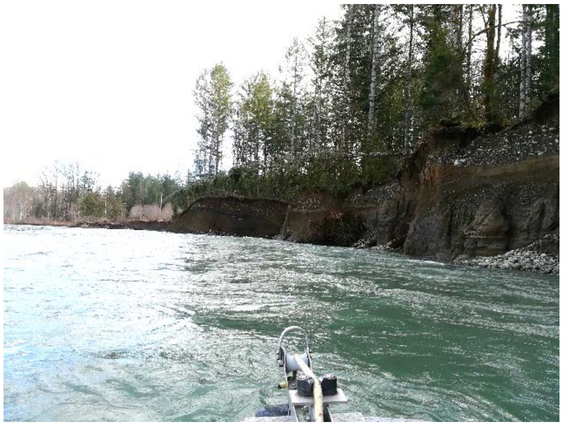

COWICHAN RIVER - RIVERBOTTOM ROAD AREA FLOOD AND EROSION HAZARD MAPPING

FINAL REPORT – REVISION 1

Prepared for:

Cowichan Valley Regional District
Duncan, BC

3 September 2020

NHC Ref. No. 3004940

northwest hydraulic consultants
water resource specialists

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Cowichan Valley Regional District
175 Ingram Street, Duncan, BC

Prepared by:

Northwest Hydraulic Consultants Ltd.
Nanaimo, BC

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CREDITS AND ACKNOWLEDGEMENTS

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The following staff from NHC participated in this study:

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EXECUTIVE SUMMARY

In July 2019, the Cowichan Valley Regional District (CVRD) retained Northwest Hydraulic Consultants Ltd. (NHC) to conduct updated floodplain mapping studies for the lower Cowichan-Koksilah River. The CVRD subsequently requested that NHC carry out a concurrent study for an 11 km reach of the upper Cowichan River near Riverbottom Road. Previous floodplain and erosion hazard maps of the Riverbottom Road area were last produced by BC Ministry of Environment (1997) and Hardy BBT Ltd. (1989).

This report provides information on project methodologies, key findings, and deliverables, including updated floodplain and erosion hazard mapping products. The main components of the project included:

- Background information and review of existing studies and data;
- Field investigations;
- Hydrological studies, including an assessment of the designated 200 year flood for a future (Year 2100) climate change scenario;
- Hydraulic modelling and floodplain delineation;
- Erosion hazard mapping; and
- Updated floodplain and erosion hazard maps (referred to in this report as channel migration zone maps).

The field investigations included a bathymetric survey of the Cowichan River within the study reach, as well as topographic check point surveys to verify 2019 LiDAR data quality. An overview geomorphic field assessment was carried out to characterize the river's morphology and stability. A site visit was completed during the significant flood of 1 February 2020, to survey high water marks and document flood impacts.

A hydraulic model was developed to determine flood levels in the study reach under design conditions. Hydrologic inputs to the model were adapted from the lower Cowichan-Koksilah River study and included consideration of future climate change. The model geometry was developed using the bathymetric and LiDAR data. Model calibration and validation were carried out using continuous water surface profile surveys and high water mark surveys from the 1 February flood. A sensitivity analysis was completed to assess the potential uncertainties in the modelling results, and a design freeboard was developed on this basis.

The modelling outputs and freeboard were used to develop two floodplain mapping products. The first depicts inundation extents and depths under 200-year flood conditions, with no freeboard. The second depicts inundation extents under 20-year flood conditions and 200-year flood conditions. The 200-year flood condition includes freeboard and represents the Flood Construction Levels (FCL) for the study reach. The second mapping product is suitable for regulatory and land-use planning purposes.

Channel Migration Zone (CMZ) mapping was carried out using available imagery, soils and surficial geology mapping, and topographic data supplemented by field investigations. The CMZ focussed on two primary channel processes: channel erosion and channel avulsions. The CMZ mapping shows two hazard areas: 1) the Modern Valley Bottom (MVB), which includes areas potentially susceptible to future channel migration or channel avulsions, and 2) the Erosion Hazard Area (EHA), which includes areas potentially susceptible to future channel erosion. The CMZ mapping is intended to provide a planning level boundary to inform land development considerations on the potential for future channel erosion or other channel processes. It does not include a geotechnical analysis of any banks, terraces, or valley slopes which could require the assignment of additional development setbacks.

The following summarizes key recommendations from the study:

- The floodplain and channel migration zone maps should be consulted together to assess overall hazards to the study area. Both mapping products are administrative tools only, and any site-specific engineering analysis must be completed by a Qualified Professional.
- The floodplain and channel migration zone maps depict the flooding conditions at the time of surveys. Future changes to the river channels, floodplain, and future climate; a large geotechnical event due to land instabilities at the site or farther upstream; or a channel avulsion or other event that substantially alters the supply of sediment and logs to the study reach will render site-specific map information obsolete. The information on the maps should be reviewed after 10 years have elapsed since publication or after any large flood occurrence (similar to or greater than the 2020 flood).
- The major avulsion that occurred in 2020 has significantly altered the local river hydraulics both upstream and downstream of the avulsion channel. Several other incipient avulsion paths have been identified, which could further modify river hydraulics and flood levels along the river. Regular monitoring should be carried out to assess how the river is reacting to the unusual events in 2020. Monitoring should be conducted annually, during the early part of the summer low flow period. Log jams, sediment accumulation, erosional features, and altered channel patterns should be identified and interpreted to inform the need for channel management. Monitoring conducted using a fixed wing aircraft, helicopter, or unmanned aerial vehicle (UAV) would provide a channel scale vantage point of the river system.

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1 INTRODUCTION

1.1 Project Overview and Objectives

In December 2019, the Cowichan Valley Regional District (CVRD) retained Northwest Hydraulic Consultants Ltd. (NHC) to conduct updated floodplain and erosion hazard mapping studies along a 11 km reach of the upper Cowichan River near Riverbottom Road. The objectives of the study include:

- Updating hydraulic modelling analyses for the reach;
- Developing floodplain maps, including delineation of floodway and flood fringe zones; and
- Developing channel migration zone maps.

This report summarizes methods, key findings, and deliverables for the Riverbottom Road floodplain mapping study, including:

- Background information and review of existing studies and data;
- Field investigations;
- Hydrological analysis to estimate flood flows under historic and a future (Year 2100) climate change scenario;
- Hydraulic modelling and floodplain delineation;
- Erosion hazard mapping; and
- Updated floodplain and erosion hazard maps (referred to in this report as channel migration zone maps).

1.2 Study Location

Cowichan River near Riverbottom Road is an approximately 14 km long river reach located downstream of Cowichan Lake and upstream of Duncan, BC. **Figure 1** provides an overview of the study area.

Land use within the study area generally consists of rural residential properties and forested land. CVRD electoral areas within the study area include Electoral Area E (Cowichan Station/Sahtlam/Glenora) and Electoral Area F (Cowichan Lake South/Skutz Falls). There are two First Nations reservations located within the study area (Kakalatza 6 and Tzart-Lam 5).

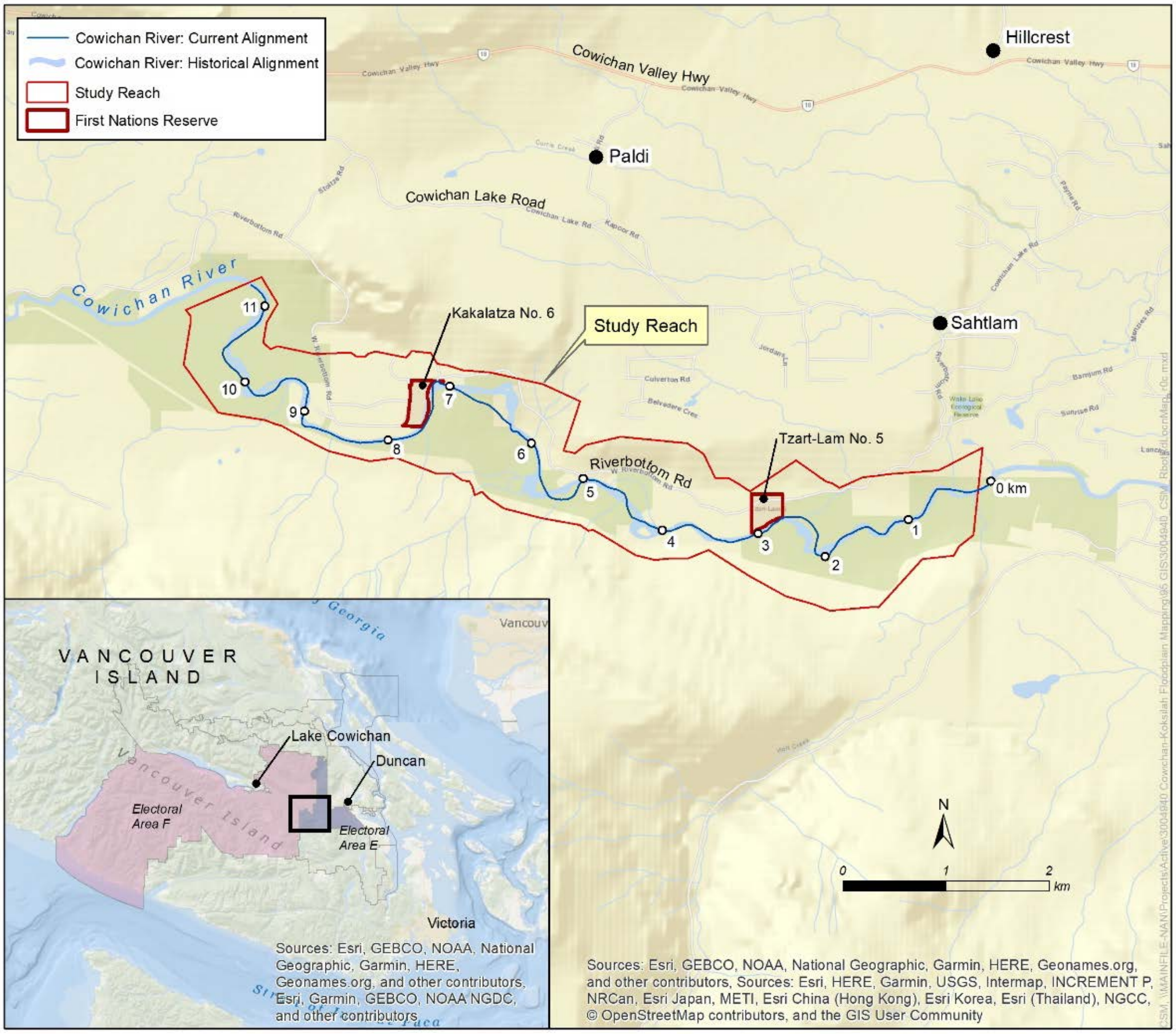


Figure 1: Overview of study area

1.3 Flood Hazard Assessment Guidelines

1.3.1 Floodplain Mapping

The following publications have been consulted to plan the modelling and floodplain mapping tasks in this investigation:

- Natural Resources Canada, and Public Safety Canada (2019a). *Federal Geomatics Guidelines for Flood Mapping, Version 1.0* (General Information Product 114e). Government of Canada. 59 pp

- Natural Resources Canada, and Public Safety Canada (2019b). *Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation, Version 1.0* (General Information Product 114e). Government of Canada. 75 pp.
- Natural Resources Canada, and Public Safety Canada (2018b). *Federal Flood Mapping Framework, Version 2.0* (General Information Product 112e). Natural Resources Canada. 28 pp
- EGBC (2018). *Legislated Flood Assessments in a Changing Climate in BC, Version 2.1*. Engineers & Geoscientists British Columbia, Burnaby, BC. 192 pp.
- FLNRORD (2018). *Flood Hazard Area Land Use Management Guidelines*. Ministry of Forests, Lands, Natural Resource Operations and Rural Development.
- 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.

1.3.2 Erosion Hazard Mapping

There are no specific guidelines in BC for preparing erosion hazard or channel migration zone maps on rivers subject to channel shifting, meander migration and avulsions. The following publications from Washington State have been consulted to plan the erosion hazard mapping tasks in this investigation:

- Olson et al. (2014). *A Methodology for Delineating Planning-Level Channel Migration Zones.* Washington State Department of Ecology, Olympia, Washington.
- Legg, N.T., and Olson P.L. (2014). *Channel Migration Processes and Patterns in Western Washington: A Synthesis for Floodplain Management and Restoration*. Washington State Department of Ecology, Olympia, Washington.
- Rapp, R.G., and Abbe, T.B. (2003). *A Framework for Delineating Channel Migration Zones.* Washington State Department of Ecology, Washington State Department of Transportation. Ecology Final Draft Publication #03-06-027.

The approach described in these references was considered appropriate because the geomorphic setting and types of river instability in Washington State and Vancouver Island are similar.

2 PREVIOUS STUDIES

2.1 Hardy BBT Ltd. (1989)

Hardy BBT Ltd. (1989) conducted a channel stability assessment of the Cowichan River in the Riverbottom Road reach. The purpose of the study was to assist the CVRD in regulating development by assessing the risk of erosion and flooding on this section of the Cowichan River. The study established a hazard map showing areas where river erosion (and associated flooding) are likely to occur. This process involved preparing channel shift maps from historical aerial photography (1958, 1972, and 1986) and 1:5000 scale cadastral mapping to delineate channel changes with time. The analysis showed that a substantial part of the upper 10.9 km reach was characterized by significant lateral erosion and channel shifting. A hazard map was prepared delineating zones having varying flood and erosion potential:

- Zone A: represents land that was unconditionally unsuitable for development based on the estimated potential for lateral erosion within a 50-year planning horizon. The zone was delineated by assuming future river movement could fall within a band 30 m from each side of the Zone A boundary.
- Zone B: represents land that was conditionally suitable for development based on an assessment of erosion and flooding hazards. Within this zone, the land was reportedly beyond the probable limits of erosion within the 50-year planning horizon but may still be subject to flooding.
- Zone C: represents land that was determined to be unconditionally suitable for development as these areas were identified to lie beyond the interpreted zone of lateral erosion and flooding.

2.2 BC Ministry of Environment (1997)

The BC Ministry of Environment (MoE) (1997) subsequently published floodplain maps on the Riverbottom Road reach. The surveys of the river channel were carried out in 1991. Flood discharges for the analysis were based on the WSC gauge Cowichan River at Duncan (08HA002), with discharges as follows:

- 20-year instantaneous and daily average discharges: 523 and 453 m^3/s
- 200-year instantaneous and daily average discharges: 700 and 600 m^3/s

These values were identical to the flows used for the lower river at Duncan, which is a conservative assumption since the drainage area for the Riverbottom Road area is substantially smaller than at Duncan.

The hydraulic model used for the analysis was calibrated using 8 high water marks obtained after the 4 December 1990 flood event. This flood event had a 2- to 5-year return period. Flood flows used for calibration were also based on the WSC gauge at Duncan.

Flood construction levels (FCLs) were determined using the 200-year average daily discharge (600 m^3/s) with a freeboard of 0.6 m.

2.3 CVRD Climate Change Projections (2017)

The CVRD publication Climate Change Projections for the Cowichan Valley Regional District (2017) provides estimates of key climate change indicators for CVRD watersheds. The estimates are based on RCP8.5 climate change scenario, corresponding to “business as usual” greenhouse gas emissions.

The publication differentiates three watershed types in its analysis: Developed area watersheds, water supply watersheds, and west coast watersheds. The upper Cowichan River watershed is classified as a water supply watershed, while the lower watershed below Lake Cowichan is classified as a developed area watershed.

For flood hydrology at Riverbottom Road, the most important climate change indicator is extreme precipitation. Snowpack has some influence, and rain-on-snow events can result in severe flooding. However, the climate change projections report does not investigate the potential impacts of climate change on rain-on-snow events.

Extreme precipitation indicators for the developed area and water supply watersheds are summarized in **Table 1**. Mean estimates correspond to the mean of RCP8.5 ensemble predictions, while estimate ranges correspond to the 10th and 90th percentiles of the ensemble predictions.

Table 1: CVRD key climate change projections for developed area watersheds

Climate Change Indicator	2050s Change	2080s Change
Developed Area Watersheds		
24-Hour annual maximum precipitation	Mean estimate: +16% Range: 3 to 31%	Mean estimate: +30% Range: 10 to 46%
5-Day annual maximum precipitation	Mean estimate: +10% Range: 4 to 21%	Mean estimate: +24% Range: 6 to 34%
20-Year return period 24-Hour precipitation	Mean estimate: +24% Range: 8 to 43%	Mean estimate: +36% Range: 14 to 55%
Water Supply Watersheds		
24-Hour annual maximum precipitation	Mean estimate: +18% Range: 3 to 30%	Mean estimate: +30% Range: 10 to 44%
5-Day annual maximum precipitation	Mean estimate: +11% Range: 2 to 20%	Mean estimate: +23% Range: 8 to 32%
20-Year return period 24-Hour precipitation	Mean estimate: +32% Range: 9 to 50%	Mean estimate: +42% Range: 23 to 60%

2.4 CVRD Climate Change Flood Risk Study (2019)

NHC (2019) completed a risk assessment of floodplains and coastal sea level rise for the CVRD, with a specific focus on climate change. The study used climate change projections prepared by the Pacific Climate Impacts Consortium (PCIC) as published in CVRD (2017) and included a range of future flood scenarios. The preliminary risk assessment at Riverbottom Road used the BC MoE's 1997 hydraulic model for assessing flood scenarios and historical channel shift maps to assess erosion risks. The study recommended that more detailed erosion and floodplain mapping studies be carried out using updated river geometry data.

3 FLOOD ISSUES AND FLOOD HISTORY

3.1 Flood and Erosion Hazards

The most severe floods typically occur from November to March when warm Pacific cyclonic depressions pass over the Strait of Georgia and generate high rates of precipitation when they are forced to rise over the mountains on Vancouver Island. Floods on the Cowichan River are often generated by rain-on-snow events (high precipitation combined with snowmelt).

Within this reach, the river has an irregular meandering pattern with frequent irregular bars and wooded islands. This type of channel pattern is classified as a "wandering" or anabranched river (Desloges and Church, 1989; Neill, 1973), indicating the river is subject to intermittent, rapid channel shifting and avulsions. The channel is often confined on one or both sides by steep terraces of glacial and glaciofluvial materials. The channel typically has a top width of between 40 m and 60 m. Flooding and bank erosion can be aggravated by debris jams and localized sediment deposition, so that the most severe flood damages may not necessarily correspond to the most severe hydrometeorological events.

3.2 Historical Flood Events

Historical disturbances and flooding are well documented in the lower reach of the Cowichan River; however, they are not as well documented in the Riverbottom Road reach. A review of Daily Colonist newspaper articles from 1858 to 1980 returned three accounts of flood damages near Riverbottom Road, associated with the floods of 1961 and 1968 (Daily Colonist, 1964, 1968; Merriman, 1968):

- 11 October 1964 – "A 30-foot section of Riverbottom Road which was washed away by flood waters more than two years ago has been repaired by the provincial highways department… The washout had forced residents of the area and sport fishermen wishing to get to Cowichan Lake to take a long detour at Paldi."
- 19 January 1968 – "Practically all rivers, except the Big Qualicum, were in full flood Thursday and no relief appeared in sight… Floods washed out the Cowichan River footpath suspension bridge at Skutz falls last weekend."
- 25 January 1968 – " … The family had to evacuate its 11-room house when river erosion from the swollen Cowichan River almost washed the house into the river."

Based on discussions with CVRD staff, portions of Riverbottom Road have been subject to moderate erosion damage during the past decade. BC Parks indicate that several trail, campground, and parking lot closures have been recorded in Cowichan River Provincial Park as a result of flooding and erosion damages in recent years (Albert et al., 2019).

Table 2 summarizes the largest historical floods for the Cowichan River, based on analysis of Water Survey of Canada gauge data.

Table 2: Summary of largest historical floods for the Cowichan River

Year	Peak Flow at WSC 08HA002, Outlet of Lake Cowichan	Peak Flow at 08HA011, Cowichan River at Duncan	Event Return Period
1961	314	638	50-100 year
1968	331	514	50-100 year
2020	271	564	20-50 year

3.3 2020 Flood Event

3.3.1 Meteorological Conditions

A strong low-pressure system passed over Vancouver Island and the south coast of BC during the period between 30 January and 1 February 2020, causing heavy rainfall and higher freezing elevations, which contributed to increased snowmelt. These events are commonly referred to as “atmospheric rivers”. A brief summary of the meteorological conditions during this event was described in MacDonald et al. (2020). Precipitation for the three days exceeded 430 mm on the west side of Vancouver Island, 95.6 mm at Shawnigan Lake, and 76.4 mm at North Cowichan. **Figure 2** shows a weather chart produced by Environment Canada on 31 January.

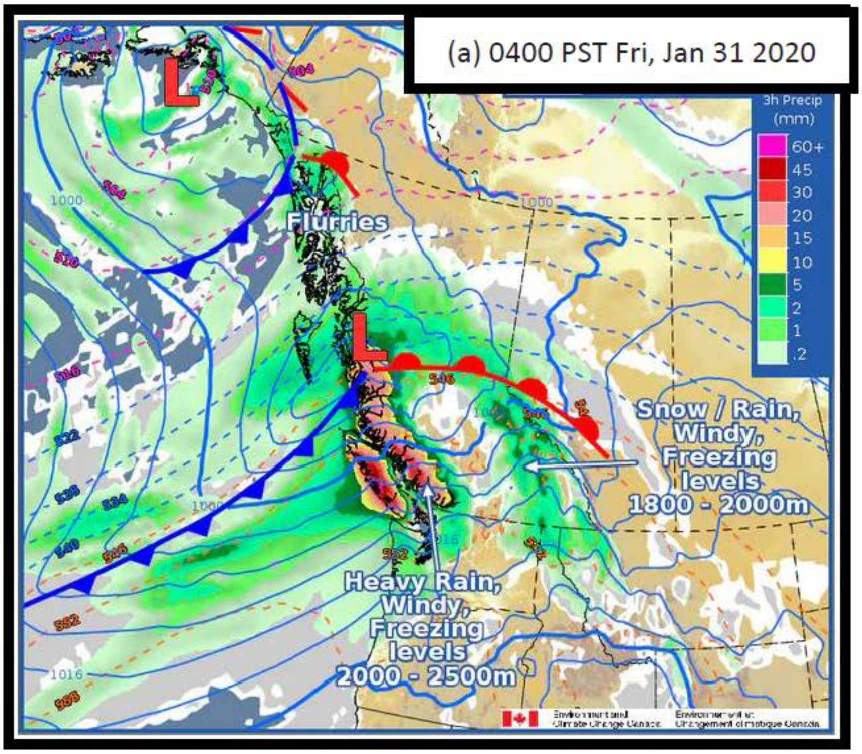


Figure 2: Weather chart showing the low-pressure system (red L) and associated fronts crossing the BC coast on 31 Jan. The colour shading represents 3-hr precipitation amounts (from ECCC 2020)

Peak flows were most extreme on Vancouver Island, particularly on the San Juan, Cowichan, Koksilah, and Chemainus Rivers. The return period of the peak floods on these rivers ranged between 5 and 50 years (MacDonald et al., 2020).

3.3.2 Flooding at Riverbottom Road

Before the atmospheric river event of 30 January to 1 February, there had been significant snowfall throughout the Cowichan Valley in mid-January. The Environment Canada climate station at Lake Cowichan recorded 68 cm of snowfall during this period, and public schools were closed for several days. There had also been significant rainfall in early January, which resulted in a 1- to 2-year return period flood on the Cowichan River.

As a result of these prior hydrologic conditions, the water level in Lake Cowichan was high at the end of January, and there was residual snowpack in much of the watershed. When the atmospheric river event occurred, rain-on-snow conditions led to large runoff volumes. Based on an analysis of provisional Water Survey of Canada data, peak flood flows for the Cowichan River at Lake Cowichan and upstream of Duncan were 271 m^3/s and 564 m^3/s, respectively. The return period of these flood flows was between 20 and 50 years.

NHC completed a visit to the study reach on 1 February 2020 during the receding limb of the flood. Flood impacts were documented, and local residents provided useful insight into flood conditions on their properties. NHC also completed an assessment of changes to river morphology during the bathymetric survey (See **Section 4.5**). Key findings and observations from the site visit are summarized below. Photograph locations are referenced in **Figure 3**.

- Overbank flooding occurred at several riverfront properties (**Photo 1**). One house between Sandy Pool Regional Park and the Cowichan Bible Camp was flooded (**Photo 2**) with approximately half a foot of water (K.Miller, Pers. Comm.)
- Bank protection works, such as riprap revetments, were overtopped and damaged at several locations (**Photo 1**, **Photo 3**, **Photo 4**).
- Sandy Pool Regional Park and Stoltz Pool Campground at Cowichan River Provincial Park were flooded (**Photo 5, Photo 6**). There was damage to the boat launch and trails at Sandy Pool. Bank erosion occurred throughout Stoltz Pool Campground and much of the study reach (**Photo 7**). Online advisories from BC Parks indicated that severe trail and footbridge washout occurred along the Cowichan Valley Trail and Cowichan River Footpath near the downstream end of the study reach at Holt Creek.
- A main channel avulsion (change in river course) occurred approximately 500 m downstream of Riverbottom Road at Jenny Place. (**Figure 4**). The former main channel was filled up with sediment and wood debris, while the new avulsion channel formed a steep chute roughly 20 m wide.

- Large volumes of wood debris and sediment were transported during the flood. Several log jams formed in the study reach (**Photo 8**).

Figure 3: Reference image showing approximate photo locations

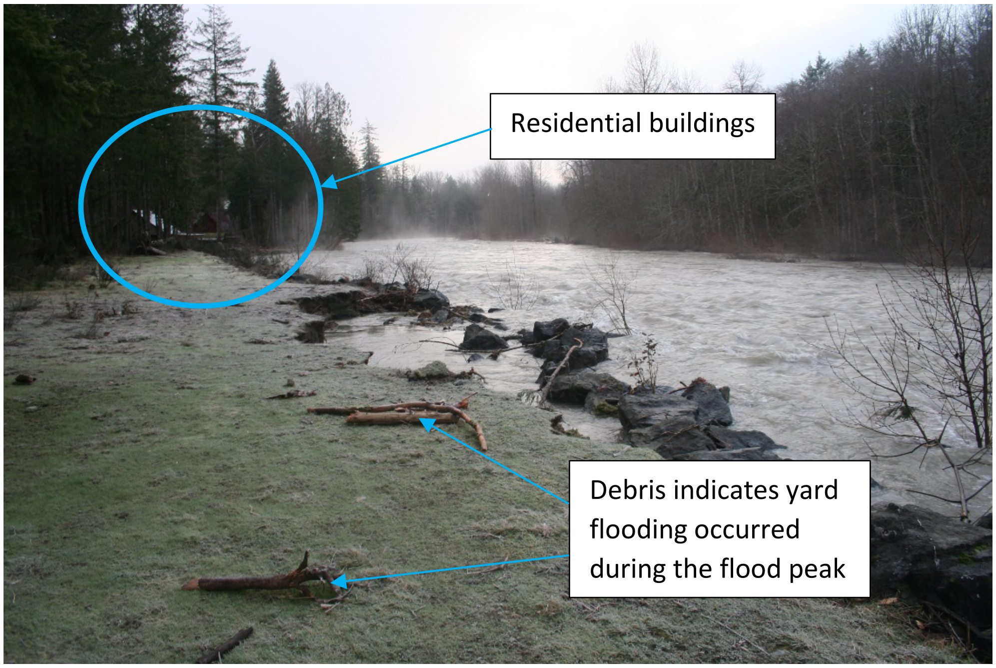


Photo 1: Example of private property flooding on 1 February 2020. Yard areas were flooded but water levels reached few buildings. Riprap revetments were overtopped, resulting in bank washout

Photo 2: Example of private property flooding on 1 February 2020 (Photo provided by CVRD).

Photo 3: Example of damage to bank protection works along private property, 18 February 2020

Photo 4: Severe overtopping and scour damage to riprap revetment along Riverbottom Road near Jenny Place, 1 February 2020

Photo 5: Example of flooding at Sandy Pool Regional Park on 1 February 2020

Photo 6: Overbank flow through Sandy Pool Regional Park on 1 February 2020 (Photo provided by CVRD)

Photo 7: Example of bank erosion at Stoltz Pool Campground on 1 February 2020

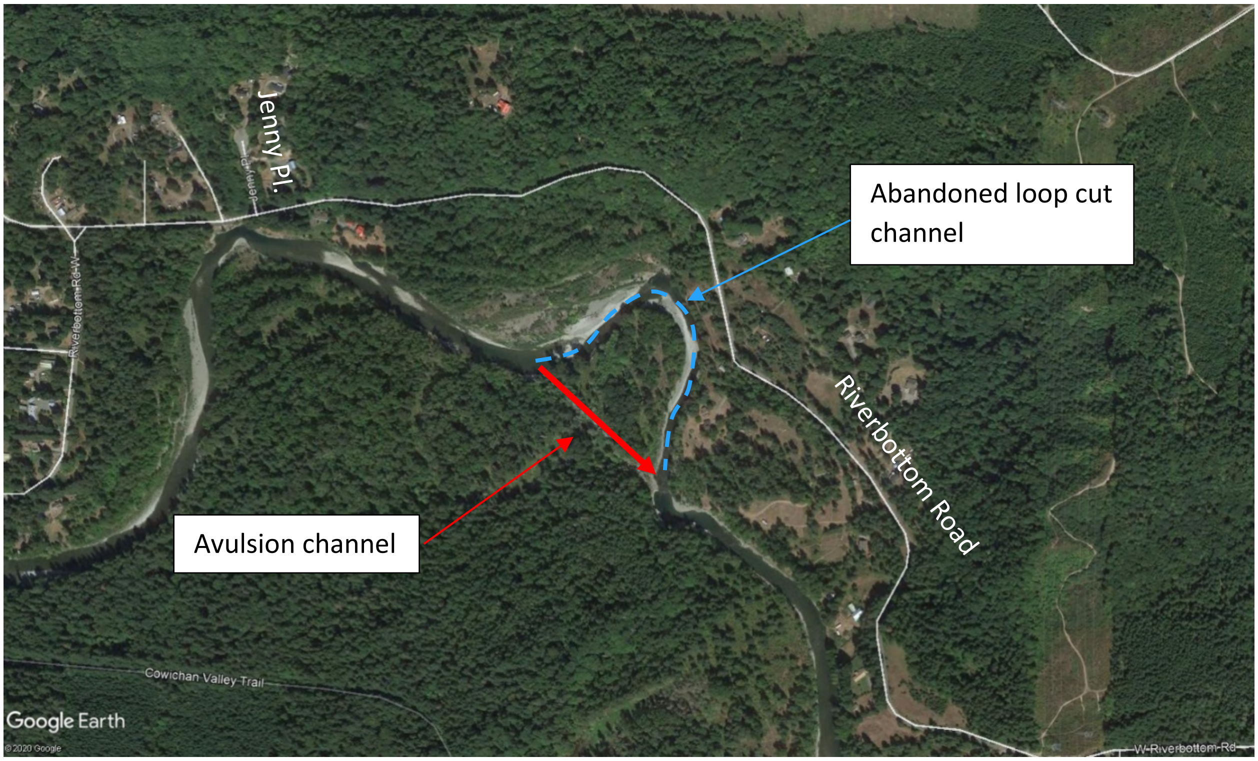


Figure 4: Avulsion path during the 1 February 2020 flood (aerial imagery from Google Earth)

Photo 8: Example of log jam on 18 February 2020; location is near the avulsion channel

4 FIELD INVESTIGATIONS AND DATA

4.1 LiDAR Data and Orthoimagery

GeoBC completed an aerial acquisition of topographic LiDAR and orthoimagery for the CVRD in 2019. The horizontal and vertical control for the data were as follows:

- Horizontal Datum: North American Datum 83 (NAD83) CSRS
- Projection: UTM Zone 10 North
- Vertical Datum: CGVD2013

All surveys and mapping in the study have been referenced to this coordinate system.

4.2 Control Surveys and LiDAR Checkpoint Surveys

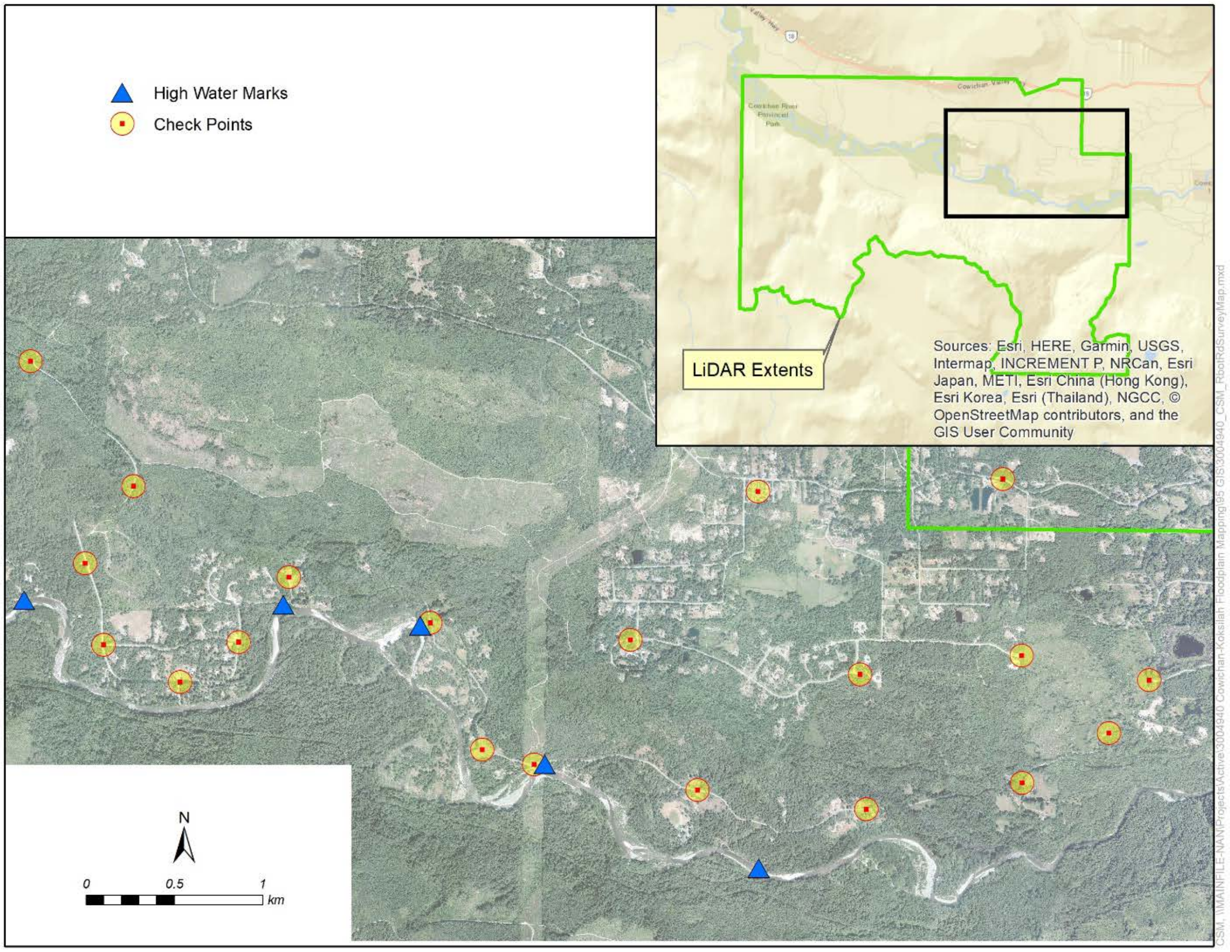
NHC carried out a series of surveys that included setting up a control network and collecting ground surveys. The following equipment was used to complete this work:

- Trimble R8 GNSS RTK GPS rover receiver
- Trimble R8 GNSS RTK GPS base receiver with Pacific Crest TDL 450 35-watt radio
- Trimble TSC3 controller with Trimble Access field software
- Trimble Business Center desktop software

The control network for the project area was set using a static survey. A base receiver was set up in the morning each day at a central location and left to log static data for 8 hours. The full-day occupation static data was submitted to National Resources Canada Precise Point Positioning (NRCAN PPP) post-processing service. The resulting coordinates were checked to British Columbia Provincial survey monument GCM 932657. The resulting checks were within tolerance; as such, no adjustments were made to the coordinates produced from NRCAN PPP.

In December 2019, NHC completed a LiDAR check point survey to verify 2019 LiDAR vertical accuracy. The survey included 22 points, evenly dispersed through the study area (**Figure 5**). The survey elevations were compared to elevations taken at the same geographic point on a surface derived from the 2019 LiDAR data. The elevation differences were then used to calculate a Root Mean Square Error (RMSE) for the LiDAR dataset.

The calculated RMSE for the 2019 LiDAR dataset was 0.074 m. The *Federal Airborne LiDAR Data Acquisition Guideline* (Natural Resources Canada and Public Safety Canada, 2018a) recommends a maximum RMSE of 0.10 m. Therefore, the LiDAR data appears adequate for representing the floodplain topography and for floodplain mapping purposes.



Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, © OpenStreetMap contributors, and the GIS User Community

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Figure 5: Summary of high water mark and LiDAR checkpoint survey locations

4.3 High Water Mark Survey

NHC staked out 12 high water marks on 1 February 2020, during the receding limb of the significant flood event (**Section 3.3**). High water marks included actual water surface elevations, as well as implied peak high water marks interpreted from the locations of rafted debris. The high water marks were later surveyed and were used for hydraulic model validation (see **Section 6.3**). A summary of the high water mark survey locations is provided in **Figure 5**.

4.4 Bathymetric Survey

NHC completed a bathymetric survey of the river reach on 18 and 19 February 2020. A limited topographic survey was also carried out for wadable or dry side channels. The following equipment was used to complete the survey work:

- Trimble R8 GNSS RTK GPS rover receiver

- Trimble R8 GNSS RTK GPS base receiver with Pacific Crest TDL 450 35-watt radio
- Trimble TSC3 controller with Trimble Access field software
- Trimble Business Center desktop software
- Ohmex Sonarmite 200 kHz sounder sounding at 2 Hz
- Panasonic CF31 Toughbook with Intel I5 processor
- Hypack 2017 hydrographic software
- Aluminum jet boat

The following are equipment accuracies in ideal field conditions:

- Trimble R8 GPS RTK receivers: +/-0.05 m
- Ohmex Sonarmite sounder: +/- 0.02 m

The surveys included 45 bathymetric cross sections, each of which was surveyed twice to ensure data consistency. Three longitudinal bed profiles (centreline, left bank, and right bank) were also surveyed. Longitudinal water surface profiles were calculated during post-processing using sonar depths and instrument offsets from the water surface.

The bathymetric survey data was utilized in developing the hydraulic modelling geometry (**Section 6.2**) while the longitudinal water surface profiles were used for model calibration (**Section 6.3**).

4.5 Overview Geomorphic Assessment

NHC carried out a reconnaissance level geomorphic assessment of the river reach on 14 January 2020. A second visit was conducted on 18 February 2020 following the flood of 31 January to 1 February, to collect more detailed observations and evaluate changes to the channel caused by the flood event.

The assessments were qualitative and focused on the following key geomorphic features:

- Locations of bank erosion;
- Extents and condition of bank protection works such as riprap;
- Bank heights and material composition, including areas of bedrock control;
- Log jams and areas of wood debris accumulation;
- Areas of side-channel formation and avulsion; and
- Aggradation and degradation zones;

Information gathered during the geomorphic assessment was used in the erosion hazard assessment and mapping (**Section 8**).

5 HYDROLOGY

5.1 Watershed Characteristics

5.1.1 Climate

The Cowichan region is located in Canada's only Maritime Mediterranean climatic zone, resulting in the warmest mean year-round temperature anywhere in Canada (https://www.cvrd.bc.ca/650/Climate). Mean annual precipitation and temperature vary within the region, depending on the location's elevation and proximity to the ocean.

Figure 6 provides monthly temperature and precipitation for Cowichan Lake at the Town of Lake Cowichan (elevation 171 m). The annual precipitation averages 2,207 mm at Cowichan Lake, with approximately 80% of the annual precipitation falling between October and March.

5.1.2 Topography

The Cowichan River has its headwaters at Hooper Mountain (el. 1,490 m) near the western end of Cowichan Lake and then flows east for 46 km before entering Cowichan Bay in the Strait of Georgia. The drainage area of the Cowichan River increases from 594 km^2 at the outlet of Cowichan Lake to 826 km^2 at Allenby Bridge in Duncan. Cowichan Lake has a significant effect on moderating flood flows on the lower Cowichan River.

Key watershed parameters are presented in **Table 3**. A map of the watershed is provided in **Figure 7**.

Table 3: Cowichan River at Riverbottom Road watershed parameters

Watershed Parameter	Value
Drainage area	735 km^2 (at downstream boundary of the study reach)
Cowichan Lake surface area	62 km^2
Elevation range	40 to 1,490 m
Land cover	Predominantly secondary growth coniferous forest

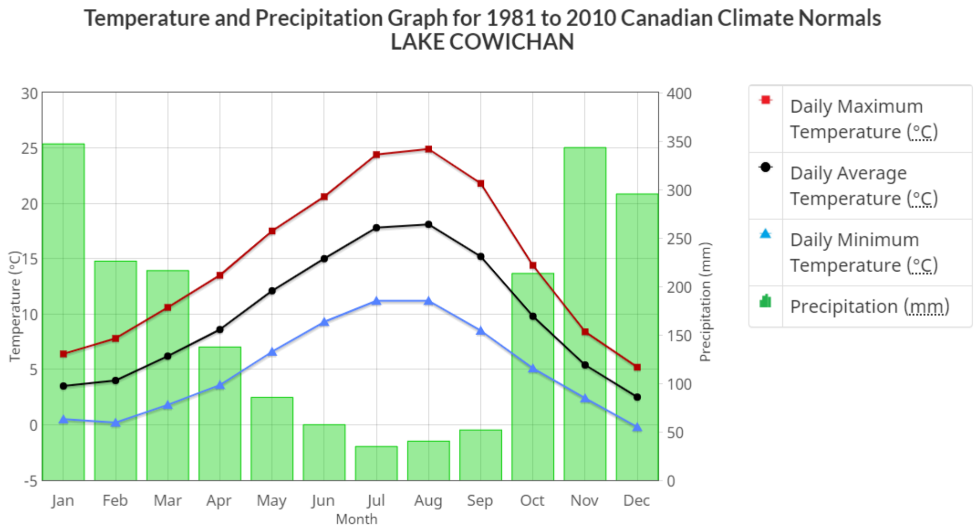
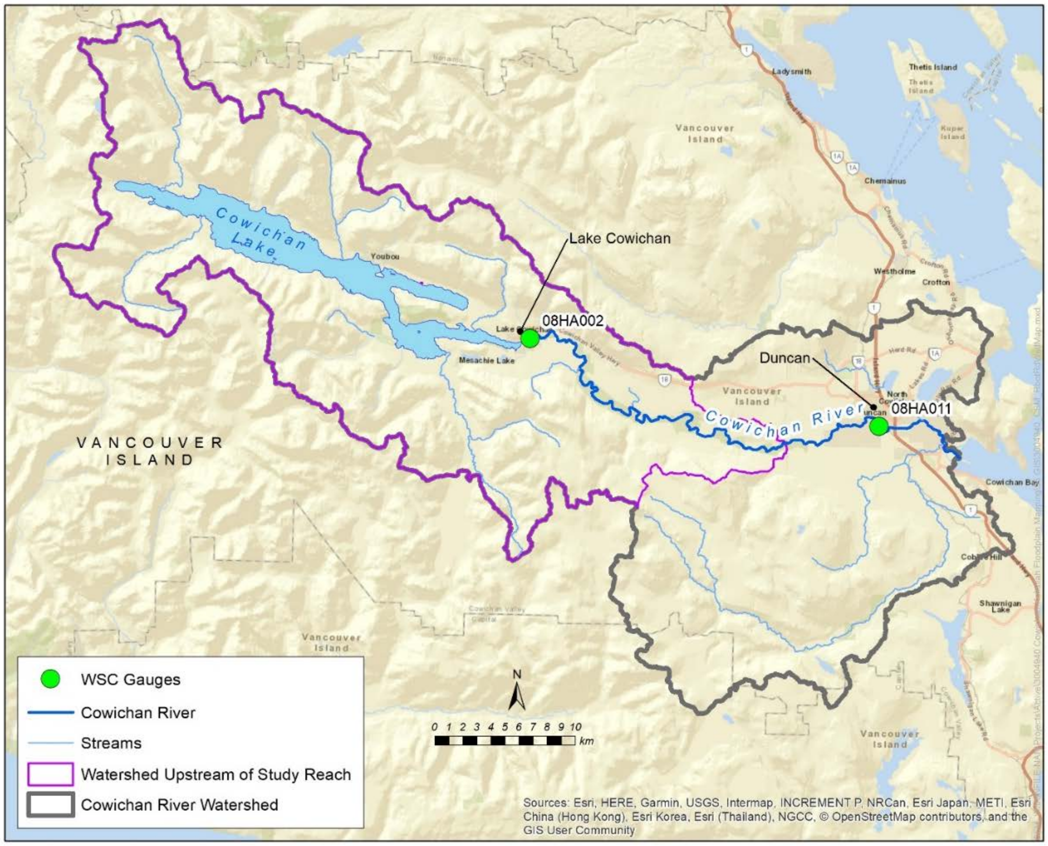


Figure 6: Lake Cowichan 1981-2010 Climate Normals, from Environment and Climate Change Canada (https://climate.weather.gc.ca/climate_normals/)



Sources: Esri, HERE, Garmin, USGS, Intermap, INCREMENT P, NRCan, Esri Japan, METI, Esri China (Hong Kong), Esri Korea, Esri (Thailand), NGCC, © OpenStreetMap contributors, and the GIS User Community

Figure 7: Study area watersheds

5.2 Flood Hydrology

5.2.1 Method of Approach

The Riverbottom Road reach of the Cowichan River is located between two Water Survey of Canada (WSC) gauges:

- 08HA002 Cowichan River near Lake Cowichan
- 08HA011 Cowichan River near Duncan.

The previous BC Ministry of Environment (1997) floodplain mapping used the lower river gauge at Duncan to determine input hydrology for Riverbottom Road. This gauge is located over 10 km downstream of the Riverbottom Road reach. The 1997 approach is very conservative because the watershed area at WSC 08HA011 near Duncan is 826 km2. For the Riverbottom Road reach, the watershed area is 703 km2 at the upstream boundary and 735 km2 at the downstream boundary.

For the present study, an area-based approach has been used to better represent the anticipated flows at Riverbottom Road. The following steps were carried out.

1) Flood frequency analyses were carried out at WSC stations 08HA002 and 08HA011 to determine flood flows for a range of return periods (2-year flood to 500-year flood).

2) The incremental increase in flood flows from station 08HA002 to 08HA011 by watershed area was scaled using the Modified Index Flood (MIF) method, and the resultant flood flow at Riverbottom Road was estimated.

3) An overview climate change assessment was completed and a climate change factor of 20% was determined and applied to the estimates.

4) The uncertainty of the flood frequency estimates was assessed.

These steps are summarized in the following sections.

5.2.2 Flood Frequency Analysis

The flood frequency analyses carried out for the lower Cowichan-Koksilah River floodplain mapping project (Northwest Hydraulic Consultants Ltd., 2020) were adapted for use in the present study. The following summarizes key approaches and results of the analyses.

Overview of Water Survey of Canada Gauges Used in the Study

Table 4 summarizes the available records at the two WSC gauges. The Environment Canada Data Explorer (version 2.1.8) HYDAT (version 1.0, 18 Jan 2020) was used to access WSC data. For years 2018 to 2020, provisional WSC data was accessed through data requests and via the real-time WSC website (https://wateroffice.ec.gc.ca/mainmenu/real_time_data_index_e.html)

The drainage areas at the stations were reviewed using Esri ArcGIS software and spatial layers from the BC Freshwater Atlas and basin shapefiles from WSC. Polygons were overlaid on LiDAR and in Google Earth to confirm correct boundary delineation.

Data records were assessed for completeness, and years with instantaneous peaks (Q_{PI}) and maximum daily peaks (Q_{PD}) were noted. Years with partial winter data that did not represent peak flows were removed. WSC site description sheets were reviewed for additional metadata.

Table 4: Water Survey of Canada stations used for design inflows

River	WSC gauge	Record	Q_{PI} Record	Q_{PD} Record	Basin Area (km^2)
Cowichan River at Lake Cowichan	08HA002	1913-1919, 1940-present	1940-present	1914-1918, 1940-present	594
Cowichan River near Duncan	08HA011	1960-present	1977-present	1960-present	826

Data Inspection and Stationarity

The first step in flood frequency analysis was to undertake a basic analysis of the peak flow time series to check for obvious errors and non-stationarity. Trends in peak flow were assessed using the Mann-Kendal test. For the Mann-Kendal test, a trend (Z_{obs}) is considered significant when p-values are less than 0.05. If the p-value is greater than 0.05 then the Z_{obs} can indicate whether values are increasing or decreasing over time, but the change is not significant.

Table 5 and **Table 6** present the results of the Mann-Kendal test for peak instantaneous discharge and maximum daily discharge, respectively. No significant trends exist for all stations except for peak instantaneous flows for 08HA011 Cowichan River at Duncan. The Mann-Kendal test indicates a significant increasing trend for this gauge. Visual inspection of peak flows (**Figure 8**) indicates that the trend is gradual. A gradual increase in peak flows over time may be due to changes in climate or land use, or reflective of Pacific Decadal Oscillation (PDO) and El Nino Southern Oscillation (ENSO) cycles. PDO and ENSO are reviewed in the next section.

Table 5: Results of the Mann-Kendal test at the 95% confidence level (α = 0.05) for instantaneous peak flows (QPI)

River	WSC Stn	n_i	Z_{obs}	P-value	H_0
Cowichan River near Duncan	**08HA011**	**41**	**0.2295**	**0.0357**	**reject**
Cowichan River at Cowichan Lake	08HA002	74	0.0746	0.3506	maintain

Table 6: Results of the Mann-Kendal test at the 95% confidence level (α = 0.05) for maximum daily flows (QPD)

River	WSC Stn	n_i	Z_{obs}	P-value	H_0
Cowichan River near Duncan	08HA011	59	0.0965	0.2835	maintain
Cowichan River at Cowichan Lake	08HA002	86	0.0685	0.3530	maintain

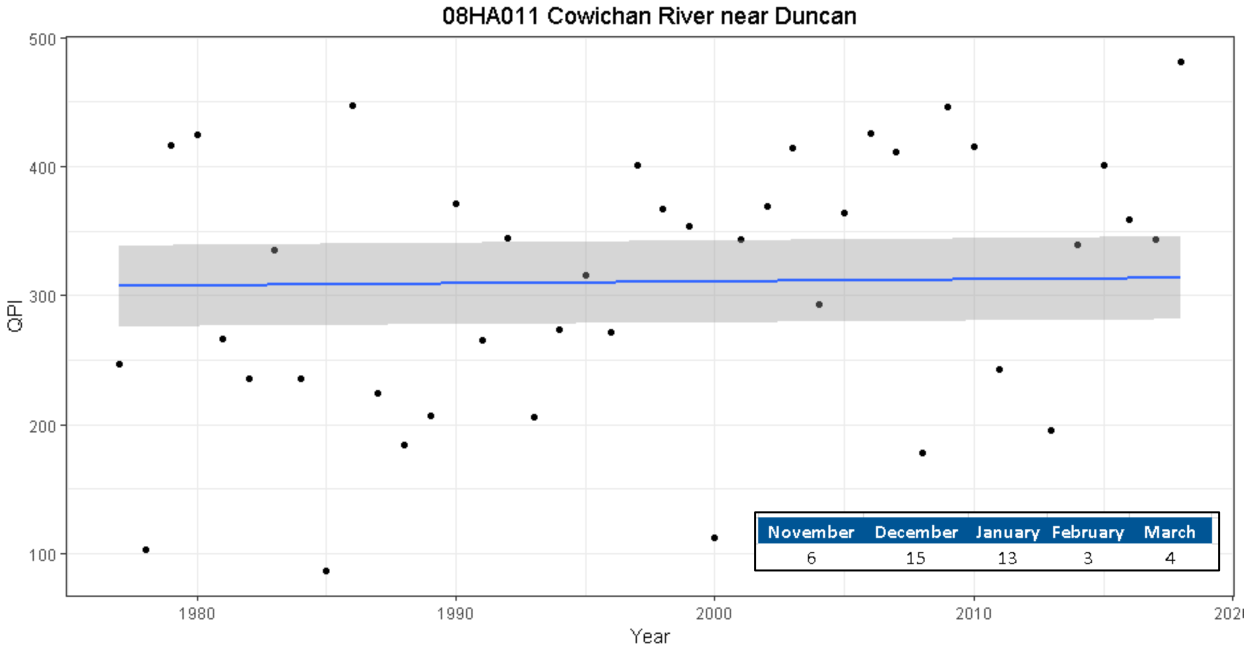


Figure 8: Annual maximum instantaneous discharge for 08HA011 Cowichan River near Duncan; lower right table indicates temporal occurrence of peak instantaneous flows

Trend Analysis and Climatic Variability

Two important cyclic climate influences in BC are the PDO and ENSO. Both phenomena are associated with cyclic changes in the surface temperature of the Pacific Ocean that impact air temperature and precipitation throughout the Pacific. NHC completed a review of the potential impacts of PDO and ENSO on flood discharges for the Cowichan River. It is important to consider whether WSC records used to estimate design flows are long enough to capture both wet and dry phases. For example, if design flows are based upon data collected during a dry phase only, then estimates of flood levels may be low and result in safety risks. It was concluded that WSC records for the Cowichan River are sufficiently long to cover both warm and cold PDO and ENSO periods.

Defining Hydrologic Water Year

The timing of peak floods for each gauge was inspected in order to define the water year. The water year for the Cowichan watershed depends on meteorological factors since precipitation in the fall and winter can accumulate as snow in the upper watershed and does not drain until the following spring snowmelt. The United States Geological Survey (USGS) defines the water year as the period from 1 October through 30 September. The Cowichan watershed experiences peak flows in the fall and winter between November and March. Since WSC publishes peak instantaneous flows according to the calendar year, there are several instances for all gauges where a reported fall and winter peak flow fall on different calendar years but are on the same water year. In this instance, the next water year was then not reported. The USGS water year timing was adopted for this study.

Record Extension and Infill of Missing Records

The infill of missing peak flow (QPI) records was based upon daily (Q_{PD}) records. One peak flow (Q_{PI}) per water year was selected, and missing peak flows were infilled using the maintenance of variance extension (MOVE) regression method (Hirsch, 1982) as recommended by Bulletin 17C (England Jr. et al., 2019). The MOVE model extends the peak flow record while maintaining the same variance as directly observed data and thus are expected to be a more reliable method than simple linear regression from an extension of peak flow records.

Determination of Flood Frequency Curve

Lastly, once all Q_{PI} records were infilled and extended, flood frequency analysis was completed using the log-Pearson type III (lp3), the generalized extreme value (gev), the gumbel (gum), and log-normal3 (pe3) probability distributions. The distribution that visually presented the best fit was selected for each gauge. For all distributions, parameters were estimated using L-moments, and a bootstrap procedure was used to estimate confidence intervals in each non-exceedance probability.

Flood Frequency Analysis Results

The degree of regulation was reviewed for the Cowichan River gauges. The Cowichan Lake weir was constructed in 1957. The weir is approximately 1 metre high and functions to hold water back during the spring, summer, and fall dry season. During the winter, the gates are fully open, and water flows freely over the top of the weir. The channel control that determines the height of the lake is a naturally occurring channel constriction at Greendale Trestle.

WSC gauge 08HA002 is located approximately 0.75 km immediately downstream of the weir. WSC also operates a water level gauge (08HA009 Cowichan Lake) on Cowichan Lake, approximately 1.5 km upstream of the weir. A rating curve between the Cowichan Lake water level and Cowichan River outflow was developed. The rating curve demonstrated that the lake level control has shifted over time. Higher lake levels and outflows have been measured post-1957, the year in which the weir was established. Without reviewing the data sets and weir operation in detail, it is difficult to determine whether the shift in channel control is due to the installation of the weir or due to changes in the data collection methodology before 1957. As such, frequency analysis was completed on WSC data post-weir installation.

Flood frequency analysis results for the Cowichan River gauges at Lake Cowichan and near Duncan are presented in **Table 7** and **Table 8**, respectively.

Table 7: Flood frequency estimates for the Cowichan River at Lake Cowichan

08HA002-Cowichan River at Lake Cowichan (1957-2020)				
Return Period	Percent chance of occurrence in any given year	Lower (pe3)	Estimate (pe3)	Upper (pe3)
2	50.0%	170	185	199
5	20.0%	216	233	251
10	10.0%	239	260	282
20	5.0%	257	283	311
50	2.0%	275	309	347
100	1.0%	286	328	374
200	0.5%	296	344	400
500	0.2%	308	365	433

Table 8: Flood frequency estimates for the Cowichan River near Duncan

08HA011-Cowichan River near Duncan (1960-2020)				
Return Period	Percent chance of occurrence in any given year	Lower (gum)	Estimate (gum)	Upper (gum)
2	50.0%	270	296	324
5	20.0%	358	400	446
10	10.0%	414	468	529
20	5.0%	467	534	610
50	2.0%	535	619	715
100	1.0%	585	683	794
200	0.5%	636	747	872
500	0.2%	702	830	976

5.2.3 Designated Flood Flows at Riverbottom Road

Analysis

The Modified Index Flood (MIF) method was used to estimate the design flood flows at Riverbottom Road. The MIF is given by the following equation:

$$Q_2 = Q_1 \left(\frac{A_1}{A_2}\right)^n$$

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 n is a scaling exponent. For British Columbia, the accepted average n value is 0.75 (Eaton et al., 2002).

The approach used in applying the MIF method is first to determine the *incremental* flow gain from Lake Cowichan (08HA002) to Duncan (08HA011). The incremental flow gain is scaled by incremental watershed area using the MIF to estimate the incremental flow gain from Lake Cowichan to Riverbottom Road. The total flood flow at Riverbottom Road is the sum of the Lake Cowichan flood flow and the incremental flow gain to Riverbottom Road.

The watershed area considered for Riverbottom Road is that of its downstream boundary (735 km^2), rather than its upstream boundary (703 km^2). The nature of tributary and runoff inflows along Riverbottom Road is unknown, and the higher downstream boundary area results in a greater flood discharge estimate when applying the MIF method. The adoption of the downstream boundary area, therefore, provides a reasonable level of conservatism to the approach. **Table 9** summarizes the MIF results.

Table 9: Summary of MIF flood estimates for Riverbottom Road

Return Period (Years)	Flood Flow (m³/s)				
	08HA002 (594 km²)	08HA011 (826 km²)	Increment 08HA011-08HA002 (232 km²)	MIF Scaled Increment to Riverbottom Rd. (141 km²)	Est. Flow at Riverbottom Road (735 km²)
2	185	296	112	77	262
5	233	400	167	115	348
10	260	468	208	144	404
20	283	534	251	173	456
50	309	619	310	214	523
100	328	683	356	245	573
200	344	747	402	277	622
500	365	830	465	321	686

Climate Change

NHC (2019) reviewed available guidelines and best management practices for incorporating climate change to boundary conditions for the Cowichan Watershed. Climate change projections from PCIC for the Cowichan watershed were reviewed along with EGBC guidance. NHC recommended that a 20% increase in peak flows be adopted for this study to account for climate change. This recommendation was approved by the CVRD and has been adopted for the present floodplain mapping study.

Adopted Maximum Instantaneous Flood Discharges

The adopted flood flows (including the 20% climate change factor) that were used in the hydraulic investigations and mapping are summarized in **Table 10**.

Table 10: Summary of adopted flood flows at Riverbottom Road

Return Period (Years)	Discharge (m³/s)
2	314
5	418
10	485
20	547
50	628
100	687
200	746
500	823

5.2.4 Uncertainty Analysis

The designated flood flows at Riverbottom Road are subject to the following uncertainties:

- Uncertainty in the flood frequency analysis for 08HA002;
- Uncertainty in the flood frequency analysis for 08HA011;
- Uncertainty in the scaling exponent n used in the MIF; and
- Uncertainty in the adopted climate change factor.

Global uncertainty in the designated flood flows is difficult to quantify since it represents a complex interaction between the individual uncertainty components. To investigate potential uncertainties, a simplified Monte Carlo uncertainty analysis was carried out. The following assumptions were made:

- Flood frequency analysis uncertainty at the two gauges was quantified by fitting log-normal error distributions around the mean flood estimates;
- Uncertainty in the scaling exponent n was quantified using the 95% confidence limits of the exponent (Eaton et al., 2002);
- Uncertainty in the adopted climate change factor was **not** considered. The projections of future precipitation changes in the region by PCIC ranged from 15% to over 40% for some parameters, which gives an indication of the variability of the results (CVRD, 2017). No information on changes to the corresponding peak river discharges was provided. The uncertainty associated with climate change projections of future flood discharges is generally considered to be very high (Kundzewicz (2014)) and is essentially not quantifiable at this time;
- Uncertainty in the choice of distribution at the two gauges (LP3, Log-Normal, etc.) was **not** considered.

A histogram of the Monte Carlo simulation results is provided in **Figure 9**. The mean 200-year flood estimate was 746 m^3/s, with a 95% confidence interval of 668 to 834 m^3/s.

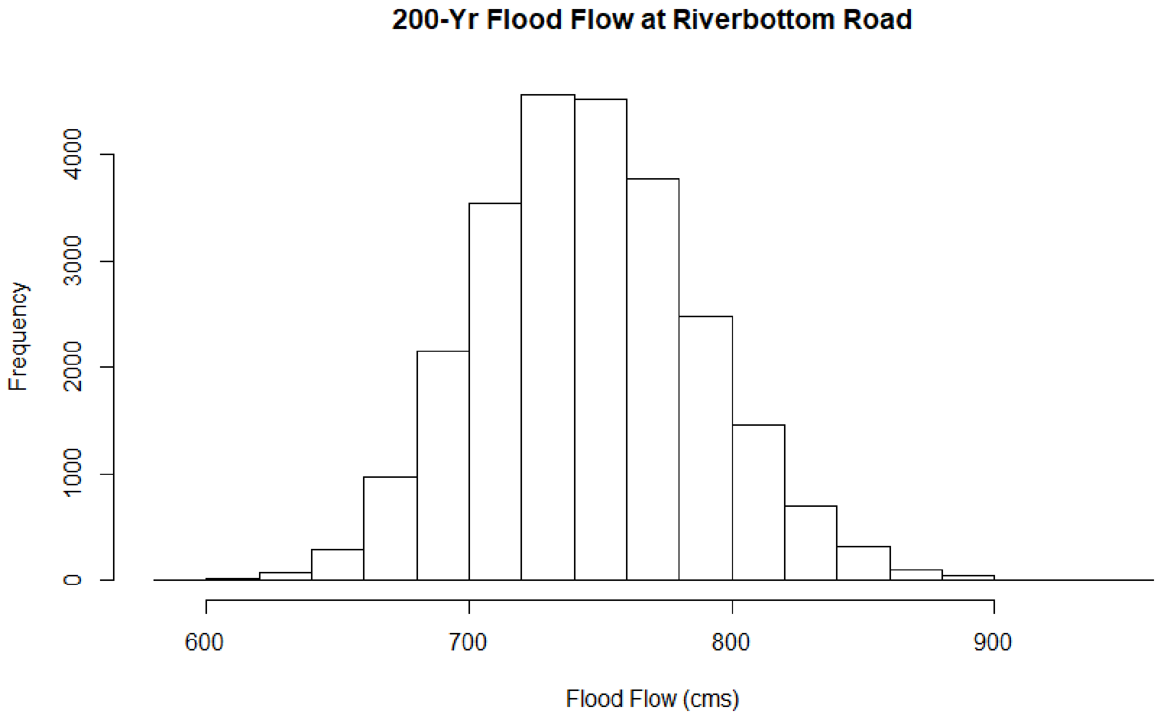


Figure 9: Histogram of Monte Carlo uncertainty analysis results. The histogram represents the range of Q200 estimates for Riverbottom Road over 25,000 Monte Carlo simulations

6 HYDRAULIC MODEL DEVELOPMENT

6.1 Description of the Modelling Approach

6.1.1 Model Description

The US Hydrologic Engineering Center (HEC) one-dimensional hydraulic model HEC-RAS 5.0.7 was used to assess the hydraulic conditions in the study reach. The model is widely used for floodplain mapping projects in the USA and Canada and is suitable for the particular conditions on the Cowichan River. The model represents the channel and floodplain topography using cross sections spaced along the river as well as empirical coefficients (Manning's n values) to represent the channel and floodplain boundary roughness. River discharge is specified at the upstream end of the model as a boundary condition. The model then solves the equations of motion to estimate the water levels, mean velocities, and depths at each corresponding cross section. Since the model was run for a steady-state condition, it assumed the total discharge remained constant over the simulation interval.

6.1.2 Modelling Methodology

The cross sections of the channel and floodplain were processed in GIS and imported into the model, along with other key parameters such as distances between cross sections and preliminary estimates of roughness. After a period of initial testing, the model was calibrated by comparing predicted and observed water levels for specific flood events and adjusting the model roughness coefficients until the difference in water levels was deemed acceptable. The model was then re-run for a second flow condition using a second dataset of observed water levels to compare with the model predictions. This comparison was used to validate the model predictions. After this phase was completed, a sensitivity analysis was conducted by varying the key input parameters (discharge and roughness) to assess how uncertainties in these parameters may affect the accuracy of the predicted water levels. Final runs were then made for the various flood scenarios, including the designated 200-year discharge (with a 20% adjustment to account for climate change) to provide input for the floodplain mapping.

6.2 Initial Model Setup

The initial model geometry was developed in HEC-RAS using a combination of the bathymetry survey data and topographic LiDAR data (see **Section 3**). The geometry included a total of 45 cross sections, with an average spacing of approximately 250 m. This is an improvement over the previous 1997 floodplain mapping, which included only 24 cross sections.

Manning's n values were initialized based on the values previously used in the 1997 floodplain mapping. The average channel and overbank Manning's n values were 0.033 and 0.11, respectively. These values were used as a starting point for calibration and validation (see **Section 6.3**).

Ineffective flow areas were delineated based on a qualitative analysis of the topographic LiDAR data, as well as locations of floodplain ponding noted during the site investigation. There are no dikes located within the study limits.

The model's downstream boundary condition was set to normal depth, with a slope condition of 0.4%. The downstream boundary is located approximately 250 m downstream of the study limit.

6.3 Calibration and Validation

Model calibration was carried out using the continuous water surface profile measured during the bathymetry survey. During the survey, the upper and lower WSC gauges on the Cowichan registered provisional flows of 78 and 80 m^3/s, respectively. An average flow of 79 m^3/s was adopted as the calibration flow. Calibration was completed by varying the channel and overbank Manning's n values to minimize the error between the modelled water surface elevations and those measured in the field. The average channel and overbank Manning's n values were 0.048 and 0.11, respectively.

Once Manning's n values were calibrated, model validation was carried out using data from the high water mark surveys. Flows at Riverbottom Road during the high water mark survey were estimated by scaling recorded flows between the upper and lower WSC gauges using the procedure described in **Section 5.2**. The data includes three data subsets:

1) Inferred high water marks (3 point-measurements) associated with the peak of the 1 February 2020 flood (464 m^3/s);

2) Water surface elevation (1 point-measurement) from 1 February 2020 during the receding limb of the flood (400 m^3/s); and

3) Water surface elevations (4 point-measurements) from 3 February 2020 during the receding limb of the flood (278 m^3/s).

The calibration and validation results are presented in **Table 11**.

Table 11: Summary of calibration and validation results

Parameter	Calibration	Validation
Associated flow	79 m^3/s	278-464 m^3/s
Number of measurements	45	8
Mean error	-0.002 m	0.054 m
Max absolute error	0.170 m	0.373 m
Root mean squared error (RMSE)	0.085 m	0.186 m

For the calibration dataset, there is uncertainty in the measured water surface profile stemming from instrument uncertainty, lateral boat sway, and wave action. It is estimated that total uncertainty is about +/- 7 cm.

For the validation dataset, there is uncertainty in the measured water surface elevations stemming from instrument uncertainty (+/- 5 cm). The inferred high water marks have much higher uncertainty, potentially about +/- 30 cm. There is also uncertainty in the flow scaling methodology used to estimate flows at Riverbottom Road during the high water mark surveys. The total uncertainty is not quantifiable but may be about +/- 10 to 30 cm.

With this in mind, the calibration and validation results support the reasonableness of the model geometry and final Manning's n values. RMSE values for calibration and validation are comparable to the inherent measurement uncertainty of the calibration and validation datasets.

It should be noted that the calibrated channel Manning's n values are approximately 40% to 50% greater than the values reported in the 1997 MoE floodplain mapping study. The 1997 study model was calibrated using flood flows from the WSC gauge at Duncan, which has higher flows than at Riverbottom Road. To match modelled flood levels to observed flood levels during calibration, it would have been necessary to use relatively low Manning's n values to compensate for overestimated flow inputs. For this reason, it is unsurprising that the 2020 model has higher n values than previously reported.

As a final check, the calibrated Manning's n values were compared to an independent Manning's n estimate prepared using the methodology recommended by Arcement and Schneider (1989). The methodology considers multiple contributors to overall hydraulic roughness, such as channel materials, variations in channel cross section, obstructions such as wood debris, degree of vegetation, and effects of losses through meander bends. Based on this analysis, the average channel and overbank Manning's n values were estimated as 0.04 to 0.06 and 0.10 to 0.13, respectively. These values are very comparable to the final calibrated Manning's n values.

6.4 Sensitivity Analysis

A sensitivity analysis was carried out to determine the influence of flow and Manning's n uncertainty on the hydraulic modelling results.

For flow uncertainty, the sensitivity analysis considered the mean, 68% confidence interval, and 95% confidence intervals of the 200-year flood flows estimated in **Section 5.2.4**. The results are presented in **Figure 10**. The blue lines represent the change in modelled water surface elevations associated with the 68% confidence interval flows. The average of these was +/- 10 cm. The red lines represent the change associated with the 95% confidence interval. The average of these was +/- 20 cm. Changes in modelled water surface elevation were greatest in the channelized canyon sub-reaches, and smallest in the unconfined sub-reaches with shallow overbank floodplains.

For Manning's n uncertainty, a preliminary analysis was carried out to determine reasonable upper and lower bounds on the Manning's n values. The analysis started with the calibration dataset, with Manning's n being varied globally by +/- 5% to +/- 25%. It was found that varying Manning's n by +/- 10% resulted in mean water surface elevation changes that were quite comparable to the RMSE of calibration. Varying Manning's n by +/- 25% resulted in changes of roughly two times the RMSE of calibration. Next, Manning's n was varied by +/- 10% and +/- 25% in the validation dataset. It was found that the +/- 10% change resulted in mean water surface elevation changes that were somewhat less than the RMSE of validation. Similarly, the +/- 25% change resulted in changes that were somewhat less than two times the RMSE of validation. Given that the validation dataset is subject to much greater uncertainty than the calibration dataset, it was considered reasonable to adopt the +/- 10% and +/- 25% values as bounds on the Manning's n sensitivity analysis.

The results of the sensitivity analysis for design Q200 flood conditions are presented in **Figure 11**. The blue lines represent the change in modelled water surface elevations associated with a +/- 10% global change in Manning's n. The average of these was +/- 17 cm. The red lines represent the change associated with a +/- 25% global change in Manning's n. The average of these was +/- 41 cm. Again, changes in modelled water surface elevation were generally greatest in the channelized canyon sub-reaches, and smallest in the unconfined sub-reaches with shallow overbank floodplains. The downstream boundary is particularly sensitive to changes in Manning's n, due to the assumption of normal depth at this location.

In addition to uncertainty in flow and Manning's n, hydraulic modelling results for the design flood conditions are subject to the following uncertainties which have not been quantified:

- Numerical uncertainty inherent to the model;
- Changes in channel geometry during floods;
- Potential for channel obstruction by wood debris and sediment;
- Superelevation effects at river bends and potential for standing waves in the channel.

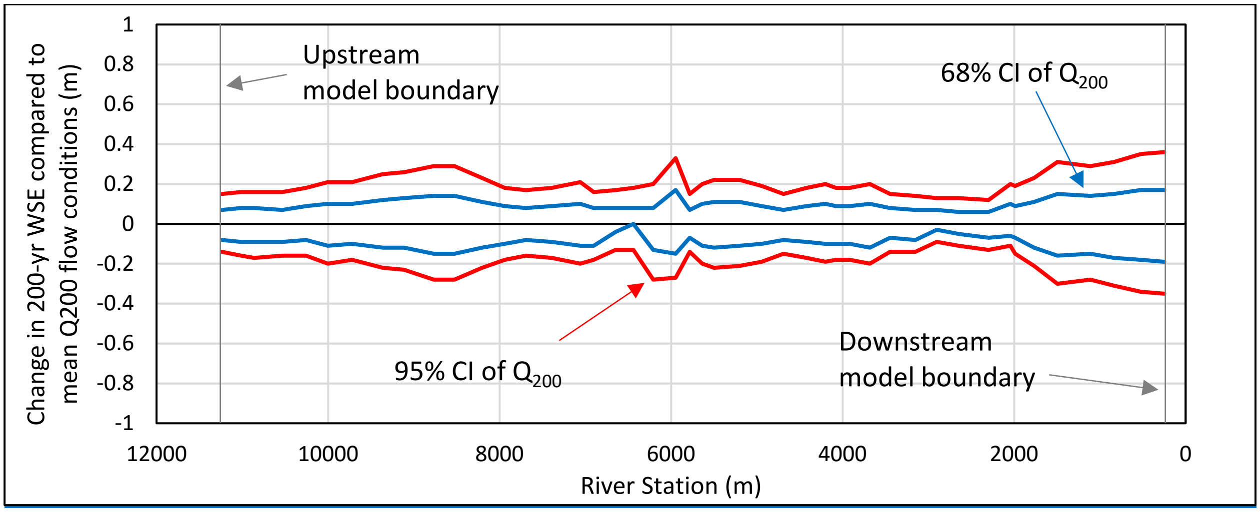


Figure 10: Model sensitivity analysis results for change in Q200 flood flow

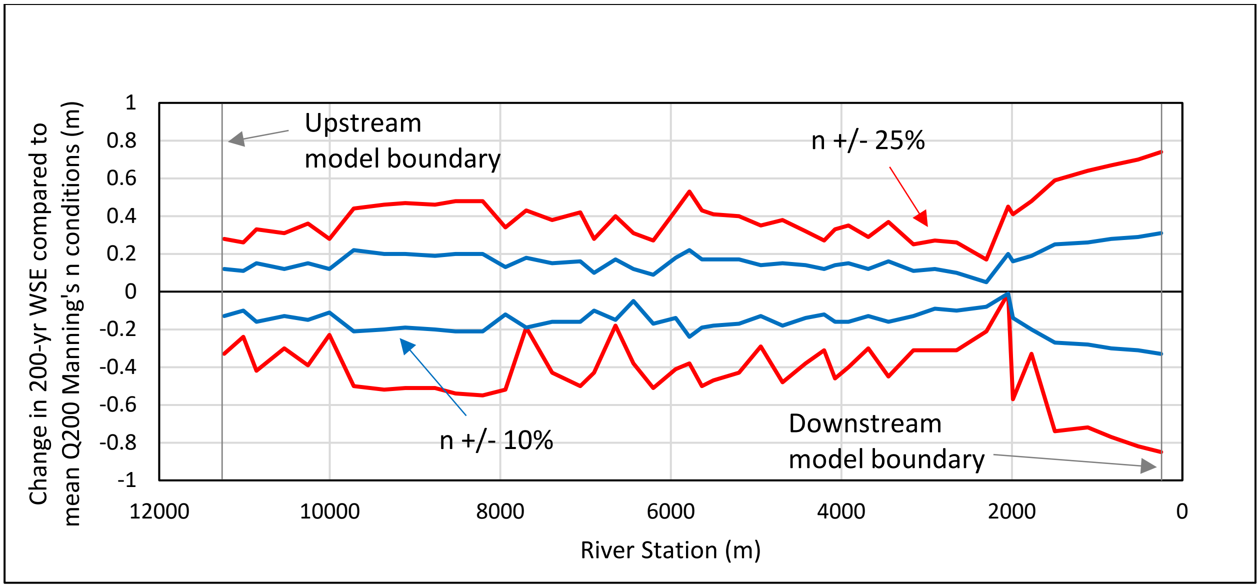


Figure 11: Model sensitivity analysis results for change in Manning's n

6.5 Model Results

6.5.1 Flood Levels

Figure 12 shows the computed water surface profile for the 1/20- and 1/200-year climate change scenarios. The locations of stationing and cross sections are shown on the Index Map Sheet for the floodplain maps in Appendix B. River stations (in kilometres) are also shown on **Figure 1**. The flood profile is reasonably smooth through most of the study area. The profile is less smooth near the avulsion channel (Sta. 6200-6600) due to the irregular channel geometry and bed slope nick points.

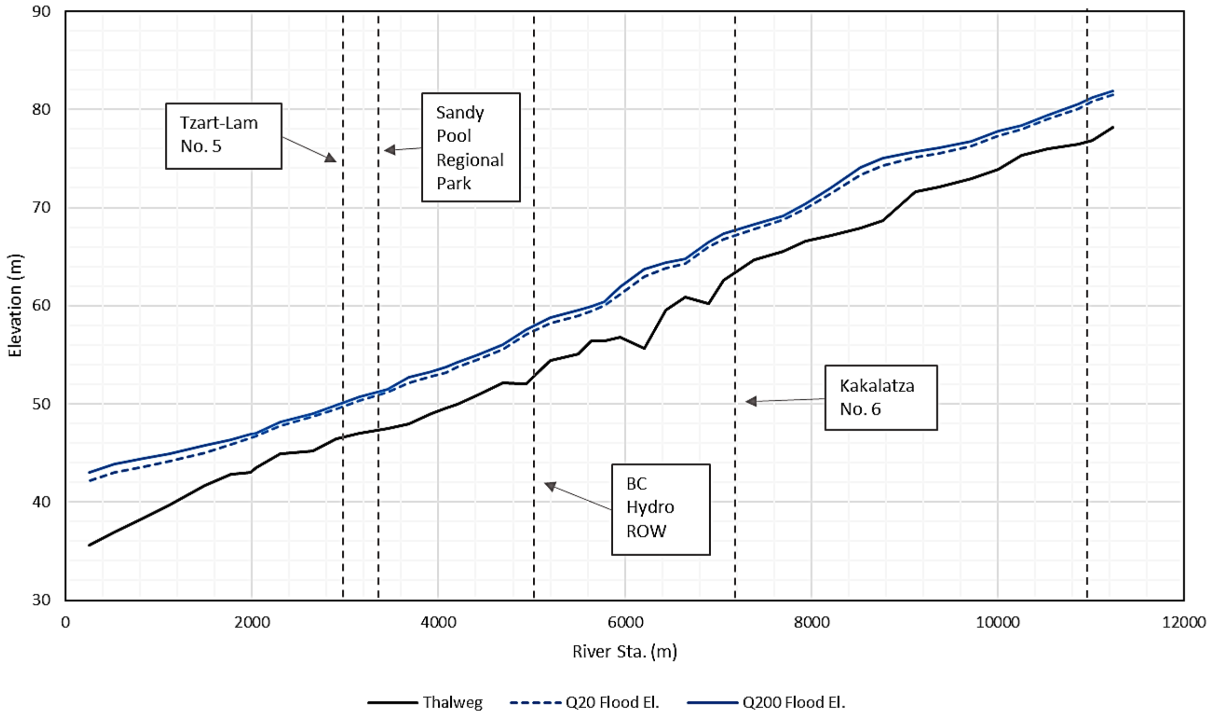


Figure 12: Cowichan River water surface profile: 200-year and 20-year floods with 20% climate change adjustment

Figure 13 plots the elevation difference between the 200-year and 20-year flood profiles. The 200-year flood averages 0.5 m higher than the 20-year. The difference is greatest in the canyon reaches where the channel is narrow and confined. The 500-year flood profile averages 0.2 m higher than the 200-year. Again, the difference is greatest in the canyon reaches. With respect to climate change impacts, the 200-year flood profile with climate change averages 0.3 m higher than the 200-year without climate change.

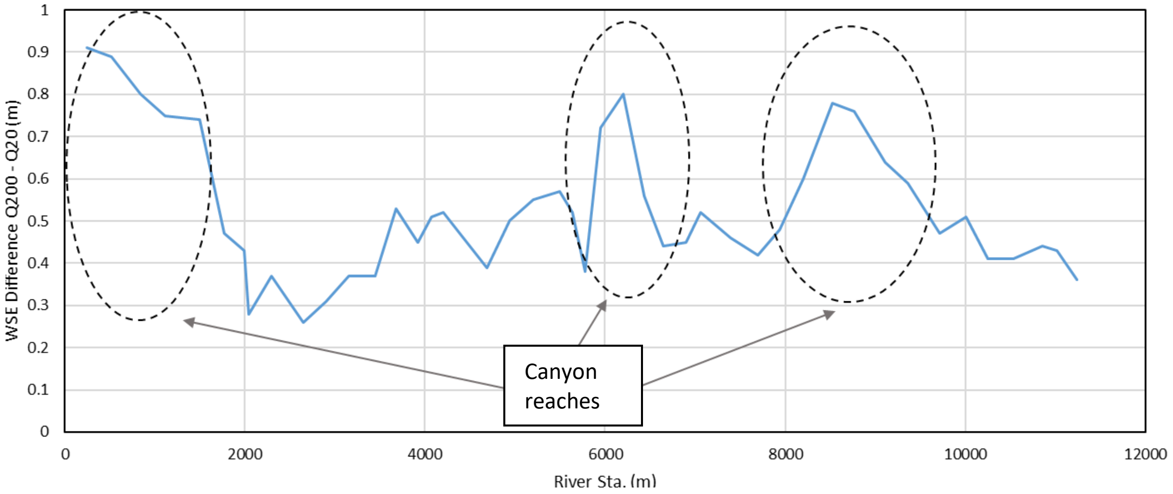


Figure 13: Difference between 200-year and 20-year flood levels

6.5.2 Freeboard

A freeboard allowance is normally added to the estimated flood levels to account for uncertainties in estimating the magnitude and frequency of flood discharges, uncertainties in hydraulic modelling, local hydraulic effects such as waves and surges, and potential changes to the river due to sediment deposition, channel shifting, and erosion. Historically, the minimum recommended freeboard values in British Columbia ranged between 0.3 to 0.6 m, using the following procedure:

- 0.6 m added to the estimated flood level for daily average flood discharge conditions.
- 0.3 m added to the estimated flood level for instantaneous maximum discharge conditions.

The higher of the two values was then adopted for final floodplain mapping or design applications.

In the last decade, a more conservative approach has generally been adopted on most riverine floodplain mapping projects, with a minimum value of 0.6 m being used. Higher freeboards are appropriate where there is potential for debris jams, sedimentation, and other phenomena that are harder to predict (APEGBC, 2017). Based on the sensitivity analysis and the potential for debris jams and sedimentation in the study reach, NHC has recommended adopting a freeboard of 0.60 m on the peak instantaneous flood modelling results. This value is consistent with the freeboard that has been used on the lower Cowichan and Koksilah Rivers in previous studies.

6.5.3 Flood Construction Levels

The flood construction levels for the floodplain maps was computed as follows:

FCL = DFL+FB

Where DFL is the designated flood level based on the 200-year instantaneous maximum discharge, increased by 20% to account for future climate change, and FB is the adopted freeboard (0.6 m). **Table 12** summarizes the adopted DFL and FCL values at each cross section.

Table 12: Computed 20-year, DFL and FCL values along Cowichan River

River Sta. (m)	20-Year Flood Elevation (m)	200-Year DFL (m)	200-Year FCL (m)
11238	81.52	81.88	82.48
11014	80.79	81.22	81.82
10861	80.07	80.51	81.11
10533	79.03	79.44	80.04
10255	77.95	78.36	78.96
10004	77.31	77.82	78.42
9718	76.27	76.74	77.34
9362	75.47	76.06	76.66
9113	75.09	75.73	76.33
8767	74.25	75.01	75.61
8525	73.33	74.11	74.71
8206	71.41	72.01	72.61
7939	69.92	70.40	71.00
7694	68.76	69.18	69.78
7392	67.85	68.31	68.91
7060	66.81	67.33	67.93
6901	66.03	66.48	67.08
6649	64.35	64.79	65.39
6439	63.80	64.36	64.96
6207	62.94	63.74	64.34
5945	61.16	61.88	62.48
5782	60.02	60.40	61.00
5637	59.41	59.93	60.53
5500	58.94	59.51	60.11
5199	58.26	58.81	59.41
4943	57.08	57.58	58.18
4688	55.60	55.99	56.59
4421	54.50	54.96	55.56
4201	53.74	54.26	54.86
4076	53.22	53.73	54.33
3916	52.80	53.25	53.85
3682	52.15	52.68	53.28
3447	51.15	51.52	52.12
3153	50.32	50.69	51.29
2903	49.52	49.83	50.43
2648	48.73	48.99	49.59
2298	47.81	48.18	48.78
2042	46.72	47.00	47.60
1987	46.49	46.92	47.52
1769	45.87	46.34	46.94
1495	45.03	45.77	46.37
1110	44.13	44.88	45.48
836	43.63	44.43	45.03
520	43.03	43.92	44.52
249	42.14	43.05	43.65

6.5.4 Comparison to Previous Studies

The 2020 model results were compared to the previous 1997 floodplain mapping where model cross section locations were reasonably close between the two studies (+/- 20 m offset) or coincident. The results are summarized in **Table 13**.

In general, the 2020 model predicts higher FCL values than those reported in the 1997 study. The reasons for this are summarized as follows:

- The 1997 study used average daily discharge values with no consideration of climate change (600 m^3/s). The 2020 study used peak instantaneous discharge along with a 20% climate change factor as per current engineering practices (746 m^3/s). Higher design flows result in higher predicted water levels.
- The 1997 study model was calibrated using discharge measurements at Duncan, rather than at Riverbottom Road. Manning's n values were likely underestimated compared to actual conditions. The higher Manning's n values used in the 2020 model increased the modelled flood elevations compared to the 1997 model.

Table 13: Comparison of 2020 modelling results to 1997 MoE study

MoE 1997 Cross Section ID	NHC 2020 River Sta.	MoE 1997 FCL (m)	NHC 2020 FCL (m)	Difference (m)	Location Reference
3	10255	78.61	78.96	+ 0.35	Near Stoltz Pool Campground
5	9718	76.24	77.34	+ 1.10	Near Stoltz Pool Campground
8	8525	72.92	74.71	+ 1.79	Near 5700 block of Riverbottom Rd. W
9	7939	70.11	71.00	+ 0.89	Upstream of Kakalatza No. 6
14	5945	61.62	62.48	+ 0.86	Near 5200 block of Riverbottom Rd. W
15	5500	59.22	60.11	+ 0.89	Upstream of the BC Hydro ROW
18	3916	53.86	53.85	- 0.01	Near Cowichan River Bible Camp
19	3447	51.44	52.12	+ 0.68	Near Sandy Pool Regional Park
20	2903	49.86	50.43	+ 0.57	Tzart-Lam No. 5
23	1110	43.97	45.48	+ 1.51	Canyon portion of study reach
24	520	42.55	44.52	+ 1.97	Canyon portion of study reach

7 FLOODPLAIN MAPPING

7.1 Floodplain Mapping Products

Two floodplain mapping products have been prepared for this study:

1) A 1:10,000 scale flood depth map showing the limits for flooding (without freeboard) for the designated 200-year flood.

2) Designated floodplain maps (1:5,000 scale) showing FCLs for the 200-year flood with the recommended allowance for climate change. The flood extent and FCL values shown on the maps include an allowance for freeboard. These maps are suitable for regulatory and land-use planning purposes.

The maps are submitted in digital format.

Two flood inundation zones are delineated on the floodplain maps. The *floodway zone* corresponds to the main channel and a portion of the overbank area that experiences relatively frequent flooding and is exposed to higher velocities, higher flood depths, and more hazards from debris. Flows in this zone are likely to be more destructive and more difficult to mitigate against. Consequently, new development in the floodway is usually discouraged. The *flood fringe zone* represents the portion of the overbank area that is outside of the floodway but is still subject to inundation and ponding during the designated 200-year flood event. Overbank flows in the flood fringe are generally shallower and have a lower velocity. New development in the flood fringe is usually permitted, subject to floodproofing measures. This generally involves raising the underside or floor slab of the structure above the Flood Construction Level (incorporating effects of future climate change and freeboard). **Figure 14** illustrates the difference between the two zones. Differentiating between the floodway and a flood fringe provides planners with additional hazard information when making regulatory and land-use decisions.

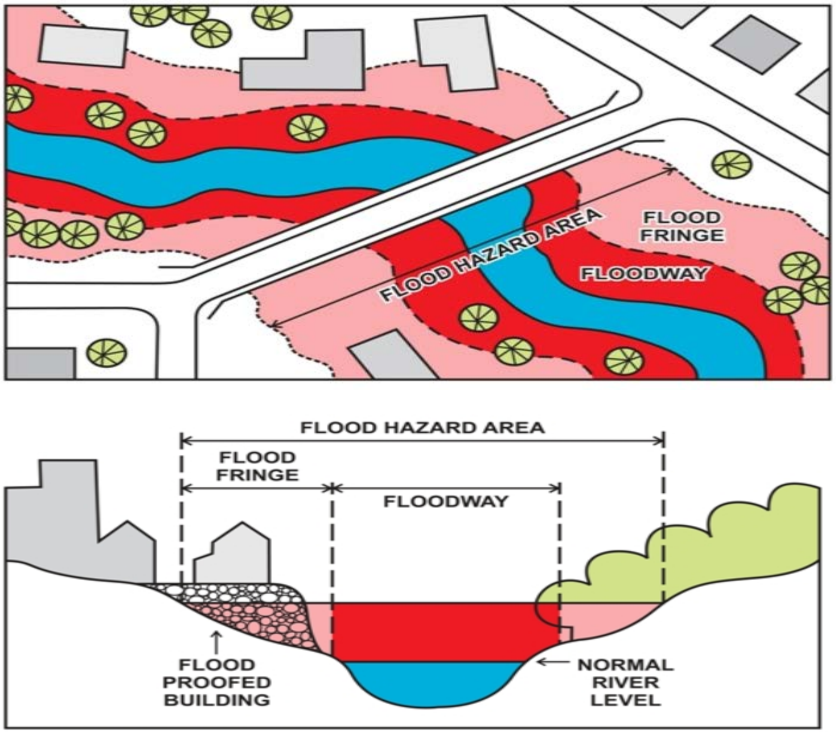


Figure 14: Flood fringe and floodway diagram (retrieved from the Government of Alberta)

Several different methods have been used for defining the floodway and flood fringe by different jurisdictions in Canada and there is currently no requirement for identifying a floodway on BC floodplain maps. An overview of the various methods is described in Sandink et al (2010). The simplest approach involves defining the floodway in terms of the flood extent from a relatively frequently occurring flood (such as a 20-year flood). Agencies such as FEMA in the USA and provinces such as Alberta use a hydraulic conveyance approach, such that encroachment into the overbank flow from future developments will not raise flood levels by more than 0.3 m. When two-dimensional modelling is carried out, the floodway can be defined in terms of some combination of water depth and velocity.

For the purposes of this study, the floodway is defined from the hydraulic model results and represents the estimated flood extent for a 20-year flood event (without accounting for freeboard). The boundary of the flood fringe represents the extent of the designated 200-year flood level plus an allowance for freeboard (0.6 m).

7.2 Limitations and Use of Floodplain Maps

The following limitations should be reviewed prior to use of the floodplain maps:

- 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 any site-specific engineering analysis.

- The maps depict the flooding conditions at the time of surveys. Future changes to the river channels, floodplain, and future climate change will render the maps obsolete. The information on the maps should be reviewed after 10 years have elapsed since publication or after any large flood occurrence (similar to or greater than the 2020 flood).
- 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.
- The floodplain maps do not represent flooding from local stormwater runoff, ponding from rainwater on the floodplain, groundwater seepage, or local drainage courses. Consequently, additional flooding may occur outside of the designated boundaries.
- Roads, railways, bridges, new dikes, and future developments on the floodplain can restrict water flow and increase local water levels. Obstructions such as debris jams and channel sedimentation can also increase flood levels above the levels shown on the maps.
- The floodplain maps do not represent hazards due to erosion, avulsion or channel migration. Information on erosion hazards has been provided in this report (**Section 8**) and should be consulted for assessing these additional hazards.
- Industry best practices were followed to generate the floodplain maps. However, actual flood levels and extents may vary from those shown; Northwest Hydraulic Consultants Ltd. and the Cowichan Valley Regional District do not assume any liability for such variations.

7.3 Effects of Future Channel Shifting on Flood Levels

The major avulsion that occurred in 2020 has significantly altered the local river hydraulics both upstream and downstream of the avulsion channel. Rapid deposition and infilling is occurring on the abandoned north channel, while the new southern channel continues to deepen and widen. It is expected that headcutting[1] will occur upstream of the cutoff (causing bed lowering). The newly eroded sediments from the avulsion channel may deposit on the bars downstream of the avulsion, promoting further instability and possible changes in water levels and flood paths. Several other incipient avulsion paths have been identified, which could further modify river hydraulics and flood levels along the river. Regular monitoring should be carried out to assess how the river is reacting to the unusual events in 2020.

Monitoring should be conducted annually, during the early part of the summer low flow period. Log jams, sediment accumulation, erosional features, and altered channel patterns should be identified and interpreted to inform the need for channel management. Monitoring conducted using fixed wing aircraft or helicopter would provide a channel scale vantage point of the river system.

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[1] Headcutting refers to erosion of the channel bed at a nick point causing channel incision that progresses in the upstream direction.

8 CHANNEL MIGRATION ZONE ASSESSMENT

The CMZ assessment considers two hazard areas: 1) the Modern Valley Bottom (MVB), which includes areas potentially susceptible to future channel migration or channel avulsions, and 2) the Erosion Hazard Area (EHA), which includes areas potentially susceptible to future channel erosion. The CMZ mapping is intended to provide a planning level boundary to inform land development considerations on the potential for future channel erosion or other channel processes. It does not include a geotechnical analysis of any banks, terraces, or valley slopes which could require the assignment of additional development setbacks.

8.1 Overview

Channel migration is the movement of a river across its alluvial valley. It is a natural process that commonly occurs in river systems with wide valley bottoms and erodible riverbanks. The Cowichan River at Riverbottom Road is dominated by a meandering channel pattern with intermittent and localized wandering channel segments formed by channel avulsion and cut-off processes. The channel meanders across the floodplain and becomes constrained in several places by the valley margin or in other locations along the floodplain where bank armouring has been constructed or at localized bedrock outcrops.

The purpose of this assessment is to identify the area of the floodplain through which the river can be expected to migrate naturally over time, referred to in this report as the Channel Migration Zone (CMZ). The planning level CMZ includes the following components:

- The Modern Valley Bottom (MVB), which is interpreted as, “the area where channel migration has occurred in the current climatic and hydrologic regime, which is assumed to encompass the last thousand years” (Olson et al., 2014). The MVB is delineated based on interpretation of fluvial landforms on the geomorphic surface and represents areas that may be susceptible to future channel processes.
- The Erosion Hazard Area (EHA) is an additional area that extends the overall CMZ beyond the MVB to consider future potential for channel erosion that could eventually widen the valley. The EHA is delineated based on an analysis of historical bank migration rates and interpretation of valley wall surficial geology.

Bank migration occurs when the river’s hydraulic forces are sufficient to erode its bank materials. In the Cowichan River reach at Riverbottom Road, hydraulic forces are often concentrated along the outer banks of meander bends. Over time, the river erodes its outer banks while depositing sediment along its inner banks, resulting in lateral shifting of the channel alignment and formation of meander patterns across the flood plain. Migration rates are highly variable and dependant on the erodibility of bank materials. Accumulations of woody debris and sediment, or the presence of in-stream structures such as bank armour, can influence channel flow patterns and result in localized bank erosion. This study focuses on historical rates and patterns of erosion to evaluate the future erosion potential. The analysis considers surficial geology maps and air photos, available topographic information, observable bank materials, and areas of notable sediment and wood debris accumulation.

Avulsion refers to the river “changing course” and shifting to a new channel location. Avulsions may occur rapidly during peak floods, and are often triggered by log jams, sediment deposition, and other obstructions that direct flow away from the main channel. Avulsions often begin as small side channels and gradually increase in size over time. Eventually, an avulsion channel may become the new main channel while the former main channel carries little to no flow. Avulsions are sporadic and more difficult to predict than progressive bank erosion. Avulsion hazard potential has been evaluated based on interpretation of fluvial landforms on the floodplain and an assessment of past avulsion events within the study reach that are visible in the aerial photograph record and available imagery.

8.2 Methods

8.2.1 Aerial Photograph and Orthophoto Analysis

Archival aerial photographs of the study area were used to determine historical channel occupancy positions and assess channel migration patterns. **Figure 15** summarizes the available aerial and ortho imagery used for the study, along with reported annual maximum daily flows at WSC station 08HA011. The estimated 100-year, 20-year, and 2-year annual maximum daily flows for this gauge have been estimated using the results of the flood frequency analysis (**Section 5.2**) and the corresponding ratio between reported annual maximum daily and annual maximum instantaneous flows.

Using ESRI ArcGIS software the imagery was georeferenced to a common datum and the active channel banklines were delineated by interpreting the location of channel banks and riparian vegetation. The accuracy of the historical channel mapping is dependant on the photo quality and scale and orthophoto resolution. The historical channel migration analysis is described in more detail in **Section 9.2.1**.

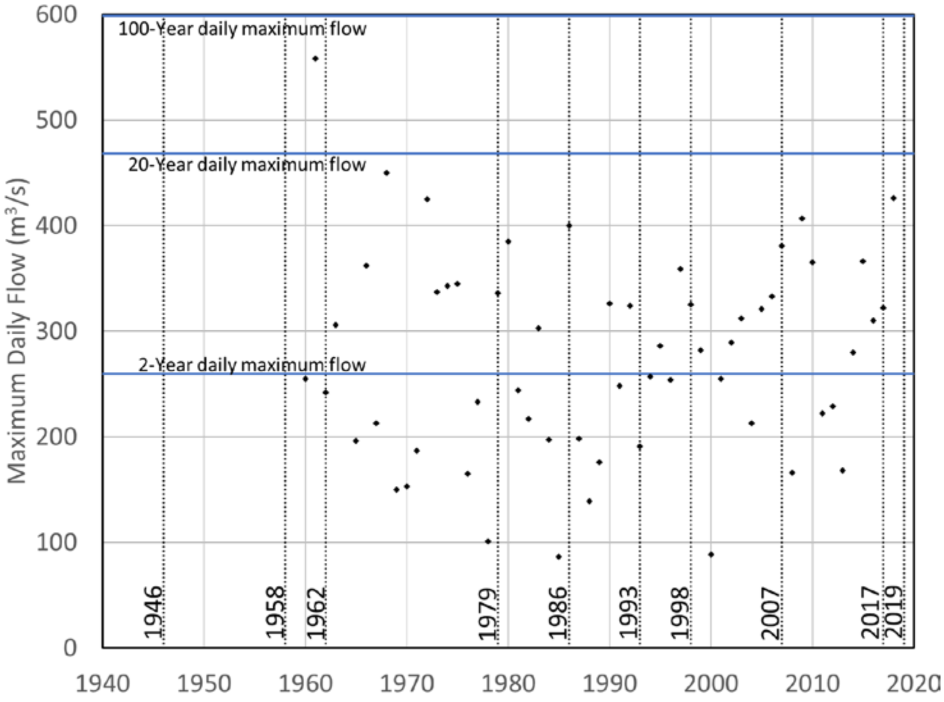

Figure 15: Summary of available aerial and ortho imagery used for historical channel occupancy analysis, along with annual maximum daily flows at WSC 08HA011.

8.2.2 Relative Elevation Model Analysis

Detailed 2019 topographic LiDAR (see **Section 4.1**) was used to develop a digital elevation model (DEM) of the study area. The DEM surface was then compared to the results of the flood modelling to develop a relative elevation model (REM) that relates the DEM surface to the simulated 2-year flood level, which is used to approximate a channel forming flood event[2]. A REM is useful because it presents the elevation data as a relative difference between the ground surface and the flood surface, which highlights fluvial the features in the valley such as relic floodplain features , flow paths, and valley terraces. **Figure 16** illustrates the REM used for the analysis. The REM was interpreted alongside available imagery, bankline mapping information, and DEM data to delineate the MVB, described in **Section 9.1**.

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[2] A 2-year flood event (50% annual exceedance probability flood event) is considered to be a relatively frequent flow condition that has the capability of causing substantial channel erosion and sedimentation processes that could lead to lateral channel migration and avulsions.

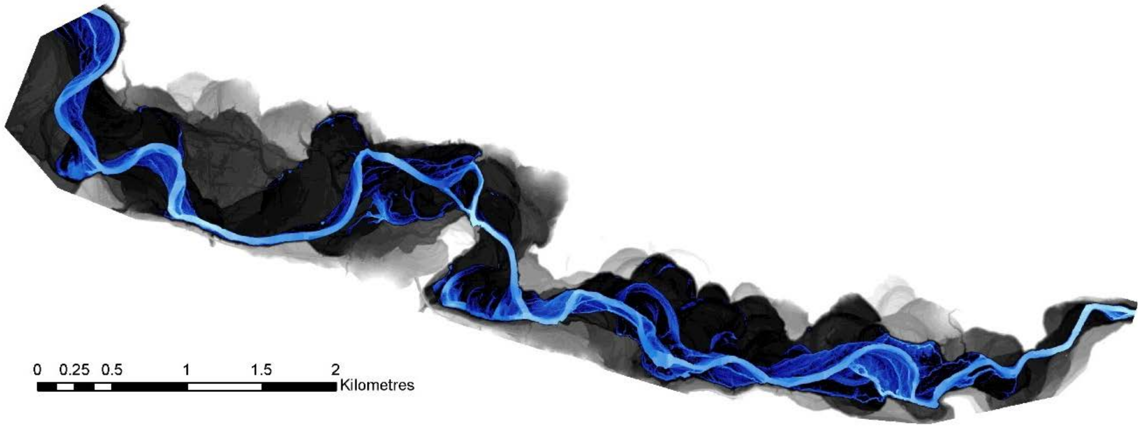

Figure 16: REM of the Riverbottom Road study reach. Blue shading represents locations where the ground surface lies below the 2-year flood level and grey shading represents locations where the ground surface lies above (up to 20 m relative difference)

8.2.3 Site Investigations

Information gathered during the geomorphic site investigations (see **Section 4.5**) was used to inform the channel migration and erosion hazards analysis. Key information included locations of bank armouring (e.g. riprap), bank material characteristics, presence of bedrock control, and evidence of side channel formation and avulsion.

8.3 Basin Context

8.3.1 Geomorphic History and Surficial Geology

Almost all of Vancouver Island was glaciated during the Fraser Glaciation, which lasted from approximately 30,000 to 11,700 years ago. Available mapping indicates the presence of the following surficial geology in the study area: till, glaciolacustrine and glacial outwash deposits, fluvial deposits, and bedrock outcrops. **Figure 17** presents a map showing the method of deposition of surficial materials, based on integration of various datasets ranging in 1:20,000 to 1:250,000 scale by the Provincial government.

Figure 18 presents 1:100,000 scale surficial geology mapping produced by the Province, as well as observed outcrops of bedrock and till. Both figures are overlaid with the 2019 channel alignment for reference.

While the two figures provide different information from different mapping sources and scales, they indicate that the floodplain is generally covered with Quaternary sediments (sand and gravel) deposited following deglaciation by fluvial processes that cut into and formed glaciofluvial and glaciolacustrine terraces along the outer valley margin. These surficial geology types are generally considered to be relatively erodible, with potential for geotechnical instabilities along steep and high valley terraces that form the boundary of the active channel or modern valley bottom.

Quadra sediments are a fluvial and glaciofluvial material comprised of interbedded layers of sand, gravel, silt, and clay, likely deposited in front of the advancing glacier. Quadra sediments are located along the upper half of the study reach along the north side of the channel, including Stoltz bluff (**Photo 9**). Vashon drift sediments are more recent deposits comprised of glaciofluvial, glaciolacustrine and till. These deposits are mapped along the southern valley wall and are exposed at several locations along the south side of the channel. Haslam Formation refers to a type of bedrock exposed in several locations along the lower half of the study reach. Bedrock exposures along the channel margin were identified and mapped with a handheld GPS during the geomorphic assessment.

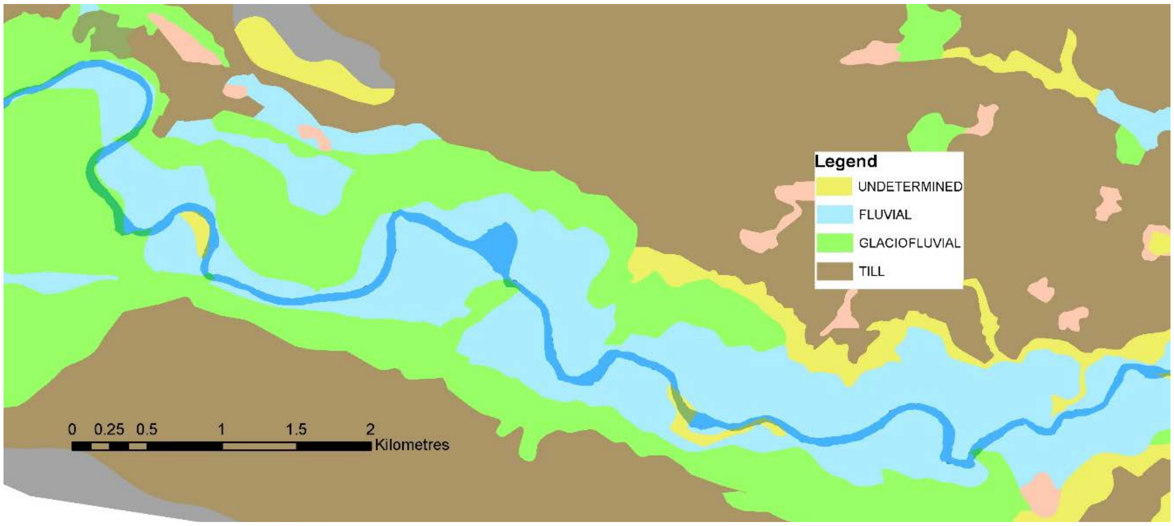

Figure 17: BC Soil Mapping data for Riverbottom Road region (published by the Ministry of Environment and Climate Change Strategy – Knowledge Management, licensed under Open Government License – British Columbia: catalogue.data.gov.bc.ca)

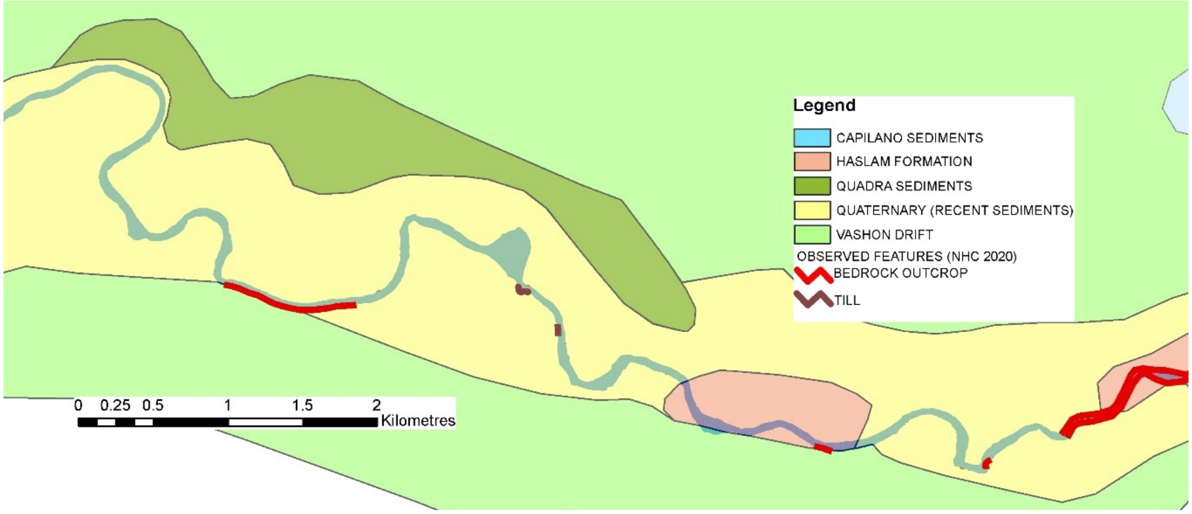

Figure 18: Surficial Geology for Riverbottom Road region (J.E. Muller, 1983)

Photo 9: View toward Stoltz Bluff and exposed Quadra sediments

8.3.2 Logging Impacts

In the late 1800s and early 1900s the river was used for log driving, resulting in large-scale disturbances to the river morphology. Explosives were used to remove impediments to log movement, including the removal of 29 waterfalls and 125 rapids (Pike et al., 2017). During the 1900s, much of the old growth timber was harvested within the Cowichan basin. This resulted in changes to watershed hydrology and the overall stability of the river and floodplains. The legacy of historical stream channel disturbances continues to this day. Wood debris can have a substantial influence on channel processes. For instance, large accumulations of wood can trap sediment and promote localized infilling, which thereby promotes further accumulation of wood and sediment. During a flood event, accumulations of wood and sediment in the channel can create localized water level increases and promote water to flow to other, less active parts of the floodplain. Potentially, these processes can trigger a channel avulsion.

8.3.3 Sediment Sources

Channel migration can be influenced by upstream sediment sources if sediment supply is greater than the channel's sediment transport capacity. Upstream of the study reach, sediment sources include mobilized bed materials, eroded bank materials, and inputs from hillslopes and tributaries. Historical aerial imagery indicates areas of recent channel migration upstream of the study reach, including evidence of avulsions. Channel migration upstream and within the study reach clearly contributes sediment to the channel. Areas of local deposition include channel side bars, point bars, and channel areas upstream of log jams.

8.4 Channel Bed Elevation Changes

For this study, channel bed elevation changes refer to a long-term trend in the channel bed profile as a result of an altered volume, rate, or material composition of sediment supply; or in response to an altered channel pattern. Channel aggradation is an increase in bed elevation associated with sediment deposition. Channel degradation is channel lowering associated with erosion or scour.

Channel aggradation rates were evaluated by comparing channel bed elevation changes at locations that were surveyed in 1993 and repeated in 2020. **Figure 19** presents a comparison plot of the change in the thalweg elevation between 1993 to 2020[3]. Between approximately NHC 2020 STA 525 and STA 3450 the thalweg at five monitoring cross sections aggraded by between 0.4 to 2.2 m over the 27-year period. Between STA 3920 and STA 5515 there was no obvious trend, with up to 1 m degradation and 0.7 m aggradation in some locations and negligible changes in other locations. Between STA 5945 and STA 6945 the thalweg at three monitoring cross sections degraded by between 0.4 to 1.6 m, likely attributed to a channel response to the avulsion that occurred between 2017 and 2019 (described in **Section 9.1.2**).

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[3] The thalweg is a line that joins the lowest points along the entire length of stream bed, defining the deepest points of the channel. The thalweg usually defines the line of fastest flow in the river.

Farther upstream the thalweg showed no change, and between STA 8520 and STA 11175 the thalweg at five monitoring sections aggraded by between 0.1 and 1.1 m.

Channel aggradation patterns at the upstream and downstream ends of the study reach illustrate that this channel reach receives a relatively high influx of sediment and has a relatively high output of sediment to downstream reaches. Large sediment accumulation rates at localized locations along the channel indicate these areas have an elevated potential for trapping wood debris and could be an early indication that an area is becoming more prone to a future channel avulsion. Channel degradation patterns at the locations noted above appear to be related to a longer term adjustment of the channel to historical channel avulsions.

Trends of aggradation and degradation throughout the study reach are apparent, suggesting that, over a decadal time scale, the sediment load into the channel reach is being balanced by sediment transport through the reach, channel incision, lateral bank erosion, and channel avulsions. Over the long term, change to the channel profile within this reach is strongly correlated to upstream sediment supply, ongoing channel shifting processes across the floodplain and conveyance of sediment farther downstream.

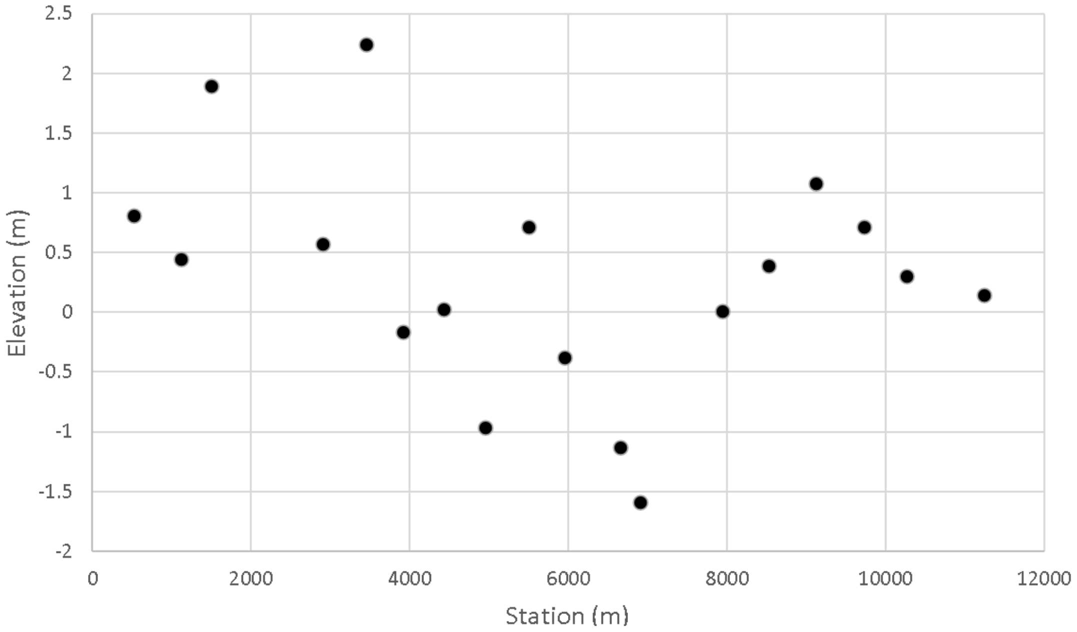

Figure 19: Thalweg elevation comparison (1993 to 2020)

9 CHANNEL MIGRATION ZONE MAPPING

The planning level Channel Migration Zone (CMZ) includes two components: the Modern Valley Bottom (MVB, described in **Section 9.1**) and the Erosion Hazard Area (EHA, described in **Section 9.2**). **Figure 20** provides a schematic of the MVB and EHA components of a CMZ map. The MVB includes areas that are considered prone to future channel migration processes that could occur over a relatively short timeframe. The EHA includes areas that could be susceptible to more gradual erosion processes over a relatively longer timeframe. Differentiating between the MVB and EHA provides planners with additional hazard information when making regulatory and land-use decisions.

The meander belt width is also shown on **Figure 20** for context. The meander belt width is the lateral distance between the outside edges of a series of channel meanders. Meander belt width mapping can be used for planning purposes to define locations on the floodplain that are presently occupied by channel activity. Meander belt width mapping provides a limited degree of insight into future potential areas of channel occupancy because it relies on an assessment of the present day channel pattern to inform future changes. It also doesn't account for variability in the site geomorphology or topography, in contrast to the approach used to define the MVB (described in **Section 9.1**).

For this assessment, the study reach was classified into four sub-reaches based on valley scale characteristics and channel pattern. Each reach is described below:

- Reach 1: it is frequently confined by bedrock. The MVB is relatively narrower than in the other reaches, ranging between 60 to 200 m in width and approximately equal to the channel meander belt width.
- Reach 2: the MVB ranges between 150 to 680 m with a meander belt width in the order of 580 m. In several locations the channel impinges on the valley edge, and a compound meander bend has formed where the channel is constrained by channel armouring.
- Reach 3: it is the most dynamic reach and includes two zones of repeated historical channel avulsions. The MVB width is irregular and ranges from approximately 200 m at the upstream and downstream ends of the channel reach to more than 800 m at its widest point. The meander belt width is approximately equal to the valley width, and the channel is occasionally confined by the valley walls and by bank armour in several locations.
- Reach 4: the MVB ranges from 165 to 550 m and is approximately equal to the meander belt width. The channel is occasionally confined by the valley walls and by bank armour in several locations.

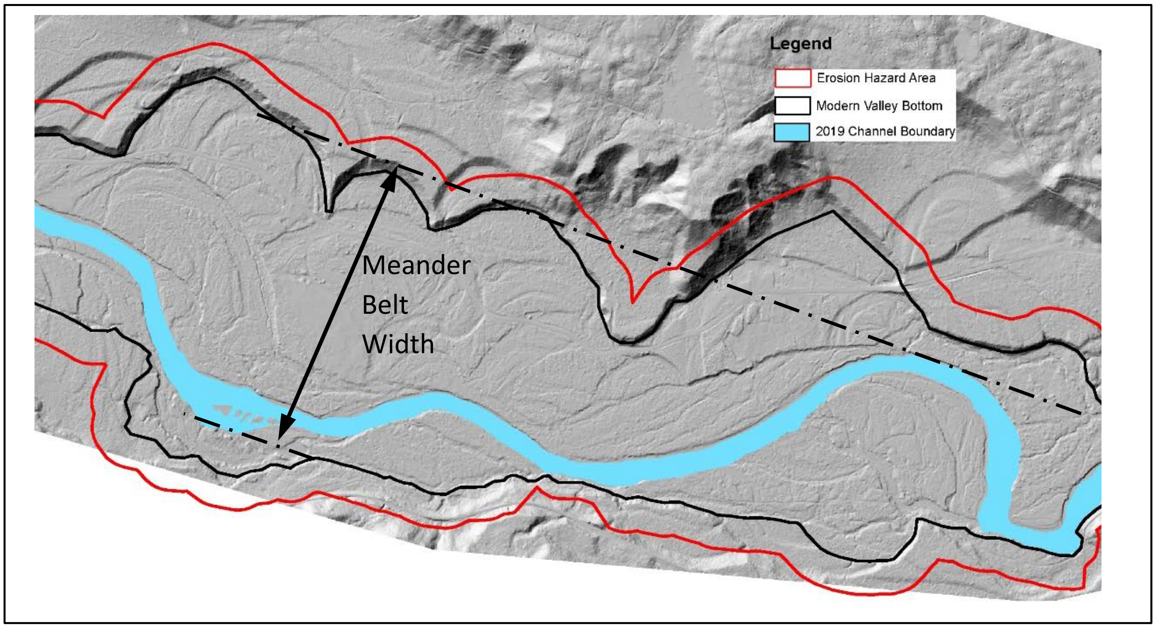

Figure 20: Diagram of the MVB and channel meander belt width

9.1 Modern Valley Bottom

The MVB includes areas that have in the past been susceptible to channel migration processes such as lateral erosion and channel avulsion, forming a geomorphic floodplain dominated by abandoned or semi-active channel meander features. The valley margin is often well defined where terrace features have formed through channel degradation and are no longer connected to the MVB. The active floodplain includes wetland habitat and backwatered side channels in formerly active channels, and erosional floodplain channels that could become more active in the future.

9.1.1 Modern Valley Bottom Delineation

MVB delineation is based on interpreted geomorphic features, historical and present-day channel position, and ground elevation relative to the 2-year flood level. This analysis includes consideration of the potential for localized accumulations of sediment or channel spanning log jams that could potentially elevate water levels above the 2-year flood level. For this study, locations on the floodplain that are within 2 m elevation of the 2-year water surface are generally considered to be connected to the MVB, based on the supply potential of large wood and sediment to the study reach.

From the REM analysis described in **Section 8.2.2**, the interpreted MVB was delineated as shown in **Figure 21**. The REM is shown for reference and to highlight that the interpreted MVB frequently aligns with features that lie much higher above the valley bottom.

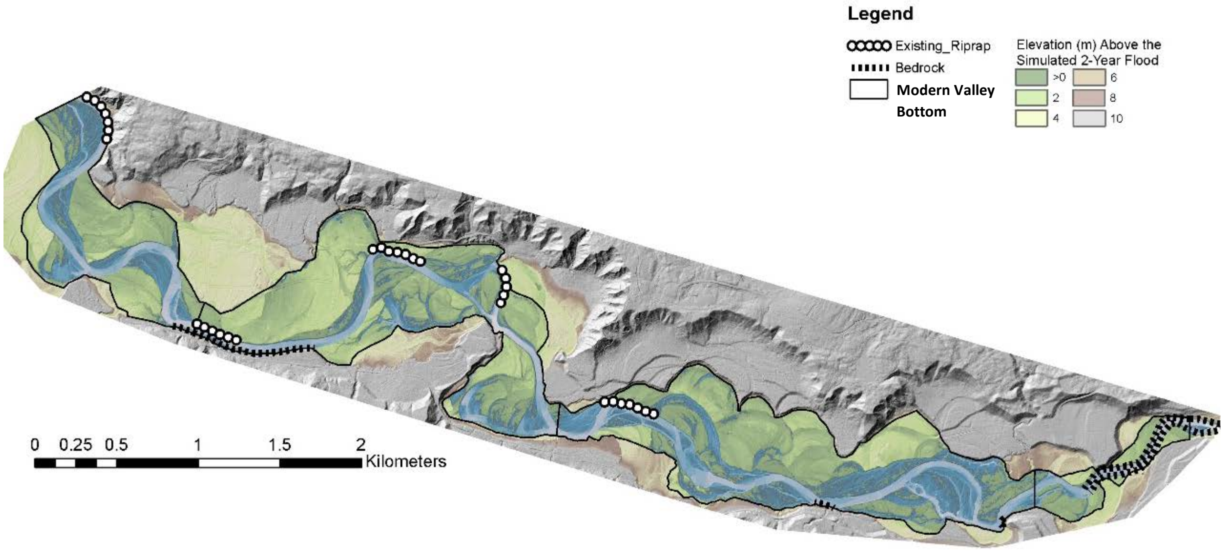

Figure 21: Interpreted Modern Valley Bottom

9.1.2 Channel Avulsion Potential

Channel avulsions are an important part of the natural channel migration processes in the study area and are possible where topographically low elevation terrain exists on the floodplain. The potential for channel avulsions to occur within the MVB was evaluated by analysing historical avulsion channels over the available aerial photo and ortho-imagery records to determine the ratio between the pre- and post-avulsion channel path length. This avulsion ratio provides an indication of the relative potential for an avulsion to occur on the floodplain, based on the existing channel length and length of floodplain features that could potentially become occupied by the channel in the future.

Table 14 summarizes the results of the analysis. Nine avulsion events occurred over the 73 years of record between 1946 and 2019. Avulsions generally occurred between STA 2090 to 2880 (3 events); STA 3960 to 4690 (1 event); STA 5450 to 5720 (3 events); and STA 6200 to 7750 (2 events). The range in computed avulsion ratio is between 1.0 and 2.4, which indicates that channel avulsions could potentially occur in conditions where the future potential flow path (and gradient) is relatively equivalent to that of the existing channel. In other words, it is infeasible to determine with any degree of certainty where future channel avulsions might occur based on an analysis of past channel avulsions. The analysis suggests the primary driving force triggering a channel avulsion is a channel blockage or accumulation of sediment or wood that promotes channel flow toward other parts of the floodplain.

Riprap is visible along the channel at approximately five locations, shown in **Figure 22**. The precise year that the riprap was constructed at each location is uncertain; however, the approximate period that the riprap was constructed has been labelled according to the corresponding imagery dates that these structures first become visible.

Table 14: Summary of channel avulsion analysis

Event Period	Approx. NHC 2020 STA (m)	Pre-Avulsion Length (m)	Post-Avulsion Length (m)	Ratio
1946 to 1958	2090 to 2860	810	610	1.3
1946 to 1958	5490 to 5720	1170	700	1.7
1962 to 1979	2120 to 2780	580	580	1.0
1962 to 1979	5450 to 5690	800	460	1.7
1962 to 1979	6200 to 7750	1740	1700	1.0
1979 to 1986	3960 to 4690	850	690	1.2
1998 to 2007	5450 to 5670	420	230	1.8
2017 to 2019	6310 to 6560	610	250	2.4
2017 to 2019	2110 to 2880	730	520	1.4

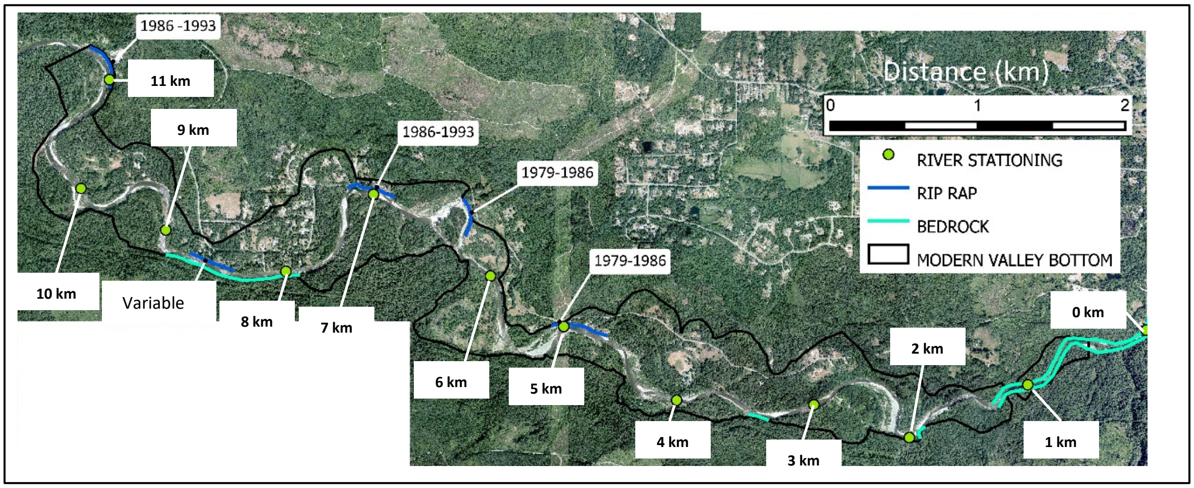

Figure 22: Study reach, showing channel stationing (measured in km), and riprap labelled with approximate timeframe of riprap construction

In general, the two structures built between 1979 and 1986 appear to have been constructed in response to channel shifting patterns. Riprap placed near STA 7000 (between 1986 to 1993) appears to be in response to increasing lateral instability at this location after 1962. Riprap placed upstream of STA 11000 (between 1986 to 1993) was placed to help stabilize Stoltz Bluff. This site is located at an outside channel bend that showed channel migration throughout the photo record leading up to the installation of erosion countermeasures. The age of the riprap placed near STA 8500 is uncertain. The quality and resolution of the early air photos renders them difficult to interpret the presence or absence of bank hardening structures; however, it appears to have been constructed in phases over time in response to ongoing bank erosion processes.

In some cases, the presence of bankline hardening has cut-off a substantial portion of the MVB to channel processes and semi-permanently altered the channel alignment. Bankline hardening can have unintended impacts in other locations on the floodplain that should be evaluated when considering erosion countermeasure projects.

9.2 Erosion Hazard Area

The EHA is an additional area that extends the overall CMZ beyond the MVB to considers future potential for bank erosion that could eventually widen the valley. The EHA is delineated based on an analysis of historical bank migration rates and interpretation of valley wall surficial geology.

9.2.1 Historical Channel Migration

Historical channel migration was mapped by delineating the active channel from ten years of georeferenced aerial photo and ortho-imagery, which ranged over a 73 year period extending from 1946 to 2019. **Figure 23** and **Figure 24** show an overlay of the mapped channel boundary for each of the ten years of record, with the former showing the oldest to most recent channel alignment and the latter showing the most recent to the oldest. The former illustrates locations where the channel has eroded into the floodplain over time in response to channel migration processes, and the latter highlights accretionary processes at the inside bend of meanders that promotes the onset of meander migration.

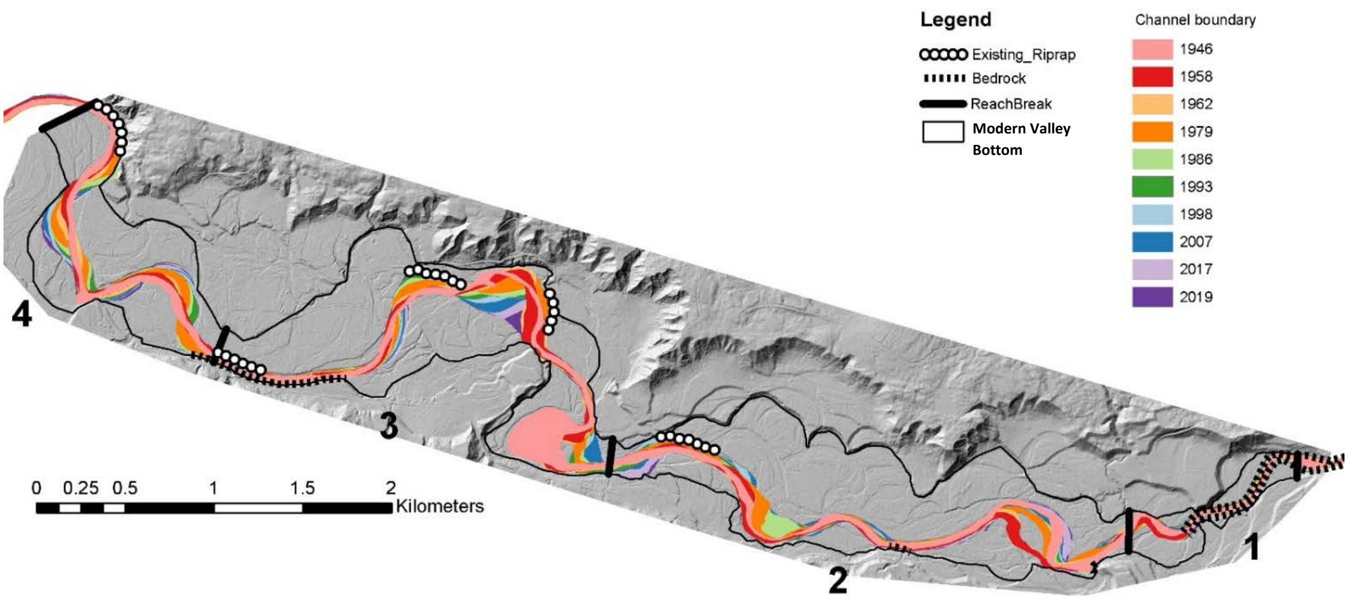

Figure 23: Historical channel migration (oldest to most recent)

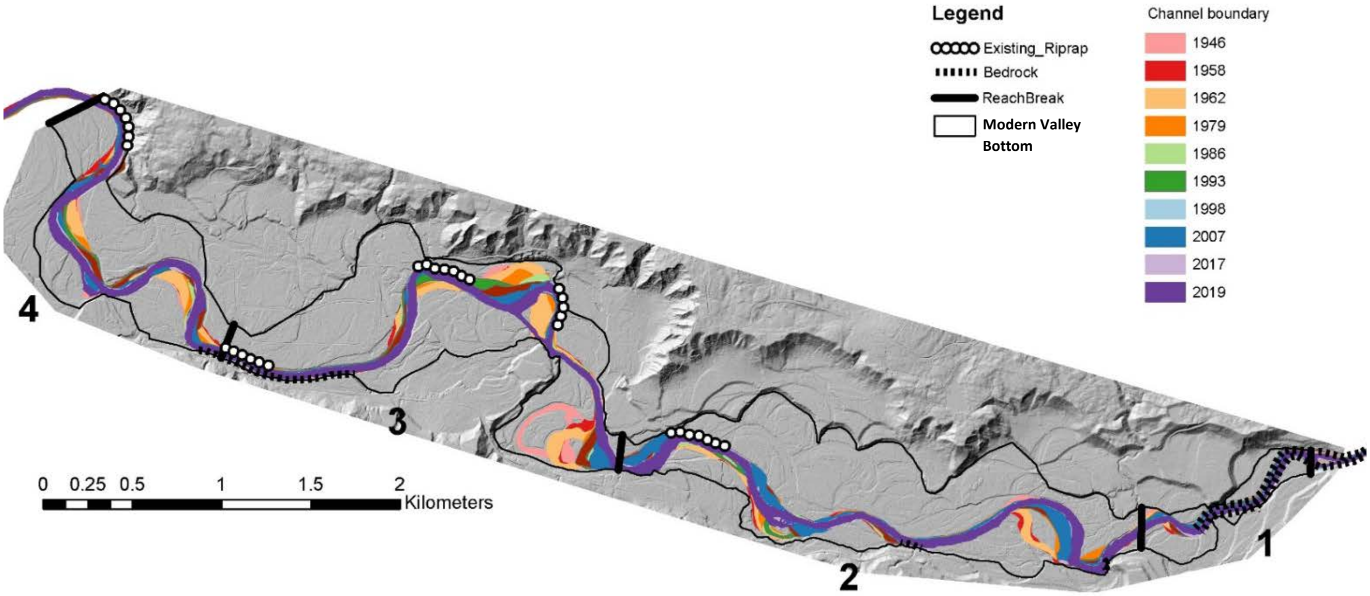

Figure 24: Historical channel migration (most recent to oldest)

Table 15 presents the results of the historical channel migration analysis based on a comparison of successive channel imagery records, averaged by reach and over the period of record. Channel locations identified with confining bedrock or bank armour were removed from the analysis to limit the analysis to erodible bank types only. Channel shifting over the entire 73-year period of record provides an indication of relatively longer-term annual rates. Average annual erosion rates vary considerably over the period of record, with the largest computed value (10.6 m/year) occurring in Reach 3 during the period between 2017 and 2019 and the lowest computed values (0.9 m/year) occurring in Reach 1 and 2 during the period between 1986 and 1993.

Table 15: Summary of Historical Channel Migration Rates

Time Interval	Reach Averaged Annual Erosion Rate (m/year)			
	Reach 1	Reach 2	Reach 3	Reach 4
1946 to 1958	2.4	1.6	2.3	1.2
1958 to 1962	-	1.7	3.2	4.2
1962 to 1979	1.8	1.3	1.6	2.3
1979 to 1986	1.5	2.1	1.8	2.4
1986 to 1993	0.9	0.9	1.4	2.2
1993 to 1998	2.5	2.5	2.1	5.5
1998 to 2007	4.2	2.0	1.8	1.7
2007 to 2017	2.3	2.0	1.5	1.0
2017 to 2019	5.3	2.8	10.6	1.8
1946 to 2019	2.7	1.4	1.8	2.0

9.2.2 Erosion Hazard Area Delineation

For planning purposes, the cumulative average annual erosion rates for the period between 1946 and 2019 have been adopted for determining the Erosion Hazard Area (EHA). For this study, the EHA has been delineated assuming a planning time horizon of 50 years. As noted in **Section 9.2.1**, bank erosion rates were computed only for those areas that are prone to erosion. As such, banklines along bedrock outcrops were excluded from the analysis. Similarly, hardened banks (e.g. riprap) were excluded from the analysis for any compared photo years where bank hardening was visible.

Table 16 presents the computed EHA setback distance, which is a planimetric distance measured beyond the limits of the MVB. The computed EHA setback distance ranges from 72 m to 137 m beyond the delineated MVB. The setback is applied to all channel areas except where bedrock has been identified along the bankline. For bedrock banklines an EHA setback equivalent to one channel width is applied. Reach 1 has the largest computed EHA setback distance; however, this setback only applies to approximately the upstream most 400 m of bankline within this channel reach because the remainder of this channel reach is confined by bedrock, which has remained more or less stable during the period of record.

Table 16: Computed Setback Distance For Establishing the 50-Year Planning Time Horizon EHA

Reach	EHA Setback Distance (m)
1	137
2	72
3	89
4	99

9.3 Channel Migration Zone Mapping Product

The CMZ maps are submitted in digital format.

Two areas are delineated on the CMZ maps. The *modern valley bottom* corresponds to the portion of the floodplain and channel that is susceptible to active channel processes. The *erosion hazard area* represents areas potentially susceptible to future channel erosion over a 50-year planning time horizon.

9.4 Limitations and Use of Channel Migration Zone Maps

The following limitations should be reviewed prior to use of the CMZ maps:

- CMZ maps are an administrative tool that depict the potential extent of active Cowichan River channel processes, and future erosion potential for a 50-year planning time horizon. A Qualified Professional with experience in fluvial geomorphology must be consulted for a site-specific engineering or geosciences analysis.

- The CMZ maps depict the potential extent of active channel processes and future erosion potential at the time of the assessment. Future changes to the river channels or floodplain, future climate change, a large geotechnical event due to land instabilities at the site or farther upstream, or a channel avulsion or other event that substantially alters the supply of sediment and logs to the study reach will render site-specific map information obsolete. The information on the maps should be assessed regularly (5 to 10-year intervals) or after any extreme flood occurrence.
- The CMZ boundaries have not been established on the ground by legal survey. The accuracy of these boundaries is limited by the LiDAR base mapping and orthophotography.
- The CMZ maps do not represent alluvial fan hazards from tributary channels, slope instabilities, or Cowichan River floodplain limits.
- The CMZ maps do not represent channel erosion, channel avulsions or other natural processes from tributaries, local stormwater runoff, ponding from rainwater, groundwater seepage, local drainage courses, or geotechnical instabilities. Consequently, additional impacts from such natural processes may occur outside of the designated boundaries.
- Areas within the CMZ boundaries may be susceptible to tributary fan hazards that are not represented on these maps. In addition to channel migration hazards, a Qualified Professional should assess for potential hazards from tributary channels.
- Roads, railways, bridges, new dikes, and future developments on the floodplain can alter channel processes and increase local erosion rates or potential for channel avulsions. Obstructions such as debris jams and channel sedimentation can also increase local erosion rates and potential for channel avulsions shown on the CMZ maps.
- Areas within or adjacent to the CMZ boundaries may be susceptible to geotechnical instabilities that are not represented on these maps. In addition to channel migration hazards, a Qualified Professional should assess for potential hazards from geotechnical instabilities.
- Industry best practices were followed to generate the CMZ maps. However, extents of channel migration zone hazards may vary from those shown; Northwest Hydraulic Consultants Ltd. and the Cowichan Valley Regional District do not assume any liability for such variations

10 CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

1) Updated floodplain maps were prepared for the Cowichan River near Riverbottom Road. The maps represent flooding from a 200 year event with a 20% increase in discharge to account for potential climate change. The maps update previous flood maps published by MoE in 1997.

2) A 1-D hydraulic model was developed using the program HEC-RAS. Model geometry was based on 2019 topographic LiDAR and 2020 bathymetric surveys. The model was calibrated and validated using data collected during the significant 2020 flood event on the Cowichan River.

3) The hydraulic model and input hydrology were used to model flood extents and elevations for a range of design conditions (2-year flood to 500-year flood). Model results were compared to previous floodplain mapping estimates (BC MoE, 1997). The model results were generally higher than the previous estimates.

4) The following floodplain maps were prepared:

   - A 1:10,000 scale flood depth map showing the limits for flooding (without freeboard) for the designated 200-year flood;
   - Designated floodplain maps (1:5,000 scale) showing Flood Construction Levels (FCLs) for the 200-year flood with the recommended allowance for climate change. The flood extent and FCL values shown on the maps include an allowance for freeboard. These maps are suitable for regulatory and land-use planning purposes.

5) 1:5000 scale Channel Migration Zone (CMZ) maps were prepared to update erosion hazard maps previously prepared for the Cowichan River near Riverbottom Road by Hardy BBT Ltd. in 1989. The CMZ maps provide a planning level boundary to inform land development considerations on the potential for future channel erosion or other channel processes. It does not include a geotechnical analysis of any banks, terraces, or valley slopes which could require the assignment of an additional ‘safe’ setback distance.

10.2 Recommendations

1) The floodplain and channel migration zone hazard maps should be consulted together to assess overall hazards to the study area. Both mapping products are administrative tools only, and any site-specific engineering or geosciences analysis must be completed by a Qualified Professional.

2) The floodplain maps depict the flooding conditions at the time of surveys. Future changes to the river channels, floodplain, and future climate change will render the maps obsolete. The

information on the maps should be reviewed after 10 years have elapsed since publication or after any large flood occurrence (similar to or greater than the 2020 flood).

3) The major avulsion that occurred in 2020 has significantly altered the local river hydraulics both upstream and downstream of the avulsion channel. Several other incipient avulsion paths have been identified, which could further modify river hydraulics and flood levels along the river. Regular monitoring should be carried out to assess how the river is reacting to the unusual events in 2020. Monitoring should be conducted annually, during the early part of the summer low flow period. Log jams, sediment accumulation, erosional features, and altered channel patterns should be identified and interpreted to inform the need for channel management. Monitoring conducted using fixed wing aircraft, helicopter, or unmanned aerial vehicle (UAV) would provide a channel scale vantage point of the river system.

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