actual observed flood levels and extents. Roads, railways, bridges, new dikes and future developments on the floodplain can restrict water flow and increase local water levels. Obstructions, such as log-jams, blockages, local storm water inflows, groundwater, other land drainage or tributary flows beyond those indicated were not modelled and may cause flood levels to exceed those indicated on the maps. Additionally, flooding may occur outside of the designated boundaries caused by ponding from rainwater on the floodplain, groundwater seepage, or local drainage courses.
4. The floodplain limits have not been established on the ground by legal survey. The accuracy of the flood boundaries is limited by the Lidar base mapping and orthophotography.
5. The flood maps do not represent hazards due to erosion, avulsion, or channel migration. Details on those hazards can be found in the Erosion Hazard Maps prepared in the same study (NHC, 2022).
6. Industry best practices were followed to generate the flood maps. However, actual flood levels and extents may vary from those shown. Residual flood risk beyond that mapped exists for flood events more extreme than the design events; Northwest Hydraulic Consultants Ltd. (NHC) and the Cowichan Valley Regional District do not assume any liability for such variations.

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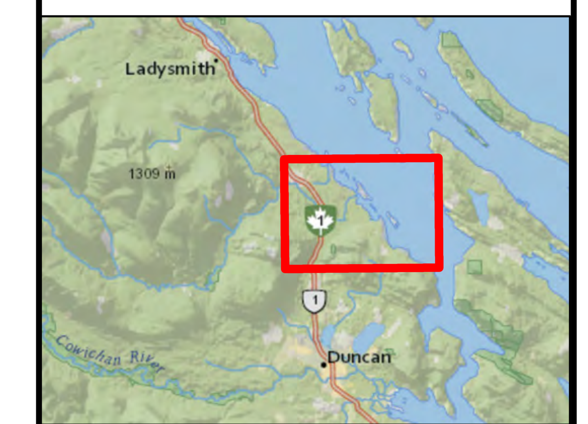


1:5,000 MAP SHEET
FIRST NATION ADMINISTRATIVE BOUNDARY
ELECTORAL AREA BOUNDARY

SCALE - 1:15,000
0 250 500 750 1,000 M

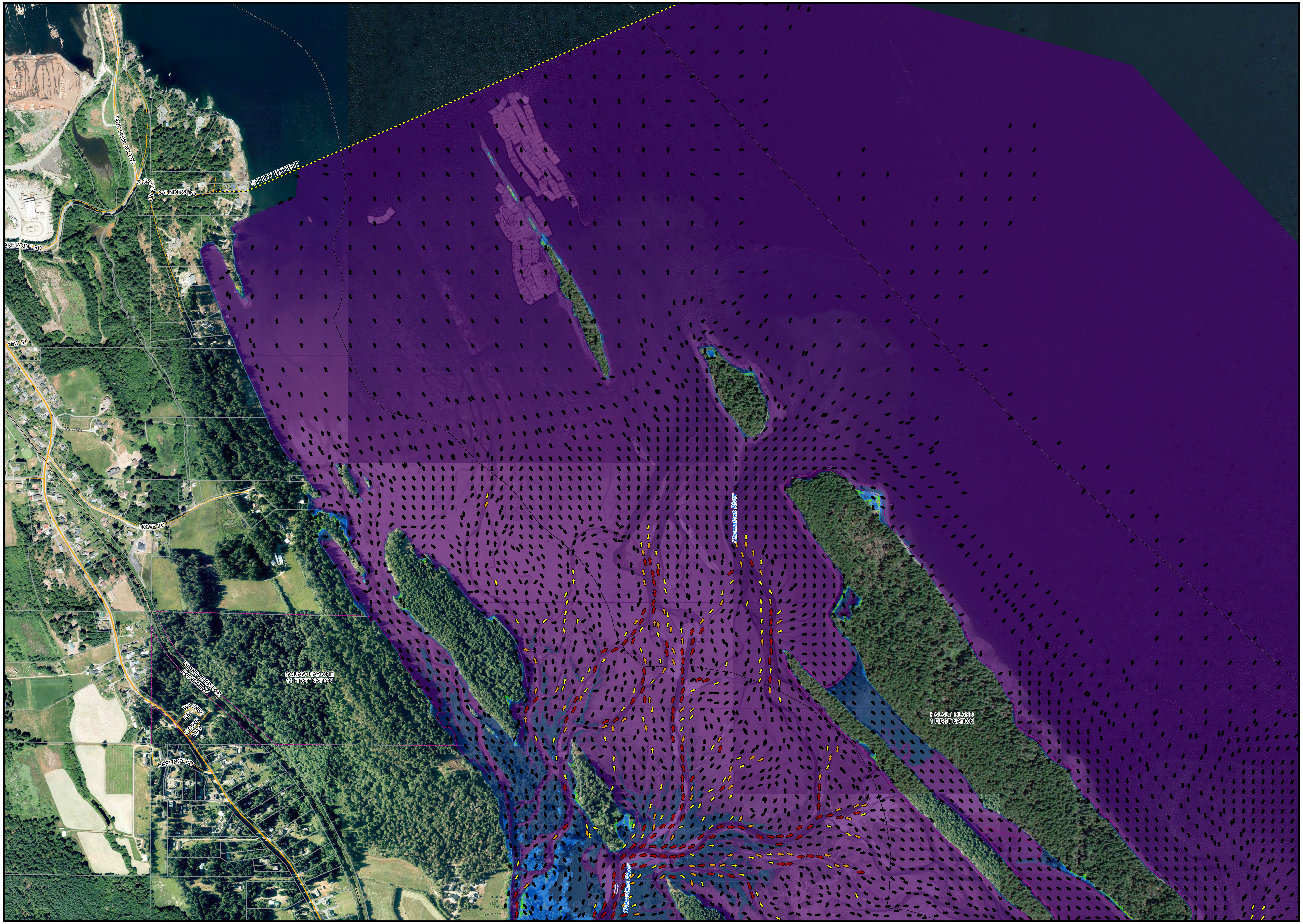
Coordinate System: NAD 1983 CSRS UTM Zone 10N
Units: Metres; Vertical Datum: CGVD2013

Engineer	GIS	Reviewer
VCCM	BLH, SWM	DGM

Job Number	Date
3006373	20-OCT-2022

CHEMAINUS RIVER
FLOOD MAPPING PROGRAM

HAZARD MAPPING
INDEX SHEET



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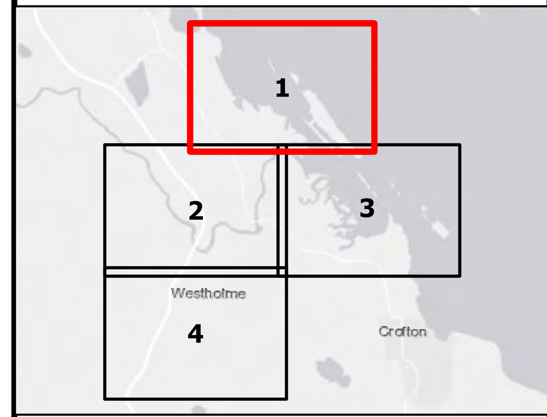

VELOCITY
- < 0.25 m/s
- 0.25 - 0.50 m/s
- 0.50 - 1.00 m/s
- > 1.00 m/s

DEPTH
- 0 to 0.1 m
- 0.1 to 0.3 m
- 0.3 to 0.5 m
- 0.5 to 1.0 m
- 1.0 to 2.0 m
- > 2.0 m
- FLOW DIRECTION
- EXTENT OF STUDY
- FIRST NATION ADMINISTRATIVE BOUNDARY
- CVRD ELECTORAL AREA BOUNDARY
- MINOR ROAD
- MAJOR ROAD
- RAIL
- PARCEL BOUNDARY

REFER TO GENERAL NOTES AND LIMITATIONS ON INDEX MAP

SCALE - 1:5,000

0 100 200 300 M

N

Coordinate System: NAD 1983 CSRS UTM Zone 10N
Units: Metres; Vertical Datum: CGVD2013

Engineer	GIS	Reviewer
VCCM	BLH, SWM	DGM

Job Number	Date
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CHEMAINUS RIVER
FLOOD MAPPING PROGRAM

200 YEAR FLOOD WITH YEAR 2100
CLIMATE CHANGE SCENARIO
FLOOD HAZARD MAP
SHEET 1 OF 4

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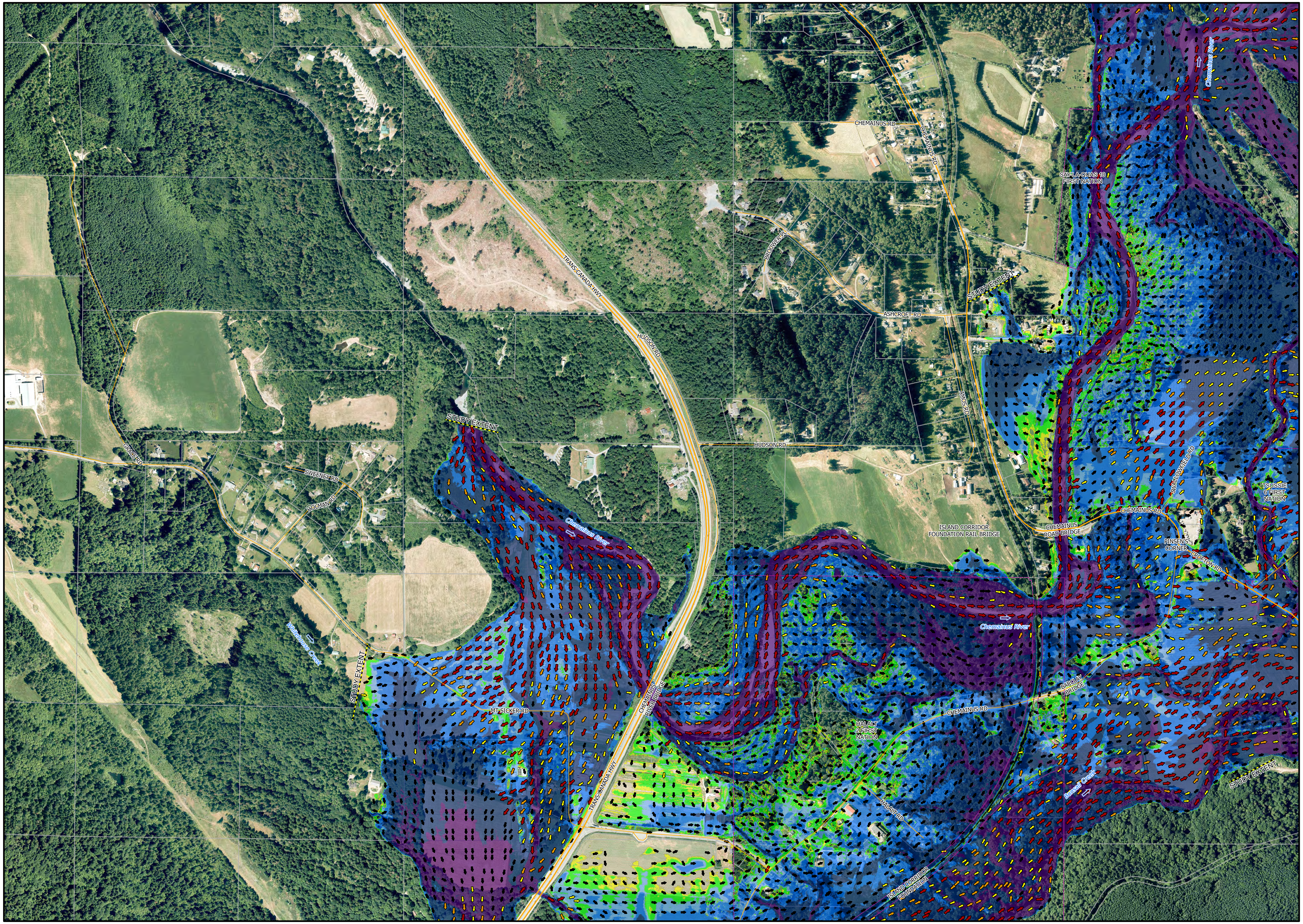

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VELOCITY
- < 0.25 m/s
- 0.25 - 0.50 m/s
- 0.50 - 1.00 m/s
- > 1.00 m/s

DEPTH
- 0 to 0.1 m
- 0.1 to 0.3 m
- 0.3 to 0.5 m
- 0.5 to 1.0 m
- 1.0 to 2.0 m
- > 2.0 m

FLOW DIRECTION
EXTENT OF STUDY
FIRST NATION ADMINISTRATIVE BOUNDARY
CVRD ELECTORAL AREA BOUNDARY
MINOR ROAD
MAJOR ROAD
RAIL
PARCEL BOUNDARY

REFER TO GENERAL NOTES AND LIMITATIONS ON INDEX MAP

SCALE - 1:5,000
0 100 200 300 M
N

Coordinate System: NAD 1983 CSRS UTM Zone 10N
Units: Metres; Vertical Datum: CGVD2013

Engineer	GIS	Reviewer
VCCM	BLH, SWM	DGM

Job Number	Date
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CHEMAINUS RIVER
FLOOD MAPPING PROGRAM

200 YEAR FLOOD WITH YEAR 2100
CLIMATE CHANGE SCENARIO
FLOOD HAZARD MAP
SHEET 2 OF 4

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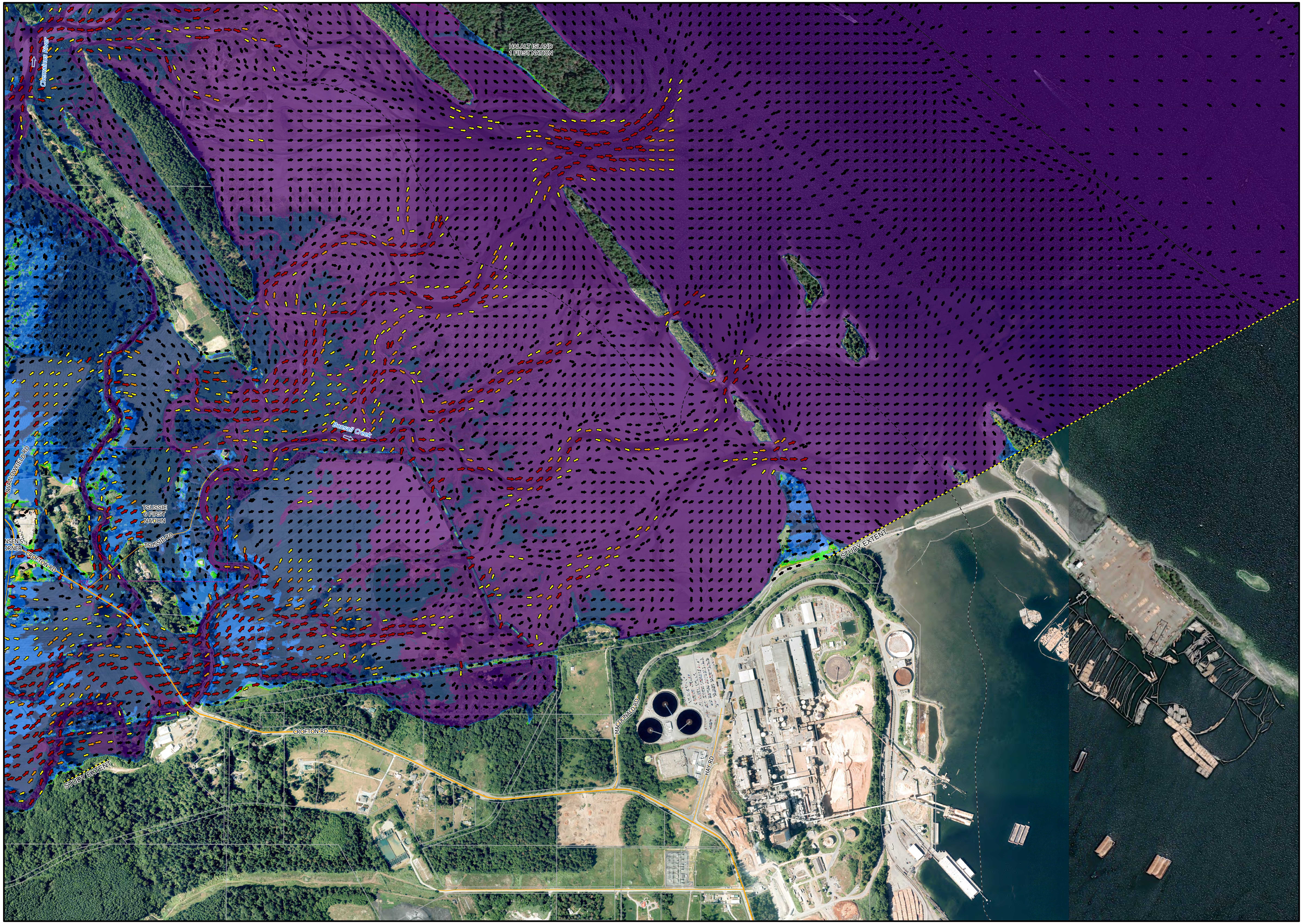
SHEET 2 ↑



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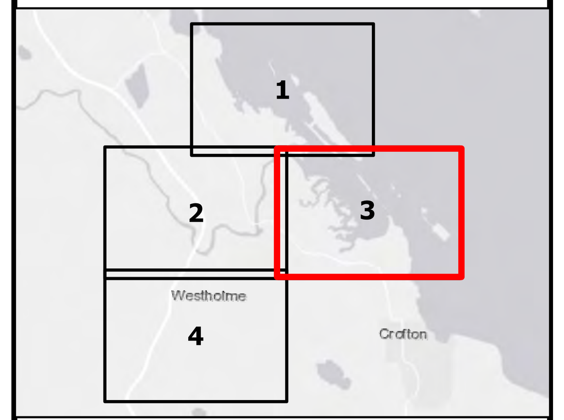

VELOCITY
- < 0.25 m/s
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- > 1.00 m/s

DEPTH
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- FLOW DIRECTION
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- CVRD ELECTORAL AREA BOUNDARY
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- PARCEL BOUNDARY

REFER TO GENERAL NOTES AND LIMITATIONS ON INDEX MAP

SCALE - 1:5,000

0 100 200 300 M

N

Coordinate System: NAD 1983 CSRS UTM Zone 10N
Units: Metres; Vertical Datum: CGVD2013

Engineer	GIS	Reviewer
VCCM	BLH, SWM	DGM

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CHEMAINUS RIVER
FLOOD MAPPING PROGRAM

200 YEAR FLOOD WITH YEAR 2100
CLIMATE CHANGE SCENARIO
FLOOD HAZARD MAP
SHEET 3 OF 4

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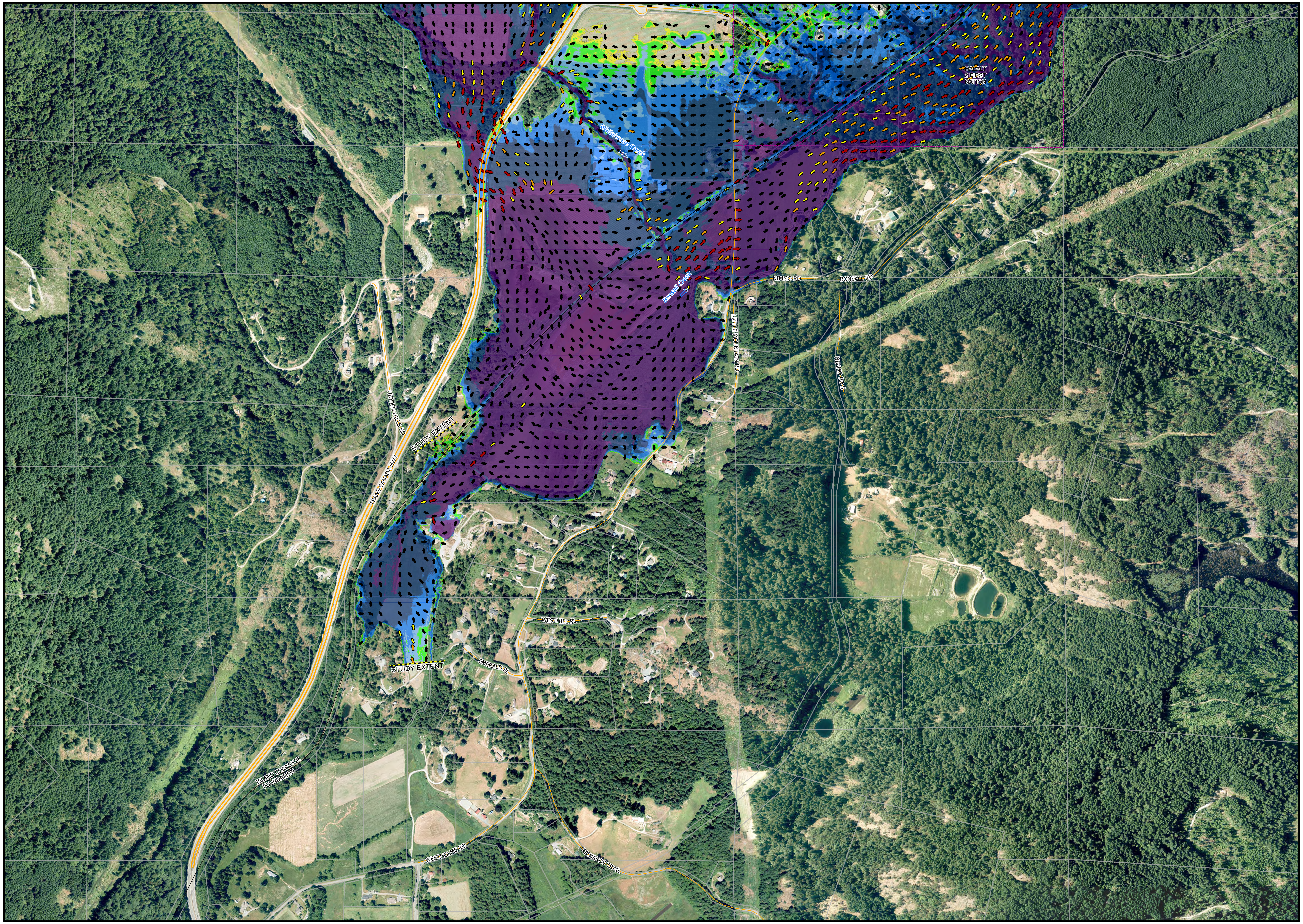

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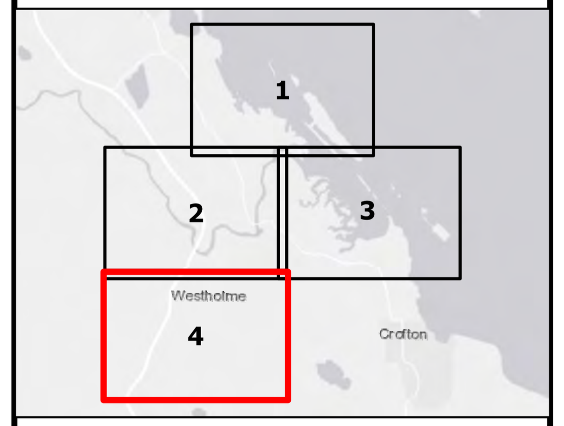

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- > 1.00 m/s

DEPTH
- 0 to 0.1 m
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- 0.5 to 1.0 m
- 1.0 to 2.0 m
- > 2.0 m

FLOW DIRECTION
EXTENT OF STUDY
FIRST NATION ADMINISTRATIVE BOUNDARY
CVRD ELECTORAL AREA BOUNDARY
MINOR ROAD
MAJOR ROAD
RAIL
PARCEL BOUNDARY

REFER TO GENERAL NOTES AND LIMITATIONS ON INDEX MAP

SCALE - 1:5,000
0 100 200 300 M
N

Coordinate System: NAD 1983 CSRS UTM Zone 10N
Units: Metres; Vertical Datum: CGVD2013

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VCCM	BLH, SWM	DGM

Job Number	Date
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CHEMAINUS RIVER
FLOOD MAPPING PROGRAM

200 YEAR FLOOD WITH YEAR 2100
CLIMATE CHANGE SCENARIO
FLOOD HAZARD MAP
SHEET 4 OF 4

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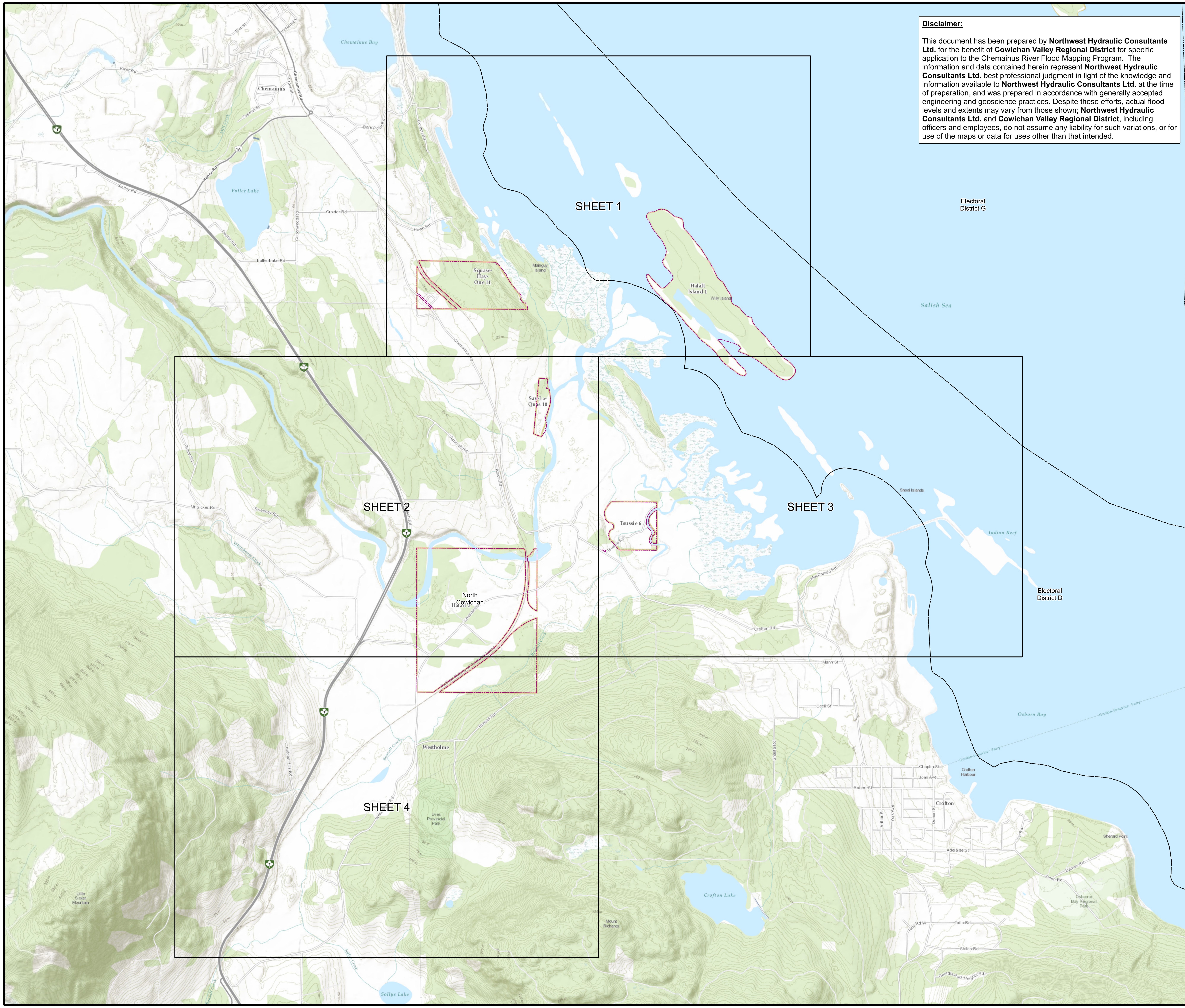
APPENDIX H

DESIGNATED FLOOD MAPS



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General Notes:

1. Please Refer to the Disclaimer.
2. The flood maps were prepared under the Cowichan Valley Regional District's "Chemainus River Flood Mapping Program" by Northwest Hydraulic Consultants Ltd (NHC) in 2021-2022. This study's final report should be consulted prior to use of the flood maps.
3. The maps delineate potential flooding caused by a designated flood event. Two types of floods are assessed:

a. Riverine floods, having a 200-year return period event with a 20% climate change allowance.

b. Coastal floods, having a 200-year return period event + 1 m global sea level rise (with an adjustment for local tectonics) and local wave effects.

4. The future climate change scenario represents plausible conditions in the year 2100. However, the actual time frame for the changes is uncertain.
5. The Flood Construction Levels (FCL) shown on the maps include a freeboard of 0.6 m. It has been added to account for local variations in water level and uncertainty in the design event estimates.
6. All elevations are referenced to Canadian Geodetic Vertical Datum 2013 (CGVD2013).

Data Sources:

1. Floodplain topography is based on Lidar flown by GeoBC between October 14, 2018 – October 1, 2019. Chemainus River and immediate overbank topography is based on Lidar acquisitioned by the Cowichan Watershed Board on March 27, 2021 and was provided to NHC by the CVRD.
2. River channel bathymetry on Chemainus River and Bonsall Creek were surveyed by NHC on various dates from May 2021 – June 2021. Offshore bathymetry in Stuart Channel was supplied by Canadian Hydrographic Service (CHS) Non-Navigational 10 m Gridded Bathymetric Data (NONNA-10).
3. Municipal boundaries and cadastral information were provided by the CVRD and GeoBC.
4. High-resolution orthoimagery flown in June 2019 was provided by the CVRD and displayed on the maps where it exists. 2020 orthoimagery from Esri is displayed where the high-resolution data does not exist.

Use and Limitations of Floodplain Maps:

1. Floodplain maps are an administrative tool that depict the potential flood extent and minimum recommended Flood Construction Levels for the adopted designated flood. A Qualified Professional must be consulted for a site-specific engineering analysis.

a. FCLs are shown on the map as smoothed isolines to create a user-friendly interpretation of FCL. The upstream face or point of any structure should be used to determine the structure's FCL. The FCL can either i) be determined as the next upstream isoline (next greatest) or ii) calculated through interpolation by distance between the isoline upstream and downstream of the upstream face or point of the structure.

2. The maps depict the flooding conditions at the time of surveys. Future changes to the river channels, floodplain, and future climate change/sea level rise will render the maps obsolete. The information on the maps should be reviewed after 5 years have elapsed since publication or after any extreme flood occurrence.
3. Underlying hydraulic analysis assumes channel and shoreline geometry is stationary. Erosion, deposition, degradation, and aggradation are expected to occur and may alter actual observed flood levels and extents. Roads, railways, bridges, new dikes, and future developments on the floodplain can restrict water flow and increase local water levels. Obstructions such as log-jams, blockages, local storm water inflows, groundwater, other land drainage or tributary flows beyond those indicated were not modelled and may cause flood levels to exceed those indicated on the maps. Additionally, flooding may occur outside of the designated boundaries caused by ponding from rainwater on the floodplain, groundwater seepage, or local drainage courses.
4. The floodplain limits have not been established on the ground by legal survey. The accuracy of the flood boundaries is limited by the Lidar base mapping and orthophotography.
5. Isolated areas of inundation smaller than 100 m^2 and some manually flagged areas larger than 100m^2 were removed from the maps. Holes in the inundation extents with areas less than 100 m^2 were also removed.
6. The flood maps do not represent hazards due to erosion, avulsion, or channel migration. Details on those hazards can be found in the Erosion Hazard Maps prepared in the same study (NHC, 2022).
7. Industry best practices were followed to generate the flood maps. However, actual flood levels and extents may vary from those shown. Residual flood risk beyond that mapped exists for flood events more extreme than the design events; Northwest Hydraulic Consultants Ltd. (NHC) and the Cowichan Valley Regional District do not assume any liability for such variations.

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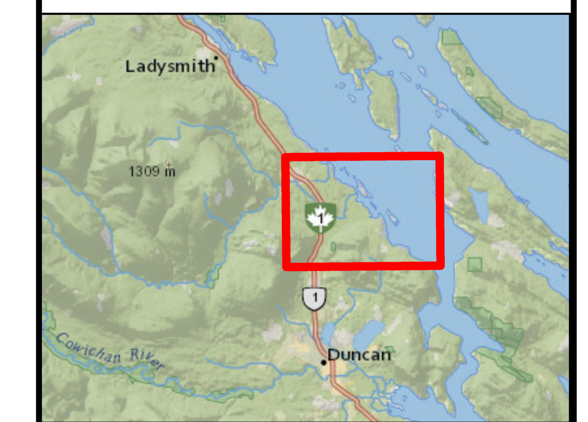

1:5,000 MAP SHEET
FIRST NATION ADMINISTRATIVE BOUNDARY
ELECTORAL AREA BOUNDARY

SCALE - 1:15,000
0 250 500 750 1,000 M
N

Coordinate System: NAD 1983 CSRS UTM Zone 10N
Units: Metres; Vertical Datum: CGVD2013

Engineer	GIS	Reviewer
VCCM	BLH	DGM

Job Number	Date
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CHEMAINUS RIVER
FLOOD MAPPING PROGRAM

FLOODPLAIN MAPPING
INDEX SHEET

SHEET 2 ↓

SHEET 3 ↓

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- RIVERINE FLOOD CONSTRUCTION LEVEL (FCL) INCLUDING FREEBOARD *Labelled with FCLs in metres*
- COASTAL FLOOD CONSTRUCTION LEVEL (FCL) ZONE INCLUDING FREEBOARD *Labelled with FCLs in metres*
- INUNDATION EXTENT - DESIGN WITH FREEBOARD (FCL)
- INUNDATION EXTENT - DESIGN WITHOUT FREEBOARD
- FLOW DIRECTION
- EXTENT OF STUDY
- FIRST NATION ADMINISTRATIVE BOUNDARY
- CVRD ELECTORAL AREA BOUNDARY
- MINOR ROAD
- MAJOR ROAD
- RAIL
- PARCEL BOUNDARY

REFER TO GENERAL NOTES AND LIMITATIONS ON INDEX MAP

SCALE - 1:5,000

0 100 200 300 M

N

Coordinate System: NAD 1983 CSRS UTM Zone 10N
Units: Metres; Vertical Datum: CGVD2013

Engineer	GIS	Reviewer
VCCM	BLH	DGM

Job Number	Date
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CHEMAINUS RIVER
FLOOD MAPPING PROGRAM

200 YEAR FLOOD WITH YEAR 2100
CLIMATE CHANGE SCENARIO
FLOODPLAIN MAP SHEET 1 OF 4

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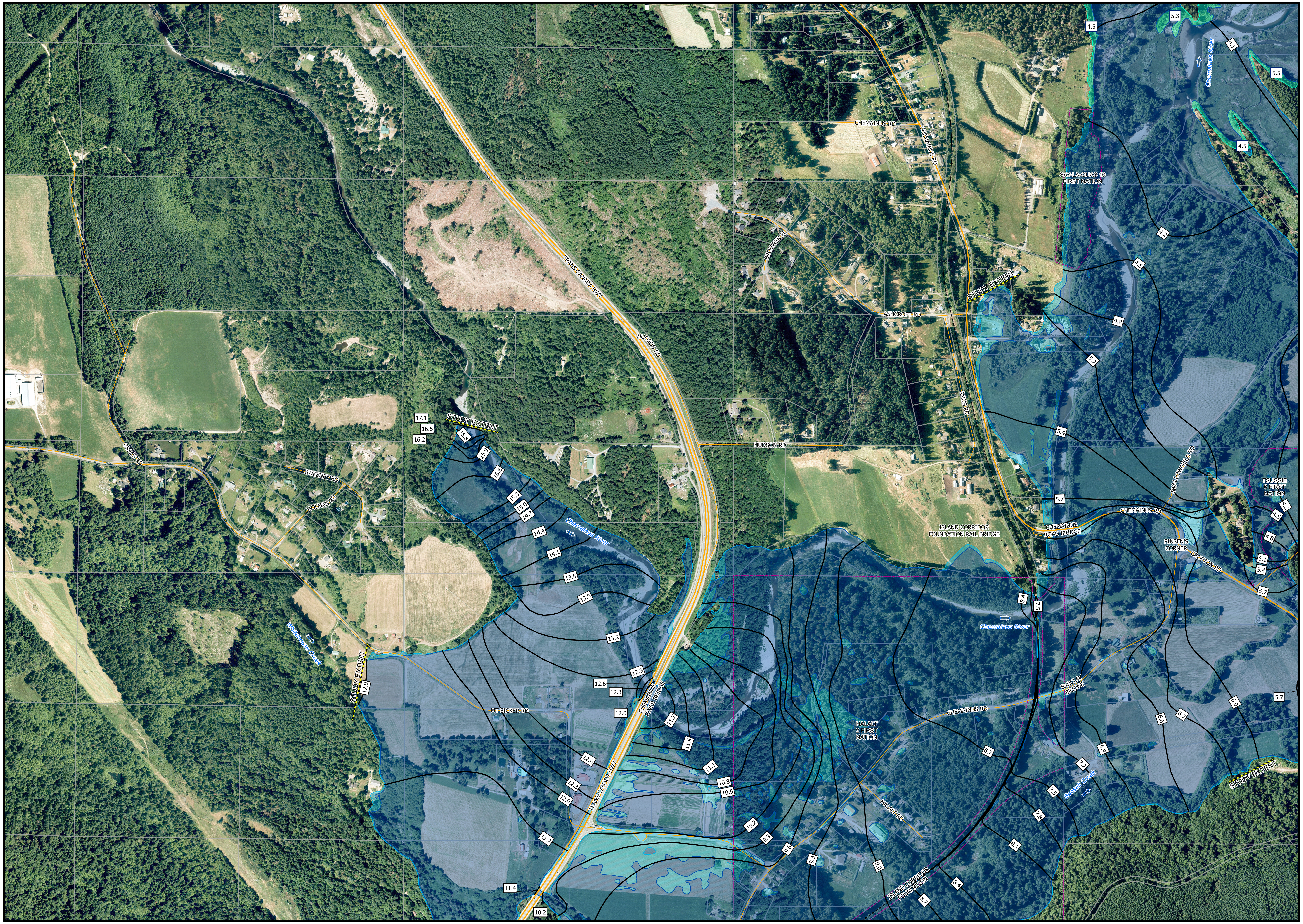

SHEET 4 ↓

SHEET 3 →

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RIVERINE FLOOD CONSTRUCTION LEVEL (FCL) INCLUDING FREEBOARD *Labelled with FCLs in metres*

COASTAL FLOOD CONSTRUCTION LEVEL (FCL) ZONE INCLUDING FREEBOARD *Labelled with FCLs in metres*

INUNDATION EXTENT - DESIGN WITH FREEBOARD (FCL)

INUNDATION EXTENT - DESIGN WITHOUT FREEBOARD

FLOW DIRECTION

EXTENT OF STUDY

FIRST NATION ADMINISTRATIVE BOUNDARY

CVRD ELECTORAL AREA BOUNDARY

MINOR ROAD

MAJOR ROAD

RAIL

PARCEL BOUNDARY

REFER TO GENERAL NOTES AND LIMITATIONS ON INDEX MAP

SCALE - 1:5,000

0 100 200 300 M

N

Coordinate System: NAD 1983 CSRS UTM Zone 10N
Units: Metres; Vertical Datum: CGVD2013

Engineer	*GIS*	*Reviewer*
VCCM	*BLH*	*DGM*

Job Number	*Date*
3006373	*20-OCT-2022*

CHEMAINUS RIVER
FLOOD MAPPING PROGRAM

200 YEAR FLOOD WITH YEAR 2100
CLIMATE CHANGE SCENARIO
FLOODPLAIN MAP SHEET 2 OF 4

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SHEET 1 ↑

SHEET 2 ↑

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- RIVERINE FLOOD CONSTRUCTION LEVEL (FCL) INCLUDING FREEBOARD *Labelled with FCLs in metres*
- COASTAL FLOOD CONSTRUCTION LEVEL (FCL) ZONE INCLUDING FREEBOARD *Labelled with FCLs in metres*
- INUNDATION EXTENT - DESIGN WITH FREEBOARD (FCL)
- INUNDATION EXTENT - DESIGN WITHOUT FREEBOARD
- FLOW DIRECTION
- EXTENT OF STUDY
- FIRST NATION ADMINISTRATIVE BOUNDARY
- CVRD ELECTORAL AREA BOUNDARY
- MINOR ROAD
- MAJOR ROAD
- RAIL
- PARCEL BOUNDARY

REFER TO GENERAL NOTES AND LIMITATIONS ON INDEX MAP

SCALE - 1:5,000

0 100 200 300 M

N

Coordinate System: NAD 1983 CSRS UTM Zone 10N
Units: Metres; Vertical Datum: CGVD2013

Engineer	GIS	Reviewer
VCCM	BLH	DGM

Job Number	Date
3006373	20-OCT-2022

CHEMAINUS RIVER
FLOOD MAPPING PROGRAM

200 YEAR FLOOD WITH YEAR 2100
CLIMATE CHANGE SCENARIO
FLOODPLAIN MAP SHEET 3 OF 4

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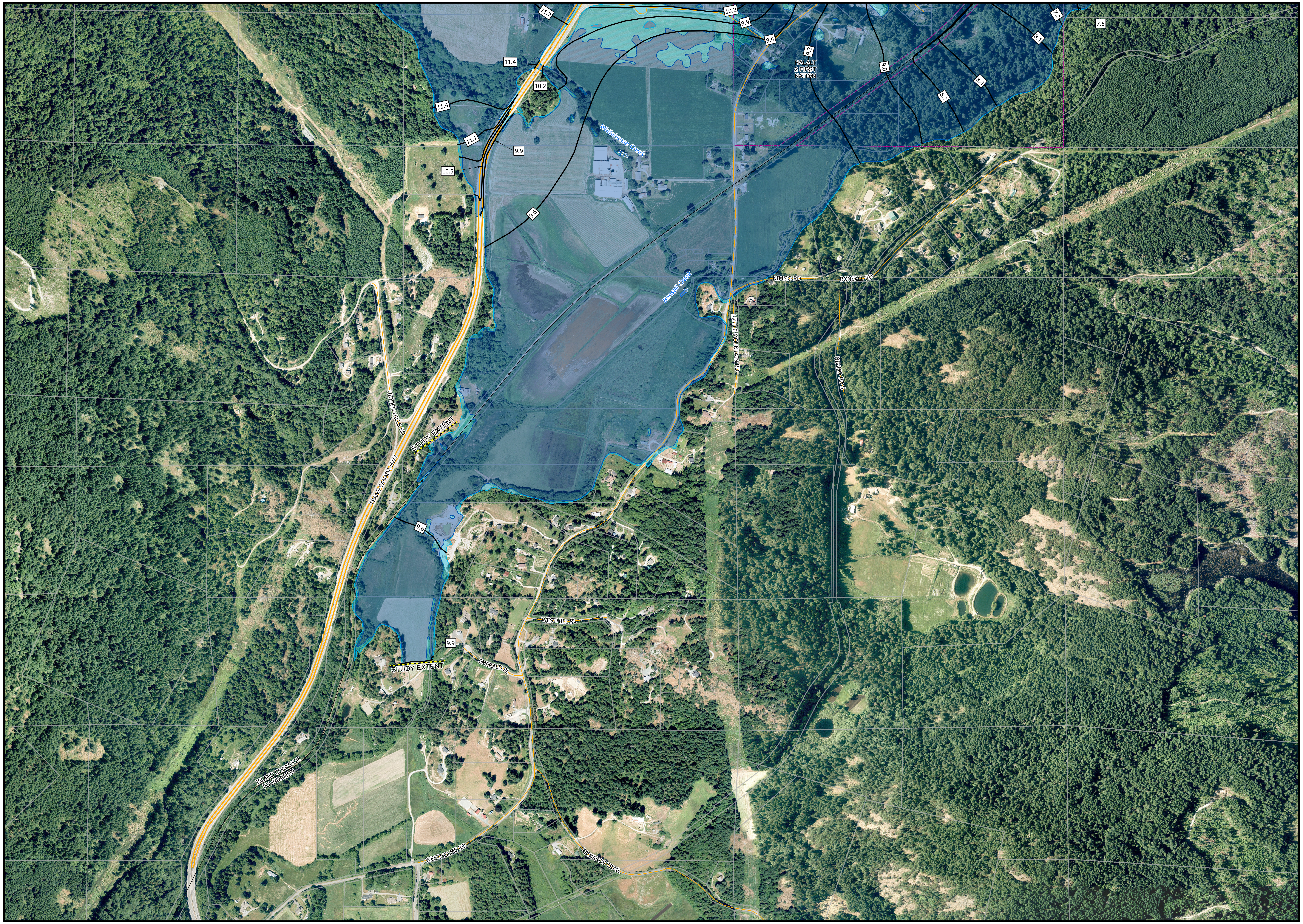
SHEET 2 ↑



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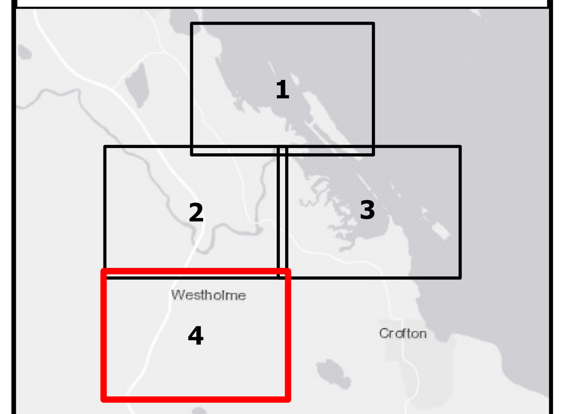


RIVERINE FLOOD CONSTRUCTION LEVEL (FCL) INCLUDING FREEBOARD *Labelled with FCLs in metres*

COASTAL FLOOD CONSTRUCTION LEVEL (FCL) ZONE INCLUDING FREEBOARD *Labelled with FCLs in metres*

INUNDATION EXTENT - DESIGN WITH FREEBOARD (FCL)

INUNDATION EXTENT - DESIGN WITHOUT FREEBOARD

FLOW DIRECTION

EXTENT OF STUDY

FIRST NATION ADMINISTRATIVE BOUNDARY

CVRD ELECTORAL AREA BOUNDARY

MINOR ROAD

MAJOR ROAD

RAIL

PARCEL BOUNDARY

REFER TO GENERAL NOTES AND LIMITATIONS ON INDEX MAP

SCALE - 1:5,000

0 100 200 300 M

N

Coordinate System: NAD 1983 CSRS UTM Zone 10N
Units: Metres; Vertical Datum: CGVD2013

Engineer	*GIS*	*Reviewer*
VCCM	*BLH*	*DGM*

Job Number	*Date*
3006373	*20-OCT-2022*

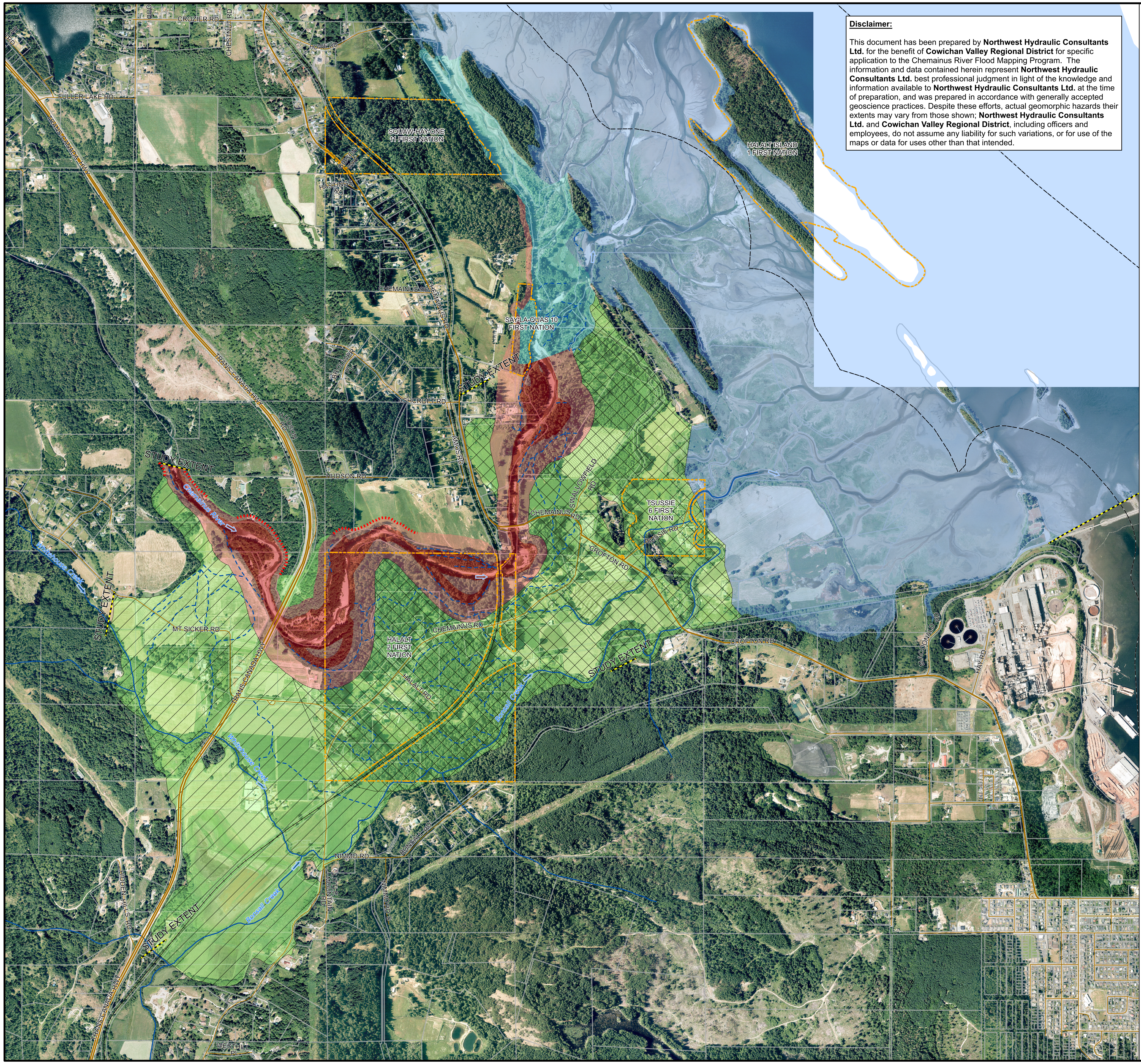
CHEMAINUS RIVER
FLOOD MAPPING PROGRAM

200 YEAR FLOOD WITH YEAR 2100
CLIMATE CHANGE SCENARIO
FLOODPLAIN MAP SHEET 4 OF 4

BLH, \\mainfile-nan\Projects\Active\3006373 Chemainus IFMP\95 GIS\3006373_BLH_MapSheetLayout1.aprx

APPENDIX I

GEOMORPHIC HAZARD MAP



Disclaimer:

This document has been prepared by **Northwest Hydraulic Consultants Ltd.** for the benefit of **Cowichan Valley Regional District** for specific application to the Chemainus River Flood Mapping Program. The information and data contained herein represent **Northwest Hydraulic Consultants Ltd.** best professional judgment in light of the knowledge and information available to **Northwest Hydraulic Consultants Ltd.** at the time of preparation, and was prepared in accordance with generally accepted geoscience practices. Despite these efforts, actual geomorphic hazards their extents may vary from those shown; **Northwest Hydraulic Consultants Ltd.** and **Cowichan Valley Regional District**, including officers and employees, do not assume any liability for such variations, or for use of the maps or data for uses other than that intended.

General Notes:

1. Please Refer to the Disclaimer.
2. The geomorphic hazard map was prepared under the Cowichan Valley Regional District's "Chemainus River Flood Mapping Program" by Northwest Hydraulic Consultants Ltd (NHC) in 2021-2022. This study's final report, Chemainus River Flood Mapping Program Part 1 – Floodplain Mapping, should be consulted prior to use of the geomorphic hazard maps.
3. The map delineates areas that are susceptible to channel and shoreline migration hazards. Seven types of geomorphic hazards are identified:

3.1. Modern Valley Bottom (MVB): Area where channel migration has likely occurred in the past several thousand years and is susceptible to occurring under the present-day hydroclimate regime.

3.2. Historical Channel Migration Zone (HMZ): Area that the channel occupied in the historical record, based on available imagery and survey data. This area is also susceptible to erosion and avulsion hazards.

3.3. Channel Erosion Hazard Zone (EHZ): Area susceptible to bank erosion by stream flow over a 60-year planning horizon. This area is also susceptible to avulsion hazards.

3.4. Avulsion Hazard Zone (AHZ): Area that is susceptible to avulsion. This area may also be susceptible to estuary distributary channel hazards in tidally influenced areas. The AHZ is classified into two categories:

3.4.1. First-order avulsion: sudden and major shift to a new part of the floodplain

3.4.2. Second-order avulsion: sudden reoccupation of an old channel on the floodplain. Second-order avulsion zones may also be subject to first-order avulsions.

3.5. Potential Geotechnical Hazard (Unrated): Area with steep slopes within the channel erosion hazard zone, which may become geotechnically unstable due to inundation or erosion of the toe of the slope. A geotechnical assessment is required to determine an appropriate geotechnical setback for land that may potentially be subject to any potential geotechnical hazards. Only steep slopes within 10 m of the erosion hazard zone boundary were flagged as potential geotechnical hazards. Additional steep slope hazards not flagged may exist outside areas identified as potential geotechnical hazard.

3.6 Estuary Distributary Channel Hazard Zone (DHZ): Relatively lower gradient area influenced by tidal processes and susceptible to the formation of distributary channels. This area is also susceptible to channel erosion and avulsion hazards.

3.7 Coastal Erosion Hazard Zone (CHZ): Landward extent of area likely to be susceptible to erosion from tidal currents and waves generated during coastal storms, with 1 m sea level rise. This area is also susceptible to channel erosion, avulsion, and estuary distributary channel hazards.

Data Sources:

1. Geomorphic hazard zones were developed in part using floodplain topography information based on Lidar flown by GeoBC between October 14, 2018 – October 1, 2019 and Chemainus River and immediate overbank topography information based on Lidar acquisitioned by the Cowichan Watershed Board on March 27, 2021. Data was provided to NHC by the CVRD.
2. Geomorphic hazard zones were developed in part using river channel bathymetry on Chemainus River and Bonsall Creek, surveyed by NHC on various dates from May 2021 to June 2021. Offshore bathymetry in Stuart Channel was supplied by Canadian Hydrographic Service (CHS) Non-Navigational 10 m Gridded Bathymetric Data (NONNA-10).
3. Municipal boundaries and cadastral information were provided by the CVRD and GeoBC. High-resolution orthoimagery flown in June 2019 was provided by the CVRD and displayed on the maps where it exists. 2020 orthoimagery from Esri is displayed where the high-resolution data does not exist.

Use and Limitations of Geomorphic Hazard Maps:

1. Geomorphic hazard maps are an administrative tool that depict the potential extent of geomorphic hazards for a given planning horizon. However, a Qualified Professional must be consulted for a site-specific analysis of geomorphic hazards.
2. In the context of this mapping, geomorphic hazards refer specifically to hazards associated with channel avulsion, lateral channel instabilities and shoreline erosion. The geomorphic hazard limits have not been established on the ground by legal survey. The accuracy of the geomorphic hazard boundaries is limited by the Lidar base mapping and orthophotography.
3. The geomorphic hazard maps do not represent flood levels or extents. Details on flooding, including Flood Construction Levels, can be found in the Flood Maps prepared in the same study (NHC, 2022).
4. The maps depict the geomorphic hazard potential at the time that the surveys, field investigations and desktop-based assessment was carried out. Future changes to the river channels, floodplain, and future climate change or sea level rise will render the maps obsolete. The information on the maps should be reviewed after 5 years have elapsed since publication or after any extreme flood occurrence, or if the physical conditions of the watershed or floodplain substantially change.
5. Geotechnical hazards were not analyzed as a part of this study. Areas with steep slopes within the erosion hazard zone have been flagged, but these areas have not undergone a geotechnical assessment. Areas with steep slopes may exist outside the erosion hazard zone and such areas have not been flagged. A geotechnical assessment is required to identify and evaluate potential geotechnical hazards.
6. The geomorphic hazard analysis performed was limited only to the Chemainus River reach located within the map study extents. The geomorphic hazard zones delineated on this map do not include the geomorphic hazard potential from channel processes on Bonsall Creek, Whitehouse Creek, or other tributaries to the Chemainus River.
7. The hazard maps do not include other hazards, such as those associated with stormwater, fire, seismic, geotechnical, wildlife, etc. The maps do not account for other, uncertain future changes that could alter the landscape and may alter the geomorphic hazard potential, nor do they account for sediment sources, terrain assessment, or assessment of the potential or frequency of slope instabilities, debris flow, debris flood, potential for channel jamming and outburst flooding, or hyper-concentrated flow. Additional, undetected geomorphic hazards may exist on the Chemainus River upstream of the map extent; Northwest Hydraulic Consultants Ltd. (NHC) and the Cowichan Valley Regional District do not assume any liability for such variations.

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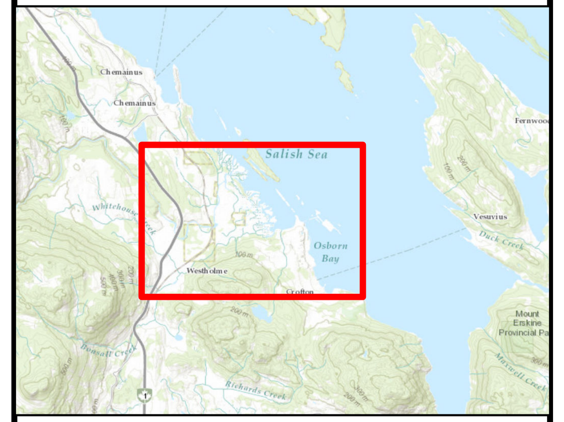

- MODERN VALLEY BOTTOM
- HISTORICAL MIGRATION ZONE
- CHANNEL EROSION HAZARD ZONE
- FIRST ORDER AVULSION HAZARD ZONE
- SECOND ORDER AVULSION HAZARD ZONE
- POTENTIAL GEOTECHNICAL HAZARD FLAG
- ESTUARY DISTRIBUTARY CHANNEL HAZARD ZONE
- COASTAL HAZARD ZONE
- FLOW DIRECTION
- EXTENT OF STUDY
- FIRST NATION ADMINISTRATIVE BOUNDARY
- CVRD ELECTORAL AREA BOUNDARY
- MINOR ROAD
- MAJOR ROAD
- RAIL
- PARCEL BOUNDARY
- DETECTED RELIC CHANNEL PATHS
- CREEKS

REFER TO GENERAL NOTES AND LIMITATIONS ON MAP

SCALE - 1:10,000

0 210 420 630 M

N

Coordinate System: NAD 1983 CSRS UTM Zone 10N
Units: Metres; Vertical Datum: CGVD2013

Geomorphologist	GIS	Reviewer
WPH, IBK, RAM	IBK, RAM	WPH

Job Number	Date
3006373	20-OCT-2022

CHEMAINUS RIVER
INTEGRATED FLOOD
MANAGEMENT PROGRAM

GEOMORPHIC HAZARD MAP
SHEET 1 OF 1