APPENDIX A:

SURVEYS

1 BACKGROUND

This appendix describes the data used to support the hydraulic modelling components of the project. Ground elevation data was drawn from existing data sets and from a series of surveys carried out for the project. The acquisition of topographic, bathymetric and hydrographic information forms the basis of inputs for the hydraulic modelling component.

2 DATUM AND COORDINATE SYSTEM DETAILS

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

In summary, specific coordinate system details are:

- Horizontal Datum: North American Datum 83 (NAD83) CSRS 3.0.0.BC.1.NVI
- Projection: UTM Zone 10 North
- Vertical Datum: CGVD 2013
- Geoid Model: CGG2013a

3 LIDAR

GeoBC originally communicated to the CVRD that processed LiDAR would be available for this project by August 15, 2019, which was then revised to September 18, 2019. On September 24, the CVRD informed NHC that GeoBC would not be able to deliver processed LiDAR for the Cowichan floodplain until the spring of 2020.

NHC reviewed the data quality of two other available LiDAR datasets that cover portions the Cowichan floodplain. The two alternative LiDAR data sets are available from the CVRD and District of North Cowichan (DNC).

The CVRD LiDAR was flown on November 18, 2016 by McElhanney Consulting Services and covers the majority of the floodplain with the exception of a 1.5 km portion of the Koksilah River by Cowichan Station. The available DNC LiDAR was flown on May 29, 2017 by Eagle Mapping and was classified by Aeroquest Mapcon. The DNC LiDAR covers the City of Duncan bounded by the Cowichan River to the south. The coverage of both these LiDAR datasets is shown in Figure 1.

The Federal Government Natural Disaster Mitigation Program (NDMP) funding for this project specifies that the LiDAR must adhere to the Federal Flood Mapping Framework (Natural Resources Canada and Public Safety Canada, 2018b), which in turn references the Federal Lidar Acquisition Guidelines (Natural Resources Canada and Public Safety Canada, 2018a). The data accuracy and density specifications are a function of flood risk category and are considered approximate as they are based upon several existing provincial and territorial guidelines. The definitions for flood risk categories is presented in Table 1.

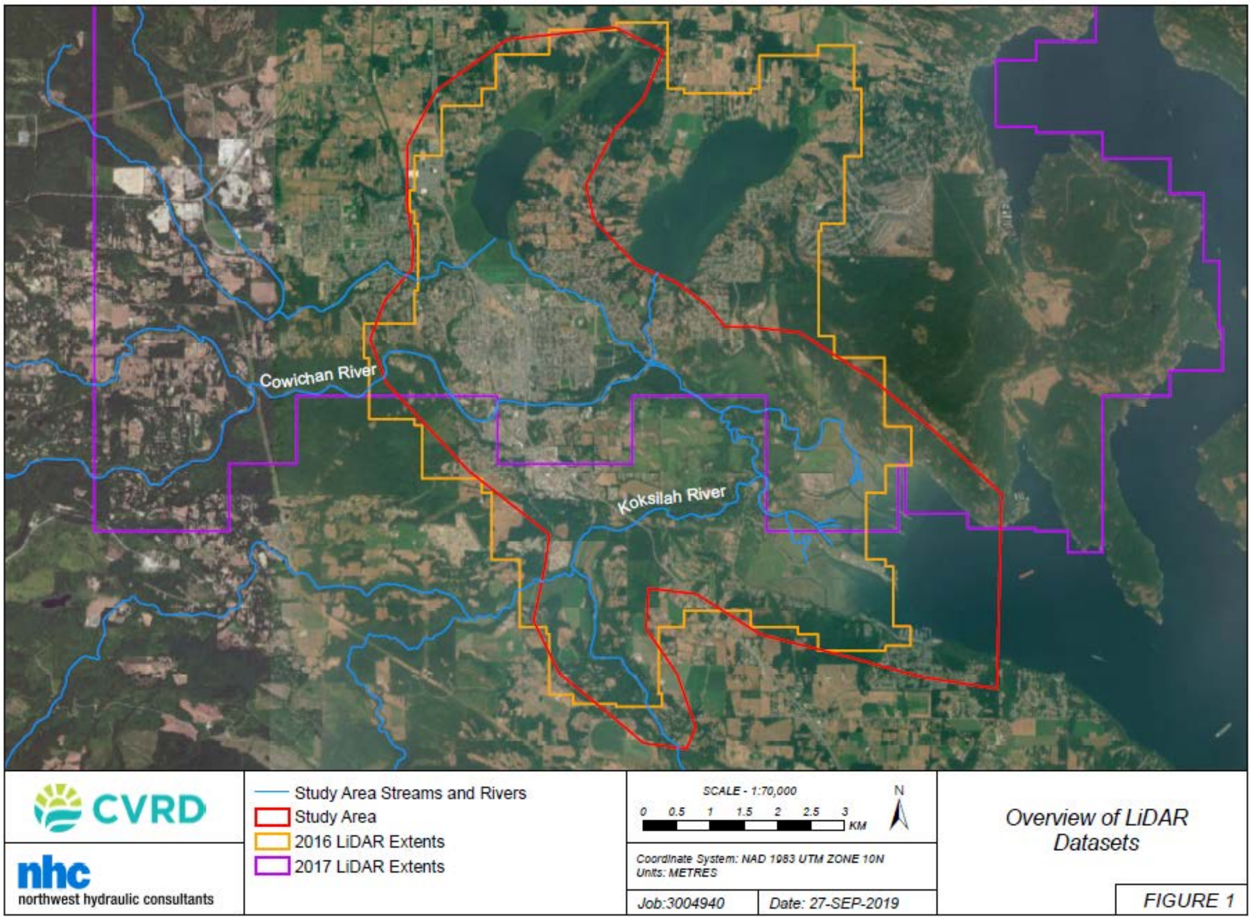

Figure 1: **Overview of alternative LiDAR datasets**

Table 1: **Flood risk categories (Natural Resources Canada and Public Safety Canada, 2018a)**

Flood Risk Category	Description
High	All urban areas and rural areas that are protected by diking
Medium	All other areas that include settlements and agricultural lands
Low	Sparsely populated areas

The Cowichan River floodplain falls into a high flood risk category as the area is surrounded by the City of Duncan and is protected by a series of dikes. The Koksilah River floodplain spans agricultural lands that contain some non-standard, low or breached dikes. Sections of the Koksilah floodplain would therefore fall into a medium to high risk category.

The data quality standards specified for flood mapping outlined in the Federal LiDAR Acquisition Guidelines along with the data quality of the 2016 and 2017 LiDAR data sets are presented in Table 2.

The data quality information for the 2016 and 2017 LiDAR data was taken from the metadata documentation. NHC has not conducted any LiDAR check points.

The 2016 LiDAR has optimal coverage of the two datasets however the bare earth point density (DSM) is 1.3 pts/m^2 which in accordance with the Federal Guidelines should only be used in areas that fall into the low flood risk category. NHC was unable to confirm information regarding the bare earth point density of the 2017 LiDAR as the sub-contractor, Aeroquest Mapcon, did not provide it in their processing. The 2017 LiDAR was flown with a raw density of 8 points/m^2.

Table 2: Recommended approximate LiDAR data accuracy and density for floodplain mapping applications.

Data accuracy	Flood Risk Category			LiDAR dataset	
	High	Medium	Low	CVRD 2016	DNC 2017
Vertical Accuracy (open, level, hard surfaces)					
Non-vegetated Vertical Accuracy (NVA) – Vertical Root Mean Square Error ($RMSE_Z$)	≤ 5.0-7.5 cm	7.5-10.0 cm	15 cm	9.1 cm	3.7 cm
Non-vegetated Vertical Accuracy (NVA) – 95% confidence level (≈ 1.96 * $RMSE_Z$)	≤ ±10-15 cm	±15-20 cm	±30 cm	*not reported in metadata 1.96*$RMSE_z$ = 17.8 cm	7.3 cm, reported in metadata 1.96*$RMSE_z$ = 7.3 cm
Horizontal Accuracy (open, level, hard surfaces)					
Horizontal Root Mean Square Error ($RMSE_r$)	≤ 11-15 cm	30-45 cm	60 cm	*information not available	*information not available
Horizontal Accuracy – 95% confidence level (≈ 1.7308 * $RMSE_r$)	≤ ±20-25 cm	±50-75 cm	±100 cm	*information not available	*information not available
Data density					
Aggregate nominal point density (ANPD) for DSM (first return) and DEM (last return)	≥ 4-10 pts/m^2	2-4 pts/m^2	1-2 pts/m^2	DSM: 11 pts/m^2 DEM: 1.3 pts/m^2	DSM: 8-10 pts/m^2 DEM: information not available

NHC utilized alternative LiDAR to develop the hydraulic model and simulate preliminary outputs. GeoBC LiDAR was obtained by NHC in during the last week of May 2020. Subject to funding approval, NHC is planning on developing a new digital elevation model using the GeoBC LiDAR and re-running the hydraulic model to produce updated outputs. As such the LiDAR adopted for this phase of the study was used to produce preliminary results that should not be used for final flood mapping.

4 BATHYMETRY DATA

4.1 Existing Bathymetry Data

Virtually all the Cowichan River in the project area has been surveyed at least twice between 2008 and 2018. Figure 2 and Table 3 provide an overview of large scale channel bathymetry data sets that NHC used to create the RAS2D digital elevation model.

Figure 3 and Table 4 provide an overview of sediment management and log jams sites that have been surveyed within the study area. In reaches where gravel management projects have been implemented, several years of repeat surveys are available. NHC has calculated volumes of sediment that has been removed from various project sites since 2005. NHC used the survey information in Figure 2 and Table 2 to inform the mitigation options portion of this study.

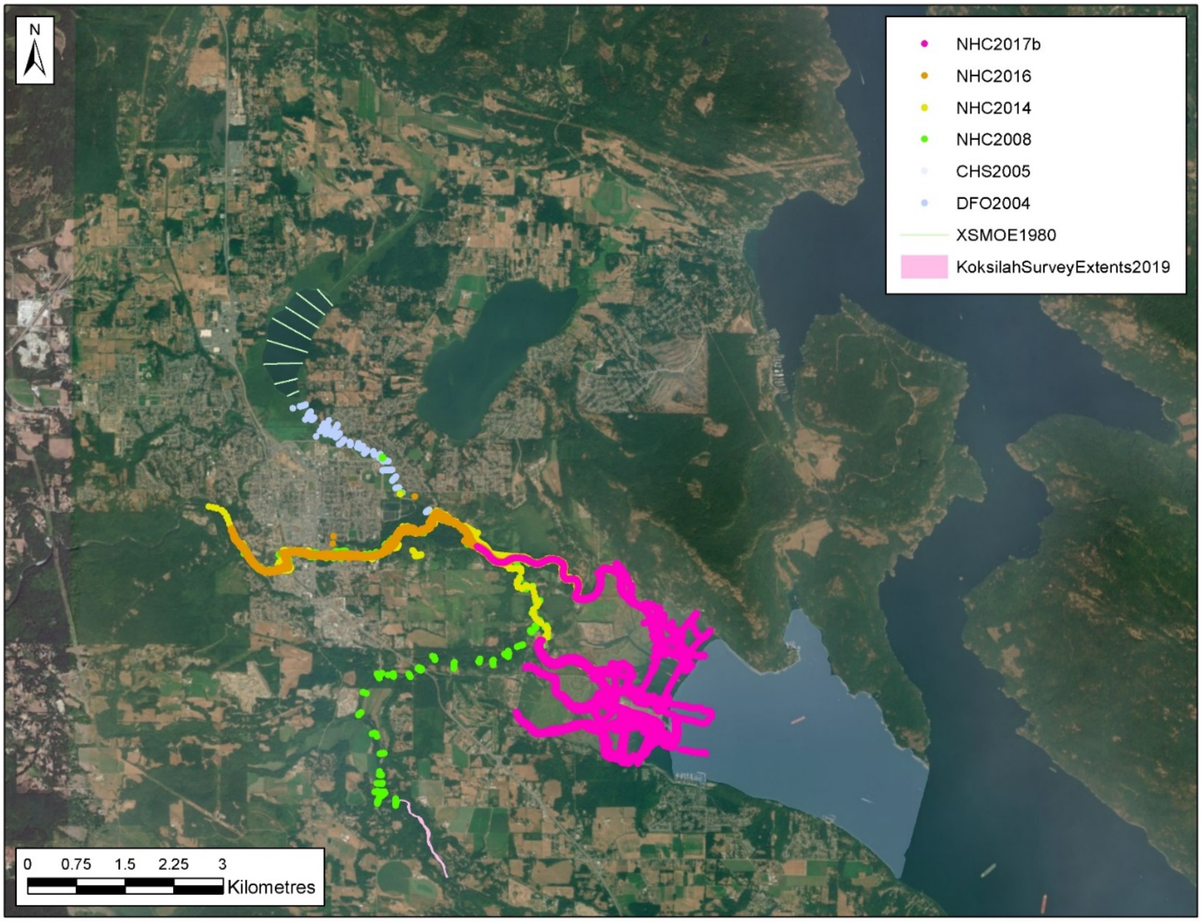

Figure 2: **Overview of bathymetry data and associated year collected for the study area.**

Table 3: **Overview of channel bathymetry data collected for the study area.**

Year	Project Description	Site	Data Type
2017b	Cowichan Estuary Restoration Study	Cowichan Estuary	NHC bathymetry CHS bathymetry 2016 LiDAR
NHC2016	Cowichan River survey from CR6 to upstream of Allenby Bridge	Cowichan River	NHC bathymetry
NHC2014	Tier 4 Cowichan Flood study	Cowichan River	NHC bathymetry
NHC2008	Integrated flood management plan	Cowichan River Koksilah River	NHC bathymetry
CHS2005	Cowichan Estuary Restoration	Cowichan Estuary	CHS bathymetry
DFO2004	Integrated flood management plan	Somenos Creek	DFO bathymetry
MOE1980	Integrated flood management plan	Somenos Lake	MOE bathymetry

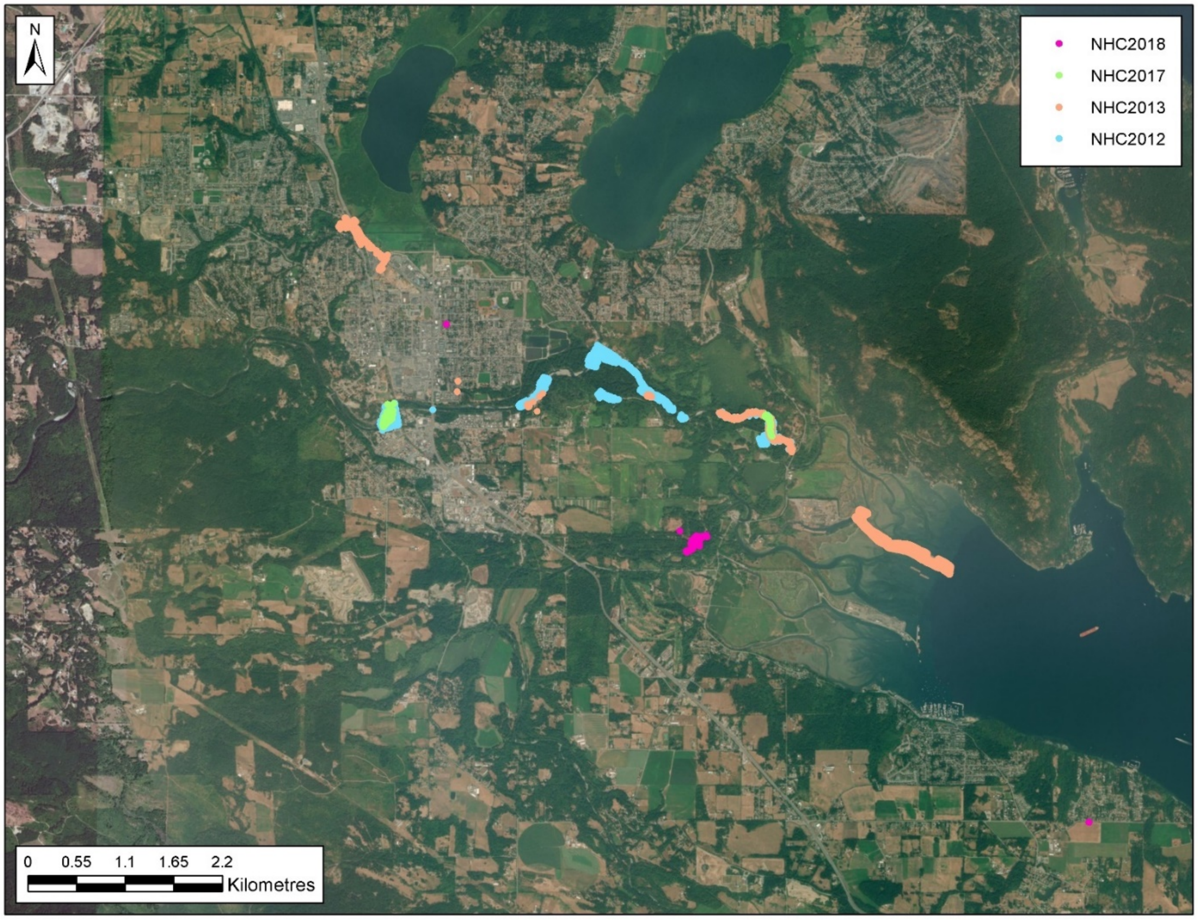

Figure 3: **Overview of channel bathymetry locations collected for sediment management and log jam sites within the study area.**

Table 4: Overview of channel bathymetry collected for sediment management and log jam sites within the study area.

Year	Project Description	Site	Data Type
NHC2018	Koksilah Log Jam Management	Koksilah River	NHC bathymetry
NHC2017	CR1	Cowichan River	NHC bathymetry
	CR6	Cowichan River	NHC bathymetry
NHC2013	Cowichan Bay	Cowichan Estuary	NHC bathymetry
	Gravel removal CR6	Cowichan River	NHC bathymetry
	Holmes Creek/Canada Ave	Holmes Creek	NHC bathymetry
NHC2012	Sediment and LWD management near Tooshley Island	Cowichan River, CR6 Sept/Oct	NHC bathymetry
	LWD management near Hatchery Dike	Cowichan River, CR5 June	NHC bathymetry
	Sediment and LWD management near Quamichan Road	Cowichan River, CR4 June	NHC bathymetry
	Sediment and LWD management near JUB sewage outfall	Cowichan River, CR3 June	NHC bathymetry
	LWD removal near John Charlie's property	Cowichan River, CR2 June	NHC bathymetry
	Sediment management at a left bank bar located upstream of Black Bridge	Cowichan River, CR1-March	NHC bathymetry

4.2 Current Bathymetry Surveys

NHC undertook bathymetry surveys on sections of both the Koksilah and Somenos channels where there were gaps in existing bathymetry. The study reach for the Koksilah River was extended beyond the study boundary for the 2009 IMFP as shown by the 2019 Koksilah River survey extents shown in Figure 1. Cross section bathymetry surveys were completed on the Koksialah River starting at the Water Survey of Canada (WSC) gauge at Cowichan Station and continued just downstream of Bright Angel Regional Park. Cross section bathymetry surveys were also completed at two locations on Somenos Creek downstream of Tzouhalem Road to supplement gaps in the existing bathymetry data. The uppermost section of the Koksilah bathymetry survey is not however represented in the interim version of the hydraulic model due to the limitations in the LiDAR coverage as shown in Figure 1.

5 TERRESTRIAL SURVEYS

A series of terrestrial surveys were completed to support development of the hydraulic model. The following is an overview of the terrestrial data:

- A control survey was completed for the project area using Provincial monuments.
- High water marks based upon photo documentation for January 2018 and January 2019 floods were surveyed and used to support model calibration.
- Hydrometric benchmarks surveys were completed at the gauges listed in Table 6 to shift the water level data into CGVD2013 datum.

6 HYDROMETRIC DATA

Hydrometric data for this project was provided by the Ministry of Forests, Lands and Natural Resource Operations (FLRNO), the District of North Cowichan (DNC), the CVRD (represented by NHC stations in Table 6) and WSC. The hydrometric stations listed in Table 6 and Figure 4 were installed in various years to serve the specific data needs of each stakeholder. Hydrometric stations were selected based upon individual gauge operation dates as they related to calibration flood events used in the hydraulic modelling.

Aquarius time-series software was used for dataset management. Water level data was shifted into CGVD2013 datum based upon benchmark surveys. The following quality assurance steps were applied to datasets from FLNRO, CVRD and DNC:

- Spike removal
- Gap-filling via linear interpolation for short gaps

Additional data corrections tools were not applied as sufficient meta data for individual gauges was not available. The NHC gauges had detailed Quality Assurance and Quality Control as these gauges were installed for the CVRD under various contracts.

Table 5: Hydrometric gauges used in this study.

Name	Owner	Stream	Data type
Duncan Well	FLNRO	Cowichan	Level
Trailer Park	FLNRO	Cowichan	Level
Log Jam	FLNRO	Cowichan	Level
Hatchery Road	FLNRO	Cowichan	Level
Koksilah River at Hwy 1	CVRD	Koksilah	Level
Quamichan Village	NHC	Cowichan	Level
Black Bridge	NHC	Cowichan	Level
JUB Lagoon	NHC/DNC	Cowichan	Level
Bings Creek Near The Mouth	WSC	Bings	Flow and Level
Cowichan River Near Duncan	WSC	Cowichan	Flow and Level
Koksilah River at Cowichan Station	WSC	Cowichan	Flow and Level
North Side of Causeway	NHC	Estuary	Level
South Side of Causeway	NHC	Estuary	Level
Causeway Breach	NHC	Estuary	Level
Clem Clem	NHC	Koksilah	Level
Pimbury Bridge	NHC	N. Cowichan	Level
Beverly Street Pump Station	DNC	Somenos	Level
Lakes Road Pump Station	DNC	Somenos	Level
Canada Avenue Station	DNC	Somenos	Level

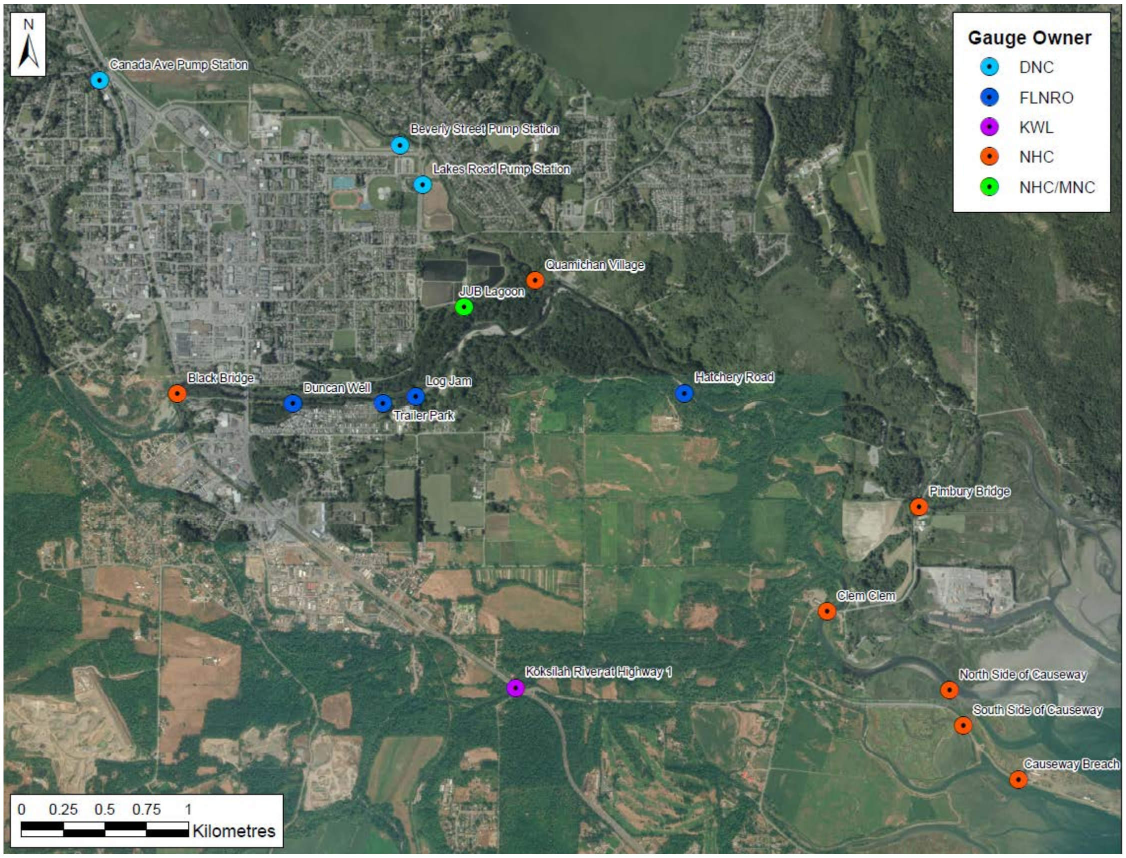

Figure 4: **Locations of hydrometric gauges.**

7 REFERENCES

Natural Resources Canada, and Public Safety Canada (2018a). *Federal airborne LiDAR data acquisition guideline, Version 2.0* (General Information Product 117e). Government of Canada. 64 pp. [online] Available from: http://publications.gc.ca/collections/collection_2019/rncan-nrcan/M113-3-4-2018-eng.pdf (Accessed 10 September 2019).

Natural Resources Canada, and Public Safety Canada (2018b). *Federal Flood Mapping Framework* (112e). 112e pp. [online] Available from: https://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/fulle.web&search1=R=308128 (Accessed 25 September 2019).

APPENDIX B:

HYDROLOGY

1 THE COWICHAN WATERSHED

Figure 1 shows the main rivers and tributaries in the study area. The Cowichan River has its headwaters at Hooper Mountain (el. 1,490 m) near the western end of Cowichan Lake and then flows in an easterly direction 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.

Somenos Lake is a low-lying freshwater marsh situated north of Duncan and has a surface area of approximately 1 km2 during summer low water conditions. Several small tributaries flow into Somenos Lake, including Bings Creek, Averill Creek and Richards Creek. The drainage areas of these streams are 19.9 km^2, 16.8 km^2 and 20.8 km^2 respectively. Somenos Creek flows out of Somenos Lake in a southeasterly direction for 2.7 km before joining the Cowichan River near Quamichan village. During periods of high runoff, the flooding extent and depth of inundation along Somenos Creek and Somenos Lake are backwater controlled and are governed mainly by the water level in the Cowichan River near the Somenos Creek confluence.

The Koksilah River has its headwaters at Waterloo Mountain (el. 1,072 m). The drainage area of the Koksilah River at Cowichan Station is 209 km^2. Kelvin Creek (58 km^2 drainage area) and a smaller unnamed tributary flow into the Koksilah River upstream of Highway 1. The Koksilah River joins the south branch of the Cowichan River approximately 1.5 km upstream of Cowichan Bay.

The average slope of the Cowichan River from Hwy-1 to the estuary is 0.2 percent. The average slope of the Koksilah floodplain is 0.1 percent, approximately half of the Cowichan River gradient. Due to its lower gradient, backwater effects from the ocean extend further up the Koksilah River than the Cowichan River.

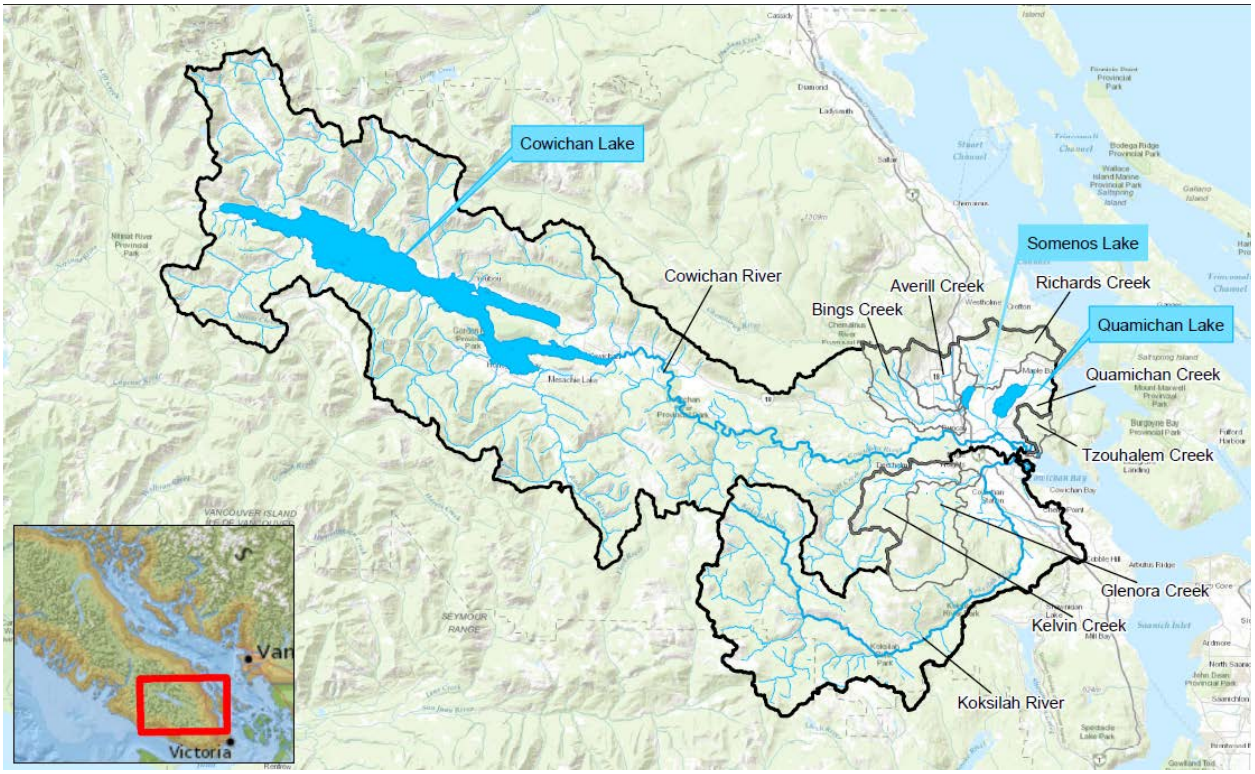

Figure 1: Overview of Cowichan Watershed.

2 FLOOD HISTORY

The study area is subject to several types of flooding:

1) riverine flooding from extreme winter storms
2) coastal flooding from high tides and storm surges

An overview of historical river floods is presented in (Table 1). The maximum instantaneous discharge recorded for the Cowichan River at station 08HA011 was 564 m^3/s on February 1, 2020. The second largest recorded discharge occurred on January 15, 1961 with a daily discharge of 558 m^3/s. The 1961 event was measured via a manual gauge reading therefore this value does not necessarily correspond to the average daily discharge or the peak daily discharge.

Table 1: **Overview of the 10 largest historic floods on the Cowichan River. When available, the instantaneous annual peak flow (QPI) values are presented, otherwise the daily peak flow (QPD) during the flood event is provided. Estimated values are indicated by 'Est.'**

Year	Cowichan River Flow (08HA011) (m^3/s)	Approximate Return Period	Reported Flooding from (Septer, 2006) until 2006, thereafter local and NHC reports.
Jan 15, 1961	558 (QPD)	25	Fifty families in the Duncan North Cowichan area were evacuated. Large quantities of logs were transported in the rivers.
Jan 19, 1968	514 (Est. QPI)	16	Boil water advisory. In Duncan several homes were evacuated due to failure of sewage system.
Dec 25-26, 1972	485 (Est. QPI)	13	Beverly Street was flooded, more than 50 families were forced to leave their homes. High tides damaged the docks. The Cowichan Bay area and the First Nations Reserve were flooded.
Dec 23-27, 1980	425	6	Flooding on Cowichan Lake
Jan 15-18, 1986	447	7	No information available
Nov 15, 2006	426	6	Heavy rain and wind affected Vancouver Island and Lower Mainland. Around 50,000 homes on Vancouver Island had no power due to fallen trees and tree limbs. Flood warning issued for Cowichan River.
Nov 16-21, 2009	446	7	Seven year flood event flooded Lakes Road and JUB Sewage Treatment Plant, flooding the Cowichan Tribes Reserve. Three hundred homes were evacuated and $810k was required for long-term support for 121 families. Extensive flooding caused partially by accumulated gravel deposits and log jams.
Jan 29, 2018	476	11	Heavy rainfall over 2-days flooded several areas of the Cowichan Valley. Several main roads were closed including Canada Avenue.
Jan 24, 2019	425	6	Heavy rain brought flooding to the Cowichan Valley.
Feb 1, 2020	564	27	Flooding closed Highway 1, Westholme Road and Chemainus Road. Approximately 28 residents evacuated from North Cowichan and Halalt First Nation.

3 OVERVIEW OF WSC GAUGES USED

Design flows for this study were based primarily on 4 WSC gauges as shown in Table 2. The gauges were selected based upon the inflow requirements of the hydraulic model. The Environment Canada Data Explorer (version 2.1.8) HYDAT (version 1.0, Jan 18, 2020) was used to access WSC data. For years 2018-2020 provisional WSC data was accessed through data requests and via the real-time WSC website.

Once gauges were selected the drainage area and data record were reviewed. Drainage areas 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 (QPI) and maximum daily peaks (QPD) were noted. Years with partial winter data that did not represent peak flows were removed. WSC site description sheets were reviewed for additional meta data.

Table 2: Water Survey of Canada stations used for design inflows.

River	WSC gauge	Record	Regulated	QPI Record	QPD Record	Basin Area (km^2)
Cowichan River at Lake Cowichan	08HA002	1913-1919, 1940-present	Y	1940-present	1914-1918, 1940-present	594
Cowichan River near Duncan	08HA011	1960-present	Y	1977-present	1960-present	826
Koksilah River at Cowichan Station	08HA003	1914-1917, 1954-present	N	1990-present	1915-1916, 1960-present	209
Bings Creek near the mouth	08HA016	1961-present	N	1994-present	1962-present	15.5

4 FLOOD FREQUENCY ANALYSIS - METHODS

4.1 Data inspection and stationarity

The first step in flood frequency analysis was to undertake 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 then 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 3 and Table 4 present 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 and the Cowichan River gauge at Duncan. Visual inspection of peak flows

(Figure 2) indicates that different populations are not obvious. A gradual increase in peak flows over time may be due to changes in climate, landscape or reflective of Pacific Decadal Oscillation (PDO) and El Nino Southern Oscillation (ENSO) cycles which is reviewed in the next section.

Table 3: **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
Koksilah River near Cowichan Station	08HA003	25	-0.0167	0.9255	maintain
Bings Creek near mouth	08HA016	24	-0.1159	0.4419	maintain

Table 4: **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
Koksilah River near Cowichan Station	08HA003	64	0.0856	0.3217	maintain
Bings Creek near mouth	08HA016	58	0.1617	0.0743	maintain

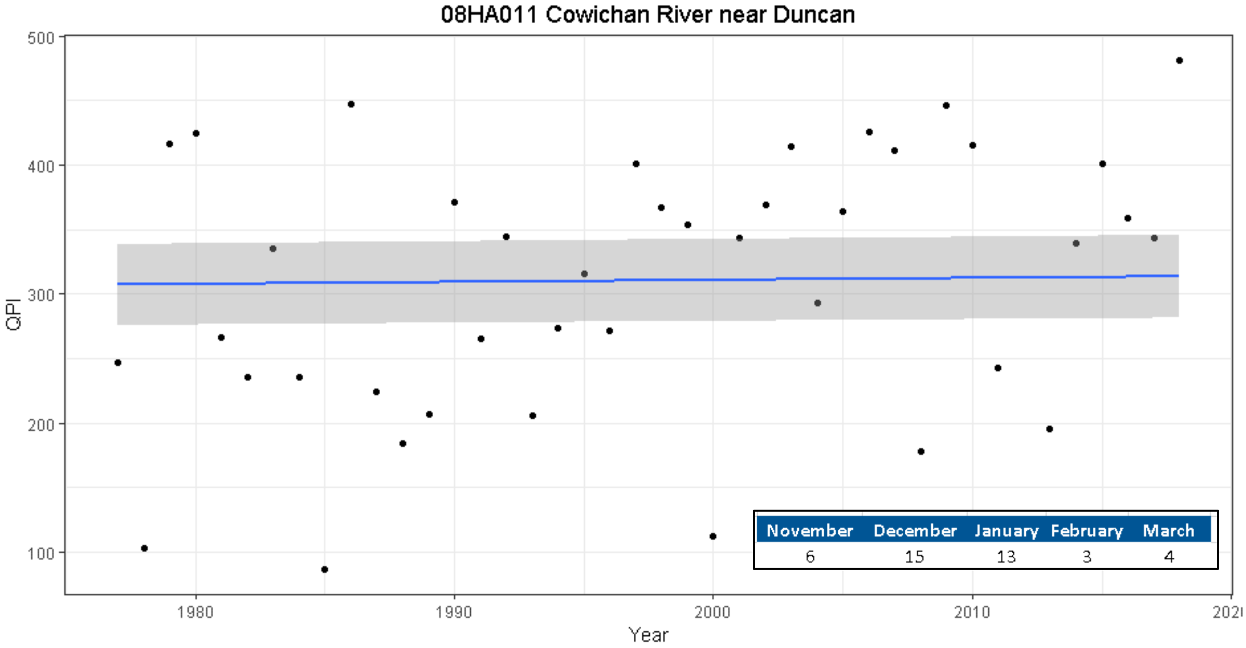

Figure 2: **Annual maximum instantaneous discharge for 08HA011 Cowichan River near Duncan. Lower right table indicates temporal occurrence of peak instantaneous flows.**

4.2 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. The PDO is a long-term temperature phase that waxes and wanes approximately every 20 to 30 years. A positive PDO phase is associated with warmer winter temperatures throughout western Canada and a reduced snowpack while a negative PDO phase brings cooler winter temperatures and an increased snowpack (Pike et al., 2010). The last clearly detected shift in the PDO occurred in the mid-1970's shifting from a cold to warm phase (Figure 2, (Whitfield et al., 2010) and there is indications of a recent PDO shift into a cool phase.

The ENSO is a coupled phenomenon in which sea surface temperatures in the Pacific influence atmospheric circulation and occur at a frequency of 2 to 8 years and last from 6 to 18 months. In BC, winters following an El Nino event are warmer and drier and La Nina winters are cooler and wetter (Pike et al., 2010). Major historical El Nino events that had a pronounced impact on the BC coast took place in 1982/1983, 1991/1992, and 1997/98. The MEI (multivariate El Nino/Southern Oscillation index) represents an index of ENSO and can provide an indication of ENSO intensity (Figure 3, Figure 4). Presently, we are in a warm ENSO phase. Since 1976, ENSO events have become more frequent and intense, with documented impacts off the coast between Oregon and BC with sea level changes ranging from 0.30 to 0.40 m (Bornhold, 2008).

It is important to consider if 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. For this study, as indicated in Table 1, there are numerous WSC records with substantially long records that cover historical warm and cold PDO and ENSO periods. The peak instantaneous flows recorded at the Cowichan River at Duncan gauge may be more representative of a warm PDO phase however further investigation is required to determine factors leading to an increasing trend in peak instantaneous discharge. That is beyond the scope of this work program. For this project the entire QPI record for 08HA011 Cowichan River at Duncan was adopted for frequency analysis.

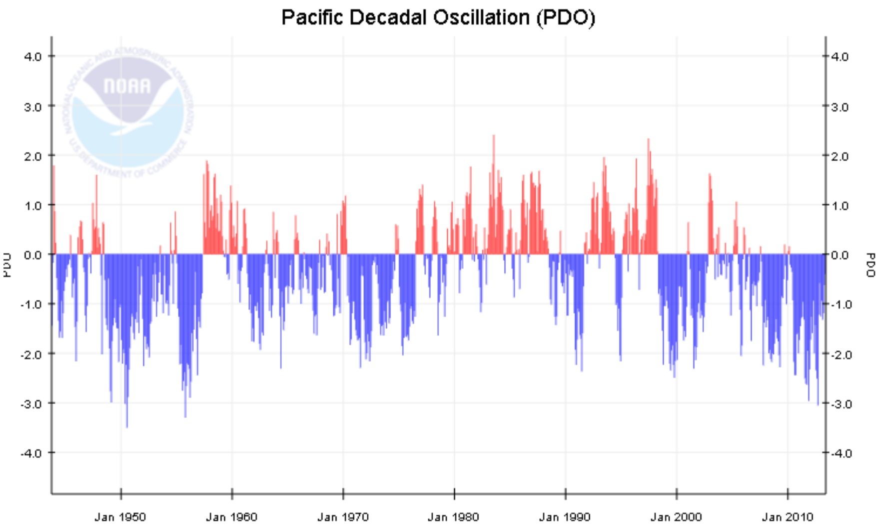

Figure 3: The PDO index based upon NOAA's reconstruction of sea surface temperatures, taken from https://www.ncdc.noaa.gov/teleconnections/pdo/

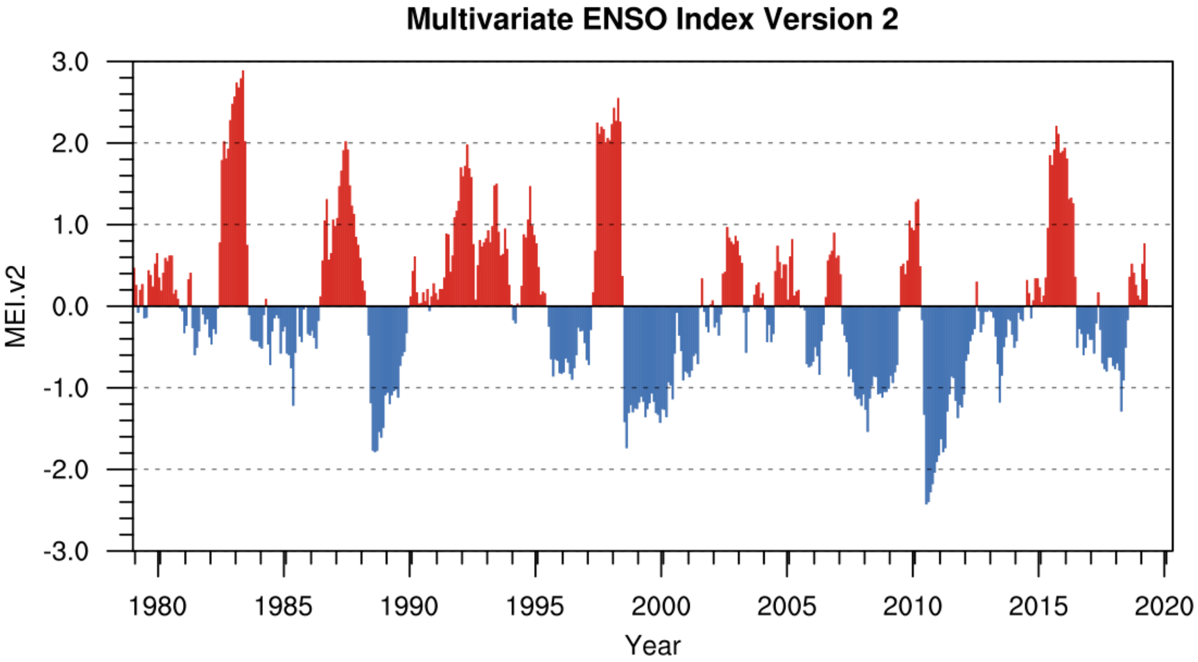

Figure 4: ENSO index taken from NOAA, Physical Sciences Division, https://www.esrl.noaa.gov/psd/enso/mei/

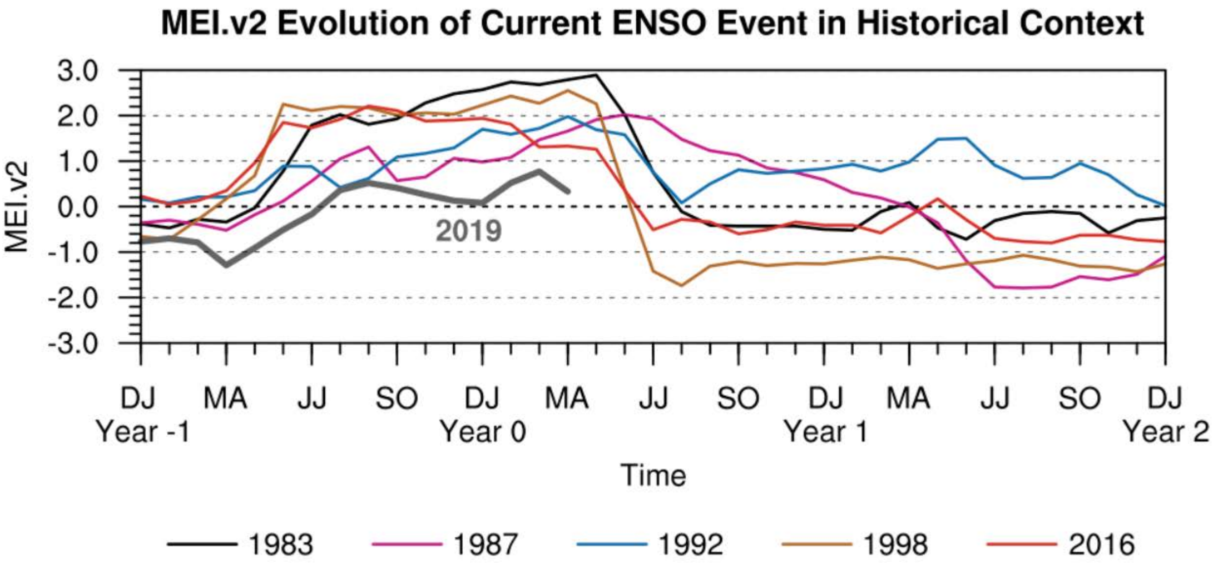

Figure 5: **Current ENSO versus historical ENSO events, taken from NOAA, Physical Sciences Division, https://www.esrl.noaa.gov/psd/enso/mei/.**

4.3 Defining the 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 October 1st through September 30th. The Cowichan watershed experiences peaks 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.

4.4 Record extension and infill of missing records

The infill of missing peak flow (QPI) records was based upon daily (QPD) records. One peak flow (QPI) 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. 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 extension of peak flow records. The MOVE type 2 regression techniques (Hirsch, 1982) in the USGS 'smwrStats'[1] package were used for infilling all missing peak flow records.

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[1] https://github.com/USGS-R/smwrStats

4.5 Determination of the Flood Frequency Curve

Lastly, once all QPI 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.

5 FLOOD FREQUENCY ANALYSIS - RESULTS

5.1 08HA002 Cowichan River at Lake Cowichan

The degree of regulation was reviewed for the Cowichan River gauges. The Cowichan Lake weir was constructed in 1957. The weir is approximately 1 meter tall 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 as shown in Figure 5. The rating curve in Figure 5 shows 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 prior to 1957. As such frequency analysis was completed on WSC data post-weir installation.

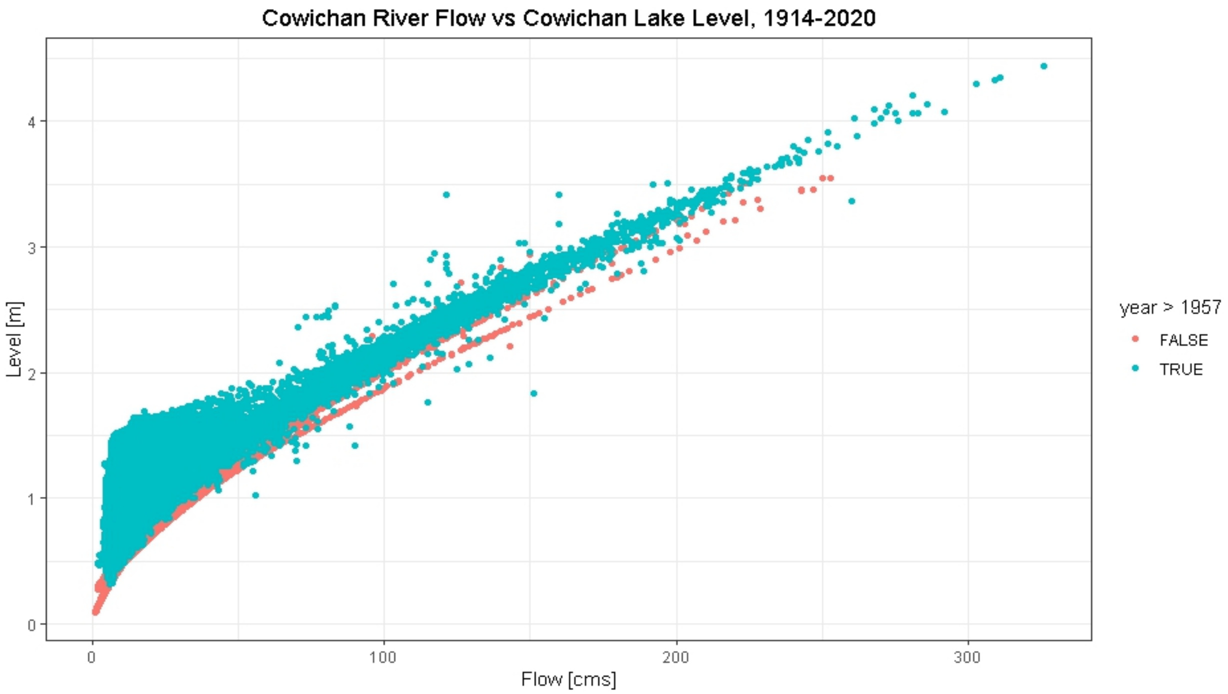

Figure 6: **Correlation between Cowichan River outflows and Cowichan Lake levels for 1913-1919 and 1940-present. Lake level values are in local WSC datum.**

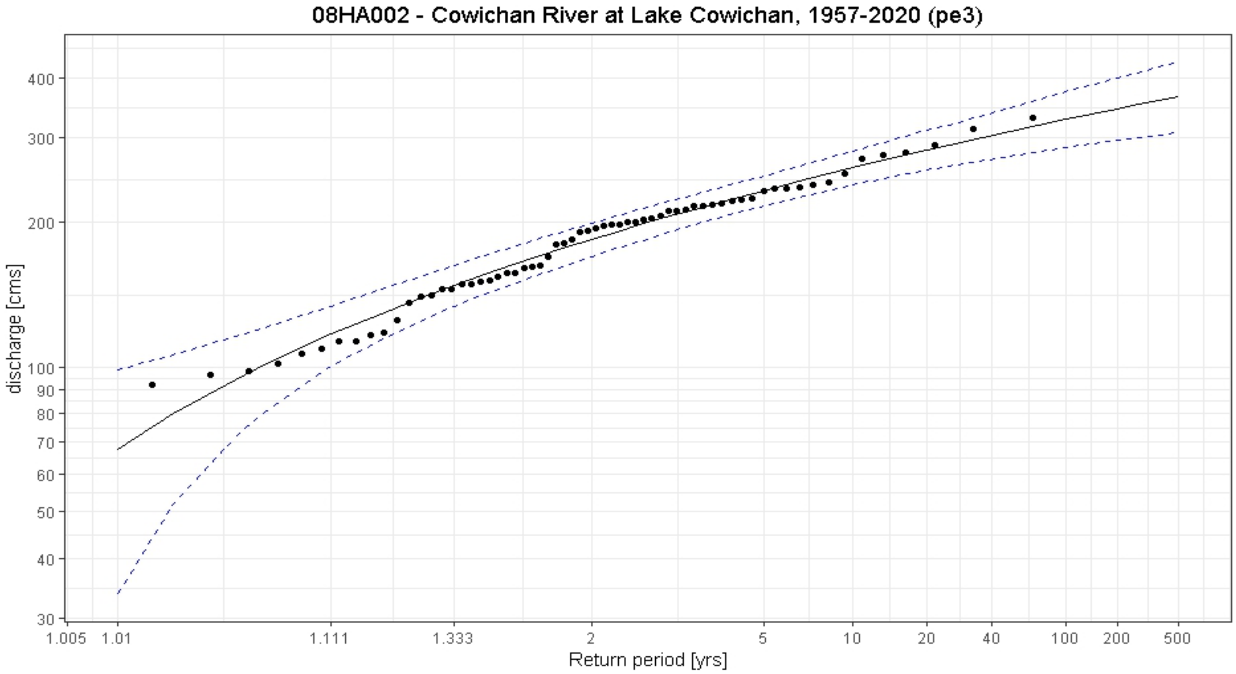

Figure 7: **Flood frequency analysis results, using the log-normal3 probability distribution, for the Cowichan River at Lake Cowichan.**

Table 5: **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

5.2 08HA011 Cowichan River near Duncan

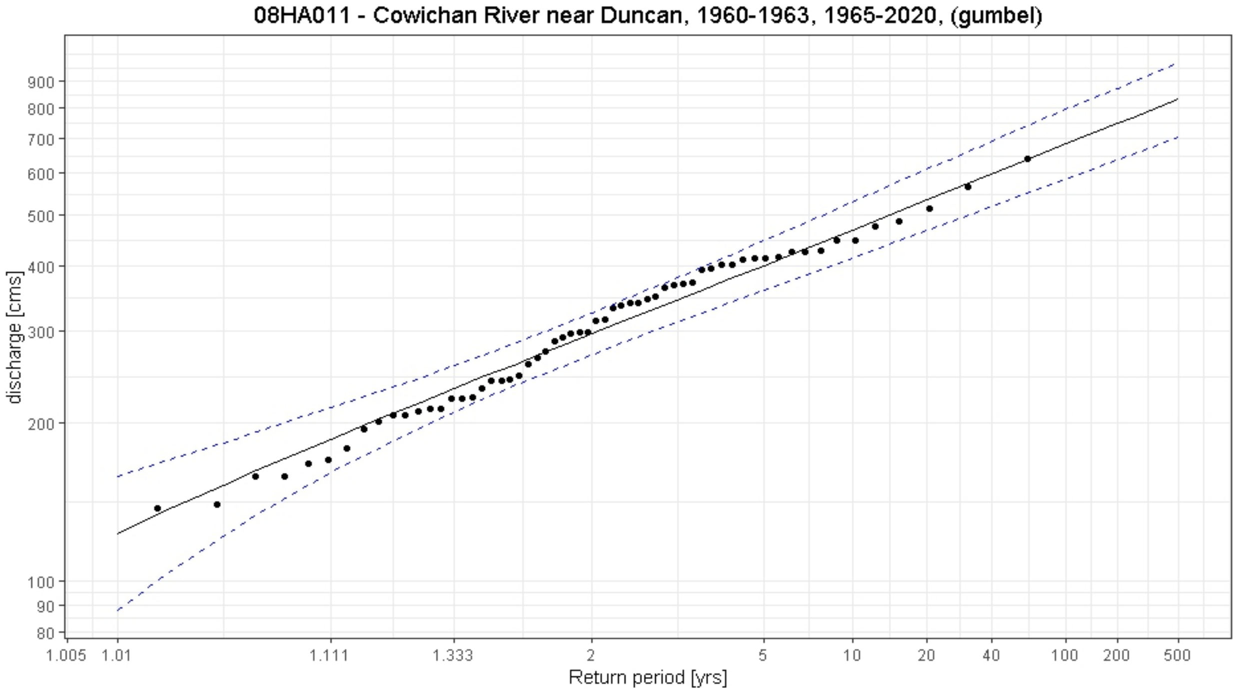

Figure 8: **Flood frequency results using the gumbel probability distribution, for the Cowichan River near Duncan.**

Table 6: 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

5.3 08HA003 Koksilah River at Cowichan Station

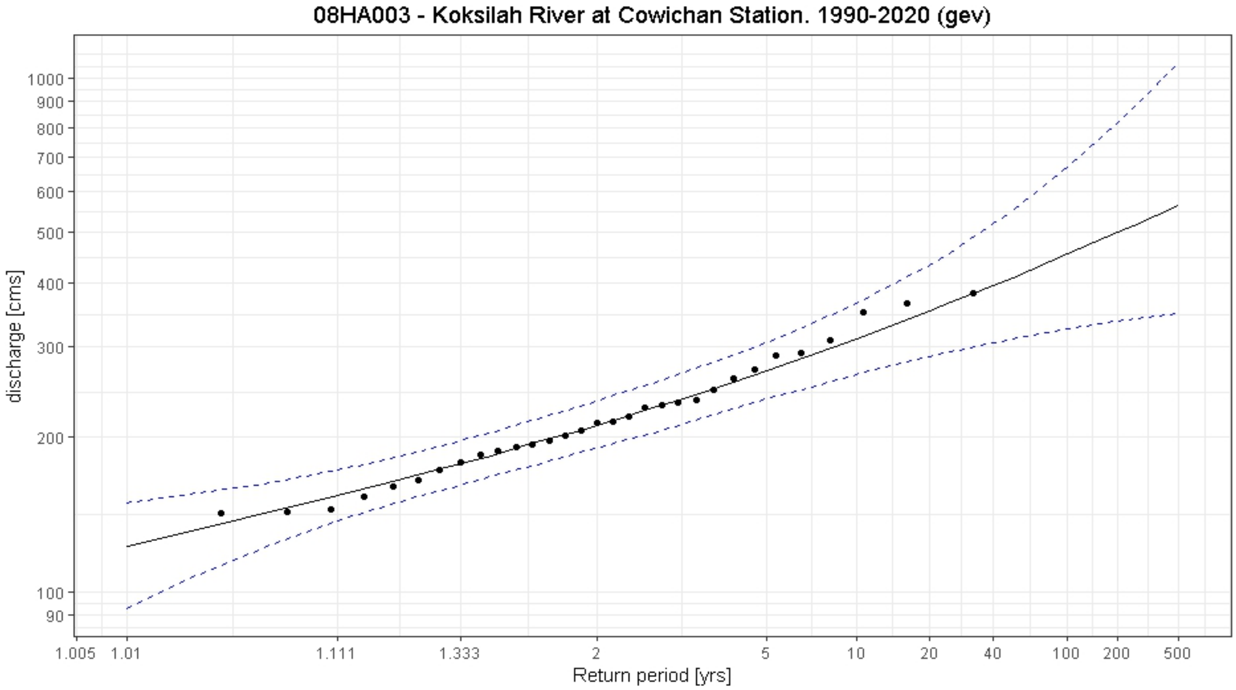

Figure 9: **Flood frequency results using the generalized extreme value probability distribution for the Koksilah River at Cowichan Station.**

Table 7: **Flood frequency estimates for the Koksilah River at Cowichan Station.**

08HA003-Koksilah River at Cowichan Station (1990-2020)				
Return Period	**Percent chance of occurrence in any given year**	**Lower (gev)**	**Estimate (gev)**	**Upper (gev)**
2	50.0%	190	211	235
5	20.0%	237	270	306
10	10.0%	265	311	364
20	5.0%	288	352	433
50	2.0%	311	409	552
100	1.0%	325	454	671
200	0.5%	336	501	819
500	0.2%	349	566	1072

5.4 08HA016 Bings Creek near the mouth

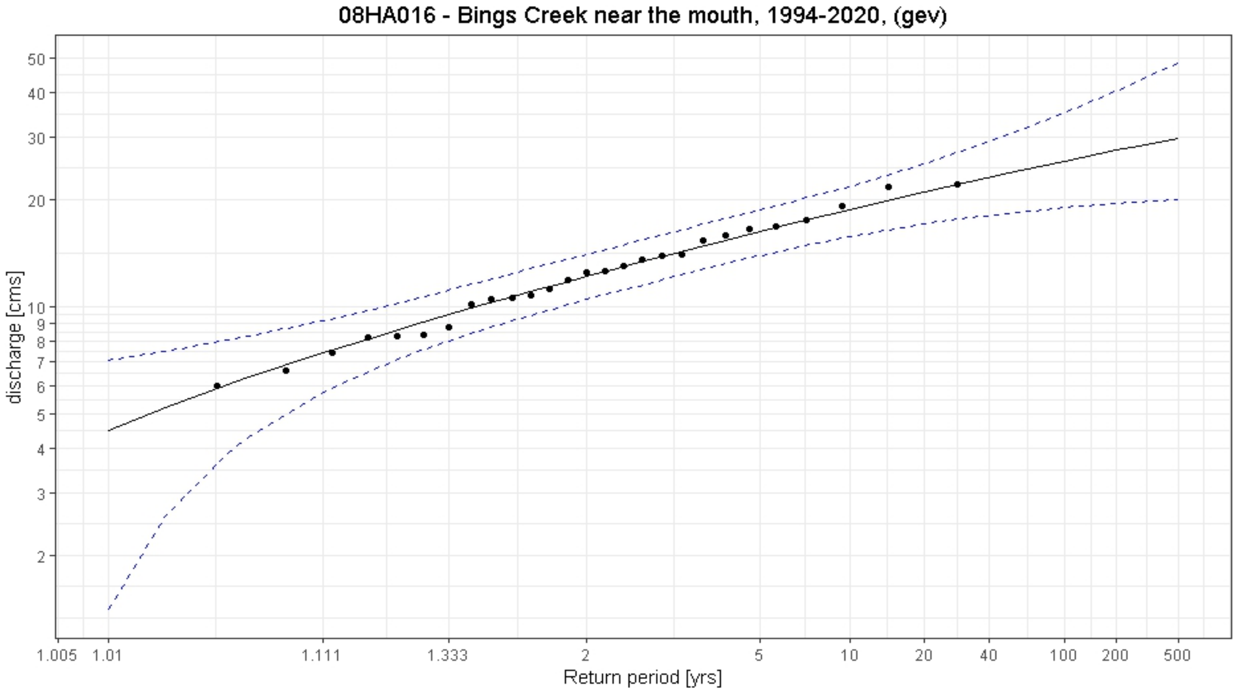

Figure 10: **Flood frequency results using the generalized extreme value probability distribution for Bings Creek near the mouth.**

Table 8: **Flood frequency estimates for Bings Creek near the mouth.**

08HA016-Bings Creek near the mouth (1994-2020)				
Return Period	Percent chance of occurrence in any given year	Lower (gev)	Estimate (gev)	Upper (gev)
2	50.0%	10	12	14
5	20.0%	14	16	19
10	10.0%	16	19	22
20	5.0%	17	21	25
50	2.0%	18	24	30
100	1.0%	19	26	35
200	0.5%	19	27	40
500	0.2%	20	30	48

6 CLIMATE CHANGE

In the fall of 2019, NHC submitted a memo to the CVRD that reviewed available guidelines and best management practices for incorporating climate change to boundary conditions for the Cowichan Watershed (NHC 2019). Climate change projections from PCIC for the Cowichan watershed were reviewed along with EGBC guidance. NHC recommended and the CVRD approved of a 20 percent increase in peak flows be adopted for this study for regulatory floodplain maps in order to account for climate change.

7 BOUNDARY CONDITIONS

7.1 Gauged points of inflow

The resulting frequency analysis values adopted for model inflows are presented in Table 9 and with the addition of a 20 percent climate change factor in Table 10. The design flow values for the river systems have increased since the last flood study by NHC (NHC, 2009). Several large floods have occurred since 2007 (Table 1) that have shifted the frequency analysis.

Table 9: **Summary of adopted design flows for this study.**

Return Period (years)	Cowichan River near Duncan (08HA011)	Cowichan River near Lake Cowichan (08HA002)	Koksilah River near Cowichan Station (08HA003)	Bings Creek near the mouth (08HA016)
	QPI (gum)	QPI (pe3)	QPI (Gev)	QPI (gev)
	1960-2020	1957-2020 post weir	1990-2020	1994-2020
10	468	260	311	19
20	534	283	352	21
25	555	290	366	22
50	619	309	409	24
100	683	328	454	26
200	747	344	501	27
250	767	350	517	28
500	830	365	566	30

Table 10: **Summary of adopted design flows with a 20 percent increase to discharge to account for climate change.**

Return Period (years)	Cowichan River near Duncan (08HA011)	Cowichan River near Lake Cowichan (08HA002)	Koksilah River near Cowichan Station (08HA003)	Bings Creek near the mouth (08HA016)
	QPI (gum)	QPI (pe3)	QPI (Gev)	QPI (gev)
	1960-2020	1957-2020 post weir	1990-2020	1994-2020
10	562	312	373	22
20	641	339	423	25
25	666	348	439	26
50	743	371	491	28
100	820	393	545	31
200	896	413	601	33
250	920	420	620	34
500	996	439	680	36

Table 11: **Design flows used in NHC (2007) compared to present study.**

Return Period	Cowichan River near Duncan (08HA011)		Koksilah River at Cowichan Station (08HA003)		Bings Creek near mouth (08HA016)	
	NHC 2007	NHC 2020	NHC 2007	NHC 2020	NHC 2007	NHC 2020
200	700	747	450	501	23	27

7.2 Ungauged points of inflow

The frequency analysis results for Bings Creek were transferred to tributary model reaches using area-based scaling. Area based scaling is a common approach to estimating flood flows in ungauged basins and has been tested by Eaton et al. (2003). Area based scaling can be estimated according to the following equation:

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

where Q_1 is the known peak discharge, Q_2 is the unknown peak discharge, A_1 is the known basin area, A_2 is the basin area for the unknown discharge and b is the scaling factor. Eaton et al. (2003) analyzed non-regulated WSC stations across British Columbia and found that a scaling factor of 0.75 provides an approximate estimate that is realistic for BC watersheds. A scaling factor of 0.75 was adopted for design inflow estimates for tributaries as shown in Table 10. Tributary inflows were increased by 20 percent for climate change runs.

Table 12: **Adopted design inflows for tributary reaches**.

Return Period (years)	Averyll Creek (m3/s)	Richards Creek (m3/s)	Quamichan Creek (m3/s)	Tzouhalem Creek (m3/s)	Kelvin Creek (m3/s)	Unnamed Tributary (Koksilah) (m3/s)
10	19.94	23.28	20.35	8.87	49.96	11.28
200	28.80	33.63	29.40	12.81	72.18	16.29

8 INFLOW HYDROGRAPHS

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

8.1 Calibration and Validation Events

For calibration and validation events described in the Hydraulic Modelling Appendix, hourly discharge data was obtained from WSC. Unsteady inflow hydrographs for tributary reaches were scaled based upon Bings Creek discharge.

8.2 Design Scenarios

For design simulations it was assumed that the Cowichan and Koksilah Rivers peaked at the same time. This assumption appears to be reasonable given review of the calibration floods for this study indicate the two rivers peaked within hours of each other for all calibration flood events.

To determine the appropriate return periods for ocean levels during a 200-year flood event NHC undertook a joint probability analysis. The methodology and results of the joint probability assessment are presented in Appendix D. The adopted design conditions for the designated flood maps are presented in Table 13.

For model simulations of design scenarios, synthetic flood hydrographs were developed with the assumption that the flood hydrograph shape follows that of a recorded WSC hydrograph shape. The February 2020 flood hydrograph was scaled up for the 200-year and 40-year design flow events. The 2020 flood hydrograph was selected as it represents a larger flood event for the watershed and the hydrograph shape is that of a single peak (versus double peak hydrograph). For smaller design flows

(<15 year) the January 2018 flood hydrograph was selected. The 2018 flood hydrograph shape is also that of a single peak; the receding limb scaled well to smaller flood return periods. It was assumed that inflow hydrographs peaked simultaneously.

9 SUMMARY

Table 13 lists the key scenario that was used to develop flood mapping for the study area.

Table 13: Scenario adopted resulting from the joint probability analysis.

Scenario	Riverine		Ocean Levels	Mapping product produced with associated boundary conditions
	Return period	% change in flood discharge for climate change	Return Period	
Design Event	1:200-year	20	1:10-year	Regulatory floodplain map

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APPENDIX C:

COASTAL ASSESSMENT AND WAVE MODELLING

1 OVERVIEW

1.1 Purpose

This study was undertaken to assess the design sea states and shoreline wave effects for coastal shorelines with the project area in order to estimate the flood construction level (FCL) in Cowichan Bay. In British Columbia the FCL is generally based on an event with an annual exceedance probability (AEP) of 0.5%. This is often referred to as the 200-year event; since on average it would be expected to occur or be exceeded once every 200-years. For the marine environment it is also important to include allowances for sea level rise (SLR) and future conditions are considered for the year 2100.

1.2 Approach

The BC Ministry of Environment’s published Climate Change Adaptation Guidelines for Sea Dikes and Coastal Flood Hazard Land Use (BC Ministry of Environment, 2011b) and the BC Ministry of Forests, Natural Resource Operations and Rural Development’s amendment to the Flood Hazard Area Land use Management Guidelines (BCMFLNRD, 2018) present two approaches for determining the 200-year coastal FCL: 1) combined method and 2) probabilistic method. Parameters that are used to calculate the FCL for each method are illustrated in Figure 1 and Figure 2**.** The combined method is calculated as the sum of the effects of HHWLT tide, storm surge, wave run-up, and SLR assuming the design event for each of these parameters occur simultaneously. The probabilistic method is calculated accounting for the joint probability that each of the parameters occur simultaneously. The combined method tends to be more conservative than the probabilistic approach, and hence provincial guidelines allow use of a reduced freeboard for mitigation based on this method. The difference in freeboard allowance applied to each method results in their determinations of FCL often having similar elevations. For this assessment the probabilistic method has been applied for Cowichan Bay.

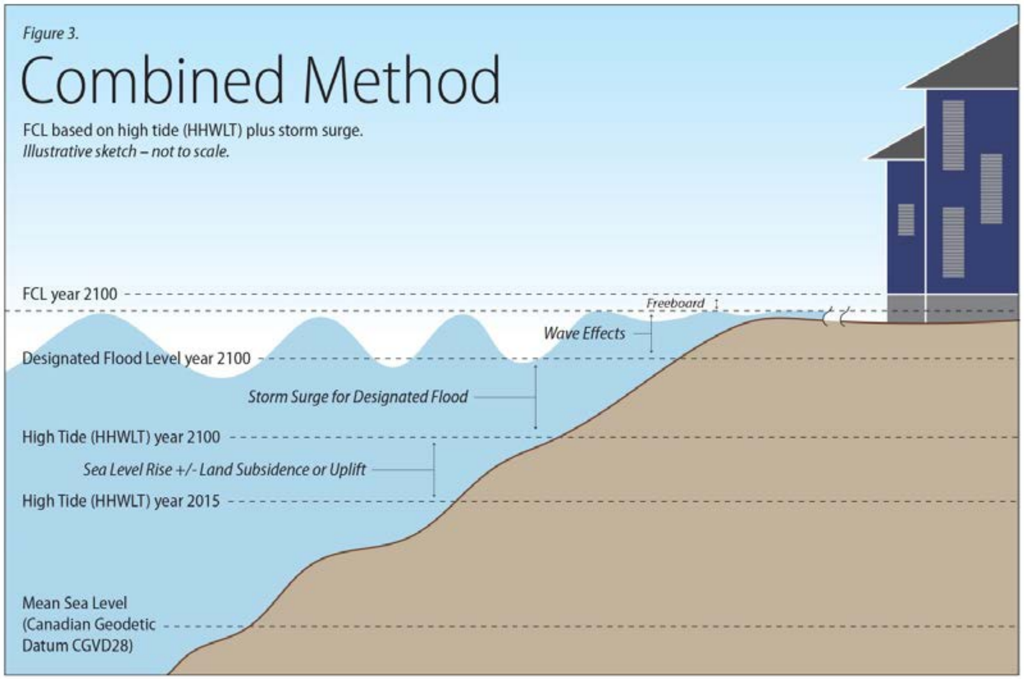

Figure 1: FCL based on combined method (BCMFLNRD, 2018)

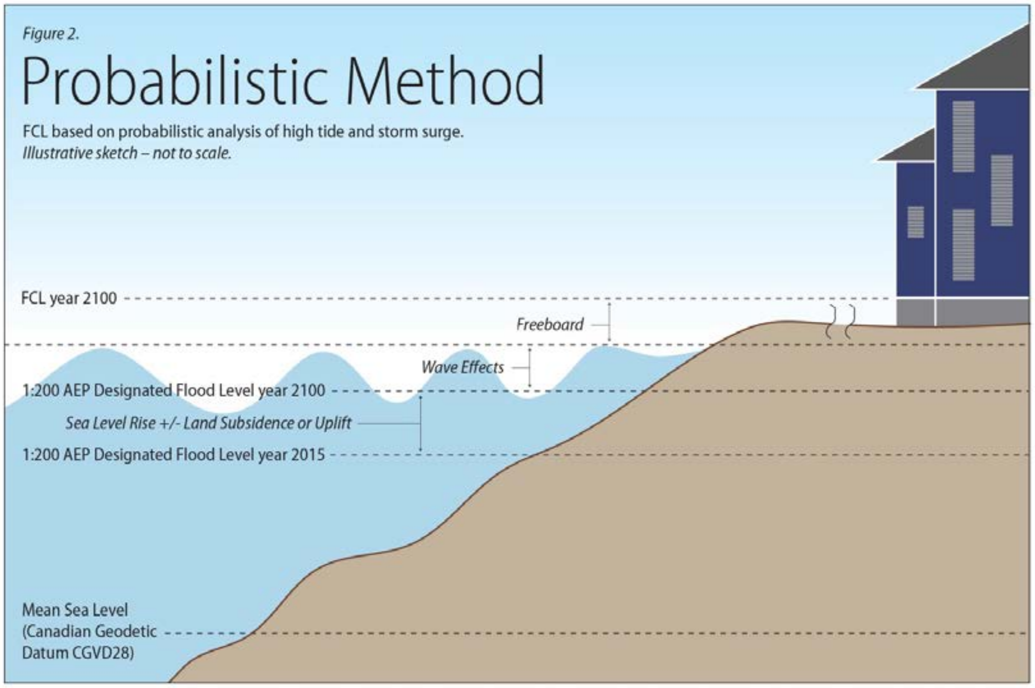

Figure 2: FCL based on probabilistic analysis (BCMFLNRD, 2018)

Each of the components that make up the coastal FCL are described in the following sections as noted below.

The coastal flood construction level using the probabilistic method is the sum of:

- 200 Year total water level (joint probability of occurrence of tides and storm surge)
- Allowances for future SLR and regional uplift or subsidence to the year 2100
- Estimated wave effects associated with the designated storm with a 200 year return period
- Freeboard

Predicted changes in storm intensity and frequency over the next 80 years, which could influence storm surge and wave effects, are highly variable and no conclusive studies at this time are available which suggest any strong trends of increased storm intensity due to climate change. Such influence has not been incorporated in this analysis.

2 WATER LEVEL ANALYSIS FOR COWICHAN BAY

2.1 Data

The published tide statistics for Cowichan Bay provided by the Canadian Hydrographic Service (CHS) in the 2020 Canadian Tide and Current Tables Volume 5 are summarized in Table 1. Unless explicitly stated, all tide levels and water levels in this section are referenced to Geodetic Datum (CGVD 2013). The Higher High Water Large Tide (HHWLT) value is the average of the higher high waters from each year over 19 years of tide predictions. HHWLT represents the highest astronomical tide that typically occurs in any given year. However, it does not represent the highest water level expected in Cowichan Bay for any given year, because it does not account for storm surge, wave runup, or effects from river inflows.

Table 1: Tide levels for Cowichan Bay referenced to Chart Datum and to Geodetic Datum

Tide	Chart Datum (m CD)	Geodetic Datum (m CGVD 2013)
Higher High Water Large Tide (HHWLT)	3.80	1.56
Higher High Water Mean Tide (HHWMT)	3.40	1.16
Mean Sea Level (MSL)	2.40	0.16
Lower Low Water Mean Tide (LLWMT)	1.00	-1.24
Lower Low Water Large Tide (LLWLT)	0.10	-2.14

2.2 Tide Level Analysis

The design still water level for Cowichan Bay is governed by sea level including the combined effect of tide, storm surge, wind setup, and effects from river inflows. Water levels were obtained from the Fisheries and Ocean Canada Water Level Station 7277 – Patricia Bay, located in the Saanich Inlet as shown in Figure 3. The water level record includes both tidal effects and non-astronomical effects of wind setup and storm surge. A total of 45 years of data (1976 to 2020) was recorded at the station as shown in Figure 4. The highest recorded water level at Patricia Bay was 2.22 m on December 16, 1982.

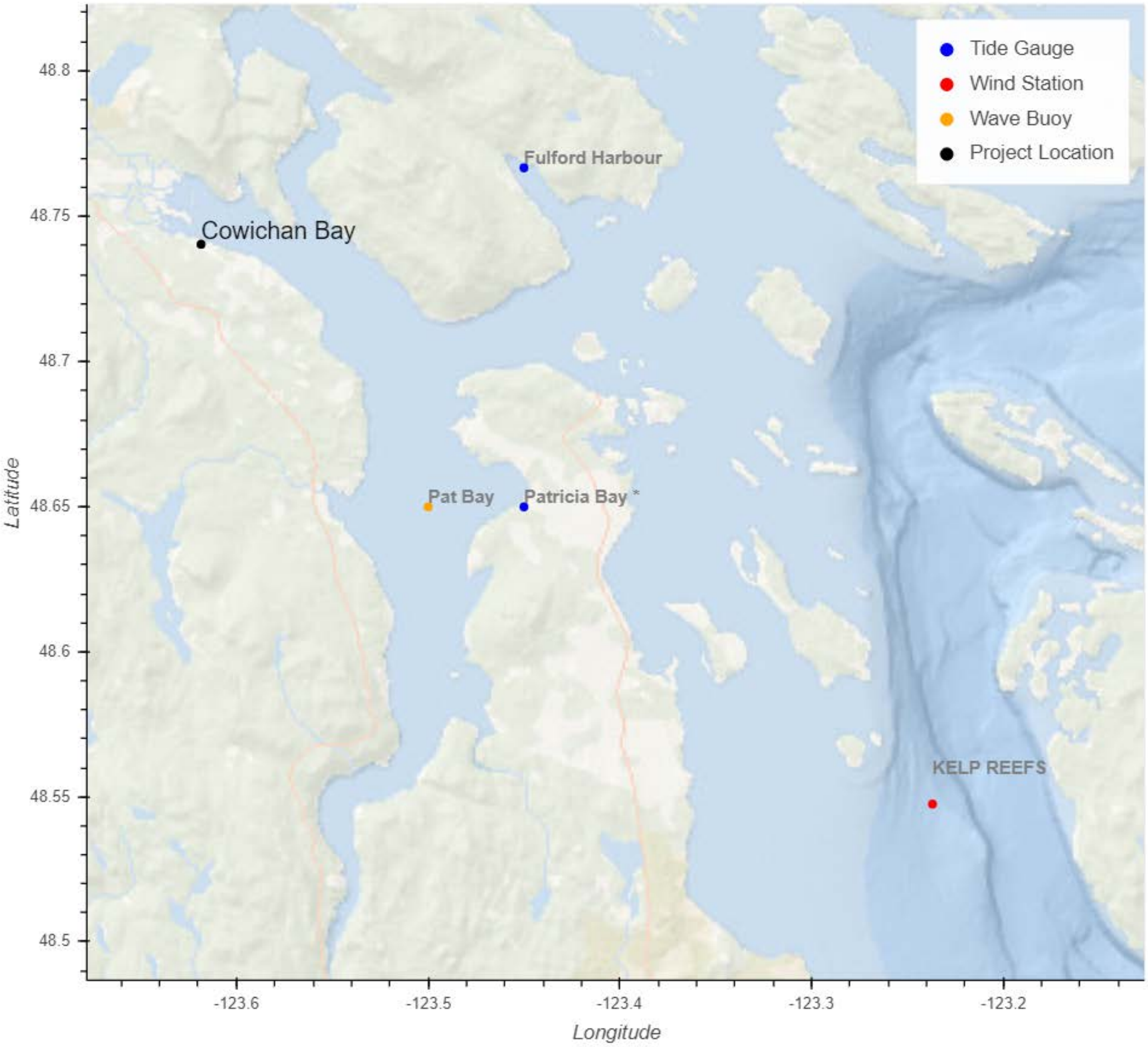

Figure 3: Tide gauge locations

The monthly average water level was calculated in order to check for trends indicative of SLR. No significant trend was detected from the data indicating that tectonic uplift or other effects have offset any impacts of global SLR in Cowichan Bay so far.

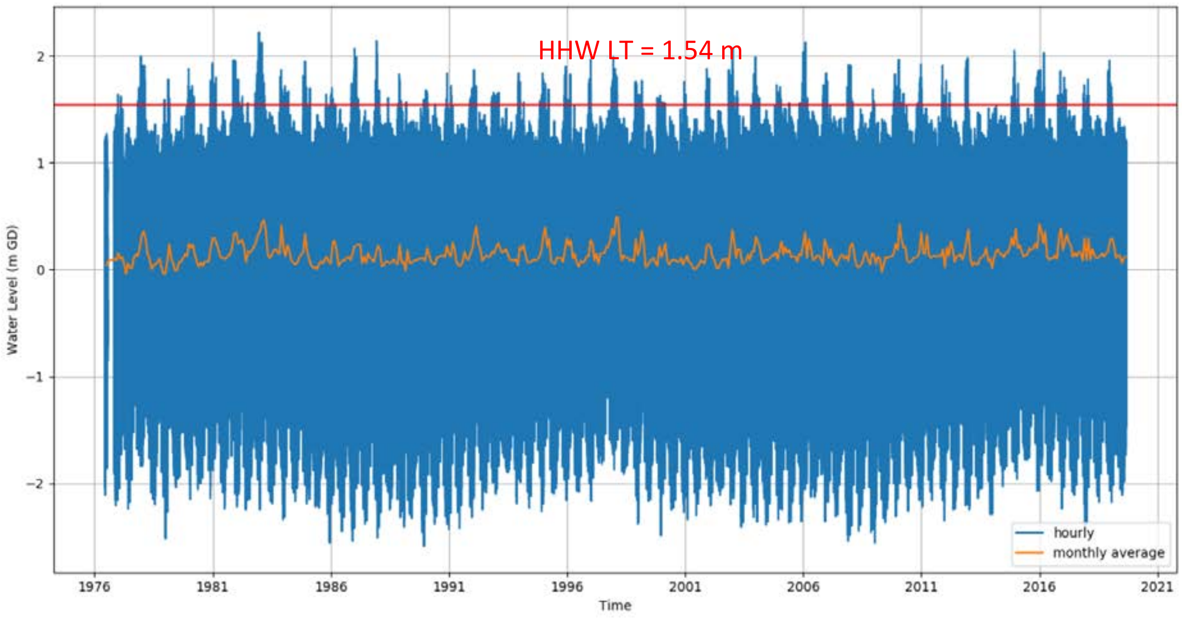

Figure 4: **Hourly and monthly-average water level record for Patricia Bay tide gauge**

An extreme event analysis was conducted using the recorded water level data for Patrician Bay using an annual maxima (Gumbel and GEV distributions) and peak-over-threshold (GPD) methods (Holthuijsen, 2007). This methodology follows the Probabilistic Method described in the Flood Hazard and Land Use Management Guidelines (BC Ministry of Environment and Climate Change, 2018) to determine the Designated Flood Level. The best fitting distribution was used to determine water levels for varying return periods as shown in Table 2.Water levels were applied to Cowichan Bay by adjusting for an increase in HHWLT of 0.1m compared to Patricia Bay. The 1-in-200-AEP total water level in Cowichan Bay including effects of tide and storm surge is 2.41 m GD.

Table 2: Water level events for various return periods for Cowichan Bay

Return Period (year)	Water Level (m GD)
2	2.04
10	2.23
20	2.28
50	2.34
100	2.38
200	2.41
500	2.45

3 CLIMATE CHANGE & REGIONAL SEA LEVEL RISE

The amended Flood Hazard Area and Land Use Guidelines (BC Ministry of Environment and Climate Change, 2018) recommends using a 1.0 m global mean SLR by 2100 for the calculation of the FCL. The global mean SLR is adjusted for regional effects such as subsidence or tectonic uplift. The recommended regional SLR rates for Cowichan Bay are provided in Table 3. Uplift is not included in the calculation of the regional SLR rate for Cowichan Bay due to the uncertainties surrounding estimates of global SLR and potential subsidence of the Cowichan Estuary.

Table 3: Regional Sea Level Rise modelling scenarios

Sea Level Rise Scenario	Year	Global Sea Level Rise (m)	Uplift (m)	Regional Sea Level Rise (m)
1	2010	0.00	0.00	0.00
2	2100	1.00	0.00	1.00

There is very large uncertainty in SLR projections, with the range in the rise varying from about 0.5 m to 1.3 m by the year 2100 and between 1.4 m and 3.4 m by the year 2200, as shown by Figure 5. It should be noted that while there is significant uncertainty with regards to the timing of when various levels of SLR estimates will occur (as can be seen by the wide grey area), there is very little uncertainty in the science that various levels of SLR will occur. Recent science has tended to suggest that SLR could occur more quickly than was previously thought due to various potential feedback mechanisms in the polar regions that could accelerate ice melt.

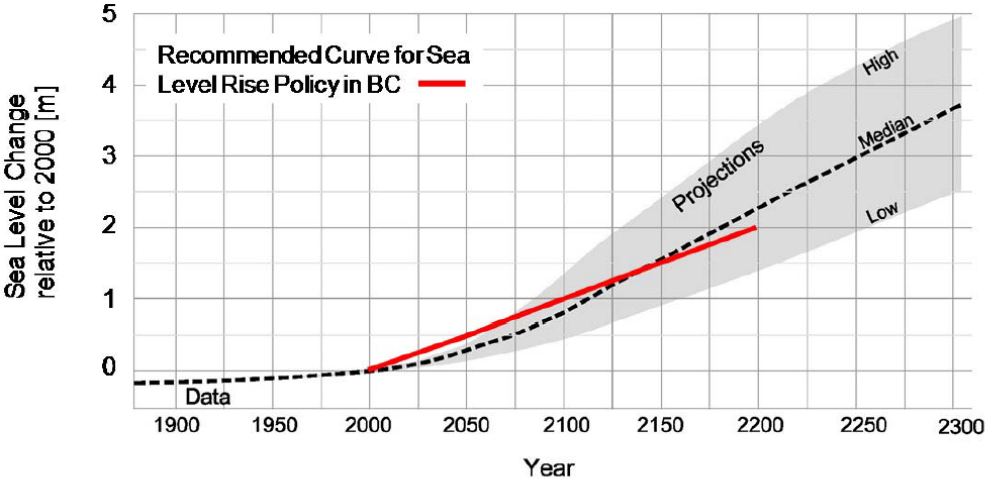

Figure 5: Recommended global sea level rise curve for planning and design in BC (BC Ministry of Environment and Climate Change, 2018)

4 WAVE EFFECTS

Since there is no comprehensive measurement of waves in the vicinity of the study site, a wind and wave analysis was required to determine the incident wave climate. The wave analysis allows for the determination of the incident wave height and the corresponding wave effect at the shoreline.

4.1 Wind Analysis

A wind and wave analysis was carried out to determine the wave climate in the project area. The local and regional wind climate were analyzed from eleven Environment Canada (EC) meteorological wind stations; 3 buoys and 8 land stations (Table 4).

Table 4: Environment Canada wind stations

Station Name	Station No.	Latitude	Longitude
Halibut Bank	c46146	49.34	-123.73
Sentry Shoal	c46131	49.91	-124.99
Patricia Bay	c46134	48.65	-123.5
Ballenas Island	1020590	49.35	-124.16
Entrance Island	1022689	49.21	-123.81
Nanaimo Airport	1025370	49.05	-123.87
Sandheads CS	1107010	49.11	-123.30
Saturna Island CS	1017101	48.78	-123.04
Sisters Island	1027403	49.49	-124.43
Victoria Int'l A	1018620	48.65	-123.43
Kelp Reefs	1013998	48.55	-123.24

Observed wind speed magnitudes were transformed to the standard 10 m wind speed (U_{10}), based on the common exponential wind profile assumption. To deduce return periods for wind events, an extreme event analysis was conducted on the wind data from Halibut Bank (**Table 5**). As Cowichan Bay is susceptible to wave events originating from the South east, wind speed data from wind directions of 0° to 90° and 180° to 360° was omitted from the analysis.

Table 5: Wind events from 90° to 180° for various return periods for Halibut Bank.

Return Period (year)	Wind Speed (South East) (m/s)
2	19.0
10	20.7
20	21.4
50	22.3
100	23.0
200	23.7
500	24.6

By utilizing the results from the extreme event analysis of wind speeds at Halibut Bank, wind storm events from the past could be identified that are very similar in magnitude to the values shown above in **Table 5**. Two storms from the past were identified, a 1:10-year wind event and a 1:200-year wind event. As shown in **Table 6** no wind events from the south east sector with wind speed magnitudes similar to the 1:10-year event exist in the time series. Therefore, a storm with similar wind speed magnitudes but directions outside the original analysis were used.

Table 6: Historical wind events observed at Halibut Bank

Similar Return Period	Date	Wind Speed (m/s)	Wind Direction (degrees)	Correction Factor
1:10-year	15-Dec-2006	20.8	307	1.00
1:200-year	2-Apr-2010	22.1	118	1.07

The eleven Environment Canada meteorological wind stations (Table 4) were used to develop a spatially varying wind field to drive the wave model. The spatially varying wind field was created by using the peak wind data from the wind events and correction factors listed above, and conducting a linear interpolation on a 250 km by 250 km square grid (Figure 5).

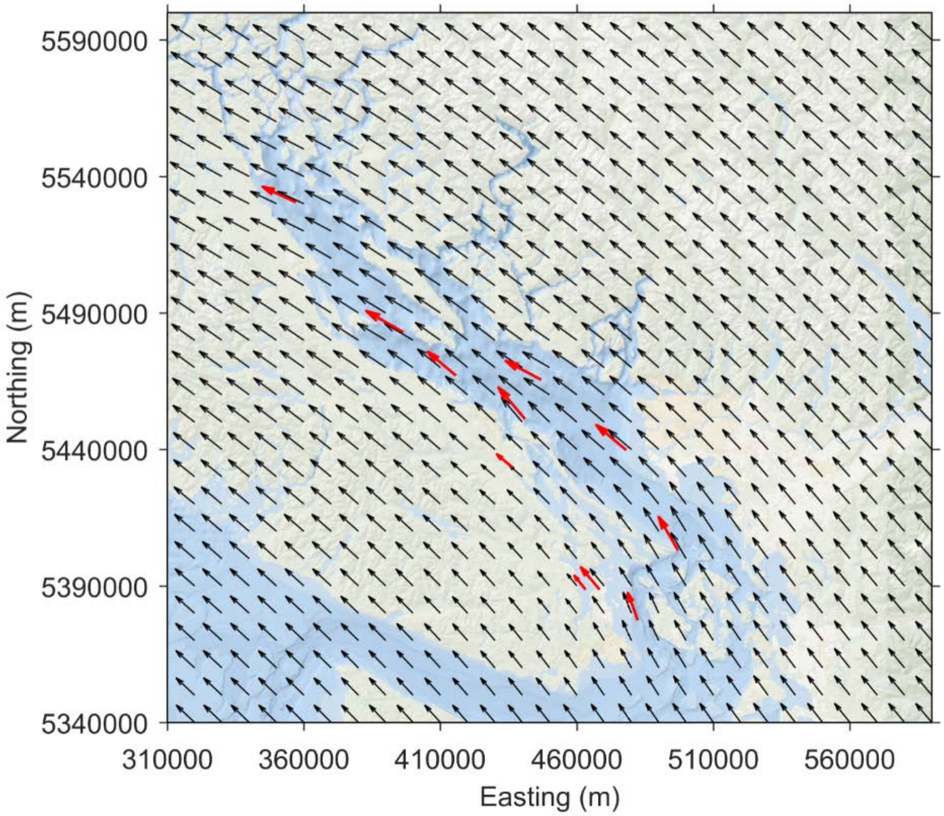

Figure 5: Synthesized wind field of the 1:200-year wind storm.

4.2 Wave Analysis

4.2.1 Wave Generation and Propagation

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

The wave model consists of three grids 'within' or nested in each other, increasing with resolution and as the extents narrow in on the project site. The wave model grid parameters can be found in **Table 7** below.

Table 7: Wave model grid parameters.

Grid	Origin (UTM 10N – m)	Rotation (degrees-cw)	Grid Cells (#)	Grid Size (m)
Strait of Georgia	470000E, 5349000W	38	226x506	500m
Saanich Inlet	459000E, 5370000W	14	126x390	100m
Cowichan Bay	456000E, 5397500W	70	400x750	10m

Seafloor elevations or bathymetry for the wave model was collected for the Strait of Georgia, Saanich Inlet and Cowichan Bay from multiple sources. Topography of Cowichan Bay was received from GeoBC LiDAR and processed by NHC GIS analysts. Wave model bathymetry was compiled by grid cell averaging and triangular interpolation to achieve a smooth surface. **Table 8** provides a summary of elevation data used for the wave modelling.

Table 8: Wave model bathymetry.

Bathymetry Source	Product	Wave Model Area Uses
Canadian Hydrographic Service	Digitized Navigation Charts	Strait of Georgia Saanich Inlet Cowichan Bay
NHC Bathymetric Survey	Single Beam	Cowichan Bay
Canadian Digital Elevation Model	Digital Product	Cowichan Bay
GeoBC LiDAR	Airborne LiDAR	Cowichan Bay

The wave model grid Cowichan includes wave damping due to vegetation typical to brackish salt marsh in British Columbia. The extents of vegetation in the Cowichan Bay SWAN model are shown in **Figure 6**. Wave dampening due to vegetation was implemented for four areas in the Cowichan Bay grid: forests, agricultural plots, rural property and wetlands.

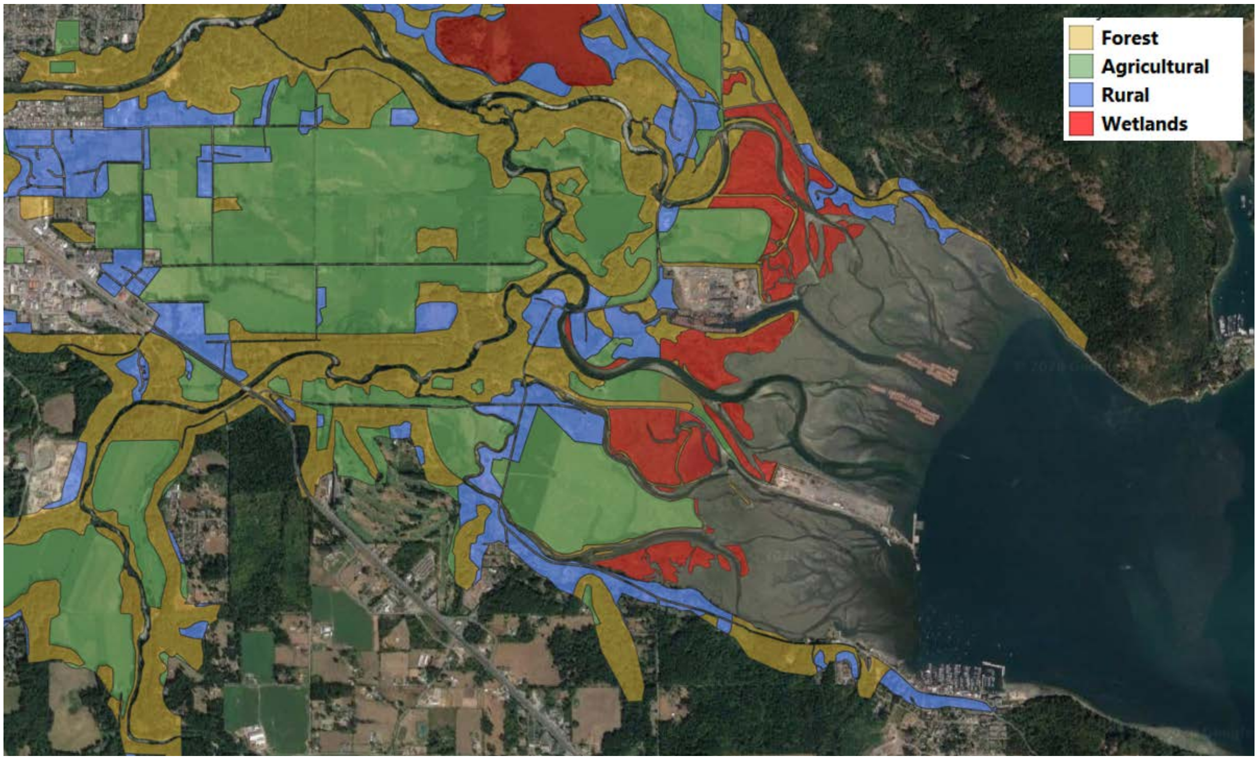

Figure 6: **Vegetation extents in Cowichan Bay SWAN wave model.**

The 10-year and 200-year AEP spatially varying wind field is applied over the model domain to simulate the wind-generated component of waves within the model. The winds are assumed to align with the Cowichan Bay geometry, and the wind direction follows the general alignment of the estuary. The model was run using the 10-year or the 200-year AEP total water level calculated in **Section 2** for present day and 2100 climate change scenario.

In addition to the standard EGBC guidelines for coastal flood construction level analysis, an additional three scenarios were modelled to investigate model sensitivity and determine the most conservative scenario. A summary of these conditions can be found in **Table 9**. The wave generation modelling scenario resulting in the highest waves for Cowichan Bay was Scenario B and was used for the analysis.

Table 9: **Wave model base scenarios**

Coastal Model Scenario	Wind Speed Event	Water Level Event	Sea Level Rise Event
Scenario A	10-yr	200-yr	+0.0m
Scenario B	10-yr	200-yr	+1.0m
Scenario C	200-yr	10-yr	+0.0m
Scenario D	200-yr	10-yr	+1.0m

The results of the 200-year wind-generated significant waves for the year 2100 climate change scenario are shown in Figure 7, Figure 8 and Figure 9. The corresponding significant wave heights along the shoreline of Cowichan Bay are provided for the "reaches" as shown in **Table 10**.

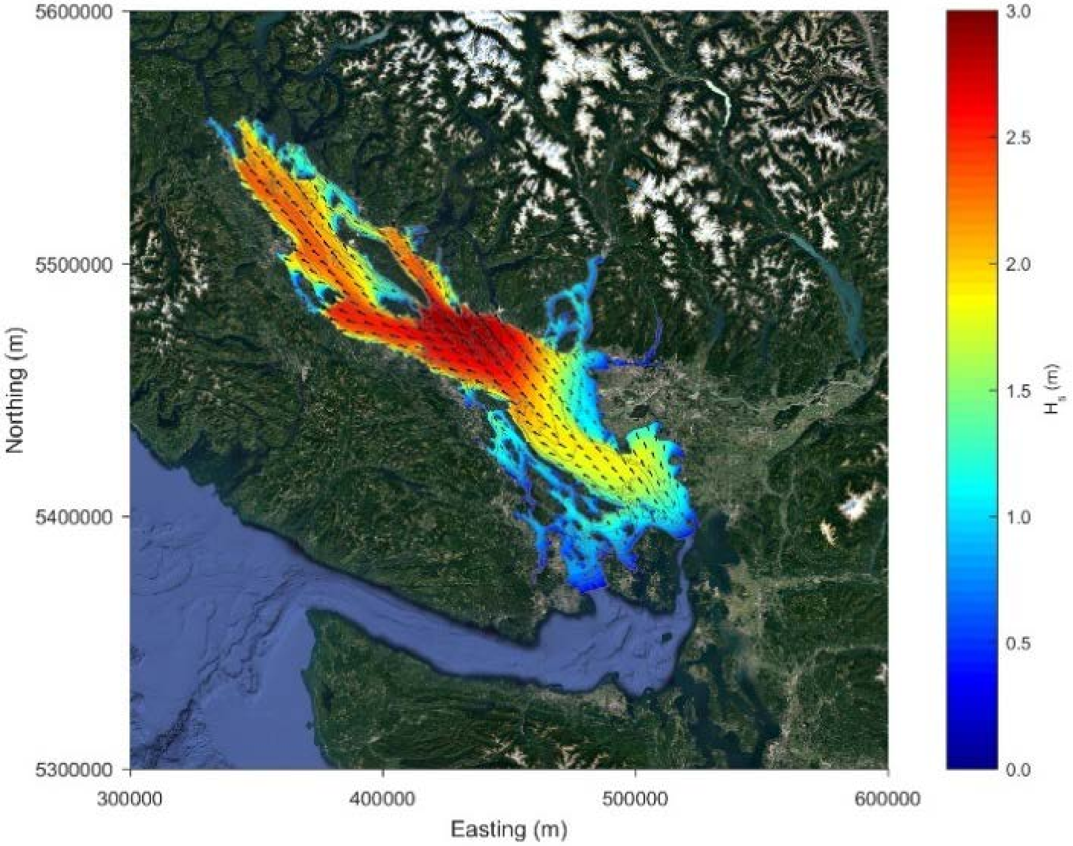

Figure 7: **Strait of Georgia wave model results – Scenario B – 200-year southwesterly wave map for the year 2100.**

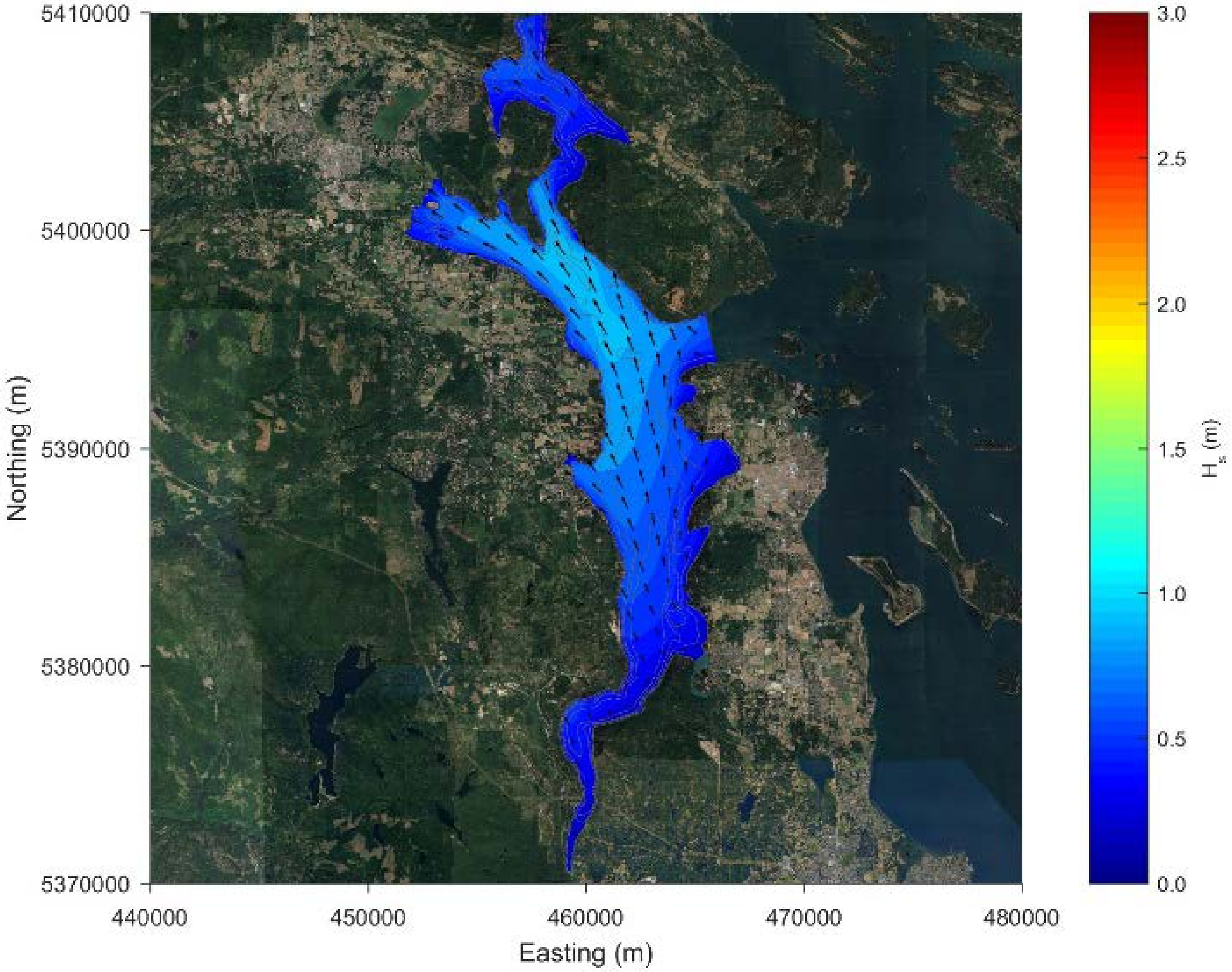

Figure 8: Saanich Inlet wave model results – Scenario B – 200-year southwesterly wave map for the year 2100.

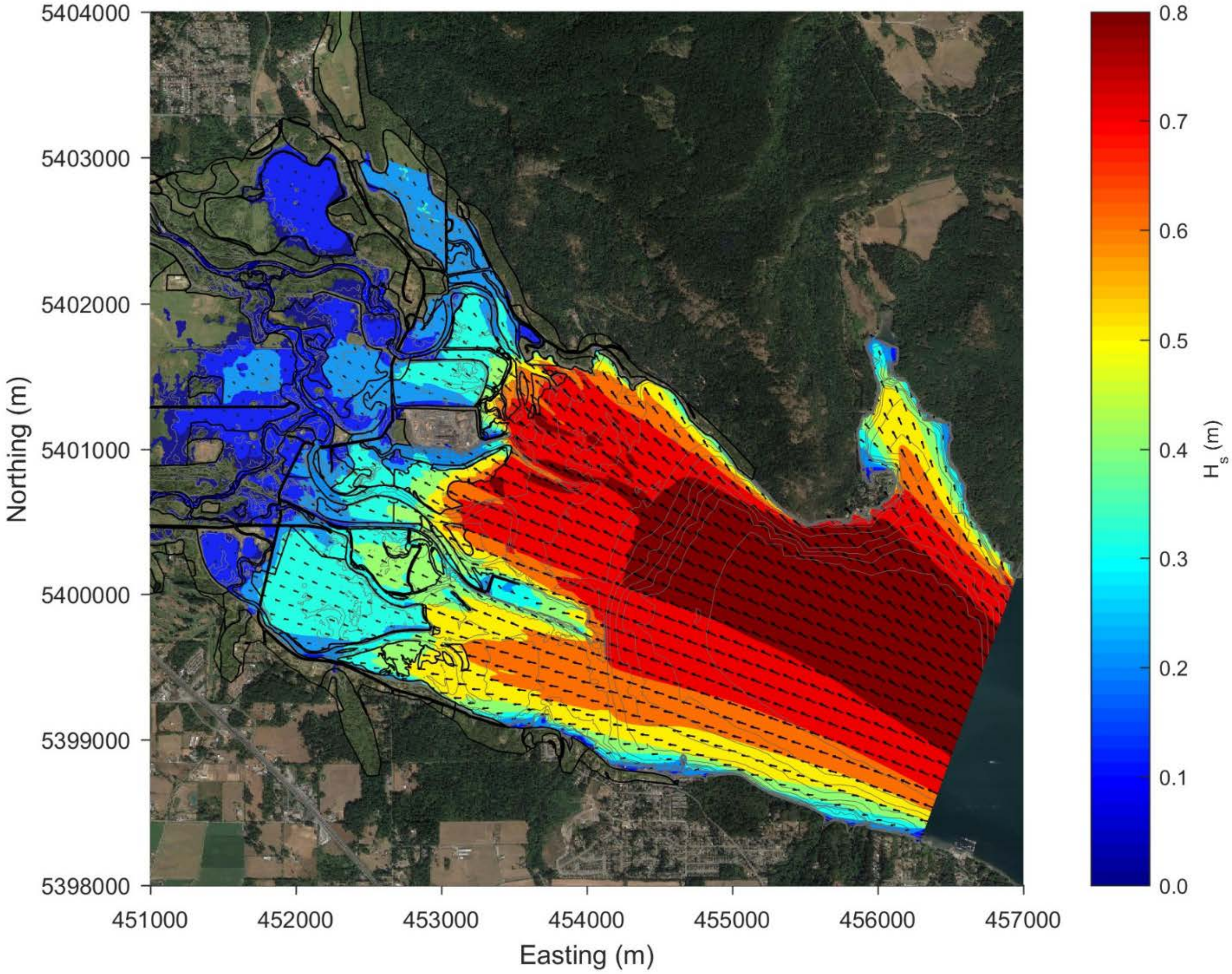

Figure 9: Cowichan Bay model results – Scenario B – 200-year southwesterly wave map for the year 2100. Vegetation polygons outlined in black.

Table 10: Significant Wave Height and Peak Period along Cowichan shoreline for scenario B (Year 2100)

Shoreline Reach	Significant Wave Height (m)	Peak Period (s)
CB-1	0.8	3.0
CB-2	0.7	2.7
CB-3	0.6	2.4
CB-4	0.5	2.1
CB-5	0.4	1.8
CB-6	0.3	1.5

4.2.2 Wave Effects Analysis

The results of the wave analysis are used to estimate the local wave runup along the shoreline for Cowichan Bay. Wave run-up represents the height that the waves will reach above the still water level after breaking. Wave run-up depends on the incident wave height at the point of breaking offshore of the shoreline, as well as the local shoreline topography (slope) and roughness. Wave run-up is calculated using the EurOtop (EurOtop, 2016) methodology, but differs depending on the shoreline characteristics. For anthropogenic shoreline types such as rip-rap, a reduction factor is used to account for rubble mound structures; for vegetated areas, such as wetlands or forested areas, a reduction factor is to account for vegetation, for oblique shorelines, a reduction factor is used to account for wave obliqueness.

The wave effects for Cowichan Bay were calculated by shoreline reach and shoreline type as shown in **Table 11** and **Figure 10**. The shoreline characteristics for Cowichan Bay vary significantly from property to property. Calculating the wave effects on this scale would be outside the scope of this study. Therefore, the results are presented depending on the characteristics of the shoreline.

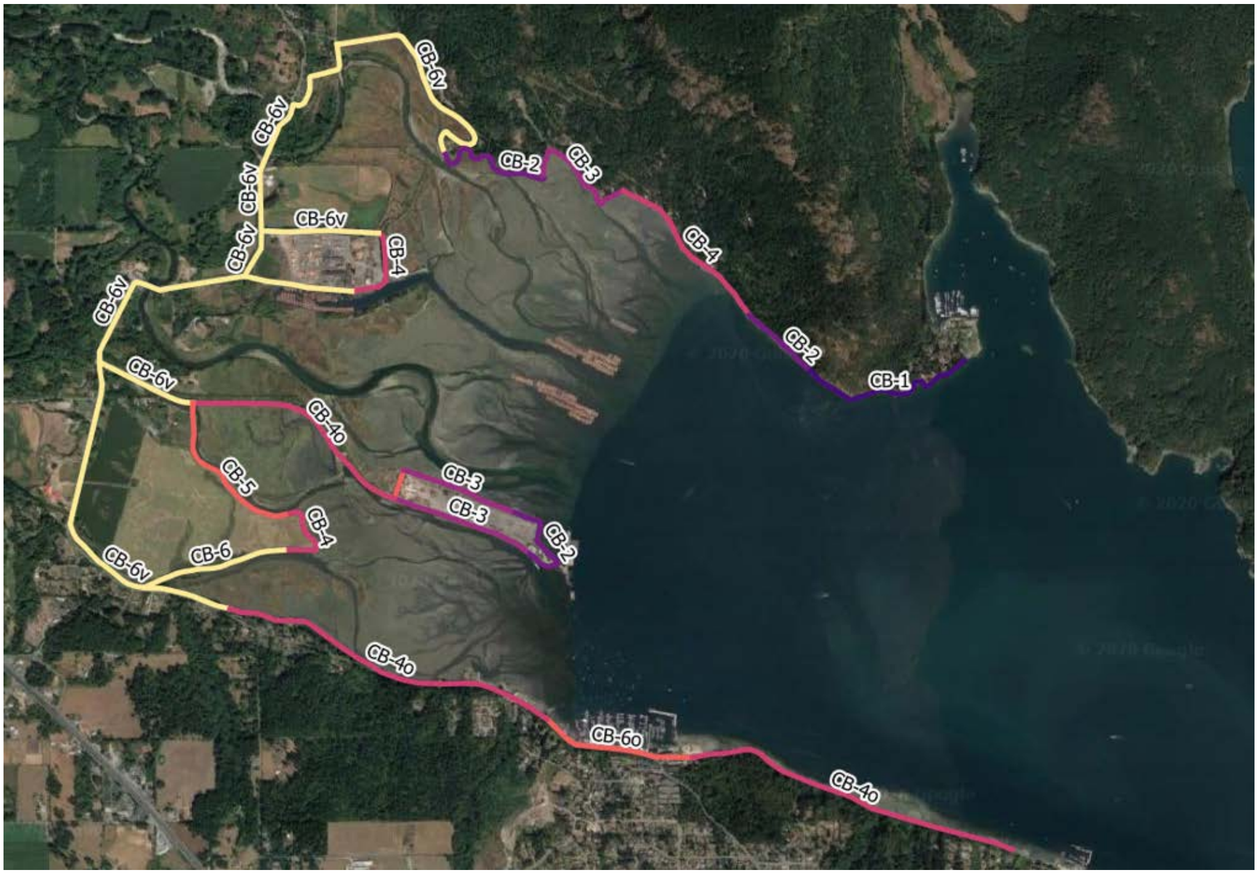

Figure 10: Shoreline reaches and wave effects for Cowichan Bay. Shoreline reach labels are differentiated by their wave run-up specific shoreline characteristics – no abbreviation for rip rap, 'v' for vegetation and 'o' for oblique

The delineation of shoreline reaches was made to be conservative (i.e. the highest wave runup was selected for a given reach) regarding wave exposure and wave runup due to the regional scale of this study. It is acknowledged that this approach could result in some properties having conservatively estimated FCL values and that a detailed study of an individual property might yield a lower FCL. However, such site specific analysis was not possible within the scope and scale of this project.

The largest wave effects are for a rip rap structure on the shoreline normal to the oncoming wave direction. The wave effects provided in **Table 11** are applicable for all SLR scenarios.

Table 11 Wave effects for Cowichan Bay shoreline by shoreline reach and type

Shoreline Reach		Wave Run-up (m)	
	Rip Rap ( )	Oblique Shoreline (-o)	Vegetated (-v)
CB-1	1.5	1.2	1.0
CB-2	1.4	1.1	1.0
CB-3	1.2	1.0	1.0
CB-4	1.0	0.8	0.9
CB-5	0.8	0.7	0.8
CB-6	0.6	0.5	0.6

4.3 Freeboard

The freeboard is applied to account for temporal and spatial variances in wave climate and surge, as well as precision of the data and assessment. Freeboard for infrastructure according to the amendment to the Flood Hazard Area Land Use Management Guidelines (BCMFLNRD, 2018) is 0.6 m when using the probabilistic method. This value is appropriate for this study for coastal shorelines due to the nature of the assessment.

4.4 Coastal Flood Construction Level

Coastal FCLs apply to Cowichan Bay shorelines within the study limits that are exposed to coastal processes including: storm surge, wave effects, wind setup and/or wave setup. Coastal FCLs are provided in the following sections.

The FCL is the sum of design water level, future SLR allowance, subsidence/uplift, wave effect and freeboard. The FCL for the year 2100 Cowichan Bay shoreline reaches are summarized in Table 12.

Table 12: Cowichan Bay flood construction levels for year 2100

Component	Shoreline Reach							
	CB-1	CB-2	CB-3	CB-4	CB-5	CB-4o	CB-6o	CB-6v
1-in-200 AEP Total Water Level (m CGVD2013)	3.41	3.41	3.41	3.41	3.41	3.41	3.41	3.41
Sea Level Rise (m)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Subsidence/Uplift (m)	0	0	0	0	0	0	0	0
Wave Effects (R2% Run-up) (m)	1.5	1.4	1.2	1.0	0.8	0.8	0.5	0.6
Freeboard (m)	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
2100 Flood Construction Reference Plane (m CGVD2013)	**5.52**	**5.38**	**5.22**	**5.01**	**4.84**	**4.83**	**4.53**	**4.59**

5 REFERENCES

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APPENDIX D:

JOINT PROBABILITY ANALYSIS

1 INTRODUCTION

1.1 Flooding in Coastal Rivers and Estuaries

The Cowichan and Koksilah rivers discharge into Cowichan Bay. In the lower reaches of these rivers, the water levels are governed by the inflowing river discharge, the astronomical tide level and the magnitude of any storm surge. Extreme flood levels are governed by the complex interaction of discharge, tide and surge and the highest water levels at any location do not necessarily correspond to the highest inflow discharge or highest ocean level. The available guidelines for floodplain mapping in British Columbia do not provide useful guidance on how to quantify the risk of flooding in tidally-affected rivers and estuaries. It has been common practice in BC to assume the 200 year river flood discharge coincides with the 200 year maximum ocean level (including astronomical tide, surge and local wind set-up). However, in many cases the probability of these two events occurring simultaneously may be very low. More rigorous methods have been used for many years in other jurisdictions such as the US (FEMA) and United Kingdom (Hawkes, 2005; White, 2007).

1.2 Purpose

This annex describes an analysis of the joint probability of extreme inflow discharges and extreme ocean levels on the Cowichan and Koksilah rivers. Assessing the joint occurrence river inflows and tides was used to develop realistic boundary conditions for the flood modelling.

The annex is divided into the following sections:

- Review of the available river discharges and ocean level data
- An overview of the methods used
- Review of the annual occurrence of extreme river flows and tides
- Assessment of the joint probability of Cowichan and Koksilah discharges and tides

2 AVAILABLE INFORMATION

2.1 River Discharge

River discharges were obtained from two Water Survey of Canada (WSC) gauges: Cowichan River Near Duncan (08HA011) (Cowichan gauge) and Koksilah River At Cowichan Station (08HA003) (Koksilah gauge). Discharge information was available for 58 years from both the Cowichan and Koksilah gauges beginning January 1, 1960 to December 31, 2018. The Koksilah gauge also provided data from May 1914 to March 1917, but this was prior to tide level and Cowichan River discharge data and was left unused. Hourly data was not continuously available, and only available from both gauges starting in 2009. To remain consistent, only daily discharges were used throughout the analysis.

2.2 Ocean Levels

Hourly observed water levels were obtained from Canadian Hydrographic Service (CHS) tide stations: Fulford Harbour (7330) and Patricia Bay (7277). Fulford Harbour was used to fill missing data from Patricia Bay. Water levels were converted to CGVD2013 from the chart datum. Daily maximum water levels were used, rather than the available hourly data, so as to remain consistent with the daily maximum discharge data. The record for tide data began November 26, 1952 and ended August 31, 2019. Discharge data restricted the water level data to begin and end on the same dates of January 1, 1960 and December 31, 2018, respectively. To determine dependence between the two parameters, both are required on each date.

3 METHOD OF APPROACH

3.1 Review of Methods

The following steps were used to determine the joint probability of extreme flood and tide events:

1) Create joint distribution matrices (Section 4)

2) Determine percent exceedance of discharges and tide levels (Section 5.1)

3) Determine threshold for extreme events (Section 5.1)

4) Determine dependence factor for given threshold (Section 5.2)

5) Determine joint probability of occurrence (Section 5.3)

Joint distribution matrices were created using extreme discharge events noted by Septer (2000, 2006) on the Cowichan and Koksilah rivers. To visually determine the relationship between extreme events (Figures provided in Section 4), pairs of matrices were created by 1) determining what the maximum daily water level was for the date of an extreme flood event and 2) by determining the maximum daily discharge on the date of the maximum annual tide. The same process was used for comparing the Koksilah River discharge against the Cowichan River discharge.

The percent exceedance of discharges and tide levels was determined using histograms and cumulative percent frequencies. The data from January 1, 1960 to December 31, 2018 was refined such that the spring and summer low flows and tides between April and September, inclusive were removed. To create the histograms, the Cowichan River used a bin range of 25 m^3/s, since these discharges had a much greater range than the Koksilah River, which had a bin range of 12.5 m^3/s.

White (2007) determined a fairly consistent dependence between the 80% and 98% maximums for discharge and tide levels. An 80% maximum indicates the highest 20% of one variable, independent of the other. Since White (2007) showed a constant, unchanging dependence between 80% and 85% for the studied New Haven tide and Barcombe Mills flow, 85% was used as the lowest threshold for this study. Above a threshold of 98%, dependence decreases to zero (completely independent) due to lack of data (White, 2007). Four thresholds were tested for dependence between the Cowichan river and Cowichan Bay tides, and the Koksilah River and tides : 85%, 90%, 95%, and 98%. Discharges and tide levels were linearly interpolated to determine values for these thresholds. Section 5 provides more detail on the percent exceedance and thresholds used to calculate a Dependence factor.

3.2 Dependence of Flood Discharges and Tides

White (2007) states that "The basis of dependence theory is the probability of exceedance of a selected threshold level… The level of dependence is then calculated not just from the extremes of one variable, but also from the simultaneous occurrence of extreme values from both variables".

The procedure described by White (2007) in Appendix F, section F.1.3 was followed to calculate dependence factors for this analysis. The dependence factor is calculated using Equation 2, which was broken into Equation 3 (numerator of Equation 2) and Equation 4 (denominator of Equation 2).

$$x(u) = 2 - \frac{lnP(U \leq u, V \leq u)}{lnP(U \leq u)}\ for\ 0 \leq u \leq 1 \tag{2}$$

$$P(U \leq u, V \leq u) = 2 - \frac{Number\ of\ (X,Y) such\ that\ X \leq x^{*} and\ Y \leq y^{*}}{Total\ number\ of\ (X,Y)} \tag{3}$$

$$lnP(U \leq u) = \frac{1}{2} ln\left[\frac{Number\ of\ X \leq x^{*}}{Total\ number\ of\ X} \cdot \frac{Number\ of\ Y \leq y^{*}}{Total\ number\ of\ Y}\right] \tag{4}$$

Where x is the dependence factor, X is discharge and Y is water level, $x*$ is the threshold value for discharge, and $y*$ is the threshold value for tide water level.

Dependence factors were calculated for each of the four thresholds by further refining the data used to create the histograms. Dates of Cowichan River discharges were compared to dates of Cowichan Bay tides and data was only used when both parameters were available. Dates of Koksilah River discharges were separately compared to the tides and data was used where both of these parameters were available. The result was the ability to determine dependence factors specific to each river with Cowichan Bay tides, using the greatest amount of relevant data. Results and more details on dependence factors for the Cowichan River and Cowichan Bay, and Koksilah River and Cowichan Bay are provided in Section 5.

3.3 Joint Probability

Using the dependence factors for each threshold and both rivers, joint probability matrices were created to determine return periods related to the statistical dependence of the tides and river discharges. Probability tables for the extreme joint exceedance of each river with Cowichan Bay tides was created using return periods of 1, 1.5, 2, 5, 10, 20, 30, 50, 75, 100, and 200 years on opposing axes. Equation 1 was utilized to determine joint return periods for each pair for exceedance of a given threshold. Four joint probability matrices for each of the two rivers were created using every combination of the return periods.

$$T_{xy} = \frac{1}{\left(1 - \frac{1}{\sqrt{T_x \cdot T_y}}\right)^{2-x} + \left(\frac{2}{\sqrt{T_x \cdot T_y}}\right) - 1} \tag{1}$$

The dependence factor is represented by $\mathbf{X}$, the return period for river discharge is represented by T_x, the return period for Cowichan Bay water level is represented by T_y, and T_{xy} represents the joint return period. Due to the joint probability of extreme events, several combinations yield approximately equivalent return periods for the river and tide levels. Section 5.3 provides further discussion of results.

4 ANNUAL OCCURRENCE OF EXTREME RIVER FLOWS AND TIDES

4.1 Cowichan River and Koksilah River

The Cowichan and Koksilah rivers are also anticipated to have minor dependence because of being hydraulically connected. Due to Cowichan Lake, flooding on the Cowichan River is typically after or coincident with flooding on the Koksilah River. If the Koksilah is flooding, the Cowichan may not yet be, due to the delay from the lake reservoir. Table 1 provides the dates of major storm events on the Cowichan and Koksilah rivers noted by Septer (2000, 2006). For these flood events, the Cowichan River does not peak before the Koksilah River.

Table 1: Dates when the Koksilah and Cowichan rivers reached maximum discharge during major flood events noted by Septer (2000, 2006)

Date Koksilah Peaks	Date Cowichan Peaks	Date Koksilah Peaks	Date Cowichan Peaks
29-Jan-1960	29-Jan-1960	15-Nov-1983	16-Nov-1983
15-Jan-1961	15-Jan-1961	18-Jan-1986	20-Jan-1986
01-Jan-1963	01-Jan-1963	04-Dec-1990	05-Dec-1990
23-Dec-1963	23-Dec-1963	19-Mar-1997	19-Mar-1997
13-Dec-1966	18-Dec-1966	29-Jan-1999	29-Jan-1999
19-Jan-1968	19-Jan-1968	07-Jan-2002	08-Jan-2002
19-Jan-1971	20-Jan-1971	19-Jan-2005	23-Jan-2005
15-Feb-1971	15-Feb-1971	15-Nov-2006	18-Nov-2006
20-Jan-1972	21-Jan-1972	04-Dec-2007	04-Dec-2007
25-Dec-1972	26-Dec-1972	16-Nov-2009	20-Nov-2009
14-Jan-1974	15-Jan-1974	15-Jan-2010	15-Jan-2010
03-Dec-1975	04-Dec-1975	09-Dec-2015	09-Dec-2015
26-Dec-1980	27-Dec-1980	29-Jan-2018	29-Jan-2018
28-Oct-1982	29-Oct-1982		

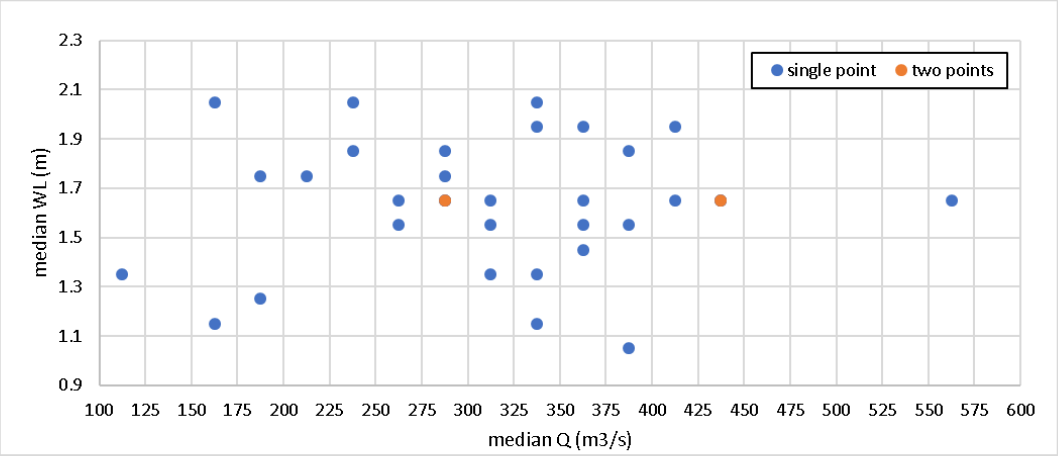
Note: Red text indicates simultaneous peak discharge dates

This is a preliminary comparison of the Cowichan and Koksilah river dependence. The dependence and joint probability between the these rivers could be investigated further.

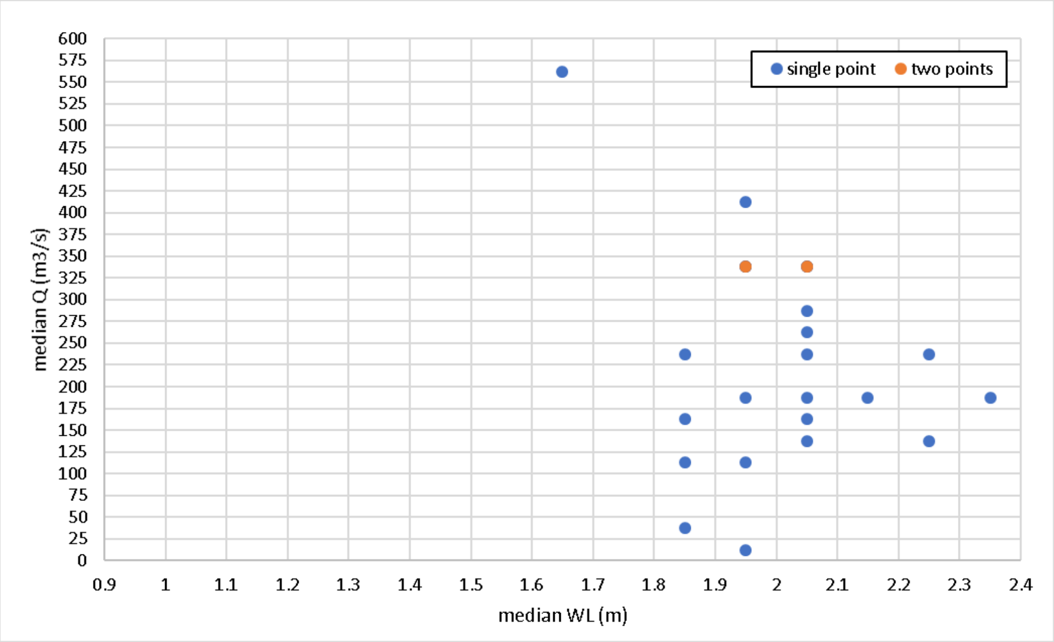
4.2 Cowichan River and Ocean Levels

To compare the dependence of the Cowichan River and Cowichan Bay tides, dates of high discharge events noted by Septer (2000, 2006) were used, and water levels were determined for the given day. This yielded a range of water levels, though most were in the medium to high range (Figure 1A). For the years that Septer (2000, 2006) noted major flood events on the Cowichan and koksilah rivers, the annual maximum water levels were determined, along with discharges for these dates (Figure 1B). There is a large spread in discharge, but still around the medium intensity range.

For both the Cowichan River (Section 4.2) and the Koksilah River (Section 4.3), matrices were set up so that the discharges had a range of 25 m^3/s, and the water levels had a range of 0.1m. For example, if discharge was 105 m^3/s, it would fall into the range of 100-125 m^3/s. If the water level was 0.87 m it would fall within the range of 0.80-0.90 m. Values falling on the extreme bound were entered into the lower range (ex. 100 m^3/s would fall into the 75-100 m^3/s range). This method was because the intent of this visual representation of dependence was to determine the amount of data that fell within a certain range, rather than the exact values for tide levels and discharges. The median value was used for each range in discharge (25 m^3/s) and water level (0.1 m).



A) Cowichan Bay water levels during flood events on the Cowichan River noted by Septer (2000, 2006). Annual maximum daily discharges for the year of the flood, and maximum daily discharges during flood events are depicted



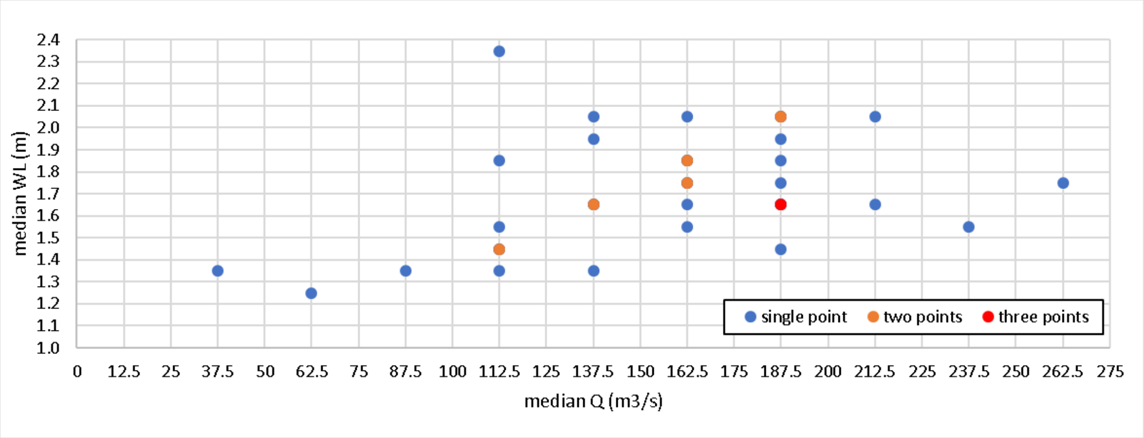
B) Cowichan River discharges during annual maximum tide level in Cowichan Bay for years when Septer (2000, 2006) reported extreme flood events

Figure 1: **Joint Distributions for A) Cowichan River discharge and resulting Cowichan Bay water level, and B) Annual maximum Cowichan Bay water level and resulting Cowichan River discharge**

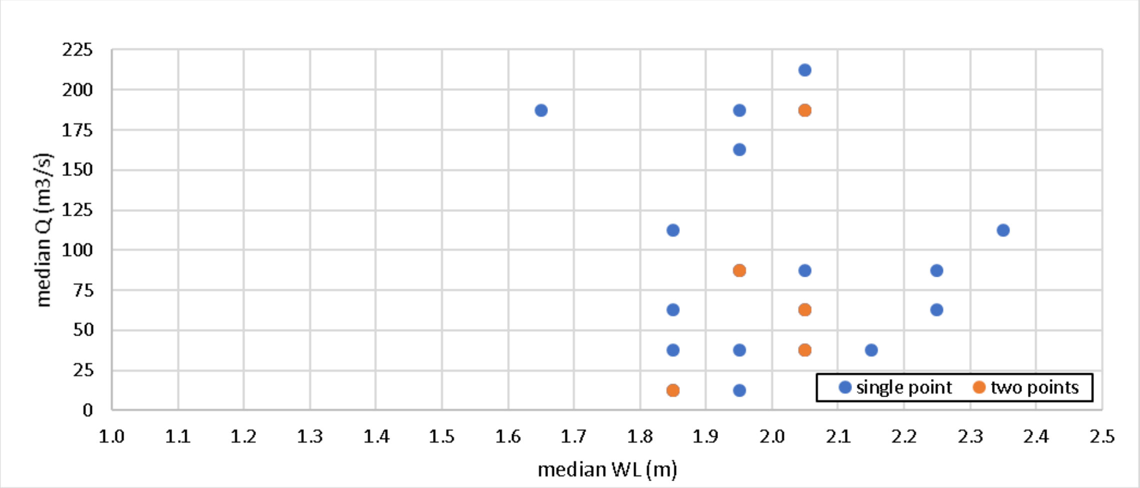
From Figure 2A, dependence between Cowichan Bay tides and Cowichan River discharge is visible. Most of the data is around the medium to high range for discharge and tide level. When beginning with the tide levels and determining the resulting discharge (Figure 1B), the dependence seems to be weaker. Some discharges are near zero, though most remain in the medium to high range, while the tides are all in the high range. Figure 1 indicates there is a minor dependence between Cowichan Bay tides and Cowichan River discharges.

4.3 Koksilah River and Ocean Levels

As in the previous section, dates of storm events on the Cowichan and Koksilah rivers noted by Septer (2000, 2006) were used to ensure extreme events were analyzed. Water levels in Cowichan Bay were determined for dates of high discharge on the koksilah River (Figure 2A). Discharges for dates of annual maximum tides for years where a storm event was reported by Septer (2000, 2006) were also determined (Figure 2B). As in Section 4.2, the median values for each range in discharge and tide levels were used.



A) Cowichan Bay water levels during flood events on the Koksilah River noted by Septer (2000, 2006). Annual maximum daily discharges for the year of the flood, and maximum daily discharges during flood events are depicted



B) Koksilah River discharges during annual maximum tide level in Cowichan Bay for years when Septer (2000, 2006) reported extreme flood events

Figure 2: Joint Distributions for A) Koksilah River discharge and resulting Cowichan Bay water level, and B) Annual maximum Cowichan Bay water level and resulting Koksilah River discharge

Minor dependence between the Koksilah River and Cowichan Bay is clear from Figure 2A. The majority of data is around the medium to high range in both discharge and water level. Figure 2B shows a greater spread in data with the discharge near zero and reaching a smaller maximum range than in Figure 2A.

This may indicate a weaker dependence of the tides on the discharge, compared to the dependence of the discharge on the tides. Overall this proves a minor dependence between the Koksilah River and Cowichan Bay.

4.4 Discussion of Results

Figures 1A and 2A depict a range of water levels during the high discharge events with enough points in the moderate to high water level range to show a dependence. Figures 1B and 2B show a wider range of discharges when the water level in Cowichan Bay is at an annual maximum. There are enough discharges in the medium to high range to show there is some dependence of the tides on the discharge. There seems to be a greater dependence of discharge on the tide water level, which is reasonable because when tides are higher, there is more backwater effect and thus a higher river stage. When discharge is higher, it does not affect the tide, rather the water levels in Cowichan Bay may be higher due to the weather event causing the higher discharge. There is a minor mutual dependence between the discharge and water level.

5 JOINT PROBABILITY OF DISCHARGES AND TIDES

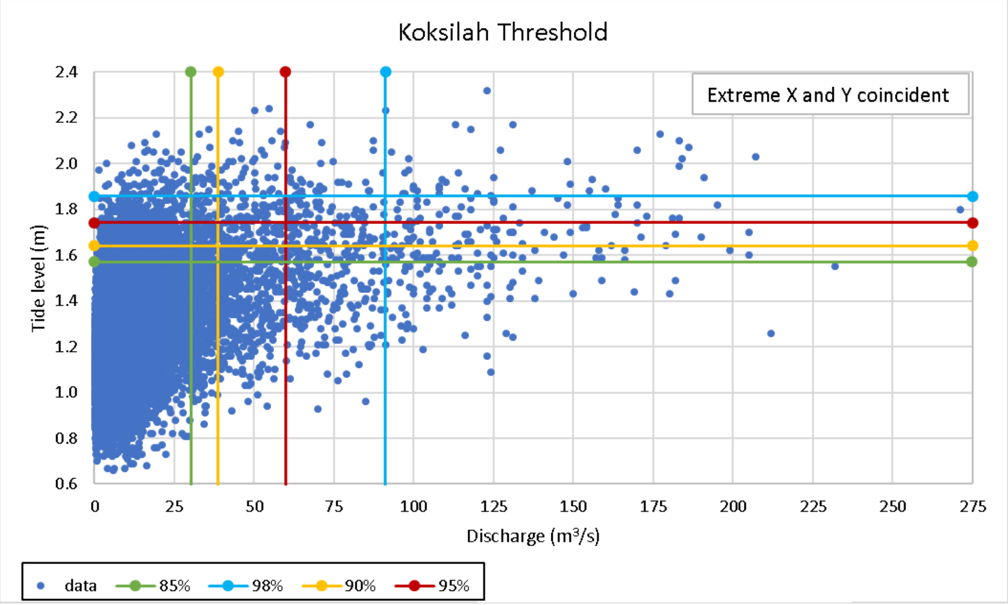
5.1 Definition of Thresholds

Acceptable thresholds for extreme tide and discharge events were determined based on cumulative percents for each parameter. For example, on the Cowichan River, the discharge at a cumulative percent of 85% was 141.8 m^3/s, and only 15% of discharges exceeded this value. Thresholds that are too low are too inclusive, and do not accurately represent extreme events. Thresholds that are too high do not have enough data to determine dependence and ensure accuracy. Table 2 provides the cumulative percent, discharge and water level for the four thresholds under analysis.

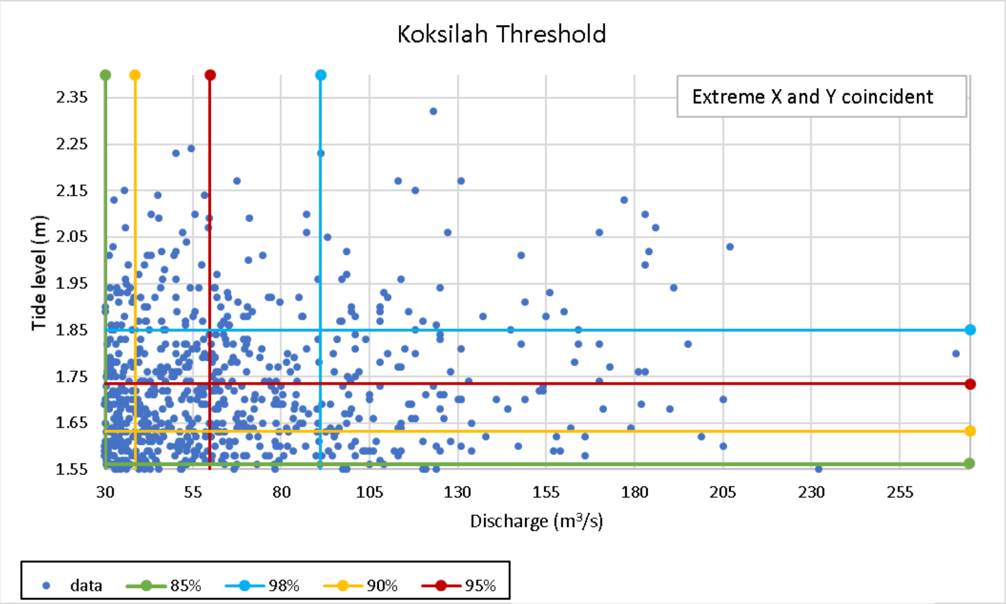
Table 2: Thresholds to isolate extreme discharge and water levels

Cumulative (%)	Cowichan Bay Water Level (m)	Cowichan River Discharge (m^3/s)	Koksilah River Discharge (m^3/s)
85%	1.57	141.8	30.28
90%	1.64	163.6	38.70
95%	1.74	199.2	59.81
98%	1.86	250.6	91.19

Visuals of the thresholds intended to limit data to extreme values are provided for the Koksilah and Cowichan Rivers in Figures 3 and 4, respectively. Part A provides the entire data set with thresholds, Part B provides a refined view of the extreme data within the four thresholds.

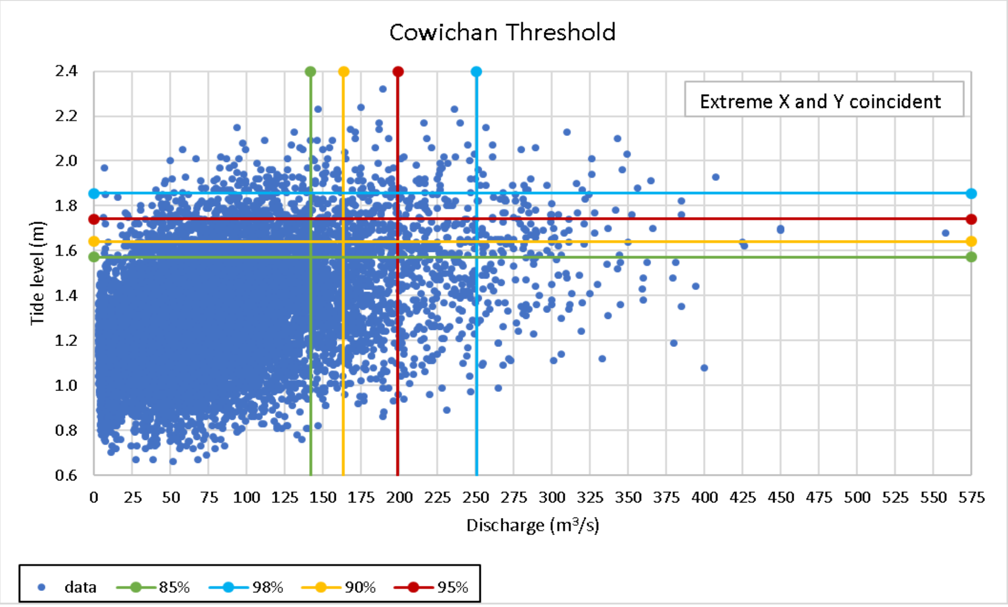


A) Full data set of Koksilah River discharges and Cowichan Bay water levels with thresholds for extreme events

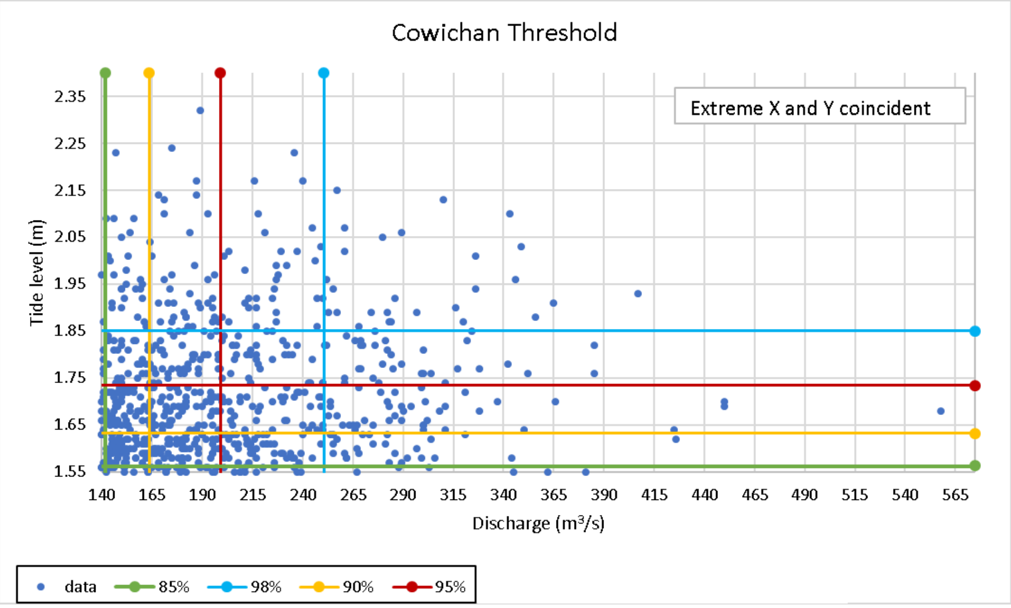


B) Koksilah River discharges and Cowichan Bay water levels exceeding the four thresholds for extreme events

Figure 3: **Koksilah River discharges and Cowichan Bay water levels between January 1, 1960 to December 31, 2018, excluding April through September with A) full data set, and B) refined, above threshold data**



A) Full data set of Cowichan River discharges and Cowichan Bay water levels with thresholds for extreme events



B) Cowichan River discharges and Cowichan Bay water levels exceeding the four thresholds for extreme events

Figure 4: **Cowichan River discharges and Cowichan Bay water levels between January 1, 1960 to December 31, 2018, excluding April through September with A) full data set, and B) refined, above threshold data**

The four thresholds provided in Table 2 and depicted in Figures 3 and 4 were used to determine dependence factors between the Koksilah River and Cowichan Bay tides, and the Cowichan River and Cowichan Bay tides. From Figures 3 and 4, thresholds of 90% and 95% are more reasonable, since the 98% threshold does not look to have enough data for accuracy, and the 85% threshold could be too inclusive for extreme event definition.

5.2 Dependence

The dependence factor is a percentage risk of occurrence for simultaneous extreme events with the river and tide. If one parameter (either the discharge or water level) is above the threshold delimiting an extreme event, the dependence factor indicates the percent chance of the other parameter simultaneously exceeding this threshold (White, 2007). A dependence factor of one indicates complete dependence, where both parameters would always exceed the threshold simultaneously. A dependence factor of zero would indicated complete independence.

The dependence factor is determined from calculating the probability of occurrence of events where neither variable simultaneously exceed the threshold (Equation 3) and where each variable independently exceeds the threshold (Equation 4). Table 3 provides the dependence factors between the Koksilah River and Cowichan Bay, and the Cowichan River and Cowichan Bay for the four thresholds.

Table 3: Dependence factors for Cowichan Bay with Cowichan River, and with Koksilah River

Threshold	Dependence Factor (x)	
	Cowichan River	Koksilah River
85%	0.301	0.328
90%	0.257	0.303
95%	0.197	0.227
98%	0.110	0.164

The dependence factors at the 98% threshold are very low, though they still indicate a slight joint probability of occurrence. The dependence factor nearly doubles for the Cowichan River with only a three percent decrease in threshold. For the Koksilah River, the dependence factor also has a substantial increase from a threshold of 98% to 95%, though not as substantial as with the Cowichan River. It is anticipated that the dependence factor is more spread between threshold limits with the Cowichan River due to a greater range in discharge compared to the Koksilah River. The considerable change in dependence between 98% and 95% is further reason that the 98% threshold is not reasonable. The 90% and 95% thresholds are more reasonable, since they are within the tolerance of limiting extreme events while providing enough data to calculate a dependence. Dependence factors from the 90% threshold offer more of a safety factor for predicting extreme events. Dependence factors using a threshold of the 95th percentile could still be lacking enough data for accuracy, and would yield greater probabilities of occurrence of extreme events (smaller return periods).

5.3 Joint Probability Assessment

Joint probability matrices were created for each of the dependence factors provided in Table 3 using Equation 1. Table 4 provides a sample matrix for the joint probability between the Cowichan River and Cowichan Bay using the dependence factor associated with a 90% threshold. Table 5 provides the joint probability matrix for the Koksilah River also with the 90% threshold. Table 6 provides the matrix for complete independence and is provided for comparison to the results in Table 5.

Table 4: Joint return periods for the Cowichan River and Cowichan Bay using a 90% threshold and resulting dependence factor of 0.303.

Return Period in Years	Cowichan River Discharge											
Tide	**1**	**1.5**	**2**	**5**	**10**	**20**	**30**	**50**	**75**	**100**	**150**	**200**
1	1	1	2	4	7	11	15	20	26	31	40	47
1.5	1	2	3	5	9	15	19	26	33	40	50	59
2	2	3	3	7	11	18	23	31	40	47	59	69
5	4	5	7	13	20	31	40	53	67	78	98	114
10	7	9	11	20	31	47	59	78	98	114	142	165
20	11	15	18	31	47	69	86	114	142	165	204	237
30	15	19	23	40	59	86	108	142	175	204	252	292
40	18	23	27	47	69	101	126	165	204	237	292	339
50	20	26	31	53	78	114	142	185	229	266	328	380
75	26	33	40	67	98	142	175	229	283	328	404	467
100	31	40	47	78	114	165	204	266	328	380	467	541
150	40	50	59	98	142	204	252	328	404	467	575	665
200	47	59	69	114	165	237	292	380	467	541	665	769

Note: Values in red text represent combinations of river inflow and tide level that have a total probability of around 200 years

Table 5: Joint return periods for the Koksilah River and Cowichan Bay using a 90% threshold and resulting dependence factor of 0.303.

Return Period in Years	Koksilah River Discharge											
Tide	**1**	**1.5**	**2**	**5**	**10**	**20**	**30**	**50**	**75**	**100**	**150**	**200**
1	1	1	2	4	6	10	13	18	23	28	35	41
1.5	1	2	3	5	8	13	17	23	30	35	44	51
2	2	3	3	6	10	16	20	28	35	41	51	60
5	4	5	6	12	18	28	35	46	58	68	84	98
10	6	8	10	18	28	41	51	68	84	98	122	142
20	10	13	16	28	41	60	75	98	122	142	175	203
30	13	17	20	35	51	75	93	122	151	175	215	250
40	16	20	24	41	60	87	108	142	175	203	250	289
50	18	23	28	46	68	98	122	159	196	227	280	324
75	23	30	35	58	84	122	151	196	241	280	344	398
100	28	35	41	68	98	142	175	227	280	324	398	461
150	35	44	51	84	122	175	215	280	344	398	489	566
200	41	51	60	98	142	203	250	324	398	461	566	654

Note: Values in red text represent combinations of river inflow and tide level that have a total probability of around 200 years

Table 6: **Joint return periods for the Koksilah River and Cowichan Bay using a dependence factor of 0.0, indicating complete independence.**

Return Period in Years						Koksilah River Discharge						
Tide	**1**	**1.5**	**2**	**5**	**10**	**20**	**30**	**50**	**75**	**100**	**150**	**200**
1	1	2	2	5	10	20	30	50	75	100	150	200
1.5	2	2	3	8	15	30	45	75	112	150	225	300
2	2	3	4	10	20	40	60	100	150	200	300	400
5	5	8	10	25	50	100	150	250	375	500	750	1000
10	10	15	20	50	100	200	300	500	750	1000	1500	2000
20	20	30	40	100	200	400	600	1000	1500	2000	3000	4000
30	30	45	60	150	300	600	900	1500	2250	3000	4500	6000
40	40	60	80	200	400	800	1200	2000	3000	4000	6000	8000
50	50	75	100	250	500	1000	1500	2500	3750	5000	7500	10000
75	75	112	150	375	750	1500	2250	3750	5625	7500	11250	15000
100	100	150	200	500	1000	2000	3000	5000	7500	10000	15000	20000
150	150	225	300	750	1500	3000	4500	7500	11250	15000	22500	30000
200	200	300	400	1000	2000	4000	6000	10000	15000	20000	30000	40000

Note: Values in red text represent combinations of river inflow and tide level that have a total probability of around 200 years

A 200-year return period has a greater probability of occurrence in Table 6 compared to Table 5, indicating an underestimation for predictions of extreme events. The matrix showing complete dependence between the Koksilah River and Cowichan Bay is provided in Table 7. This was the assumption used prior to determining dependence factors.

Table 7: **Joint return periods for the Koksilah River and Cowichan Bay using a dependence factor of 1.0, indicating complete dependence.**

Return Period in Years						Koksilah River Discharge						
Tide	**1**	**1.5**	**2**	**5**	**10**	**20**	**30**	**50**	**75**	**100**	**150**	**200**
1	1	1	1	2	3	4	5	7	9	10	12	14
1.5	1	2	2	3	4	5	7	9	11	12	15	17
2	1	2	2	3	4	6	8	10	12	14	17	20
5	2	3	3	5	7	10	12	16	19	22	27	32
10	3	4	4	7	10	14	17	22	27	32	39	45
20	4	5	6	10	14	20	24	32	39	45	55	63
30	5	7	8	12	17	24	30	39	47	55	67	77
40	6	8	9	14	20	28	35	45	55	63	77	89
50	7	9	10	16	22	32	39	50	61	71	87	100
75	9	11	12	19	27	39	47	61	75	87	106	122
100	10	12	14	22	32	45	55	71	87	100	122	141
150	12	15	17	27	39	55	67	87	106	122	150	173
200	14	17	20	32	45	63	77	100	122	141	173	200

Note: Values in red text represent combinations of river inflow and tide level that have a total probability of around 200 years

In Table 7, the only time a 200-year return period occurs is when both the tide and river are undergoing a 200-year event. This is a more conservative prediction method to ensure a factor of safety around flood predictions.

5.4 Discussion of Results

The matrices of joint probability of extreme events on the Cowichan River and Cowichan Bay, and Koksilah River and Cowichan Bay are all more accurate than the assumption of complete dependence. From the four thresholds under analysis, the most accurate dependence factors are likely resultant from either the 90% or 95% thresholds. To provide a greater factor of safety, the 90% threshold and associated dependence factors are recommended.

6 CONCLUSIONS

Return periods for a river that discharges into the ocean are complicated by the changing water levels from tides. The joint probability of occurrence of extreme events should be determined to accurately predict flood water levels and extents for a given return period. Flood models for the CVRD rely on a conservative assumption of complete dependence between the Cowichan Bay tides and Cowichan River, and Koksilah River and tides. Four thresholds for determining dependence factors for each river with Cowichan Bay were established, and a threshold of 90% is recommended. This yields dependence factors of 0.257 for Cowichan River and Cowichan Bay, and 0.303 for Koksilah River and Cowichan Bay. A threshold of 90% ensures a factor of safety while increasing the accuracy of model results of flood levels.

7 REFERENCES

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APPENDIX E: HYDRAULIC MODELLING

1 INTRODUCTION

A fully 2-dimensional (2D) hydraulic model was developed to simulate different flood scenarios in the Cowichan-Koksilah river system. This document describes the model development, calibration and validation, and includes model results for different base design scenarios, dike breach scenarios, and mitigation scenarios.

Including this brief introduction, this document consists of 7 sections. Section 2 SOFTWARE SELECTION presents the main criteria considered in model selection. Section 3 MODEL DEVELOPMENT provides an overview of the development process for the three models, including model domain, geometry, roughness coefficients, structures, and boundary conditions. Section 4 MODEL CALIBRATION AND VALIDATION summarizes the model calibration and validation process, including the events used and calibration targets. Section 5 BASE RUNS presents the list of model base runs and their boundary conditions, and includes a series of plots, tables, and maps summarizing the results. 6 DIKE BREACH MODELLING describes the selected breach locations and summarizes the results. Section 7 MODELLING OF MITIGATION OPTIONS summarizes the mitigation options assessed and their results.

2 SOFTWARE SELECTION

Selecting the appropriate hydraulic model is an important decision. Several hydraulic modelling software packages have a proven track record for flood hazard and floodplain mapping projects on large rivers and have been widely adopted by regulatory agencies and government organizations. Although several software packages were initially considered, the decision to select HEC-RAS 5.0.7 was based mainly on the following reasons:

- HEC-RAS is an open-source software, and it has a large user base with ample support material readily available.
- It allows the integration of 1D and 2D models. Despite the models not being coupled at this time, this opens the possibility for a model integration should it become advantageous to merge the different models for future applications.
- HEC-RAS has a superior graphic user interface than other free packages such as TELEMAC 2D, making it easier to set up, modify and run model simulations.
- HEC-RAS 2D's modelling technique of combining a large cell with underlying terrain allows for readily simulating the interaction of overland flow with topographic controls on the floodplain such as roads or dikes. Traditional models, which use one terrain elevation per cell, require a mesh with a greater number of elements to produce similar effects.
- 1D equations can be incorporated into 2D models, for hydraulic structures such as bridges and weirs.
- HEC-RAS allows the user to manage the inventory of structures within the program's working environment.

The software selection process is further described in the Software Selection memo, previously provided to the CVRD.

3 MODEL DEVELOPMENT

Hydraulic model development involves:

1) determining the required model domain;
2) developing a model DEM and a model mesh for 2D models or a series of cross section geometry for 1D models;
3) adding special hydraulic structures such as dikes;
4) applying roughness coefficients for the mesh or cross sections; and,
5) applying boundary conditions.

These steps are described in the following sub-sections.

3.1 Model Domain

The model domain covers the lower Cowichan and Koksilah Rivers and their floodplains. It also includes Somenos River and Somenos Lake, which provide backwater storage. The general model layout and chainage (river kilometres increasing in the upstream direction) are shown in Figure 3-1.

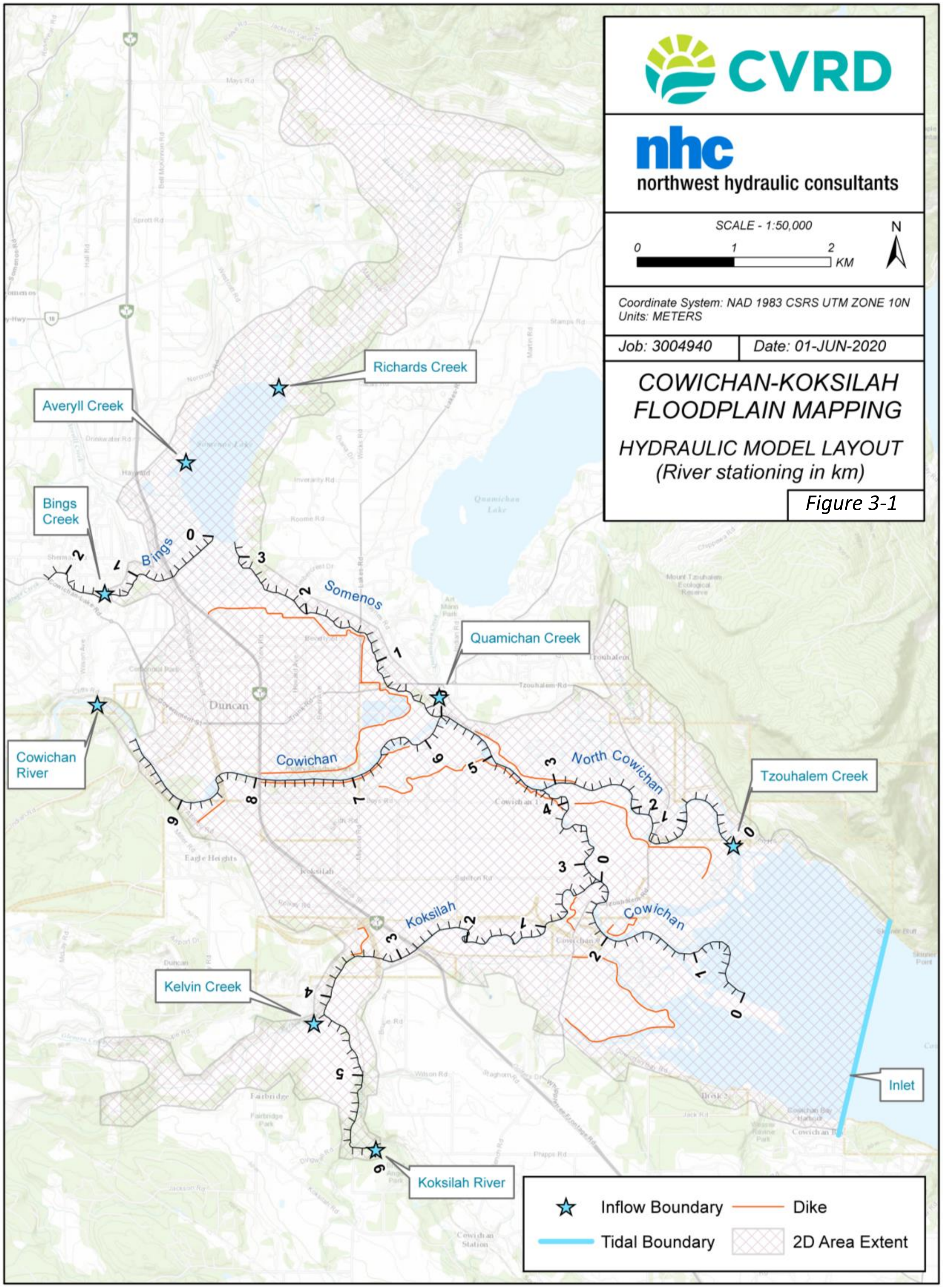

Figure 3-1: Model layout

Model DEM

The Digital Elevation Model (DEM) forms the main building block of the 2D model. It constitutes a seamless representation of the Cowichan-Koksilah floodplain and channel topography suitable for 2D numerical modelling. The DEM combines LiDAR data to represent the overbank terrain and bathymetric surveys to characterize the lower Cowichan, lower Koksilah and Somenos Rivers bottom elevations as well as bathymetric data of the Somenos Lake and the bay area. The DEM has a 0.5 m cell size.

The DEM was used a variety of data sources, shown in Figure 3-2.

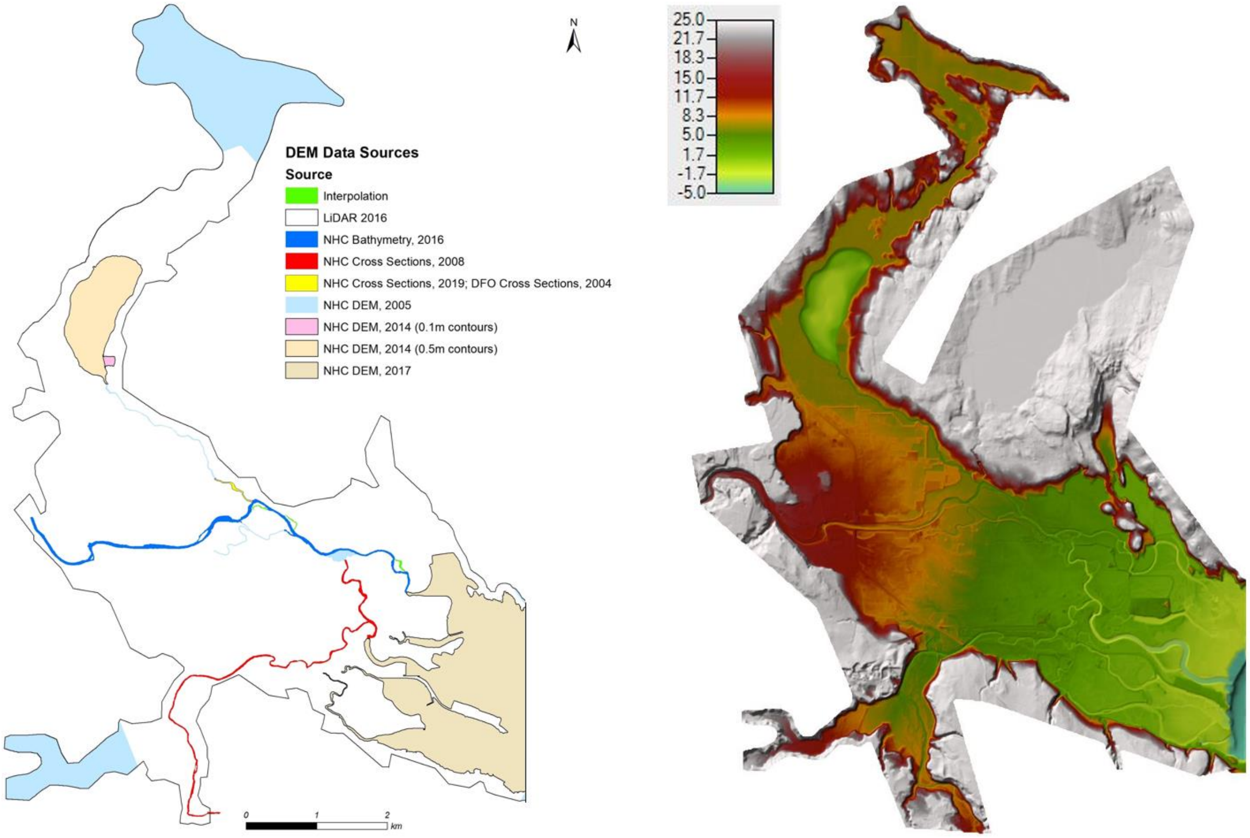

Figure 3-2: DEM data sources (left) and final product (right)

Model Mesh

The 2D mesh was generated in the RAS Mapper module of HEC-RAS using variable cell resolutions. Cell sizes were selected to optimize model result accuracy and computational times based on NHC's experience with similar models elsewhere. Breaklines were used extensively to capture the effects of all major raised roads and railroad embankments, natural high ground, and other topographic controls that could obstruct and direct overbank flows across the floodplain. Elevation data was extracted from the model DEM. The final model has over 30,000 cells.

Figure 3-3 summarizes the model geometry creation process including DEM, mesh, and roughness layers. It shows sample cell resolutions and breaklines. The roughness value selection is further described in Section 3.3.

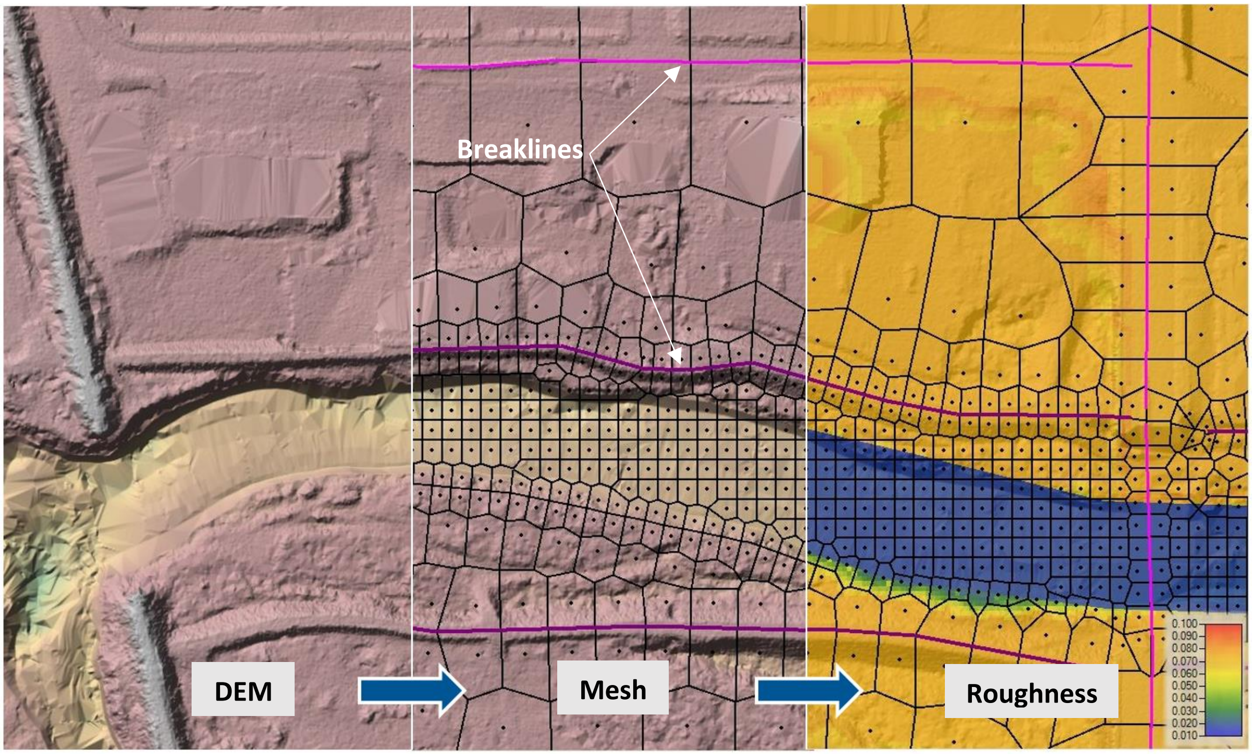

Figure 3-3: **Model geometry creation process. Left: DEM. Middle: Mesh showing different cell resolutions. Right: Mesh with underlying roughness values**

3.2 Hydraulic Structures

Dikes

A total of 12 primary dikes and 7 secondary dikes were included in the model (see Table 3-1). DEM data was used to enter the dike crest profiles.

Table 3-1: Summary of dikes

	No.	Flood Dike	River	Bank	Length (m)	Date	Jurisdiction
Primary Dikes	1	Cowichan Phase 2-Allenby	Cowichan	Left	160	2015	CT
	2	Cowichan Phase 2-Dike A	Cowichan	Left	1,020	2015	CT
	3	Cowichan Phase 2-Dike B	Cowichan	Left	420	2015	CT
	4	Cowichan (City of Duncan) Dike	Cowichan	Left		1987	MNC
	5	JUB Lagoon Dike	Cowichan	Left	1,240	2011	JUB
	6	Lakes Road/Beverly St. Dike	Somenos	Right	2,365	2012/14	MNC
	7	Cowichan Phase 2-Dike D	Cowichan	Right	380	2015	CT
	8	Cowichan South Side Dike	Cowichan	Right	1,000	1983	MNC
	9	Cowichan South Side Spur Dike	Cowichan	Right	600	2014	CT
	10	Connector Dike	Cowichan	Right	200	2014	CT
	11	Mission Road Dike	Cowichan	Right	1,060	2014	CT
	12	Hatchery Dike	Cowichan	Right	790	2014	CT
Secondary Dikes	1	Quamichan Dike	N. Cowichan	Right	1,270	-	CT
	2	Tooshley Island Dike	N. Cowichan	Right	1,050	-	CT
	3	Blackley Farm Dike	N. Cowichan	Right	930	-	None
	4	Rodenbush Dike	Koksilah	Left	590	-	Ducks Unlimited
	5	Dinsdale Farm Dike	Cowichan Bay			-	Ducks Unlimited
	6	Clem Clem Dike	Koksilah	Right	470	-	CT
	7	Koksilah Village Dike	Koksilah	Left	470	-	

Bridges

Bridges were reflected directly in the model DEM and not added as ‘bridge’ elements. Table 3-2 summarizes the bridges in the model domain, Table 3-3 indicates the amount of clearance or surcharge at each bridge, and Figure 3-4 shows their locations.

Table 3-2: Summary of bridges

ID	Bridge/Road	Watercourse	Station (m)	Overtopping during Present Day flow conditions?	Overtopping during CC2100 flow conditions?
1	Lakes Road	Somenos Creek	1380	no	yes
2	Quamichan Park Road	Somenos Creek	1270	yes	yes
3	Tzouhalem Road near Beveryly Street Dike Trail	Somenos Creek	700	yes	yes
4	Tzouhalem Road south of Joe Road	Cowichan River north branch	1490	no	no
5	Highway 1 north of Boys Road	Cowichan River	7970	no	no
6	Railroad north of Boys Road	Cowichan River	8400	no	no
7	Allenby Road	Cowichan River	9510	no	no
8	Railroad south of Miler Road	Koksilah River	3270	no	no
9	Highway 1 at Cowichan Bay Road	Koksilah River	2810	no	no
10	Tzouhalem Road south of Wescan Terminal Road	Koksilah River north side channel	-	no	no
11	Cowichan Bay Road (north-south) at Robert Service Memorial Park	Koksilah River south side channel	-	no	no
12	Cowichan Bay Road (east-west) west of name change to Lochmanetz Road	Koksilah River east side channel	-	no	no
13	Tzouhalem Road west of Samuel Road	Cowichan River south branch	2410	no	no
14	Tzouhalem Road north of Westcan Terminal Road	Koksilah River north-north side channel	-	no	yes
15	Cowichan Bay Road (east-west) east of Ryan Road	Koksilah River west side channel	-	yes	yes
16	Highway 1 at Watt's Walk	Bings Creek	600	no	yes
17	Railroad near Watt's Walk	Bings Creek	640	no	yes
18	Canada Avenue	Bings Creek	660	yes	yes
19	New Koksilah Bridge	Koksilah River	990	no	no

Table 3-3: Summary of bridge surcharge and clearance conditions

ID	Bridge/Road	Watercourse	Bridge Low Cord (m)	Present Day flow conditions			CC2100 flow conditions		
				Water Level at bridge (m)	surcharge (m)	Clearance (m)	Water Level at bridge (m)	surcharge (m)	Clearance (m)
1	Lakes Road	Somenos Creek	7.87	8.18	0.31	0	8.44	0.57	0
2	Quamichan Park Road	Somenos Creek	8.8*	8.16	0*	0.64*	8.4	0*	0.4*
3	Tzouhalem Road near Beverly Street Dike Trail	Somenos Creek	7.67	8.15	0.48	0	8.4	0.73	0
4	Tzouhalem Road south of Joe Road	Cowichan River north branch	4.96	3.33	0	1.63	3.71	0	1.25
5	Highway 1 north of Boys Road	Cowichan River	13.57	12.49	0	1.08	12.86	0	0.71
6	Railroad north of Boys Road	Cowichan River	16.37	14.15	0	2.22	14.61	0	1.76
7	Allenby Road	Cowichan River	16.78	16.47	0	0.31	16.93	0.15	0
8	Railroad south of Miler Road	Koksilah River	7.77	7.54	0	0.23	7.85	0.08	0
9	Highway 1 at Cowichan Bay Road	Koksilah River	7.87	6.22	0	1.65	6.36	0	1.51
10	Tzouhalem Road south of Wescan Terminal Road	Koksilah River north side channel	3.1*	3.47	0.4*	0*	3.69	0.6*	0*
11	Cowichan Bay Road (north-south) at Robert Service Memorial Park	Koksilah River south side channel	2.7*	2.47	0*	0.2*	3.27	0.6*	0*
12	Cowichan Bay Road (east-west) west of name change to Lochmanetz Road	Koksilah River east side channel	3.8*	4.11	0.3*	0*	4.19	0.4*	0*
13	Tzouhalem Road west of Samuel Road	Cowichan River south branch	3.66	2.83	0	0.83	3.45	0	0.21
14	Tzouhalem Road north of Westcan Terminal Road	Koksilah River north-north side channel	3.0*	3.14	0.1*	0*	3.61	0.6*	0*
15	Cowichan Bay Road (east-west) east of Ryan Road	Koksilah River west side channel	3.5*	4.83	1.3*	0*	4.9	1.4*	0*
16	Highway 1 at Watt's Walk	Bings Creek	7.65	8.61	0.96	0	8.8	1.15	0
17	Railroad near Watt's Walk	Bings Creek	8.57	8.82	0.25	0	8.97	0.40	0
18	Canada Avenue	Bings Creek	7.56	8.92	1.36	0	9.05	1.49	0
19	New Koksilah Bridge	Koksilah River	5.60	3.79	0	1.81	3.94	0	1.66

Note: * Bridge low chord survey data unavailable. Rough estimates provided for low chord, surcharge, and clearance values based on typical bridge dimensions.

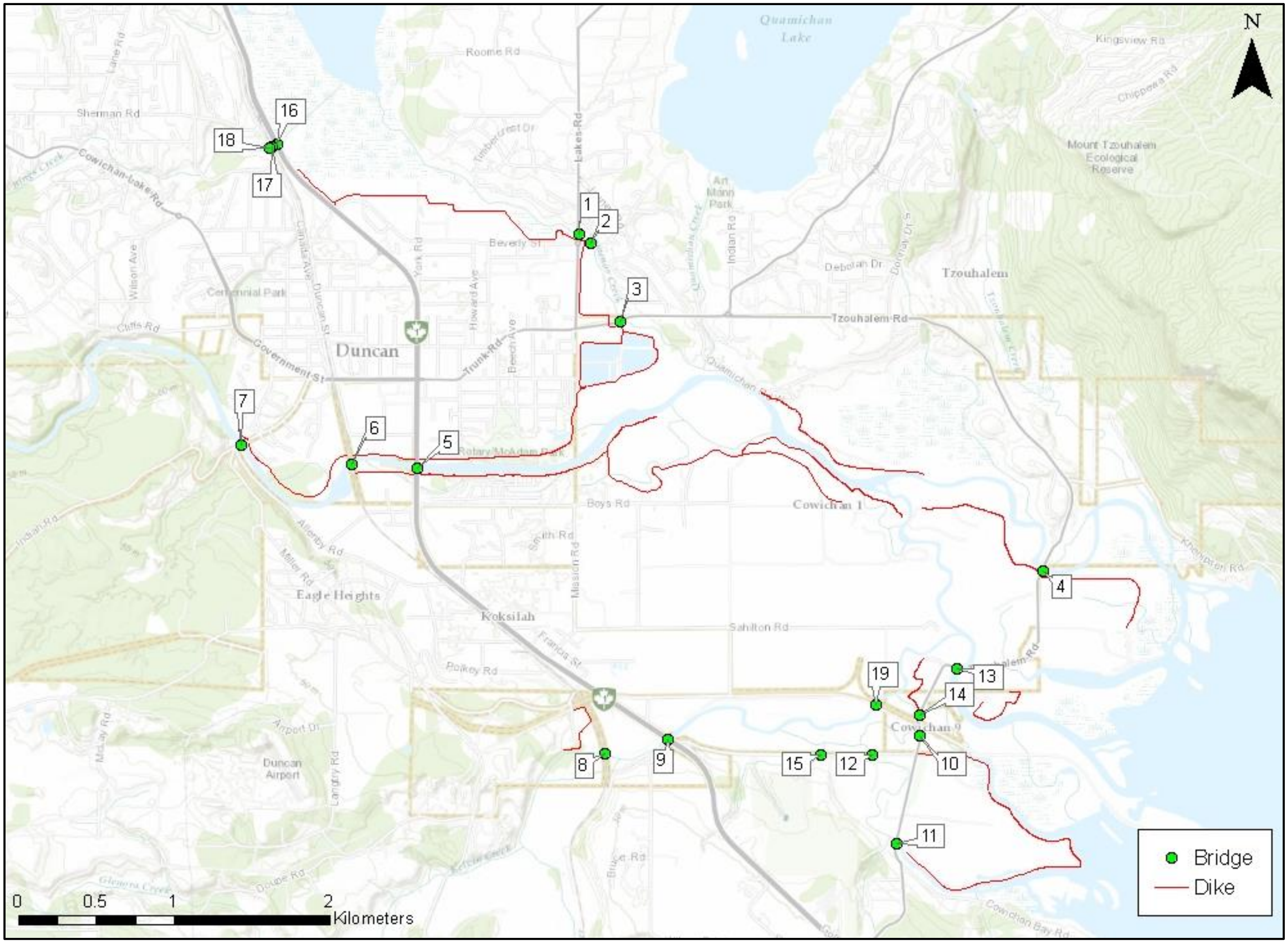

Figure 3-4: Bridge locations

3.3 Roughness Coefficients

Typically, initial roughness coefficients based on river characteristics, land use and ground cover are assigned and then refined during the calibration process. The roughness, represented by Manning's n values, are the primary parameter used for calibration of the 2D model.

Following the model calibration (described in Section 4) the values listed in Table 3-4 were adopted for the channel. The variation in roughness values is generally representative of changes in channel morphology, slope, and bed material.

Table 3-4: Final calibrated in-channel roughness coefficients

Watercourse	From Station (km)	To Station (km)	Manning's Roughness Coefficient (n)
Cowichan River	0	4.0	0.022
	4.0	4.3	0.08
	4.3	9.8	0.025
Cowichan River North Branch	0	1.42	0.03
	1.42	1.45	0.08
	1.45	3.1	0.03
Koksilah River	0	0.9	0.03
	0.9	1.0	0.08
	1.0	1.3	0.03
	1.3	1.4	0.08
	1.4	8.7	0.03
Somenos River	0	0.45	0.025
	0.45	3.11	0.035
	3.11	3.16	0.022

Ortho imagery was used to identify different land use areas. A total of six land cover categories were identified for the purpose of representing overbank roughness in the model, as indicated in Table 3-5.

Table 3-5 Overbank roughness coefficients

Reach	Manning's Roughness Coefficient (n)
Agricultural	0.036
Forest	0.065
Rural	0.065
Urban	0.072
Lake or ponded water	0.022
Wetlands	0.032

Modelled water levels are typically less sensitive to overbank roughness than channel roughness because channels typically convey most of the flood flow. There is no reliable calibration information for overbank flows. Some variations in depth may be expected if the overbank estimated roughness values are not accurate, but the overall flood extents are expected to change very little. Within the dike channel portion, the volume of overtopping flow is the primary determinant of the extent and depths of flooding, not floodplain roughness.

4 MODEL CALIBRATION AND VALIDATION

Calibration and validation of hydraulic models are crucial steps in establishing confidence in the ability of a model to reliably and accurately simulate a range of flow conditions. Calibration involves the refinement of model parameters within physically plausible limits in order to best match simulated results to those observed in the field for one or more flow events. Hydraulic model calibration parameters include most importantly channel roughness, and may also include modifying floodplain roughness, mesh cell size, weir coefficients, and time steps. Validation involves holding the calibrated parameters constant and simulating a flood that was not used in the calibration process. The calibration process involved dozens of intermediate runs, whose results are not presented, varying model parameters in various reaches to optimize the results. A combined calibration/validation approach was applied using five different historic flood events. Under this approach, model parameters are adjusted based on results from all the events considered.

4.1 Calibration/Validation Flood Events

Calibration/validation events should ideally approach the magnitude of the design flood. However, that information is unavailable for the Cowichan-Koksilah river system. It is also important that the terrain conditions during the selected events be similar to those reflected in the model geometry.

The model was calibrated and validated using the 2019 and 2020 freshet events, as indicated in Table 4-1. These storm events were selected as they were large flow events that occurred close to when the channel bathymetry data was collected. Moreover, the 2020 freshet is the largest event in recent years with an approximate return period or 30 years on both Cowichan and Koksilah rivers. The model was calibrated using a series of water level gauges in the study area as outlined the following section.

Table 4-1: Summary of calibration/validation flood events

Event	Cowichan River near Duncan (08HA011)			Koksilah River at Cowichan Station (08HA003)		
	Date of Peak	Instantaneous Flow (m^3/s)	Approx. Return Period	Date of Peak	Instantaneous Flow (m^3/s)	Approx. Return Period
Jan 2019	Jan 04	427	7	Jan 04	296	8
Feb 2020	Feb 01	564	27	Feb 01	382	30

4.2 Available Data

Data collected at several hydrometric gauges were used for calibration/validation of the model. Figure 4-1 shows the location of the different gauges.

Table 4-2 provides a summary of the water level data available at each gauge for calibration/validation of the model.

Table 4-2: Summary of available water level data for calibration/validation

Watercourse	Gauge	Station (m)	Time Step	Operator	Storm Events	
					Jan 2019	Feb 2020
Cowichan	Cowichan WSC	9540	Hourly	WSC	y	y
	JUB	6400	Hourly	NHC	y	y
	Clem Clem	2410	5 min	NHC	y	y
	Northside of Causeway	1270	5 min	NHC	y	-
Cowichan Estuary	Southside of Causeway	1150	5 min	NHC	y	-
Somenos	Beverly Pump Sta	1460	Hourly	DNC	y	y
	Lakes Rd Pump Sta	1060	Hourly	DNC	y	y
	Quamichan	160	5 min	NHC	y	y
Koksilah	Koksilah Highway 1	2810	5 min	KWL	y	-
Bings	Canada Ave		Hourly	DNC	y	y

Note: Hourly discharge data from WSC gauge 08HA011 was used to model inflows for Cowichan River, gauge 08HA003 for Koksilah River, and gauge 08HA016 for Bings Creek.

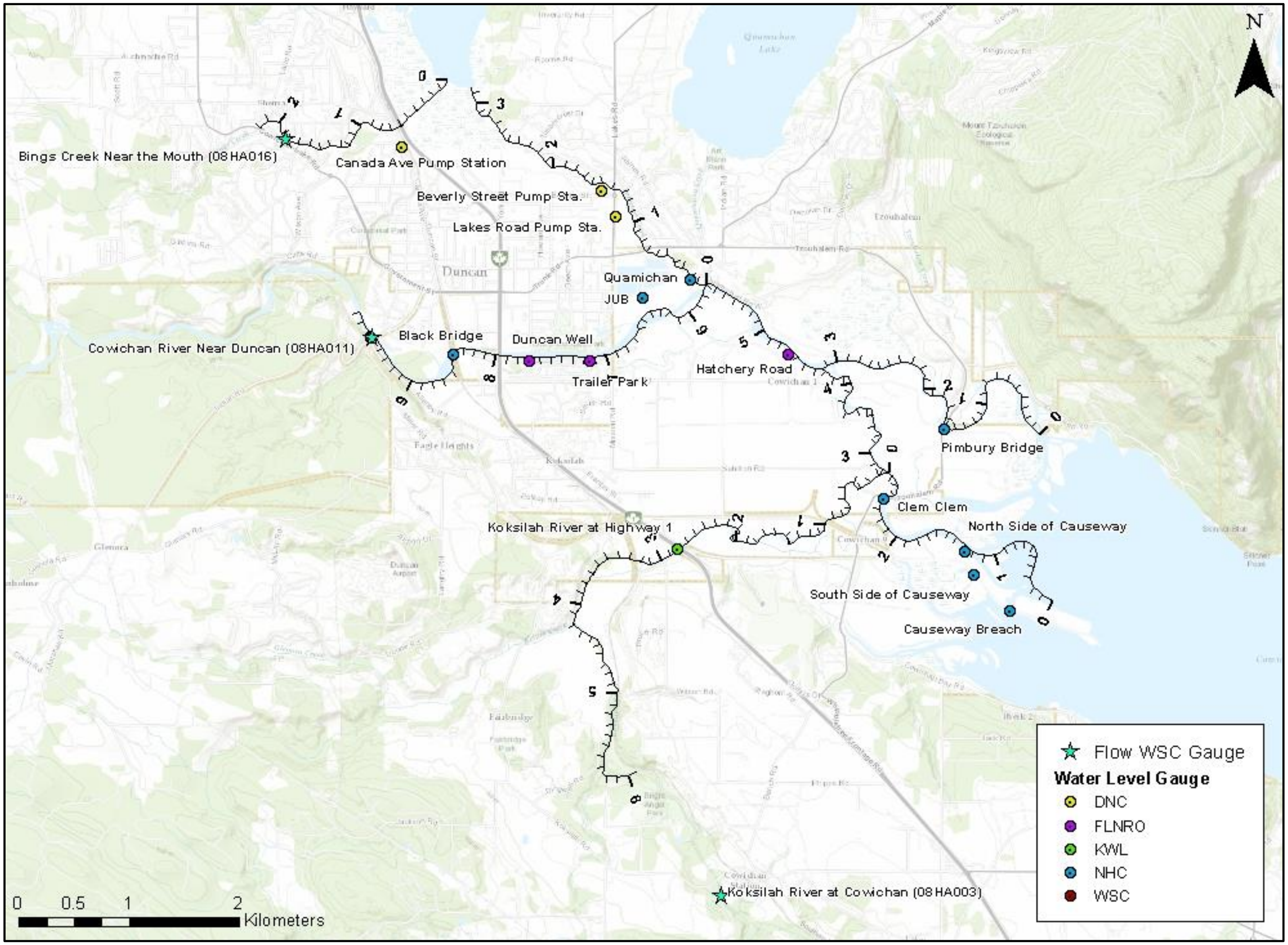

Figure 4-1: Available gauges for calibration and validation (river chainage in km)

4.3 Model Calibration/Validation

Peak Water Levels

Ideally, an agreement of ±0.15 m between observed and simulated water levels was sought. This degree of accuracy was not always possible to achieve mainly due to the dynamic nature of the Cowichan-Koksilah river system, with log jams present at different locations for each flood event and periodic gravel removal works taking place. Other sources of uncertainty correspond to the relative coarseness of the river bathymetry; potential geometric changes that may occur during a flood; any localized features not captured in the model; and measurement uncertainties associated to the observed data. Calibration results for peak flows are summarized in Table 4-3. The results are deemed acceptable. Below are key calibration results for each event, including the overall Root Mean Square Error (RMSE) which is the standard deviation of errors.

- Jan 2019: 7 out of 10 locations within the target and with an overall RMSE of 0.18 m.
- Feb 2020: 4 out of 7 locations within the target and with an overall RMSE of 0.18 m.

A difference plot of observed and modelled values is shown in Figure 4-2 for Cowichan River.

The observed water levels and modelled long profiles along Cowichan River, for the Nov 2017 and Feb 2020 events, are shown in Figure 4-3.

Table 4-3: Simulated and observed water levels at study gauges for calibration/validation events. Peak Water Level in m (CGVD20

			January 2019			February 2020		
Watercourse	Gauge	Station (m)	Sim	Obs	Diff	Sim	Obs	Diff
Cowichan	Cowichan WSC	9540	15.28	15.14	0.14	15.84	15.71	0.13
	JUB	6400	8.33	8.26	0.07	8.57	8.49	0.07
	Clem Clem	2410	2.40	2.30	0.10	2.55	2.59	-0.04
	Northside of Causeway	1270	2.07	2.15	-0.08	-	-	-
Cowichan Estuary	Southside of Causeway	1150	2.07	2.08	-0.02	-	-	-
Somenos	Beverly Pump Sta	1460	7.60	7.64	-0.04	7.91	7.94	-0.03
	Lakes Rd Pump Sta	1060	7.54	7.39	0.15	7.84	7.97	-0.13
	Quamichan	160	7.46	7.62	-0.16	7.75	7.95	-0.20
Koksilah	Koksilah Highway 1	2810	5.80	6.14	-0.33			
				RMSE	0.19		**RMSE**	0.13

Note: The difference (diff) is calculated as simulated (sim) minus observed (obs).

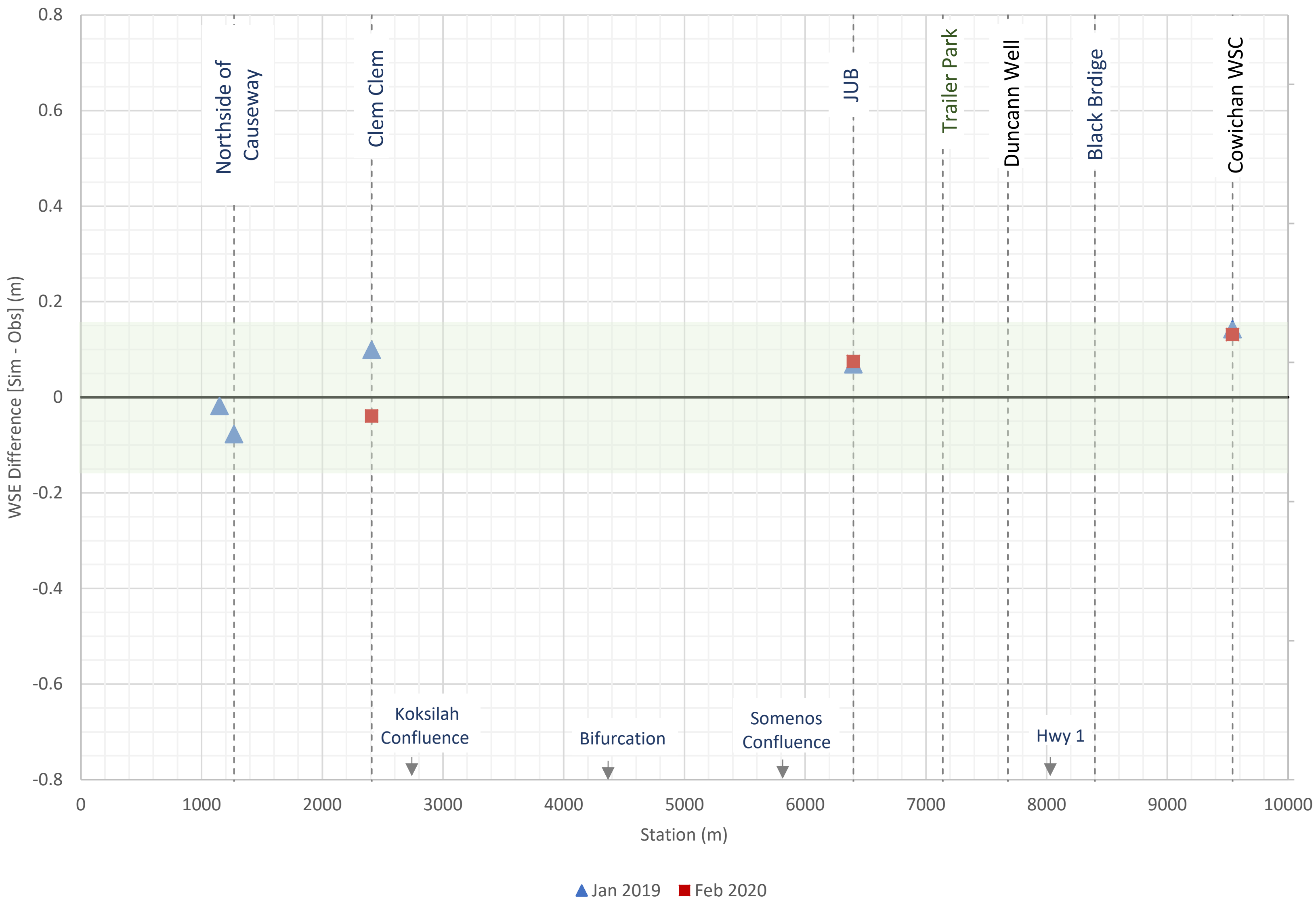

Figure 4-2: Calibration/validation difference plot – Cowichan River

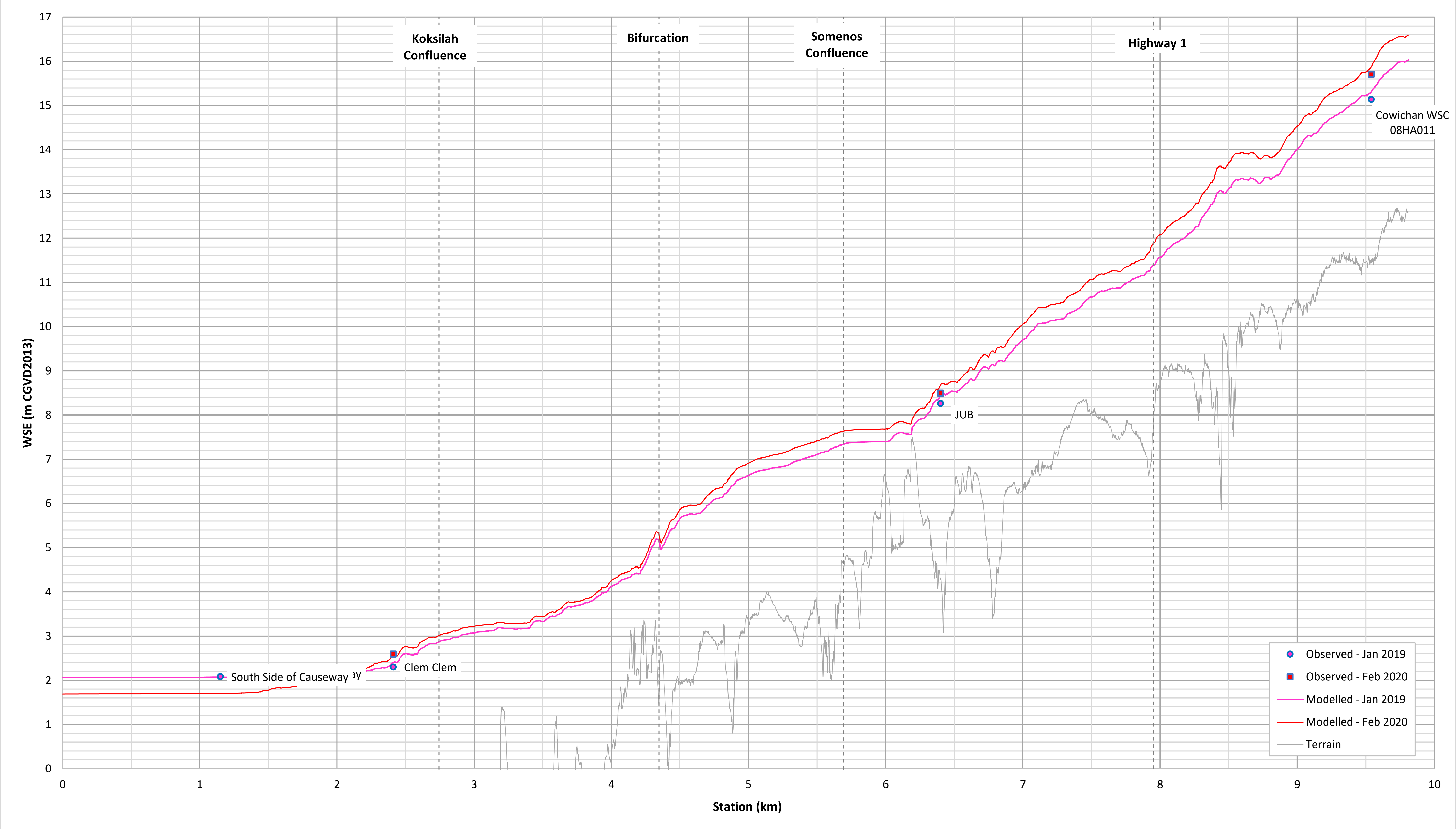

Figure 4-3: Calibration/validation water surface elevation profiles – Cowichan River

Stage Hydrographs

In addition to peak flood levels, calibration efforts considered stage hydrographs through the simulation period. A comparison of time series of the modelled and observed water levels at selected gauges, is provided in Figure 4-5.

Rating Curve at Cowichan WSC gauge 08HA011

Figure 4-4 shows the modelled and measured rating curves at the Cowichan WSC gauge 08HA011. As expected, based on the previous peak water level results, the rating curves show that the model is generally overestimating water levels for flows under 400 m^3/s, but is accurately representing the water levels for higher flows.

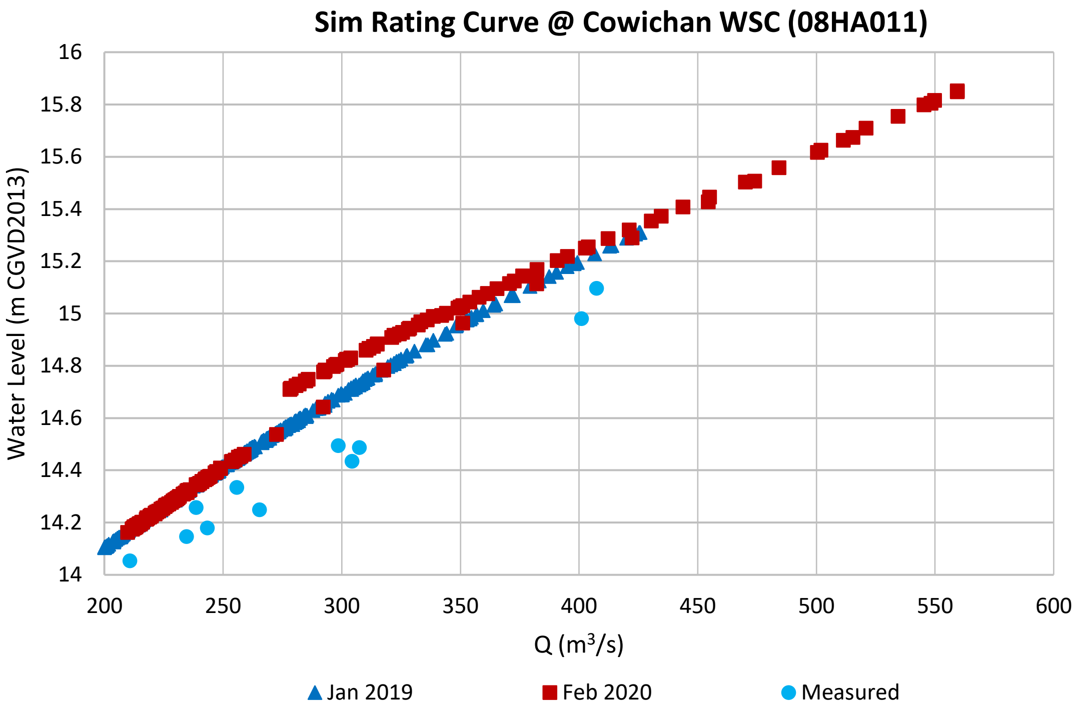

Figure 4-4: Modelled rating curve at Cowichan WSC gauge 08HA011 and discrete flow measurements

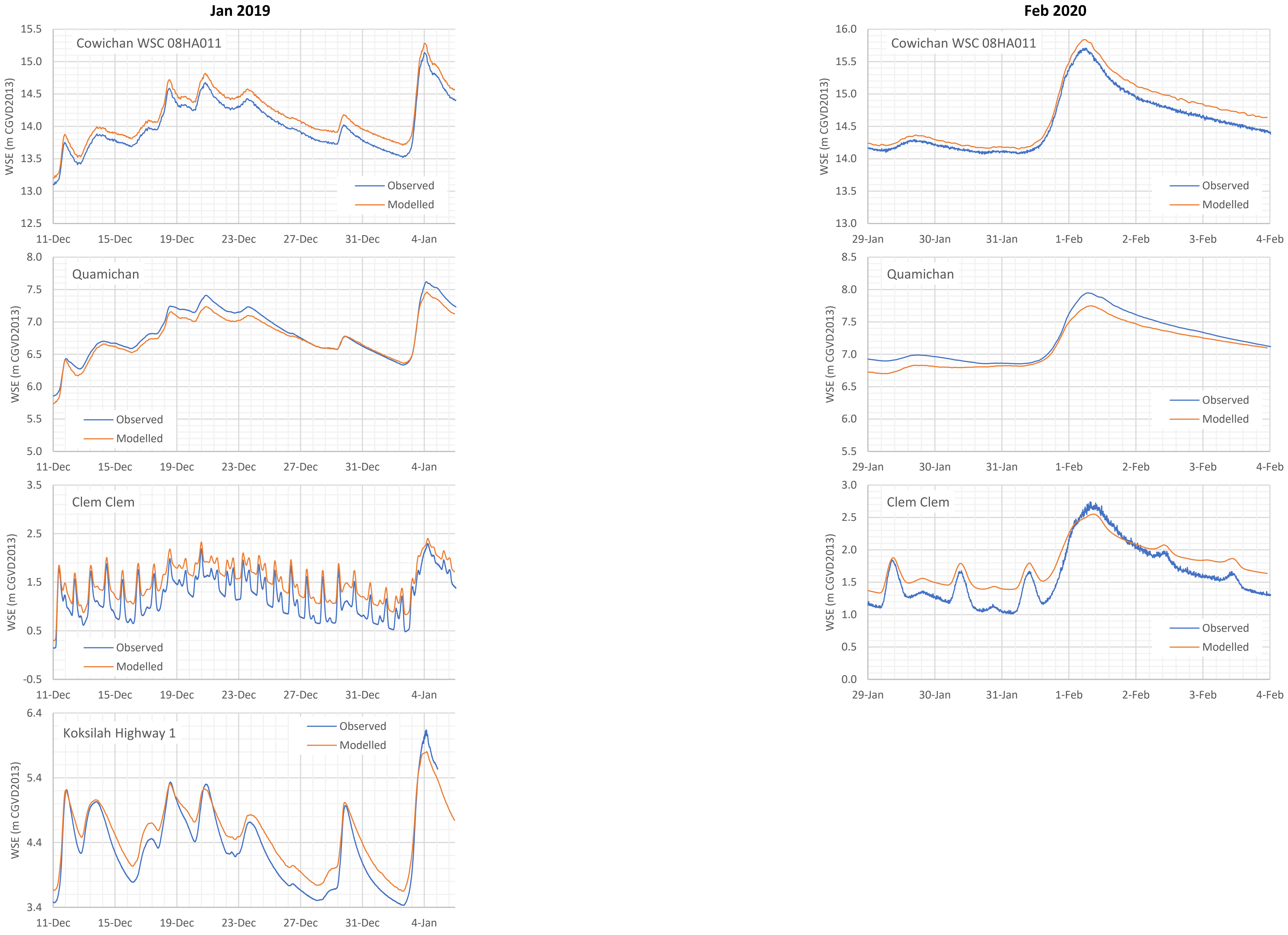

Figure 4-5: Stage hydrograph at representative gauges – Jan 2019, Feb 2020

4.4 Model Limitations and Uncertainty

Key model limitations and sources of uncertainty are described below.

- Uncertainty associated with inflows due to different rating curves being used at the Cowichan WSC gauge 08HA011, for different flood years. Review of the rating curve for 08HA011 Cowichan River near Duncan, shows that no discharge measurements have been made between 300-400 m3/s. There also appears to be different rating curves for different years. The stage discharge relationship for 2015-2019 is lower than the stage discharge relationship for 2020. This difference is most pronounced for discharges above 250 m^3/s. For discharges around 400 m^3/s the difference in the stage discharge relationship for 2019 and 2020 is up to 40 cm. Model calibration scenarios simulate Cowichan River flows that range from 200-564 m3/s for the 2019 and 2020 flood events. The uncertainty presented by the variation in rating curve for calibration scenarios will get translated into uncertainty in modelled flood levels.
- Uncertainty associated with observed water levels at hydrometric gauges. As described in Appendix A, some hydrometric stations were not accompanied by metadata and only minimal quality assurance review was able to be completed.
- Log jams have occurred at different locations during the calibration/validation events. In general, log jams slow down the flow and increase the water surface elevation upstream of the log jam location. To represent these conditions, specific log jam locations would have to be modelled for each historic event. However, because the model is a fixed-bed model, all calibration/validation events were run using the same bathymetry and roughness values. Events whose conditions differ largely from the conditions reflected in the model geometry, result in higher errors.
- Gravel removals have also occurred in different years at various locations. Generally, gravel removals result in lower water levels near the gravel removal location. Events with gravel removal conditions significantly different from the conditions reflected in the model geometry, would show higher errors.

5 BASE RUNS

Present day design flow as well as future climate change conditions were simulated. Design flows correspond to the 200-year return period flow for each watercourse. For the climate change (CC) year 2100, a 20% increase was added with respect to the Present Day design flows. For the tidal boundary, a 10-year tide level was considered for the Present Day scenario and a sea level rise allowance of 1 m was added to the CC 2100 ocean level. Additional information is provided in Appendix A.

All dikes were assumed to remain intact throughout the entire simulation period for the base runs. Results for dike failure simulations are presented in Section 6.

Table 5-1: Model base run scenarios

Scenario	Upstream Boundary - Inflows		Downstream Boundary - Ocean Levels	
	Return period	% increase in flood discharge for climate change	Return Period	Sea level rise (m)
Present Day	1:200-year	0	1:10-year	0 m
Climate Change 2100	1:200-year	20	1:10-year	1 m

Figure 5-1 and Figure 5-2 show max. flood depth maps for the Climate Change 2100 and the Present Day base scenarios, respectively. Figure 5-3 and Figure 5-4 include plots of the simulated profiles along Cowichan River and Koksilah River, respectively.

Figure 5-5 indicates the dike alignment and stationing for primary dikes. Dike segments along the same riverbank were combined to simplify result extraction. Figure 5-6 to Figure 5-7 Figure 5-8 show the water level profile along primary dikes, for the Climate Change 2100 flood event.

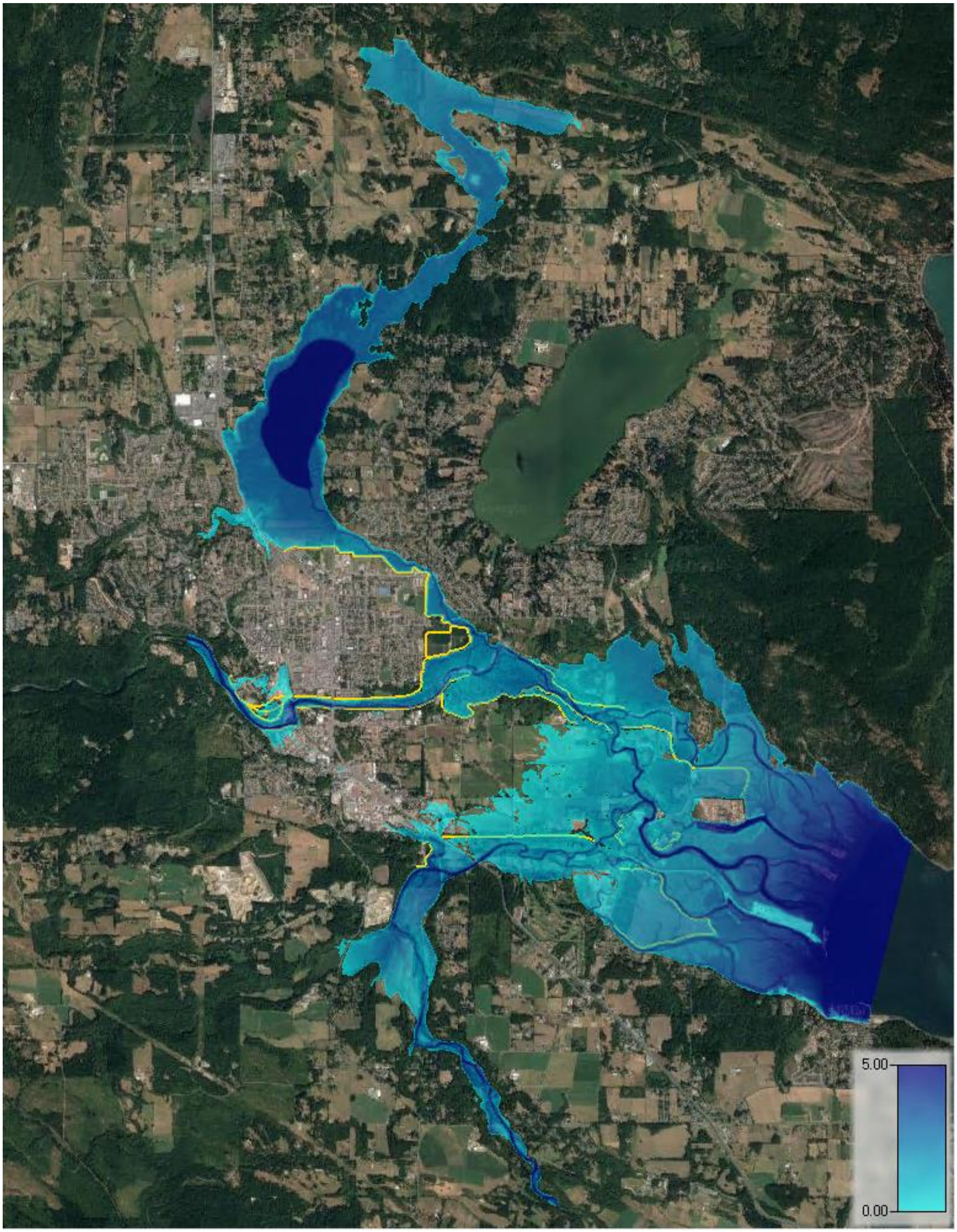

Figure 5-1: Climate Change year 2100 flood - Max Flood Depth (m)

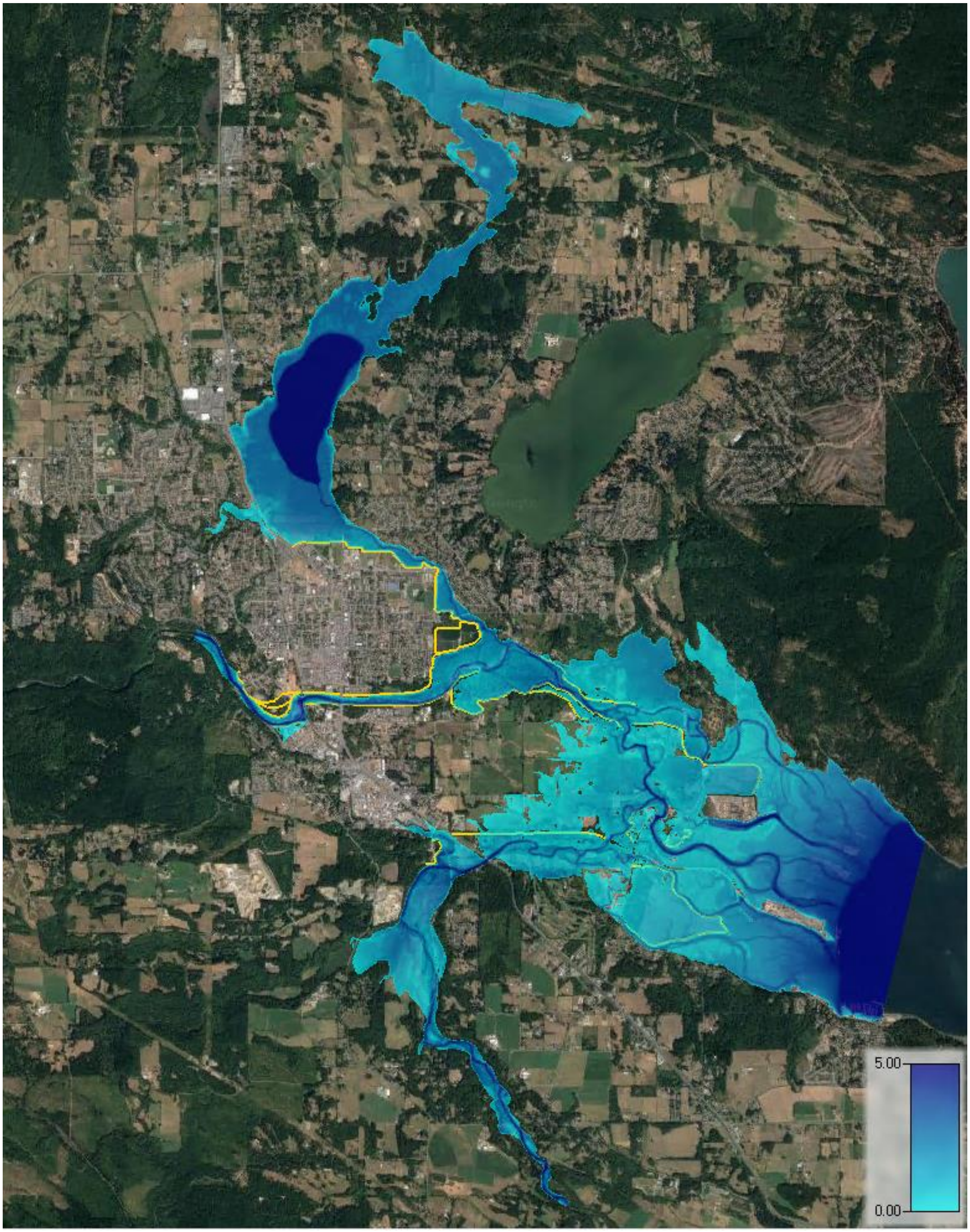

Figure 5-2: Present Day flood - Max Flood Depth (m)

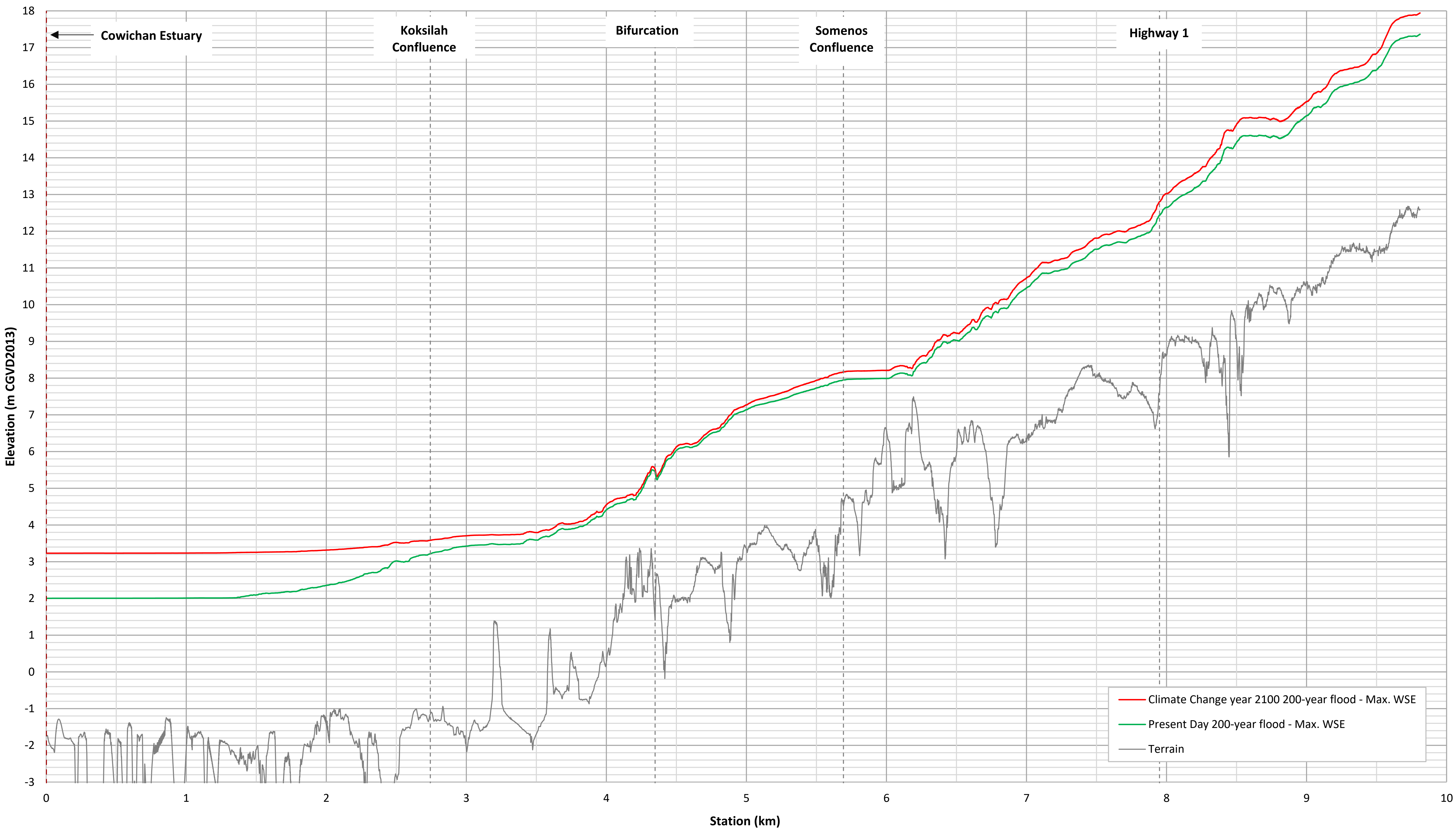

Figure 5-3: Base run water surface elevation profiles – Cowichan River

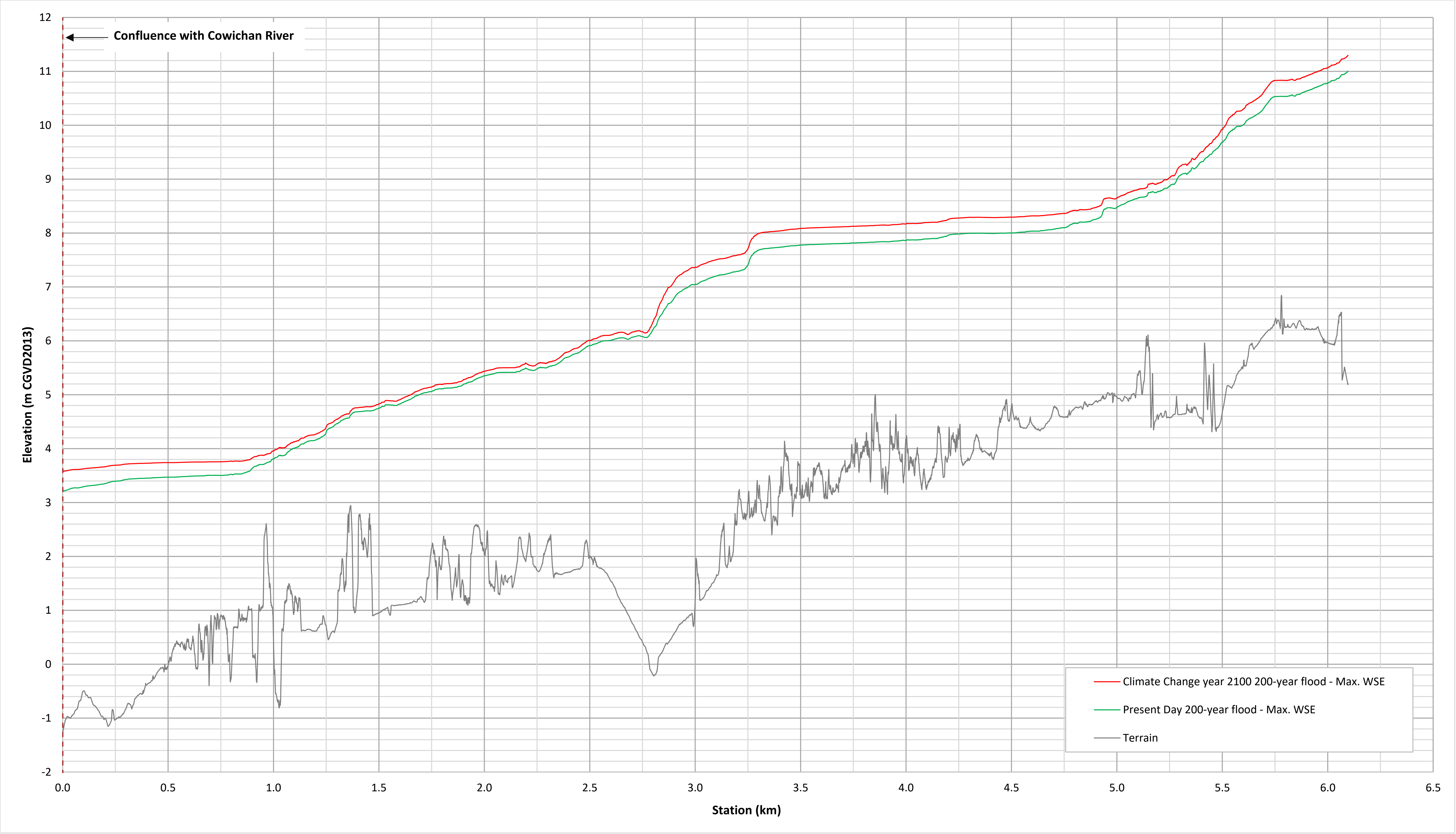

Figure 5-4: Base run water surface elevation profiles – Koksilah River

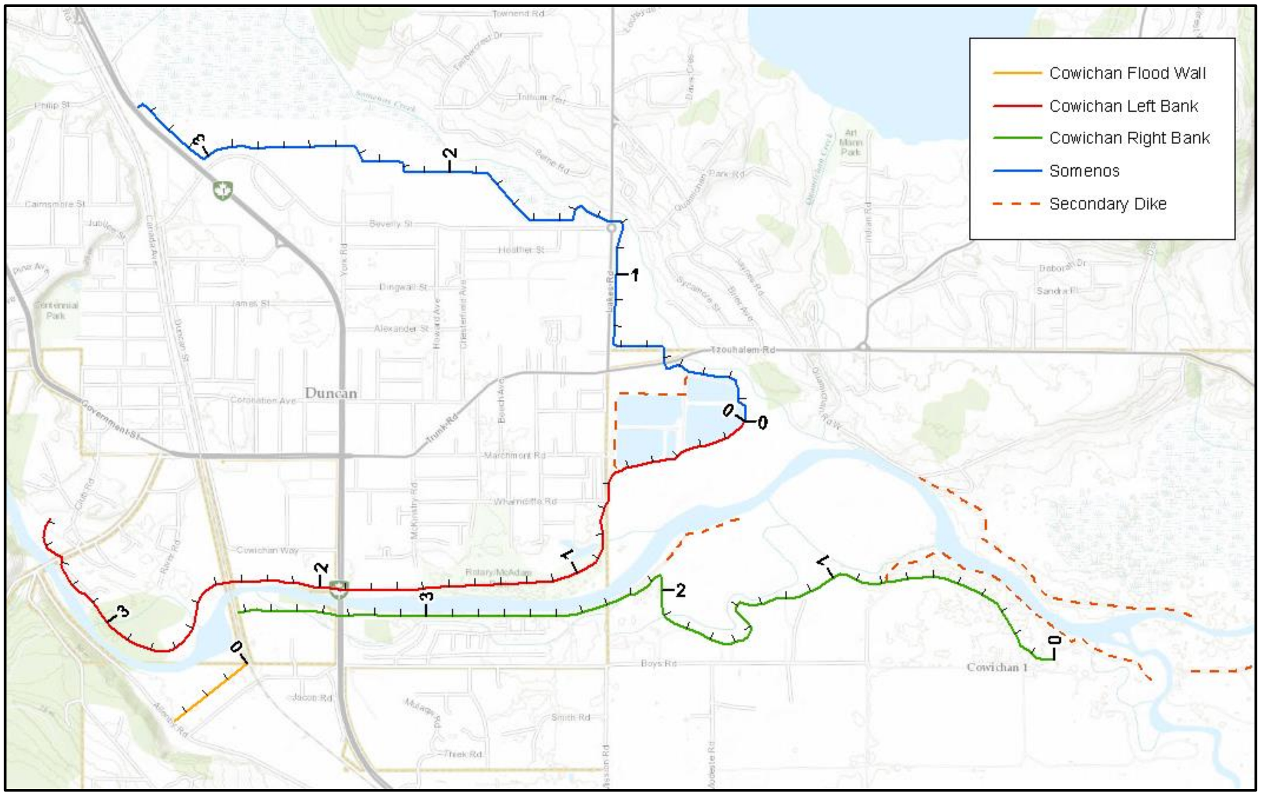

Figure 5-5: Dike alignment and stationing in km

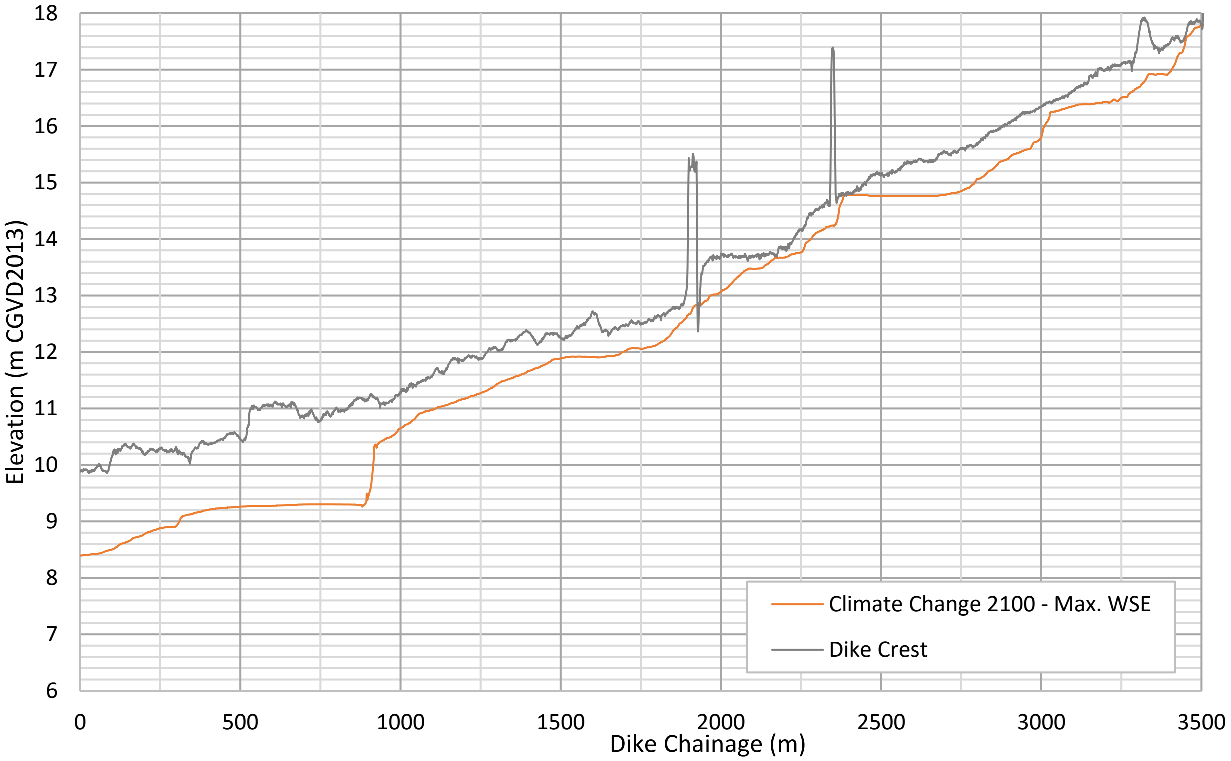

Figure 5-6: Cowichan Left Bank Dike crest and flood profile comparison

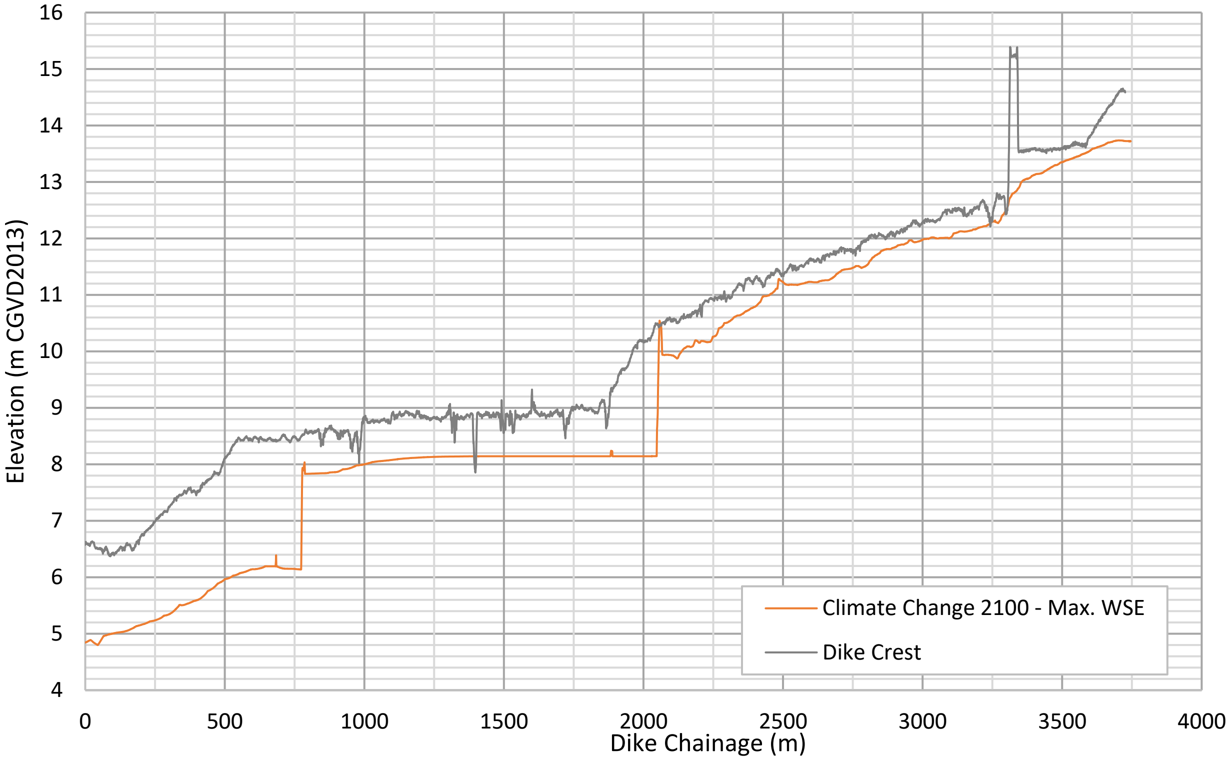

Figure 5-7: Cowichan Right Bank Dike crest and flood profile comparison

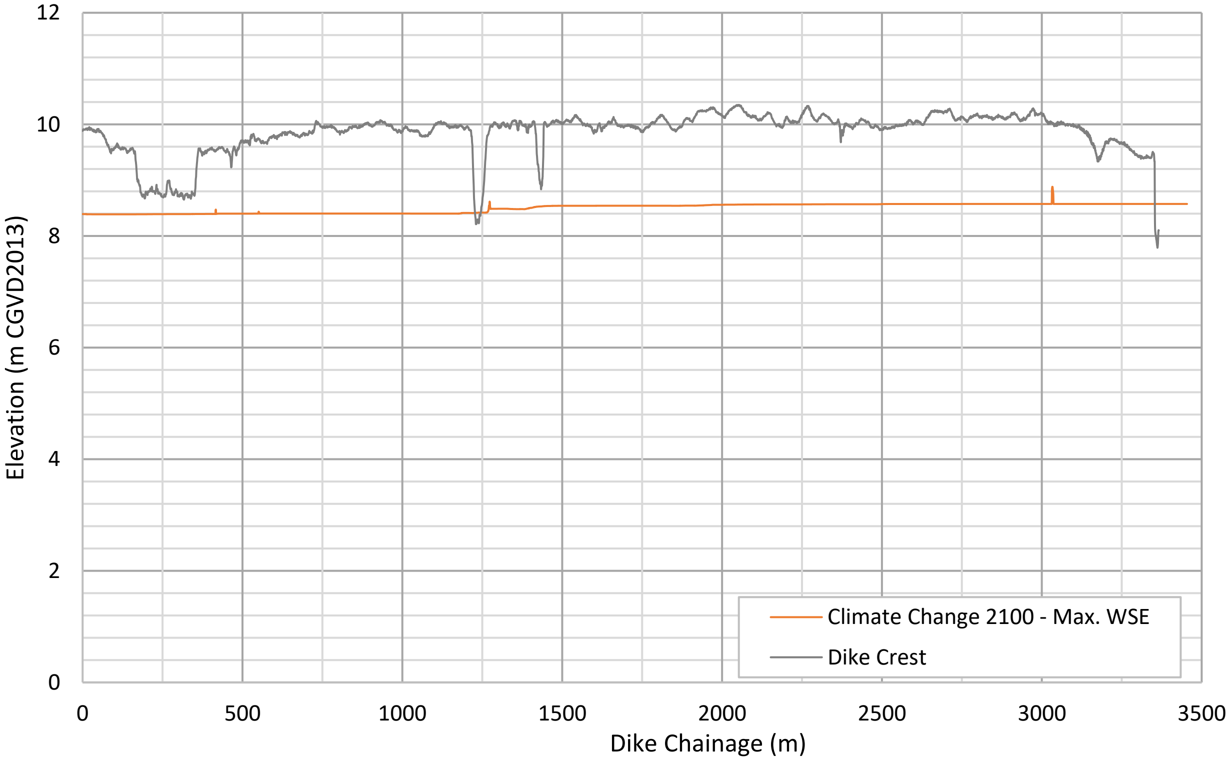

Figure 5-8: Somenos Dike crest and flood profile comparison

6 DIKE BREACH MODELLING

6.1 Dike Breach Locations

The study area is comprised of two types of dikes:

a) primary dikes: engineered structures designed for a 200-year flood, monitored and maintained by a local government entity; and
b) secondary dikes: dikes not engineered or designed to a 200-year flood standard and no ongoing monitoring or maintenance by local government. Most of the secondary dikes shown in Figure 6-1 have limited ability to function as flood control structures since they are either very low or have openings that will allow flood water to enter.

A total of 12 dike breach scenarios were considered for primary dikes only as outlined in Figure 6-1 and Table 6-1. Dikes may breach as a result of scour, erosion and geotechnical failure. Conceivably, an almost infinite number of dike breach scenarios could be considered. Dike breach locations were selected based on review of structure vulnerability and breach locations that would lead to severe and wide-spread flooding. Structural vulnerability for example includes review of where dike crest elevations are low or where structural barriers need to be installed at existing dike openings. Breach locations were further refined based upon input from the stakeholder group.

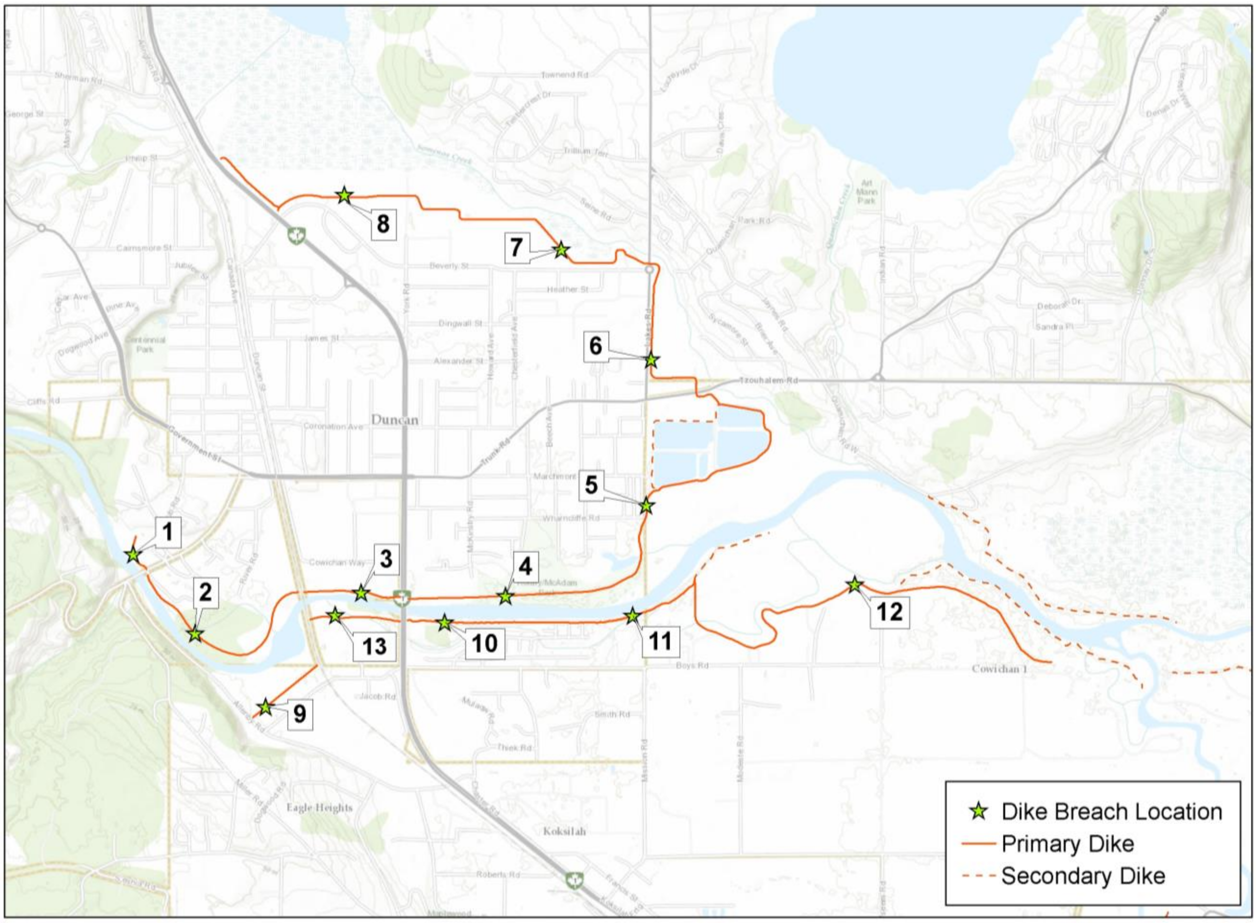

Figure 6-1: Dike breach locations

Table 6-1: Summary of dike breach locations for primary flood control dikes

ID	Dike	Watercourse	Station (km)	Bank
1	Cowichan Phase 2-Allenby	Cowichan	9.6	Left
2	Cowichan Phase 2-Dike A	Cowichan	9.1	Left
3	Cowichan Phase 2-Dike B	Cowichan	8.1	Left
4	Cowichan (City of Duncan) Dike	Cowichan	7.5	Left
5	Cowichan (City of Duncan) Dike	Cowichan	6.5	Left
6	Lakes Road/Beverly St. Dike	Somenos	0.9	Right
7	Lakes Road/Beverly St. Dike	Somenos	1.7	Right
8	Canada Avenue	Somenos	2.6	Right
9	Flood Wall /Cowichan Phase 2-Dike D	Cowichan	8.8	Right
10	Cowichan South Side Dike	Cowichan	7.8	Right
11	South Side Spur Dike	Cowichan	7.0	Right
12	Mission Road Dike	Cowichan	6.0	Right
13	Cowichan South Side Dike	Cowichan	8.3	Right

6.2 Dike Breach Model Parameters

For all dike breach scenarios, it was assumed that breach formation occurred at the peak of the flood hydrograph and breach width for all dikes was 150 metres.

Table 6-2: General dike breach parameters

Parameter	Description
Failure mode	Geotechnical instability (slope instability or piping
Breach bottom width	150 m
Breach formation time	1 hour
Breach base elevation	Ground level (based on adjacent terrain)
Water surface elevation trigger	Peak modelled water level

6.3 Modelled Dike Breach Results

Dike breach scenarios were simulated for the two base flow conditions, Present Day and Climate Change 2100. Figure 6-2 shows the flood extents for all dike breach scenarios under Climate Change 2100 flow conditions. Envelope flood depth maps, which include the combined extent of all breach scenarios and the base scenario, are presented in Figure 6-3 for the Climate Change 2100 scenario and in Figure 6-4 for the Present Day scenario.

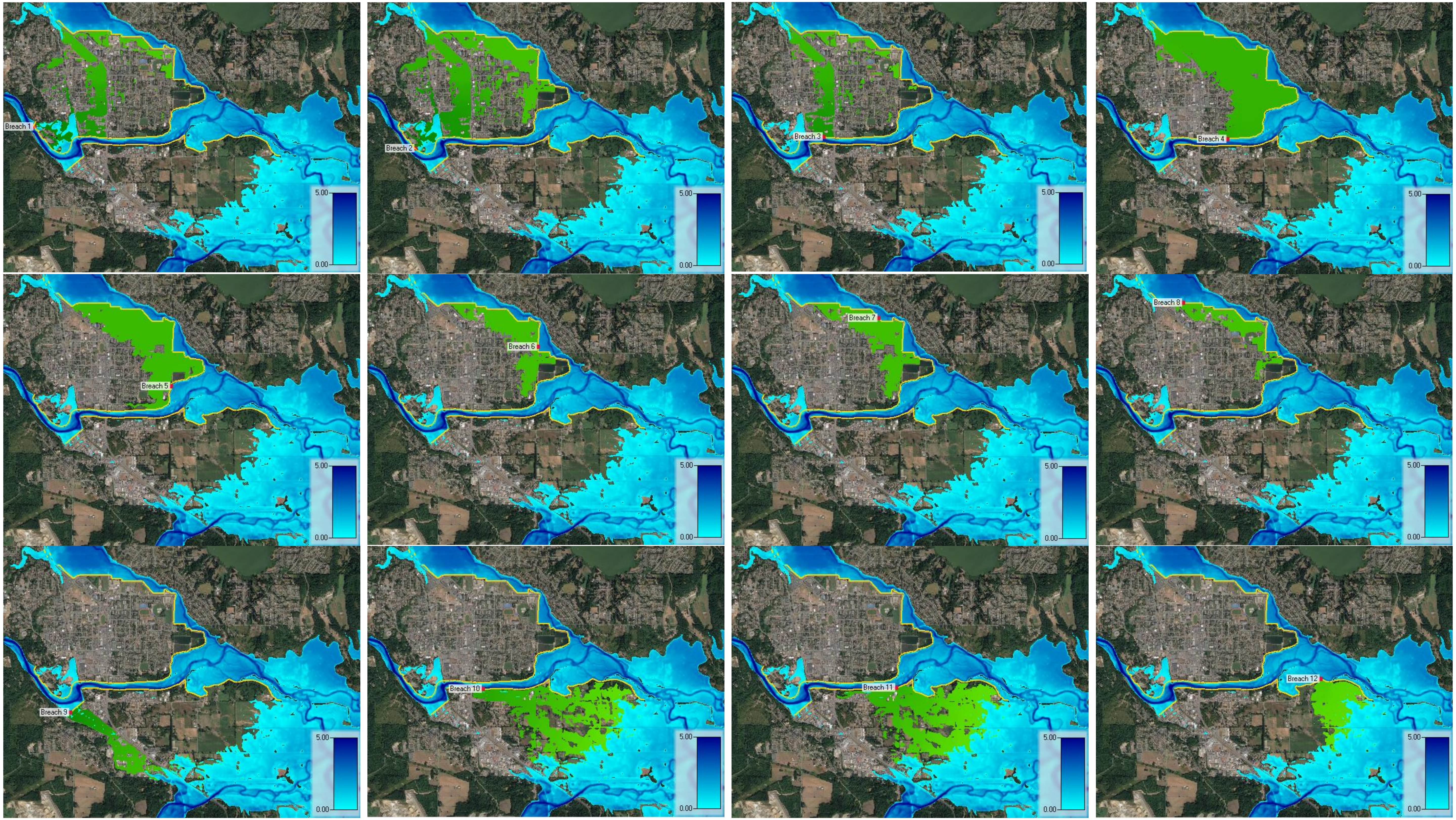

Figure 6-2: Climate Change year 2100 flood -Breach Scenarios - Max Flood Depth (m). The green surface represents the additional breach flooding with respect to the base scenario.

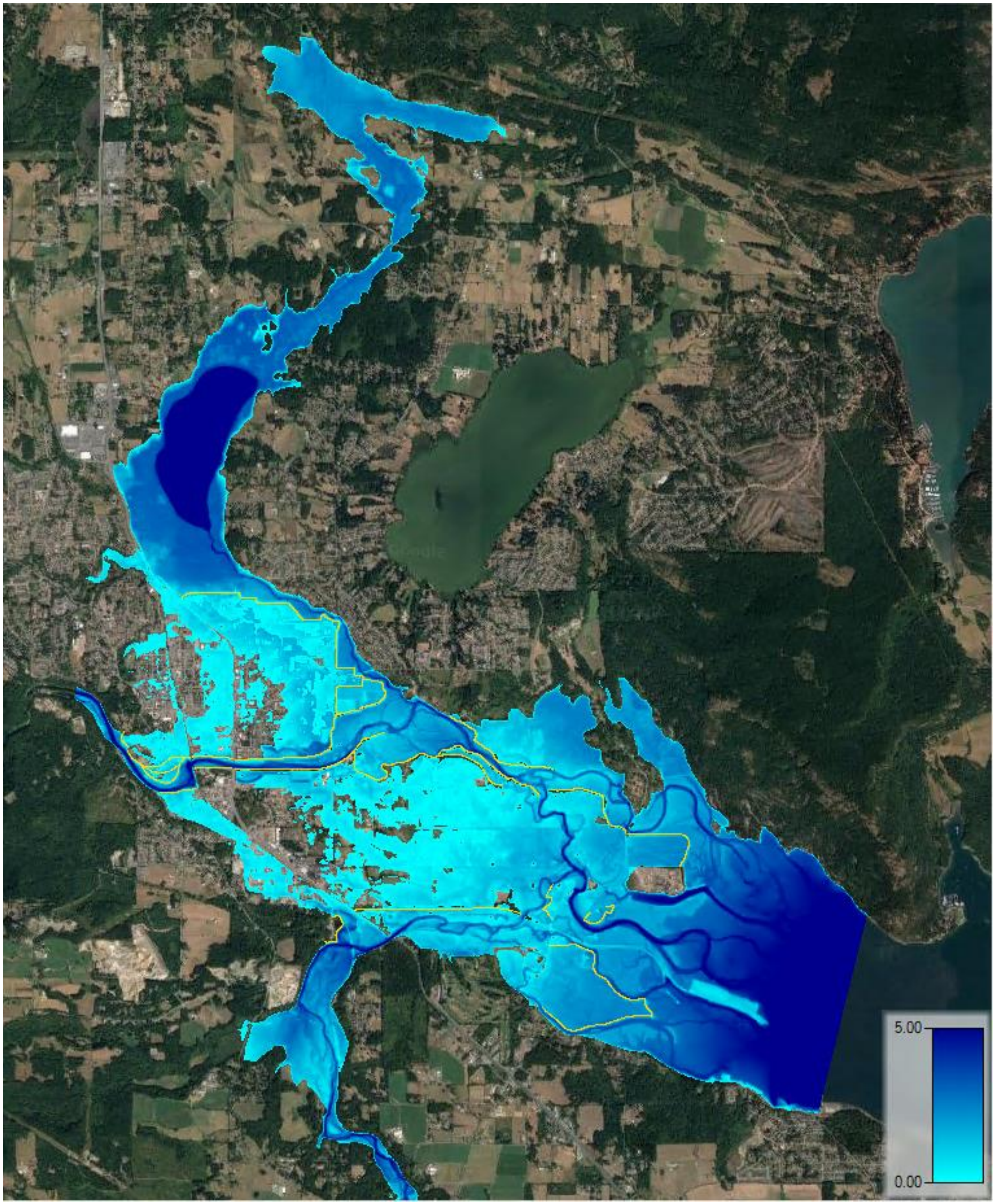

Figure 6-3: Climate Change year 2100 flood - Envelope of Base run and Breach Scenarios - Max Flood Depth (m)

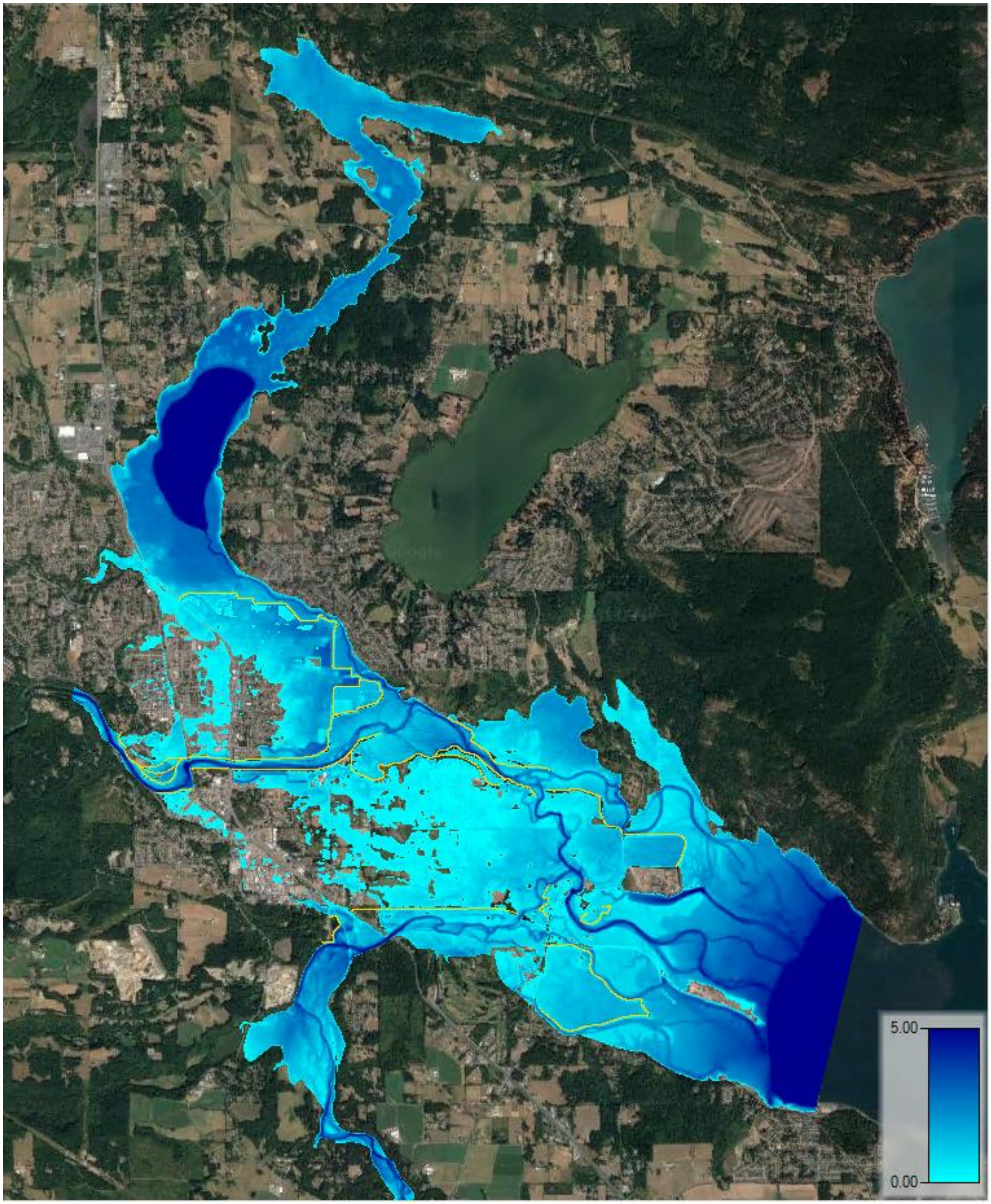

Figure 6-4: Present Day flood - Envelope of Base run and Breach Scenarios - Max Flood Depth (m)

7 MODELLING OF MITIGATION OPTIONS

7.1 Proposed Mitigation Scenarios

Through consultation with the stakeholder group a list of mitigation concepts was identified as listed in Table 7-1.

Table 7-1: Overview of mitigation scenarios

Scenario	Description	Notes
1	New South Cowichan-Koksilah Dike	This mitigation option requires Hwy 1 to be raised to meet the Q200 flood construction level
2	Sediment Management Scenarios	Gravel removal creates a minor impact to water levels

Mitigation 1: New South Cowichan-Koksilah Dike

For this mitigation concept the proposed dike alignment was added to the model geometry. The dike was tied into the Hatchery Dike near the Cowichan River and into Highway 1 near the Koksilah River, as shown in Figure 7-1. The section of Highway 1 indicated in the figure does not meet the 200-year flood level; therefore, it was raised in the model geometry. Model simulations were completed for the Present Day flow scenario (Figure 7-2). Results indicate that the south Cowichan-Koksilah dike alignment only provides protection for the low-lying floodplain area between the Cowichan and Koksilah Rivers if a portion of Highway 1 is also raised.

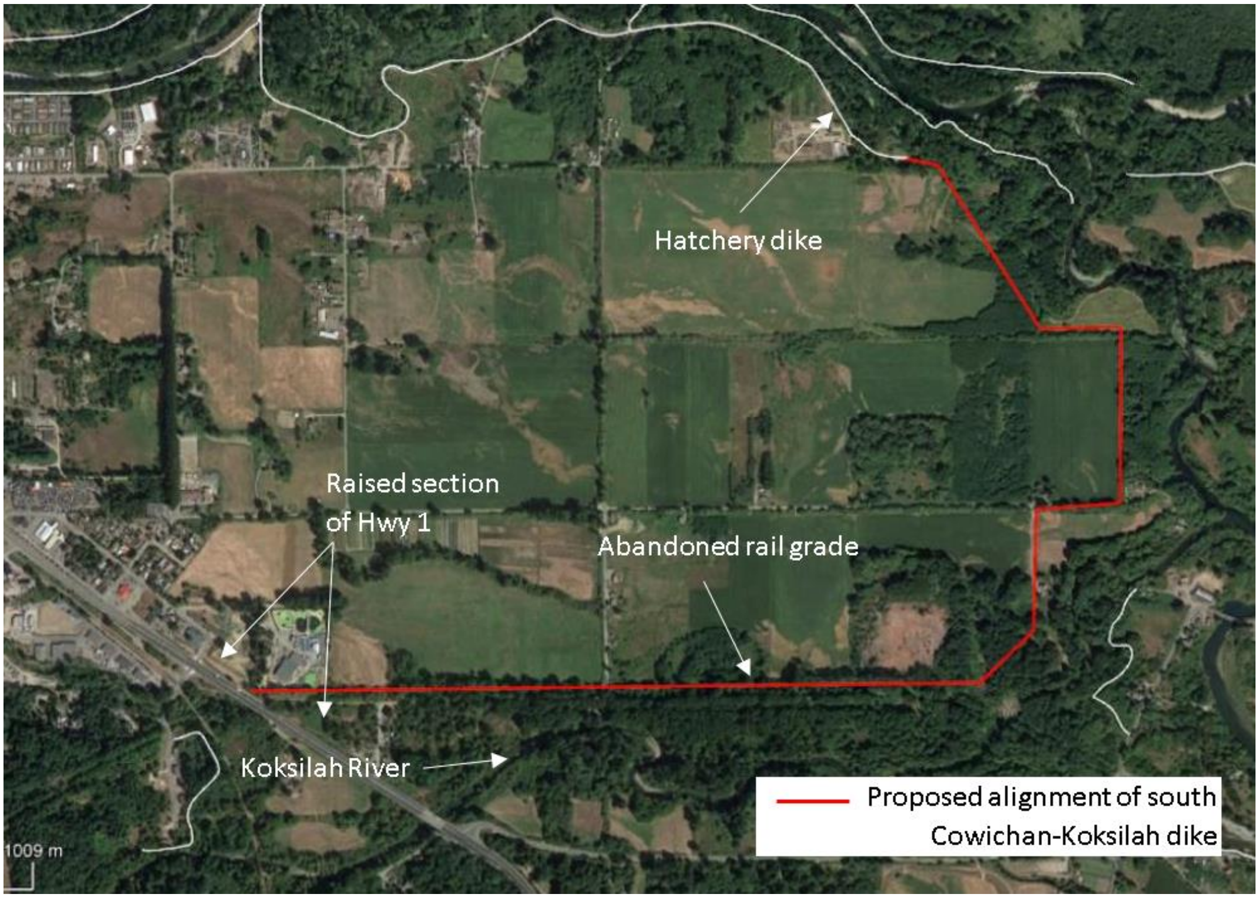

Figure 7-1: Proposed alignment for the new south Cowichan-Koksilah dike

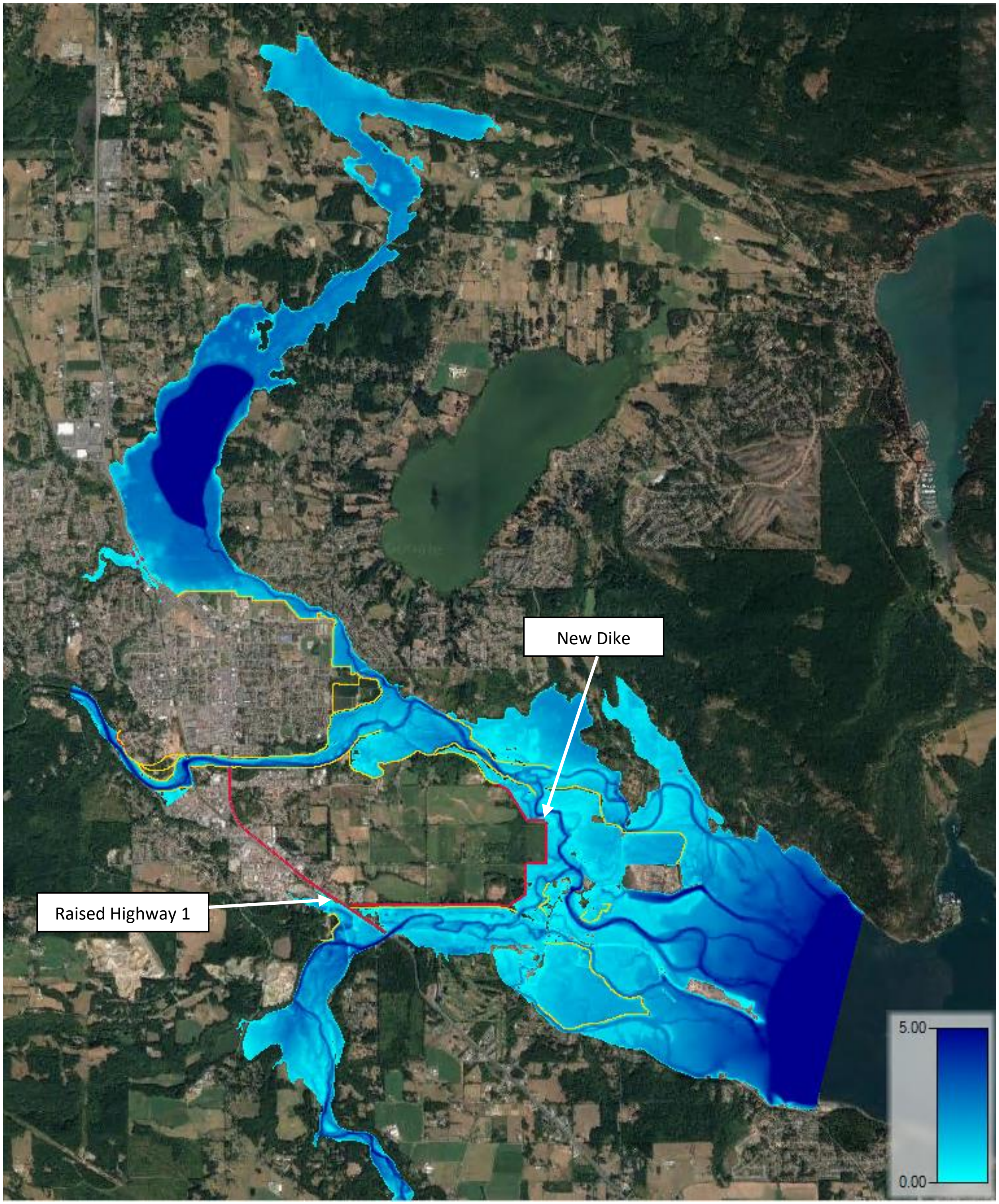

Figure 7-2: Mitigation 1 - Present Day 200-year flood - Max Flood Depth (m)