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Technical Memorandum #4

DATE: April 23, 2021

TO: Robyn Holme, RPP, MCIP
Comox Valley Regional District

FROM: Eric Morris, M.A.Sc., P.Eng.

RE: **COASTAL FLOOD MAPPING PROJECT**
Technical Memorandum #4 – Coastal Modelling
Our File 2623.014-300

1. Introduction

Kerr Wood Leidal Associates Ltd. (KWL) has been retained by the Comox Valley Regional District (CVRD) to provide consulting engineering services for the preparation of coastal floodplain mapping. The coastal floodplain mapping includes the anticipated effects of sea level rise and will be used by the CVRD for land use planning, emergency planning and risk assessment.

This technical memorandum (#4) describes the approach taken for the coastal modelling component of the project including the estimation of design water levels, deep water wave conditions and wave effects and provides a summary of the model results. Other technical memoranda document the remaining project components.

1.1 Project Scope

The main project tasks include:

1. Conducting a mapping workshop to discuss mapping objectives and deliverables.
2. Collection and integration of topographic and bathymetric mapping from a variety of sources including bathymetric data collected in the Oyster River as part of the project scope, bathymetric data in the sea obtained from the Canadian Hydrographic Service and topographic data in upland and intertidal areas obtained from GeoBC and other sources.
3. Hydrologic and hydraulic modelling of the Oyster River downstream of Highway 19 to its mouth at the Strait of Georgia and the lower reaches of the Courtenay River, Puntledge River (downstream of the BC Hydro Powerhouse) and Tsolum River (downstream of the Piercy Road Bridge/North Courtenay Connector). Modelling was conducted for floods having annual exceedance probabilities (AEP) ranging from 10% to 0.2% and included the anticipated effects of climate change.
4. Hydraulic modelling of coastal water levels (tide plus storm surge) and wave effects in deep and shallow water to determine wave heights in the surf zone and the maximum elevation of wave run-up for storm events with AEPs ranging from 10% to 0.2% and sea levels ranging from current conditions to a projected scenario with two metres of sea level rise (to Year 2200). This project task is the focus of this technical memorandum.
5. A desktop geomorphologic assessment of the lower Oyster River and shoreline to identify areas that may be non-erodible or exceptionally vulnerable to erosion.

6. Determination of flood levels for the Oyster River, the lower Courtenay/Puntledge/Tsolum River system and coastal areas.
7. Preparation of 1:4000 scale regulatory floodplain maps which show flood levels and floodplain extents and digital mapping for flood levels, setbacks, inundation depths, wave heights, and climate change planning areas.

A series of reports and memoranda are provided to describe data sources, analysis approaches, assumptions, and study findings:

1. Technical Memorandum #1 – Coastal and River Base Map Development
2. Technical Memorandum #2 – Fluvial and Coastal Geomorphology
3. Technical Memorandum #3A – Fluvial Modelling – Oyster River Hydrology and Model Assumptions
4. Technical Memorandum #3B – Fluvial Modelling – Courtenay River Hydrology and Model Assumptions
5. Technical Memorandum #4 – Coastal Modelling
6. Technical Memorandum #5 – Coastal and Fluvial Mapping Products
7. Final Report – Coastal Flood Mapping Project
8. Coastal and Fluvial Models User Guide

This is Technical Memorandum #4, which describes the approach taken for coastal modelling including the estimation of design water levels, deep water wave conditions and wave effects and provides a summary of the model results.

1.2 Glossary and Abbreviations

AEP = Annual Exceedance Probability. Probability of an event (e.g., flood event) of equal or greater magnitude occurring in a given year. The AEP is the inverse of the Return Period.

Astronomical Tide = Tide caused by forces of the sun and the moon.

CGVD28 = Canadian Geodetic Vertical Datum, original vertical datum used in Canada, roughly equal to mean sea level.

CGVD2013 = Canadian Geodetic Vertical Datum 2013, updated vertical datum used for mapping in this study.

CD = Chart Datum. Datum typically used in marine charts which is roughly equivalent to the lowest astronomical tide in the area depicted in the chart.

CHS = Canadian Hydrographic Service of Fisheries and Oceans Canada.

DEM = Digital Elevation Model. A generic term for a map that represents the topographic elevation of the earth's surface. A DEM can be represented as a raster (a grid of squares, also known as a heightmap when representing elevation) or as a vector-based triangular irregular network (TIN).

El Niño = El Niño is a periodic ocean circulation phenomenon that results in atypically warm surface water in the equatorial central and east-central Pacific Ocean. El Niño events can last for several years. The warm surface water results in changes to atmospheric circulation patterns (weather) and ocean water levels throughout the Pacific Ocean, and to a lesser extent, the entire globe.

GNSS = Global Navigation Satellite System. A GNSS is a system that uses satellites to provide geo-spatial positioning. It uses electronic receivers to determine their location (longitude, latitude, and altitude/elevation) to high precision (within a few centimeters to metres) using time signals transmitted along a line of sight by radio from the satellites.

Significant Wave Height (H_{m0}) = Significant Wave Height in deep water as estimated from the wave spectrum. The Significant Wave Height is the average height of the highest 1/3 of the waves in a sea state.

HAT = Highest Astronomical Tide, the highest astronomical tide over the 18.6 year tidal cycle.

HHWLT = Higher High Water, Large Tide, the average of the highest annual tides over the 18.6 year tidal cycle.

LiDAR = Light Detection and Ranging. A remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. LiDAR collected at a regional scale is usually collected by aircraft.

LLWLT = Lower Low Water, Large Tide, the average of the lowest annual tides over the 18.6 year tidal cycle.

MHWMT = Mean High Water, Mean Tide.

MLWMT = Mean Low Water, Mean Tide.

MWL = Mean Water Level.

Refraction = A change in wave direction in water of varying depth due to change in wavelength.

Return Period = An estimate of the average interval of time between events of a certain intensity or size. The inverse of the Annual Exceedance Probability.

Seiche = Standing wave which forms in a fully or partially enclosed body of water. Seiches can be caused by a changes in wind speed or atmospheric pressure, storm surge, wind-generated waves, or tsunami.

Shoaling = Change of wave height in shallow water due to water depth.

Spectral Wave Period ($T_{m-1,0}$) = Characteristic wave period obtained via the integration of the wave spectrum.

Storm Surge = Increase in water level caused by low atmospheric pressure and winds.

Tidal Residual = The arithmetic difference between the predicted water level and the measured water level. Tidal residuals are largely due to storm surge, although other effects such as changes in ocean current circulation (e.g., due to El Nino) and

		non-tidal water level oscillations such as seiche can affect the tidal residual value as well.
Wave Runup	=	The maximum vertical extent of wave uprush on a beach or structure above the still water level. The wave runup includes the wave setup.
Wave Setup	=	An increase in mean water level in the breaking wave or "surf" zone due to the effect of transferring wave-related momentum to a local increase in the water level.
WSC	=	Water Survey of Canada.

1.3 References

The following references have been used in our work on this memorandum:

1. Ausenco Sandwell. (2011a). *Climate Change Adaption Guidelines for Sea Dikes and Coastal Flood Hazard Land Use - Draft Policy Discussion Paper.*
2. Ausenco Sandwell. (2011b). *Climate Change Adaption Guidelines for Sea Dikes and Coastal Flood Hazard Land Use – Guidelines for Management of Coastal Flood Hazard Land Use.*
3. British Columbia Ministry of Forests, Land and Natural Resource Operations (FLNR). (2018). *Flood Hazard Area Land Use Management Guidelines.*
4. Canadian Hydrographic Service of Fisheries and Oceans Canada (CHS). (2020). *Canadian Tide and Current Tables – Volume 5 – Juan de Fuca Strait and Strait of Georgia.*
5. Cascadia Coast Research. (2020, October). *Storm Wave Analysis: Comox Valley Regional District, BC.*
6. EurOtop. (2018). *EurOtop - Manual of Wave Overtopping of Sea Defences and Related Structures-Second Edition.*
7. French. (1982). *Memorandum on Special Computation Procedure Developed for Wave Runup Analysis for Casco Bay - FIS - Maine, 9700-153.* Camp Dresser & McKee.
8. Goda. (2010). *Random Seas and Design of Maritime Structures – Advanced Series on Ocean Engineering – Volume 88 – 3rd Edition.* World Scientific.
9. Stockdon et al. (2005). *Empirical Parameterization of Setup, Swash and Runup.* Coastal Engineering 53.
10. United States Federal Emergency Management Agency (FEMA). (2015). *Guidance for Flood Risk Analysis and Mapping – Coastal Wave Setup.*
11. United States Federal Emergency Management Agency (FEMA). (2019). *Guidance for Flood Risk Analysis and Mapping- Coastal Floodplain Mapping.*
12. United States Federal Emergency Management Agency (FEMA). (2018). *Guidance for Flood Risk Analysis and Mapping- Coastal Wave Runup and Overtopping.*

2. Coastal Modelling Approach

2.1 Modelling Objective and Approach

The objective of the coastal modelling phase of the project is to estimate the **total water level** at the shoreline throughout the study area for different sea level rise scenarios and storm events of different probabilities. The total water level was estimated by dividing it into components and calculating the value of each component. The total water level components are as follows:

1. Astronomical tide plus storm surge (extreme static water level).
2. Sea level rise.
3. Wave effects.

The relationship between the total water level components is shown in Figure 1. A process flow diagram for the estimation of the total water level is provided in Figure 2; a detailed description of how estimates were prepared for each component is provided in Sections 3, 4, and 5.

As part of this study, total water levels with a 10%, 5%, 1%, 0.5%, and 0.2% probability of being equalled or exceeded in a given year (annual exceedance probability, AEP) have been estimated for existing sea levels and scenarios with 0.5 m, 1.0 m, and 2.0 m of sea level rise.

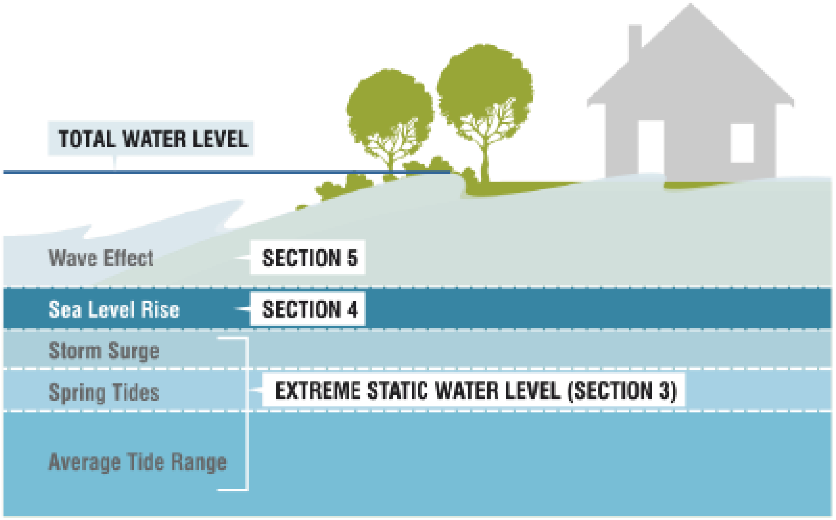

Figure 1: Coastal Water Level Components

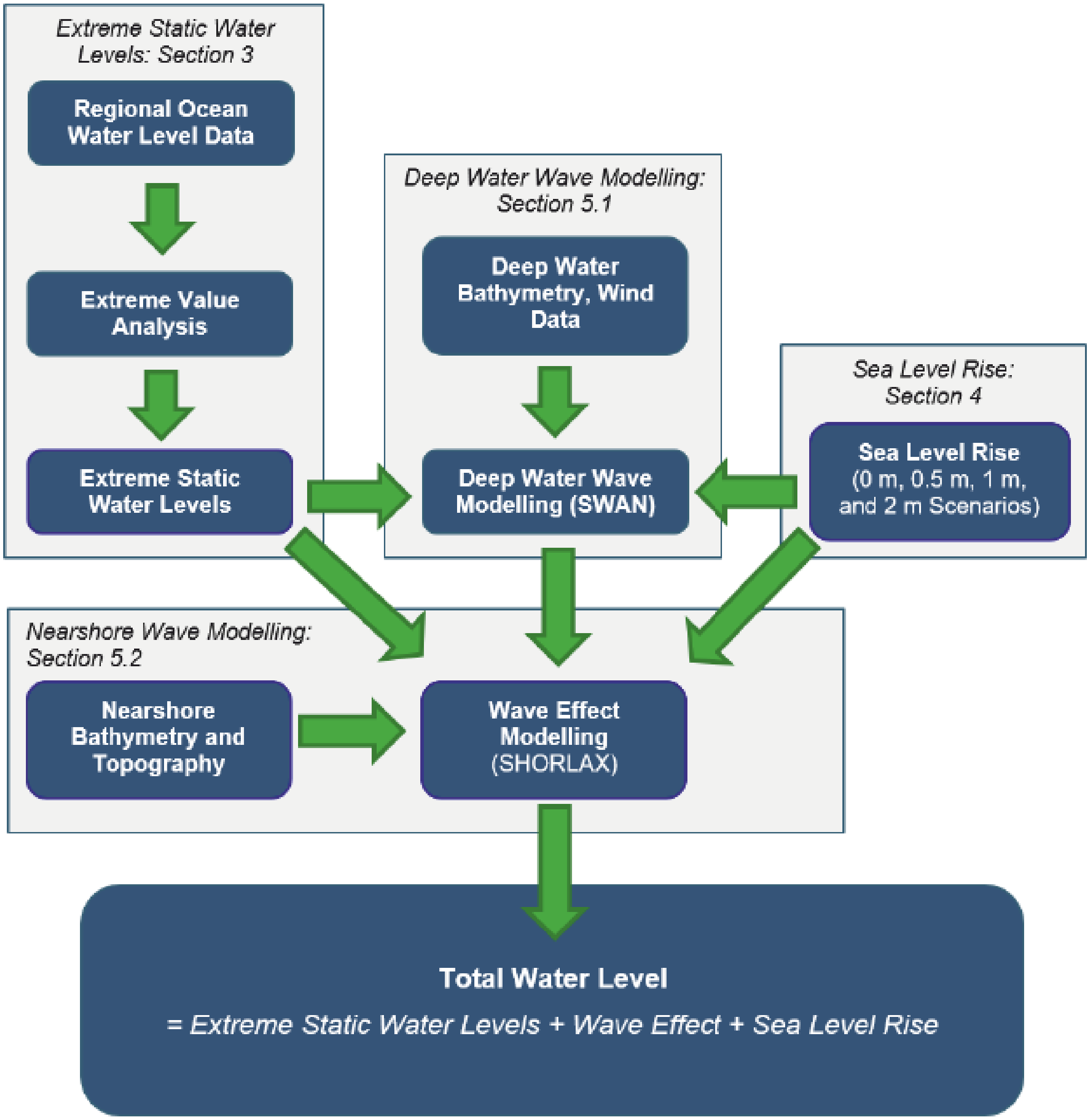

Figure 2: Process Flow Diagram for Calculation of Total Water Level

2.2 Computational Methodology

There are two fundamental approaches that are commonly used to calculate total water levels: **event-based approaches** and **continuous simulation**. In event-based approaches, discrete storm events with a given AEP are modelled to estimate values of related parameters. For example, a storm event that has a 0.2% AEP would be modelled to estimate the flood level that has a 0.2% AEP. In continuous simulation approaches, a model simulation is performed using many years of data to generate estimates of the entire statistical population of the parameters of interest. For example, winds, waves, and water levels would be modelled with 50 years of data to generate a synthetic dataset of flood levels, which are then analysed to determine extreme values.

A shortcoming of event-based approaches is that judgements need to be made regarding the appropriate values of the input parameters to achieve a given AEP. In coastal floodplain mapping, an appropriate combination of water level and wind speed (which determines wave heights) must be selected for each event. These judgements do not need to be made in a continuous simulation approach since a large (ideally almost the full) population of input parameters is modelled. However, continuous simulation approaches are computationally intensive, and in practice, trade-offs such as accepting a lower spatial resolution of outputs parameters, must be made to make continuous simulation feasible.

For this project, an event-based approach was taken to model total water levels. This approach was selected for two key reasons:

1. The approach aligns with the BC Flood Hazard Area Land Use Management Guidelines (FLNR, 2018), herein referred to as the "provincial guidelines'"; which specify the AEP of extreme water levels and storm events when calculating flood levels.
2. Waves in the study area are generated locally by wind, and therefore there is a direct relationship between wind speeds and wave heights which can be determined by modelling discrete storm events. Use of an event-based approach has allowed us to achieve a higher spatial resolution of wave runup and flood levels which improves the accuracy of the floodplain mapping.

Further to the above, the "probabilistic method" from the provincial guidelines for floodplain mapping was applied to calculate flood levels and setbacks (FLNR, 2018). This method was used because there is sufficient data to perform the analysis and it is generally considered to provide a less conservative (i.e., lower) coastal flood level than the alternative "combined method". In the probabilistic method, the extreme static water levels are determined through probabilistic analyses of tides and storm surge and are combined with allowances for wave effects, local land uplift or subsidence, sea level rise and freeboard (where appropriate) to estimate the flood level and setbacks.

3. Extreme Static Water Level

The static water level is the sum of the astronomical tide and storm surge; these water level components are described in Section 3.1 and 3.2 along with the methodology used to calculate extreme values of the static water level. The extreme static water level does not include wave effects and is referred to as the "still water level" in this memorandum when combined with sea level rise.

3.1 Astronomical Tides

Astronomical tides (commonly called "tides") are variations in sea level due to the gravitational interaction of the earth, the moon, and the sun. Because the orbital periods of the earth and moon are relatively fixed in duration, the astronomical tides are periodic with an 18.6 year cycle. The astronomical tides also have a shorter cycle, with roughly two high and two low tides per day (i.e., a diurnal pattern) although the magnitude and timing of the high and low tides changes from day to day and throughout the year.

Astronomical tide levels vary throughout the world due to variations in gravitational effects and large-scale ocean currents. Astronomical tide levels also vary throughout Coastal BC due to local hydraulic effects caused by the flow of water between islands and into bays and inlets. Larger "spring" tides occur when the gravitational forces of the sun and moon are synchronized and the earth, moon and sun are closer to each other in their elliptical orbits.

There are several terms that are commonly used to describe the various levels and phases of astronomical tides as follows:

Higher High Water, Large Tide (HHWLT): the highest of the high-water levels during a spring tide. The HHWLT is calculated as the average of the highest tides in each of the 18.6 years of the astronomical tide cycle.

Higher High Water, Mean Tide (HHWMT): the average, or "mean" of the high-water levels in the mean, or average, tidal range.

Mean Water Level (MWL): the statistical average of the water levels. The MWL is often the same as, or close to the elevation of **Geodetic Datum**.

Lower Low Water, Mean Tide (LLWMT): the average of the low water levels in the mean, or average tidal range.

Lower Low Water, Large Tide (LLWLT): the lowest of the low water levels during a spring tide. The LLWLT is calculated as the average of the lowest tides in each of the 18.6 years of the astronomical tide cycle. LLWLT is often the same as, or close to the elevation of **Chart Datum**.

In Canada, sea level data is collected by the Canadian Hydrographic Service (CHS) of Fisheries and Oceans Canada. Astronomical tide data for select tidal stations in the CVRD and Strait of Georgia are summarized in Table 2; these locations are shown on Figure 3. Water levels are presented to Chart Datum (CD) and to project Geodetic Datum 2013 (CGVD2013)[1]. Elevations for CHS's tide gauges are provided to both CD and Geodetic Datum 1928 (CGVD28). Technical Memorandum #1, Coastal and River Base Map Development, provides details on the conversion from CGVD28 to CGVD2013 datum for the ocean bathymetric and topographic data sources. The same methodology (application of a constant

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[1] The astronomical tide and extreme water levels presented in Cascadia Coast Research's deep water wave modelling report (2020) are to CGVD28 datum and are therefore lower than those presented in this memorandum.

shift of 0.114 m) is considered to be appropriate to convert the ocean water levels as well since the estimated conversion error is within the accuracy of the study results (estimated 4 cm maximum error).

Table 2: Astronomical Tide Data

Tidal Level	Station			
	Little River[1]	Comox[2]	Denman Island[3]	Point Atkinson[4]
Chart Datum (CD)				
Higher High Water, Large Tide (HHWLT)	5.3	5.4	5.2	5.0
Higher High Water, Mean Tide (HHWMT)	4.7	4.8	4.7	4.5
Mean Water Level (MWL)	3.2	3.3	3.2	3.1
Lower Low Water, Mean Tide (LLWMT)	1.2	1.3	1.2	1.2
Lower Low Water, Large Tide (LLWLT)	0	0.2	0.2	0.1
Geodetic Datum (CGVD2013)				
Higher High Water, Large Tide (HHWLT)	2.3	2.3	2.1	2.0
Higher High Water, Mean Tide (HHWMT)	1.7	1.7	1.6	1.5
Mean Water Level (MWL)	0.2	0.2	0.1	0.1
Lower Low Water, Mean Tide (LLWMT)	-1.8	-1.8	-1.9	-1.8
Lower Low Water, Large Tide (LLWLT)	-3.0	-2.9	-2.9	-2.9

Notes:

1. Conversion to CGVD28 based on CHS Monument M12C6005 (1).
2. Conversion to CGVD28 provided by CHS via e-mail; conversion is based on benchmark which is known to be unstable.
3. Conversion to CGVD28 based on CHS Monument 21-1971 (71C9506).
4. Conversion to CGVD28 based on CHS Monument 128-1950.
5. Conversion from CD to CGVD28 datum for all stations was obtained from CHS in late-2019.

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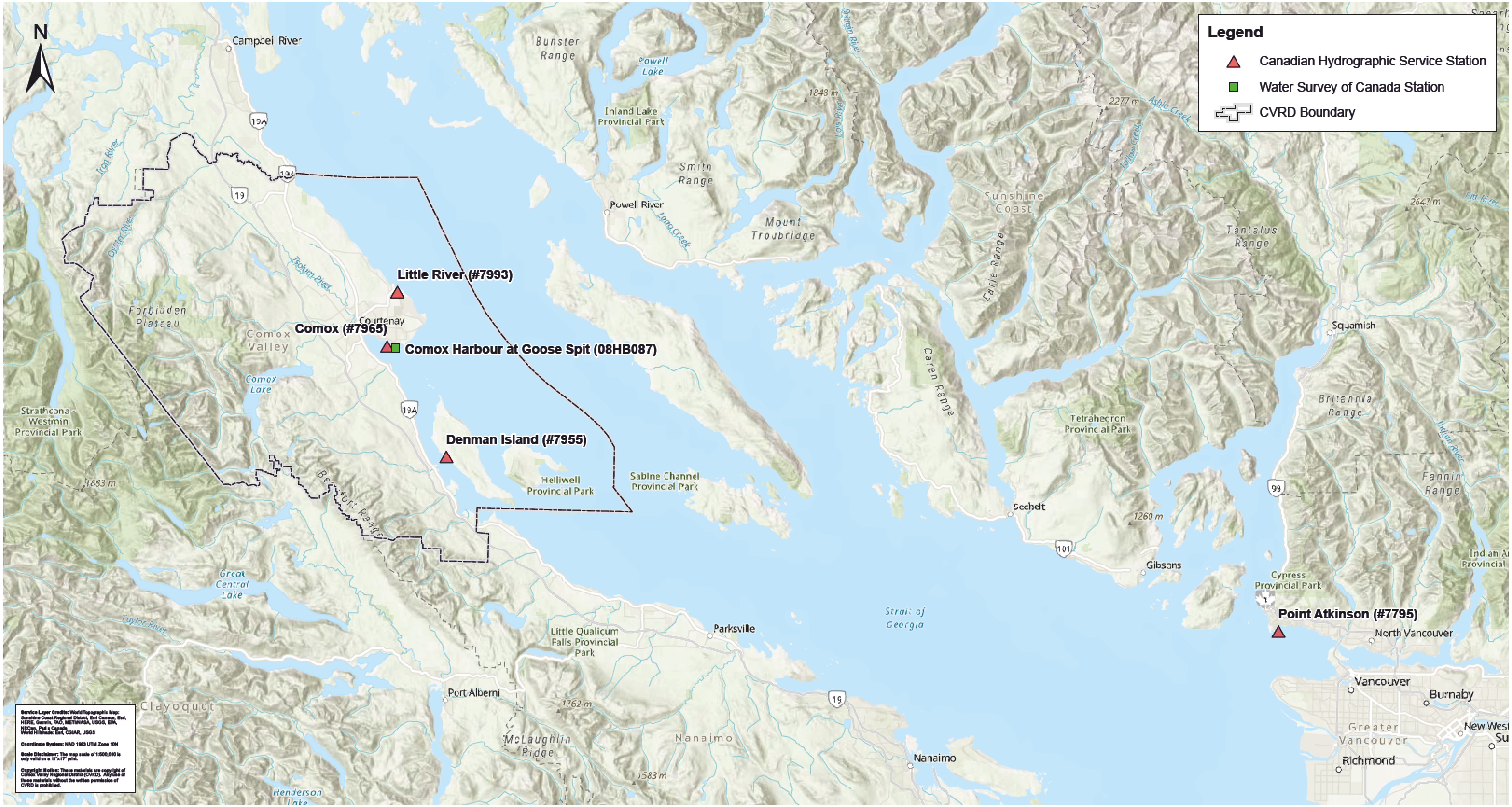

Service Layer Credits: World Topographic Map: Sunshine Coast Regional District, Esri Canada, Esri, HERE, Garmin, FAO, METI/NASA, USGS, EPA, NRCan, Parks Canada
World Hillshade: Esri, CGIAR, USGS

Coordinate System: NAD 1983 UTM Zone 10N

Scale Disclaimer: The map scale of 1:500,000 is only valid on a 11"x17" print.

Project No.	2623-014
Date	April 2021
Scale	1:500,000

0 2.5 5 10 Kilometres

Tide Station Locations

Figure 3

3.2 Extreme Static Water Level

Extreme high-water levels occur when storm surges occur at the same time as higher astronomical tides. Storm surges are increases and decreases in the sea level caused by storm generated atmospheric pressure fluctuations and wind. When a large storm surge occurs at the same time as a high tide, extreme water levels and flooding can occur.

There are several approaches which can be taken to estimate storm surges and extreme water levels; the selection of what approach to take should consider the geography/oceanography of the region being studied and the availability of water level data. If enough historical water level data has been collected in key locations such that local water level variations can be resolved, an analysis method which is based on the analysis of observed water levels can be used. If water level measurements are few and far between or if there are large gaps in the data, it may be necessary to build a hydrodynamic model to estimate water levels.

Each approach to estimating extreme water levels has limitations. When using regional water level data to estimate extreme values, techniques need to be employed to address data sets that are either short duration or have gaps in the data (as was done for this project as outlined in this section). Judgement also needs to be employed to define the geographic extents of the water levels since they are estimated at discrete locations. Modelling approaches, unless extremely sophisticated, usually do not resolve all influences on the water levels such as seasonal variations due to river flows or global weather patterns (discussed later in this memorandum) and rely on the accurate assembly of input data and calibration to produce reliable estimates.

The CVRD is located on a relatively open stretch of shoreline within the northern Strait of Georgia with no large inlets with the exception of Comox Harbour. Water level data was collected at several locations within the CVRD as listed in Table 3 and shown in Figure 3. As can be seen in Figure 3, water levels have been recorded over a wide geographic area and there is historical data available (although some of it is of relatively short duration) in most areas including Comox Harbour. Given the adequate data coverage, an extreme water level estimation approach that is based on the analysis of historical data was adopted.

Table 3: Water Level Record Stations

Station Name	Owner (Station ID)	Data Collection Period	Number of Years of Usable Data
Little River	CHS (#7993)	1967 - 1993	26
Comox Harbour	CHS (#7965)	1949 - 1953, 1967 - 1969	8
Comox Harbour	WSC[1]	1997 - 2019	23
Hornby Island	CHS (#7953)	1967 - 1971	4
Denman Island	CHS (#7955)	1971	1
Point Atkinson	CHS (#7795)	1915 - 2019	80

Notes:
1. Station is operated by the Water Survey of Canada for the operation of BC Hydro's Comox Lake dam.

One key challenge faced in the extreme water level analysis was that, with the exception of the Point Atkinson data set, none of the data sets in and of themselves were sufficiently long to be appropriately used to estimate extreme values. Therefore, a longer "synthetic" observed water level series was generated based on predicted tides for each tide station plus scaled "tidal residual" values recorded at Point Atkinson. These "synthetic" water level time series include both tide and storm surge and therefore extreme values of water level can be obtained through direct analysis of the data set with no need to separate tides and storm surge. Point Atkinson was selected as the "base" data set because it has a record that is considered to be long enough (80 years) to produce reliable estimates of extreme events with annual exceedance probabilities of 0.5% and 0.2%.

The synthetic water level can be calculated as follows:

$$Z_{SYNTHETICi} = Z_{PREDICTEDi} + \alpha R_{PT\_ATKINSON}$$

Where Z is the water level, R is the tidal residual and α is the scaling factor for tidal residual obtained through analysis of local and Point Atkinson data as described below. As Point Atkinson data was used as the basis for the synthetic records, the synthetic data sets have the same duration (80 years).

The "tidal residual" is the arithmetic difference between the predicted water level and the measured water level and is largely the result of storm surge, although other effects such as changes in global weather and ocean current circulation (e.g., due to El Niño), river flows (e.g., the Fraser River) and non-tidal water level oscillations such as seiche can affect the tidal residual value as well. Scaling factors (α) for the tidal residual were determined by analyzing tidal residual values measured concurrently at Point Atkinson and the station of interest in the CVRD. The scaling factors were found to be approximately 1.1 (i.e., the magnitude of large storm surges is on average 10% greater in the CVRD than at Point Atkinson) with minimal variation throughout the CVRD; therefore, a 1.1 factor was used at each tide station.

Once the scaling factors were determined and the synthetic data sets were created, extreme value analysis of the annual maximum values was performed. The analysis of scaling factors provided confidence in the relative magnitudes of the tidal residuals, but there was still some uncertainty in timing of peak tidal residuals relative to the astronomical tides at Point Atkinson and in the CVRD. In order to address this uncertainty, several extreme value analyses were conducted with scaled tidal residuals at different phases (i.e., time shifted) relative to the predicted tide series. The largest values obtained from the extreme value analysis of the ensemble of synthetic water level series were conservatively used for this study. Extreme value analyses were performed using the Fisher-Tippett Type I (Gumbel), II (Fréchet) and III (Weibull) Distributions. The annual maxima of the water level time series where best fit by the FT-III (Weibull) Distribution; the coefficient of determination (R^2) of the fit is 0.97 (a good fit).

A final check was conducted by performing an extreme value analysis of the actual 23-year Little River observed water level data set and comparing it to the results obtained from the "synthetic" version. The comparison is favourable with higher probability events slightly over-estimated by the synthetic dataset and lower probability events (less than 1% AEP) under-estimated. This is considered to be reasonable due to the short duration of the Little River observed data set. The resulting extreme values for water levels at various locations in the CVRD for annual exceedance probabilities ranging from 10% to 0.2% are presented in Table 4. The water levels in Table 4 are best estimates, with the exception of the values for Comox Harbour which are 90% upper bound confidence values due to the potential benchmark instability noted in Table 2. Relative water levels for Little River are shown graphically in Figure 4.

Table 4: Extreme Values of Water Levels in the CVRD

Annual Exceedance Probability	Water Level (m)			
	Little River (Observed)[1]	Little River (Synthetic)	Comox Harbour (Synthetic)	Denman Island (Synthetic)
Geodetic Datum (CGVD28)				
10%	2.71	2.75	2.79	2.65
5%	2.81	2.83	2.88	2.73
1%	3.03	2.98	3.04	2.89
0.5%	3.11	3.04	3.11	2.95
0.2%	3.22	3.11	3.19	3.03
Geodetic Datum (CGVD2013)				
10%	2.82	2.86	2.90	2.76
5%	2.92	2.94	2.99	2.84
1%	3.14	3.09	3.15	3.00
0.5%	3.22	3.15	3.22	3.06
0.2%	3.33	3.22	3.30	3.14

Notes:
1. Not used for analysis; provided for comparison only.

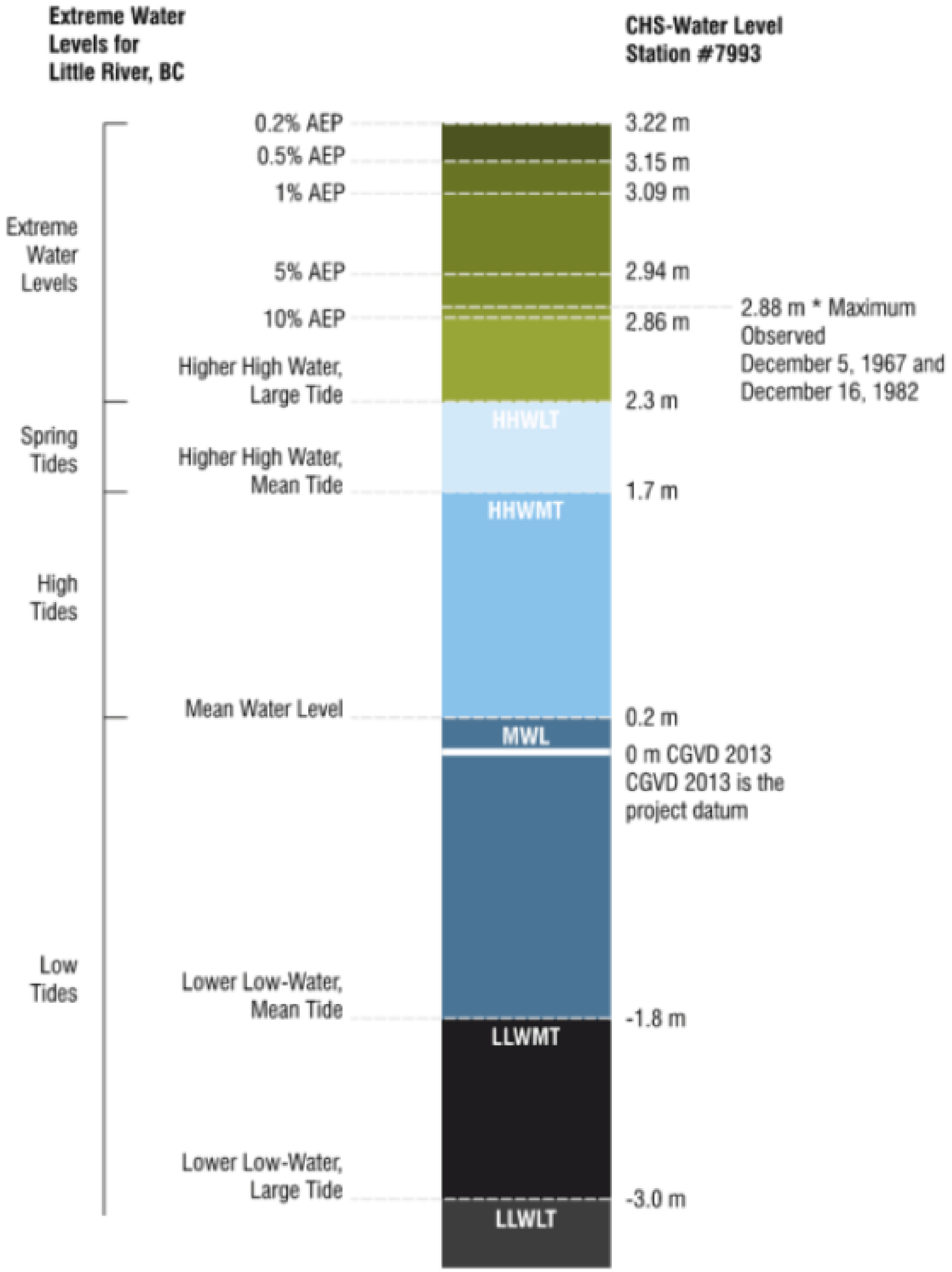

Figure 4: Relative Water Levels for Little River

4. Sea Level Rise and Relative Sea Level

Total water levels have been calculated for four sea level rise scenarios: current levels based on the levels in Table 4, and scenarios with 0.5 m, 1.0 m, and 2.0 m of sea level rise. The latter two scenarios are consistent with provincial guideline policy planning values for the year 2100 and 2200, respectively (FLNR, 2018).

Coastal model runs are often performed using **relative sea levels** which include the effects of land movement relative to the sea level. For example, if the land is rising along with the sea (e.g., due to tectonic uplift), the relative sea level rise is less than the sea level rise alone. Conversely, if the land is falling as the sea rises (e.g., due to subsidence of sedimentary deposits), the relative sea level rise is greater the sea level rise alone.

An estimate of land uplift/subsidence rate for Little River is available from Ausenco Sandwell (2011a); the estimated uplift is 2.4 to 3.6 mm/year based on analysis of 25 years of tide gauge data. This project included a review of available information on land movement velocities as collected by the Canadian Active Control System (CACS). The CACS system is the primary land movement monitoring system in Canada and is administered by Natural Resources Canada. CACS consists of unattended tracking stations, referred to as Active Control Points (ACPs), equipped with a high precision dual frequency Global Navigation Satellite System (GNSS) receiver and an atomic clock, which continuously records location information. The closest CACS stations to the CVRD are located on Winchelsea Island north of Nanaimo, in Port Alberni and on Quadra Island. All the ACPs are located on bedrock and are showing average uplift rates ranging from 1.1 mm/year to 5.1 mm/year; this is consistent with the movement of Vancouver Island in general which is known to be rising due to tectonic plate movement at the nearby Cascadia Subduction Zone.

Despite the land movement monitoring data above which indicates land uplift, the conservative decision was made to assume a region-wide land movement value of zero for the following reasons:

1. There are ground movement monitoring stations located close to the CVRD that have relatively low uplift rates.
2. The shoreline of the CVRD is comprised of areas of both bedrock and sedimentary deposits. Assuming a positive land uplift value for all areas is inappropriate since some localized areas, particularly those with sedimentary deposits, may be subsiding although KWL does not have the data to confirm this.
3. A large earthquake related to the Cascadia Zone Subduction has a non-negligible probability of occurring within the study timeframe (mapping nominally up to the year 2200). This earthquake is expected to cause land subsidence on Vancouver Island as the slow land uplift that has been occurring over many centuries partially reverses. An assumption of continuous land uplift would not account for the subsidence expected with the Cascadia Subduction Zone Earthquake and therefore would result in an under-estimate of flooding extents after the earthquake occurs.

5. Wave Effects

Wave effects were calculated using a two-step process. Firstly, deep water wave conditions were calculated using a two-dimensional spectral wave model (SWAN). The deep-water wave conditions were then input into a one-dimensional model (SHORLAX[2].) which calculates nearshore wave conditions and wave runup. The deep and nearshore wave modelling approaches and results are summarized in the following sections.

5.1 Deep Water Wave Modelling

The deep-water wave modelling for this project was performed by Coast Cascadia Research Ltd. Cascadia's report titled "Storm Wave Analysis: Comox Valley Regional District, B.C." is provided in Appendix A. A summary of Cascadia's report and findings is provided in this section.

Model Development

Cascadia developed a two-dimensional spectral wave model based on the SWAN wave modelling software package (version 41.20). The model uses an unstructured grid and covers the Strait of Georgia from the San Juan Islands in the south-east to the Discovery Islands in the north-west. The model accounts for wave generation by wind, shoaling and refraction due to currents and depth, non-linear wave-wave interactions, white-capping, bottom friction, depth-induced breaking, and, to a limited extent, transmission through and reflection from obstacles and diffraction.

Average element length in the grid is about 200 m through most of the grid but decreases to 40 m at the CVRD shoreline. Bathymetric and topographic data were linearly interpolated onto the grid nodes from the digital elevation model (DEM). The model is driven by local winds; no wave or current boundary conditions are included.

The DEM on which the grid is based was assembled from a variety of sources including electronic navigation charts (ENCs) from the CHS, a high-water data set for the Pacific from the CHS, and a compilation of single and multi-beam survey data covering the CVRD coast out to about 70 m depth (CHS, 2020). The unstructured wave model grid developed from the DEM is shown in Figure 5. The deep-water wave model extends nominally to the high-water contour however, results were extracted for use in the nearshore wave model in deeper water because the nearshore wave model was constructed using a more accurate bathymetry in shallower areas (LiDAR dataset). Refer to Technical Memorandum #1 – Coastal and River Base Map Development for further details on how the mapping was developed for the model.

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[2] SHORLAX is an acronym for SHOReLine Analysis by Xsection

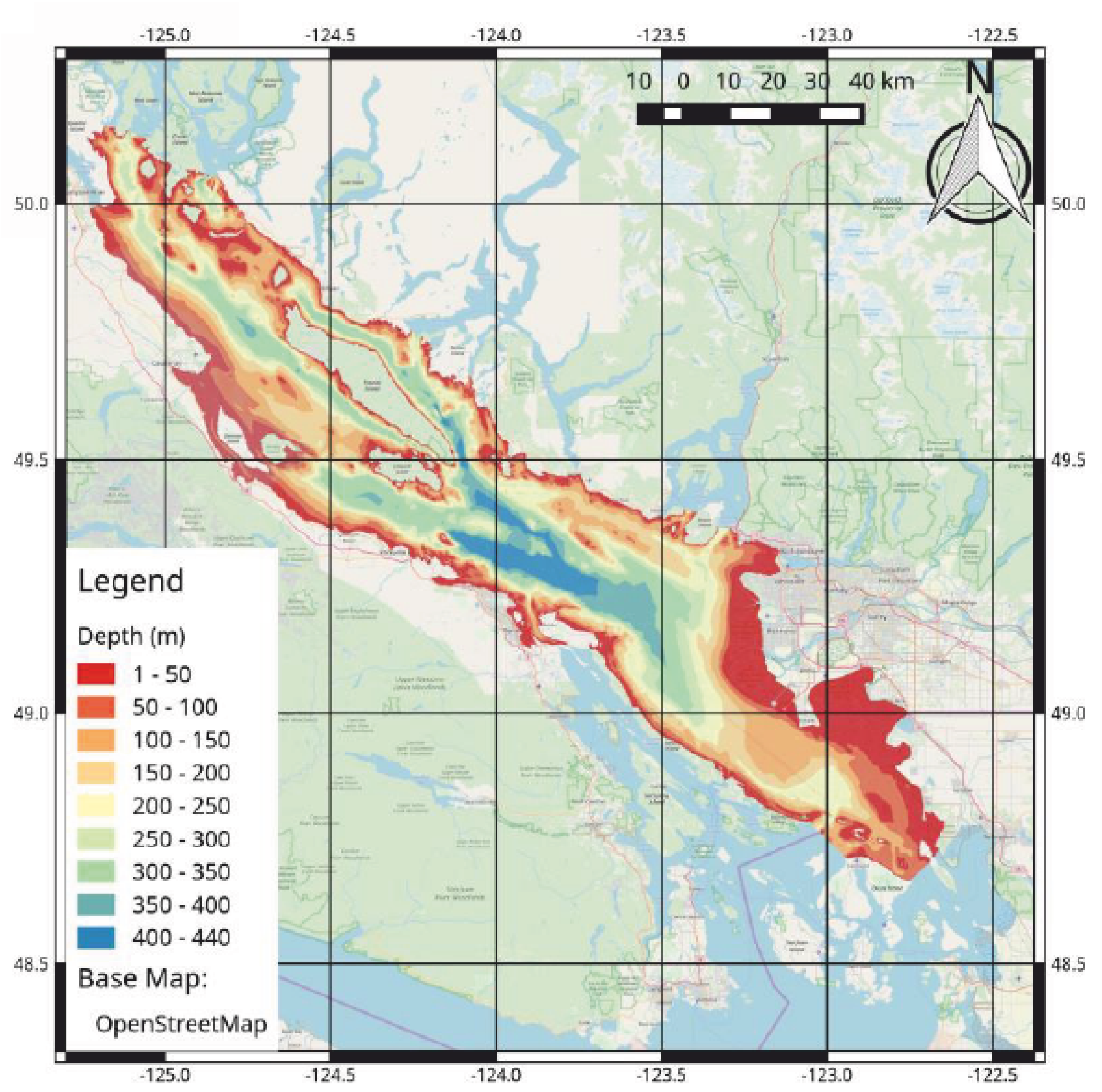

Figure 5: Unstructured Computational Wave Model Grid with Colour Bathymetric Elevation

Model Runs

A range of storm scenarios were developed for modelling. The full range of sea level rise scenarios (0.0, 0.5, 1.0, 2.0 m) were considered along with the full range of storm intensities (10%, 5%, 1%, 0.5%, 0.2% AEP) and a range of wind directions as noted in this section. The model setup was simplified by using the 0.2% AEP (500-year return period) extreme static water level for all model runs. This approximation has the effect of making the water level as much as 0.36 m too high for some runs which in theory could result in an overestimation of the wave height in shallow water conditions. However, the effect of this approximation is mitigated by the fact that the SWAN model results are converted to equivalent deep-water values when input to the nearshore wave model (see 5.2 Nearshore Wave Modelling) and therefore appropriate shallow water effects on wave heights and breaking end up being fully included in the analysis.

Wave conditions in the Strait of Georgia are generated almost entirely by local winds, therefore winds were used as a proxy to seek storm wave conditions associated with the target levels of probability. Eight storm directions (eight directional octants) were considered. Extreme value analysis was applied to the direction partitioned wind measurements from a weather station located in the middle of the study area close to the shoreline (Comox Airport) to find the wind velocity associated with 10%, 5%, 1%, 0.5% and 0.2% AEP events.

The wind data collected at Comox Airport spans from 1953 to 2020 with only small gaps in the data set. Extreme value analysis was performed on the Comox Airport data set using a peaks-over-threshold approach. The threshold was set for each analysis to yield an average of about four storms per year. The analysis partitioned the wind data into directional octants. A Generalized Pareto Distribution was fit to each storm set and was used for estimating the magnitude of specific probability events. The results are presented in Table 5; a wind rose for the Comox Airport data is provided in Figure 6.

Table 5: Extreme Value Estimates of Comox Airport Hourly Average Wind Speeds (m/s), Partitioned by Directional Octant

Annual Exceedance Probability	Wind Direction							
	45	90	135	180	225	270	315	360
10%	8.4	20.0	22.8	16.3	12.9	11.8	14.6	13.4
5%	9.3	21.3	23.7	17.2	14.0	13.4	15.3	14.0
1%	11.6	24.0	25.5	19.1	16.4	18.2	16.7	15.2
0.5%	12.7	25.1	26.2	19.9	17.5	20.8	17.2	15.6
0.2%	14.3	26.5	27.0	20.9	18.9	24.8	17.8	16.1

Spatially and temporally variable wind fields for the storm events were developed based on observations from Environment Canada weather stations within the Strait of Georgia. In total, 160 storm wave scenarios were developed and modelled (5 storm intensities (AEPs), 4 sea levels, 8 directions). Wave model results were validated by comparing them to measurements taken at several temporary and operational wave measurement buoys throughout the Strait of Georgia. The wave model results were found to adequately represent the observations.

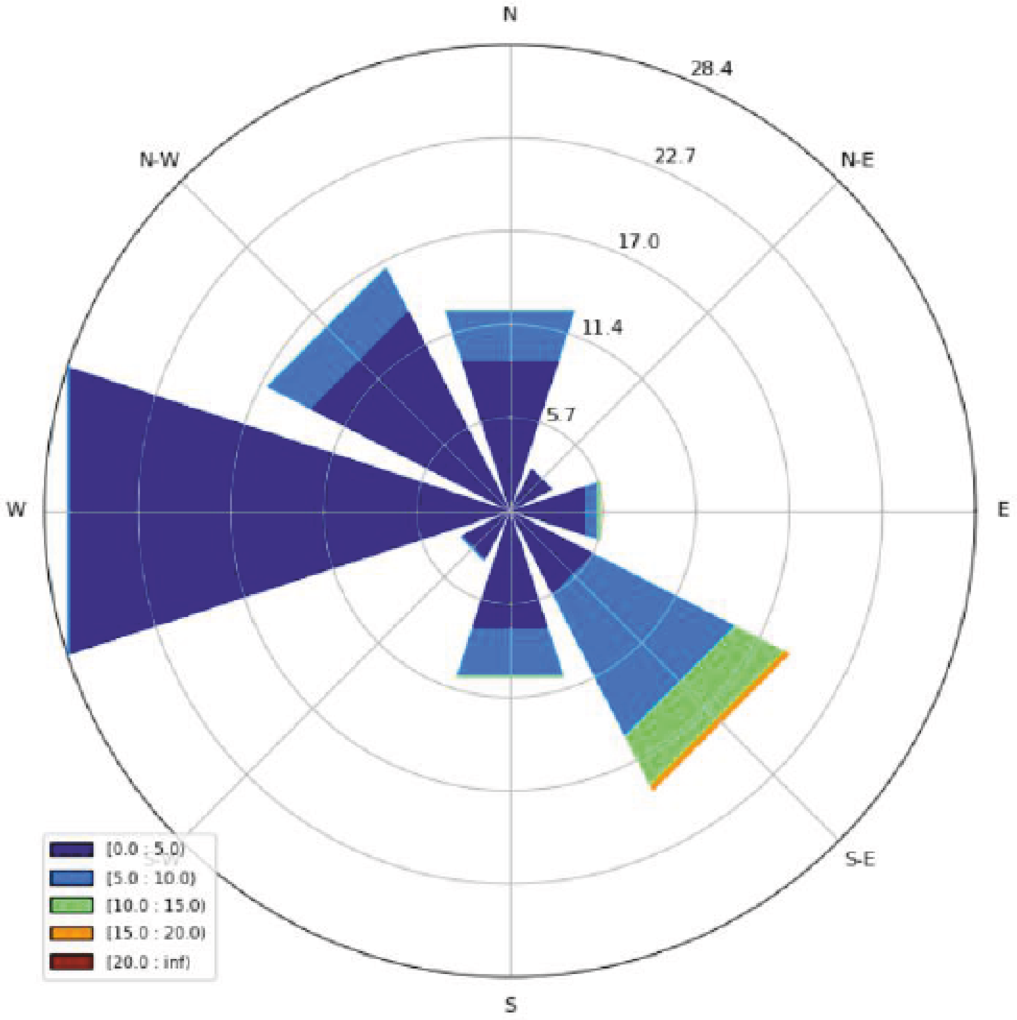

Figure 6: Wind Rose for the Comox Airport Weather Station. The Radial Extent of the Rays Indicate Frequency of Occurrence (as a Percentage) in that Directional Bin, the Point of the Rays Indicates the Direction the Wind is Blowing to, the Colours Indicate the Wind Speed Bins in [m/s].

Model Results

Locations for the output of wave data from each model run were selected to align with the input locations required for the nearshore wave model. These locations correspond to 50 m horizontal spacing along the 233 different shore-normal transects used for nearshore wave modelling. For each wave model run, parametric wave data was output at these locations for the entire duration of the storm being modelled at a 15-minute time step. The number of time steps in each model run varies with the wind direction because a different spatially and temporally variable wind field (storm) is used for each direction.

Figure 7 shows the maximum significant wave height (H_{m0}) at each output location for all of the scenarios with a 0.2% AEP and sea level rise of 0.0 m and 2.0 m, respectively. The figures show a very similar distribution of wave heights through the geographic area. However, with larger sea level rise, larger waves are evident closer to shore. This is consistent with the notion that with deeper water depths, larger wave heights are able to get closer to the shoreline before breaking.

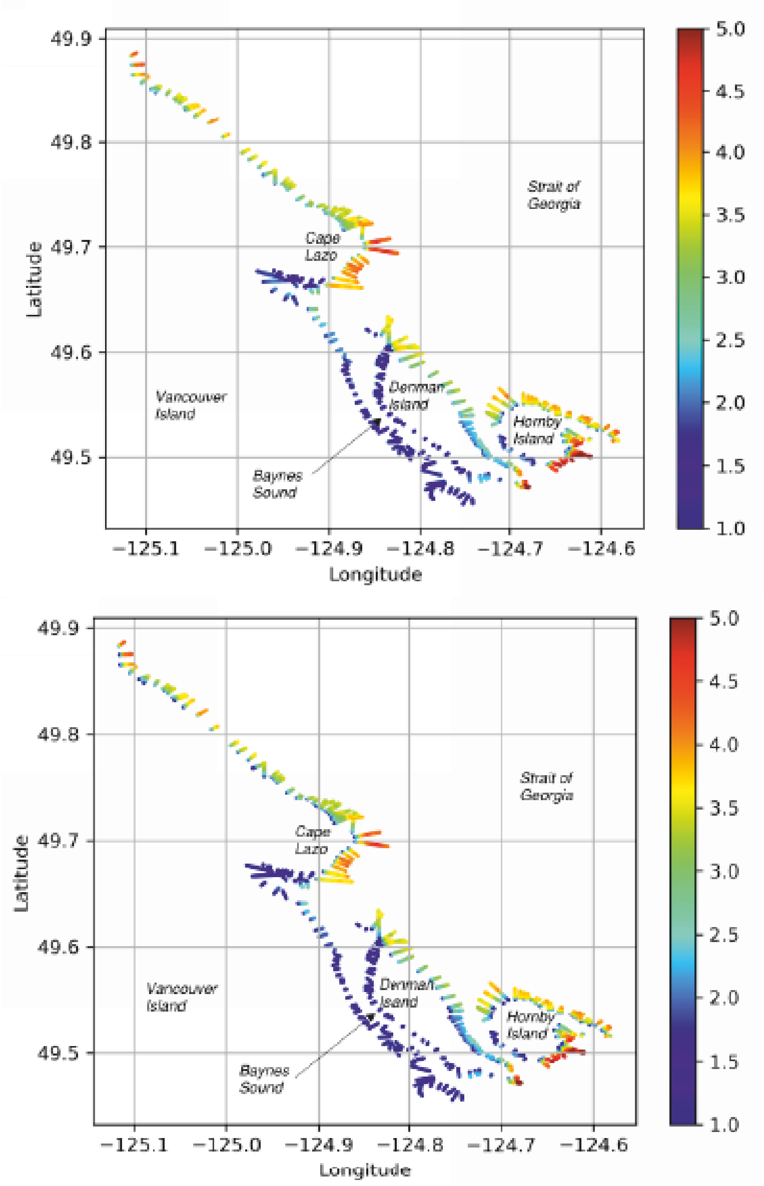

Figure 7: Maximum Significant Wave Height [m], for all Scenarios with an AEP of 0.2% for Sea Level Rise = 0 m (Top) and 2 m (Bottom)

The largest wave heights on CVRD shores (up to 5.4 m significant wave height for the 0.2% AEP event) occur on the south-east side of Denman Island and Hornby Island, where the islands are exposed to the full fetch of the Strait of Georgia to the south-east. Waves are nearly as large on the south-east side of Cape Lazo, but Denman and Hornby Islands provide this area with some protection. North of Cape Lazo the shoreline has less exposure to the prominent south-east storm direction, and consequently has smaller storm wave heights, up to about 4 m significant wave height. Baynes Sound is largely protected from waves propagating in from the Strait of Georgia, but local waves up to about 1.5 m can be generated within the Sound.

5.2 Nearshore Wave Modelling

Nearshore wave modelling was performed using custom software developed by KWL for high-resolution regional wave effect analysis (SHORLAX).

SHORLAX is a one-dimensional, transect-based wave model with calculation engines based on empirical equations which are commonly used for contemporary coastal floodplain mapping. The model uses the results of the deep-water wave model (SWAN) as its input. SHORLAX is coded in Python and runs in a parallel processing configuration. Computations are done by nine Raspberry Pi 3 computers (36 cores total) interfaced with a SQL server which stores the SWAN input data and the SHORLAX model output.

SHORLAX has two modules: a wave effects module and a module that calculates breaking wave heights in the surf zone. A description of the modelling approach for each module and the model results is provided in the following sections.

General Model Setup

As noted above, SHORLAX is a one-dimensional, transect-based wave model. One of the first steps in the model setup was to define the transect locations and generate the transects. During the transect selection process, the CVRD shoreline was divided into a series of “coastal zones’ with similar topography/bathymetry[3] and wave exposure. A single transect location was then defined within each coastal zone at a location which is considered to be representative of the topography/bathymetry and wave exposure in that zone. In general, there is a lower density of transects in stretches of shoreline with uniform topography, and the transect density is increased in areas with more a heterogeneous topography to provide better model resolution.

An important consideration in the selection of coastal zones and transects was to strike a balance between computational accuracy (which is best served through closely spaced transects) and computational efficiency (which is best served by minimizing the number of transects). In the end, 233 transects were selected to represent the shoreline of the CVRD; this translates into an average transect spacing of 760 m over the approximately 177 km of shoreline. The transects extend from -20 m elevation to +20 m elevation (CGVD2013). Locations and numbering of the transects is provided in Figure 8A and 8B. The transect numbering is not completely consecutive and there are some gaps in the transect numbering due to modifications made to the model as the modelling proceeded and results were obtained.

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[3] Refer to the KWL Technical Memorandum #1 – Coastal and River Base Map Development for further information on the development of the integrated topographic and bathymetric mapping.

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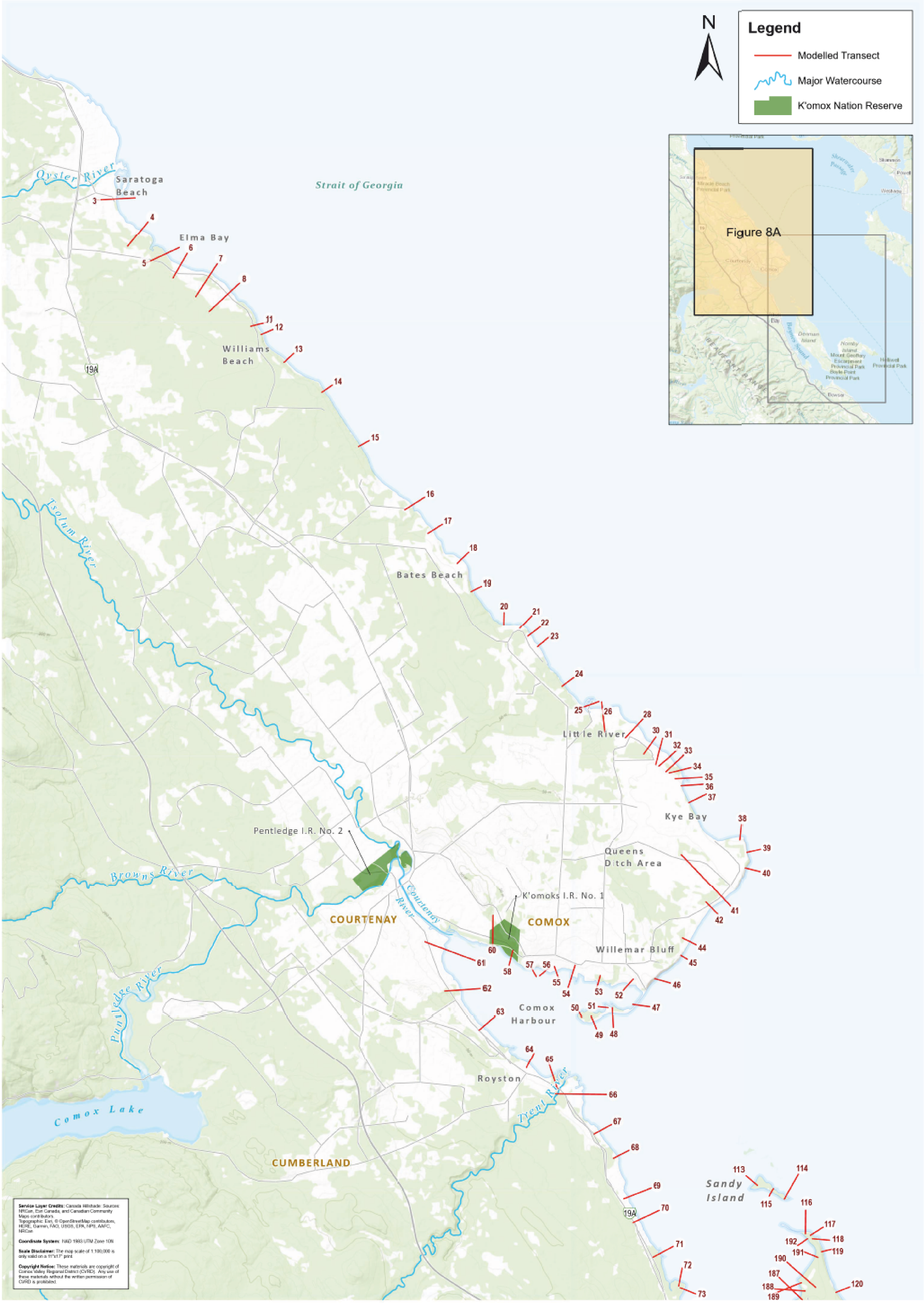
Comox Valley Regional District
Coastal Flood Mapping Project

KERR WOOD LEIDAL
consulting engineers



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Scale	1:100,000

0 0.5 1 2 Kilometres

Modelled Transect Locations

Figure 8A

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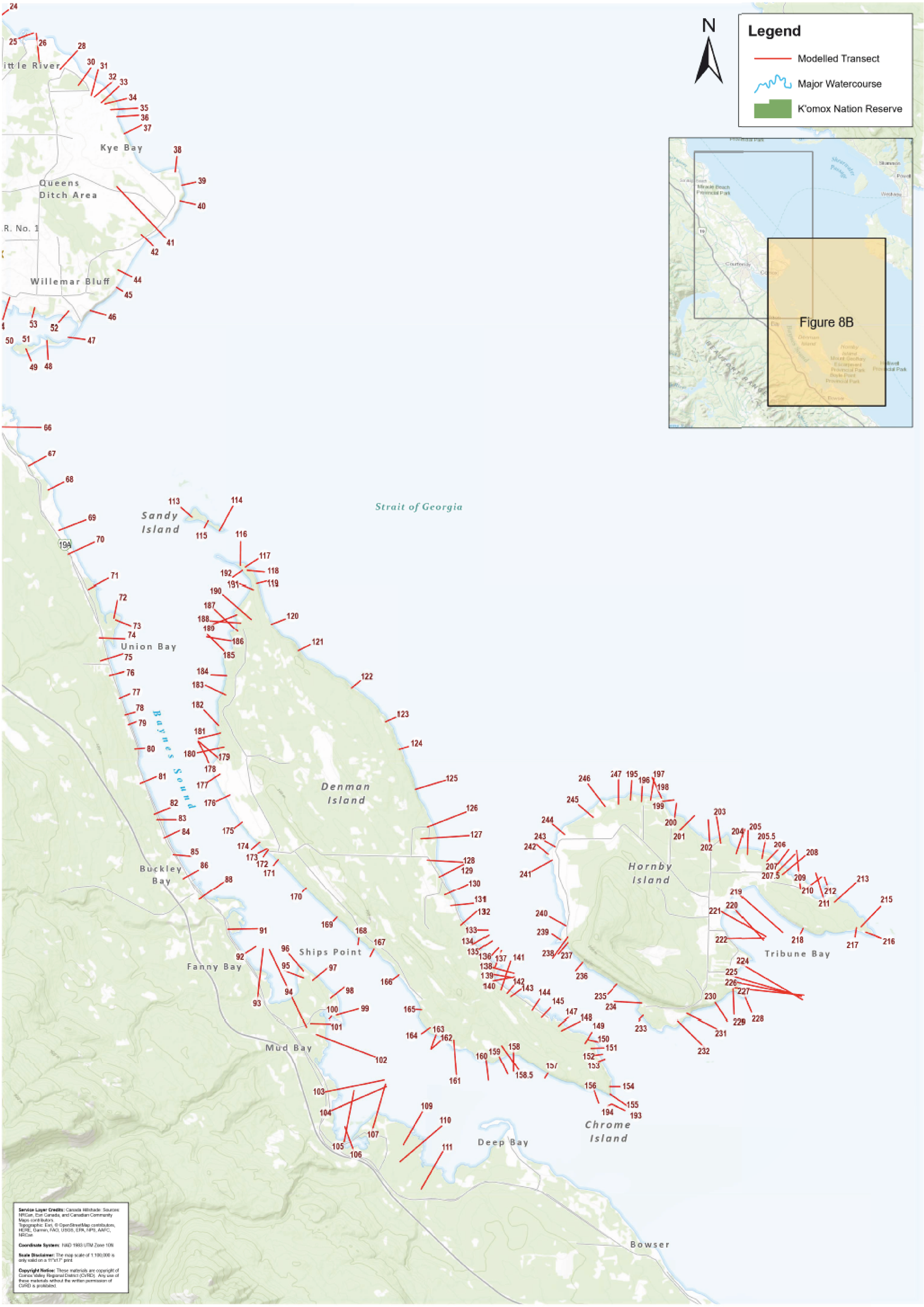

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Date	April 2021
Scale	1:100,000

0 0.5 1 2 Kilometres

Modelled Transect Locations

Figure 8B

Model runs were conducted for each transect, sea level rise scenario, extreme water level, storm direction, annual exceedance probability and time step. Computations are made for every time step in the storm event because the wave conditions change throughout the storm duration and it is not possible to determine a priority, which combination of wave height and period will produce the governing wave effect (i.e., the highest wave height may not necessarily govern).

A model run matrix is provided in Table 6. In accordance with the provincial guidelines (FLNR, 2018), water level and storm annual exceedance probabilities were matched when calculating wave effects and nearshore wave heights (i.e., the 0.2% AEP storm winds are assumed to occur at the same time as the 0.2% AEP extreme water level). This approach is conservative because high water levels and high winds do not always occur at the same time. In total, approximately 2.2 million model runs were conducted to cover the full range of transects, sea level rise scenarios, extreme water levels, storm directions, annual exceedance probabilities and time steps.

Table 6: SHORLAX Model Runs

Transect	Sea Level Rise Scenario	Extreme Water Level[1] and Storm Intensity	Storm Direction	Timestep[2]
1 to 233	0 m 0.5 m 1.0 m 2.0 m	10% AEP 5% AEP 1% AEP 0.5% AEP 0.2% AEP	45 90 135 180 225 270 315 360	1 to T_{max}

Notes:
1. Little River water levels were used for all transects except for Transects 50 through 65 in Comox Harbour where Comox Harbour levels were used.
2. The number of timesteps varies from 32 to 96 depending on the storm direction.

Wave Effect Module

The wave effect module estimates the **wave runup**. The wave runup elevation is measured from the still water level, as shown in Figure 9. The still water level is the sum of the extreme static water level and relative sea level rise for each scenario. The **wave setup**, also shown on Figure 9, is an increase in the still water level in the surf zone caused by a transfer of momentum from the breaking waves into a local increase in the water level as the waves propagate into shallow water and lose energy. The wave setup is important because it influences nearshore wave heights as discussed below.

The amplitude of the wave runup and wave setup is time varying within a given sea state (i.e., point in time in a storm event) and the variation can be described by a statistical distribution. In current coastal floodplain mapping practice, the wave runup value exceeded by only 2% of the waves, $R_{2\%}$, is often used to define the coastal floodplain boundary (FEMA, 2018). The 2% wave setup value is similarly used to calculate nearshore water levels (FEMA, 2015). It is common practice to use the wave runup value exceeded by 50% of the waves, $R_{50\%}$, to estimate the location of the future natural boundary when establishing setbacks (Ausenco Sandwell, 2011b). The $R_{50\%}$ value can be directly determined from the $R_{2\%}$ value based on the assumption that the wave run-up elevations are Rayleigh distributed as is common practice (FEMA, 2018).

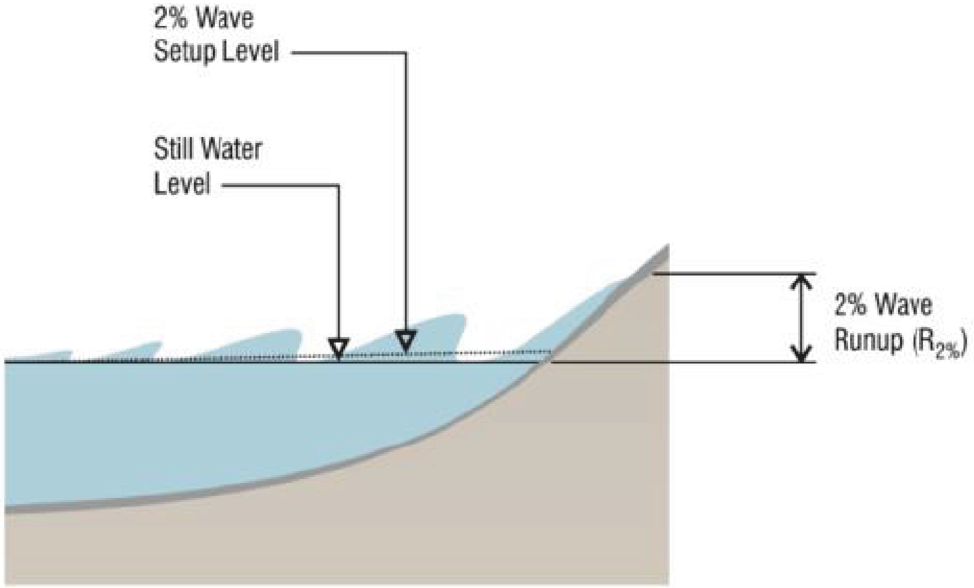

Figure 9: 2% Wave Runup ($R_{2\%}$) and 2% Wave Setup

A flow chart for the SHORLAX wave effect module is provided in Figure 10. Each step of the algorithm is described and elaborated on in the sections below; note that each step in the flow chart is contained in a separate box which is designated by a unique letter.

Box A – SWAN Input

The input to SHORLAX is the output from the SWAN deep water wave model. SWAN model results are output for each transect at 50 m intervals along the transect. The key SWAN outputs relevant to SHORLAX (SWAN variable names in brackets) are the significant wave height (HSIGN), the mean spectral wave period (TMM10), the elevation of the seabed (BOTLEV) and the quantity of energy lost to wave breaking (QB).

Box B – Pre-Processing

The pre-processing routine takes the SWAN output and converts it into the required inputs for the wave effect routine. It also develops the run control matrix which defines the set of wave effect runs which must be completed to cover each extreme water level, sea level rise scenario, wind direction, annual exceedance probability and timestep.

A key input into the wave effect routine is the **equivalent deep-water significant wave height, $H_{mo'}$**. The equivalent deep water significant wave height is calculated in the pre-processing algorithm by determining the closet location to the shoreline where the waves are unbroken based on the value of QB. The pre-processing algorithm then "deshoals" the waves to deep water using the shoaling relationship from linear wave theory. The result is a fictitious deep wave height that includes the effect of wave refraction.

Box A

Deep Water Wave Model (SWAN) Input[1]

Significant Wave Height (HSIGN)[2]

Mean Spectral Wave Period (TMM10)

Bottom Level (BOTLEV)

Energy Lost to Wave Breaking (QB)

Box B

Pre-Processing

Create Run Control Matrix:

- Extreme Water Level (10%, 5%, 1%, 0.5%, 0.2% AEP)
- SLR (0 m, 0.5 m, 1.0 m, 2.0 m)
- Storm (10%, 5%, 1%, 0.5% and 0.2% AEP)
- Wind Direction (45, 90, 135, 180, 225, 270, 315, 360)
- Timestep

Calculate $H_{mo'}$, the equivalent deep water significant wave height for each Extreme Water Level, SLR, storm, wind direction and timestep

Box C

Wave Effect Routine

For each run, i, in the Run Control Matrix:

Box C1

Stockdon Equation

Calculate $R_{2\%\_STOCKDON\_i}$

Applicable for beach slopes less that 10H:1V.

Box C2

EurOtop Equation – Variation A[4]

Calculate $R_{2\%\_EUROTOP\_A\_i}$

OR

For topographic plateaus:
Calculate $R_{2\%\_EUROTOP\_A\_FICTIOUS\_i}$

AND

Calculate $R_{2\%\_EUROTOP\_A\_OVERLAND\_i}$

Eq. 5.4 and 5.5 used for structure slopes from 10H:1V to 2H:1V. Eq. 5.7 used for steeper slopes.[3]

Box C3

EurOtop Equation – Variation B[4]

Calculate $R_{2\%\_EUROTOP\_B\_i}$

OR

For topographic plateaus:
Calculate $R_{2\%\_EUROTOP\_B\_FICTIOUS\_i}$

AND

Calculate $R_{2\%\_EUROTOP\_B\_OVERLAND\_i}$

Eq. 5.4 and 5.5 used for structure slopes from 10H:1V to 2H:1V. Eq. 5.7 used for steeper slopes.[3]

Box D

Post-Processing

1) **Calculate Total Water Level (TWL) for each run in the Run Control Matrix and equation:**

$TWL_{\_STOCKDON\_i} = R_{2\%\_STOCKDON\_i}+$ Extreme Water Level + SLR

$TWL_{\_EUROTOP\_A\_i} = R_{2\%\_EUROTOP\_A\_i}+$ Extreme Water Level + SLR

$TWL_{\_EUROTOP\_B\_i} = R_{2\%\_EUROTOP\_B\_i}+$ Extreme Water Level + SLR

For topographic plateaus:

$TWL_{\_EUROTOP\_A\_OVERLAND\_i} = R_{2\%\_EUROTOP\_A\_OVERLAND\_i}+$ Extreme Water Level + SLR

$TWL_{\_EUROTOP\_B\_OVERLAND\_i} = R_{2\%\_EUROTOP\_B\_OVERLAND\_i}+$ Extreme Water Level + SLR

2) **Graphically Review TWL values**

3) **Manually select governing TWL based on following criteria:**

- Within bounds of applicability of equation for slope

AND

- Is appropriate for case (standard, topographic plateau)

AND

- Yields highest TWL value

Box E

Results

All cases:

$TWL_{\_GOVERNING} = R_{2\%\_GOVERNING}+$ Extreme Water Level + SLR

Wave Runup Elevation ($R_{2\%\_GOVERNING}$)

Coastal Floodplain Limit: X location (distance along transect) of limit of wave runup

For topographic plateaus:

Limit of Wave Action Zone: X location (distance along transect) of the transition between impulsive wave run-up on the foreshore and the overland flow on the topographic plateau

Adjust above values for freeboard for regulatory mapping.

NOTES

1) All the variable names in this Box A are the variable names from the SWAN program.
2) "HSIGN" is the significant wave height and is commonly labeled H_s or H_{mo}.
3) Equation references are from the EurOtop overtopping manual; see Reference 6.
4) Refer to text for description of variations.

Project No. 2623-014
Date April 2021

Shorlax Flow Chart

Figure 10

Box C1 – Wave Runup Calculation Using the Stockdon Equation

The Stockdon equation is used to calculate wave run-up on natural beaches and is valid for beach slopes flatter than 10H:1V (Stockdon et al., 2005). The average beach slope is iteratively calculated between the wave breaking depth and shoreline wave setup elevations. The wave breaking depth is taken as the deep-water wave divided by 0.78 (wave breaking index). The equation uses the equivalent deep water significant wave height, $H_{mo'}$ (discussed in the previous section) as it's input. The output, $R_{2\%}$, includes both wave setup and wave runup.

Box C2 & C3 – Wave Runup Calculation Using EurOtop Equations – Variations A & B

The "EurOtop equations"[4] were developed to calculate wave run-up on structures such as coastal dikes, embankment seawalls and vertical walls and are used for structure slopes from 10H:1V to vertical (EurOtop, 2018). These equations have been used in this study to calculate wave run-up on structures and natural shorelines within the appropriate slope range because wave run-up physics for structures and natural shoreline are essentially the same. The EurOtop equation output, $R_{2\%}$, includes both wave setup and wave runup.

Application of the EurOtop equations is more complex than the Stockdon equation. The main difference is that the EurOtop equations use the wave height at the **toe of structure** as their input and the structure slope is calculated between the **toe of structure and the maximum extent of wave runup**. This introduces a couple of extra complications: the location of the toe of structure must be defined and the wave height at that location must be estimated. SHORLAX uses two approaches to determine the location of the toe of structure and calculate the wave runup:

Variation A: An algorithmic approach that estimates the toe location based on the transect geometry. The "toe of structure" is selected when the slope exceeds 8H:1V and is within the wave breaking zone.

Variation B: A manual approach in which the toe of structure location is pre-defined based on a visual review of the transect geometry and the model results from Variation A.

Figure 11 provides a schematic example of Variation A and B of the EurOtop equations at an example transect.

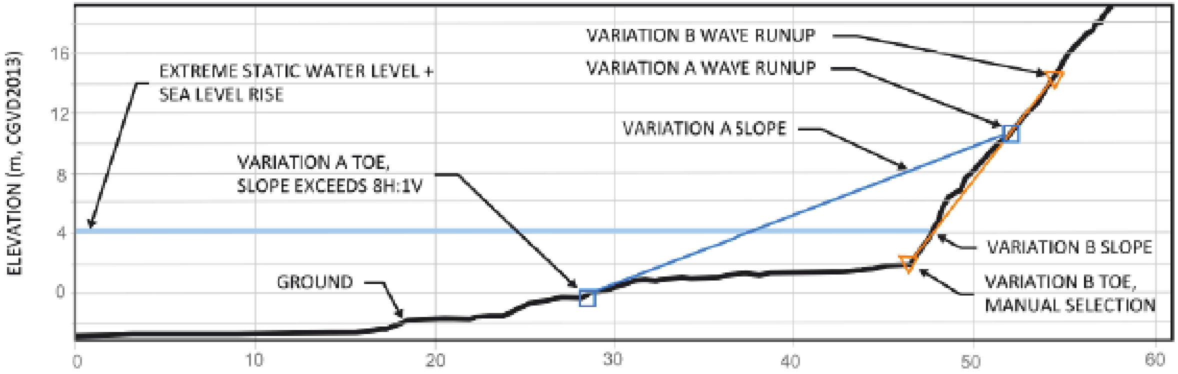

Figure 11: Variation A and B of the EurOtop Equations at an Example Transect

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[4] SHORLAX uses equations 5.4, 5.5 and 5.7 from the EurOtop manual (EurOtop, 2018). These equations are suitable for the "design" approach and produce runup values that include some safety (one standard deviation) and can be used for design and assessment of coastal structures.

Once the toe of structure location is known, the water depth at that location needs to be calculated to estimate the wave height. The water level is the sum of the extreme water level, sea level rise and wave setup. Wave setup is calculated using the Direct Integration Method (DIM) equations provided in the United States Federal Emergency Management Agency guidance on the calculation of wave setup (FEMA, 2015) using a spectral width/narrowness parameter of 3.3 which is considered to be most appropriate for the locally generated wind waves in the study area. The wave height is estimated as 0.78 times the water depth.

The EurOtop routine also includes an algorithm to identify topographic plateaus which are features with a flat or mild slope inland of a steeper foreshore slope. Topographic plateaus need to be handled in a different manner from continuously rising slopes because the extent of inundation is governed by "bore dominated" overland flow rather than the momentum present in the waves.

Topographic plateaus are algorithmically identified when the slope calculated by the iterative slope/runup algorithm drops more than a threshold value which is indicative of a sharp drop-off and "plateau". In this case, the methods outlined in FEMA (2018) to calculate the runup based on a "fictitious" slope projected from the plateau face are used. The fictitious wave runup over the crest of the topographic plateau is then used to estimate the shoreward extent of overland flooding based on the profile of the Energy Grade Line (EGL) of the overland flow. An estimated slope of the EGL of 0.04 m/m is used in SHORLAX; this value was obtained through an analysis of the work of French (1982) and represents a lower bound (conservative) value.

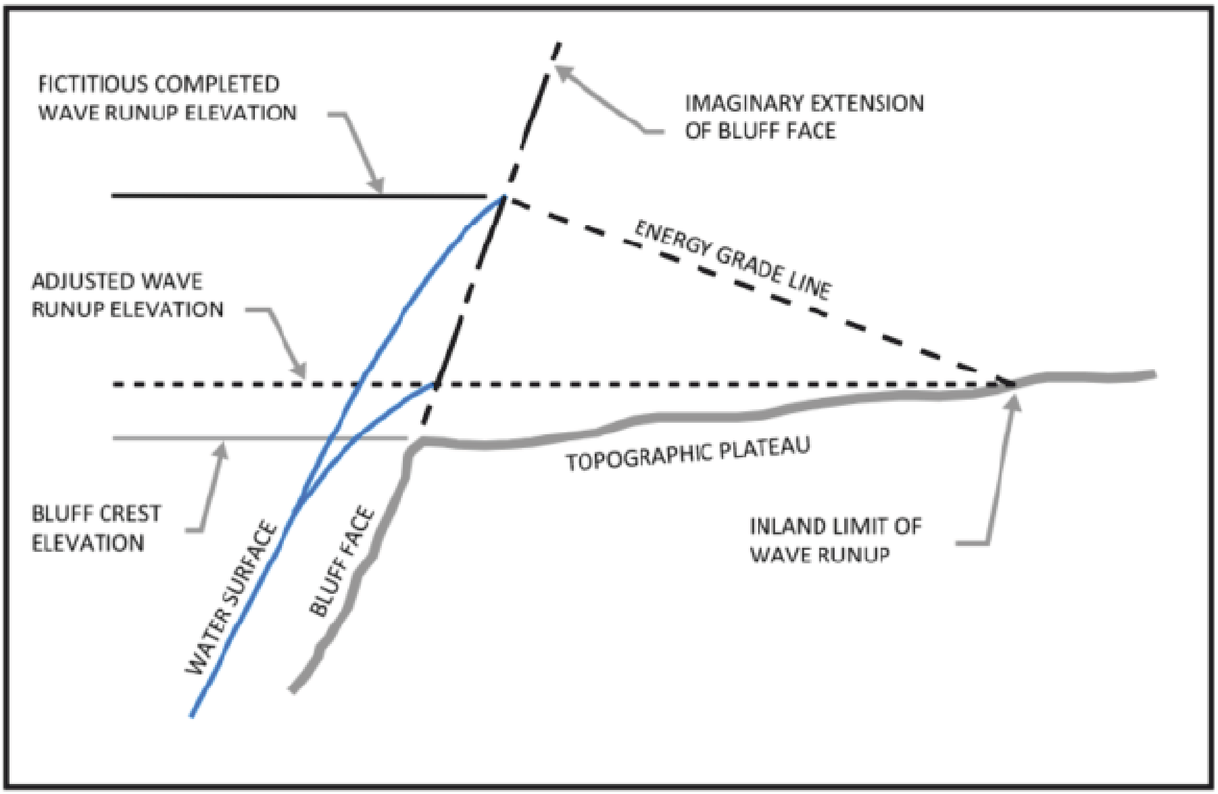

Figure 12: Wave Runup Calculation for a Topographic Plateau Based on FEMA (2018)

Box D – Post-Processing

The post-processing routine calculates the total water level for all equations and the results are viewed graphically by the user. The governing total water level and wave runup elevation is then manually selected as the highest wave runup elevation calculated using an equation in its range of slope applicability and for the appropriate scenario (e.g., topographic plateau or otherwise).

Box E – Results

The results from the SHORLAX wave effects module are then tabulated; the results are:

General

- **Governing Total Water Level Elevation:** $R_{2\%\_GOVERNING}$+ Extreme Water Level + Sea Level Rise.
- **Governing Wave Runup Elevation:** ($R_{2\%\_GOVERNING}$).
- **Coastal Floodplain Limit:** X location (distance along transect) of the limit of wave runup.

Additional Information for topographic plateaus:

- **Limit of Wave Action Zone:** X location (distance along transect) of the transition between impulsive wave run-up on the foreshore and the overland flow on the topographic plateau.

The results from SHORLAX are adjusted outside of the program to include freeboard values for regulatory floodplain mapping as appropriate.

Uncertainties and Assumptions

The uncertainties and assumptions inherent in the wave effect calculations are listed in Table 7 along with a discussion of the associated implications, reasoning, and justifications.

Table 7: SHORLAX Wave Effect Module Assumptions

Index	Assumption	Discussion
1	The topography and geomorphology of the shoreline does not change with sea level rise	SHORLAX uses the existing topography and bathymetry to estimate runup elevations for existing and future sea level rise conditions. In reality, shorelines will likely erode and flatten in the intertidal area as sea levels rise. Assuming that the topography and geomorphology of the shoreline does not change with sea level rise is considered to be conservative because wave runup is higher for steeper (i.e., non-eroded) slopes. The assumption also accommodates situations where waterfront homeowners elect to harden their shorelines "as is" to prevent erosion.

Index	Assumption	Discussion
2	Coastal erosion protection structures remain intact during storms	Further to Assumption #1, it is assumed that existing coastal structures do not fail during storm events and therefore the transect topography does not change throughout a storm event. Given that the floodplain mapping was developed on a regional scale, it has not been possible to assess individual erosion protection structures for robustness or suitability. In general, if structures fail, the foreshore slope will decrease as erosion occurs and wave runup will decrease. Therefore, in general, this is considered to be a conservative assumption; however, wave runup could conceivably increase, at least for a short period of time, if the roughness of the structure was to decrease as it failed. This possibility is addressed in Assumption #5.
3	Neglect surf zone wave refraction	A noted above, wave inputs to SHORLAX are extracted from SWAN at the closest location to the shoreline where the waves are unbroken. As a result, wave refraction in the surf zone is neglected. This is a conservative assumption because wave refraction reduces wave heights. It is also believed that the effect on the model results of this approximation is negligible and well within the accuracy of the modelling.
4	Shoreline roughness is neglected in the runup calculations for the EurOtop equations	The EurOtop manual (2018) includes a modification factor for wave runup to account for structure surface roughness (e.g., rough surfaces such as riprap). The modification factor is a reduction, and therefore not including it in SHORLAX is conservative. We believe that this is an appropriate assumption because it offers a level of conservatism should coastal structures fail and lose roughness.
5	Angle of wave incidence is neglected in the runup calculations for the EurOtop equations	The EurOtop manual (2018) includes a modification factor for wave runup to account for oblique wave incidence relative to the structure. The modification factor is a reduction, and therefore not including it in SHORLAX is conservative. We believe that this is an appropriate assumption because the majority of the CVRD shoreline is fronted by natural, shallow foreshores and therefore wave refraction will tend to refract the wave crests close to parallel to the shore in most cases. It should be noted that the Stockdon equation does not include modification factors for wave direction, likely for this reason (Stockdon et al., 2005).
6	Inland flooding limits are estimated based on local transect topography and do not account for wave overtopping rates	Inland flooding limits are estimated based on the one-dimensional transect topography and do not account for wave overtopping rates and the relative conveyance capacity and storage volume of inland water courses and drainage systems.

Nearshore Wave Height Module

The nearshore wave height module of SHORLAX is based on the empirical formulas for wave height transformation in the surf zone developed by Goda (2010). Transformed SWAN model wave results are used as the input as described in Box B in the previous section, and then the wave heights in the surf zone are calculated in a stepwise fashion at each point on the transect from deep water to shallow water. The algorithm contains logic to prevent wave heights from increasing in scenarios where the water depth decreases and then increases again (e.g., a sand bar). Calculation of the local bottom slope is needed to estimate wave heights; the algorithm averages the bottom slope over one wavelength seaward of the point of interest when calculating the bottom slope.

Results

Some samples of SHORLAX results for the Little River area (Transects 25, 26 and 28) are provided in Figures 13 through 15. The Little River area is situated on a relatively low elevation alluvial fan at the mouth of the Little River. The area is backed by a bluff which terminates in a plateau.

- Figure 13 shows total water levels (maximum water levels) for a storm and extreme static water levels with AEPs of 10%, 5%, 1%, 0.5% and 0.2% for the 1.0 m sea level rise scenario. No freeboard allowance is included. It can be seen that the alluvial fan (and Little River area) is inundated by the 10% AEP event and more severe storm events increase inundation levels but do not increase flood inundation extents to a great degree due to the presence of the bluff backing the area.
- Figure 14 shows maximum water levels (no freeboard allowance) for a storm and extreme static water level with an AEP of 0.5% for the four different sea level rise scenarios (0 m, 0.5 m, 1.0 m, and 2.0 m). It can be seen that varying sea levels have a greater impact on flood levels than varying storm intensities shown in Figure 13. The alluvial fan is partially inundated for current sea levels, but inundation is total for 2.0 m of sea level rise.
- Figure 15 shows water depths for the 0.5% AEP and 1.0 m sea level rise scenario. The water depths do not include wave effects or freeboard (only the extreme water level). It can be seen that the alluvial fan is almost completely inundated with 1.0 m of sea level rise even when no storm waves are present.

Some samples of SHORLAX results for the Tribune Bay area (Transects 218, 219 and 220) and the Ships Point area (Transect 98) are provided in Figures 16 and 17.

- Figure 16 shows maximum wave heights in the coastal floodplain in the Tribune Bay area for a water level and AEP of 0.5% and 1.0 m of sea level rise.
- An example of flood mapping in an area with a topographic plateau (Ships Point) is provided in Figure 17. It can be seen that the wave action zone is confined to the immediate foreshore, seaward of the houses in that particular area and the remainder of the flooded area is flooded by overland "wave bore" type flow.

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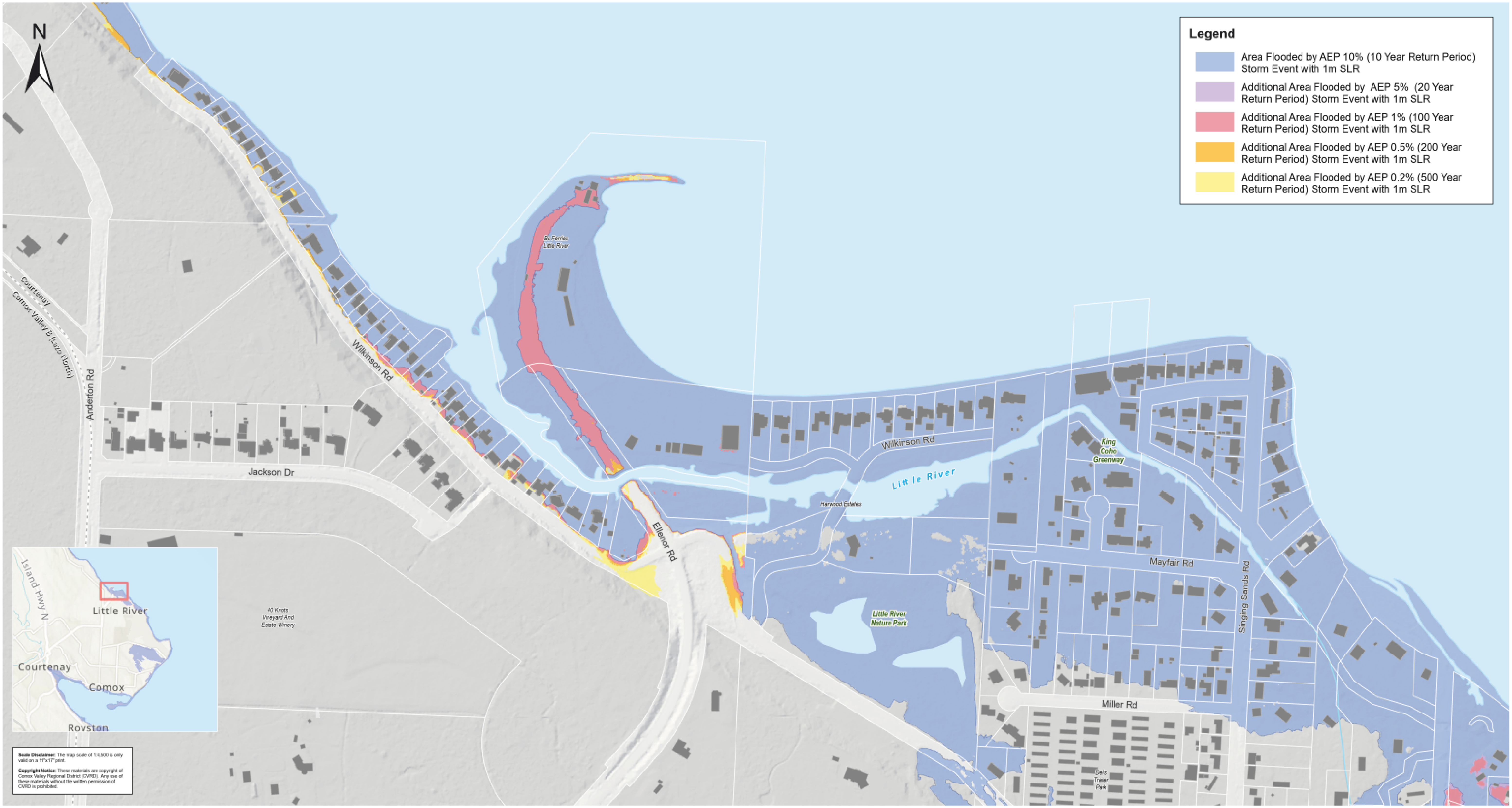
Comox Valley Regional District
Coastal Flood Mapping Project

KERR WOOD LEIDAL
consulting engineers



Legend

- 🟦 Area Flooded by AEP 10% (10 Year Return Period) Storm Event with 1m SLR
- 🟪 Additional Area Flooded by AEP 5% (20 Year Return Period) Storm Event with 1m SLR
- 🟥 Additional Area Flooded by AEP 1% (100 Year Return Period) Storm Event with 1m SLR
- 🟧 Additional Area Flooded by AEP 0.5% (200 Year Return Period) Storm Event with 1m SLR
- 🟨 Additional Area Flooded by AEP 0.2% (500 Year Return Period) Storm Event with 1m SLR

Scale Disclaimer: The map scale of 1:4,500 is only valid on a 11"x17" print.

Project No.	2623-014
Date	April 2021
Scale	1:4,500

0 25 50 100 Metres

Little River Area - Maximum Water Levels for 10%, 5%, 1%, 0.5% and 0.2% AEP Storms with 1.0 m Sea Level Rise

Figure 13

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Date April 2021
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Little River Area - Maximum Water Levels for 0.5% AEP Storm with 0 m, 0.5 m, 1.0 m and 2.0 m Sea Level Rise

Figure 14

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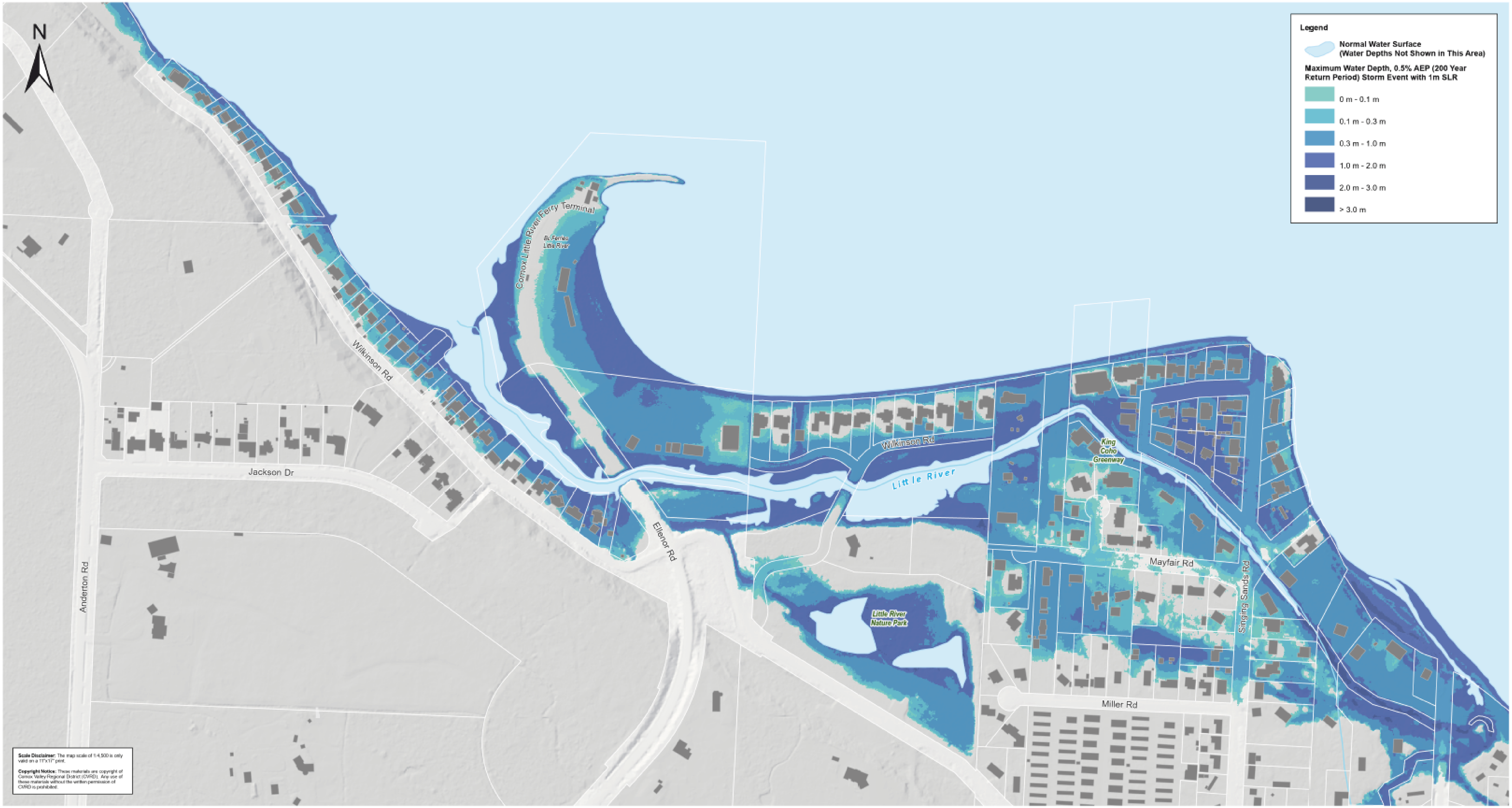

Project No. 2623-014
Date April 2021
Scale 1:4,500
0 25 50 100 Metres

Little River Area - Maximum Water Depths for 0.5% AEP Storm with 1.0 m Sea Level Rise

Figure 15

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Comox Valley Regional District
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Project No. 2623-014
Date April 2021
Scale 1:5,000
0 25 50 100 Metres

Maximum Wave Heights in the Coastal Floodplain for AEP of 0.5% and 1.0 m of Sea Level Rise

Figure 16

Path: Z:\2000-2999\2600-2699\2623-014\430-GIS\Pro Projects\2623014_Rp_RepresentativeExamples\2623014_Rp_RepresentativeExamples.aprx Date Saved: 4/20/2021 11:41 PM | Author: TSoh

Comox Valley Regional District
Coastal Flood Mapping Project

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consulting engineers

Coordinate System: NAD 1983 UTM Zone 10N

Scale Disclaimer: The map scale of 1:2,500 is only valid on a 11"x17" print.

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Project No.	2623-014
Date	April 2021
Scale	1:2,500

0 15 30 60 Metres

Ships Point - Topographic Plateau Area – 0.5% AEP, 1 m SLR

Figure 17

Complete total water level results from SHORLAX are presented in Table 1B in Appendix B. Table 1B provides the total water level for each sea level rise scenario and annual exceedance probability. Some trends that are evident from inspection of the Table 1B are as follows:

1. It can be seen that wave runup and total water level values are larger for steeper slopes and more exposed shorelines with higher incident wave heights. Notable examples of bounding cases are southeast Denman Island (Transect 151) which has bedrock cliffs and high wave exposure and Deep Bay (Transect 110), which has flatter slopes and is sheltered within Baynes Sound. A schematic illustration of these two transects is included in Figure 18 for the 0.5% AEP and 1 m of sea level rise scenario.
2. Another notable trend in the results is that the total water level tends to increase more than the magnitude of the sea level rise component, particularly in areas with steeper shoreline slopes and greater wave effect (refer to Transect 151). This is due to the typical topography of the shoreline, in which a lower gradient foreshore (current intertidal zone) is backed by a steeper backshore or bluff; this steepening of the slope inland of the present high tide has the effect of amplifying the wave effect as sea levels rise. This effect is further compounded by the fact that higher water levels result in less wave breaking and greater wave heights close to the shore.

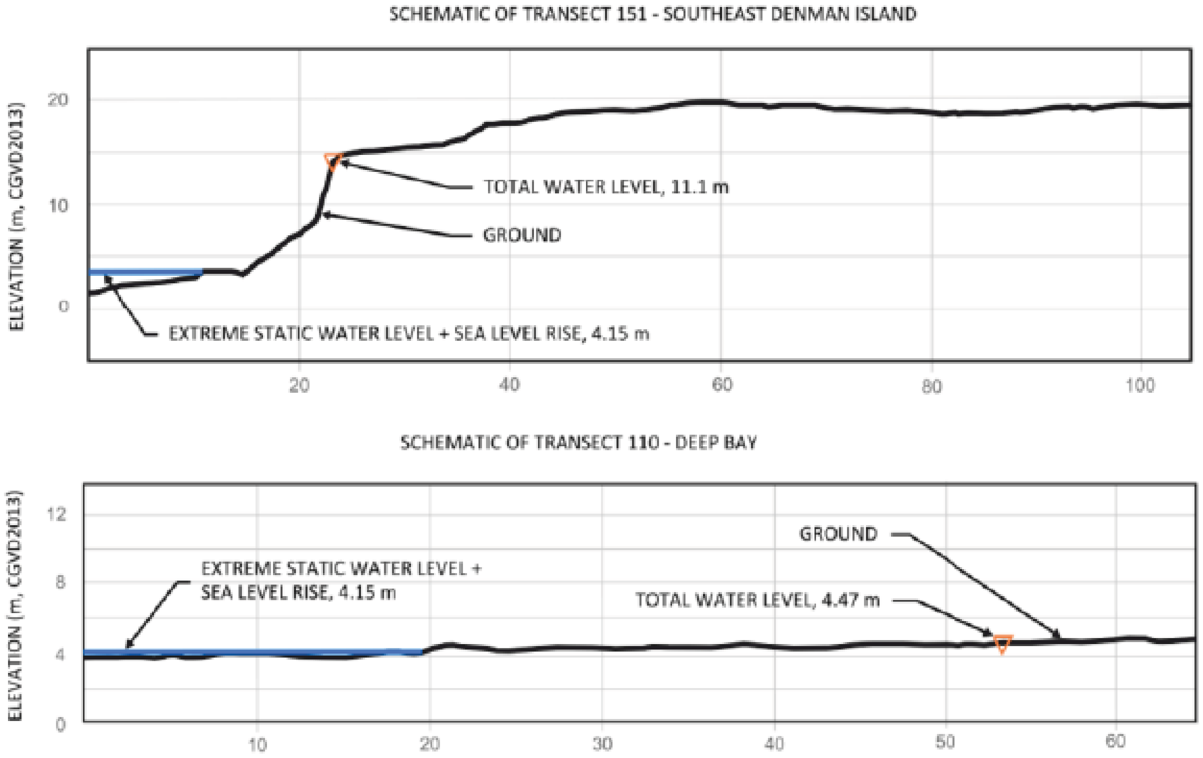

Figure 18: Schematic Illustrations of Transect 151 and Transect 110 for 0.5% AEP and 1 m Sea Level Rise Scenario

A review of the coastal modelling results in several "case study" areas can be found in the main report for the Coastal Flood Mapping Project.

6. Closing

We trust that this summary of the coastal modelling methods used for the Coastal Flood Mapping Project provides the Comox Valley Regional District with the information required. If you have any questions, please contact the undersigned at 250-595-4223.

KERR WOOD LEIDAL ASSOCIATES LTD.

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Encl.: Appendix A: Cascadia Coast Research Report
Appendix B: Tabular SHORLAX Results

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Revision History

Revision #	Date	Status	Revision Description	Author
0	April 23, 2021	Final	Final	EM

Appendix A

Cascadia Coast Research Report

Storm Wave Analysis: Comox Valley Regional District, BC

Authour:
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Technical Review:
Eric Morris, P. Eng.
Kerr Wood Leidal Associates Ltd.

October 18, 2020

October 18, 2020

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Revision History

Rev.	Date	Authour	Description	Signature
0	April 26,2020	C. Hiles	Draft to KWL for review	
1	May 24, 2020	C. Hiles	Address KWL comments	
2	June 19, 2020	C. Hiles	Address Ebbwater comments	PROFESSIONAL PROVINCE OF BRITISH COLUMBIA ENGINEER C. E. HILES Oct 10, 2020

Summary

Cascadia Coast Research was retained as a sub-consultant to Kerr Wood Leidal to perform an assessment of storm wave conditions along the shores of the Comox Valley Regional District. Cascadia Coast Research was responsible for developing, executing and analyzing the results of a two dimensional wave model capable of estimating storm wave conditions. Cascadia was also responsible for estimating storm wind conditions using extreme value analysis, and using those storm wind conditions within the wave model to estimate storm wave conditions.

For this work a two dimensional wave model was developed based on the SWAN wave modelling software (version 41.20). The model uses an unstructured grid and covers the Strait of Georgia from the San Juan Islands in the south-east to the Discovery Islands in the north-west. Average element length is about 200 m through most of the grid, but decreases to 40 m at the Comox Valley Regional District shoreline.

A range of storm scenarios were developed for modelling. Storm water levels were provided by KWL. A range of relative sea level rise levels (0.0, 0.5, 1.0, 2.0 m) and storm directions (8 directional octants) were considered. Wave heights associated with the 10%, 5%, 1%, 0.5% and 0.2% annual exeedance probability were sought.

Wave conditions in the Strait of Georgia are generated almost entirely by local winds. To reduce the required modelling, winds were used as a proxy to seek storm wave conditions associated with the target levels of probability. Extreme value analysis was applied to the direction partitioned wind measurements from a nearby weather station to find the wind velocity associated with 10%, 5%, 1%, 0.5% and 0.2% annual exeedance probability events. Spatially and temporally variable wind fields for the storm events were developed based on observations from at Environment Canada weather stations within the Strait of Georgia.

In total, 160 storm wave scenarios were developed and modelled. The scenarios and corresponding model results are presented in this report, as well as in the accompanying data files. Results were evaluated by comparison to measurements at several temporary and operational wave measurement buoys throughout the Strait of Georgia. The wave model estimates were found to adequately represent the observations.

The largest wave heights on CVRD shores (up to 5.4 m significant wave height for the 0.2% exceedance probability event) occur on the SE side of Denman Island and Hornby Island, where the islands are exposed to the full fetch of the Strait of Georgia to the SE. Waves are nearly as large on the SE side of Cape Lazo, but Denman and Hornby Islands provide this area some protection. North of Cape Lazo the shoreline has less exposure to the prominent SE storm direction, and consequently has smaller storm wave heights, up to about 4 m significant wave height. Baynes Sound is largely protected from waves propagating in from the Strait of Georgia, but local waves up to about 1.5 m can be generated within the Sound.

Contents

List of Figures

List of Tables

List of Acronyms

AEP	Annual Exceedance Probability
BC	British Columbia
CCR	Cascadia Coast Research
CD	Chart Datum
CGVD28	Canadian Geodetic Vertical Datum of 1928
CHS	Canadian Hydrographic Service
CVRD	Comox Valley Regional District
DEM	Digital Elevation Model
DFO	Department of Fisheries and Oceans Canada
EC	Environment Canada
ENC	Electronic Navigation Chart
EVA	Extreme Value Analysis
GD	Geodetic Datum
HHWLT	Higher High Water Large Tide
IPCC	Intergovernmental Panel on Climate Change
KWL	Kerr Wood Leidal
LiDAR	Light Detection And Ranging
MSL	Mean Sea Level
RSLR	Relative Sea Level Rise
SLR	Sea Level Rise
SWAN	*Simulating WAves Nearshore* software
TIN	Triangular Irregular Network

1 Introduction

The coastline of the Comox Valley Regional District (CVRD) is relatively dense in population and in economic activity compared to the inland portions of the District. The CVRD has recognized the importance of understanding their exposure to coastal flood hazard, especially in the context of rising sea levels. The CVRD has engaged Kerr Wood Leidal to conduct the analyses and mapping necessary to produce a set of modern flood hazard maps for the coastal areas of the CVRD and for the Oyster River.

Cascadia Coast Research, working as a sub-consultant to KWL, was tasked with estimating wave conditions for a range of storm scenarios developed by the client and KWL. This work involved the development of a two dimensional computational model of the Strait of Georgia, estimating storm wind conditions using extreme value analysis, and using the extreme wind conditions within the wave model to estimate storm wave conditions.

This report is structured as follows:

- Section 2 provides background on the study location as well as coastal storm exposure.
- Section 3 summarizes the methods used for coastal storm wave assessment.
- Section 4 summarizes the geo-spatial analysis required to enable the ocean modelling.
- Section 5 details the process of the coastal storm wave assessment.
- Section 6 presents and discusses the results of the storm wave assessment.

2 Background

2.1 Site Description

The Comox Valley Regional District (CVRD) encompasses a large area of 1,725 km on the east coast of Vancouver Island (see Figure 1). The CVRD includes the incorporated communities of the Town of Comox, the City of Courtenay, and the Village of Cumberland, as well as the unincorporated electoral districts of *Comox Valley A* (Denman Island, Fanny Bay, Hornby Island, Royston, Union Bay), *Comox Valley B* (Balmoral Beach, Bates Beach, Grantham, Lazo, Little River, Sandwick), and *Comox Valley C* (Bevan, Black Creek, Headquarters, Merville, Mount Washington, Puntledge, Saratoga Beach, Williams Beach). K'omoks First Nation lands are situated adjacent the CVRD within Comox Harbour.

The CVRD has approximately 150 km of coastline on the Straight of Georgia in the Salish Sea. This semi-enclosed body of water is in total about 250 km long and 20 to 60 km in width. Most of the approximately 67,000 residents of the CVRD live in close proximity of the Strait of Georgia.

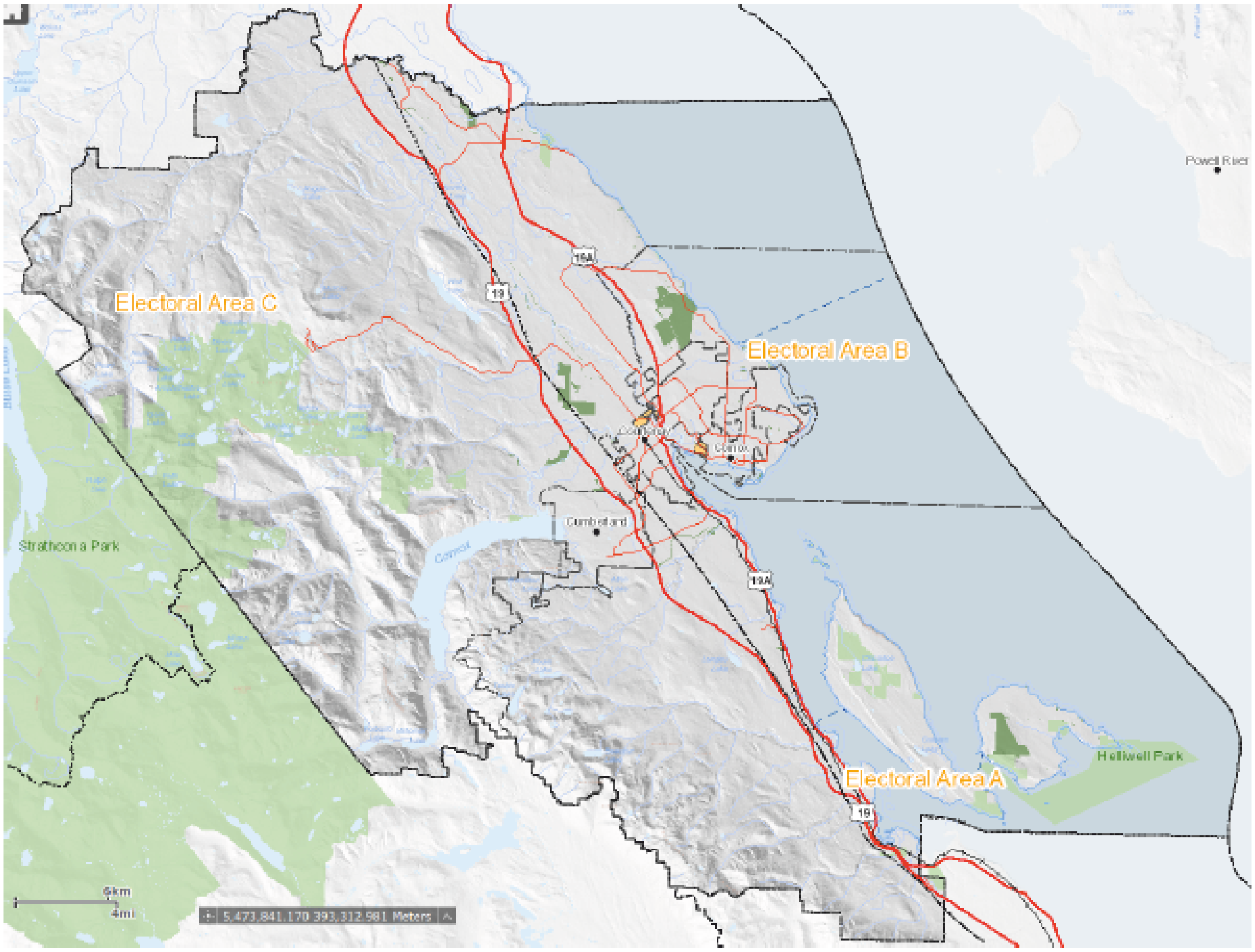

Figure 1: Map of the Comox Valley Regional District with delineation of electoral areas. Source: `http://imap2.comoxvalleyrd.ca`
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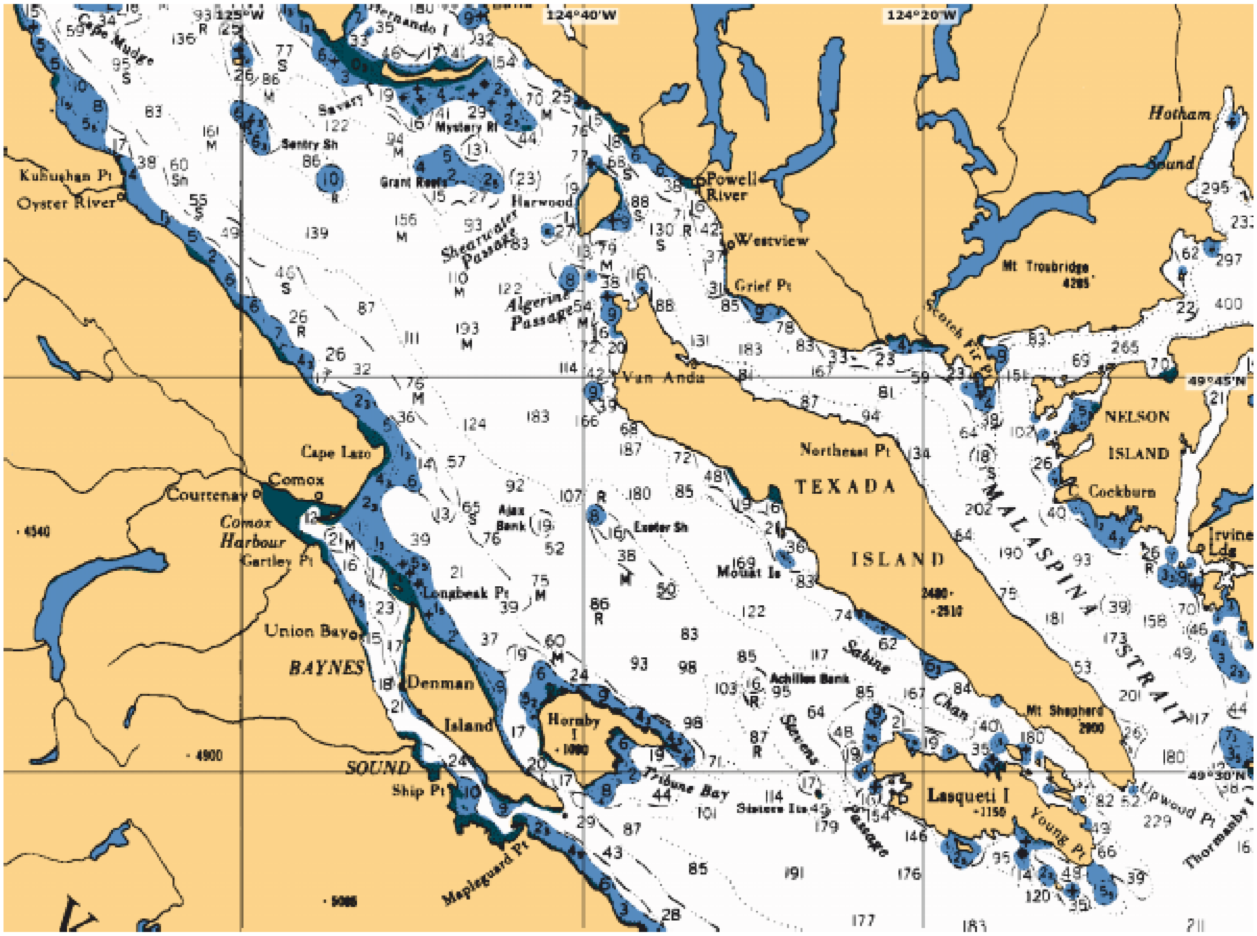

Figure 2: Screenshot of Canadian Hydrographic Service Chart for CVRD area. NOT FOR NAVIGATION.

2.2 Storm Wave Exposure

While the Strait of Georgia is sheltered from waves propagating off the Pacific Ocean, local winds can generate waves several meters in height. Different parts of the CVRD are exposed to waves from different fetch directions, but the largest winds tend to flow parallel to the primary axis of the Strait of Georgia, from the south-east (SE) or from the north-west (NW). Cape Lazo, Hornby and Denman Island are exposed to waves from both these directions. North of Cape Lazo, the main exposure is from the north-west, north and north-east (NW, N, NE). Between Denman and Vancouver Island is Baynes Sound, which is largely sheltered from waves in the Strait of Georgia. Despite this, waves generated locally within the Sound are likely still be important from a coastal flooding perspective.

3 Methods

3.1 Relative Sea Level Rise

Sea level rise due to global climate change is an important factor driving this coastal hazard study. Relative sea level rise (RSLR) is the rise in mean sea level relative to a fixed land reference. Included is both the effect of rising sea levels and vertical land movement.

According to the IPCC (2013) report, global sea levels have been rising at a rate of 3.2 mm/year since 1993 and about 1 mm/year over the last 100 years [1]. The BC Provincial Guidelines for Coastal Flood Hazard Land Use [2, 3, 4, 5, 6] suggest planning for 1m of sea level rise by 2100, however estimates in the literature vary considerably, with studies since 2013 tending to revise towards larger values [7].

Due to residual glacial isostatic effects and tectonic activity along the British Columbia Coast, relative sea level rise (RSLR) has been significantly less than the global mean. Mazzotii et al used 25 years of tide gauge measurements at the Little River Tide Station to estimate a relative sea level rise rate [8] of -1.2 mm/yr. This indicates that over the analysis period, relative sea level was actually getting lower by 1.2 mm/year. However, this estimate has high uncertainty because of the limited period of data availability.

In this study, we consider RSLR scenarios of 0, 0.5 1.0 and 2.0 m independent of any specified year of occurrence. This range of scenarios will enable short to long term planning.

While a range of RSLR scenarios are considered, the potential associated morphological changes are not. For this work the current bathymetry/topography of the region is assumed to remain constant in the future despite sea level rise.

3.2 Storm Wave Assessment

In this work, storm waves are assessed based on their probability of occurrence. Discussions with the client and KWL identified the 10, 5, 1, 0.5 and 0.2% annual exceedance probability (10, 20, 100, 200, 500 year return period, respectively), as probability targets for the storm wave conditions. In this case, the historical record is not long enough to estimate all magnitude of all of the target storm annual exceedance probabilities (AEPs). As an alternative, the magnitude of these low probability events may be estimated statistically based on the available data. There are many methods to do this, but most rely in some way on extreme value analysis.

Extreme value analysis (EVA) is a branch of statistics addressing extreme deviations from the median of probability distributions. It seeks to assess, from an ordered sample of a random variable, the probability of events that are more extreme than any previously observed. Independent extreme events contained within the historical record are ordered and fit with a theoretical extreme value distribution. The magnitude of events with probability beyond the extent of the historical record can then be estimated with the fit distribution.

A key assumption in EVA is that the climate is statistically stationary, meaning that it is not changing with time. Based on assessment of annual maximum wave records in the North East Pacific, Erikson [9] concludes that stationarity is an acceptable assumption for 1979 to 2009. However, weather patterns in the Eastern North Pacific will change with global climate change, and these changes will be different from region to region. Studies to date do not predict a large change in storm activity in the Vancouver Island region over the next century [9, 10, 11], but future research may suggest otherwise.

A historic record of wave conditions along the CVRD shoreline does not exist. However, wave conditions in the Strait of Georgia are generated almost entirely by local winds. Hence, winds can be used as a proxy when seeking the storm wave conditions with the target levels of probability. EVA can be applied to the direction partitioned wind measurements from an appropriate weather station to find the wind speed associated with the target AEP events from the directions of interest. These winds may then be applied as boundary conditions to a computational wave model, which in turn may be used to estimate the associated wave conditions along the CVRD shoreline.

3.3 Wave Model Development

For this work, a two dimensional wave model was developed for the Strait of Georgia based on the SWAN wave modelling software[12] (version 41.20). The model uses an unstructured grid and covers the Strait of Georgia from the San Juan Islands in the south-east to the Discovery Islands in the north-west (Figure 3). Average element length is about 200m through most of the grid, but decreases to 40m at the CVRD shoreline (Figure 4). Bathymetric and topographic data were linearly interpolated onto the grid nodes from the DEM (Section 4.2). The model is driven by local winds; no wave or current boundary conditions are included.

The model was evaluated by comparison to measurements made by the Department of Fisheries and Oceans at several temporary and operational wave measurement buoys stationed around the Strait of Georgia. The a quantile-quantile plot of measured and modelled significant wave height (H_{m0}) at Sentry Shoal is given in Figure 5. This shows that the model is reproducing the probability distribution of H_{m0} very well through this period. There is a deviation between the model and measurements for the largest wave height observation is the analysis period. The deviation is small (0.3 m) and represents just a single observation over a 3 month period, and therefore does not impeach the skill of the model.

For full details on the model evaluation, see Appendix A.

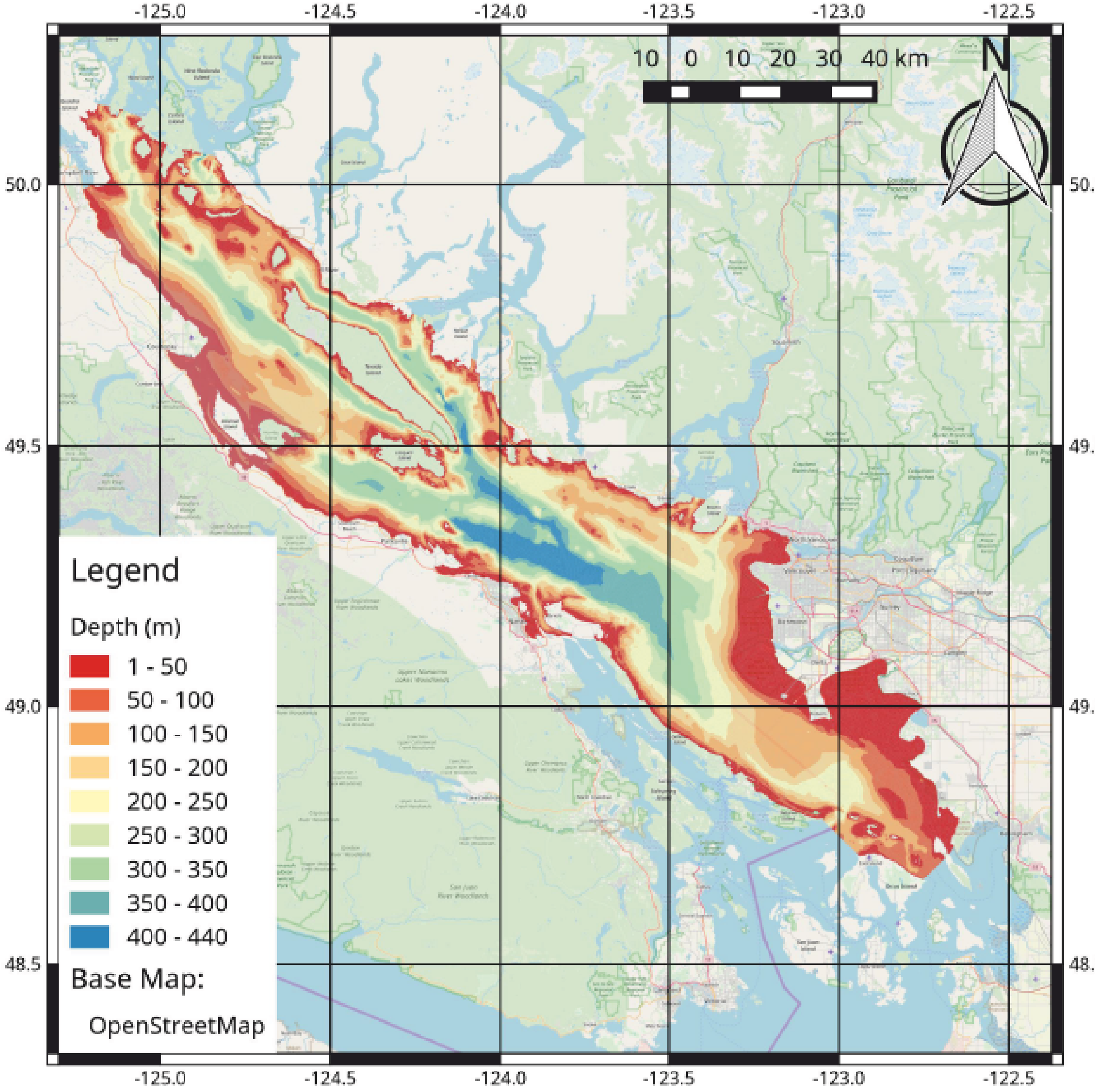

Figure 3: Coloured surface indicating the water depth throughout the domain of the wave model.

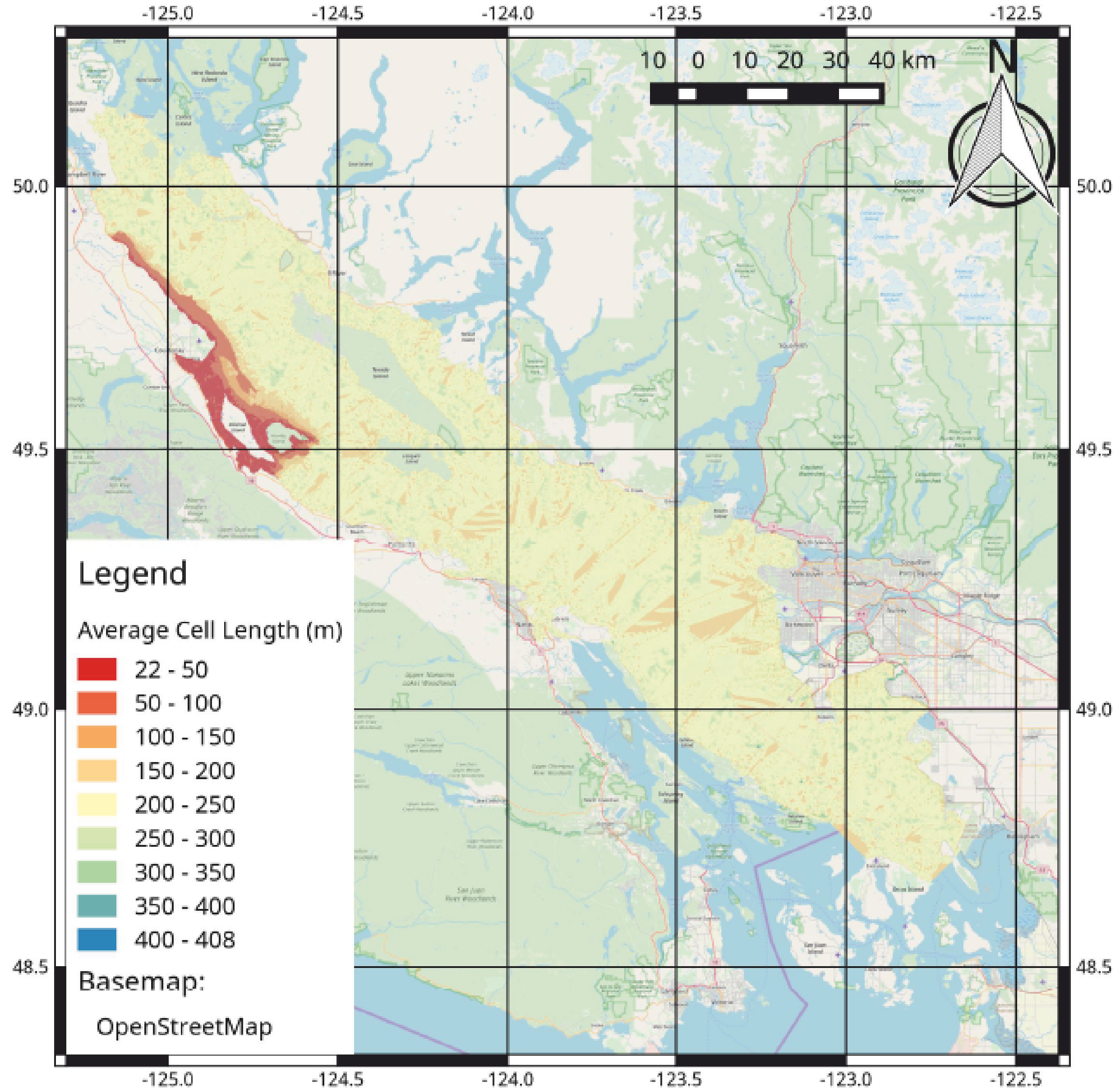

Figure 4: Coloured surface indicating the average element edge length of triangular elements in the wave model grid.

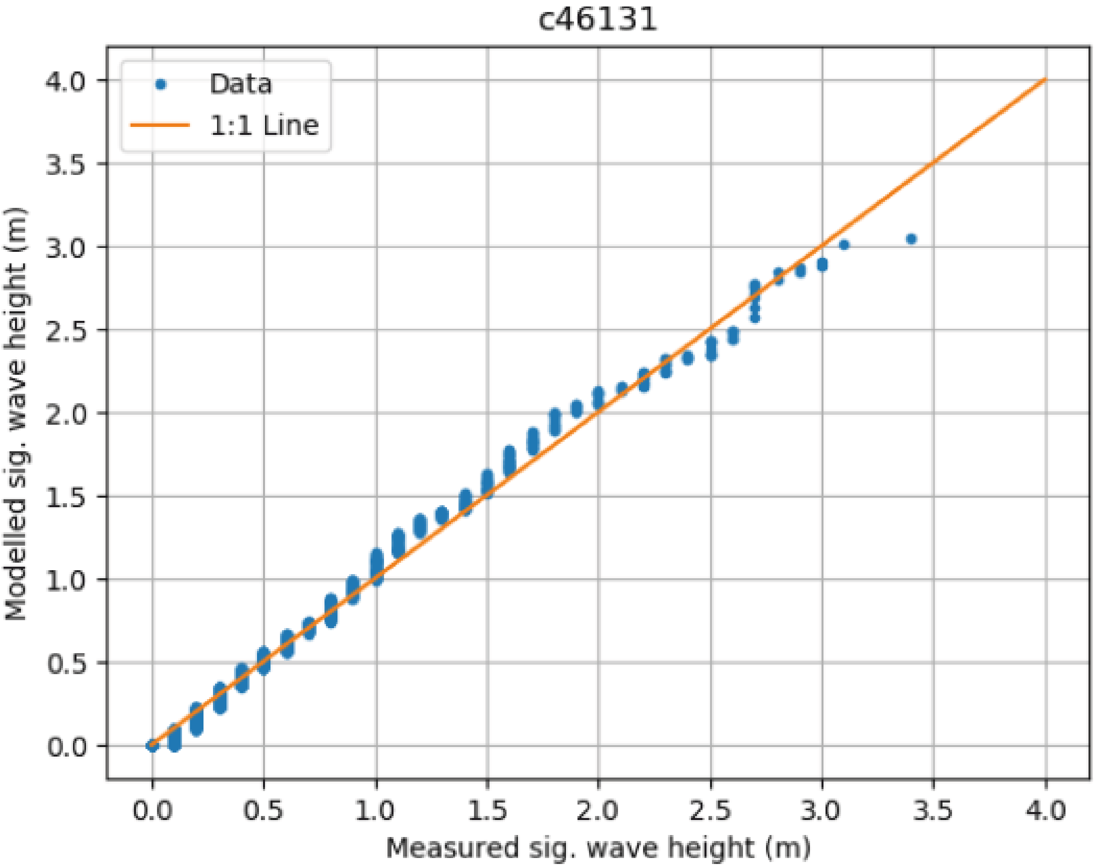

Figure 5: Quantile-quantile plot comparing modelled and measured significant wave height over the period 1997-10-01 to 1997-12-31 at the wave buoy deployed on Sentry Shoal (c46131).

4 Geo-Spatial Analysis

4.1 Vertical Datum

Unless otherwise noted, a vertical datum of CGVD28 is used in this work. This datum is used because it is the most commonly available geodetic datum available at the Canadian Hydrographic Service (CHS) tide stations. The datums at these stations are used to convert chart datum to geodetic datum

Elevations in chart datum may be converted to CGVD28 by

$$H_{CGVD28} = H_{CD} + \beta. \tag{1}$$

Based on CHS surveys at the Little River tide station[1], the offset β is -3.135 m.

4.2 Digital Elevation Model

A digital elevation model (DEM) was assembled from a variety of sources including electronic navigation charts (ENCs) from the CHS, a high water data set for the Pacific from the CHS[2], and a compilation of single and multi-beam survey data data covering the CVRD coast out to about 70m depth. The input data-sets are summarized in Table 1 below.

Table 1: Data sources for the digital elevation model

Data Description	**Coverage**	**Datum**	**Source**
ENC soundings and contours	Mid-Island Coastal Waters	Chart	CHS
High Water Contour	BC Coastal Waters	Chart	CHS
Single and Multi-beam Surveys	CVRD Coast to about 70m depth	Chart	CHS

The DEM was assembled as follows:

- Electronic Navigation Charts:
    - Extract contour and sounding data as xyz points.
    - Convert elevations from chart datum to CGVD28.
    - Merge the data from each chart, preferencing data from higher resolution charts.
    - Trim some data points where bathymetric survey data is available
- High Water Data-set:
    - Extract xyz points from high water data-set.
    - Convert elevations from chart datum to CGVD28.
    - Trim high water data where bathymetric survey data is available

---

[1] `http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/twl-mne/benchmarks-reperes/station-eng.asp?T1=7930&region=PAC&ref=maps-cartes`

[2] `http://www.charts.gc.ca/data-gestion/index-eng.asp`

- CHS bathymetric survey data:
  - Extract scatter from files as xyz points.
  - Convert elevations from chart datum to CGVD28.
- Merge xyz points from all sources.
- Triangulate points using Delaunay triangulation to create TIN.

The data sources used in the DEM are shown graphically in Figure 6.

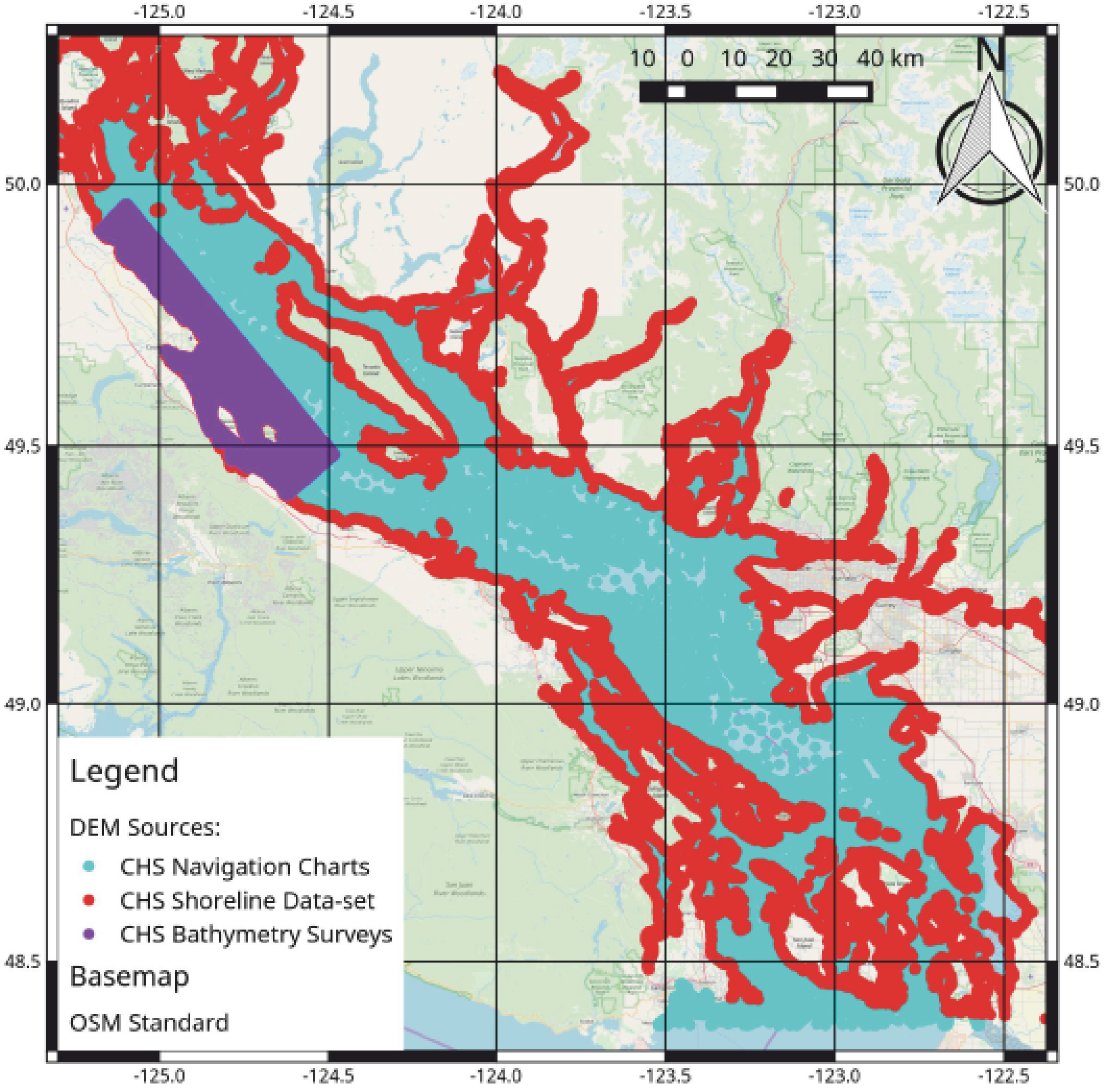

Figure 6: Bathymetric and topographic data used in constructing the DEM.

5 Storm Wave Analysis

Different regions of the CVRD are vulnerable to storm waves from different directions. Sections 5.1 and 5.2 document the tide, surge and wind data sources used to estimate storm wave conditions. Section 5.3 describes the storm selection process. Section 5.4 documents the synthesis of wind fields to drive the wave model. Section 5.5 describes the wave modelling of the selected storms.

5.1 Water Level

The still water level at CVRD shores is the superposition of the tidal level, storm surge and the background relative sea level rise.

Tides on CVRD's ocean shores are mixed semi-diurnal with a range of about 5.2 m and a maximum elevation of about 2.2 m (CGVD28) [14]. Tides are larger in the winter and smaller in the summer. The maximum tidal elevation occurs once every 18.6 years, but comes close for a few tides each year. The tides can be predicted to high accuracy based on analysis of past observations.

Storm surge can be driven by a number of physical processes, but manifests as a deviation in water level from the predicted tide. Thus, storm-surge is typically estimated as the difference between the predicted tide and the observed water level. Storm surge in the Strait of Georgia is primarily driven by water level on the West Coast of Vancouver Island and the variation in barometric pressure.

KWL was responsible for determining water levels for this project. Table 2 was provided to Cascadia by KWL. It was agreed that, to reduce the number of wave simulations, all scenarios would be run with a combined tide and surge level of 3.11 m. The sensitivity of wave conditions to water levels was investigated for storms of varying directions. It was found in all cases that increasing the water level by 0.5 m increased the maximum wave height. The change in wave height was typically 0.05 m or less, but a maximum difference of 0.25 m was observed. Based on this assessment we can conclude that using a single storm water level, based on the 0.2% AEP event, for all wave simulations is a satisfactory and somewhat conservative approach. Note that the RSLR component is varied within the set of wave simulations.

Table 2: Extreme value analysis of water levels (combined tide and surge) at various stations in the CVRD. Levels given in metres to CGVD28.

AEP (%)	Comox	Little River	Denman Island
10.0%	2.79	2.75	2.65
5.0%	2.88	2.83	2.73
1.0%	3.04	2.98	2.89
0.5%	3.11	3.04	2.95
0.2%	3.19	3.11	3.03

5.2 Extreme Value Analysis of Local Winds

The most relevant station for assessment of over-water wind speeds near the CVRD is the Environment Canada *Comox Airport* weather station (Figure 9). This station is situated on Cape Lazo, close to shore, and directly exposed to winds on the Strait of Georgia.

The Comox Airport station data is available from 1953 to 2020 with only small gaps. In 1971 the data changes from using 16 direction bins to 36, which requires some attention when attempting to characterize the direction of weather systems

A wind rose for the Comox Aiport station is provided in Figure 7. The strongest winds at the station most frequently come come from the SE and NW. The most frequent wind conditions are light winds from the west.

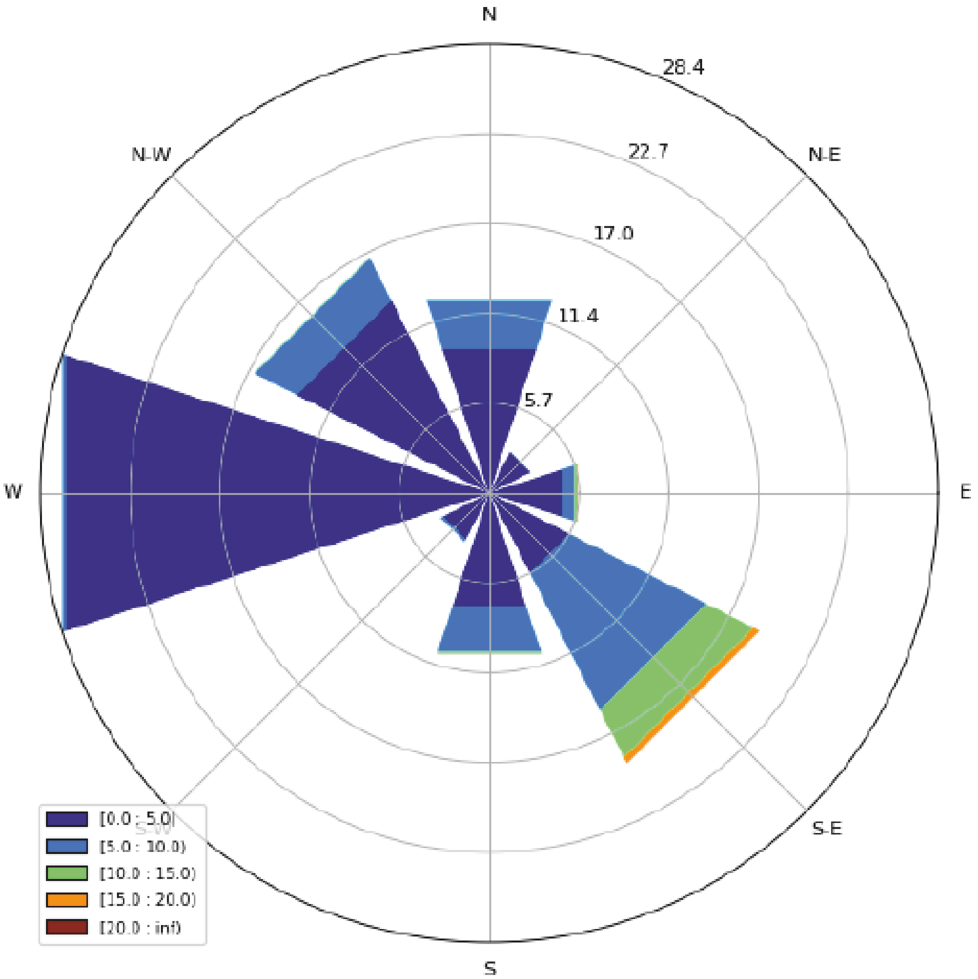

Figure 7: Wind rose for the Comox Airport weather station. The radial extent of the rays indicate frequency of occurrence (as a percentage) in that directional bin, the point of the rays indicates the direction the wind is blowing to, the colours indicate the wind speed bins in [m/s].

Extreme value analysis was performed on the Comox Aiport data-set using a peaks-over-threshold approach. The threshold was set for each analysis to yield an average of about 4 storms per year. The analysis partitioned the wind data into directional octants. A Generalized Pareto Distribution was fit to each storm set, and used for estimating the magnitude of specific probability events. The results are presented in Table 3.

Table 3: Extreme value estimates of Comox Airport wind speeds in m/s, partitioned by directional octant.

	Direction (deg)							
AEP (%)	45	90	135	180	225	270	315	360
0.2	14.3	26.5	27.0	20.9	18.9	24.8	17.8	16.1
0.5	12.7	25.1	26.2	19.9	17.5	20.8	17.2	15.6
1	11.6	24.0	25.5	19.1	16.4	18.2	16.7	15.2
5	9.3	21.3	23.7	17.2	14.0	13.4	15.3	14.0
10	8.4	20.0	22.8	16.3	12.9	11.8	14.6	13.4

5.3 Storm Selection

A representative historic storm from each wind direction was selected for modelling. Storm events were selected by examining the historic wind record from the Comox Airport, preferencing storms with strong sustained winds from the target directions and preferencing more recent storms. No consideration was made of the corresponding ambient water levels during the storm event. The selected storms are presented in Table 4.

Table 4: Details of storm events selected for modelling.

Date	Wind Dir (°)	Peak Wind Speed (m/s)
Oct 15-16, 2016	45	7.8
Dec 26-27, 2015	90	14.0
Mar 12-13, 2012	135	23.0
Nov 18-19, 2009	180	17.0
March 26,2001	225	10.3
March 24-25, 1995	270	8.9
Dec 15, 2000	315	12.8
May 23, 2017	360	14.4

For the extreme storm events, the magnitude of the wind fields were scaled so that the wind speed at Comox Airport was equal to that given by each scenario in Table 3. Each storm was run with a range of RSLR contributions (RSLR=0.0, 0.5, 1.0, 2.0m) for a total of 160 scenarios. A summary of the modelled storms is provided in Tables 5 and 6.

RUN_ID is defined to provide a a unique identifier for each model run. The first digit indicates the RSLR used where, 0 is 0m, 1 is 0.5m, 2 is 1m, and 3 is 2m. The second digit indicates the AEP of the water level, where 0 is 0.2% and is the only water level AEP used. Similarly the third digit indicates the direction of the storm event, where 0 is winds from NE, 1 is winds from E and, 2 is winds from SE, etc. Finally the fourth digit in RUN_ID indicates the wind AEP considered, where 0 is 0.2%, 1 is 0.5%, 2 is 1%, 3 is 5%, and 4 is 10%. See Figure 8 for a schematic representation of the RUN_ID.

The details of each wave model scenario are provided in Table 5 and 6.

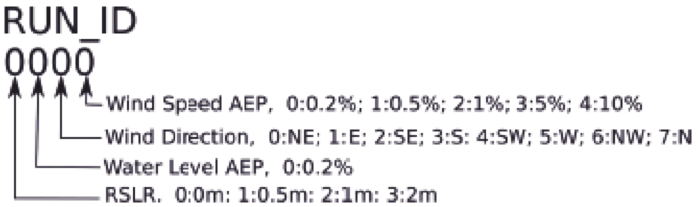

Figure 8: Schematic showing meaning of each digit in the RUN_ID

Table 5: Modelled storm specifications for RSLR levels of 0.0 and 0.5 m.

RUN_ID	Base Event	Wind Speed [m/s]	Wind Dir [deg]	Water Level [m, GD]		RUN_ID	Base Event	Wind Speed [m/s]	Wind Dir [deg]	Water Level [m, GD]
0000	Oct 15-16, 2016	14.3	45	3.11		1000	Oct 15-16, 2016	14.3	45	3.61
0001	Oct 15-16, 2016	12.7	45	3.11		1001	Oct 15-16, 2016	12.7	45	3.61
0002	Oct 15-16, 2016	11.6	45	3.11		1002	Oct 15-16, 2016	11.6	45	3.61
0003	Oct 15-16, 2016	9.3	45	3.11		1003	Oct 15-16, 2016	9.3	45	3.61
0004	Oct 15-16, 2016	8.4	45	3.11		1004	Oct 15-16, 2016	8.4	45	3.61
0010	Dec 26-27, 2015	26.5	90	3.11		1010	Dec 26-27, 2015	26.5	90	3.61
0011	Dec 26-27, 2015	25.1	90	3.11		1011	Dec 26-27, 2015	25.1	90	3.61
0012	Dec 26-27, 2015	24.0	90	3.11		1012	Dec 26-27, 2015	24.0	90	3.61
0013	Dec 26-27, 2015	21.3	90	3.11		1013	Dec 26-27, 2015	21.3	90	3.61
0014	Dec 26-27, 2015	20.0	90	3.11		1014	Dec 26-27, 2015	20.0	90	3.61
0020	Mar 12-13, 2012	27.0	135	3.11		1020	Mar 12-13, 2012	27.0	135	3.61
0021	Mar 12-13, 2012	26.2	135	3.11		1021	Mar 12-13, 2012	26.2	135	3.61
0022	Mar 12-13, 2012	25.5	135	3.11		1022	Mar 12-13, 2012	25.5	135	3.61
0023	Mar 12-13, 2012	23.7	135	3.11		1023	Mar 12-13, 2012	23.7	135	3.61
0024	Mar 12-13, 2012	22.8	135	3.11		1024	Mar 12-13, 2012	22.8	135	3.61
0030	Nov 18-19, 2009	20.9	180	3.11		1030	Nov 18-19, 2009	20.9	180	3.61
0031	Nov 18-19, 2009	19.9	180	3.11		1031	Nov 18-19, 2009	19.9	180	3.61
0032	Nov 18-19, 2009	19.1	180	3.11		1032	Nov 18-19, 2009	19.1	180	3.61
0033	Nov 18-19, 2009	17.2	180	3.11		1033	Nov 18-19, 2009	17.2	180	3.61
0034	Nov 18-19, 2009	16.3	180	3.11		1034	Nov 18-19, 2009	16.3	180	3.61
0040	March 26,2001	18.9	225	3.11		1040	March 26,2001	18.9	225	3.61
0041	March 26,2001	17.5	225	3.11		1041	March 26,2001	17.5	225	3.61
0042	March 26,2001	16.4	225	3.11		1042	March 26,2001	16.4	225	3.61
0043	March 26,2001	14.0	225	3.11		1043	March 26,2001	14.0	225	3.61
0044	March 26,2001	12.9	225	3.11		1044	March 26,2001	12.9	225	3.61
0050	March 24-25, 1995	24.8	270	3.11		1050	March 24-25, 1995	24.8	270	3.61
0051	March 24-25, 1995	20.8	270	3.11		1051	March 24-25, 1995	20.8	270	3.61
0052	March 24-25, 1995	18.2	270	3.11		1052	March 24-25, 1995	18.2	270	3.61
0053	March 24-25, 1995	13.4	270	3.11		1053	March 24-25, 1995	13.4	270	3.61
0054	March 24-25, 1995	11.8	270	3.11		1054	March 24-25, 1995	11.8	270	3.61
0060	Dec 15, 2000	17.8	315	3.11		1060	Dec 15, 2000	17.8	315	3.61
0061	Dec 15, 2000	17.2	315	3.11		1061	Dec 15, 2000	17.2	315	3.61
0062	Dec 15, 2000	16.7	315	3.11		1062	Dec 15, 2000	16.7	315	3.61
0063	Dec 15, 2000	15.3	315	3.11		1063	Dec 15, 2000	15.3	315	3.61
0064	Dec 15, 2000	14.6	315	3.11		1064	Dec 15, 2000	14.6	315	3.61
0070	May 23, 2017	16.1	360	3.11		1070	May 23, 2017	16.1	360	3.61
0071	May 23, 2017	15.6	360	3.11		1071	May 23, 2017	15.6	360	3.61
0072	May 23, 2017	15.2	360	3.11		1072	May 23, 2017	15.2	360	3.61
0073	May 23, 2017	14.0	360	3.11		1073	May 23, 2017	14.0	360	3.61
0074	May 23, 2017	13.4	360	3.11		1074	May 23, 2017	13.4	360	3.61

Table 6: Modelled storm specifications for RSLR levels of 1.0 and 2.0 m.

RUN_ID	Base Event	Wind Speed [m/s]	Wind Dir [deg]	Water Level [m, GD]		RUN_ID	Base Event	Wind Speed [m/s]	Wind Dir [deg]	Water Level [m, GD]
2000	Oct 15-16, 2016	14.3	45	4.11		3000	Oct 15-16, 2016	14.3	45	5.11
2001	Oct 15-16, 2016	12.7	45	4.11		3001	Oct 15-16, 2016	12.7	45	5.11
2002	Oct 15-16, 2016	11.6	45	4.11		3002	Oct 15-16, 2016	11.6	45	5.11
2003	Oct 15-16, 2016	9.3	45	4.11		3003	Oct 15-16, 2016	9.3	45	5.11
2004	Oct 15-16, 2016	8.4	45	4.11		3004	Oct 15-16, 2016	8.4	45	5.11
2010	Dec 26-27, 2015	26.5	90	4.11		3010	Dec 26-27, 2015	26.5	90	5.11
2011	Dec 26-27, 2015	25.1	90	4.11		3011	Dec 26-27, 2015	25.1	90	5.11
2012	Dec 26-27, 2015	24.0	90	4.11		3012	Dec 26-27, 2015	24.0	90	5.11
2013	Dec 26-27, 2015	21.3	90	4.11		3013	Dec 26-27, 2015	21.3	90	5.11
2014	Dec 26-27, 2015	20.0	90	4.11		3014	Dec 26-27, 2015	20.0	90	5.11
2020	Mar 12-13, 2012	27.0	135	4.11		3020	Mar 12-13, 2012	27.0	135	5.11
2021	Mar 12-13, 2012	26.2	135	4.11		3021	Mar 12-13, 2012	26.2	135	5.11
2022	Mar 12-13, 2012	25.5	135	4.11		3022	Mar 12-13, 2012	25.5	135	5.11
2023	Mar 12-13, 2012	23.7	135	4.11		3023	Mar 12-13, 2012	23.7	135	5.11
2024	Mar 12-13, 2012	22.8	135	4.11		3024	Mar 12-13, 2012	22.8	135	5.11
2030	Nov 18-19, 2009	20.9	180	4.11		3030	Nov 18-19, 2009	20.9	180	5.11
2031	Nov 18-19, 2009	19.9	180	4.11		3031	Nov 18-19, 2009	19.9	180	5.11
2032	Nov 18-19, 2009	19.1	180	4.11		3032	Nov 18-19, 2009	19.1	180	5.11
2033	Nov 18-19, 2009	17.2	180	4.11		3033	Nov 18-19, 2009	17.2	180	5.11
2034	Nov 18-19, 2009	16.3	180	4.11		3034	Nov 18-19, 2009	16.3	180	5.11
2040	March 26,2001	18.9	225	4.11		3040	March 26,2001	18.9	225	5.11
2041	March 26,2001	17.5	225	4.11		3041	March 26,2001	17.5	225	5.11
2042	March 26,2001	16.4	225	4.11		3042	March 26,2001	16.4	225	5.11
2043	March 26,2001	14.0	225	4.11		3043	March 26,2001	14.0	225	5.11
2044	March 26,2001	12.9	225	4.11		3044	March 26,2001	12.9	225	5.11
2050	March 24-25, 1995	24.8	270	4.11		3050	March 24-25, 1995	24.8	270	5.11
2051	March 24-25, 1995	20.8	270	4.11		3051	March 24-25, 1995	20.8	270	5.11
2052	March 24-25, 1995	18.2	270	4.11		3052	March 24-25, 1995	18.2	270	5.11
2053	March 24-25, 1995	13.4	270	4.11		3053	March 24-25, 1995	13.4	270	5.11
2054	March 24-25, 1995	11.8	270	4.11		3054	March 24-25, 1995	11.8	270	5.11
2060	Dec 15, 2000	17.8	315	4.11		3060	Dec 15, 2000	17.8	315	5.11
2061	Dec 15, 2000	17.2	315	4.11		3061	Dec 15, 2000	17.2	315	5.11
2062	Dec 15, 2000	16.7	315	4.11		3062	Dec 15, 2000	16.7	315	5.11
2063	Dec 15, 2000	15.3	315	4.11		3063	Dec 15, 2000	15.3	315	5.11
2064	Dec 15, 2000	14.6	315	4.11		3064	Dec 15, 2000	14.6	315	5.11
2070	May 23, 2017	16.1	360	4.11		3070	May 23, 2017	16.1	360	5.11
2071	May 23, 2017	15.6	360	4.11		3071	May 23, 2017	15.6	360	5.11
2072	May 23, 2017	15.2	360	4.11		3072	May 23, 2017	15.2	360	5.11
2073	May 23, 2017	14.0	360	4.11		3073	May 23, 2017	14.0	360	5.11
2074	May 23, 2017	13.4	360	4.11		3074	May 23, 2017	13.4	360	5.11

5.4 Wind Fields

Wave conditions in the Strait of Georgia are driven by local winds. As such, an accurate representation of local winds in space and time is critical to modelling the wave processes. Wind fields are significantly affected by the irregular topography of the Strait of Georgia and surrounding area. Winds tend to funnel down fjords, accelerate between islands, and channel around obstacles. This has the effect of creating complex wind patterns not easily derived from pressure conditions [15]. High resolution (2.5 km) forecasting now available from Environment Canada[3] captures these wind fields with reasonable accuracy (although a corresponding hind-cast product is not available at this time). For this work, wind fields are developed based on hourly data from available Environment Canada weather stations as shown in Figure 9. Data were sourced from Environment Canada historical archives through a special data request, from the Environment Canada Historical Data website[4], and for weather buoy data, from the Department of Fisheries and Oceans website[5]. At each time step, wind measurements available from each station were extracted from station data files. The x and y wind components were interpolated onto a $1/16°$ grid using an *inverse distance weighting* (IDW)average approach [16]. The averaging was limited to stations within 50 km and an exponent of 2 was applied in the weighting. To minimize bias in the IDW averaging, some stations which were very close together were merged and others were removed from the analysis completely. An example wind field for the peak of the March 12, 2012 storm is provided in Figure 10. Spatially and temporally varying wind fields were generated for each designated storm event in a format appropriate for use in the SWAN wave model (Section 5.5).

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[3] `https://weather.gc.ca/grib/grib2_HRDPS_HR_e.html`

[4] `https://climate.weather.gc.ca/historical_data/search_historic_data_e.html`

[5] `http://www.isdm.gc.ca/isdm-gdsi/waves-vagues/index-eng.htm`

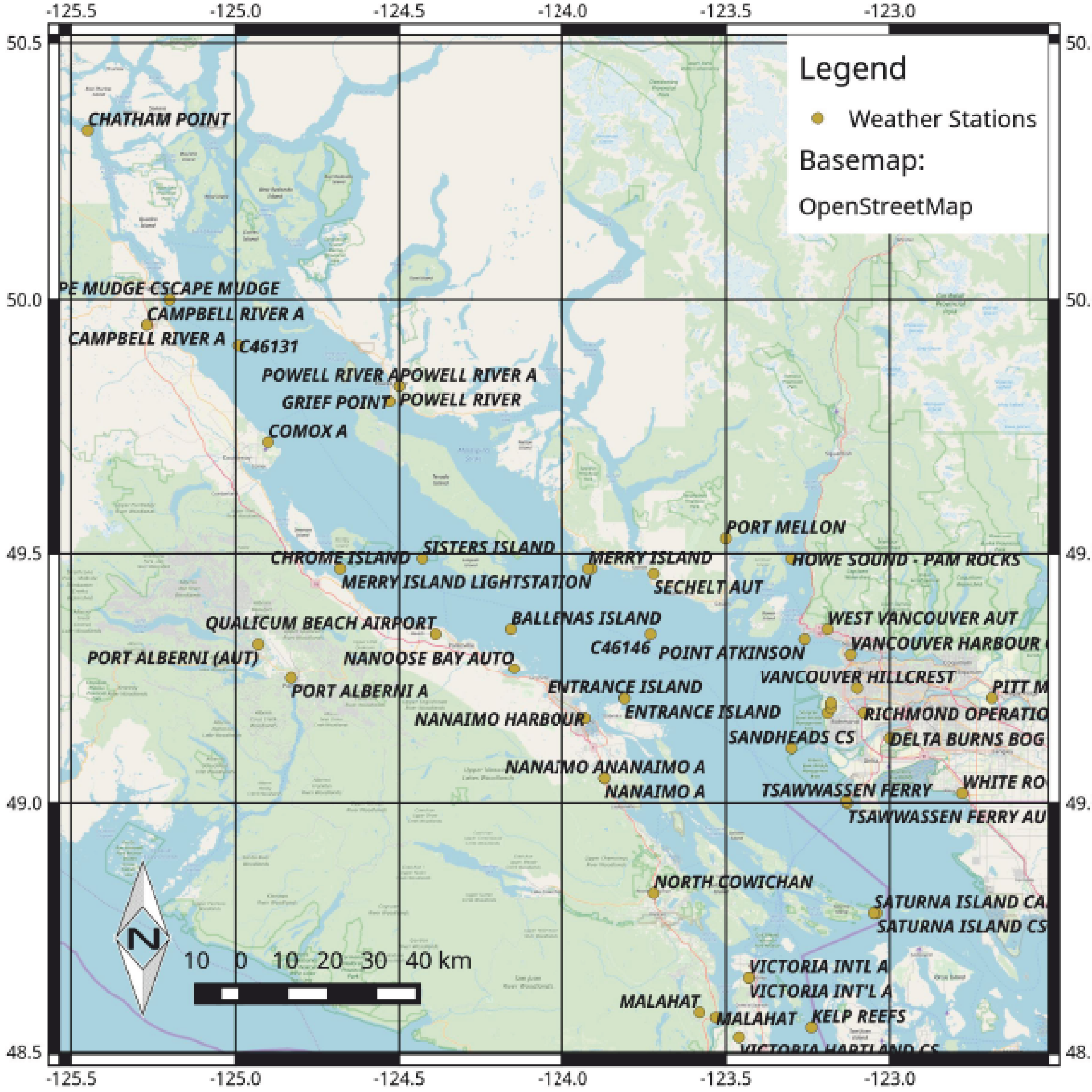

Figure 9: Locations of weather stations in the Salish Sea used for the development of wind fields. Duplicate labels indicate multiple stations with the same or similar name, usually associated with station changes over time.

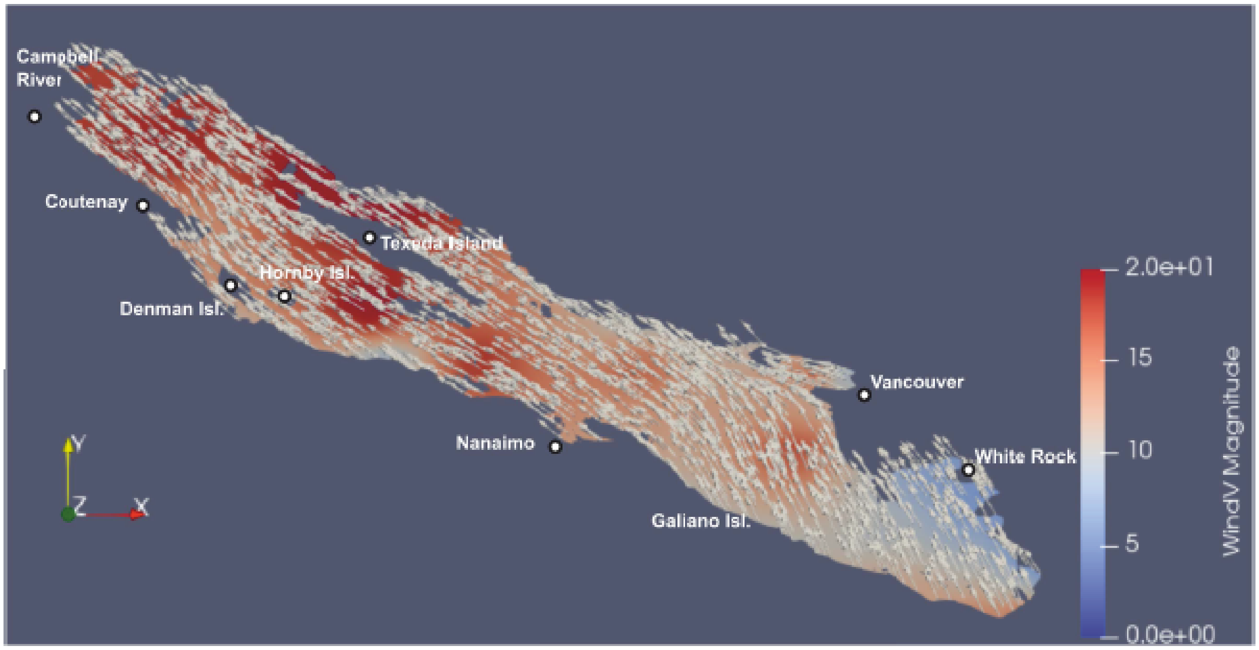

Figure 10: Interpolated wind field during storm event of March 12, 2012 (units of m/s).

5.5 Wave Modelling

Each of the storm scenarios given in Tables 5 and 6 were simulated using the 2D computational wave model developed for this work (see Section 3.3). In each model run, the water level was set spatially and temporally constant as the sum of the storm water level (Section 5.1) and RSLR (Section 3.1). Currents were not considered in these simulations as they play only a secondary role in the growth and propagation of surface waves.

Each of the variable wind storm scenarios (Section 5.3) were modelled in *non-stationary mode*, with a one minute time step, and driven by hourly 2D wind field estimates (Section 5.4). Within the model, the hourly wind field vectors are linearly interpolated at each time-step. The 1 minute time step is used to maintain the accuracy of the model numerics rather than capture short time-scale variability in the driving wind fields.

6 Results and Discussion

6.1 Storm Wave Estimates

Locations for the output of wave data from each model run were provided by KWL (see Figure 11). These locations correspond to 50 m horizontal spacing along 247 different shore-normal transects. For each wave model run (see Section 5.3), parametric wave data were output at these locations at a 15 minute time step.

The raw data files, containing time-series of wave parameters resulting from each model run, have been transferred to KWL for further analysis. Figures 11 and 12 indicate the maximum H_{m0} at each output location for all of the scenarios for with a 0.2% AEP and for RSLR of 0.0 m and 2.0 m, respectively. The figures show a very similar distribution of wave heights through the geographic area. However, with larger RSLR, larger waves are evident closer to shore. This makes sense because with deeper water depths, larger wave heights are able to get closer to the shoreline before breaking.

The largest wave heights on CVRD shores (up to 5.4 m significant wave height for the 0.2% exceedance probability event) occur on the SE side of Denman Island and Hornby Island, where the islands are exposed to the full fetch of the Strait of Georgia to the SE. Waves are nearly as large on the SE side of Cape Lazo, but Denman and Hornby Islands provide this area some protection. North of Cape Lazo the shoreline has less exposure to the prominent SE storm direction, and consequently has smaller storm wave heights, up to about 4 m significant wave height. Baynes Sound is largely protected from waves propagating in from the Strait of Georgia, but local waves up to about 1.5 m can be generated within the Sound. See Figure 2 for place names.

Figures similar to 11 to 12 are provided in Appendix B for all of the considered RSLR levels and storm probabilities.

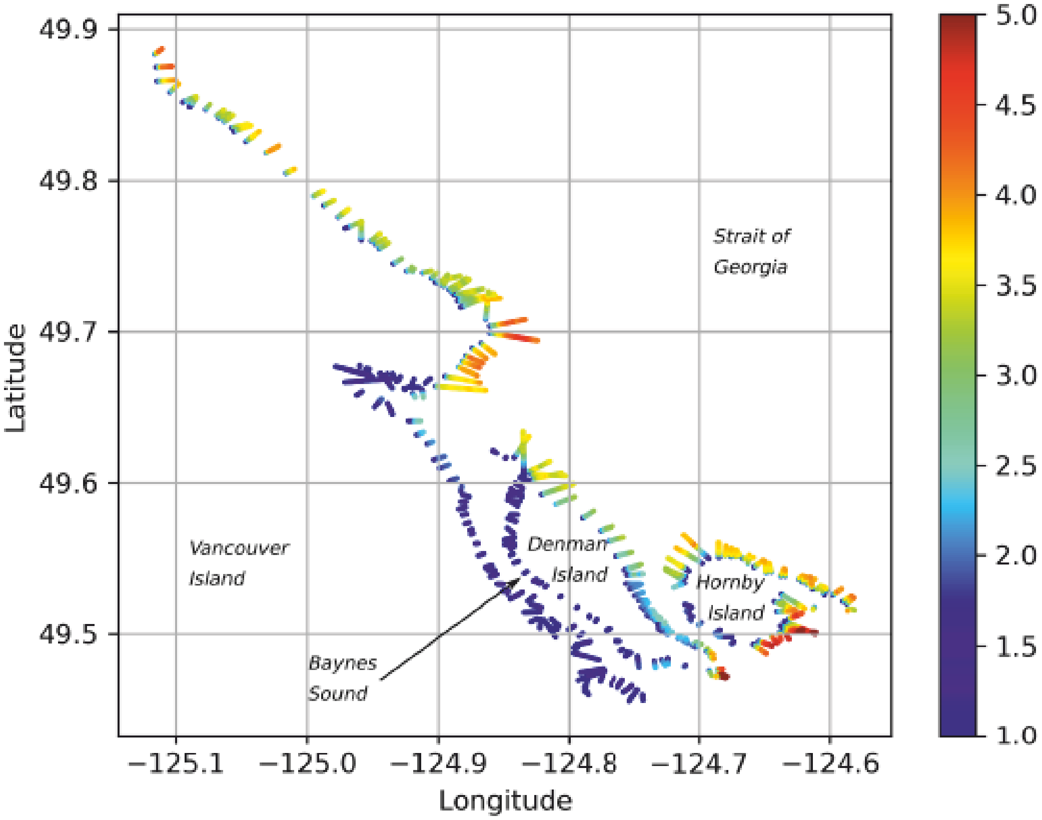

Figure 11: Maximum significant wave height [m], for all scenarios with 0.2% AEP and RSLR = 0.0m.

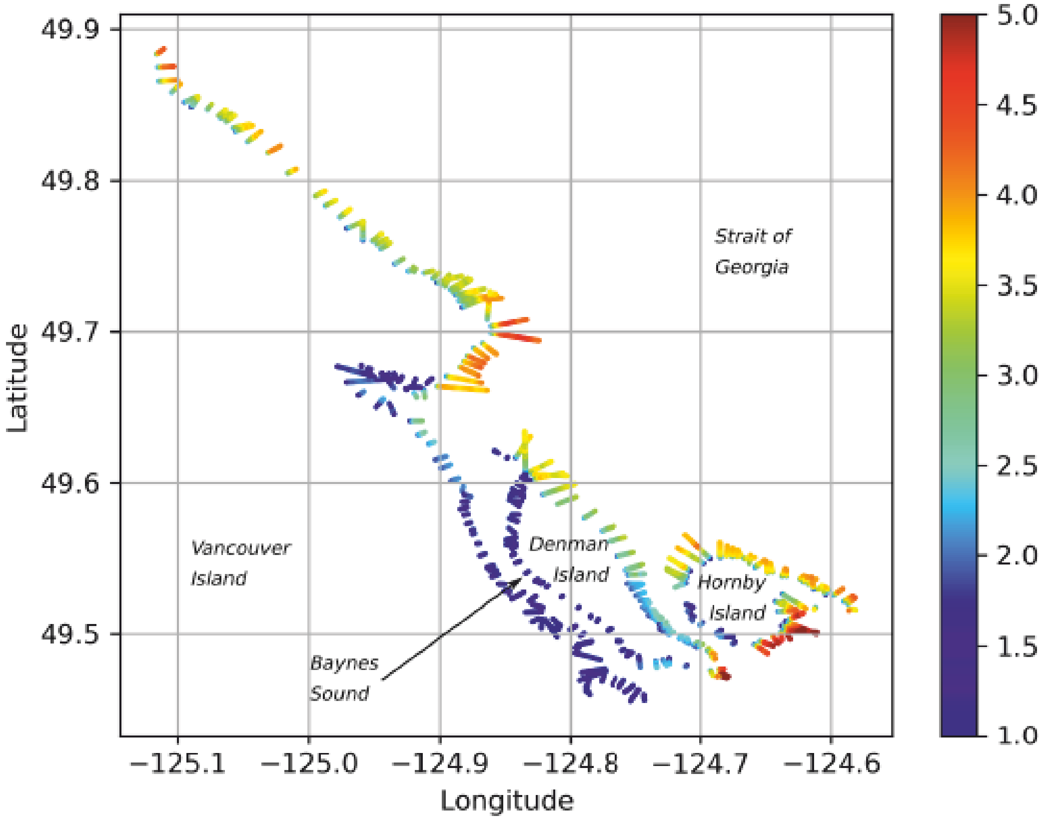

Figure 12: Maximum significant wave height [m], for all scenarios with 0.2% AEP and RSLR = 2.0m.

6.2 Uncertainties

In this analysis, the magnitude and probability of future wind storm events in the Strait of Georgia was estimated based on historic wind measurements with the inherent assumption that the future climate will be similar to the historic climate. For example, it is assumed that the Strait of Georgia will experience a similar number of storms each year with similar intensity to that which have been experienced historically. However, climate change will cause the future climate to deviate from the existing one and these changes will be different from region to region. Though the available literature suggests only minor changes to the ocean climate in this region over the next century, future research may suggest otherwise.

This work used wind speed as a proxy for wave height. This assumes that a wind condition of a given probability will produce a wave condition with the same probability. Though this is a widely used assumption, it is not strictly correct and introduces some minor uncertainty to wave heights associated with each storm.

Extreme value analysis is used to estimate the magnitude of low probability events. The uncertainty in these estimates gets larger as the target probability gets lower.

Despite evaluation of the spectral wave model using in-situ wave measurements, uncertainty persists in the wave estimates (primarily due to uncertainty in the interpolated wind fields and in the bathymetric data). Furthermore, the effect of wave current interactions has not been accounted for in the modelling.

Not withstanding the preceding discussion, the results of this work provide a solid view of the storm wave exposure of the CVRD under increasing RSLR scenarios for the assumptions made.

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Appendices

A Wave model evaluation

The wave model was evaluated by comparison to measurements made by the Department of Fisheries and Oceans at several temporary and operational wave measurement buoys stationed around the Strait of Georgia. The buoys used in this analysis are shown in Figure 13 and detailed in Table 7. The Halibut Bank (c46146) and Sentry Shoal (c46131) buoys are operational 3 m discus type weather buoys, while the others are temporary deployments of Datawell non-directional Wave Rider buoys.

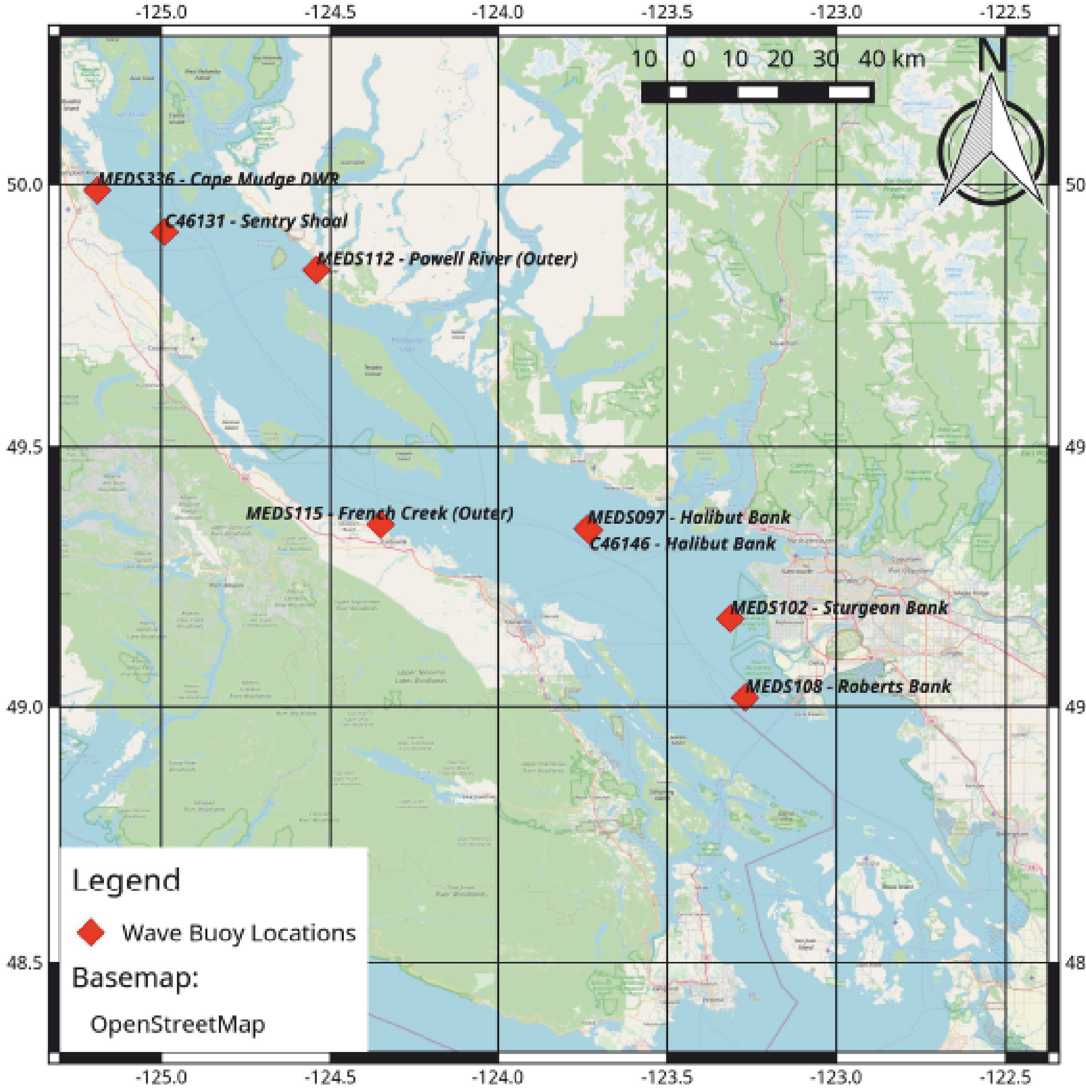

Figure 13: Map indicating position wave measurement buoys used in model validation.

Table 7: Details of wave measurement buoys used in model evaluation. Type *WR* indicates a non-directional Wave Rider buoy. Type *WD* indicates a directional Wave Rider buoy. Type *AE* indicates a 3 m discus type buoy.

ID/Name	Type	Start Date	End Date	Lat	Long	Depth
MEDS097 - Halibut Bank	WR	1974/01/11	1974/05/16	49.343	-123.735	53
MEDS102 - Sturgeon Bank	WR	1974/02/07	1976/04/03	49.17	-123.313	110
MEDS108 - Roberts Bank	WR	1974/02/07	1976/04/03	49.018	-123.269	139
MEDS115 - French Creek (Outer)	WR	1976/11/24	1977/03/15	49.351	-124.352	7
MEDS112 - Powell River (Outer)	WR	1976/12/10	1977/03/14	49.838	-124.541	9
MEDS336 - Cape Mudge DWR	WD	1997/10/01	1997/12/19	49.989	-125.189	10
C46146 - Halibut Bank	AE	1992/03/13	2019/09/26	49.34	-123.73	42
C46131 - Sentry Shoal	AE	1992/10/20	2019/06/29	49.91	-124.99	14

For buoys MEDS115, MEDS112, MEDS336, C46146, and C46131, a series of diagnostic plots which illustrate the skill of the model are presented (see Figures 14 to 29). These plots present time-series comparison of measured and modelled wave parameters, significant wave height and peak wave period (T_p). Comparisons of these parameters are also given in the form of scatter plots and quantile-quantile comparison plots. The model was also evaluated at buoys MEDS097, MEDS102, and MEDS108, but for succinctness the plots are omitted from this section.

In general, the model reproduces the significant wave height (H_{m0}) well through most conditions (Figure 22). The model appears to over estimate H_{m0} for MEDS115 and MEDS112, which are both in very shallow water, close to the shore. This may be because the validation runs were run with a water level of 2 m corresponding to a high tide. Furthermore, because these buoys are outside the area of interest, the model resolution is relatively low at 200 m, which may not be sufficient to capture wave refraction and breaking very near to shore. The model data at buoys MEDS336 and C46131, which are close to the CVRD, but in deeper water shows very good agreement (Figures 18 and 22).

Comparing the measured and modelled H_{m0} probability distributions, the model estimates tend to have a small positive bias (e.g. Figure 20). At C46146, tail of the probability distribution appears misrepresented by the model (see Figure 28). The divergence is due to a single storm event, however the reason for the under-prediction during that event is not clear.

The agreement between the model and measurement for T_p is less consistent, with good agreement during higher energy sea states but poor agreement during low energy sea states (Figure 15). This lack of correlation in low energy sea states may result in part because of sensor inaccuracy in such conditions [13]. The poorer agreement between the model and measurements for T_p during low energy sea-states is not considered a problem, as it is the high energy sea-states which are of interest to this work.

Validation Run February 1977

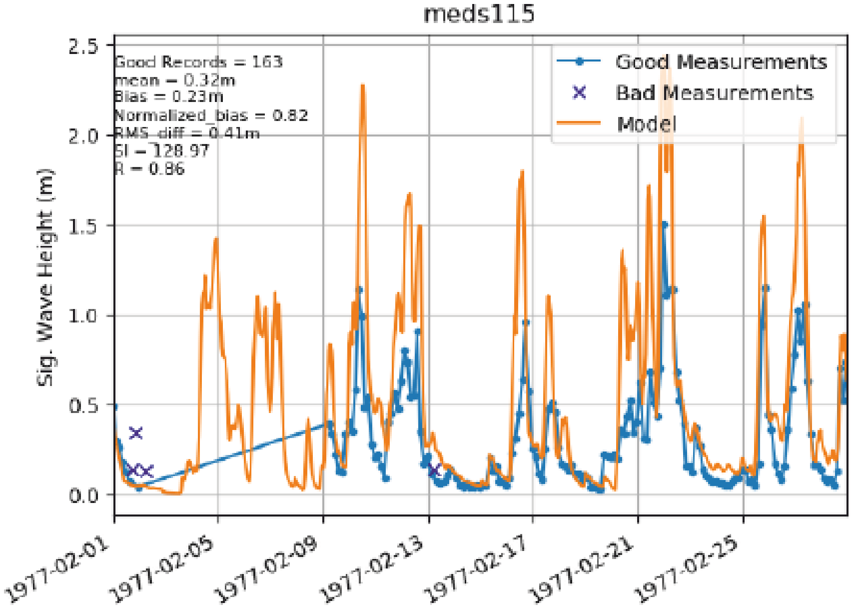

Figure 14: Modelled and measured H_{m0} time-series at meds115.

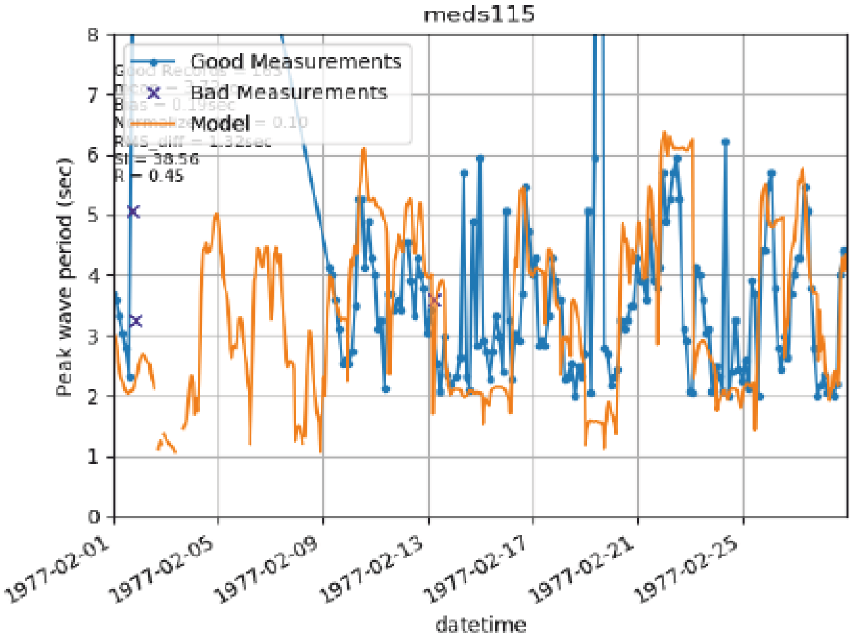

Figure 15: Modelled and measured T_p time-series at meds115.

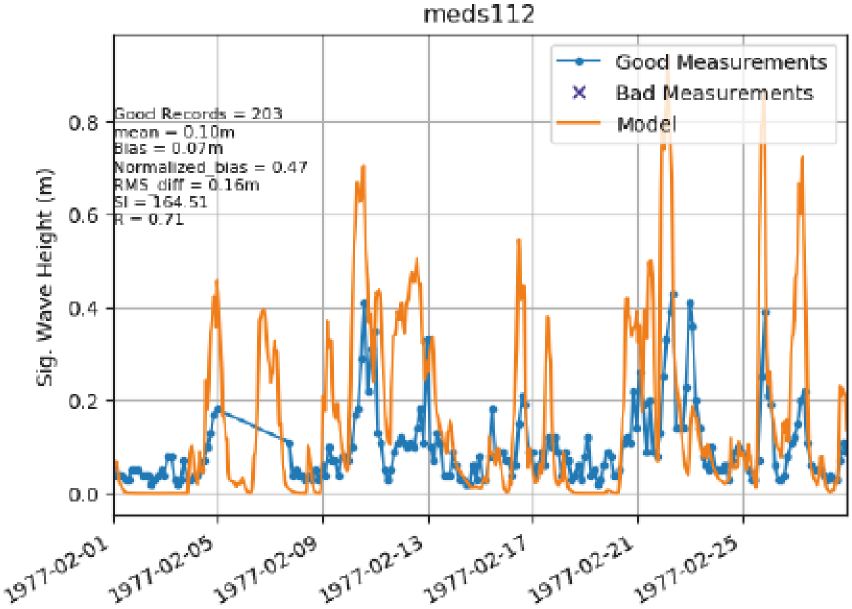

Figure 16: Modelled and measured H_{m0} time-series at meds112.

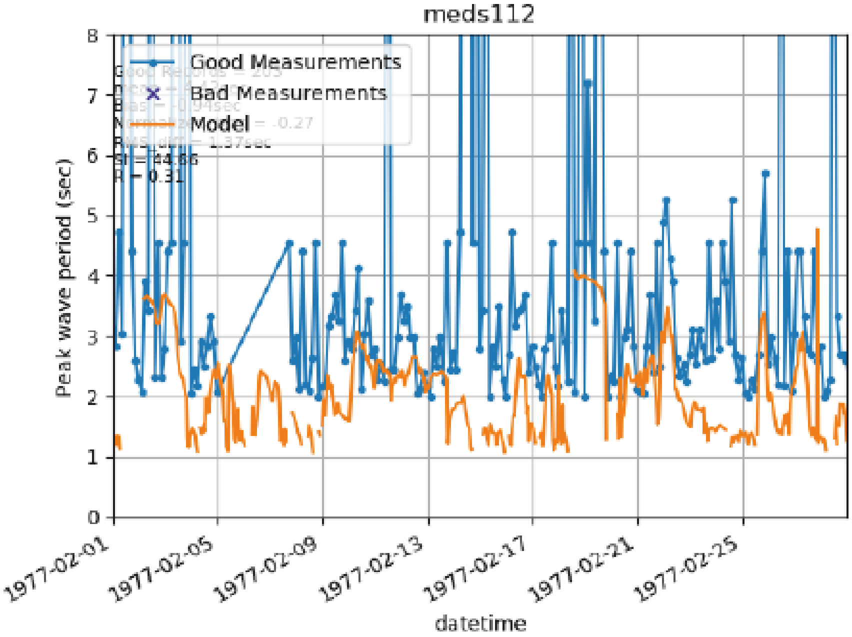

Figure 17: Modelled and measured T_p time-series at meds112.

Validation Run October to December 1997

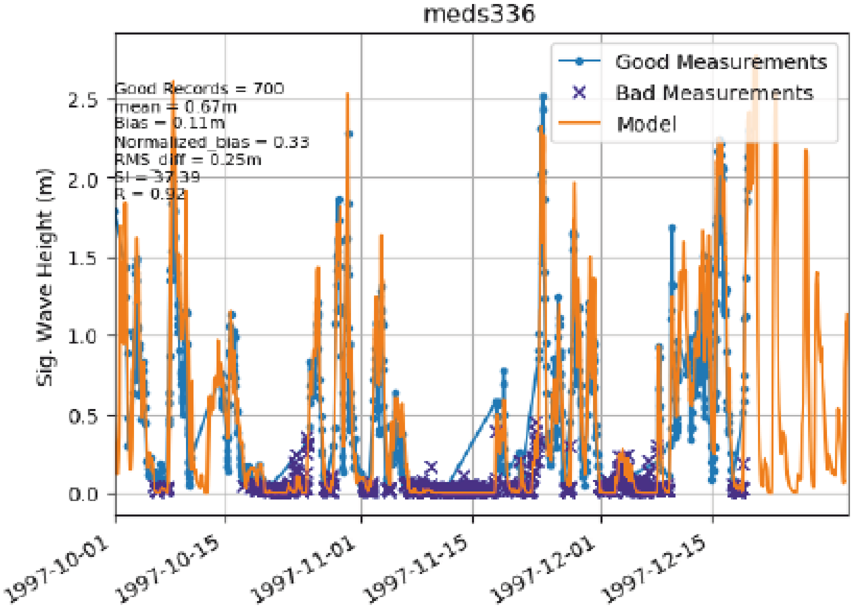

Figure 18: Modelled and measured H_{m0} time-series at meds336.

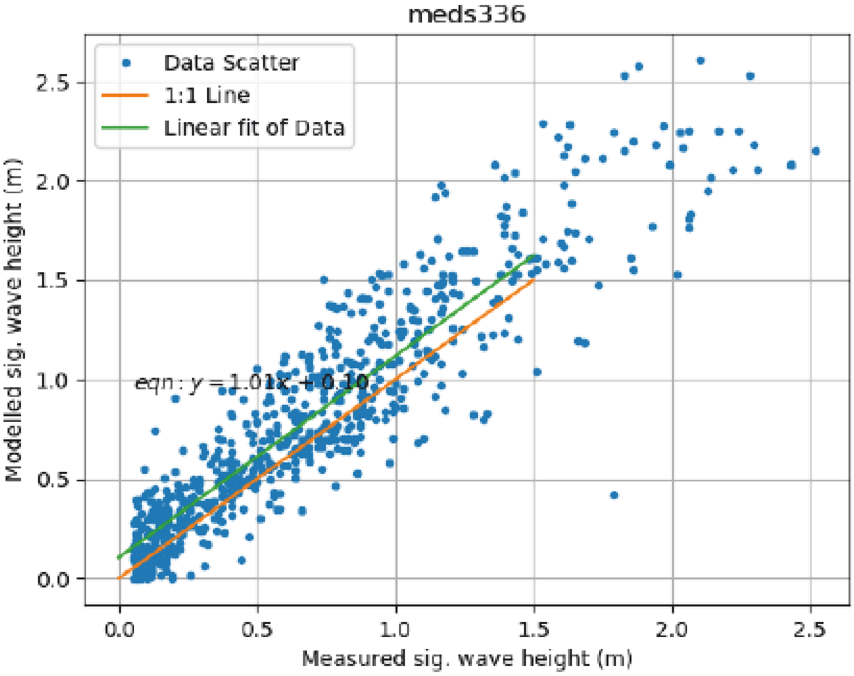

Figure 19: Modelled and measured H_{m0} scatter at meds336.

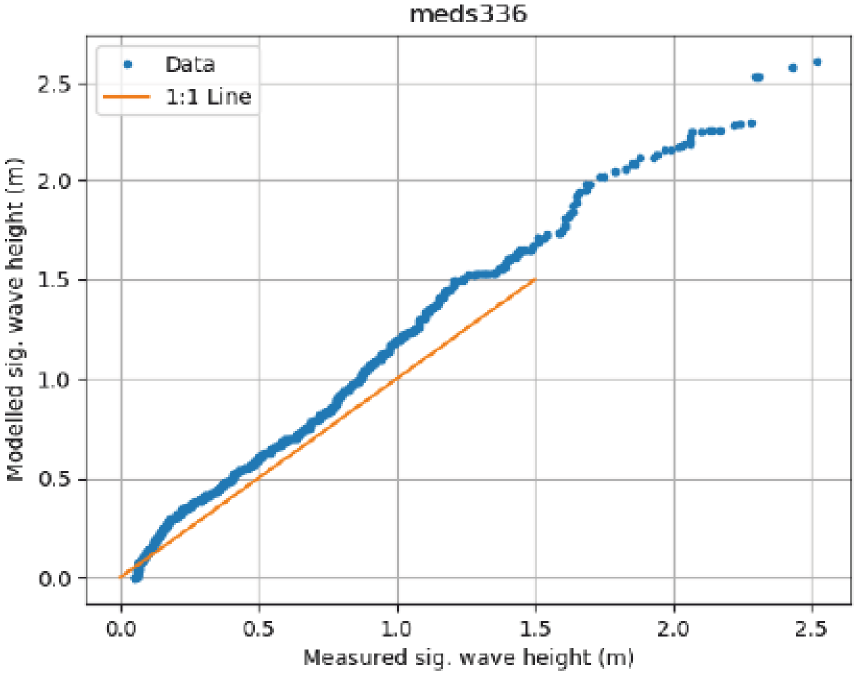

Figure 20: Modelled and measured H_{m0} qqplot at meds336.

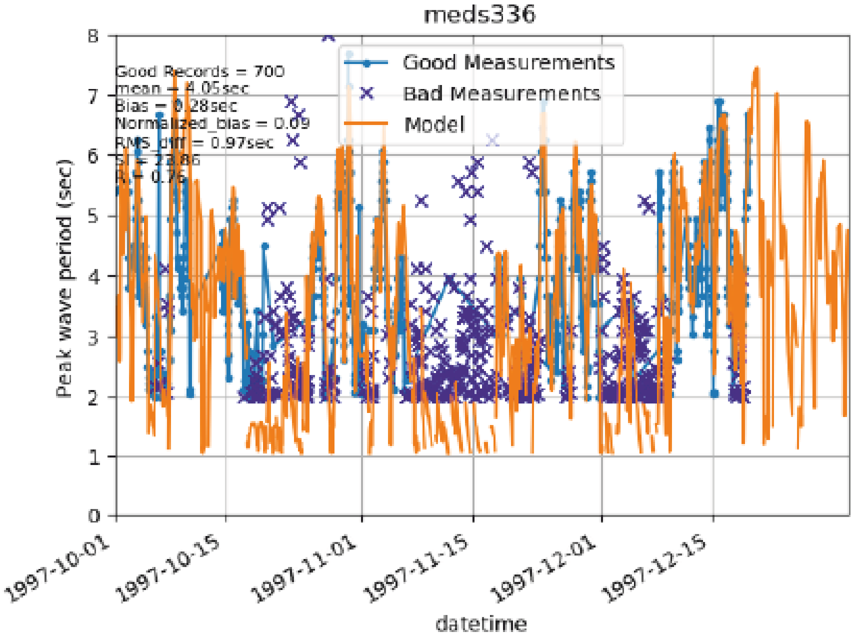

Figure 21: Modelled and measured T_p time-series at meds336.

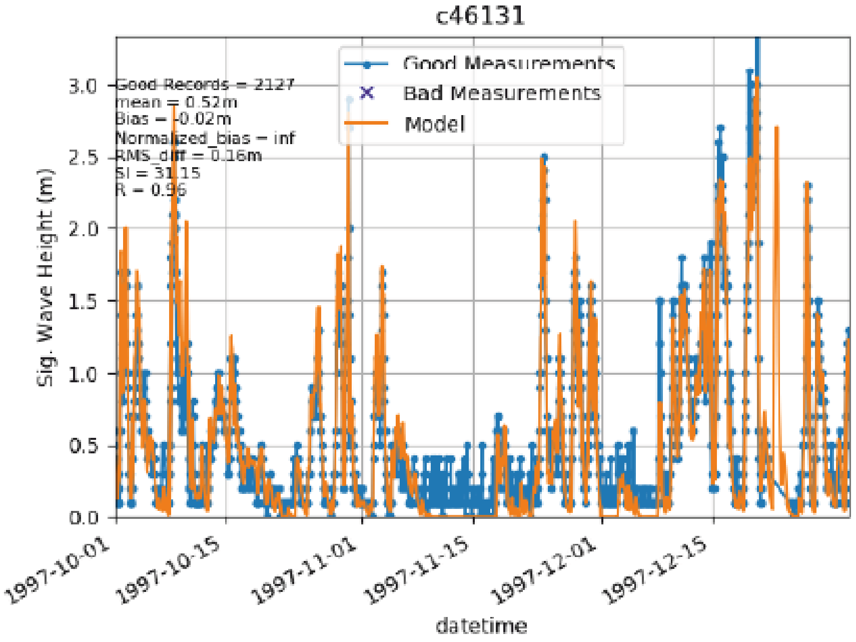

Figure 22: Modelled and measured H_{m0} time-series at c46131.

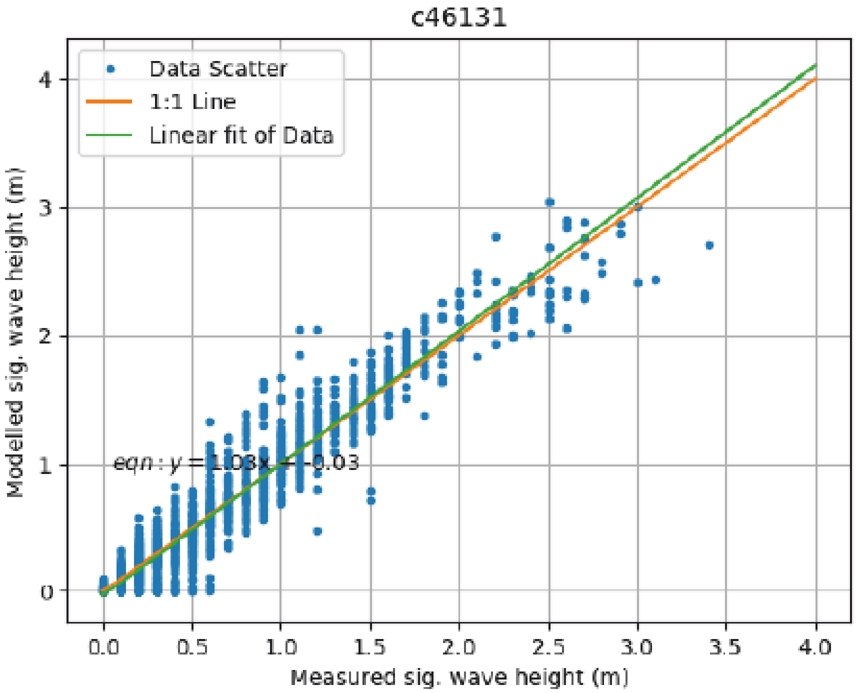

Figure 23: Modelled and measured H_{m0} scatter at c46131.

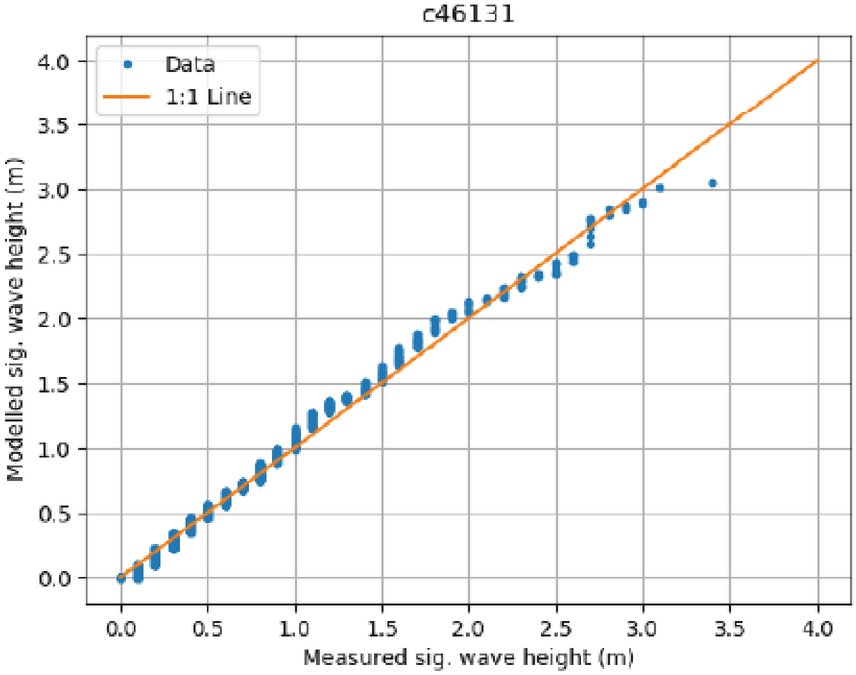

Figure 24: Modelled and measured H_{m0} qqplot at c46131.

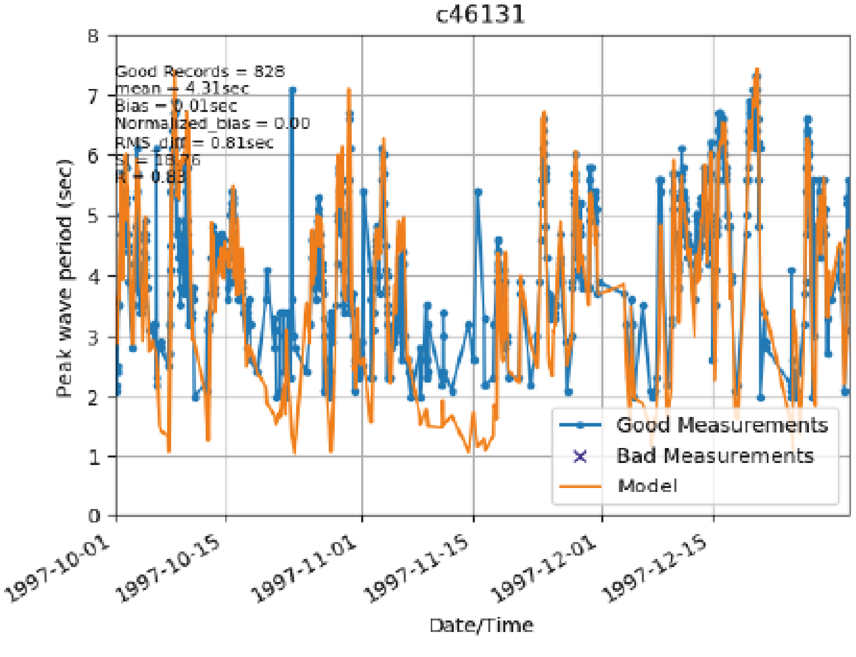

Figure 25: Modelled and measured T_p time-series at c46131.

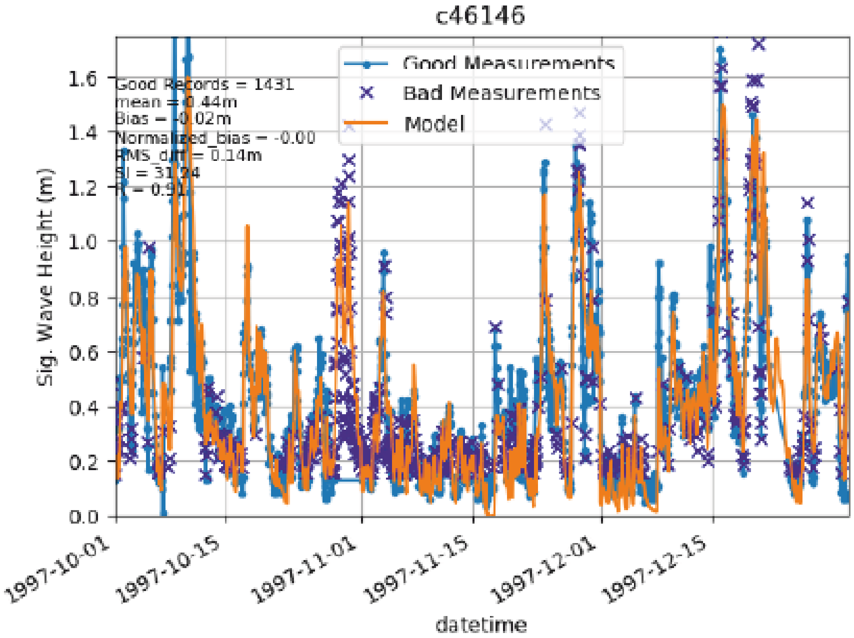

Figure 26: Modelled and measured H_{m0} time-series at c46146.

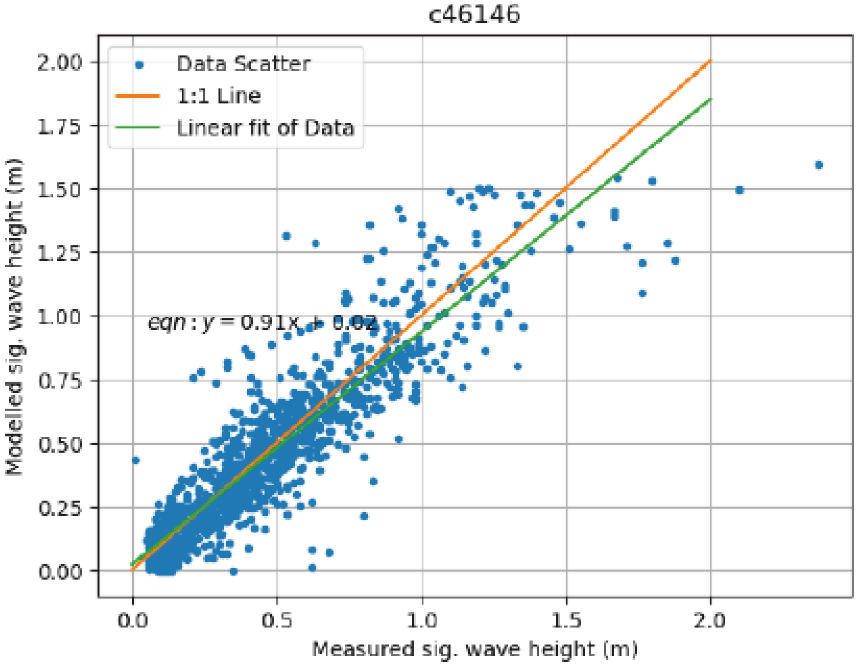

Figure 27: Modelled and measured H_{m0} scatter at c46146.

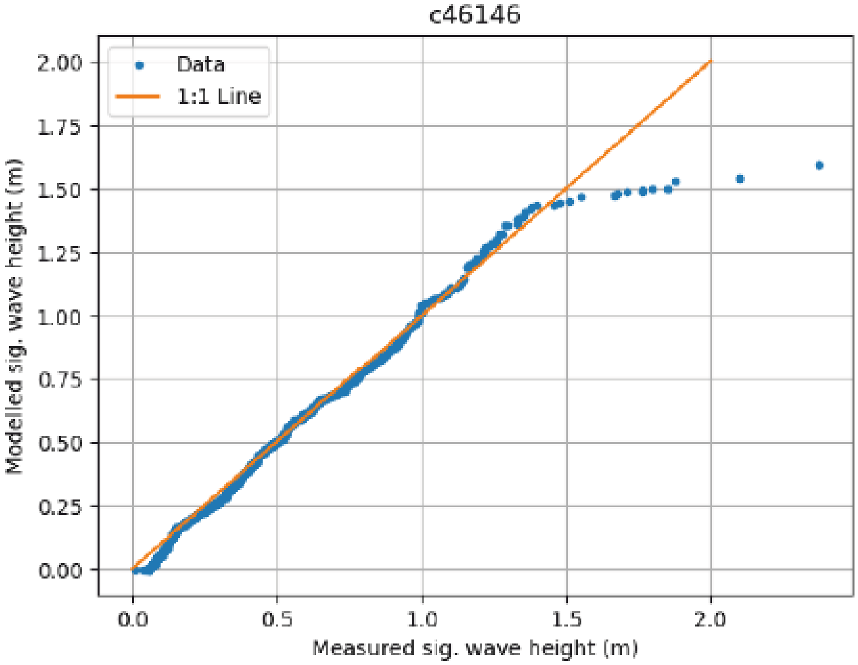

Figure 28: Modelled and measured H_{m0} qqplot at c46146.

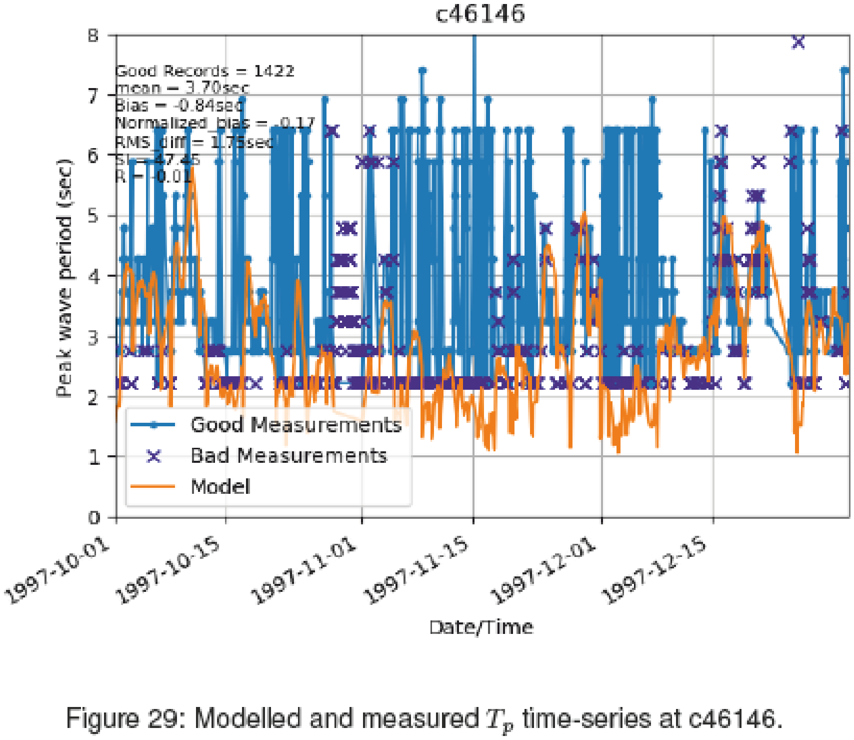

Figure 29: Modelled and measured T_p time-series at c46146.

B Wave model results

The figures in this appendix show the maximum significant wave height at each output location for all of the scenarios within the given combination of storm AEP and RSLR level.

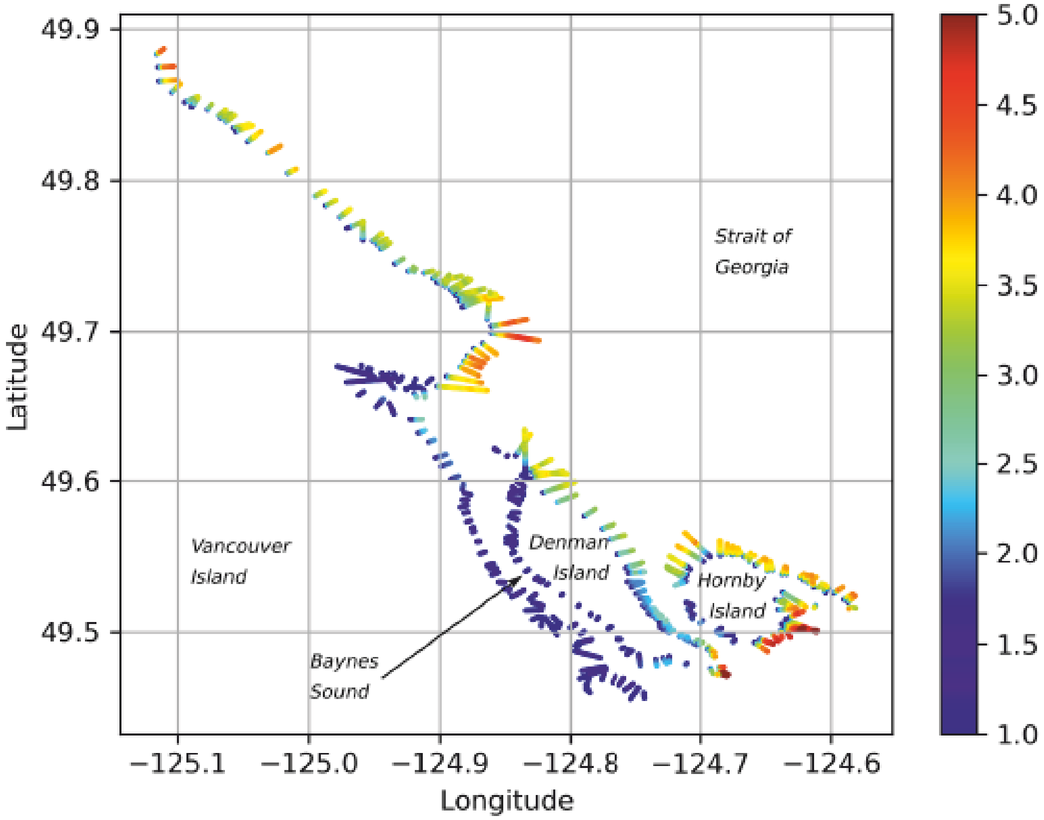

Figure 30: Maximum significant wave height [m], for all scenarios with 0.2% AEP and RSLR of 0.0 m.

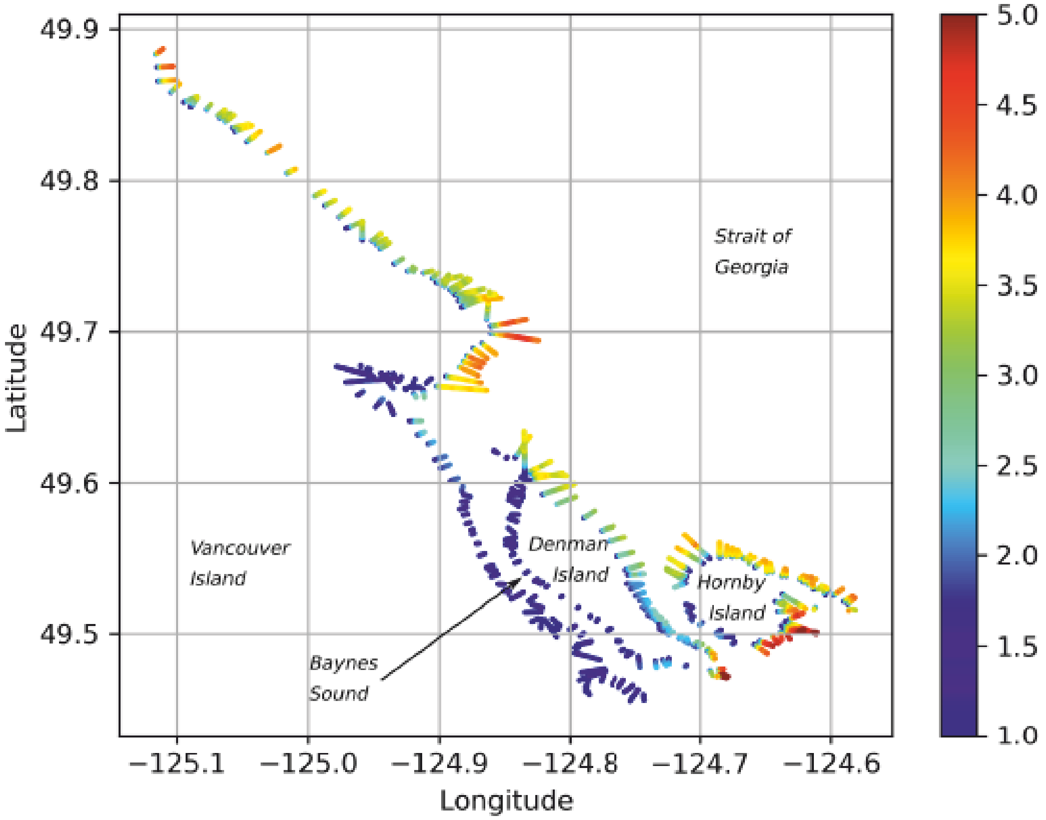

Figure 31: Maximum significant wave height [m], for all scenarios with 0.2% AEP and RSLR of 0.5 m.

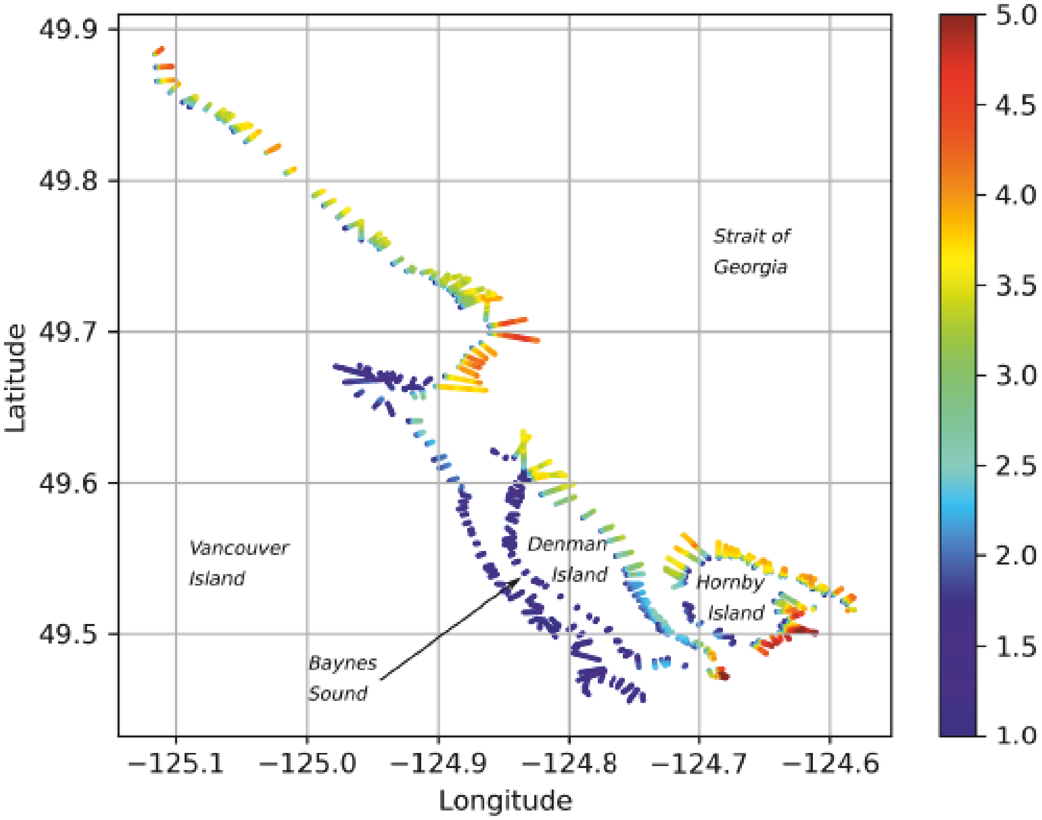

Figure 32: Maximum significant wave height [m], for all scenarios with 0.2% AEP and RSLR of 1.0 m.

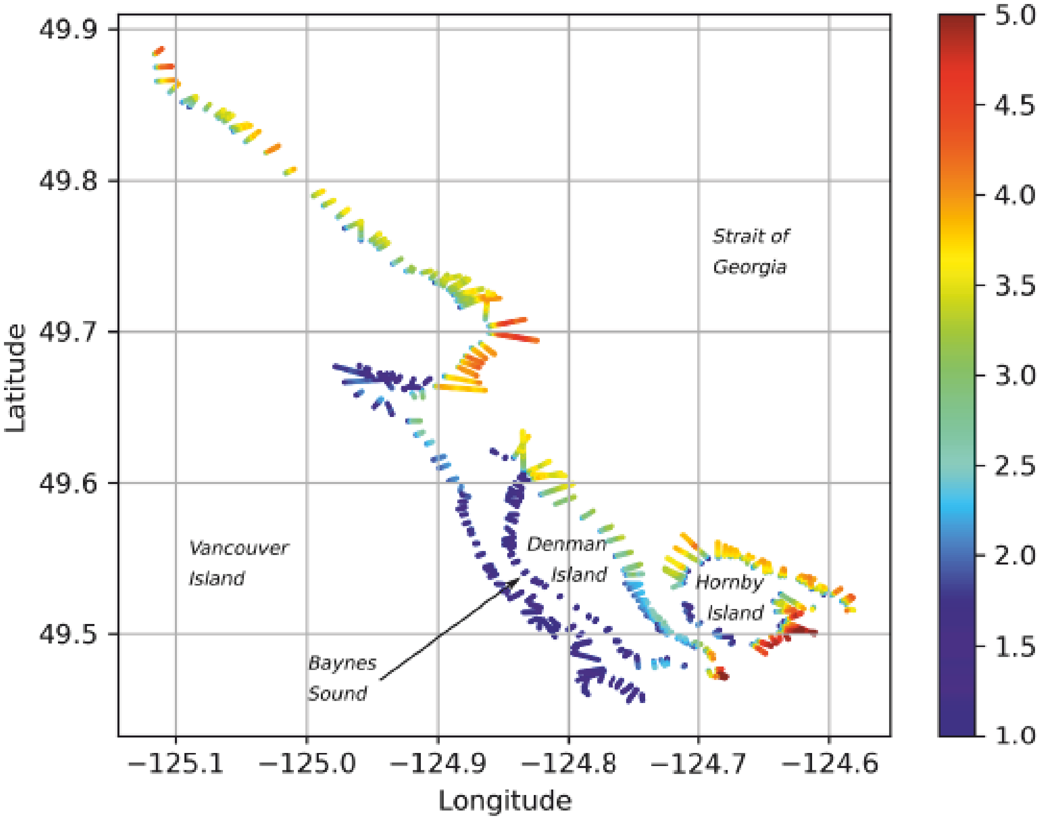

Figure 33: Maximum significant wave height [m], for all scenarios with 0.2% AEP and RSLR of 2.0 m.

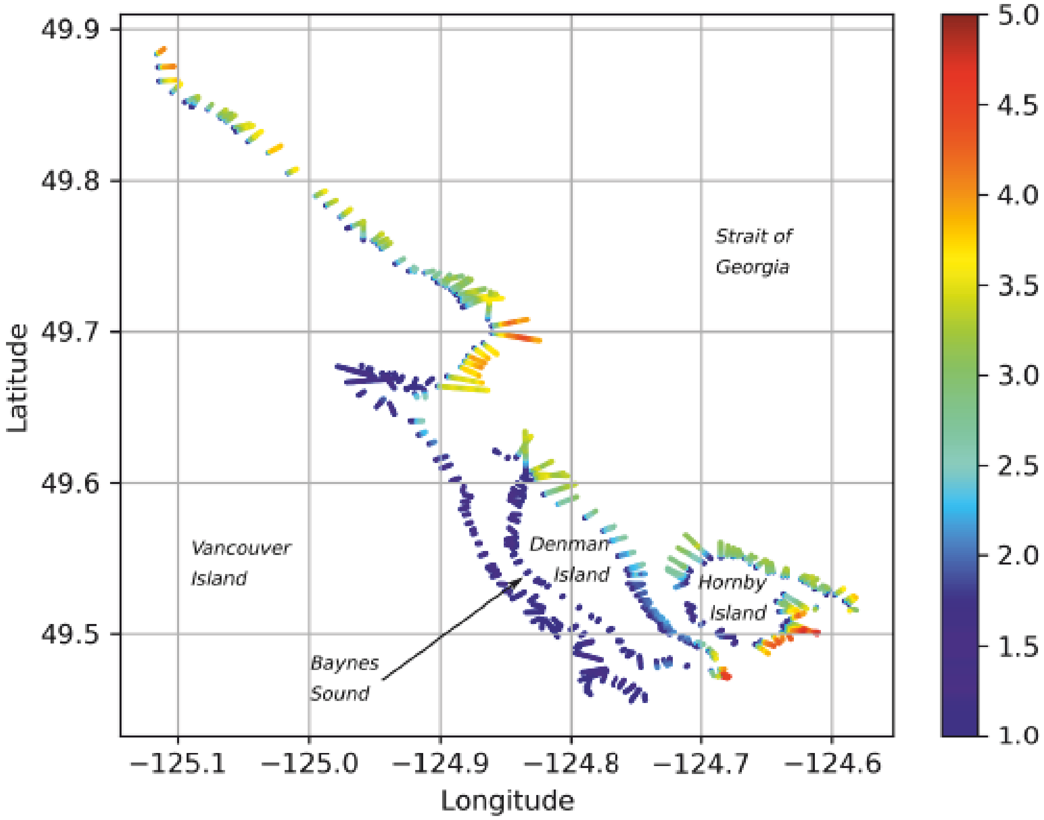

Figure 34: Maximum significant wave height [m], for all scenarios with 0.5% AEP and RSLR of 0.0 m.

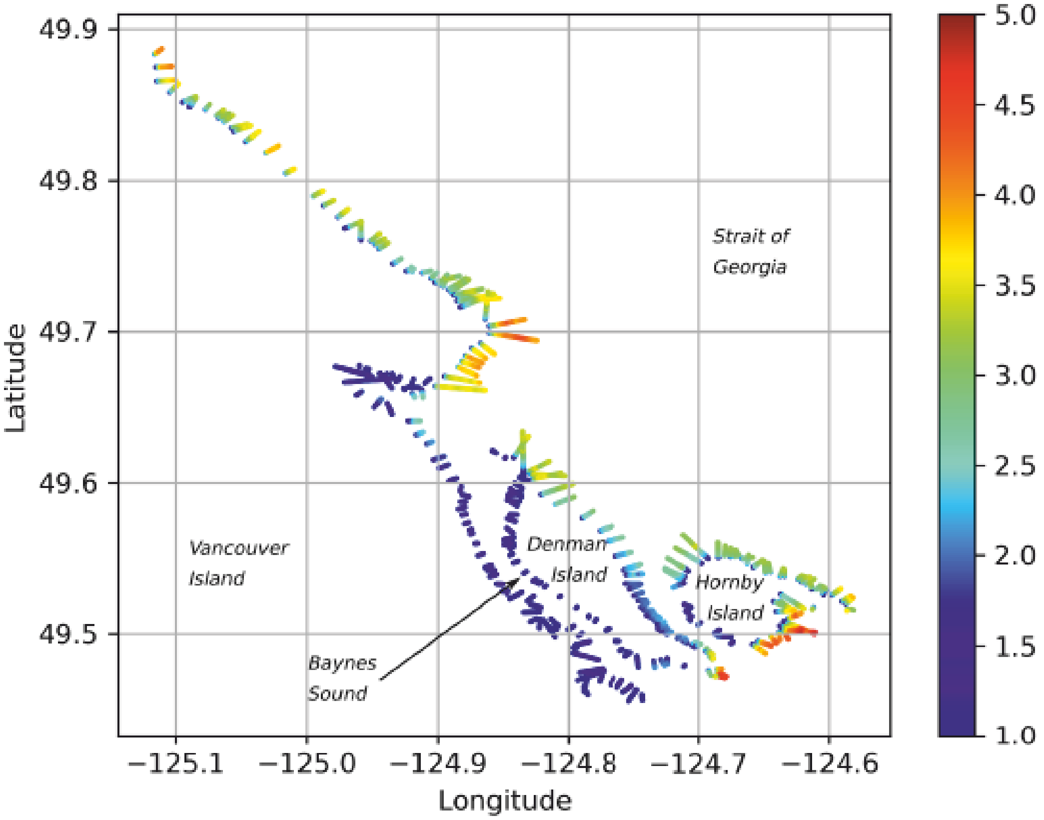

Figure 35: Maximum significant wave height [m], for all scenarios with 0.5% AEP and RSLR of 0.5 m.

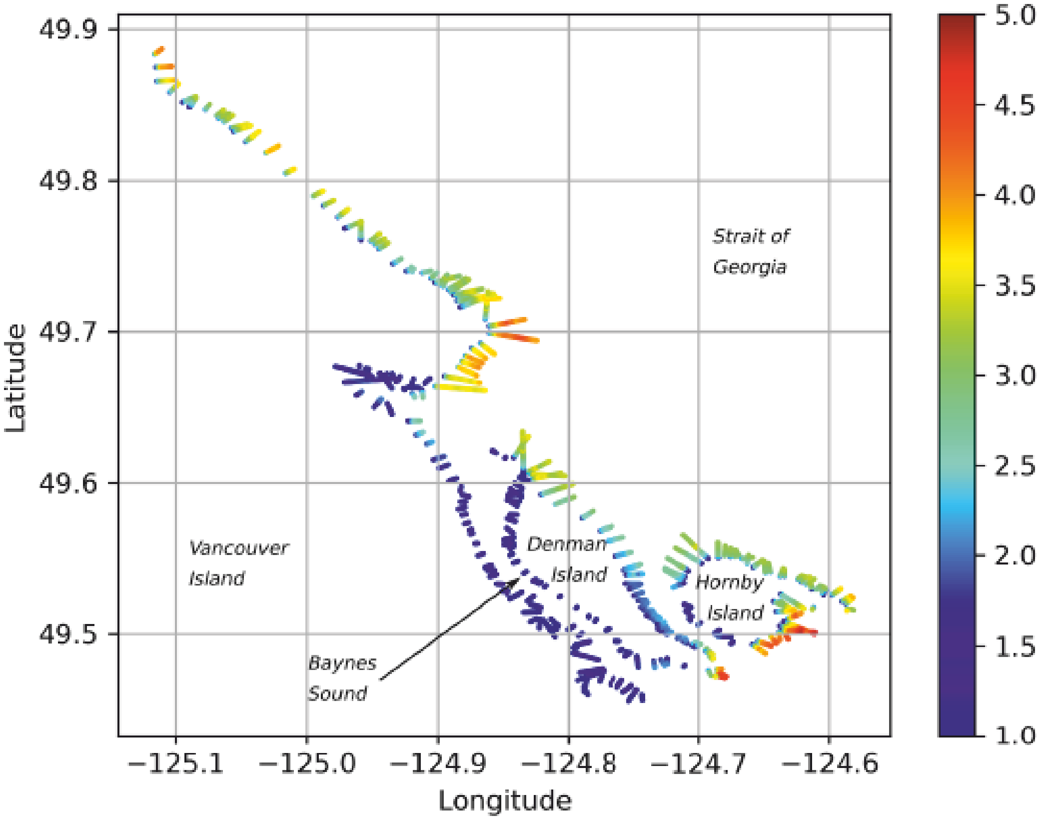

Figure 36: Maximum significant wave height [m], for all scenarios with 0.5% AEP and RSLR of 1.0 m.

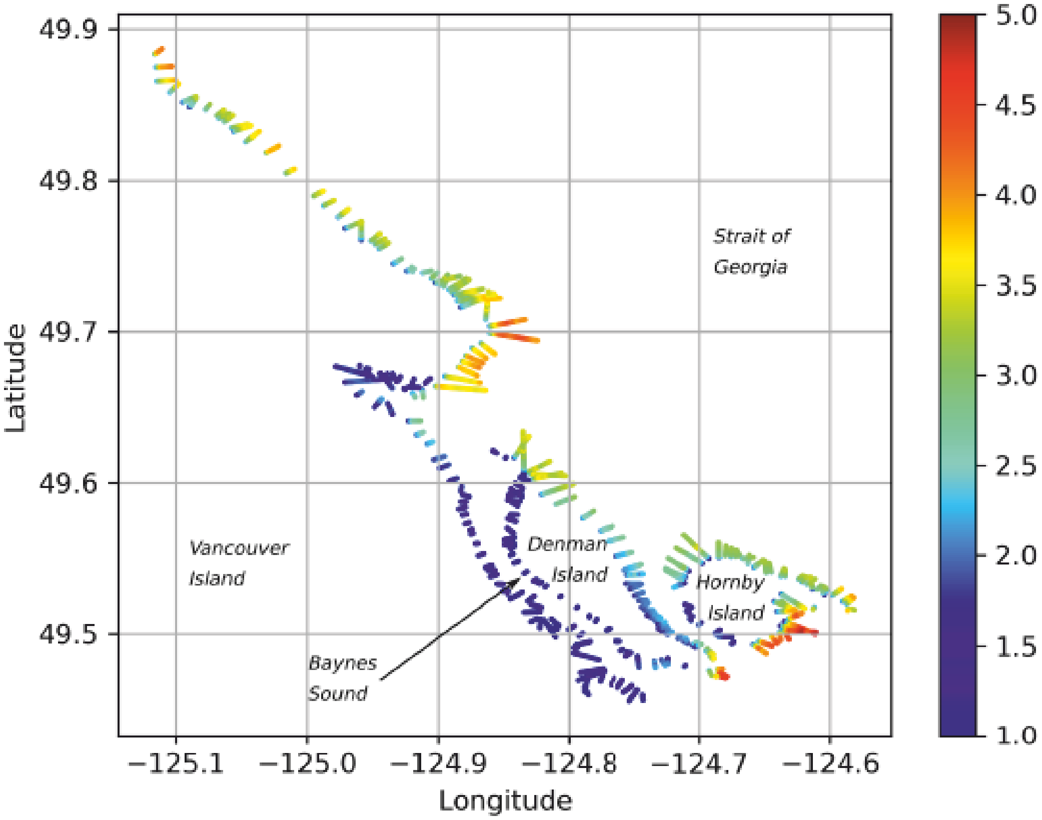

Figure 37: Maximum significant wave height [m], for all scenarios with 0.5% AEP and RSLR of 2.0 m.

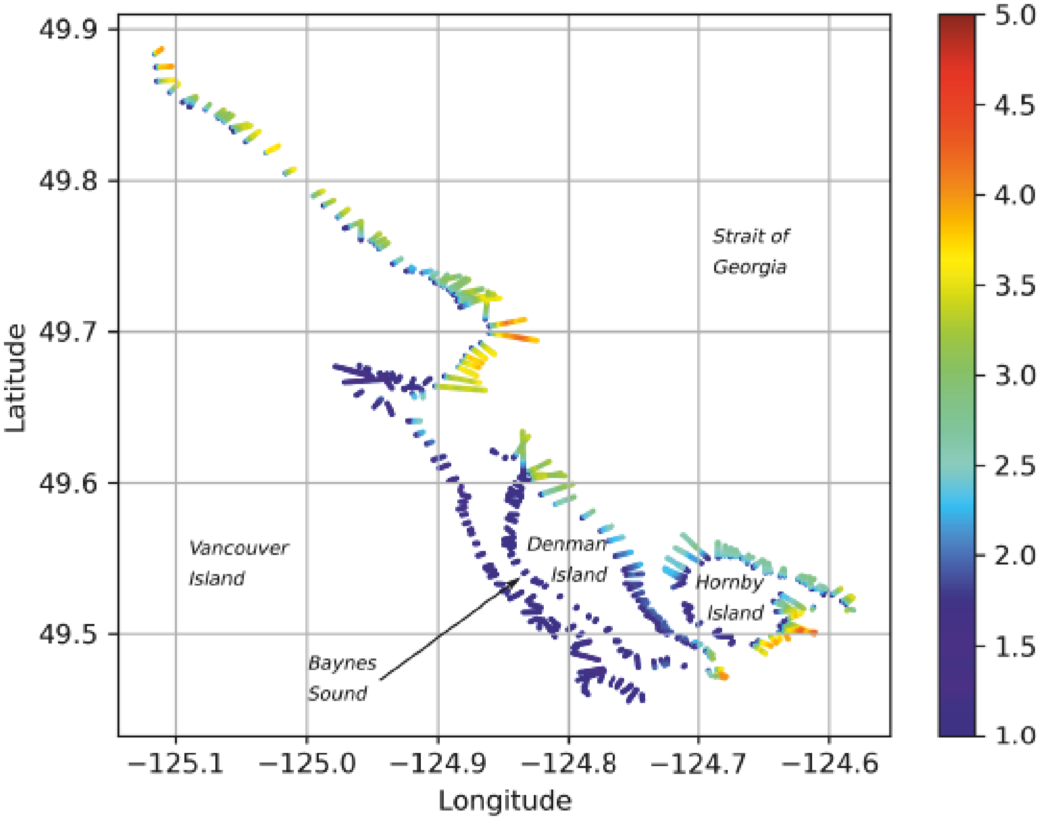

Figure 38: Maximum significant wave height [m], for all scenarios with 1% AEP and RSLR of 0.0 m.

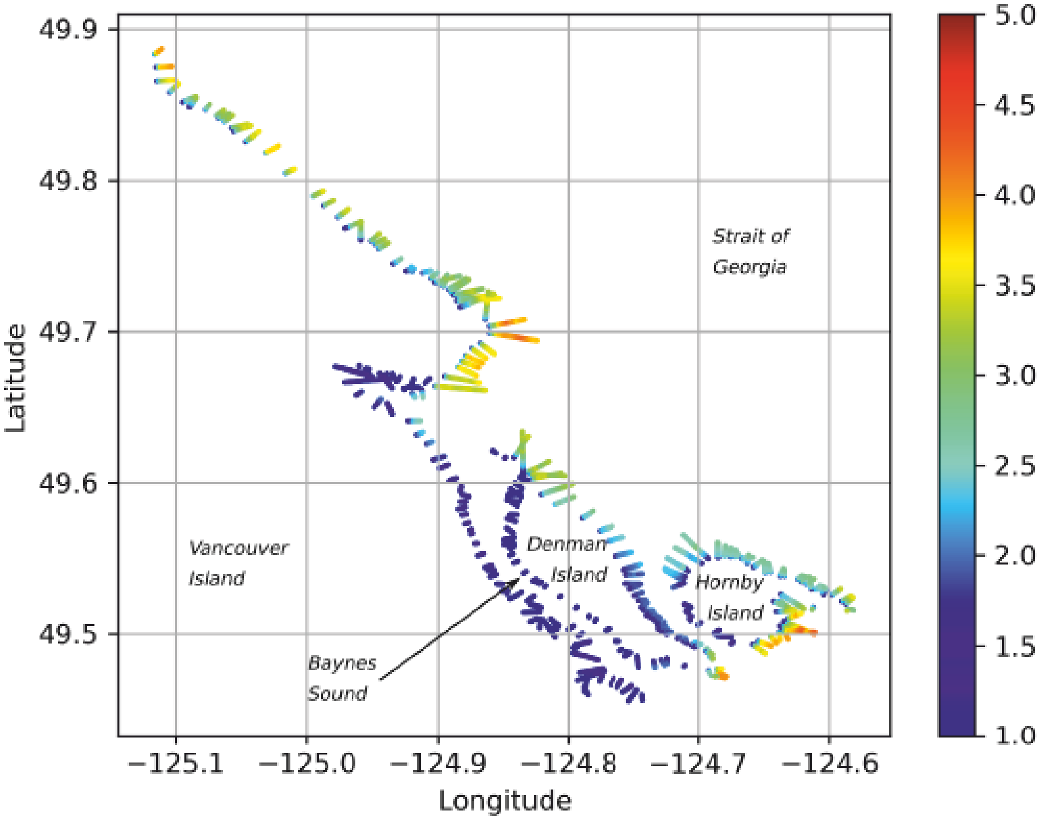

Figure 39: Maximum significant wave height [m], for all scenarios with 1% AEP and RSLR of 0.5 m.

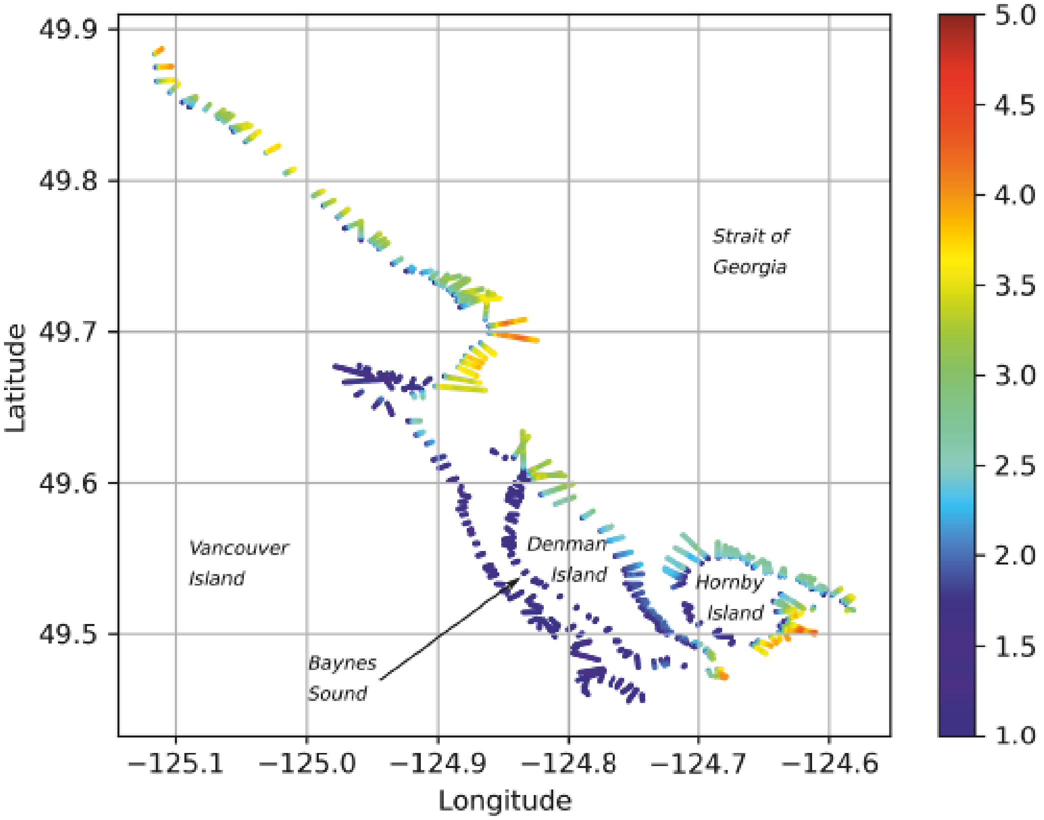

Figure 40: Maximum significant wave height [m], for all scenarios with 1% AEP and RSLR of 1.0 m.

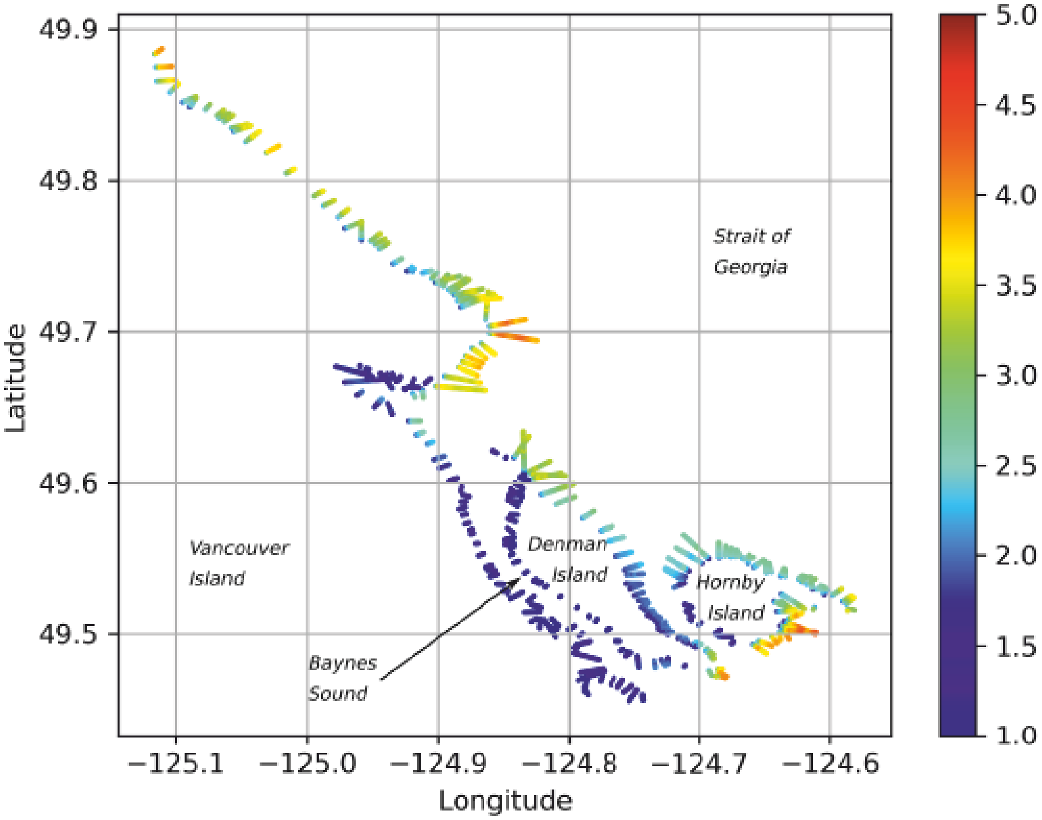

Figure 41: Maximum significant wave height [m], for all scenarios with 1% AEP and RSLR of 2.0 m.

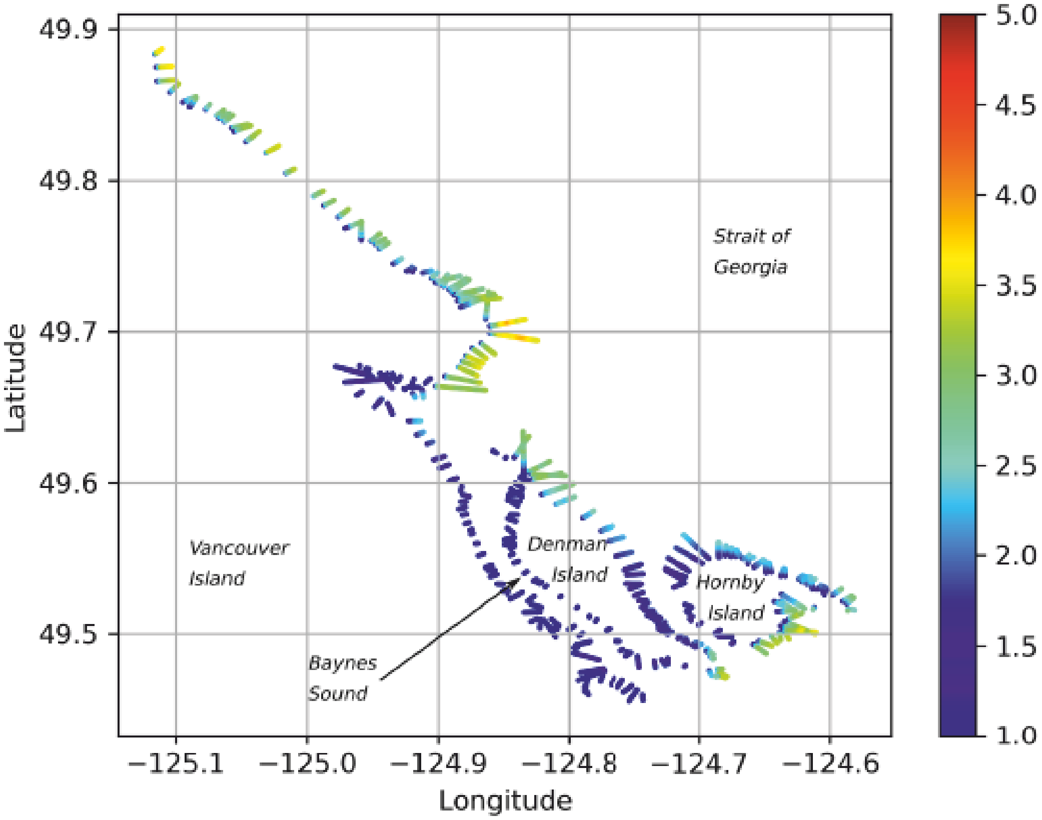

Figure 42: Maximum significant wave height [m], for all scenarios with 5% AEP and RSLR of 0.0 m.

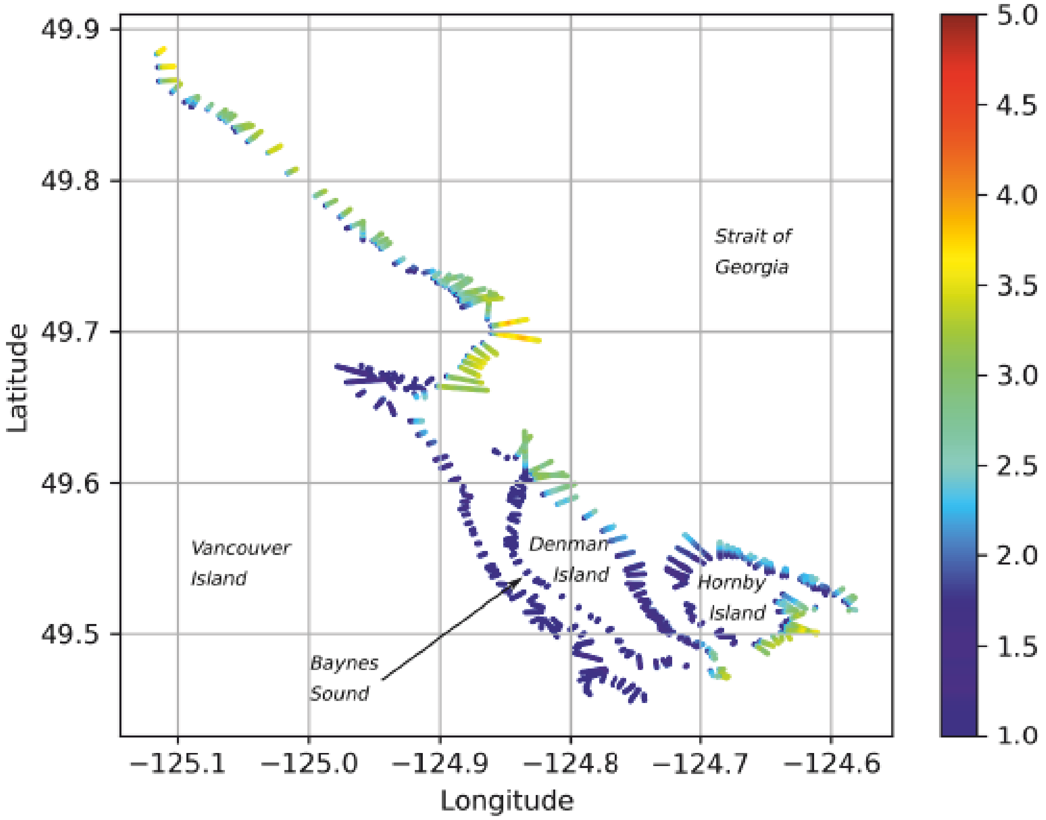

Figure 43: Maximum significant wave height [m], for all scenarios with 5% AEP and RSLR of 0.5 m.

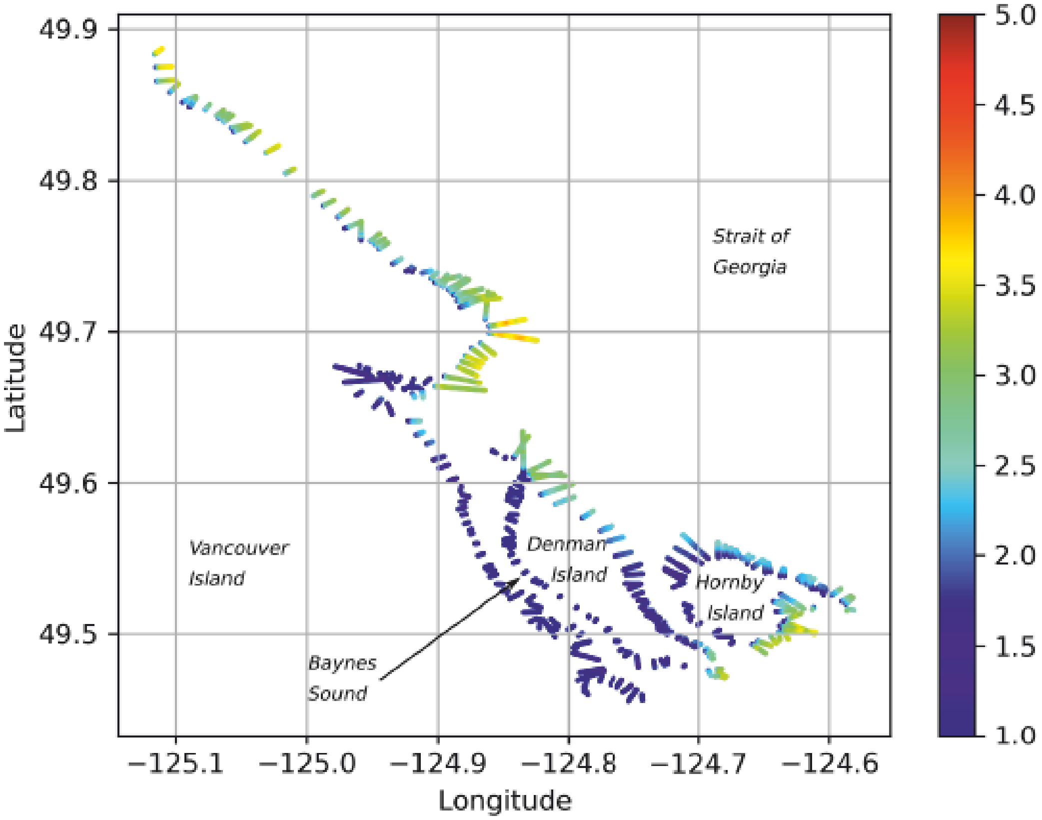

Figure 44: Maximum significant wave height [m], for all scenarios with 5% AEP and RSLR of 1.0 m.

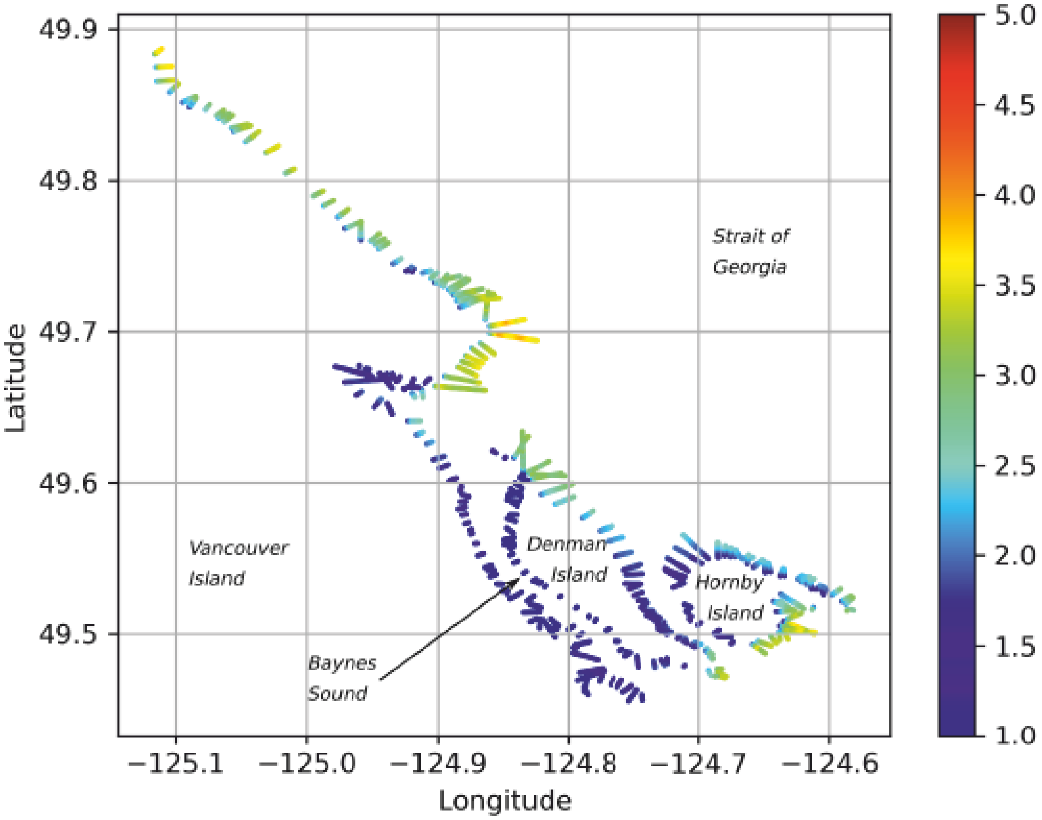

Figure 45: Maximum significant wave height [m], for all scenarios with 5% AEP and RSLR of 2.0 m.

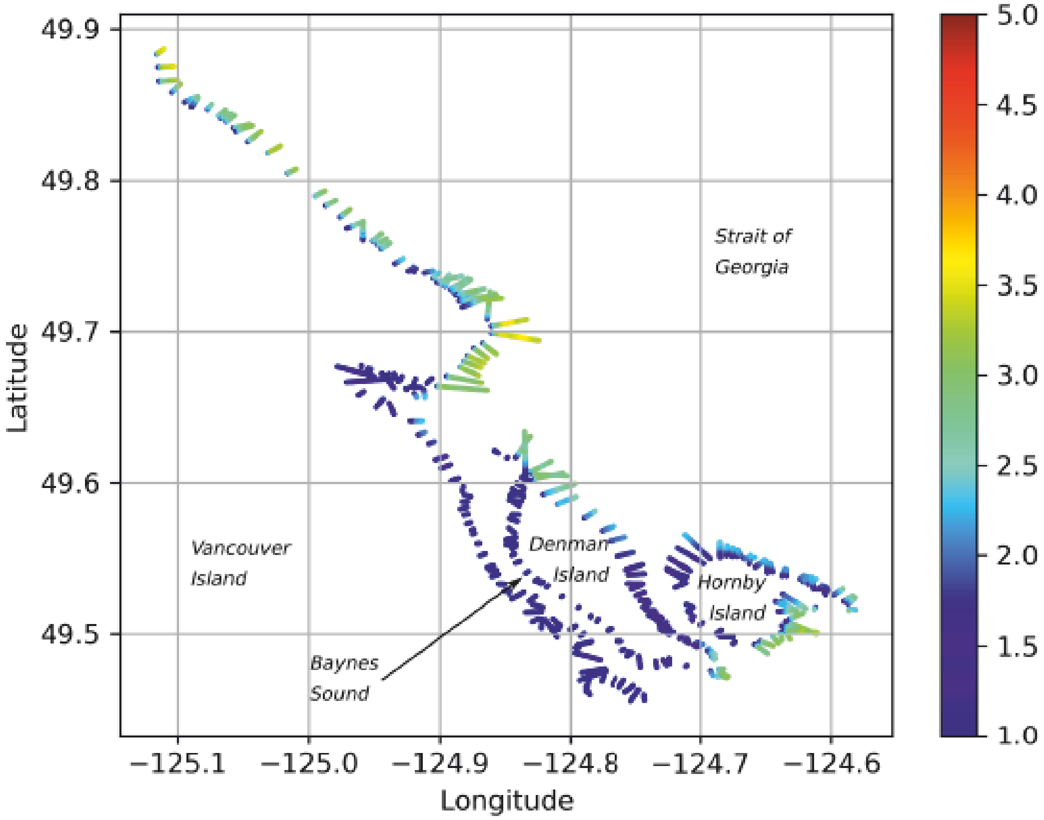

Figure 46: Maximum significant wave height [m], for all scenarios with 10% AEP and RSLR of 0.0 m.

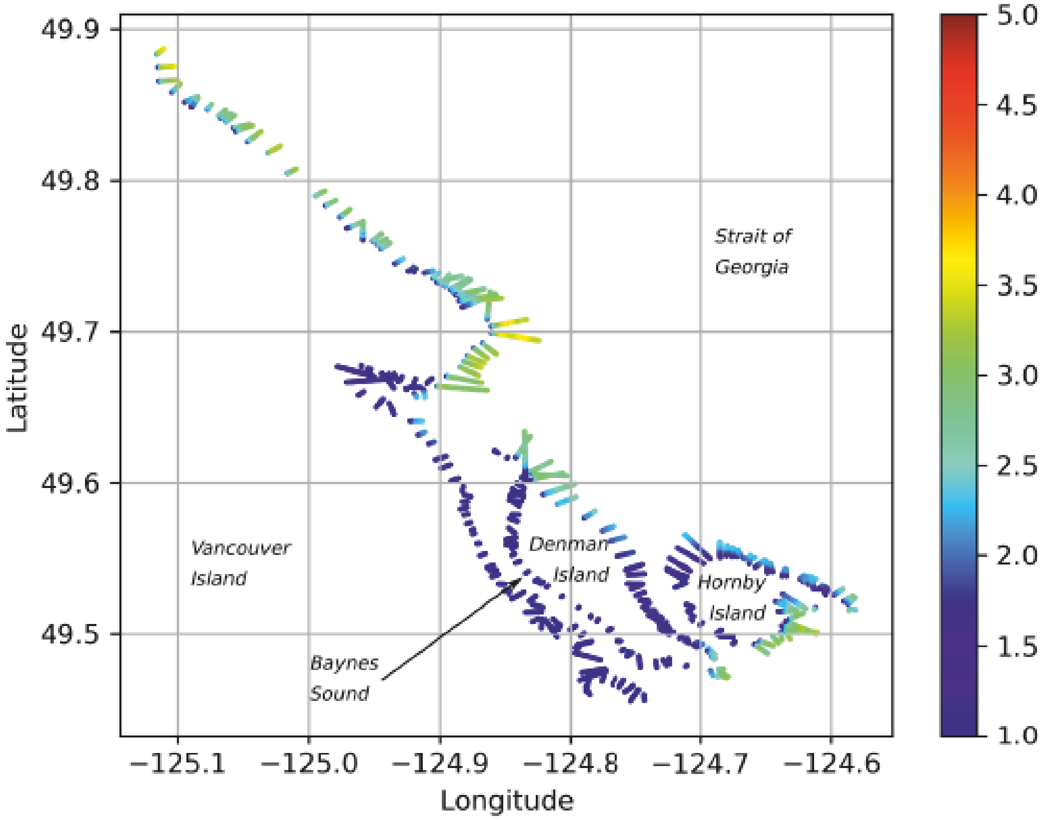

Figure 47: Maximum significant wave height [m], for all scenarios with 10% AEP and RSLR of 0.5 m.

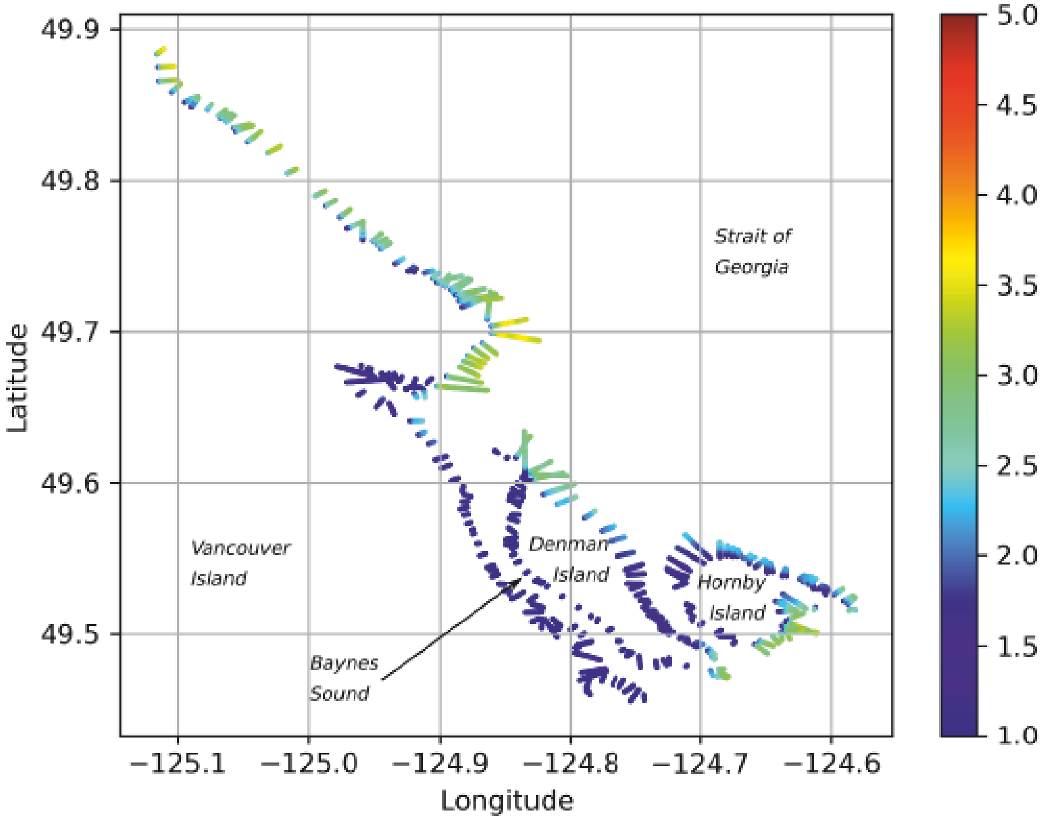

Figure 48: Maximum significant wave height [m], for all scenarios with 10% AEP and RSLR of 1.0 m.

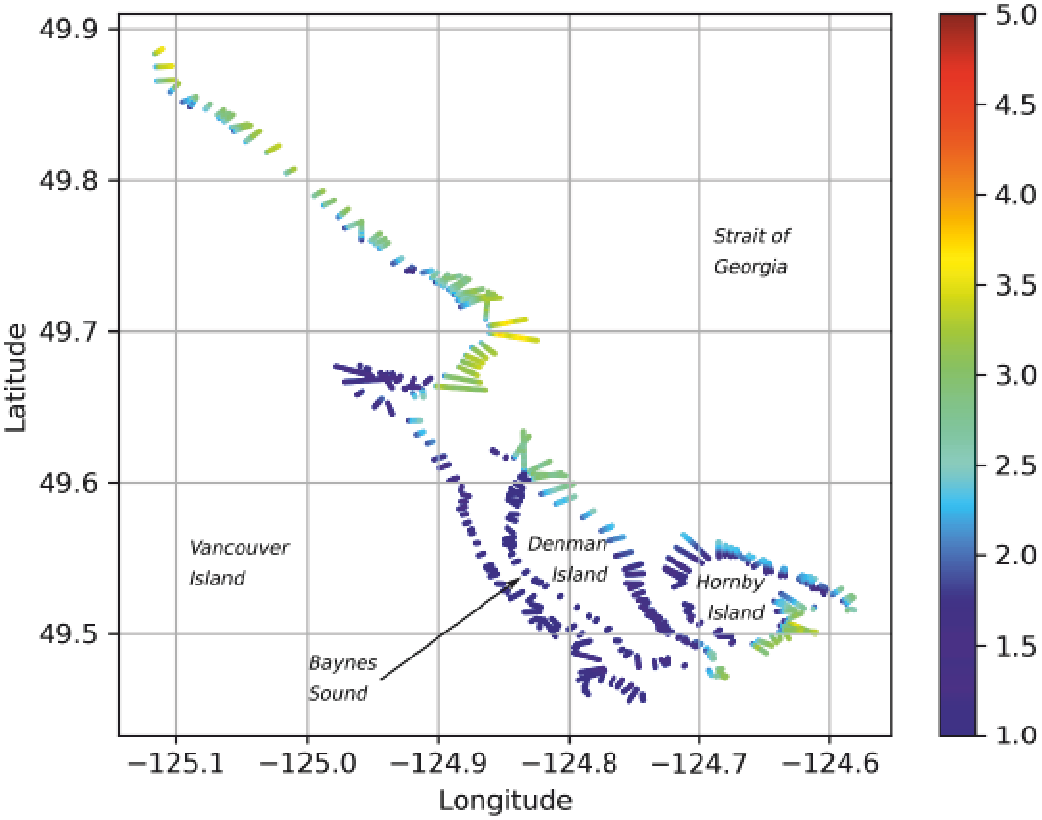

Figure 49: Maximum significant wave height [m], for all scenarios with 10% AEP and RSLR of 2.0 m.

Appendix B

SHORLAX Results

Table 1B: SHORLAX Results - Total Water Level Summary

Total Water Level[1] (m, CGVD2013)
by Annual Exceedance Probability (AEP) and Sea Level Rise (SLR)

	0 m Sea Level Rise					0.5 m Sea Level Rise					1 m Sea Level Rise					2 m Sea Level Rise				
Transect / AEP	10%	5%	1%	0.5%	0.2%	10%	5%	1%	0.5%	0.2%	10%	5%	1%	0.5%	0.2%	10%	5%	1%	0.5%	0.2%
3	3.6	3.7	3.9	4	4.1	4.1	4.2	4.4	4.5	4.6	4.6	4.7	4.9	5	5.1	5.6	5.7	5.9	6	6
4	4.5	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	5.4	5.4	5.4	5.4	5.4
5	4.1	4.2	4.3	4.4	4.5	4.7	4.8	5.2	5.2	5.2	5.2	5.2	5.4	5.5	5.6	5.9	6.1	6.1	6.1	6.1
6	4.2	4.2	4.3	4.5	4.5	4.6	4.6	4.7	4.8	5	5.4	5.4	5.4	5.4	5.5	7	7.2	7.4	7.6	7.7
7	3.9	4.1	4.3	4.4	4.5	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.8	4.8	4.9	5.5	5.5	5.5	5.5	5.5
8	4.6	4.6	4.6	4.6	4.6	4.6	4.6	5.4	5.7	5.7	5.2	5.3	5.4	5.7	5.8	5.8	5.8	5.8	5.8	5.8
11	3.6	3.8	3.9	4	4.1	4.2	4.3	4.5	4.6	4.7	4.8	4.9	5.1	5.2	5.2	5.5	5.6	7.2	7.3	7.3
12	6.1	6.4	6.6	7.1	7.4	7.8	8.1	8.7	8.9	9.1	9.7	10.1	10.6	10.7	11	13	13.6	14.1	14.1	14.4
13	6.9	7.4	8.6	8.9	9.3	8.5	8.9	9.8	10.3	10.8	9.8	10.5	11.7	11.9	12.3	10.4	14.1	15.4	15.7	15.8
14	5	5.2	5.2	5.6	5.8	5.6	5.8	6.2	6.2	6.4	6.4	6.4	6.7	6.8	7	7.5	7.6	8	8.2	8.9
15	4.2	4.3	4.4	4.5	4.8	4.5	4.8	5.4	5.5	5.5	5.5	5.5	5.8	6.1	6.2	6.8	7	7.4	7.5	7.7
16	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	4.9	5	5	5.1	5.4	5.6	5.7	5.5	5.6	5.8	5.9	6
17	4.4	4.4	4.4	4.5	4.5	4.4	4.5	4.8	4.9	5	4.9	5	5.2	5.3	5.4	6.7	6.9	7.2	7.4	7.7
18	5.3	5.3	5.3	5.3	5.4	5.7	5.9	6.2	6.3	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4
19	7	7.5	8.2	8.5	8.8	8.5	9	9.8	10.1	10.3	10	10.3	10.9	11.2	11.6	13	13.2	13.6	13.8	14
20	7	7.3	8.7	8.9	9	9	9.5	10.4	10.7	11.2	9.5	11.9	12.9	13.1	13.5	12.5	12.9	14.8	15	15.1
21	4.7	5.2	5.7	6.4	6.4	6	6.6	8.2	8.4	8.4	8.1	9	9.2	9.8	9.8	10.5	10.5	10.6	10.6	10.9
22	6.1	6.3	6.8	7	7.2	7	7.2	7.5	7.7	7.8	7.8	8	8.5	8.6	8.8	9.4	9.7	10	10.1	10.2
23	5.1	5.4	5.9	6.1	6.4	6.3	6.7	7.3	7.5	7.9	7.8	7.8	8.5	9	9.3	10.3	10.6	11.3	11.4	11.8
24	3.9	4.1	4.5	4.6	4.7	4.6	4.6	4.6	4.6	4.7	4.6	4.6	4.6	4.8	4.9	6.2	6.4	6.9	6.9	7
25	3.4	3.5	3.5	3.7	3.8	3.7	3.8	4	4.1	4.3	4.2	4.2	4.5	4.6	4.8	5.8	5.9	6.2	6.2	6.3
26	4.4	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.8	4.8	4.8	4.8	4.8	5.3	5.3	5.6	5.7	5.9
28	4.3	4.6	4.6	4.6	4.6	4.3	4.6	4.9	4.9	4.9	5	5.2	5.8	5.8	5.8	5.5	5.6	5.8	5.8	5.8
30	4	4.1	4.3	4.4	4.5	4.4	4.5	4.8	4.9	5	4.9	5.1	5.3	5.4	5.4	5.5	5.6	5.8	5.9	6
31	3.9	4	4	4	4	4.3	4.4	4.4	4.4	4.5	4.5	4.6	4.8	4.8	5	5.5	6	6.7	7	7.2
32	5.2	5.4	5.6	5.8	6	5.9	5.9	5.9	5.9	6	5.9	5.9	5.9	5.9	6	5.9	5.9	5.9	5.9	6
33	5.8	5.9	6.1	6.2	7.3	7.1	7.4	9.3	9.4	9.4	9.6	9.8	9.8	9.8	9.8	9.6	9.8	9.8	9.8	9.8
34	11.3	11.3	12.2	12.3	12.4	11.9	11.9	12.2	12.3	12.4	11.9	11.9	12.2	12.3	12.4	12	12.3	12.4	12.6	12.7
35	4.5	4.5	4.7	4.9	4.9	4.5	4.5	4.7	4.9	4.9	4.5	6.2	6.6	6.6	6.6	6.9	7.1	7.7	7.8	8.1
36	3.9	3.9	4.1	4.3	4.4	4.5	4.6	4.8	5	5	4.8	5.1	5.1	5.1	5.1	5.7	5.9	6.5	6.7	6.9
37	5.1	5.4	6.1	6.6	7	6.7	7	7.7	8	8.6	8	8.4	9.2	9.4	9.9	9.9	10.3	11.3	11.6	12.7
38	4.4	4.7	4.8	4.8	4.8	4.8	4.8	5.1	5.1	5.1	5.1	5.1	5.3	5.5	5.6	5.6	5.7	5.9	6	6.1
39	5.8	6	6.5	6.6	6.9	7.2	7.5	8.3	8.3	8.4	8.8	9.6	9.6	9.6	10.3	13.4	13.5	14.3	14.6	14.7
40	6.1	6.4	7	7.3	8.1	7.3	7.6	8.3	8.8	9.7	8.6	8.9	9.7	9.7	9.7	9.2	9.6	10.3	10.5	10.6
41	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	4.8	5.5	5.6	5.9	5.9	6.1
42	5.9	6	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.3	6.4	6.6
44	4.2	4.3	4.6	4.8	4.9	4.8	4.9	5.1	5.1	5.1	4.8	4.9	5.1	5.1	5.1	5.6	5.7	6	6.2	6.5
45	8.3	8.8	9.4	9.7	9.9	9.8	10.2	10.9	11.2	11.5	11.2	11.6	12.3	12.6	13	14.9	15.2	15.8	16.1	16.5
46	7.7	8.4	8.8	8.8	9.6	9.4	9.7	10.8	10.8	11.1	11.1	11.4	12.1	12.4	12.6	14.2	14.5	15	15.1	15.3
47	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.7	3.7	3.9	4	4.1	4.2	4.2	4.9	5	5.1	5.2	5.2
48	3.6	3.8	3.8	3.9	3.9	4.5	4.8	5.3	5.3	5.5	5.1	5.3	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
49	3.7	3.8	3.8	3.9	4	3.8	3.9	4.1	4.1	4.2	4.3	4.4	4.6	4.7	4.7	4.9	5	5.1	5.2	5.2
52	3.9	4.1	4.4	4.5	4.6	4.7	5.1	5.1	5.1	5.1	5.4	5.5	6	6.2	6.5	7.9	8.2	9	9.1	9.3
53	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.9	4	4.1	4.2	4.3	4.5	4.6	4.7	6.5	6.8	7.3	7.5	7.8
54	3.5	3.5	3.5	3.5	3.5	3.5	3.7	3.8	3.9	4	4.1	4.2	4.4	4.4	4.5	5.3	5.4	5.7	5.8	5.8
55	4.3	4.6	5.3	5.3	5.3	5.3	5.8	6.2	6.2	6.4	6.6	6.8	7.1	7.1	7.2	7.9	7.9	7.9	8	8.1
56	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.6	4.7	4.9	4.9	5.4	5.7	6.3	6.5	6.7
57	5.6	5.8	6.1	6.3	6.4	6.8	7	7.6	7.9	8.3	7.6	7.8	8.2	8.4	8.7	8.2	8.4	8.8	9	9.3
58	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.6	4.7	4.7	4.7	4.8	4.8	4.8	5	5.2	5.2	5.6	5.7	5.8
60	3.8	3.9	4.1	4.2	4.3	4.3	4.4	4.6	4.7	4.8	4.7	4.8	5	5.1	5.2	5.4	5.4	5.4	5.4	5.5
61	3.4	3.4	3.6	3.7	3.8	3.8	3.8	4	4.1	4.1	4.2	4.3	4.5	4.6	4.7	5.3	5.4	5.5	5.6	5.7
62	3.7	3.8	3.8	3.8	3.9	3.9	4	4	4.1	4.1	4.3	4.4	4.6	4.6	4.7	5.3	5.4	5.6	5.7	5.8
63	4.2	4.4	4.7	4.7	4.8	4.9	4.9	4.9	5	5.4	5.3	5.5	5.8	5.9	6.1	7	7.1	7.2	7.2	7.3
64	3.3	3.4	3.4	3.5	3.6	3.7	3.9	4	4	4	4.1	4.2	4.4	4.5	4.6	5.2	5.3	5.4	5.5	5.6
65	3.3	3.4	3.7	3.7	3.7	3.8	3.9	4.1	4.1	4.2	4.3	4.4	4.6	4.7	4.7	5.3	5.4	5.7	5.7	5.8
66	4.6	4.6	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.8	4.8	4.9	5.1	5.2	5.3	5.5	5.5	5.5	5.5	5.5
67	4	4.1	4.7	4.8	5	5	5.1	5.4	5.6	5.9	5.6	5.9	6.9	7.2	7.8	7.9	8.1	8.9	9.3	9.8
68	4.6	4.7	4.9	5.1	5.1	5.1	5.2	5.2	5.2	5.2	5.2	5.2	5.4	5.4	5.5	6.6	6.7	6.8	7	7.4
69	3.4	3.4	3.6	3.7	3.7	3.8	3.8	4	4	4.2	4.2	4.3	4.5	4.5	4.7	5.3	5.4	5.5	5.6	5.7
70	3.7	3.8	3.8	3.9	4.1	4	4.1	4.2	4.4	4.6	4.5	4.6	4.8	5.5	5.9	6.2	6.4	6.6	6.7	7.1
71	4.7	4.9	5.2	5.5	5.6	5.3	5.4	6.2	6.3	6.5	6.4	6.4	7.1	7.1	7.1	6.5	6.5	7.1	7.1	7.1

Total Water Level[1] (m, CGVD2013)
by Annual Exceedance Probability (AEP) and Sea Level Rise (SLR)

	0 m Sea Level Rise					0.5 m Sea Level Rise					1 m Sea Level Rise					2 m Sea Level Rise				
Transect / AEP	10%	5%	1%	0.5%	0.2%	10%	5%	1%	0.5%	0.2%	10%	5%	1%	0.5%	0.2%	10%	5%	1%	0.5%	0.2%
72	3.2	3.2	3.4	3.5	3.9	3.6	3.7	3.9	4	4.1	4.2	4.3	4.4	4.5	4.6	5.7	5.8	6.2	6.2	6.2
73	4.6	4.7	4.8	5.1	5.3	5.2	5.5	5.8	5.8	5.8	5.7	5.7	5.8	5.8	5.8	5.9	5.9	5.9	5.9	6
74	3.7	3.8	4.1	4.1	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.5	4.6	4.7	5.1	5.2	5.5	5.6	5.6
75	4.7	4.8	5.1	5.2	5.4	5.4	5.5	5.6	5.6	5.6	5.8	6	6.2	6.3	6.3	6.3	6.3	6.3	6.3	6.3
76	4.1	4.2	4.6	4.8	5	4.9	5.1	5.4	5.6	6.1	5.6	5.7	6.1	6.3	6.6	6.6	6.6	6.9	7.1	7.8
77	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	7.1	7.1	7.4	7.6	8
78	4.5	4.6	4.8	5.2	5.9	4.8	5.2	5.2	5.2	5.9	4.8	5.2	5.2	5.2	5.9	5.2	5.5	5.9	5.9	5.9
79	4.7	4.9	5.5	5.6	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	6.5	6.5	6.6	7.1	7.6
80	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	5.7	7.9	7.9	7.9	7.9	7.9
81	3.8	4	4.5	4.6	4.6	4.5	4.8	5	5	5	5	5	5	5	5	5.4	5.4	6	6.2	6.6
82	4.7	4.8	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	6.1	7	7	7.2	7.5
83	3.8	3.8	3.8	3.9	3.9	3.9	3.9	4.1	4.2	4.2	4.1	4.2	4.3	4.4	4.5	5.1	5.2	5.4	5.4	5.5
84	3.5	3.6	3.9	4.2	4.4	4.2	4.3	4.6	4.9	5.3	5	5.2	5.7	5.8	6.4	6.7	6.9	7.2	7.4	7.5
85	3.8	3.9	4	4.1	4.3	4.1	4.3	4.3	4.3	4.4	4.1	4.3	4.3	4.4	4.5	5.2	5.3	5.5	5.6	5.6
86	3.6	3.7	4.1	4.3	4.4	4.1	4.2	4.5	4.8	5.1	4.6	4.7	5.1	5.4	5.7	5.9	6.3	6.4	6.9	7
88	3.7	3.7	4.2	4.2	4.4	4	4.2	4.7	4.9	4.9	4.7	4.8	5	5.3	5.7	5.9	6	6.3	6.6	7.2
91	4.5	4.7	5.1	5.1	5.1	4.5	4.7	5.1	5.1	5.1	4.5	4.7	5.1	5.1	5.1	5.8	5.8	5.8	5.8	5.8
92	4.7	4.7	5	5.1	5.3	4.9	5	5.4	5.4	5.5	5	5	5.4	5.4	5.9	5	5.4	6	6.2	6.4
93	3.1	3.1	3.3	3.3	3.4	3.5	3.5	3.7	3.8	3.9	4	4.1	4.2	4.3	4.4	5	5.1	5.2	5.3	5.4
94	3	3.1	3.2	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4	4.1	4.2	4.3	4.4	4.9	5	5.1	5.2	5.2
95	3.3	3.4	3.4	3.6	3.7	3.5	3.6	3.8	3.9	3.9	4.1	4.1	4.2	4.3	4.4	5.3	5.4	5.4	5.5	5.5
96	3.4	3.5	3.9	4.1	4.3	4	4.1	4.4	4.6	4.9	4.6	4.7	5	5.1	5.3	5.5	5.6	5.8	5.9	5.9
97	5.1	5.2	5.5	5.7	6.1	5.3	5.4	5.8	5.9	6.2	5.5	5.6	6	6.1	6.3	6.5	6.7	7	7.2	7.4
98	4.6	4.9	5.3	5.5	5.6	5.7	5.9	6.3	6.3	6.6	6.6	6.6	6.7	6.8	6.8	6.8	6.8	6.8	6.9	7.1
99	3.9	4.1	4.5	4.7	4.9	5	5.1	5.4	5.8	6	6.3	6.4	6.7	6.7	6.7	6.7	6.7	7	7	7.2
100	3.3	3.4	3.4	3.4	3.5	4	4.1	4.2	4.2	4.2	4.7	4.8	5	5.2	5.2	6.2	6.5	7	7.1	7.2
101	3	3.1	3.3	3.3	3.4	3.6	3.7	3.8	3.9	3.9	3.9	4.2	4.4	4.4	4.5	5.1	5.2	5.4	5.5	5.6
102	3.3	3.3	3.7	3.7	3.7	3.6	3.7	3.9	3.9	4	4.1	4.2	4.4	4.4	4.5	5.1	5.2	5.4	5.5	5.5
103	3.6	3.6	4	4.1	4.1	3.7	3.7	4.1	4.1	4.1	4.1	4.2	4.4	4.4	4.5	5.1	5.2	5.4	5.5	5.5
104	3.6	3.6	3.6	3.6	3.7	3.6	3.6	3.8	3.9	4	4	4.1	4.3	4.4	4.7	5.4	5.4	5.6	5.6	5.6
105	3.4	3.5	3.7	3.8	3.8	3.6	3.7	3.8	4.1	4.2	4.2	4.7	5.3	5.5	5.8	6.3	6.3	6.6	6.6	6.6
106	3.2	3.2	3.4	3.4	3.7	4	4.1	4.3	4.5	4.7	4.7	4.8	5.3	5.6	5.7	5.5	5.7	6.1	6.2	6.9
107	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	5.1	5.3	5.6	5.7	6
109	3.7	3.8	4.2	4.2	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.3	4.4	4.4	4.4	5.2	5.3	5.4	5.5	5.6
110	3.1	3.2	3.4	3.4	3.5	3.6	3.7	3.9	4	4.1	4.2	4.2	4.4	4.5	4.6	5.2	5.3	5.4	5.5	5.6
112	3	3.1	3.6	3.7	3.7	3.8	3.8	4.1	4.1	4.1	4.1	4.5	4.6	4.6	4.8	5.1	5.2	5.4	5.4	5.5
113	3.3	3.3	3.3	3.3	3.3	3.6	3.7	3.8	3.9	4.4	4.4	4.4	4.4	4.4	4.4	4.9	5	5.1	5.2	5.2
114	3.5	3.6	3.8	3.9	4	4	4.1	4.3	4.4	4.5	4.7	4.9	4.9	4.9	4.9	4.9	5	5.1	5.2	5.2
115	4.2	4.3	4.5	4.6	4.6	4.6	4.6	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.7	4.9	5	5.1	5.2	5.2
116	5.5	5.9	6.9	7.2	7.9	7.2	7.6	8.6	9	9.7	8.9	9.4	10.1	10.3	10.8	10.2	10.4	11.3	11.8	12.2
117	7.1	7.1	7.8	8.1	8.2	8.7	8.9	9.4	9.9	9.9	10.3	10.5	10.9	11.2	11.3	13	13.2	14	14	14.2
118	4.1	4.2	4.2	4.2	4.2	4.1	4.2	4.4	4.4	4.5	4.5	4.7	4.9	4.9	5.2	6.1	6.2	6.7	6.7	6.9
119	7.6	7.6	7.8	8.7	8.7	7.7	8.5	9.5	9.5	10.1	9.6	10.5	11.2	11.4	11.7	13.6	13.9	14.4	14.5	14.8
120	6.4	6.8	7.9	8.5	9.2	8.2	8.3	9.7	10.1	11	9.4	9.6	10.4	11.3	12.5	11.6	12.1	12.7	13.2	14.5
121	6.9	7.1	7.1	7.3	7.6	7.7	8	8.5	8.7	9	9.1	9.4	9.9	10.1	10.4	12.4	12.8	13.5	13.6	13.8
122	7.7	8	8.7	8.9	9.4	9.6	9.9	10.5	10.7	10.7	10.6	10.9	11.4	11.6	11.9	12.1	12.6	13.5	13.9	14.9
123	4.6	4.7	5.3	5.6	6.3	5.6	5.9	6.3	6.7	6.7	6.6	6.8	7.3	7.9	8	9	9.2	9.9	10.1	10.7
124	4.3	4.5	5	5.1	5.3	5.2	5.3	5.4	5.4	6.3	5.4	5.8	6	6.3	6.8	6.9	7	7.5	7.8	8.4
125	6.6	6.9	7.6	8	8.6	8.5	8.8	9.5	9.8	10.2	10.2	10.7	11.2	11.3	11.3	10.9	11.2	12.3	12.9	14.6
126	3.5	3.5	3.6	3.7	3.9	3.7	3.8	4.1	4.2	4.4	4.2	4.3	4.6	4.7	4.9	5.2	5.5	6.6	6.8	6.8
127	3.8	3.9	4.2	4.2	4.2	3.9	4	4.2	4.2	4.4	4.2	4.3	4.6	4.7	4.9	5.3	5.3	5.6	5.7	5.9
128	3.4	3.4	3.5	3.6	3.7	3.7	3.8	4	4.1	4.2	4.2	4.3	4.5	4.6	4.7	5.5	6	6.4	6.5	7.1
129	6.9	7.5	8.2	8.5	8.9	8.6	8.9	9.6	9.6	9.9	8.6	8.9	9.6	9.6	10.8	8.9	9	10.1	10.3	10.9
130	5.4	5.8	6.8	7.5	7.5	6.2	6.4	7.6	7.6	7.6	7.7	8.1	8.8	9.3	9.3	9.7	10	10.8	11	12.4
131	6.1	6.5	7.5	7.5	7.7	7.8	8.1	9	9.2	9.2	8.9	9.1	9.7	10	10.4	10.3	10.5	10.6	10.9	11.3
132	6.7	7	7.6	7.8	8.1	8.5	8.8	9.2	9.4	9.7	9.5	9.7	10.1	10.2	10.4	9.5	9.7	11.3	11.7	12.3
133	7.2	7.6	8.4	8.6	9.2	8	8.5	9.3	9.8	10.1	8.9	9.3	10.2	10.3	10.3	9.7	10.5	10.7	11	11.6
134	4.8	4.9	5.6	5.8	6.3	5.3	5.5	6.2	6.6	7	5.9	6.1	6.8	7.3	7.8	7.3	7.4	8	8.3	8.4
135	4.2	4.5	5.4	6.3	7.3	4.8	5	5.8	6.9	8.2	5.8	6.2	7.1	7.3	8.8	8.1	8.6	9.7	9.8	10.5
136	4.7	4.9	5.5	5.7	5.7	5.5	5.7	6.2	6.4	6.6	6.5	6.6	6.7	6.8	7	7.1	7.3	8	8.2	8.2
137	3.8	3.8	4	4	4	4.1	4.1	4.1	4.1	4.3	4.2	4.3	4.5	4.7	4.8	5.9	6.2	6.6	7.1	7.2
138	3.4	3.6	3.7	3.7	3.8	3.8	3.9	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.1	5.4	5.7	5.7	7.2	7.4

Total Water Level[1] (m, CGVD2013)
by Annual Exceedance Probability (AEP) and Sea Level Rise (SLR)

	0 m Sea Level Rise					0.5 m Sea Level Rise					1 m Sea Level Rise					2 m Sea Level Rise				
Transect / AEP	10%	5%	1%	0.5%	0.2%	10%	5%	1%	0.5%	0.2%	10%	5%	1%	0.5%	0.2%	10%	5%	1%	0.5%	0.2%
139	5.5	5.8	6.6	7	7.8	6.2	6.7	7.4	7.7	8.3	7.3	7.5	8.1	8.2	8.6	9.3	9.4	9.6	9.6	9.6
140	4.4	4.6	5	5.3	5.8	5.1	5.3	5.7	5.9	6.6	5.5	5.8	6.3	6.6	7.4	7.1	7.3	8	8.2	8.4
141	5.8	6.3	7.2	8.2	9.4	7	7.4	8.5	9	10.1	7.8	8.8	9.6	9.9	10.4	8.2	8.8	9.6	9.9	11
142	4.6	4.9	5.6	6.3	7.1	5.7	6.2	7	7.7	8.5	7.5	7.7	8.8	9	10	8.4	8.7	9.6	11.4	12.6
143	4.3	4.5	5	5.3	5.7	5	5.1	5.5	5.9	6.4	5.4	5.6	6.5	6.6	7.2	6.5	6.7	8	8.5	9.2
144	4.6	5	5.9	6.4	6.8	5.6	6.2	6.8	7.1	7.2	6.9	7.1	7.3	7.4	7.8	7.8	8	8.5	8.8	8.9
145	4.6	4.8	5.4	5.8	6.3	5.1	5.3	5.8	6	6.7	5.6	5.7	6.2	6.6	6.9	6.6	6.9	6.9	7.2	7.3
147	5.7	6.2	7.4	7.8	7.9	6.3	6.8	7.8	7.9	7.9	7	7.4	7.9	7.9	7.9	7.9	7.9	7.9	8	8.1
148	5.4	5.8	6.6	6.8	6.8	6.3	6.6	6.8	6.9	7.2	6.8	6.8	7.1	7.4	7.7	7.7	7.9	8.2	8.4	8.5
149	5.9	6.2	7	7.3	7.3	6.4	6.8	7.3	7.4	7.8	6.8	7.1	7.5	7.8	8.2	7.5	7.7	8.2	8.5	8.9
150	5.2	5.5	6.3	6.6	7	5.9	6.2	7	7.5	7.9	6.5	6.8	7.6	8	8.5	7.7	8	8.6	8.9	9.3
151	6.5	7	9	9.8	10.4	7.2	7.4	9	9.8	10.4	8.4	9.5	10.9	11.1	11.1	12.9	13.4	13.9	14.2	14.5
152	9.5	10.3	11.3	11.6	11.9	10.4	11.1	12.1	12.5	12.9	11	11.5	12.7	13.4	13.9	13.7	14	14.5	14.7	15
153	11.4	13.1	14.6	16.1	17.3	11.4	13.1	14.6	16.7	18	11.4	13.1	14.6	16.7	18.5	11.4	13.1	14.6	16.7	19.6
154	6.4	6.7	7.4	7.8	8.4	7.5	7.8	8.6	9	9.5	8.7	9	9.7	10.1	10.6	11.3	11.5	12	12.5	13.1
155	8.4	8.6	10.9	11.6	12.5	9.4	9.8	12.2	12.9	13.8	10.9	11.1	12.2	14.4	15.3	13.8	13.8	14.6	14.6	17.8
156	7.2	7.6	8.3	8.5	8.7	7.8	8.1	8.8	8.9	9.4	8.3	8.5	9.1	9.9	10.6	9.5	9.8	10.8	11.8	13.1
157	6.5	6.8	7.5	7.8	8.3	7.1	7.4	8	8.3	8.9	7.6	8	8.6	8.9	9.4	8.4	8.7	9.3	9.6	10.2
158	3.7	3.7	4	4	4	3.7	3.8	4.2	4.3	4.4	4.5	4.7	5.1	5.3	5.4	6.8	7.1	7.7	7.9	8.2
158.5	6.2	6.3	6.5	6.5	6.6	6.5	6.6	6.6	6.6	6.6	6.5	6.6	6.6	6.6	6.6	6.6	6.7	6.9	7.2	7.4
159	5.4	5.8	6.7	7	7.4	6.3	6.7	7.6	8.3	8.8	8.2	8.4	8.9	9.1	9.4	9.8	9.8	9.8	9.8	9.8
160	6.8	7.1	7.8	8	8.4	8.8	9.1	9.7	9.9	10.2	10.4	10.4	10.7	11	11.2	10.9	11.4	12.4	12.6	13.3
161	3.1	3.2	3.4	3.4	3.5	3.6	3.7	3.9	3.9	4	4.1	6.2	6.2	6.2	6.2	6.4	6.7	7.1	7.2	7.3
162	3.5	3.5	3.6	3.6	3.6	3.6	3.7	3.9	4	4.6	5.1	5.4	5.7	5.9	6.3	7.7	8	8.6	8.7	8.8
163	5.2	5.6	6.3	6.6	6.8	6.7	7	7.7	7.9	8.1	7.4	7.7	8.4	8.6	8.9	7.8	8.1	8.7	8.9	9.5
164	4.1	4.4	4.7	4.8	4.9	4.9	5	5.3	5.4	5.4	5.3	5.4	5.5	5.5	5.6	5.5	5.6	5.6	5.6	5.7
165	3.6	3.7	3.9	3.9	4	3.8	3.9	3.9	4	4.1	4	4.1	4.2	4.6	4.8	6.2	6.3	6.5	6.8	7
166	4.6	4.8	5.1	5.3	6.3	4.9	5.1	5.5	5.6	6.3	5.3	5.5	5.8	6.1	6.6	6.4	6.5	6.9	7.1	7.6
167	5.3	5.6	6.1	6.3	6.5	5.8	5.9	6.4	6.6	6.8	5.8	6.2	6.7	6.8	7.1	6.9	7	7.5	7.6	7.8
168	3.5	3.6	3.9	4	4.1	4.2	4.4	4.8	4.9	5.2	6	6.3	6.9	7	7.3	7.8	8	8.2	8.4	8.6
169	5.8	5.9	6.2	6.3	6.6	6.1	6.3	6.7	6.9	7.1	6.3	6.5	6.9	7.1	7.3	6.9	7	7.4	7.6	7.8
170	5.7	6	6.5	6.7	6.9	6.1	6.3	6.7	6.9	7.1	6.3	6.5	6.9	7.1	7.3	6.9	7.1	7.5	7.7	7.9
171	5.4	5.6	6.1	6.2	6.4	5.7	5.8	6.2	6.4	6.6	5.8	6	6.4	6.5	6.8	6.7	6.9	7.3	7.4	7.6
172	3.6	3.7	4.1	4.2	4.4	4.1	4.3	4.7	4.9	5.2	5.5	5.8	6.3	6.5	6.5	7.6	7.7	8.2	8.4	8.6
173	4	4.1	4.2	4.2	4.2	4.2	4.2	4.3	4.3	4.3	4.2	4.2	4.3	4.4	4.5	6	6.2	6.6	6.8	7
174	4.6	4.7	4.7	4.8	5.1	5	5.3	5.9	6.1	6.4	6.1	6.3	7	7.2	7.5	7.3	7.6	8.3	8.5	8.7
175	4.5	4.7	5.2	5.3	5.9	5.3	5.5	5.9	6	6.4	5.9	6	6.3	6.3	6.5	7.2	7.4	7.8	7.9	8.1
176	4.6	4.9	5.3	5.5	5.9	5.2	5.3	5.9	6.1	6.3	5.7	5.8	6.2	6.3	6.5	6.7	6.9	7.2	7.4	7.6
177	3.3	3.3	3.4	3.5	3.6	3.5	3.6	3.7	3.8	4	4.3	4.3	4.5	4.6	4.7	5.2	5.2	5.5	5.6	5.7
178	4	4	4	4	4	4	4	4	4	4	4	4.1	4.3	4.4	4.5	5	5.1	5.3	5.4	5.5
179	3.9	4.1	4.3	4.6	5.1	4.5	4.5	4.9	5.3	5.8	4.5	4.7	5.7	6.1	6.6	6.7	7	7.3	7.3	7.5
180	4.4	4.7	5.7	6.4	7	5.1	5.7	6.7	7.1	7.7	5.7	6.1	7.4	7.9	8.6	6.7	7.1	8.2	8.8	9.8
181	4.4	4.7	5.7	6.5	7.2	4.6	5	6.1	6.6	7.6	5.1	5.4	6.3	6.9	7.7	6.1	6.4	7.3	7.7	8.3
182	3.2	3.3	3.3	3.4	3.5	3.5	3.6	3.8	4.1	4.4	4.8	5.1	5.6	5.9	6.1	6.8	7	7.4	7.8	7.8
183	4.5	4.9	6	6.9	8.1	5.3	5.8	7.3	7.9	9	5.6	6	7.4	8.2	9.5	6.6	7	8.1	8.7	9.7
184	4.6	4.9	5.9	6.4	6.6	4.6	5.1	6.2	6.7	7.7	5.2	5.5	6.4	6.9	7.7	6.3	6.6	7.3	7.7	8.4
185	3.2	3.3	3.3	3.4	4.3	3.8	4	4.5	4.7	5.1	5.4	5.6	5.8	6	6.1	6.8	7.3	8.8	8.8	8.8
186	4.3	4.5	6	6.6	7.4	4.6	4.8	6	6.6	7.7	5	5.3	6.1	6.7	7.7	6.1	6.5	7.3	7.7	8.3
187	3.6	3.8	4.1	4.2	4.3	4	4.1	4.3	4.3	4.5	4.1	4.2	4.5	4.5	4.7	5.4	5.6	5.6	5.6	5.6
188	4.3	4.7	5.7	6.7	7.5	5.1	5.3	6.2	6.8	7.5	5.6	5.9	6.7	7.2	8.1	6.8	7.1	8	8.6	9.6
189	4.8	5.1	6.3	6.9	7.6	5	5.3	6.6	7.2	8	5.5	5.9	6.8	7.4	8.4	6.7	7	7.9	8.4	9.1
190	4.9	5	5	5	5	5	5	5	5	5.1	5	5	5	5.3	5.6	5.4	5.7	5.7	5.7	5.7
191	3.7	3.7	3.9	3.9	4	4	4	4	4.2	4.3	4	4.1	4.3	4.3	4.4	5.1	5.2	5.3	5.3	5.4
192	4.2	4.4	4.9	5.1	5.7	5.3	5.5	5.9	6.1	6.4	5.8	6	6.4	6.5	7	6.8	7	7.4	7.6	8.2
193	11.5	12.4	17.5	17.5	17.6	11.8	13	18.1	18.1	18.1	12.1	14	18.1	18.1	18.1	13.7	15.2	18.1	18.1	18.1
194	10.2	10.8	13.5	14.7	14.9	10.8	11.5	14.8	14.9	14.9	11.5	13.1	14.9	14.9	14.9	14.4	14.8	14.9	14.9	14.9
195	7.7	8.7	9	9.2	10	8.3	9.1	10	10	10	8.3	9.5	10	10	10	8.3	10	10.2	10.9	10.9
196	5.6	5.8	6.3	6.7	8.1	8.1	8.1	8.1	8.2	8.3	8.1	8.4	8.4	8.4	8.4	8.1	8.4	8.9	8.9	8.9
197	4.4	4.7	5.1	5.2	5.3	5.3	5.4	6	6.1	6.9	6.1	6.3	6.9	7.1	7.6	8	8.2	8.4	8.6	8.7
198	5.2	5.4	5.8	5.9	6	5.6	5.8	6.2	6.5	6.8	6	6.2	6.8	7.2	7.3	7	7.3	7.3	7.3	7.3
199	4.2	4.4	4.6	4.8	4.9	5.1	5.4	5.8	6.1	6.3	6.2	6.6	7	7.5	7.5	7.8	7.9	8.1	8.2	8.3
200	7.3	7.6	7.9	7.9	8	8.3	8.4	8.6	8.6	8.7	8.3	8.4	9.2	9.2	9.5	9.2	9.2	9.9	10.1	10.1

Total Water Level[1] (m, CGVD2013)
by Annual Exceedance Probability (AEP) and Sea Level Rise (SLR)

	0 m Sea Level Rise					0.5 m Sea Level Rise					1 m Sea Level Rise					2 m Sea Level Rise				
Transect / AEP	10%	5%	1%	0.5%	0.2%	10%	5%	1%	0.5%	0.2%	10%	5%	1%	0.5%	0.2%	10%	5%	1%	0.5%	0.2%
201	6	6.3	7.1	7.6	8.3	7.5	7.8	8.5	9	9.8	9.3	9.6	10.2	10.5	11.1	11.4	11.5	12.2	12.4	12.7
202	5.2	5.8	7.3	7.9	8.5	7.3	7.6	8.7	9.4	10	8.3	9.3	10.2	10.8	11.5	9.9	10.8	13.9	14.2	14.6
203	4.5	4.7	5.2	5.5	6	4.8	5	6.1	6.6	7.3	5.8	6	6.9	7.8	8.6	7.3	7.7	8.7	9.5	11.2
204	6.4	7	7.6	8.5	9.4	8	8.2	9.3	9.3	9.6	8.8	9.3	10.1	10.2	10.5	9.4	10.4	12.2	12.2	12.4
205	4.3	4.5	4.9	5.4	5.8	5	5.2	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	6.2	6.4	6.9	6.9	6.9
205.5	5.2	5.6	6.3	6.4	6.6	6.3	6.4	6.4	6.9	7.3	6.7	6.9	7.2	7.3	7.4	7.1	7.1	7.7	8.1	8.6
206	6.4	6.7	7.2	7.2	7.7	7.1	7.2	7.6	8.6	8.7	8.6	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7	8.7
207	4.3	4.5	4.7	4.7	4.7	4.6	4.6	4.7	4.8	4.8	4.6	4.7	4.9	5	5.1	5.4	5.5	5.8	5.9	6
207.5	5.8	6.2	6.9	7.3	7.7	7.2	7.4	7.8	8	8.1	7.9	8.1	8.1	8.1	8.1	8.1	8.1	8.2	8.3	8.8
208	4	4.2	4.7	4.9	4.9	4	4.2	4.7	4.9	4.9	4.3	4.4	4.7	4.9	5.1	5.4	5.5	5.6	5.6	5.6
209	5.3	5.4	5.5	5.5	5.6	5.5	5.5	5.9	6	6	5.6	5.7	6.1	6.4	6.5	5.9	6	6.5	6.5	6.9
210	3.4	3.6	5.8	6.5	7.3	4.3	4.8	6.5	7.2	7.3	5.4	5.6	7	7.3	7.4	7.4	7.6	7.7	7.7	8
211	3.4	3.5	3.7	3.8	4	3.7	3.8	4.1	4.3	4.5	4.2	4.3	4.6	4.8	6.1	6	6.1	6.8	7	7.2
212	5.1	5.4	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5	5.5
213	4.1	4.4	4.7	4.7	4.7	4.6	4.6	4.7	5.6	5.9	5.5	5.7	6.1	6.1	6.3	6.3	6.3	6.4	6.5	6.7
215	4.9	5.2	5.8	6	6.2	5.6	5.8	6.2	6.2	6.2	6.1	6.2	6.2	6.2	6.2	6.2	6.2	6.8	7.1	7.3
216	5.3	5.7	6.4	7	7.6	5.8	6.1	7	7.4	7.9	6.2	6.5	7.5	7.7	8.2	7.2	7.5	8.2	8.6	8.7
217	8.2	8.4	8.6	8.7	8.8	8.7	8.8	9.3	9.7	9.9	8.7	9.7	10.1	10.2	10.9	9.6	9.8	11.3	11.4	11.4
218	10.3	10.9	12.2	13	14.8	10.8	11.5	12.8	13.7	15.7	11.4	12.1	13.4	13.7	15.7	11.7	12.3	13.5	14.3	15.7
219	4.1	4.1	4.1	4.1	4.1	4.1	4.1	4.2	4.3	4.5	4.6	4.7	4.8	5	5.1	5.5	5.7	6.1	6.2	6.3
220	7.8	7.8	8.5	8.7	9	9.1	9.5	9.9	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1	10.1
221	4.2	4.3	4.8	4.9	4.9	4.5	4.5	4.9	4.9	5	5	5	5.2	5.3	5.4	5.8	6	6.1	6.1	6.1
222	5.9	6.2	7	7.4	8.2	7.7	8	8	8.1	9.4	8.8	9.1	9.6	9.7	9.9	9.5	9.7	11.5	11.7	11.8
224	5.3	5.7	6.9	7.2	7.5	6.7	7.1	7.6	7.7	7.8	7.5	7.6	7.8	7.9	8	8.1	8.2	8.5	8.6	8.7
225	6.9	7.3	7.8	8	8.1	8	8.3	8.3	8.3	8.4	8.3	8.3	8.6	8.7	8.9	9.6	9.9	10.1	10.1	10.4
226	6.1	6.6	7.5	7.9	8.2	6.8	7.2	8.3	8.5	8.7	7.4	7.9	8.7	8.9	9.1	9.1	9.3	9.3	9.3	9.6
227	5.4	5.7	6.5	6.9	7.9	6.3	6.5	7.6	8.3	9.3	7.1	7.4	9	9.5	9.8	9.6	9.7	10.2	10.6	10.9
228	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.5	7.8	8.3	8.5	8.8	9.4	9.8	10.3
229	6.6	7.2	8.1	8.6	8.8	8.5	9.1	9.7	10.3	10.8	10.4	11	11.5	12.1	12.1	13.8	14.4	15.1	15.2	15.2
230	10	10.7	12.8	14.5	16.6	11.1	11.6	13.7	15.3	17.5	12.1	12.7	14.4	16.1	18.2	14.5	15.1	17	18	19.6
231	10	10.3	11.3	11.9	12.6	11.9	12.2	12.9	13.3	14	13.7	14	14.7	15	15.4	15.6	16.5	18.2	18.5	18.8
232	5	5.5	6.6	7.3	8.3	6.6	7.2	8.6	9	9.9	8.3	8.7	10	10.5	10.9	10.8	10.9	11.5	11.5	11.5
233	5.3	5.5	6	6.9	8.2	6.8	7	7.6	7.7	8.8	6.8	7	7.6	8.4	9.5	7.5	7.8	8.4	8.6	9.5
234	4.1	4.2	4.5	4.5	4.6	4.2	4.2	4.5	4.5	4.6	4.2	4.3	4.5	4.5	4.7	6	6.3	6.9	7.2	7.5
235	6	6.5	7.7	7.8	8.5	6.9	7.3	8.5	8.9	9.6	7.4	7.8	8.6	8.9	10.4	8	8.4	9.1	9.4	10.4
236	6.9	7.4	8.3	8.6	9.6	6.9	7.4	8.6	8.9	9.9	6.9	7.4	8.6	8.9	10.2	7.8	8.1	8.7	8.9	10.4
237	3.6	3.6	3.6	3.6	3.6	3.6	3.6	3.6	4	4.1	4.1	4.2	4.7	4.7	4.9	7.1	7.3	7.7	7.8	7.8
238	4.2	4.4	4.7	4.8	4.8	4.7	4.8	4.9	4.9	5.3	5.5	5.5	5.5	5.5	5.5	5.5	5.6	5.9	6	6.3
239	3.6	4	4.8	5.3	5.9	4.7	4.9	5.8	6.1	6.7	5.9	6.1	6.8	7	7.2	7	7.4	7.5	7.5	7.5
240	4.1	4.3	5.2	5.8	6	5.3	5.7	6.6	6.9	7.5	6	6.2	7.5	8.1	8.7	7	7.4	8.4	8.9	9.7
241	5	5.3	7.8	8.8	8.9	5.1	5.4	7.8	8.8	10.8	5.7	6.1	7.8	9.1	10.8	6.9	7.3	8.6	9.5	11.5
242	4.9	4.9	5.6	5.8	6.4	6.7	7.1	7.8	7.8	7.8	7.4	7.4	7.8	7.8	7.8	7.4	7.4	8.8	9.4	10.1
243	6.2	7	9.8	11.8	12	6.9	7.7	10.5	12	12.1	6.9	7.9	11.1	12.2	16	7.7	8.4	11.3	13	16.8
244	7.9	7.9	10.2	10.5	11.1	7.9	9	12.1	12.4	12.7	7.9	9.3	12.1	14.3	14.7	8	9.3	12.7	14.3	16.1
245	6.2	6.5	7.5	7.9	8.6	8	8.4	9	9.5	10	9	10	10.5	10.8	10.9	10.1	10.9	11.5	11.5	11.5
246	7.1	7.5	8.3	8.3	8.8	8.3	8.6	9.2	9.6	10	8.7	10.1	10.5	10.7	10.9	8.9	10.4	13.1	13.1	13.1
247	7.9	8.8	10.2	10.4	10.7	8.4	9.1	10.9	11	11.5	8.9	9.5	11.6	11.7	12.2	9.8	10.5	12.4	12.4	12.6

1. Total Water Level, taken as the sum of Wave Effect (R2%) + Extreme Static Water Level + Sea Level Rise + Adjustment for Land Movement; Freeboard is not included.