Photo source: Derek Ray (NHC)

Haida Gwaii Coastal Flood and Erosion Study Appendix C – Storm Wave Modelling

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EXECUTIVE SUMMARY

All residents of Haida Gwaii live in shoreline communities and depend on critical infrastructure that is subject to flooding and erosion from ocean processes. Each community is increasingly vulnerable to rising sea levels, as shown by the ongoing shoreline issues currently affecting the community of Tlell, when high tides coincide with large windstorms. Shoreline erosion is now occurring at several locations and will accelerate and expand to affect more of the coastline, as higher sea levels promote the effects of the waves reaching higher up on the shoreline.

Northwest Hydraulic Consultants Ltd. (NHC) and Ocean Networks Canada Society have been engaged to provide professional engineering, geoscience, and oceanographic consulting services for five communities in Haida Gwaii, British Columbia. This study on coastal flooding and erosion examines the effects of wind waves and tsunamis when combined with sea-level rise. The team was selected following a successful proposal submission in response to the Joint Request for Proposal No. 2020-02 issued by the North Coast Regional District, in association with the Village of Masset, the Village of Port Clements, and the Village of Daajing Giids[1]. For the purposes of this study, the communities of Tlell and Sandspit are represented by the North Coast Regional District.

This report provides a summary of the approach used to estimate the combined water levels and shoreline wave effects that form the basis of the Flood Construction Level (FCL) for hazard mapping. The coastal FCL is comprised of a water level that is a combination of the designated flood level (astronomical tide and storm surge) as well as wave effects (or wave runup). A focus of this appendix is on the storm wave modelling that was undertaken to establish the wave effect suitable for use with the corresponding water level conditions and the evaluation of combinations of waves and ocean water level which all have a 0.5% AEP to determine the highest FCL in each of the study areas.

[1] The Village of Daajing Giids was formally named the Village of Queen Charlotte and Queen Charlotte City before then.

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ABBREVIATIONS

Acronym / Abbreviation	Definition
ERA5	Fifth-generation atmospheric reanalysis of the global climate by the European Centre for Medium-Range Weather Forecasts
AEP	annual exceedance probability
BC	British Columbia
CD	chart datum
CHS	Canadian Hydrographic Service
CGVD2013	Canadian geodetic vertical datum of 2013
DEE	Dixon Entrance eastern sector of wind and wave exposure
DEW	Dixon Entrance western sector of wind and wave exposure
DFO	Fisheries and Oceans Canada
ECCC	Environment and Climate Change Canada
FLNRORD	BC Ministry of Forests, Natural Resource Operations and Rural Development[2]
HHWLT	higher high-water, large tide
HHWMT	higher high-water, mean tide
HRDPS	High-resolution Deterministic Prediction System
HSN	Hecate Strait northern sector of wind and wave exposure
HSS	Hecate Strait southern sector of wind and wave exposure
metocean	meteorological and oceanographic
MWL	mean water level
LLWLT	lower low-water, large tide
LLWMT	lower low-water, mean tide
NHC	Northwest Hydraulic Consultants Ltd.
US	United States of America
USACE	US Army Corps of Engineers

[2] This ministry has undergone many name changes including the most recent in April 2022, which created two new ministries. Namely, the Ministry of Forests and the Ministry of Land, Water and Resource Stewardship.

SYMBOLS AND UNITS OF MEASURE

Symbol / Unit of Measure	Definition
>	greater than
<	less than
°	degree
°T	Direction in degrees with respect to true north measured clockwise.
H_s	significant wave height
km	kilometre
km^2	square kilometre
m	metre
m/s	metres per second
s	wave steepness
sec	second
T_p	peak wave period

GLOSSARY

Term	Definition
Aleutian Low	A semi-permanent, subpolar area of low pressure located in the Gulf of Alaska near the Aleutian Islands during winter in the Northern Hemisphere. It is a generating area for storms and migratory lows, such as extratropical cyclones, which form in the subpolar latitudes, often reaching maximum intensity in this area.
anemometer	A device that measures wind speed and direction.
anticyclone	A weather phenomenon defined as a large-scale circulation of winds around a central region of high atmospheric pressure, clockwise in the Northern Hemisphere and counterclockwise in the Southern Hemisphere as viewed from above (opposite to a cyclone).
annual exceedance probability	The probability that a given event will be exceeded in any one year.
astronomical forcing	Influence that is driven by forces associated with atmospheric phenomena.
astronomical tides	The tidal levels and water motion resulting from the earth's rotation and the gravitational effects of the earth, sun, and moon in particular, without any atmospheric influences.
atmospheric forcing	Influence that is driven by forces associated with atmospheric phenomena.
Canadian Geodetic Vertical Datum of 1928	A vertical datum defined by the mean water level at five tide gauges: Yarmouth and Halifax on the Atlantic Ocean, Pointe-au-Père on the St. Lawrence River, and Vancouver and Prince Rupert on the Pacific Ocean.
Canadian geodetic vertical datum of 2013	Reference standard for heights across Canada. This height reference system replaced the Canadian Geodetic Vertical Datum of 1928 and is defined by a surface of equal gravitational potential (equipotential surface), which represents, by convention, the coastal mean sea level for North America.
chart datum	For navigational safety, depths on a chart are shown from a low water surface or a low-water datum. Chart datum is selected so that the water level will seldom fall below it and rarely with less depth available than what is portrayed on the chart. On most Canadian coastal charts, the surface of lower low water, large tide (also known as LLWLT) has been adopted as chart datum.
continental shelf	A portion of a continent that is submerged under an area of relatively shallow water, known as a shelf.
cyclone	A large air mass that rotates around a strong centre of low atmospheric pressure, counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere as viewed from above.

extreme value frequency analysis	The study of the probability of occurrence of events. This term is often used in regulatory contexts to determine design values for infrastructure.
fetch	The length of an ocean's or lake's surface over which the wind blows in an essentially constant direction, thus generating waves.
fetch-limited	A situation in which wave height is limited by the length of the fetch available for wave generation from a particular direction.
gale force	According to the Beaufort wind scale, gale force corresponds to wind speeds in the range of 34 to 40 knots (17.5 to 20.5 m/s) that generate moderately high waves of greater length; the edges of wave crests break into spindrift; foam is blown in well-marked streaks along the direction of the wind.
higher high-water, large tide	The average of the yearly highest high tides predicted from each year over a tidal epoch, as defined by the Canadian Hydrographic Service (CHS) in Canada.
higher high-water, mean tide	The average of the higher high-water height of each tidal day observed over a tidal epoch, as defined by the CHS in Canada.
joint probability	A statistical measure that calculates the likelihood of two events occurring together and at the same point in time.
lower low-water, large tide	The average of the yearly lowest low tide tides predicted from each year over a tidal epoch, as defined by the CHS in Canada.
lower low-water, mean tide	The average of the lower low-water height of each tidal day observed over a tidal epoch, as defined by the CHS in Canada.
mean water level	The average of all water levels over the available period of record.
Monte Carlo method	A way to use random samples of parameters to explore the behaviour of a complex system.
North Pacific High	A semi-permanent, subtropical anticyclone located in the northeastern portion of the Pacific Ocean, located northeast of Hawaii and west of California. It is strongest in the Northern Hemisphere during the summer and shifts toward the equator during the winter.
Pareto distribution	A power-law probability distribution that is used to describe social, quality control, scientific, geophysical, actuarial, and other types of observable phenomena.
peak-over-threshold analysis	Analysis that involves identifying events that exceed a certain threshold.
peak wave period	The wave period (in seconds) associated with the most energetic waves in the total wave spectrum at a specific location.
percentile	Each of the 100 equal groups into which a statistical population (i.e., sample) can be divided according to the distribution of values of a particular variable.

reference port	A location with tidal heights that are directly given in the tide tables. The tidal heights for reference ports are based on continuous observation of tide over a longer period.
residual water level	The part of the sea level that remains once the astronomical tidal component has been removed.
secondary port	A location with tidal heights that are not given directly in tide tables and must be calculated based on the tidal heights of a reference port.
significant wave height	The mean height of the highest one-third of all waves.
spindrift	The spray that blows from the wind over the crests of waves.
storm surge	Occurs in coastal areas during passing storms when strong onshore winds and low atmospheric pressure raise water levels along the shore above predicted levels.
subduction zone	The place where two tectonic plates collide, with one plate sinking into the earth’s mantle underneath the other plate.
swell	Wind waves that have travelled some distance away from the area where they were generated. Swell waves often feature relatively smooth, long wave lengths with more regular and uniform crests, which typically carry more energy.
tidal harmonic constituents	The harmonic elements in a mathematical expression for the tide producing force and in the corresponding formula for the tidal curve. Each constituent represents a periodic change or variation in the relative positions of celestial bodies such as the earth, moon, and sun.
tidal height	The vertical distance the water rises or falls due to the tide. Standard heights are published by the Canadian Hydrographic Service in Canadian waters, which are established statistically.
tidal range	The difference in height between the highest high tide and the lowest low tide at one location.
total water level	The observed water level measured by tide gauges, which include the combination of astronomical tides, storm surge, as well as local wind and wave setup, if present.
transitional sea	A swell over which locally generated wind waves are also present.
true north	The direction that points directly toward the geographic North Pole, which may vary from the magnetic north.
tsunami	A series of travelling ocean waves of extremely long length and period, triggered by a large earthquake occurring near or under the ocean, a volcanic eruption, or a submarine landslide or onshore landslide.
wave height	The vertical distance between the crest and the trough of a wave.
wave period	The time it takes for two successive crests or one wavelength to pass a specified location.

wave setup	The increase in the mean water level in a shoreward area due to the influx of breaking waves against the beach.
wave steepness	The ratio of wave height to wavelength.
wind rose	A diagram used to show wind magnitude, direction, and frequency. Each stem in the diagram characterizes the wind coming from the direction in which it expands outward; the individual length of the coloured segments along a stem represents the frequency of the wind within a specific speed range.
wind sea	Waves under the influence of local winds that generate them.
wind waves	Waves that occur on the surface of waterbodies water as a results from the wind blowing over the water surface.

1 INTRODUCTION

All residents of Haida Gwaii live in shoreline communities and depend on critical infrastructure that is subject to flooding and erosion from ocean processes. Each community is increasingly vulnerable to rising sea levels, as shown by the ongoing shoreline issues currently affecting the community of Tlell, when high tides coincide with large windstorms. Shoreline erosion is now occurring at several locations and will accelerate and expand to affect more of the coastline, as higher sea levels promote the effects of the waves reaching higher up on the shoreline. Furthermore, many residents are at risk of being affected by **tsunamis**, particularly given the island's exposure to the Alaska-Aleutian and the Cascadia **subduction zones**.

Northwest Hydraulic Consultants Ltd. (NHC) and Ocean Networks Canada Society have been engaged to provide professional engineering, geoscience, and oceanographic consulting services for five communities in Haida Gwaii, British Columbia (BC). This study on coastal flooding and erosion examines the effects of **wind waves** and tsunamis combined with sea-level rise. The team was selected following a successful proposal submission in response to the Joint Request for Proposal No. 2020-02 issued by the North Coast Regional District, in association with the Village of Masset, the Village of Port Clements, and the Village of Daajing Giids[3]. For the purposes of this study, the communities of Tlell and Sandspit are represented by the North Coast Regional District.

This report provides a summary of the wave modelling and analysis undertaken to determine the coastal flood hazard at each community. It also provides a summary of the Flood Construction Levels for each community. These results inform the overall study conclusions, which are described in the main report, *Haida Gwaii Coastal Flood and Erosion Study – Planning for Sea-Level Rise and Tsunami Hazard*. Please refer to the main report for background information about the project, including a statement of the objectives under investigation, the project goals, and the methodology used to conduct the analysis.

1.1 Study Areas

The areas of Haida Gwaii that are covered under the scope of this study include the following communities, from north to south and west to east:

- the Village of Masset and its jurisdiction
- the community of Tow Hill
- the Village of Port Clements and its jurisdiction
- the community of Tlell and neighbouring shoreline
- the Village of Daajing Giids and its jurisdiction
- the community of Sandspit

[3] The Village of Daajing Giids was formally named the Village of Queen Charlotte and Queen Charlotte City before then.

The spatial extents of the study areas are shown in Figure 1-1. It should be noted that the assessment at Tow Hill is limited to tsunami hazards only, which are not discussed in this document but in the project's main report.

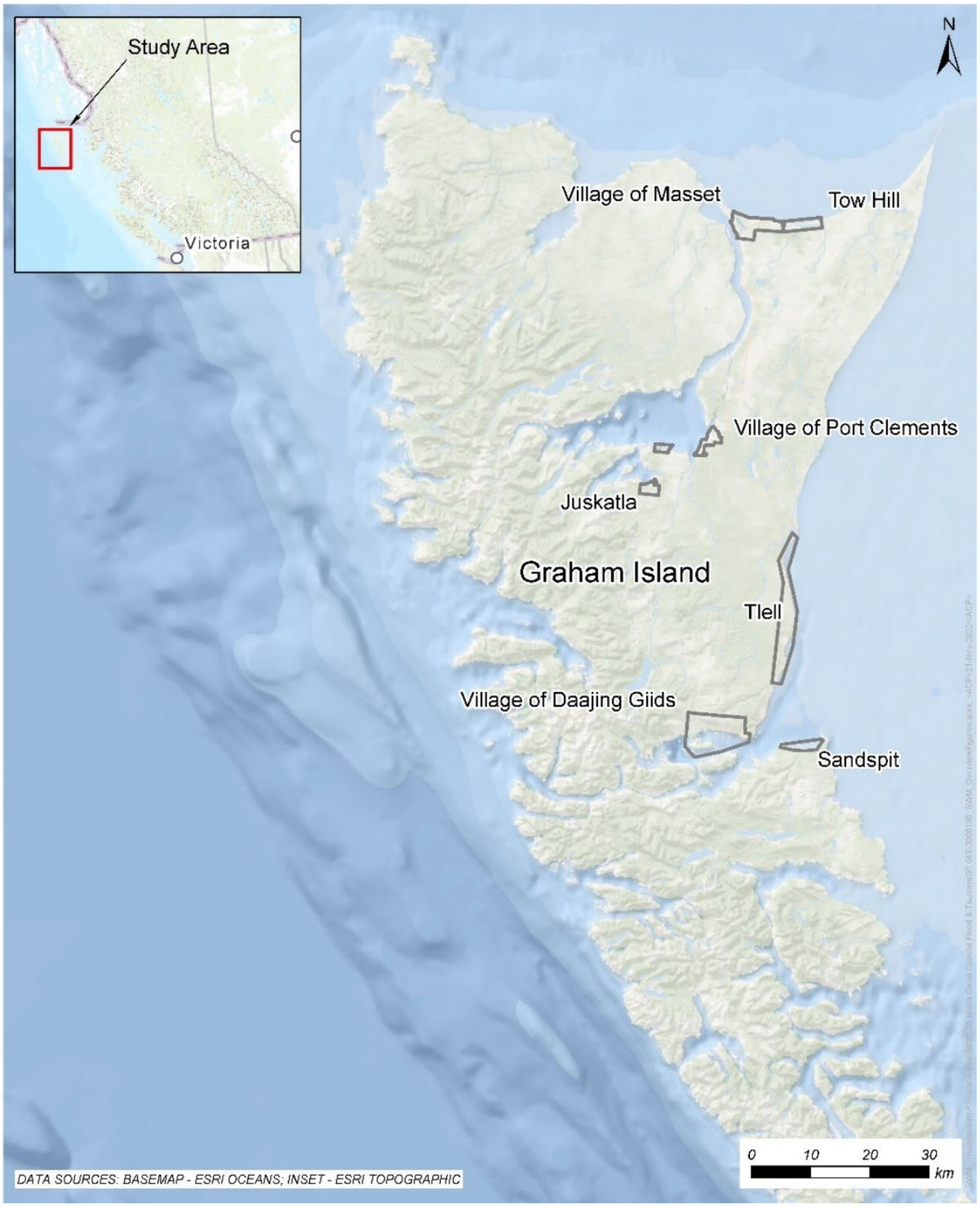

Figure 1-1. Areas of Haida Gwaii included in this project, shown in the inset with a red perimeter.

2 SUMMARY OF INPUTS TO WAVE MODELS

2.1 Water Levels and Offshore Seastate from Joint Probability Analysis

A joint probability analysis was undertaken (see Appendix B) to establish the 1-in-200 offshore seastate and water level conditions for the coastal flood hazard analysis. This analysis established joint probability curves for waves and storm surge for four sectors of concern to the study areas; Dixon Entrance West (DEW), Dixon Entrance East (DEE), Hecate Strait North (HSN), and Hecate Strait South (HSS) as indicated in Figure 1-2.

Notes: DEE – Dixon Entrance east; DEW – Dixon Entrance west; HSN – Hecate Strait north; HSS – Hecate Strait South

Figure 1-1. General open-water exposure of the project's study areas.

The joint probability curves give an infinite number of combinations of water level and wave height that have a probability of occurrence in any given year. To focus the study and constrain the number of numerical wave model runs NHC selected a limited number of combinations of water level and offshore wave height to determine shoreline wave runup elevations from. A larger wave is more likely to occur at a lower water level, and thus as wave heights decrease the joint probability water level increases. It is not assured that the worst flood hazard on a shoreline occurs from the largest offshore wave. Conversely, the worst flood hazard may not be associated with the most extreme still water level that has a correspondingly smaller wave height. For this reason a range was tested to examine which combination resulted in the highest overall flood construction level when wave effect is added to the designated flood level. The following tables (**Table 1-1** to **Table 1-4**) provide the scenario's considered in this study.

Table 1-1. Joint Probability of Offshore Wave Heights and Water Levels (AEP 1/200) - DEW

Scenario	Offshore H_s	WL (m, CGVD2013)	DFL 1m SLR	DFL 2m SLR
1	10.0	1.8	2.8	3.8
2	9.0	2.3	3.3	4.3
3	7.0	2.7	3.7	4.7
4	4.7	3.0	4.0	5.0

Notes: 1. NHC used a conversion from chart datum (CD) to CGVD2013 as 2.51m for Henslung Cove for offshore data in Dixon Entrance.

Table 1-2. Joint Probability of Offshore Wave Heights and Water Levels (AEP 1/200) - DEE

Scenario	Offshore H_s	WL (m, CGVD2013)	DFL 1m SLR	DFL 2m SLR
1	7.1	1.5	2.5	3.5
2	6.4	2.4	3.4	4.4
3	5.1	3.1	4.1	5.1
4	4.0	3.2	4.2	5.2

Notes: 1. NHC used a conversion from chart datum (CD) to CGVD2013 as 2.51m for Henslung Cove for offshore data in Dixon Entrance.

Table 1-3. Joint Probability of Offshore Wave Heights and Water Levels (AEP 1/200) - HSN

Scenario	Offshore H_s	WL (m, CGVD2013)	DFL 1m SLR	DFL 2m SLR
1	4.9	3.2	4.2	5.2
2	4.3	3.7	4.7	5.7
3	2.0	4.0	5.0	6.0

Notes: 1. NHC used a conversion from chart datum (CD) to CGVD2013 as -3.68 for Tlell.

Table 1-4. Joint Probability of Offshore Wave Heights and Water Levels (AEP 1/200) - HSS

Scenario	Offshore H_s	WL (m, CGVD2013)	DFL 1m SLR	DFL 2m SLR
1	12.0	2.9	3.9	4.9
2	11.2	3.5	4.5	5.5
3	9.2	3.9	4.9	5.9
4	7.0	4.0	5.0	6.0
5	4.0	4.1	5.1	6.1

Notes: 1. NHC used a conversion from chart datum (CD) to CGVD2013 as -3.68 for Tlell.

2.2 Storm wind Characteristics

Winds are the key input into storm wave modelling. As wind can exhibit considerable variability over large distances, and waves are generated by the wind, a good spatial definition of overwater winds is required to reliably estimate storm waves within a water body. Furthermore, the directional pattern of the winds considered for predicting the wave climate influences the angle at which waves approach a shoreline, which in turn influences the potential for flooding and erosion.

Wind observations at the numerous wind-measuring stations (see Appendix B) were employed to generate regional spatially-varying wind fields considered to be typical under storm conditions. Such special definition of overwater winds across the Dixon Entrance and Northern Hecate Strait, which are presented below, are provided as boundary input to the regional numerical wave models.

2.2.1 Dixon Entrance

Wind time-series for identified severe storms in Dixon Entrance were inspected to find instants which exhibits wind patterns that are detrimental the area of the Village of Masset. Wind fields interpolated from field observations at such instants are shown in Figure 2-1 and Figure 2-2 for a westerly and easterly storm, respectively.

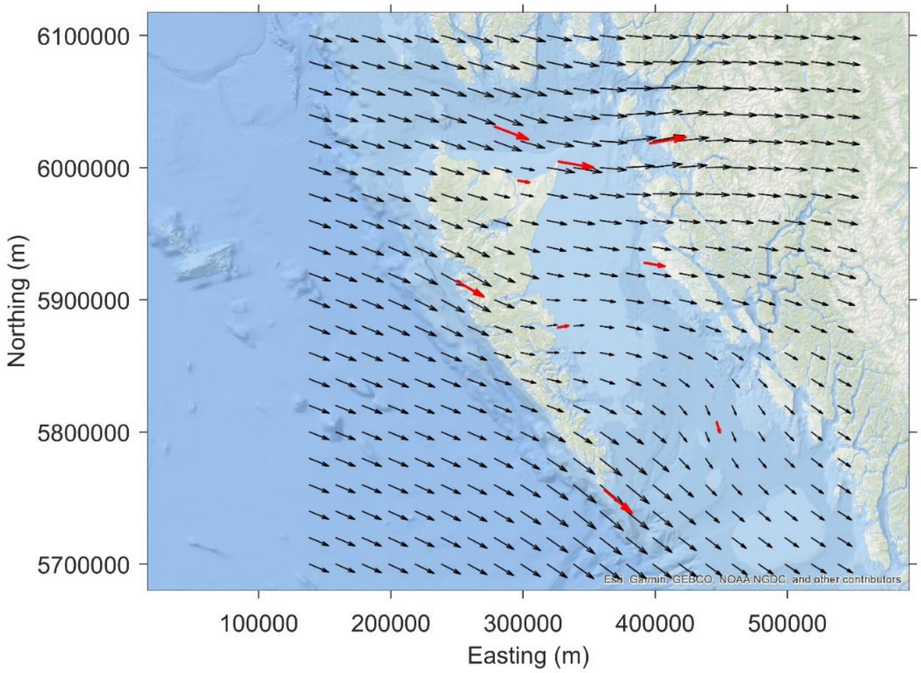

Figure 2-2. Wind field (black arrows) of westerly storm of February 5, 2008 (17h00) in Dixon Entrance interpolated from field observations (red arrows).

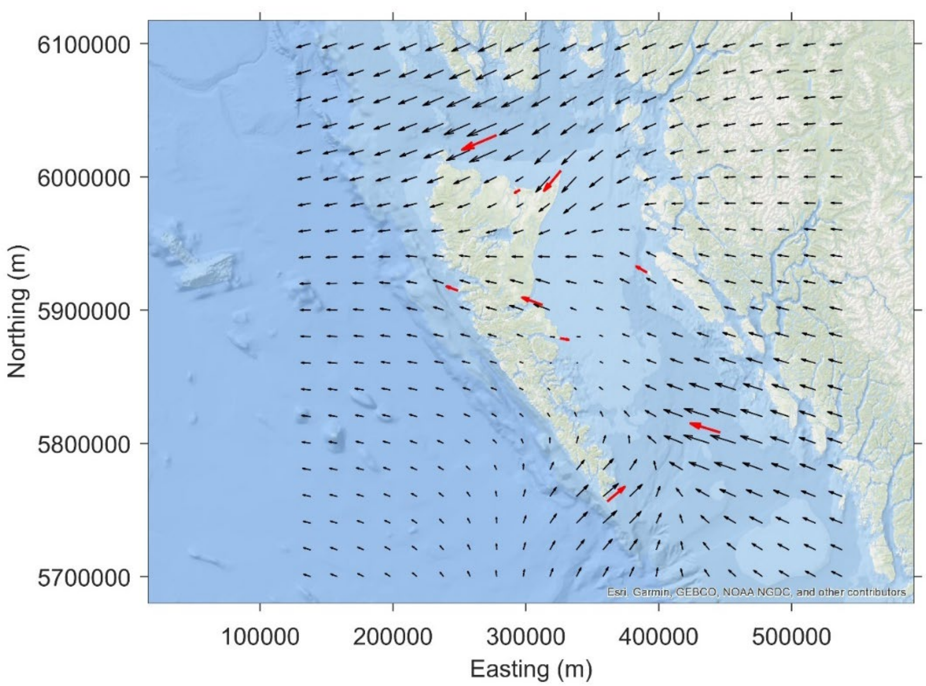

Figure 2-3. Wind field (black arrows) of easterly storm of January 4, 2015 (12h00) in Dixon Entrance interpolated from field observations (red arrows).

2.2.2 Northern Hecate Strait

While the community of Tlell is more vulnerable to the stronger southeasterly storms in Hecate Strait, the community of Sandspit and potentially the Village of Queens Charlotte are expected to be more affected by northerly events. It is possible that the Village of Queens Charlotte be more affected by waves locally generated as southeasterly winds blow across Skidegate Inlet as the village is relatively sheltered from waves generated in Hecate Strait.

Figure 2-3 shows the wind field associated to a severe northerly storm measured at the North Hecate Strait buoy. At the instant shown, which corresponds to when the strongest winds were measure, the wind direction elsewhere in the northern part of the strait is not aiming directly towards the entrance of Skidegate Inlet. However, by inspecting other instants of the storm when relatively stronger winds were measured at other stations, the winds are more directed towards the inlet (Figure 2-4). Consequently, waves associated to this wind pattern, if sufficiently sustained, are expected to be more adverse at the areas of interest.

Lastly, **Figure 2-5** shows the typical pattern of a severe southeasterly storm in the strait.

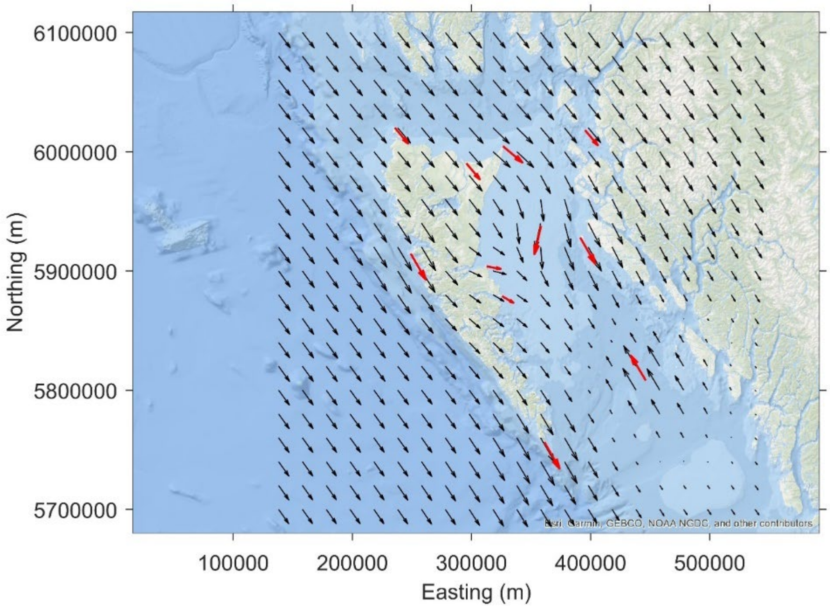

Figure 2-4. Wind field (black arrows) of northerly storm of October 30, 2020 (2h00) in northern Hecate Strait interpolated from field observations (red arrows).

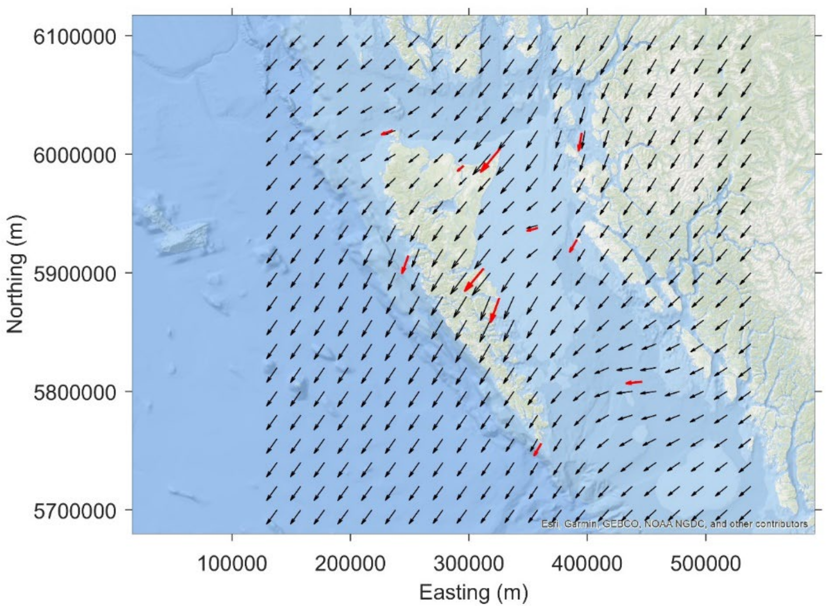

Figure 2-5. Wind field (black arrows) of northerly storm of October 30, 2020 (16h00 on October 29) in northern Hecate Strait interpolated from field observations (red arrows).

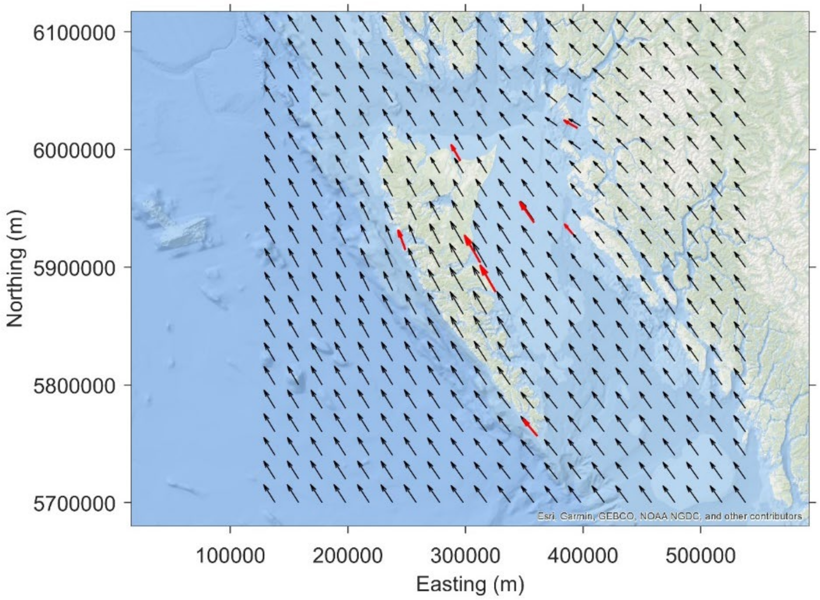

Figure 2-6. Wind field (black arrows) of southerly storm of December 15, 2018 (21h00) in northern Hecate Strait interpolated from field observations (red arrows).

3 STORM WAVE MODELLING

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

Bathymetry for the wave models was taken from the DEM as described in Appendix A.

A series of nested model grids was utilized to evaluate waves at the regional scale, and resolve the seastate at higher resolution near to the community shorelines (see **Figure 3-1**). Regional wind fields and tide conditions are used first on the 1000 m resolution grids for Dixon Entrance and Hecate Strait. Output from these models provides boundary conditions for the subsequent nested model runs.

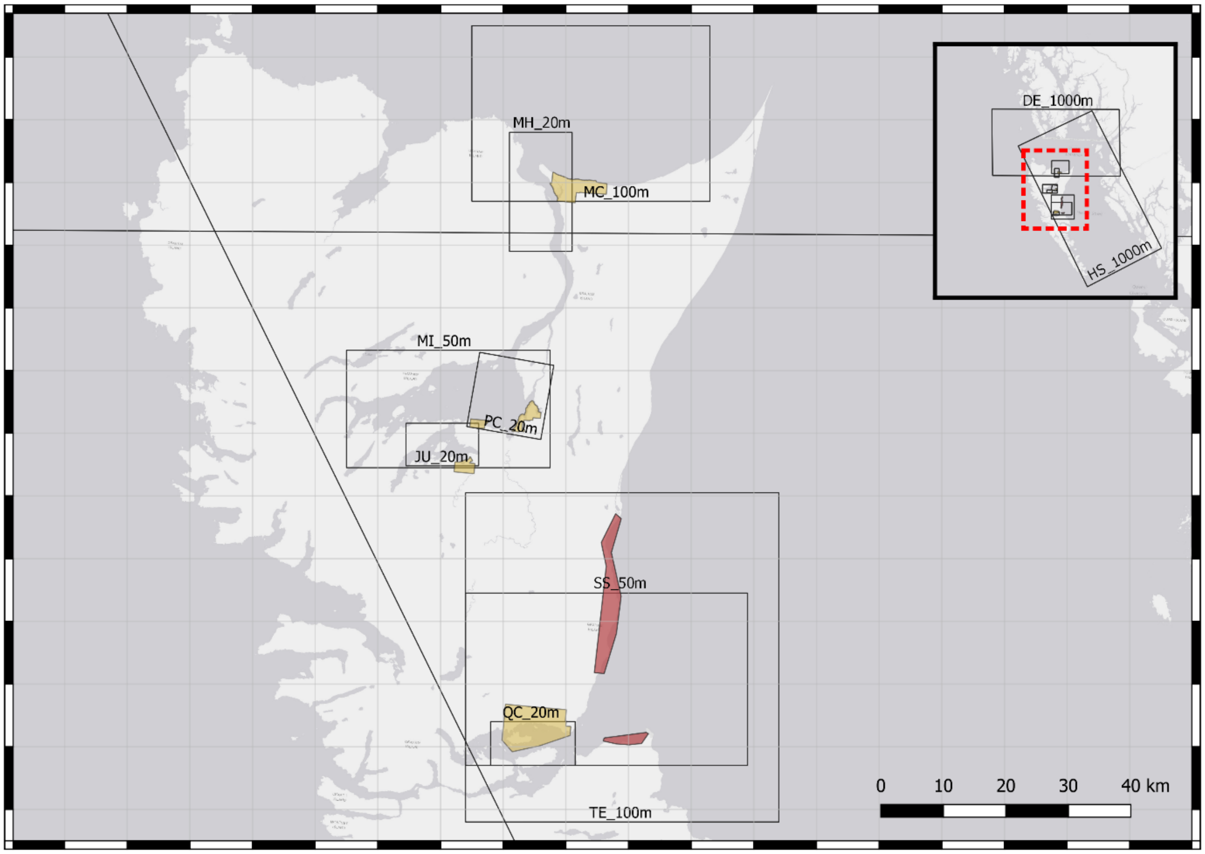

Figure 3-1. Image showing SWAN model grid extents. Inset shows the regional grids with 1000 m resolution, while the 100 m, 50 m, and 20 m nested grids for the various communities are outlined.

Results from the regional wave models show spatial variation of the seastate as expected for such large areas (**Figure 3-2** to **Figure 3-5**). The models were calibrated against historical storms, and sensitivity was checked against variations in wind direction and distribution. For example, in Dixon Entrance where there is a significant exposure to long period ocean swells the model was calibrated against wave buoy data during periods of light wind and long period swells to check the attenuation of the wave heights.

Following calibrations, the wave models were run for a series of events corresponding to the joint probability input conditions to develop a database of incident seastate conditions near the shoreline of the communities. Additional sensitivity runs were undertaken in which wind directions were varied by 10 degree increments in the model to check if small variations in wind direction (within the error of the offshore buoy data) would influence seastate conditions at the shoreline.

A different approach was adopted for Juskatla and Port Clement, in which gale force winds were run coincident with design flood levels to establish the coastal flood hazard. This was done as there was no historical wind data available for the Masset Inlet region.

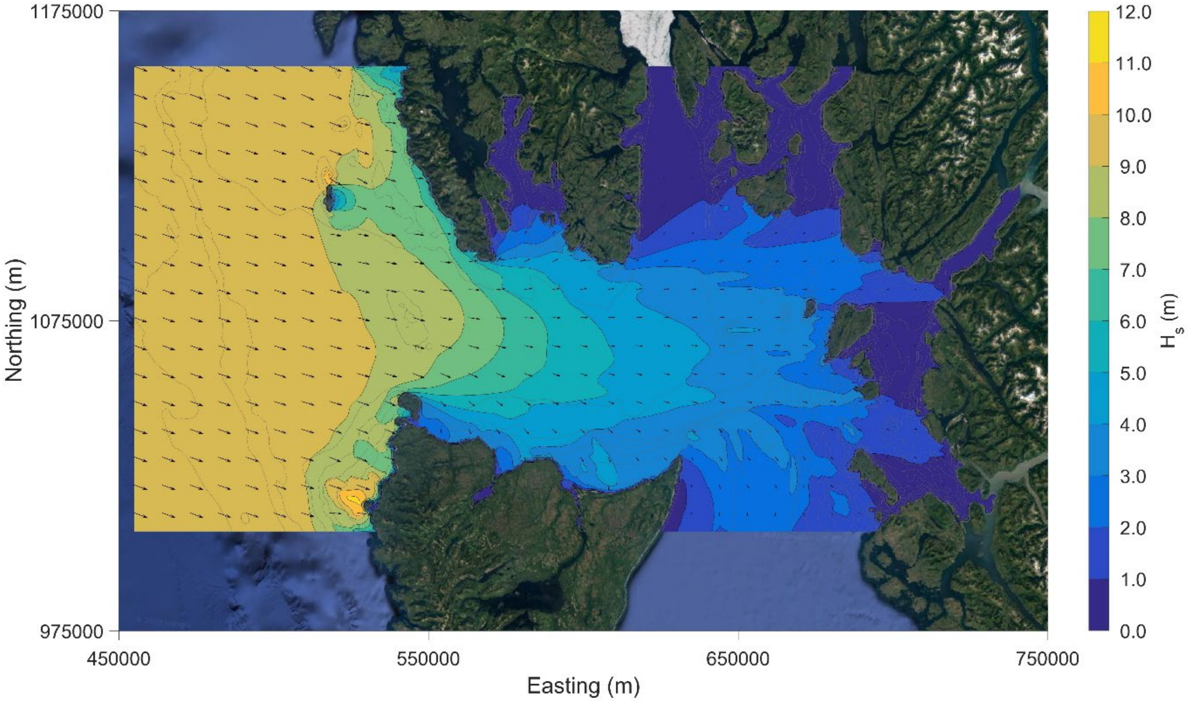

Figure 3-2. Typical pattern of wave propagation in Dixon Entrance during a westerly wave event.

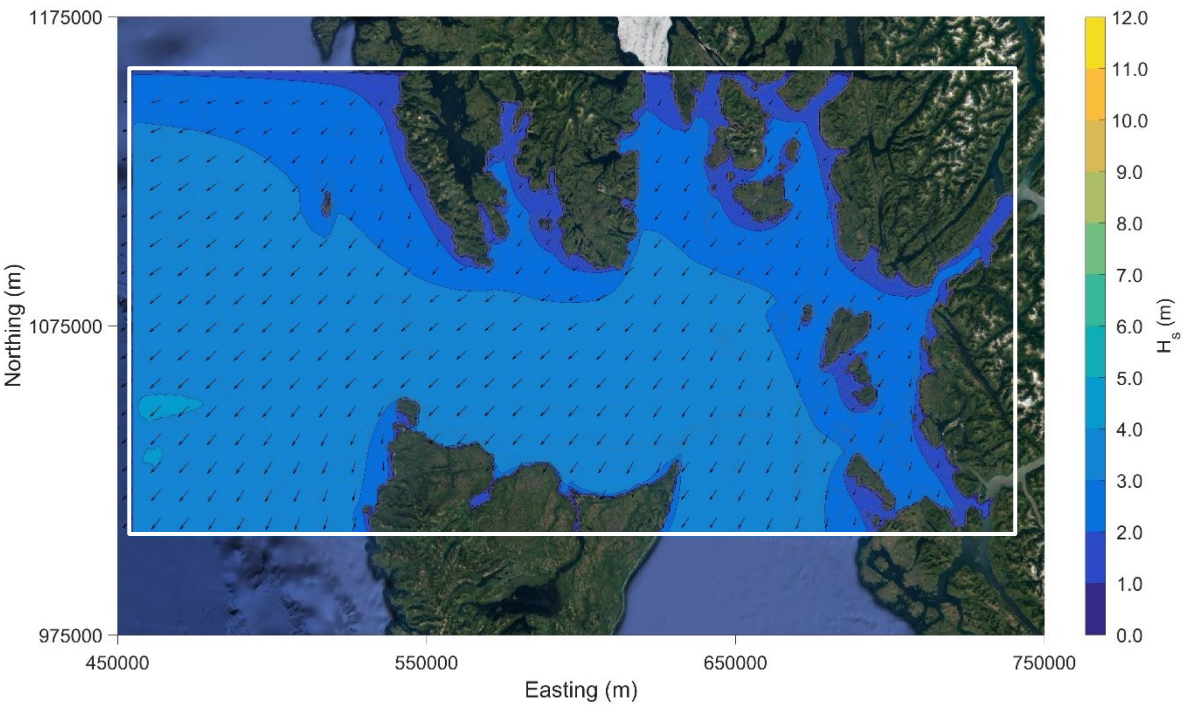

Figure 3-3. Typical pattern of wave propagation in Dixon Entrance during a northeasterly wave event.

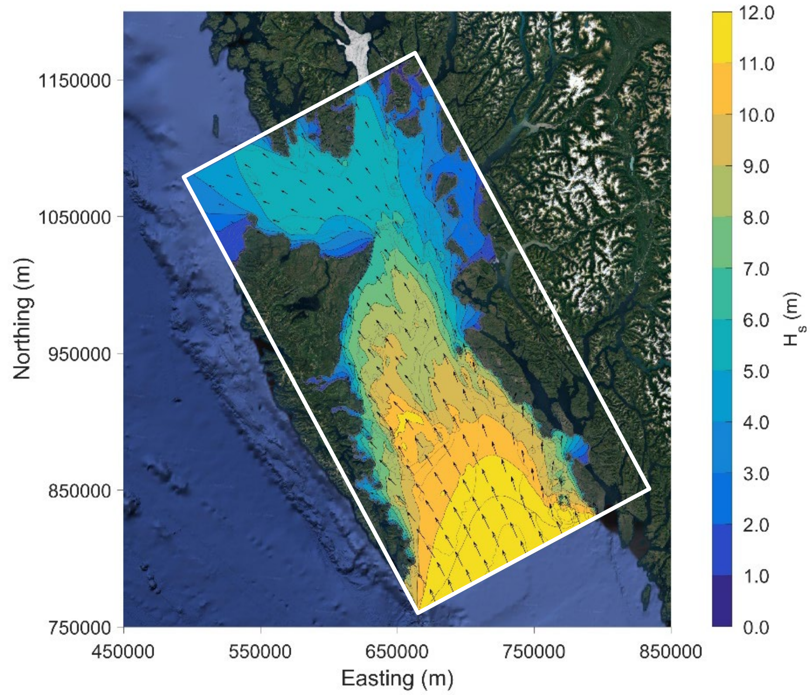

Figure 3-4. Typical pattern of wave propagation in Hecate Strait during a southeasterly wave event.

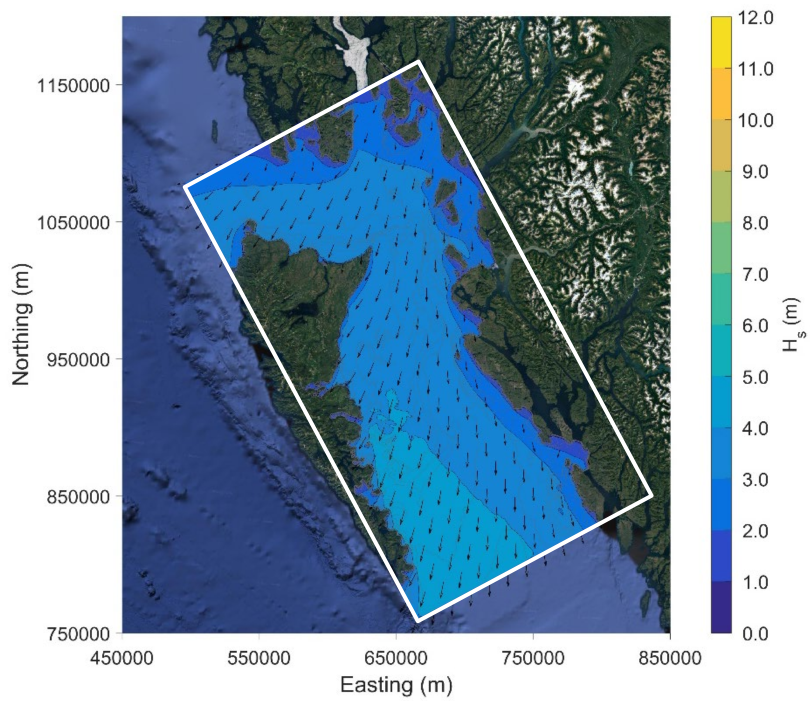

Figure 3-5. Typical pattern of wave propagation in Hecate Strait during a northeasterly wave event

3.1.1 Nest Grid Wave Model Results

The following figures show the spatial wave height variability along the study areas.

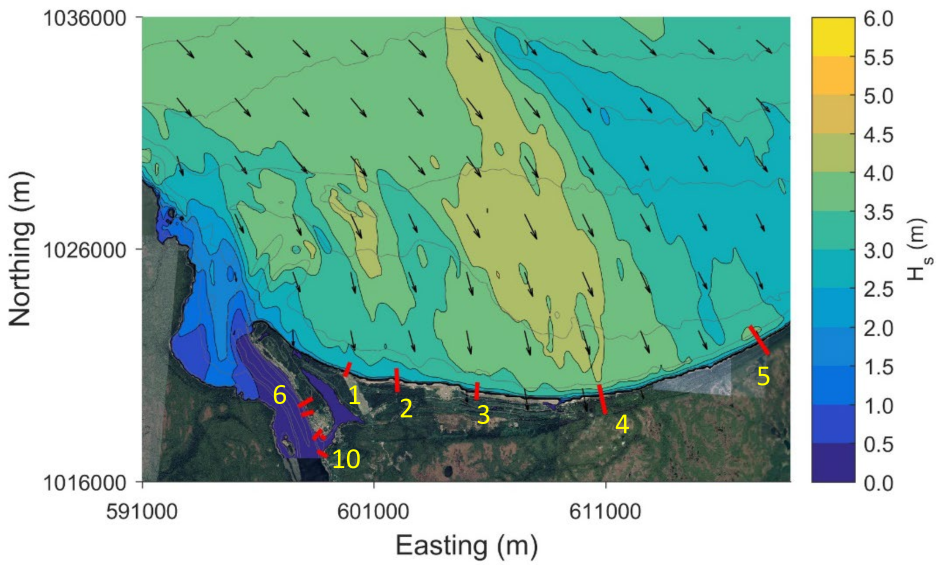

Figure 3-6. Pattern of wave propagation into McIntyre Bay from Dixon Entrance for a large NW event.

Table 3-1. Incident Design Seastate Conditions from wave model ensemble for McIntyre Bay

Transect	Easting	Northing	Depth	Hs (m)	Tp (s)	Direction
1	600800	1020900	7.1	2.9	18.9	351
2	605500	1020300	7.0	3.2	18.9	354
3	610700	1020200	8.5	4.0	18.9	347
4	618700	1023400	10.3	2.8	18.9	336
5	600000	1021100	6.0	2.8	18.9	345

Notes: 1. Water depth at offshore end of transect during simulation

Table 3-2. Incident Design Seastate Conditions from wave model ensemble for Masset Harbour

Transect	Easting	Northing	Depth	Hs (m)	Tp (s)	Direction
6	598900	1017820	6.5	0.6	2.6	200.8
7	598560	1017300	17.3	1.2	3.8	322.1
8	597880	1018860	28.4	1.2	3.8	316.7
9	598380	1017800	19.0	1.1	3.8	180.5
10	597740	1019220	30.9	1.1	3.8	172.3

Notes: 1. Water depth at offshore end of transect during simulation

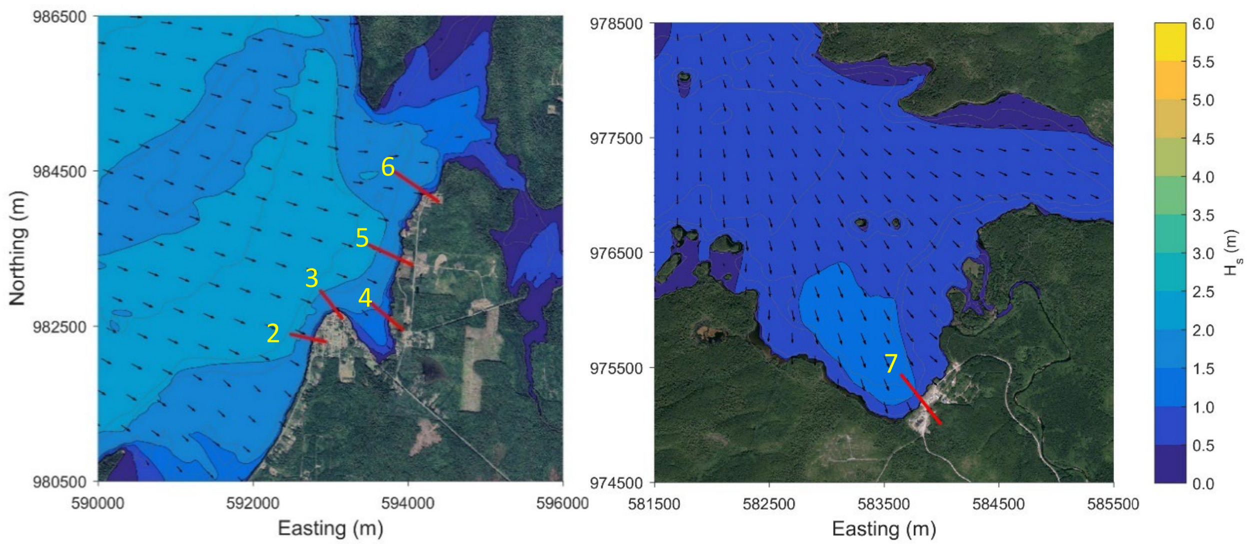

Figure 3-7. Pattern of wave propagation at Port Clement and Juskatla from west wind design storm. Transect 1 is in Ferguson Bay (not shown).

Table 3-3. Incident Design Seastate Conditions from wave model ensemble for Port Clement

Transect	Easting	Northing	Depth	Hs (m)	Tp (s)	Direction
1	586387	981609	16.7	1.7	4.6	25
2	592478	982403	13.1	2.1	5.6	288
3	592861	982965	11.4	2.0	5.6	293
4	593524	982808	4.6	1.7	5.6	304
5	593491	983545	11.6	2.0	5.6	289
6	593819	984482	11.2	2.0	6.1	265
7	583640	975440	14.5	1.0	3.5	324.3

Notes: 1. Water depth at offshore end of transect during simulation

2. Transect No. 1 at Port Clement not shown on figure. Location at log sort area.

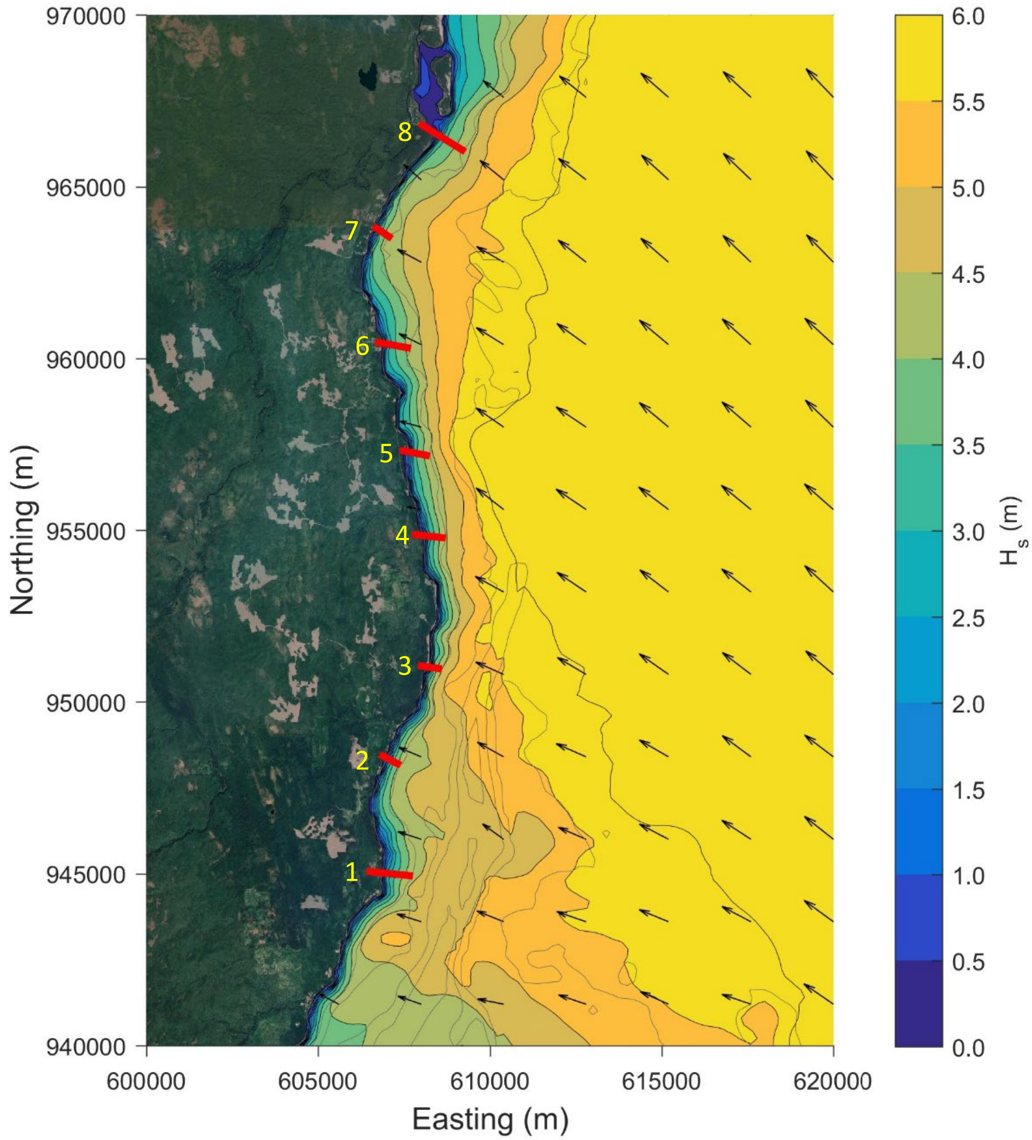

Figure 3-8. Pattern of wave propagation at Tlell during design storm.

Table 3-4. Incident Design Seastate Conditions from wave model ensemble for Tlell

Transect	Easting	Northing	Depth	Hs (m)	Tp (s)	Direction
1	607800	945000	9.7	4.2	15.7	110
2	607400	948200	9.3	4.0	15.7	114
3	608600	951000	9.2	4.4	15.7	116
4	608800	954800	10.2	4.5	15.7	110
5	608200	957200	8.6	4.0	17.2	106
6	607600	960200	8.7	3.8	17.2	111
7	607200	963400	10.6	4.3	11.8	115
8	609200	966000	10.2	4.3	11.8	125

Notes: 1. Water depth at offshore end of transect during simulation

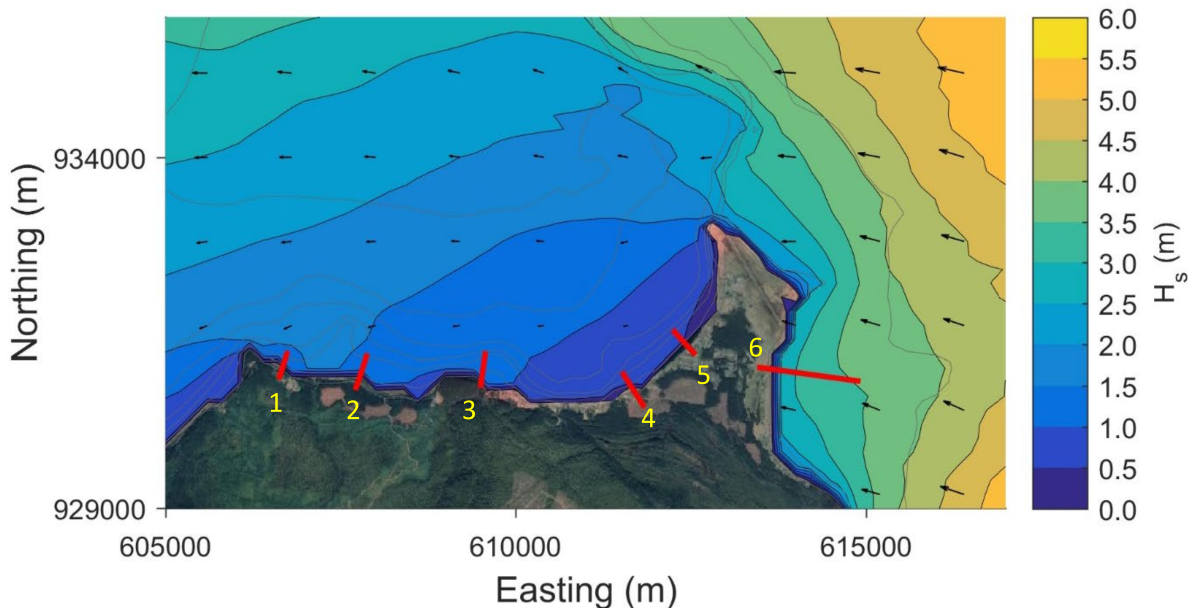

Figure 3-9. Pattern of wave propagation at Sandspit from design storm.

Table 3-5. Incident Design Seastate Conditions from wave model ensemble for Sandspit

Transect	Easting	Northing	Depth	Hs (m)	Tp (s)	Direction
1	606800	931200	12.4	2.8	8.1	21
2	607800	931200	10.6	1.4	15.7	62
3	609550	931250	14.3	2.7	8.1	9
4	611500	930950	13.0	2.2	7.4	351
5	612200	931600	16.6	2.0	8.1	350
6	615000	930800	8.9	3.6	15.7	110

Notes: 1. Water depth at offshore end of transect during simulation
2. Transect 6 is outside of the study limits.

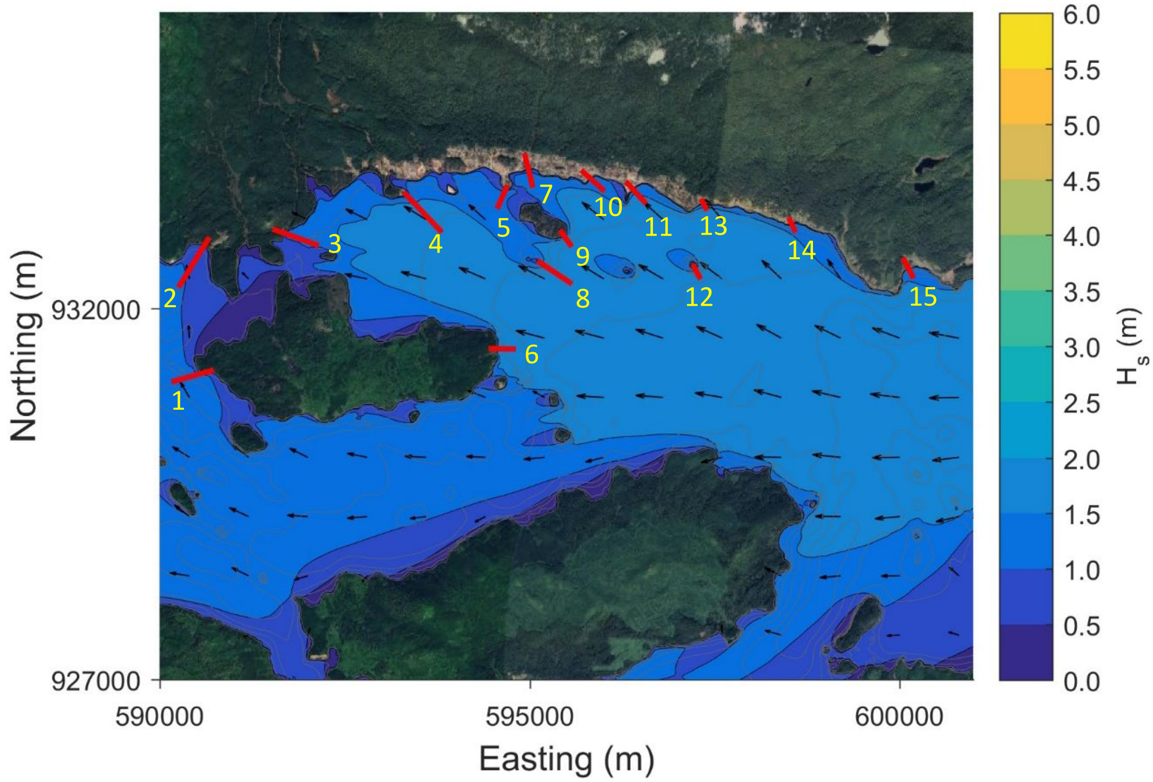

Figure 3-10. Pattern of wave propagation at Daajiing Giids from design storm.

Table 3-6. Incident Design Seastate Conditions from wave model ensemble for Daajing Giids

Transect	Easting	Northing	Depth	Hs (m)	Tp (s)	Direction
1	590160	931020	13.9	1.2	3.8	268
2	590260	932280	9.8	1.3	3.8	241
3	592140	932860	5.0	1.1	4.6	96
4	593820	933020	10.1	1.6	4.6	121
5	594560	933340	10.6	1.2	4.6	143
6	594820	931460	13.7	1.8	4.6	92
7	595040	933640	4.9	1.2	4.6	119
8	595560	932840	16.6	1.7	4.6	124
9	595560	932840	16.6	1.7	4.6	124
10	596020	933580	9.4	1.3	4.6	149
11	596580	933420	11.8	1.6	4.6	138
12	597300	932400	24.2	1.8	4.6	124
13	597400	933320	9.7	1.6	4.6	142
14	598600	933020	12.1	1.5	4.6	151
15	600180	932400	15.6	1.5	4.2	144

Notes: 1. Water depth at offshore end of transect during simulation

4 WAVE EFFECT CALCULATIONS

4.1 Background on Approach to Coastal FCL Calculations

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

The BC Ministry of Environment (MoE) guidelines (BC MoE, 2011b) and the BC Ministry of Forests, Lange, Natural Resource Operations and Rural Development’s (FLNRORD) amendment of the Flood Hazard Area Land Use Management Guidelines (MFLNRORD, 2018) present two approaches for determining the 1-in-200 year Coastal FCL using the (1) combined method and (2) probabilistic method:

- Combined: Designated event based on simultaneous occurrence of the Higher High Water Large Tide[4] (HHWLT) elevation and the estimated 1-in-200 year storm surge.
- Probabilistic: Designated event as determined by a probabilistic analysis of tides and storm surge with a joint 1-in-200 year probability of occurrence. The probabilistic method considers the joint probability of storm surge and high tide occurring simultaneously.

The combined method also tends to be more conservative than the probabilistic approach, and hence provincial guidelines (MFLNRORD, 2018) allow use of a reduced freeboard for mitigation based on this method. The difference in freeboard allowance applied to each method results in their determinations of FCL often having similar elevations. Regardless, the probabilistic approach is generally understood to result in a more precise estimation of the probability of extreme water levels than the combined method.

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

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

Designated Flood Level (DFL)

Flood Construction Reference Plane (FCRP)

Flood Construction Level (FCL)

This approach is visualized in **Figure 4-1**.

NHC has utilized a modified probabilistic method for this study in which overall joint probability of water levels and associated offshore wind and wave conditions combine as a 1-in-200 probability of occurrence. It was found in this study that the 1-in-200 AEP DFL is not typically responsible for the highest FCL conditions (as suggested by **Figure 4-1)**. The highest 1-in-200 FCL is often the combination of a slightly lower water level occurring jointly with a large storm that generates larger wave effects on the shoreline than the very highest water level for which it is less likely to have jointly occurring large storm waves.

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

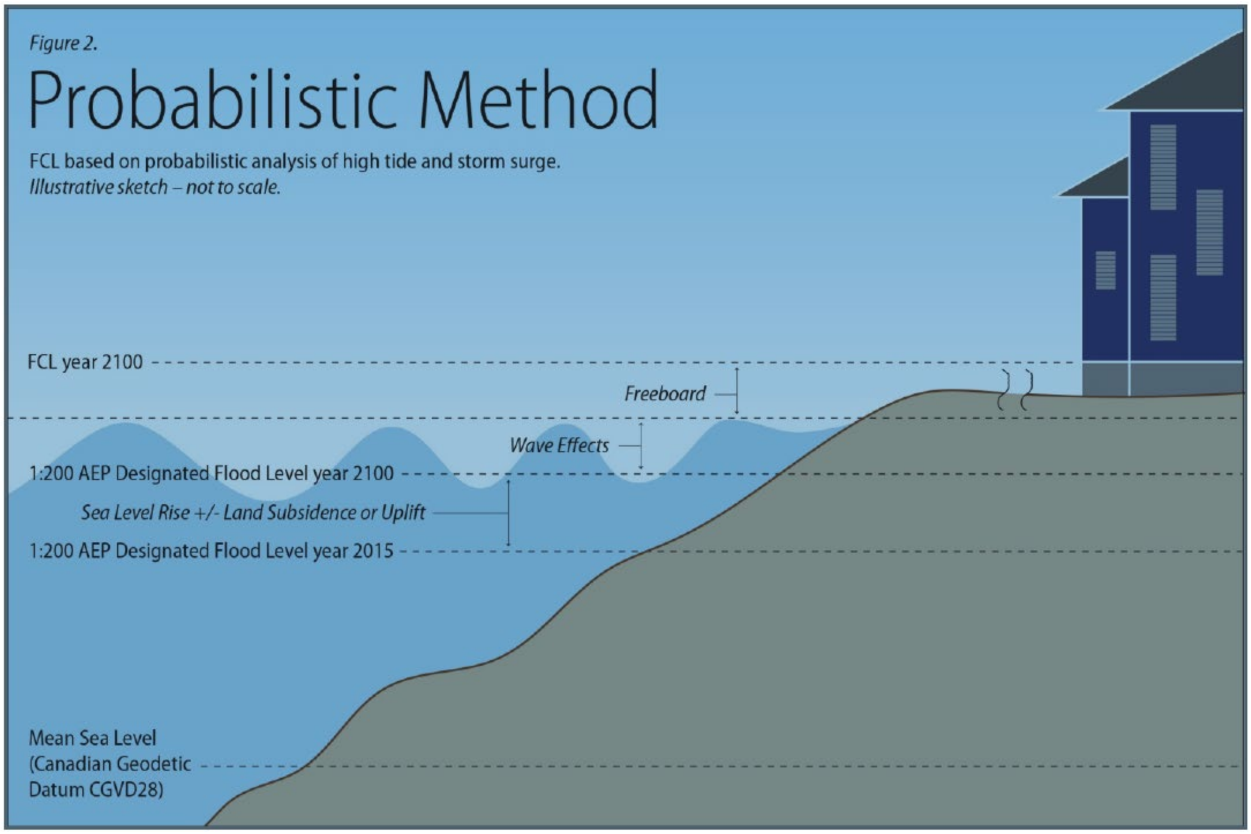

Figure 4-1. Probabilistic Method of FCL determination, from (MFLNRORD, 2018).

4.2 Wave Effect Estimates

The wave effects (or wave runup) at the shoreline was determined based on empirical equations and methodology outlined in the EurOtop '*manual on wave overtopping of sea defences and related structures*' (EurOtop, 2018). A reduction factor was applied to account for the roughness of various types of shorelines (see Table 4-1). An additional reduction factor (ranging from 0.7 – 0.9) was applied to shorelines that are exposed to predominantly oblique waves.

Table 4-1. Roughness reduction factor for wave run-up calculations

Variable	Reduction Factor for Roughness, *f*
Gravel Beach	~0.8 [1]
Vegetated Slope	0.8
Bedrock Slope	1.0
Berm / Vegetated Dike	0.8

Variable	Reduction Factor for Roughness, f
Rip-Rap	0.6
Vertical Wall	1.0

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

The overall workflow for the estimate of the wave effect for a given shoreline in this project was as follows:

1. Using the SWAN wave model, the seastate was simulated for each of the four selected 1-in-200 regional storm combinations of waves and waterlevels for each study area.
2. From each wave model run, the incident seastate was determined at the offshore extent of the shoreline transects for a community.
3. An empirical formula was used to transform the wave height, period, and direction at the offshore end of the transect to a location that was approximately one wavelength from the shoreline at the still water level for the simulation. (Note the still water level of the wave simulations changes depending upon the joint probability analysis for each run.)
4. The transformed wave height, period, and direction are used as input to the EurOtop formulae to estimate the wave runup on the shoreline. The shoreline slope at the still water level (or DFL level for the simulation) was utilized to estimate runup while a roughness reduction factor was assigned to each transect.
5. The wave effect, freeboard (0.6 m for all simulations) and DFL were added for each simulation to evaluate the total FCL estimate for each of the four joint probability conditions. The highest of the resulting FCL values was assigned for each transect.

The following tables provide a summary of the output for each community for the computed maximum FCL value.

Table 4-2. Calculated Components of FCL for McIntyre Bay and Masset (1 m SLR)

Transect	Incident Wave Height (m)	DFL (m, CGVD2013)	Wave Effect (m)	Freeboard (m)	FCL (m)
1	2.8	3.3	3.8	0.6	7.7
2	2.9	3.3	4.5	0.6	8.4
3	3.2	3.3	4.0	0.6	7.9
4	4.0	3.3	4.0	0.6	7.9
5	2.8	3.3	4.7	0.6	8.6
6	1.1	4.0	0.8	0.6	5.4
7	1.2	4.0	1.1	0.6	5.7
8	1.1	4.0	0.4	0.6	5.0
9	0.6	4.0	0.6	0.6	5.2
10	1.2	4.0	0.9	0.6	5.5

Notes: 1.

Table 4-3. Calculated Components of FCL for McIntyre Bay and Masset (2 m SLR)

Transect	Incident Wave Height (m)	DFL (m, CGVD2013)	Wave Effect (m)	Freeboard (m)	FCL (m)
1	3.1	4.3	3.9	0.6	8.8
2	3.2	4.3	4.7	0.6	9.6
3	3.5	4.3	4.1	0.6	9.0
4	4.2	4.3	4.4	0.6	9.3
5	2.8	4.3	5.6	0.6	10.5
6	1.2	5.0	0.8	0.6	6.4
7	1.2	5.0	1.1	0.6	6.7
8	1.1	5.0	0.6	0.6	6.2
9	0.7	5.0	0.8	0.6	6.4
10	1.2	5.0	0.6	0.6	6.2

Notes: 1.

Table 4-4. Calculated Components of FCL for Port Clement & Juskatla (1 m SLR)

Transect	Incident Wave Height (m)	DFL (m, CGVD2013)	Wave Effect EurOtop (m)	Freeboard (m)	FCL (m)
1	1.7	3.1	1.9	0.6	5.6
2	1.9	3.1	1.7	0.6	5.4
3	1.8	3.1	1.8	0.6	5.5
4	1.4	3.1	1.0	0.6	4.7
5	1.8	3.1	1.0	0.6	4.7
6	1.5	3.1	1.0	0.6	4.7
7	1.1	2.2	0.9	0.6	3.7

Notes: 1.

Table 4-5. Calculated Components of FCL for Port Clement & Juskatla (2 m SLR)

Transect	Incident Wave Height (m)	DFL (m, CGVD2013)	Wave Effect EurOtop (m)	Freeboard (m)	FCL (m)
1	1.7	4.1	1.9	0.6	6.6
2	2.0	4.1	1.7	0.6	6.4
3	1.6	4.1	1.1	0.6	5.8
4	1.5	4.1	0.6	0.6	5.3
5	1.8	4.1	0.8	0.6	5.5
6	1.9	4.1	1.0	0.6	5.7
7	1.0	3.2	0.7	0.6	4.5

Notes: 1.

Table 4-6. Calculated Components of FCL for Tlell (1 m SLR)

Transect	Incident Wave Height (m)	DFL (m, CGVD2013)	Wave Effect EurOtop (m)	Wave Effect Swash (m)	Freeboard (m)	FCL (m)
1	4.2	4.5	5.9	3.3	0.6	8.4
2	4.0	4.5	5.6	3.3	0.6	8.4
3	4.4	4.5	6.9	3.9	0.6	9.0
4	4.5	4.5	5.5	3.1	0.6	8.2
5	4.0	3.9	7.8	3.7	0.6	8.2
6	3.8	3.9	6.5	4.3	0.6	8.8
7	4.3	4.9	7.3	4.1	0.6	9.6
8	4.3	4.9	7.3	4.1	0.6	9.6

Notes: 1.

Table 4-7. Calculated Components of FCL for Tlell (2 m SLR)

Transect	Incident Wave Height (m)	DFL (m, CGVD2013)	Wave Effect EurOtop (m)	Freeboard (m)	FCL (m)
1	4.6	5.9	6.0	0.6	12.5
2	4.4	5.9	6.1	0.6	12.6
3	4.5	5.5	6.8	0.6	12.9
4	4.8	5.5	7.4	0.6	13.5
5	4.2	4.9	6.7	0.6	12.2
6	4.9	5.5	6.1	0.6	12.2
7	4.7	5.9	7.8	0.6	14.3
8	4.7	5.9	7.9	0.6	14.4

Notes: 1.

Table 4-8. Calculated Components of FCL for Sandspit (1 m SLR)

Transect	Incident Wave Height (m)	DFL (m, CGVD2013)	Wave Effect EurOtop (m)	Freeboard (m)	FCL (m)
1	2.8	4.9	2.8	0.6	8.3
2	1.4	4.5	2.3	0.6	7.4
3	2.7	4.9	4.1	0.6	9.6 [1]
4	2.2	4.9	3.0	0.6	8.5
5	2.0	4.9	2.7	0.6	8.2
6	3.6	4.5	4.7	0.6	9.8

Notes: 1.

Table 4-9. Calculated Components of FCL for Sandspit (2 m SLR)

Transect	Incident Wave Height (m)	DFL (m, CGVD2013)	Wave Effect EurOtop (m)	Freeboard (m)	FCL (m)
1	2.9	5.9	2.9	0.6	9.4
2	1.6	5.5	2.4	0.6	8.5
3	2.8	5.9	4.6	0.6	11.1
4	2.2	5.9	3.1	0.6	9.6
5	2.1	5.9	2.7	0.6	9.2
6	3.9	5.5	4.9	0.6	11.0

Notes: 1.

Table 4-10. Calculated Components of FCL for Daajing Giids (1 m SLR)

Transect	Incident Wave Height (m)	DFL (m, CGVD2013)	Wave Effect EurOtop (m)	Freeboard (m)	FCL (m)
1	1.2	4.9	0.5	0.6	6.0
2	1.3	4.9	1.3	0.6	6.8
3	1.1	4.9	1.3	0.6	6.8
4	1.6	4.9	1.6	0.6	7.1
5	1.2	4.9	1.5	0.6	7.0
6	1.8	4.9	2.7	0.6	8.2
7	1.2	4.9	1.2	0.6	6.7
8	1.7	4.9	1.8	0.6	7.3
9	1.7	4.9	2.0	0.6	7.5
10	1.3	4.9	2.1	0.6	7.6
11	1.6	4.9	2.3	0.6	7.8
12	1.8	4.9	2.5	0.6	8.0
13	1.6	4.9	1.9	0.6	7.4
14	1.5	4.9	2.4	0.6	7.9
15	1.5	4.9	2.0	0.6	7.5

Notes: 1.

Table 4-11. Calculated Components of FCL for Daajing Giids (2 m SLR)

Transect	Incident Wave Height (m)	DFL (m, CGVD2013)	Wave Effect EurOtop (m)	Freeboard (m)	FCL (m)
1	1.2	5.9	0.5	0.6	7.0
2	1.3	5.9	1.2	0.6	7.7
3	1.2	5.9	1.4	0.6	7.9
4	1.7	5.9	1.7	0.6	8.2
5	1.3	5.9	1.6	0.6	8.1
6	1.8	5.9	2.7	0.6	9.2
7	1.3	5.9	1.3	0.6	7.8
8	1.7	5.9	1.8	0.6	8.3
9	1.7	5.9	2.1	0.6	8.6
10	1.4	5.9	2.3	0.6	8.8
11	1.6	5.9	2.4	0.6	8.9
12	1.8	5.9	2.6	0.6	9.1
13	1.6	5.9	2.0	0.6	8.5
14	1.5	5.9	2.4	0.6	8.9
15	1.5	5.9	2.0	0.6	8.5

Notes: 1.

4.3 FCL zones

The application of the flood construction level to the maps required interpretation of the existing land features, consideration of the potential for erosion, and evaluation of the potential for wave effects to translate inland. The wave modelling output was queried by the design team to inform the decision making on the width of the shoreline FCL zones.

In general, a width of 30 m was applied to the FCL zone from the existing shoreline in areas where the shoreline was steep and the crest of the existing shoreline is above the DFL. In this scenario, the waves break upon the shoreline and while there may be significant wave overtopping at the shoreline, the potential for maximum wave effects to occur 30 m inland from where the land is above the DFL does not have a physical basis.

For shorelines that have a high erosion potential and are without active erosion protection structures, the width of the FCL zone was increased based upon the amount of overtopping expected during an extreme storm and consideration of the potential for sudden erosion in the future. Such a condition occurs in McIntyre Bay facing into Dixon Entrance, and here the relatively low lying shoreline has a wider FCL zone applied to be conservative for future changes.

For low lying areas inland of the shoreline, the coastal flood hazard was assessed by taking the maximum 1-in-200 DFL from the joint probability analysis (which typically corresponds to conditions with the smallest offshore waves) and adding a freeboard to establish an inland coastal FCL. This is to avoid extending the coastal FCL zone, which includes wave effects, a significant distance inland over an area for which the land is above the DFL (or still water level) and which waves will break and transform into bores. Over a distance such waves lose their energy and the wave effect is no longer reasonable to apply.

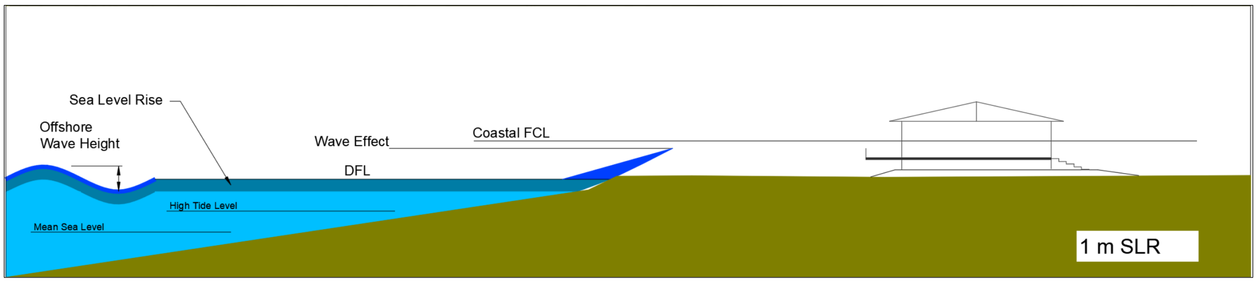

Figure 4-2. Profile view of FCL zones (not to scale). View shows traditional approach with FCL zone extending inland over low-lying areas.

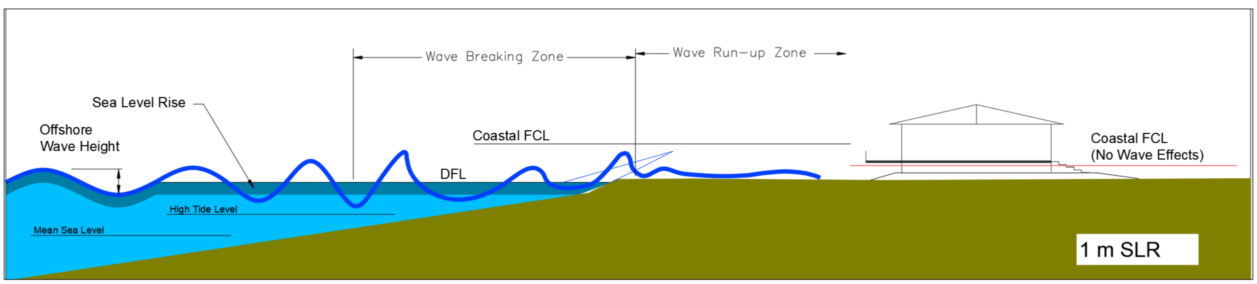

Figure 4-3. Profile view of FCL zones (not to scale). View shows project approach in which zone of wave breaking and runup on shoreline is estimated, and a lower in-land FCL zone is determined for the highest DFL and no wave effects.

In some areas the land is low and incident wave energy is high and waves may runup and continue to propagate inland for some distance. A select number of SWASH wave model runs were undertaken to characterize the potential inland wave effects under future sea level rise conditions. From this, a somewhat conservative approach of selecting 50% of the shoreline wave effect was used in a 'secondary coastal FCL zone' in high energy shoreline areas in order to widen the coastal FCL zone without unrealistically imposing overly high coastal FCL levels too far inland where such wave effects would not apply. Figure 4-4 shows how these multiple levels of FCL zones are represented on the maps for Tlell, and Figure 4-5 gives a section view showing a not-to-scale representation of these FCL zones.

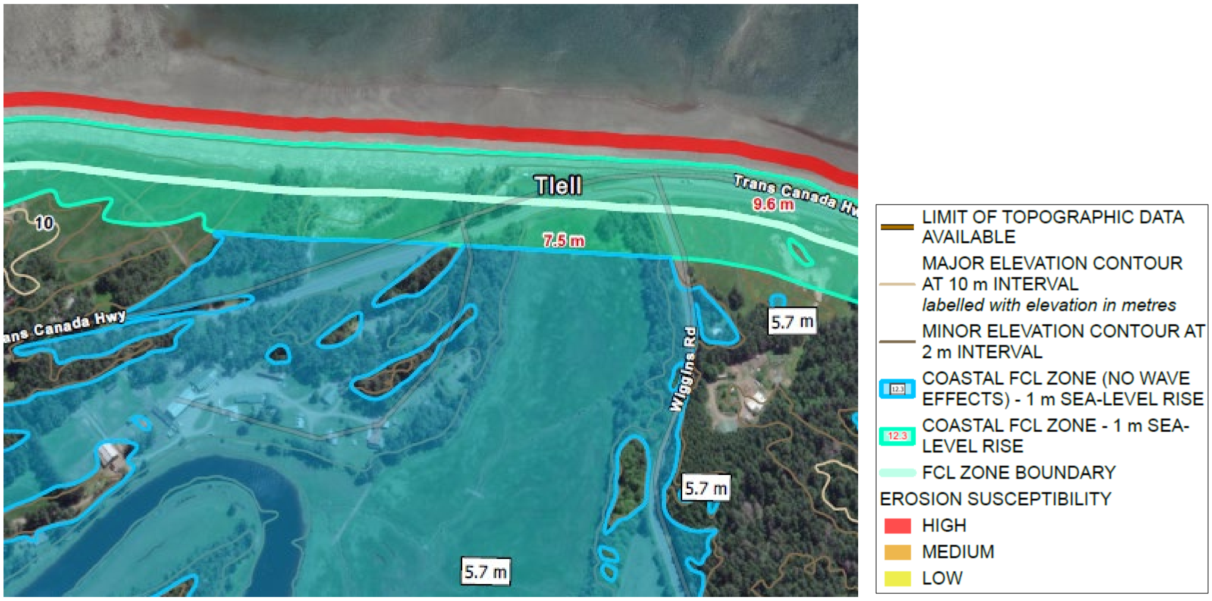

Figure 4-4. **Example of a hazard zone on the map showing the FCL at Tlell. The area outlined in blue shows the coast FCL zone with a 1 m SLR with no wave effects. The area outlined in green shows the coastal FCL zone with a 1 m SLR that includes wave effects. Erosion susceptibility is high, as shown by the thick red line that parallels the shoreline.**

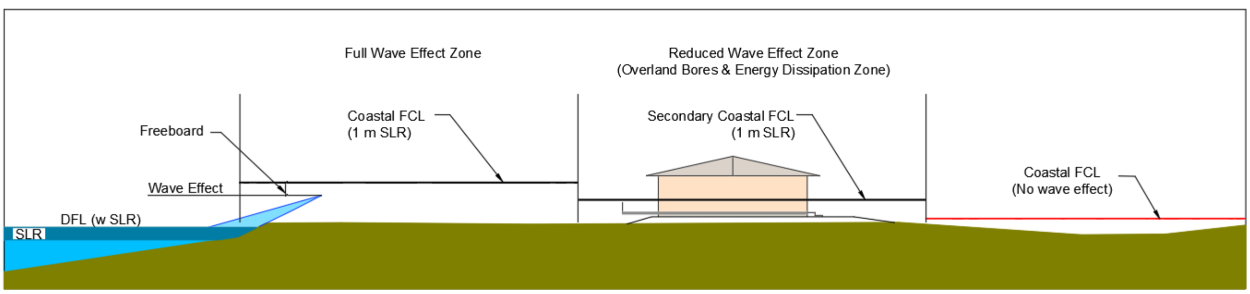

Figure 4-5. **This schematic drawing shows the predicted FCL levels in profile view, which are depicted in the coastal storm hazard maps produced for the project. In some areas where the land is flat, two FCL zones are presented with wave effects of different elevations where wave overtopping rates at the shoreline are high enough to propagate in the form of overland bores[5] in low-lying areas. Further inland where wave energy has dissipated an FCL zone is shown with no wave effects.**

[5] A hydraulic bore is a wave with a steep and turbulent front moving across standing waters or dry land. It can result from the breaking of ocean waves.

5 SUMMARY

This report presents the technical details of the metocean analysis performed to understand the governing conditions offshore of Haida Gwaii. Such conditions were assessed in detail, ensuring that results are robust and reliable, enabling their foundational use in supporting other components of this broader study. The main topics covered in this report are summarized as follows:

1. Haida Gwaii is surrounded by several water bodies that can exhibit varying sea conditions. Based on areas of interests to this study, water bodies were further divided as per the following overwater sectors:
    - Dixon Entrance westerly sector
    - Dixon Entrance easterly sector
    - Hecate Strait northerly sector
    - Hecate Strait southerly sector
2. Historical records from multiple measuring stations were collected, processed, and analyzed to understand the wind regime and wave climate in Dixon Entrance and Hecate Strait, including the definition of offshore design criteria for consideration in the subsequent assessment of coastal flood hazard at the shoreline.
3. At Langara Point, the tidal range is 5.2 m. in comparison to 7.7 m at Daajing Giids in Skidegate Inlet. The length, width, and relatively shallow depth of Masset Sound directly affects the propagation of the tide. As such, the tidal range in Masset Sound is smaller than in McIntyre Bay The tidal range as well as the height of high tides further reduces with distance away from McIntyre Bay toward Masset Inlet. As such, the tidal range at Port Clements and Juskatla is 3.0 m and 1.9 m, respectively.
4. The data from measuring stations show that the predominant winds are from the southeast in both Dixon Entrance and Hecate Strait, although strong winds (e.g., > 17.5 m/s or gale force) are more frequent in Hecate Strait in comparison to Dixon Entrance. Strong westerly winds can occur in Dixon Entrance, and strong northerly winds can also occur in Hecate Strait, but less frequently.
5. Masset Inlet is classified as its own water, since it is isolated from open ocean waves although influenced by tides, storm surges, and tsunamis from the ocean. Waves in Masset Inlet are generated by local winds.
6. Wave measurements available for the study area include wave height and wave period, but not wave direction. Since it is important to distinguish where the sector waves originate from to establish statistics, the team conducted additional analysis to infer wave direction from available metocean parameters.
7. A joint probability analysis was performed to establish design combinations of coinciding water levels and offshore wave conditions, ensuring the use of combinations that are the most adverse at each of the project's areas of interest. NHC evaluated various combinations of equal exceedance probability by means of numerical wave modelling, as presented in Appendix C.

6 REFERENCES

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