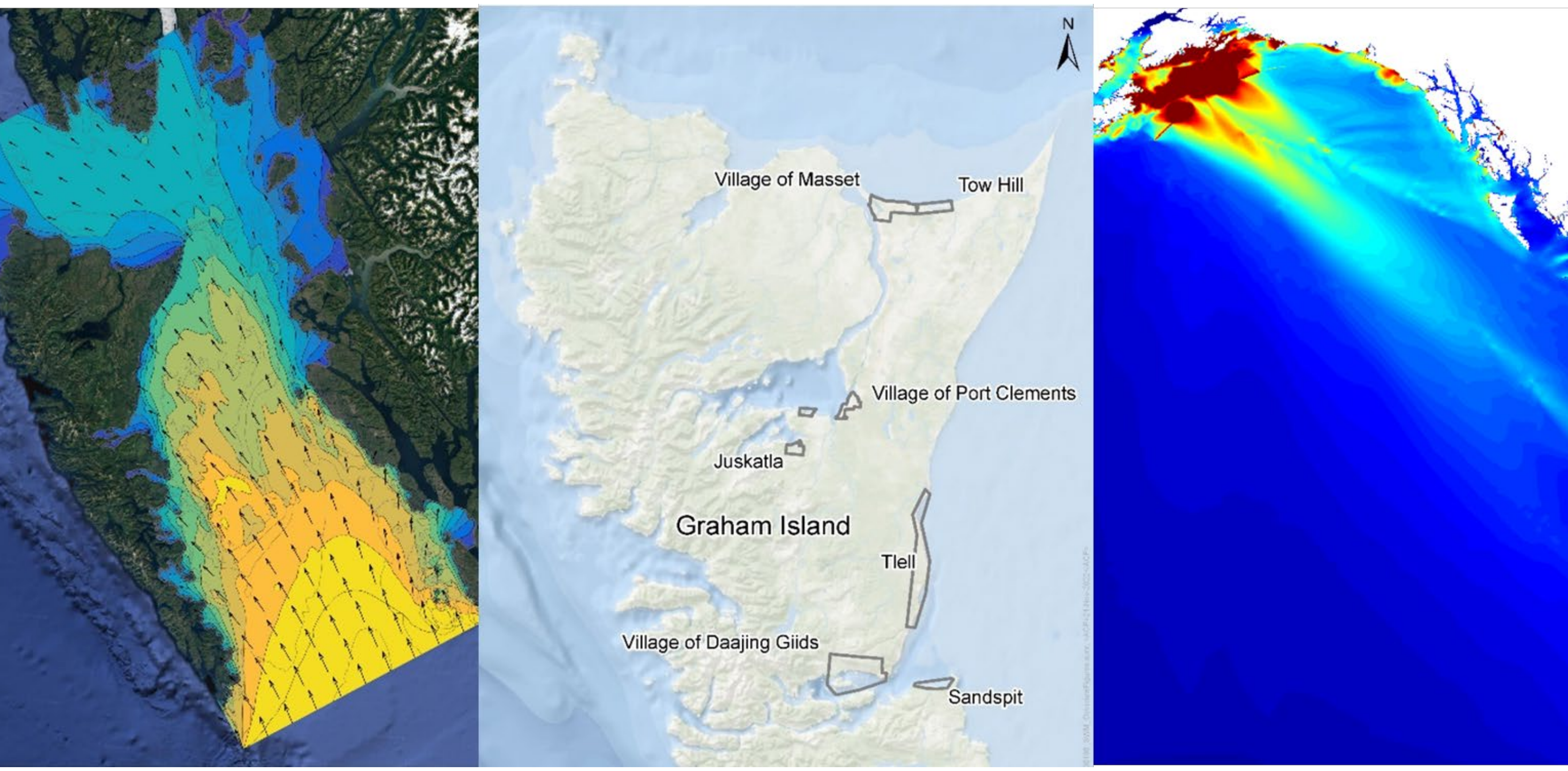

Photo source: (NHC/ONC)

Haida Gwaii Coastal Flood and Erosion Study
Planning for Sea-level Rise and Tsunami Hazards

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Acknowledgement and Place Names:

The authors acknowledge that this study is within the ancestral and unceded lands of the Haida Nation, and that there is an ongoing process in the study area to recognize ancestral Haida place names. The place names used in the reports and the maps reflect those in official use at the time of preparation of the study and will inevitably become dated in time as the important work of recognizing Haida place names continues in the communities of Haida Gwaii.

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EXECUTIVE SUMMARY

Introduction

All residents of Haida Gwaii live in communities near the shoreline and depend on critical infrastructure that is subject to potential flooding and erosion from ocean processes. Each community is increasingly vulnerable to rising sea levels. 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. In addition, 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 (ONC) have been engaged to provide professional engineering, geoscience, and oceanographic consulting services for five communities on 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 (SLR). 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 (NCRD), in association with the Village of Masset, the Village of Port Clements, and the Village of Daajing Giids.

The main objective of this study is to quantify the flooding hazards of two independent natural phenomena occurring in the future when sea levels are higher:

i. a large windstorm generating large waves

ii. a tsunami arising from an earthquake along the Alaska-Aleutian or Cascadia subduction zones

The susceptibility of shorelines to erosion has been determined within each study area to inform and support future detailed planning efforts within the study areas. The information generated as part of this project includes maps that define **flood construction levels** (FCLs) to support development, as well as tsunami inundation maps for emergency planning.

Planning Horizon

Given the uncertainty in SLR projections, in conjunction with the considerable challenges associated with higher sea levels than planned, this study explores the potential effects of specific sea levels irrespective of when they will occur. More specifically, this study is based on 1 m and 2 m of **relative sea-level rise** in relation to the land. Since it is known that 1.0 m of relative SLR will be reached at one point or another, and potentially before 2100, NHC recommends that planning and development consider this level from now on, rather than using an interim level combined with a specific time horizon. Also, plans should be adaptable so they can be revised for 2 m of relative SLR when effects of higher sea levels become more noticeable.

Coastal Storm Flood Hazard

The coastal flood hazard varies along shorelines depending upon the exposure to ocean waves, the height of the shoreline, and the nature of the shoreline (i.e., steep riprap, mild-slope beach, etc). Areas such as Tlell and McIntyre Bay, which faces Dixon Entrance, are directly exposed to long-period ocean waves, while more sheltered areas such as Port Clements have less exposure to coastal flood hazards.

BC guidance on the determination of the FCL involves three primary components: the designated flood level (DFL), wave effects, and freeboard. The following table reproduces the results provided in the main body of the report, as presented in the table below, and offers a summary of the DFL and associated FCL for both 1 m and 2 m of SLR.

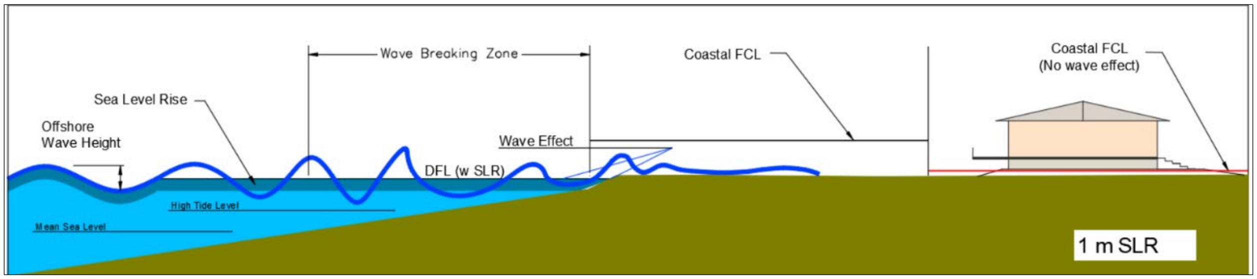
Area	DFL (1 m SLR) [1] (m CGVD2013)	DFL (2 m SLR) [1] (m CGVD2013)	FCLs for Emergency Planning[2] (CGVD2013)	
			1 m SLR (m)	2 m SLR (m)
McIntyre Bay	4.1	5.1	7.7 – 8.6	8.8 – 10.5
Masset (Village Core)	4.0	5.0	5.2 – 5.7	6.2 – 6.7
Port Clements	3.1	4.1	4.7 – 5.5	5.3 – 6.4
Ferguson Bay	3.1	4.1	5.6	6.6
Juskatla	2.2	3.2	3.7	4.5
Tlell	4.9	5.9	8.1 – 9.6	12.2 – 14.4
Daajing Giids	4.9	5.9	6.0 – 8.2	7.0 – 9.2
Sandspit	4.9	5.9	7.4 - 9.6	8.5 – 11.1

Notes: 1. The DFL is given for 1 m and 2 m of SLR. As per BC guidance, 1 m of SLR is used to provide a planning window to year 2100, and 2 m of SLR is tentatively used for planning a window from year 2150 to 2200. A high level of uncertainty remains as to the future timing of SLR, so estimates of the timing of SLR should be considered accordingly.

2. The FCL for emergency planning includes a freeboard allowance of 0.6 m. The FCL level varies spatially within an area, and thus the range of FCL levels is noted.

The project's design team queried the wave modelling output to help inform 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 is steep and the crest of the existing shoreline is above the DFL, allowing the backshore area to be dry in the absence of waves. Thus, when waves do occur, they break upon the shoreline; while there may be significant wave overtopping at the shoreline, the potential for maximum wave effects to occur more than 30 m inland from where the land is above the DFL is unlikely and physically improbable. Inland from the breaking wave zone, the overtopping water propagates as low bores (turbulent walls of water) over land.

A schematic profile view of FCL zones (not to scale) is shown below and has been reproduced from the text in Figure 4-1 to illustrate the project approach to estimate the zone of wave breaking and runup on the shoreline and determine a lower inland FCL zone for a low area that could experience flooding from waves overtopping at the shoreline.



Tsunami Inundation Hazard

Tsunamis pose a risk anywhere near the shoreline as well as over water, whereas the overland tsunami hazard varies across the study area, depending on local topography in conjunction with exposure to incoming waves. Emergency managers, risk assessors, land use planners, and members of the public should consider this variability to help individuals understand personal and community risk. The Village of Masset and its jurisdiction are particularly susceptible to tsunami hazards due to the region's relatively low-lying topography in conjunction with its exposure to larger tsunami amplitudes. Located within Masset Inlet, the Village of Port Clements is relatively sheltered in comparison. Northern Tlell is also exposed to greater tsunami hazard due to its relatively lower topography, which is also is exacerbated by the proximity of the Tlell River, which can act as pathway for the inland propagation of tsunamis. The relatively steeper topography at the Village of Daajing Giids limits inland inundation and provides an opportunity for safe evacuation to elevated ground. The low-lying topography at the community of Sandspit exposes residents to large extents of inundation if the tsunami overflows the shoreline in Shingle Bay to the west, as well as along the northern and eastern shorelines of the spit. Additional descriptions of the hazards at each study area are provided in the associated community summary reports.

A summary of the general tsunami inundation levels and tsunami arrival times at each of the study areas is provided in the table below (reproduced from the text in Table 4-2). The inundation levels reported for emergency planning include a safety factor to account for the uncertainties that are inherent in the analysis and are representative of each general area. This general information should only be used for general planning, as a tsunami inundation level can vary over small distances due to changes in local topography. Additionally, reported inundation levels do not include any freeboard to define safe refuge elevation. The tsunami arrival time is defined as the time of arrival of the first maximum tsunami waves (Intergovernmental Oceanographic Commission, 2019), and flooding may begin before this moment is reached. Additional assessment of the modelling results is required to better understand the progression of the estimated inundation over time.

Area	Arrival Time[1]	Inundation Level for Emergency Planning[2] (CGVD2013)		
		Current-day (m)	1 m SLR (m)	2 m SLR (m)
Masset Airport	2h 32min	6.9	7.6	8.6
Tow Hill	2h 37min	7.2	8.5	9.4
Masset (Village Core)	2h 38min	4.3	6.0	7.1
Port Clements	3h 31min	2.8	3.7	4.9
Ferguson Bay	3h 36min	1.8	2.9	3.8
Juskatla	3h 52min	0.4	1.4	2.4
Tlell	3h 49min	5.7	6.7	7.6
Daajing Giids	3h 52min	6.1	7.3	8.7
Sandspit	3h 43min	6.9	8.0	7.8

Notes: h – hour; min – minute

1. Arrival time is defined as the time of the first maximum height of the first tsunami wave; flooding may begin before this moment is reached.

2. The inundation level for emergency planning includes a safety factor; freeboard is not included. The location where the inundation level was determined generally corresponds to the location of maximum wave runup. The inundation level varies spatially within an area.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

APPENDICES

Appendix A	Digital Elevation Model Development
Appendix B	Meteorological and Oceanographic Conditions
Appendix C	Storm Wave Modelling
Appendix D	Tsunami Modelling
Appendix E	Regional Overwater Tsunami Hazard Maps

ABBREVIATIONS

Acronym / Abbreviation	Definition
AR5	Intergovernmental Panel on Climate Change, fifth assessment report of 2014
AEP	annual exceedance probability
ASCE	American Society of Civil Engineers
BC	British Columbia
CD	chart datum
CGVD2013	Canadian geodetic vertical datum of 2013
CHS	Canadian Hydrographic Service
DEM	digital elevation model
DFL	designated flood level
EMBC	Emergency Management BC
FCL	flood construction level
FHA	flood hazard assessment
GIS	geographic information system
HHWLT	higher high-water, large tide
HHWMT	higher high-water, mean tide
LiDAR	light detection and ranging
metocean	meteorological and oceanographic
MLWRS	BC Ministry of Land, Water and Resource Stewardship
MHW	mean high water
MHHW	mean higher high water
NHC	Northwest Hydraulic Consultants Ltd.
NCRD	North Coast Regional District
NAD83	North American datum of 1983
NRCan	Natural Resources Canada
ONC	Ocean Networks Canada Society
RCP	representative concentration pathway
USA	United States of America

SYMBOLS AND UNITS OF MEASURE

Symbol / Unit of Measure	Definition
>	greater than
<	less than
km	kilometre
km^2	square kilometre

m	metre
mm	millimetre
Mw	earthquake moment magnitude
W/m^2	watts per square metre

GLOSSARY

Term	Definition
accretion	The accumulation of sediment, often referred to in relation to the process of expanding the lateral extent of a shoreline
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.
annual exceedance probability	The probability that a given event will be exceeded in any one year.
astronomical forcing	Influence that is driven by astronomical forces associated to the movement of celestial bodies.
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 counter-clockwise in the Southern Hemisphere as viewed from above (opposite to a cyclone).
atmospheric forcing	Influence that is driven by forces associated with atmospheric phenomena.
astronomical tide	The tidal levels and water motion which would result from Earth's rotation and gravitational effects of, in particular, the Earth, Sun and Moon, without any atmospheric influences.
bare earth	Consists of a representation of the earth’s surface, free of vegetation, buildings, and other structures.
bathymetry/bathymetric	The measurement of water depth in oceans, rivers, or lakes.
Boussinesq equation	In fluid dynamics, Boussinesq equations is a set of nonlinear, partial-differential equations that approximate the behaviour of water waves.
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’s 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.
combined method	A method for determining coastal flood construction levels (FCLs) by superimposing higher high-water, large tide (HHWLT), relative sea-level rise, storm surge, wave effects, and freeboard.
continental shelf	A continental shelf is a portion of a continent that is submerged under an area of relatively shallow water, known as a shelf.
crustal fault	A fracture or zone of relatively shallow fractures that separate different blocks of the earth’s crust where tectonic forces concentrate.
cyclone	A large air mass that rotates around a strong centre of low atmospheric pressure, counter-clockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere as viewed from above.

designated flood	"A [river] flood, which may occur in any given year, of such magnitude as to equal a flood having a 1:200 [0.5%] annual exceedance probability, based on a frequency analysis of unregulated historic flood records or by regional analysis where there is inadequate streamflow data available. Where the flow of a large watercourse is controlled by a major dam, the designated flood shall be set on a site-specific basis." (MWLAP, 2004)
designated flood level	"The observed or calculated elevation for the designated flood [or designated storm] and is used in the calculation of the flood construction level." (MWLAP, 2004)
designated storm	"A [coastal] storm, which may occur in any given year, of such a magnitude as to equal a storm having the designated annual exceedance probability (AEP). The designated storm has several phenomena associated with it that will define components of the designated flood level, including storm surge, wind setup, wave runup and overtopping for the storm." (BC Ministry of Environment, 2011). Analogous to a designated flood in a riverine environment.
dip-slip fault	A fault with an inclined plane that is dominated by vertical movements.
earthquake moment magnitude	Moment is a physical quantity proportional to the slip on the fault multiplied by the area of the fault surface that slips; it is related to the total energy released in the earthquake. The moment can be estimated from seismograms and from geodetic measurements. The moment is then converted into a number similar to other earthquake magnitudes using a standard formula. The result is called the moment magnitude, which provides an estimate of earthquake size that is valid over the complete range of magnitudes, a characteristic that was lacking in other magnitude scales. (USGS, n.d.)
empirical method	A research design method based on experimentation and drawing conclusions from verifiable evidence.
flood construction level	The minimum elevation needed for the underside of a wooden floor system or top of a concrete slab of habitable buildings to protect living spaces and areas used for storing goods that could be damaged by floodwaters rising above flood levels.
flood plain	"A lowland area, whether diked, flood proofed, or not which, by reasons of land elevation, is susceptible to flooding from an adjoining watercourse, ocean, lake or other body of water and for administration purposes is taken to be that area submerged by the designated flood [or designated storm] plus freeboard." (MWLAP, 2004)
flow eddy	An ocean swirl or circular current of water that has spun away from a main ocean current. An eddy can be induced by variations in the elevation of the ocean floor, a nearby coastline, or a structure present in the water.
foreshore	The part of a shoreline situated between high- and low-water marks, or the area between the water and developed land.
freeboard	A vertical distance added to the actual calculated flood level to accommodate for the underlying uncertainties in the analysis. The selection of such distance also considers the risks and implications associated to the water level exceeding the design elevation. A freeboard is added to the designated flood (or storm) level to establish the flood construction level.
fully probabilistic method	Method for determining coastal FCLs adopted in this study, which involves superimposing a high-water level with relative sea-level rise, wave effects, and freeboard, where the tide, storm surge, and wave effects have a combined designated AEP.

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; edges of wave crests break into spindrift; foam is blown in well-marked streaks along the direction of the wind.
global sea-level rise	An increase in the average height of the entire ocean surface.
habitable area	"Any room or space within a building or structure that is or can be used for human occupancy, commercial sales, or storage of goods, possessions or equipment (including furnaces) which would be subject to damage if flooded." (MWLAP, 2004)
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 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.
Holocene epoch	Epoch that follows the Last Glacial Period and is the current period in geologic time. It began 12,000 to 11,500 years ago at the close of the Pleistocene epoch and continues through today.
infrastructure trap	Infrastructure that is vulnerable to climate change and difficult to adapt can lead to escalating operational and maintenance costs for future generations.
joint probability	A statistical measure that calculates the likelihood of two events occurring together and at the same point in time.
LiDAR	A survey method to infer the elevation of the surface, which targets a surface using a laser from the air and measuring the time for the reflected light to return to a receiver on the airborne craft used for the survey.
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 high water	The average of all the high-water heights observed over a tidal epoch, as defined by the National Oceanic and Atmospheric Administration in the USA.
mean higher high water	The average of the higher high-water height of each tidal day observed over a tidal epoch, as defined by NOAA in the USA. Similar to the higher high-water mean tide level defined by the CHS in Canada.
metocean	The combination of meteorologic and oceanographic conditions including, but not limited to water level, wind, wave, current and atmospheric pressure and their influence in a specific location, often expressed statistically.
mixed semidiurnal tide	Tides characterized by a cycle with two high tides and two low tides each day and in which the high and low tides differ in height.
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.
ortho imagery	Aerial photographs or satellite image that have been geometrically corrected to produce a uniform scale, enabling the use of the image with a specified map projection. An ortho image can be used to measure true distances due to its an accurate representation of the earth's surface.

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.
phase-resolving wave model	A method of mathematically estimating the generation, propagation, and transformation of wind waves by not treating waves individually but instead computing the variation in wave energy spectrum across the area covered by the model resulting from multiple physical phenomena.
Pleistocene epoch	Epoch spanning the period from approximately 2,580,000 to 11,700 years ago and characterized by repeated glaciations of much of the earth. Glaciers The end of the Pleistocene epoch was marked by the beginning of glacial retreat, also marking the beginning of the Holocene epoch, which is the present epoch.
probabilistic method	A method for determining coastal flood construction levels, which involves superimposing a high-water level – comprised of both a high tide and a storm surge with an overall designated AEP established by probabilistic analysis – with relative sea-level rise, wave effects, and freeboard, where the wave effects have a designated AEP irrespective of the water level.
radiative forcing	The amount of solar energy that enters the earth's atmosphere in comparison to the amount of energy that leaves it.
refuge	"A refuge is an evacuation facility that is intended to serve as a safe haven until an imminent danger has passed". (FEMA, 2019). Sufficient for occupants to survive the danger itself, but not to survive extended periods of time without supplies, medical aid, and protection from the elements.
relative sea-level rise	The increase in the sea level relative to the elevation of the land at one location.
relic shoreline	Geological evidence that the interface between the terrestrial environment and the marine environment existed at a particular location in the past.
representative concentration pathway	A standard scenario used in climate modelling to simulate how the climate might change in response to different levels of human activity.
residual water level	The difference between the measured or observed water level and the predicted astronomical tide.
Ring of Fire	Also referred to as the Circum-Pacific Belt; a path around the Pacific Ocean characterized by active volcanoes and frequent earthquakes.
setback	"A withdrawal of a building or landfill from the natural boundary or other reference line to maintain a floodway and to allow for potential land erosion." (MWLAP, 2004)
shelter	"A shelter is an evacuation facility that is intended to provide safe, accessible, and secure short-term housing for disaster survivors, typically including a place to sleep along with extended food and water supplies." (FEMA, 2019)
still water level	The level of the water surface in the absence 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.
strike-slip fault	A fault at which the plane of rupture is mostly vertical and dominated by lateral (horizontal) movements.
subduction zone	The place where two of earth's tectonic plates collide, with one plate sinking into the earth's mantle underneath the other plate.
subsidence	Downward vertical movement of the Earth's surface, which can be caused by both natural processes and human activities.

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.
thrust fault	A dip-slip fault at which the vertical movement results from the upper plate, or block moving up and over the lower block.
tidal epoch	A 19-year period established for collecting information on water levels and calculating tidal datum values.
tidal heights	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 lowest low tide at one location.
time-resolving wave model	A method of mathematically estimating the propagation and transformation of waves by computing the change in water surface elevation over time at any location within the area covered by the model.
topography/topographic	The study of the forms and features of land surfaces, which provides measurements of the land elevation.
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.
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.
tsunami arrival time	“The time of the first maximum of the tsunami waves.” (Intergovernmental Oceanographic Commission, 2019). Flooding may begin before this moment is reached.
tsunami drawdown	“Drawdown of sea level prior to tsunami flooding. The shoreline moves seaward, sometimes by a kilometre or more, exposing the sea bottom, rocks, and fish. The recession of the sea is a natural warning sign that a tsunami is approaching.” (Intergovernmental Oceanographic Commission, 2019). Tsunami drawdown is a function of physical processes related to the generation and propagation of a tsunami and may not occur before the arrival of the first tsunami wave.
tsunami inundation depth	“The depth, or height of a tsunami above the ground at a specific location...” (Intergovernmental Oceanographic Commission, 2019)
tsunami runup	“Elevation reached by seawater measured relative to some stated datum such as mean sea level, mean low water, sea level at the time of the tsunami attack, etc., and measured ideally at a point that is a local maximum of the horizontal inundation.”(Intergovernmental Oceanographic Commission, 2019)
tsunami wave amplitude	“…the absolute value of the difference between a particular peak or trough of the tsunami and the undisturbed sea level…” (Intergovernmental Oceanographic Commission, 2019)
tsunami wave velocity	The celerity or speed at which a waveform propagates across a water body. Wave velocity is not related the to how fast the water itself moves.
uplift	Upward vertical movement of the Earth’s surface, which can be caused by both natural processes and human activities.

wave breaking	When sea-surface waves become so steep that their crests outrace the body of the waves, and the waves collapse turbulently near shore or over a reef.
wave diffraction	The sudden changes in energy and direction as waves encounter an obstacle or opening. Waves bend around the corners of obstacles or past openings, blocking a portion of the waves' incoming energy and spreading the remaining energy into the sheltered area behind the obstruction.
wave effects	The increase in elevation reached by the water above the level of the ocean in the absence of waves (i.e., the still water level) as a direct result of waves. These effects may occur at the shoreline; include wave runup, wave overtopping, and wave setup; and depend on the geometry of the shoreline and foreshore in conjunction with the wave characteristics.
wave frequency dispersion	How waves of varying lengths travel at different speeds and how they interact when they pass each other.
wave energy spectrum	Distribution of energy present at different frequencies within a series of waves.
wave height	Vertical distance between the crest and the trough of a wave.
wavelength	The distance between two identical points on successive waves, e.g., from crest to crest or trough to trough.
wave overtopping	The amount of water that flows over the crest of a coastal structure, such as a dike, seawall, or breakwater due to wave action. Part of each wave is reflected and part passes over the structure; the part that passes over the structure is referred to as overtopping.
wave period	The time it takes for two successive crests or one wavelength to pass a specified location.
wave refraction	When a wave moving in shallow water approaches the shore at an angle, it changes direction. The shallowest part of the wave moves more slowly than the part in deeper water, causing the wave crests to bend toward the shoreline in a parallel alignment.
wave runup	The maximum onshore elevation reached by waves relative to the still water level or a specified vertical datum.
wave setup	The increase in the mean water level in a shoreward area due to the influx of breaking waves against the beach.
wave shoaling	Occurs when surface waves enter shallower water, causing an increase in wave height and a change in the wave's behaviour.
wave transformation	The change that waves undergo as they propagate into shallow water and interact with the coastline; includes wave shoaling, wave breaking, wave refraction, and wave diffraction.
wave train	A group of waves of equal or similar wavelengths travelling in the same direction.
wind rose	Diagram used to show wind magnitude, direction, and frequency. Each stem 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 bodies of 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 potential flooding and erosion from ocean processes. Each community is increasingly vulnerable to rising sea levels, as evidenced 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 to reach 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 (ONC) have been engaged to provide professional engineering, geoscience, and oceanographic consulting services for five communities on 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 (NCRD), 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 NCRD.

1.1 Study Objectives

The main objective of this study is to quantify the flooding hazards of two independent natural phenomena occurring in the future when sea levels are higher:

i. a large windstorm generating large waves

ii. a tsunami arising from an earthquake along the Alaska-Aleutian or Cascadia subduction zones

The susceptibility of shorelines to erosion has been determined within each study area to inform and support future detailed planning efforts within the study areas. The information generated as part of this project includes maps defining **flood construction levels** (FCLs) to support development, as well as tsunami inundation maps for emergency planning. By prescribing the minimum elevation for the underside of a wooden floor system or top of concrete slab for **habitable areas** in buildings, FCLs are

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

used to protect living spaces and areas used for the storage of goods damageable by floodwaters by elevating them above flood levels (MWLAP, 2004).

This study is not intended to form a complete assessment of the risks associated with the hazards identified. Furthermore, this study on its own does not constitute a site-specific flood hazard assessment (FHA) in accordance with applicable provincial and professional legislation and guidelines(EGBC, 2018). Any site-specific FHA with exposure to coastal flood hazards should be completed by suitably qualified professional engineers who are experienced in coastal engineering (BCMFLNRD, 2018).

Technical findings have been communicated to the municipal authorities and residents of Haida Gwaii during public information meetings. Using accessible language in reporting and visual aids such as coastal hazard maps, this study is intended to provide a basis for planning resilient communities in the future.

1.2 Study Areas

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

- 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

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.

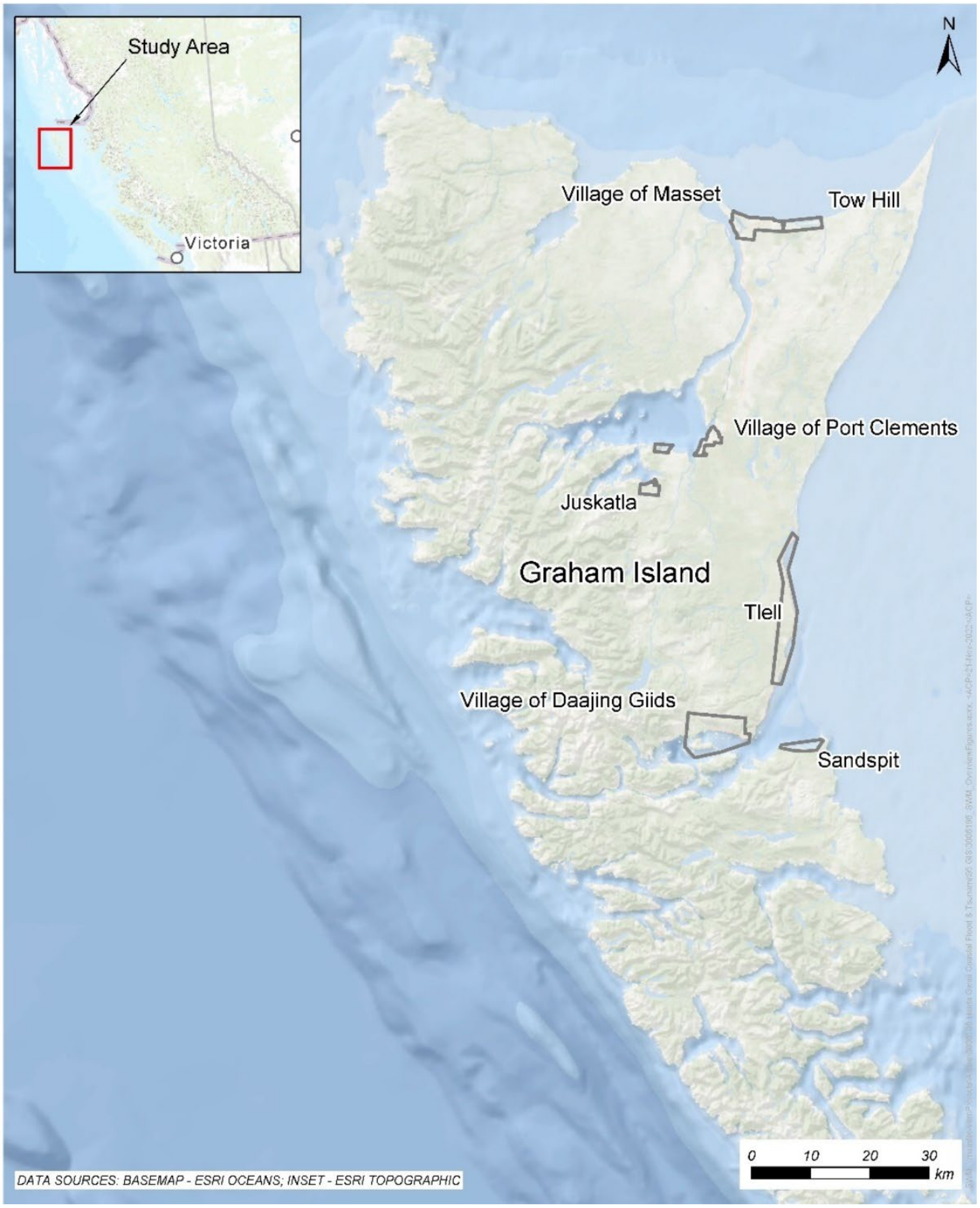

Figure 1-1. Areas of Haida Gwaii included in this project, shown with a red perimeter.

1.3 Planning Horizon

Sea levels around the world have been rising and are projected to continue to rise because of climate change and its associated increase in average temperatures. **Global sea-level rise** is caused by melting glaciers, ice caps, and ice sheets, but increased ocean volume is also due to thermal expansion from higher water temperatures. Oceans will continue to gradually rise in the future, giving communities time to embark on planning activities that can be phased in over time to minimize the upfront capital costs required to adapt coastal areas and protect critical infrastructure. Scientists have collected data and used modelling to estimate future sea levels, but the rate of continued sea-level rise is subject to considerable uncertainty. This section presents a discussion of the existing projections and provides the sea level estimates used for this analysis.

Figure 1-2 shows projections of global sea-level rise over the twenty-first century, as published by the Government of Canada (Greenan et al., 2018). The projections are relative to a baseline of 1986 to 2005 and are based on both optimistic and pessimistic greenhouse gas emission scenarios established in the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2014). Such hypothetical scenarios, also referred to as **representative concentration pathways** (RCPs), consist of RCP 2.6 and RCP 8.5, which are associated with **radiative forcings** of 2.6 and 8.5 watts per square metre (W/m^2), respectively.[2] The lines in Figure 1-2 indicate the median projection, and the shading shows the range of uncertainty (from the fifth to the ninety-fifth **percentile**). Also shown with a green triangle is an augmented or enhanced scenario for the year 2100, which is associated with greater amounts of ice melting from Antarctica.

The BC provincial Flood Hazard Area Land Use Management Guidelines (BCMFLNRD, 2018) recommend that projects consider 1.0 metre (m) of global sea-level rise above year 2000 levels for year 2100 and 2.0 m for year 2200. Such a recommendation, which effectively translates into a constant increase rate of 10 millimetres (mm) per year, generally exceeds sea-level rise projections during the twenty-first century but would under-estimate projections during the twenty-second century. Nevertheless, if the Antarctica ice sheet melts faster, then the provincial recommendation would under-estimate sea-level rise during both the twenty-first and the twenty-second centuries.

Given the uncertainty in sea-level rise projections, in conjunction with the considerable challenges that would stem from higher sea levels than planned, this study considers specific sea levels irrespective of when they will occur. More specifically, this study is based on 1 m and 2 m of **relative sea-level rise**.[3] In comparison to global average sea-level rise, relative sea-level rise observed in one location also depends on long-term vertical movements of the earth's surface, such as **uplift** (upward motion) or **subsidence** (downward motion). Such vertical movement can result from a variety of geological processes, such as post-glacial rebound and the movement of tectonic plates. Effectively, uplift will locally delay relative sea-level rise, while subsidence will accelerate it.

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[2] Radiative forcing relates to the amount of solar energy that enters the earth's atmosphere in comparison to the amount of energy that leaves it.

[3] Relative sea level rise is the increase in sea level relative to the elevation of the land at one location.

Since it is known that 1.0 m of relative sea-level rise will be reached at one point or another, and potentially before 2100, NHC recommends that planning and development consider this level from now on, rather than an interim level combined with a specific time horizon. Also, plans should be adaptable so that they can be revised for 2 m of relative sea-level rise when effects of higher sea levels become more noticeable.

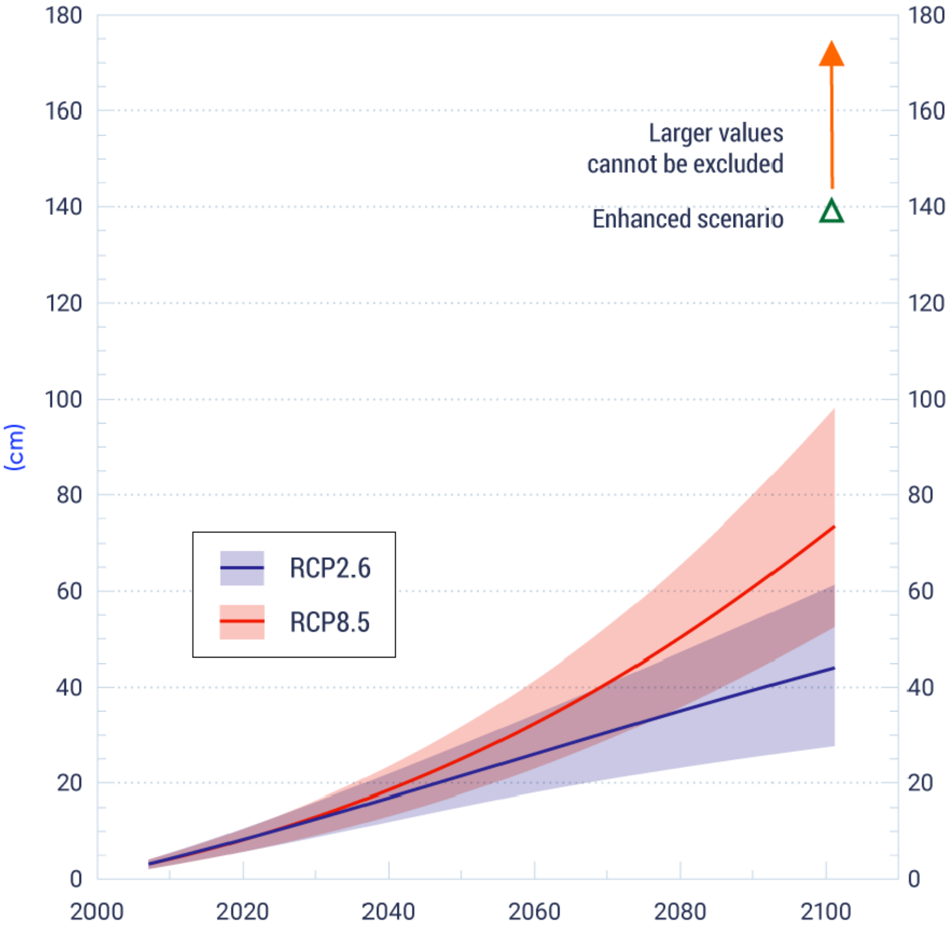

Figure 1-2. Projected global sea-level rise.
Image adapted from Greenan et al., 2018

In 2021 the IPCC released the sixth assessment reports of working group one. These reports included the assessment reports on climate science, of which chapter 9 covered updates on sea level rise. One change is that the IPCC moved away from RCP scenarios to Shared Socio-economic Pathway (SSP) scenarios to evaluate future climate change. The SSPs were developed to describe “five broad narratives of future socio-economic development” which are then used to develop scenarios of energy use, air pollution controls, land use and greenhouse gas emissions, and such on a global scale (IPCC, 2021). Of note:

- SSP1-2.6 stays below 2°C warming with implied net-zero emissions in the second half of the century.
- SSP2-4.5 is approximately in line with the upper end of the combined pledges under the Paris Agreement, resulting in a best-estimate of warming around 2.7°C by year 2100.
- SSP5-8.5 is a high reference scenario similar to a ‘business as usual’ case in which climate pledges are not kept and no additional climate policy is adopted.

Figure 1-3 shows the projected global mean sea level (GMSL) rise estimated for the different scenarios in the latest IPCC report. The BC guidance of planning for 1 m of SLR in year 2100 remains a reasonable but conservative estimate as this is at the upper end of the medium confidence range of scenarios. However, it is worth noting that there remains a high degree of uncertainty on future pathways and response of ice-sheets and glaciers to warming trends. As such, there are lower confidence (less likely to occur) estimates in which positive feedback loops accelerate ice mass loss from Greenland and Antarctica, leading to accelerated rates of sea level rise in the later half of the century and greater than 1 m of SLR occurs. The take-away from the latest IPCC update is that SLR of 1 m is likely to occur between year 2100 and 2200 under a range of future emission scenarios, while 2 m of SLR after year 2100 can not be ruled out as a possibility although it is less likely to occur until 2150 or later.

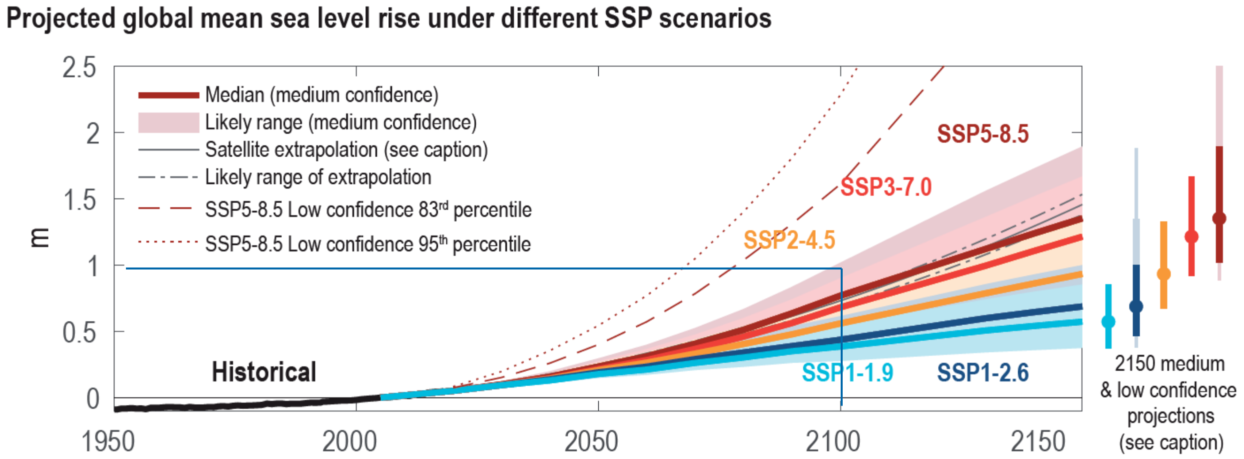

Figure 1-3. Projected global sea-level rise (IPCC WGI, 2021, Chapter 9). This figure shows projected global mean sea level rise under different SSP scenarios. Likely global mean sea level (GMSL) change for SSP scenarios resulting from processes in whose projection there is medium confidence. Black lines show historical measured GMSL change, and thick solid and dash-dot black lines show the mean and likely range extrapolating the 1993-2018 satellite trend. Projections and likely ranges at year 2150 are shown on right. Lightly shaded ranges and thinner lightly shaded lines on the right show the 17th-83rd and 5-95th percentile ranges for projections including low confidence processes for SSP1-2.6 and SSP5-8.5.

1.4 Referenced Guidelines

Following is a list of the provincial and professional guidelines that NHC reviewed and considered in our assessment of possible flood hazards incident to the areas under study:

- Professional Practice Guidelines – Legislated Flood Assessments in a Changing Climate in BC (EGBC, 2018)
- Flood Hazard Area Land Use Management Guidelines – Sea level rise amendment (BCMFLNRD, 2018)
- Climate Change Adaptation Guidelines for Sea Dikes and Coastal Flood Hazard Land Use – Guidelines for Management of Coastal Flood Hazard Land Use (BC Ministry of Environment, 2011)
- Coastal Floodplain Mapping – Guidelines and Specifications (MFLNRO, 2011)
- Flood Hazard Area Land Use Management Guidelines (MWLAP, 2004).

1.5 Report Structure

Serving as the main report for the project, this document describes the main steps of the methodology and approach followed (Section 2), provides background on the physical setting of Haida Gwaii and on the meteorological and oceanographic conditions that affects its shorelines (Section 3), and summarizes assessment results (Section 4). Section 5 presents a discussion of the general strategies for adaptation to sea-level rise, as well as potential solutions for managing the hazards identified during the study. This main report also includes a series of appendices that present the technical details of the study. Also provided as an appendix to this report are the regional overwater tsunami hazard maps produced as part of the project.

While this main report provides general information pertaining to the broader study area, findings specific to each community are summarized in a series of brief companion reports. Local maps of costal storm flood, erosion susceptibility, and tsunami hazards are provided as appendices to each community report.

A report was not produced for the community of Tow Hill as the scope of this project only included tsunami inundation mapping for that area.

A flow chart summarizing the project’s reporting structure is provided in Figure 1-4.

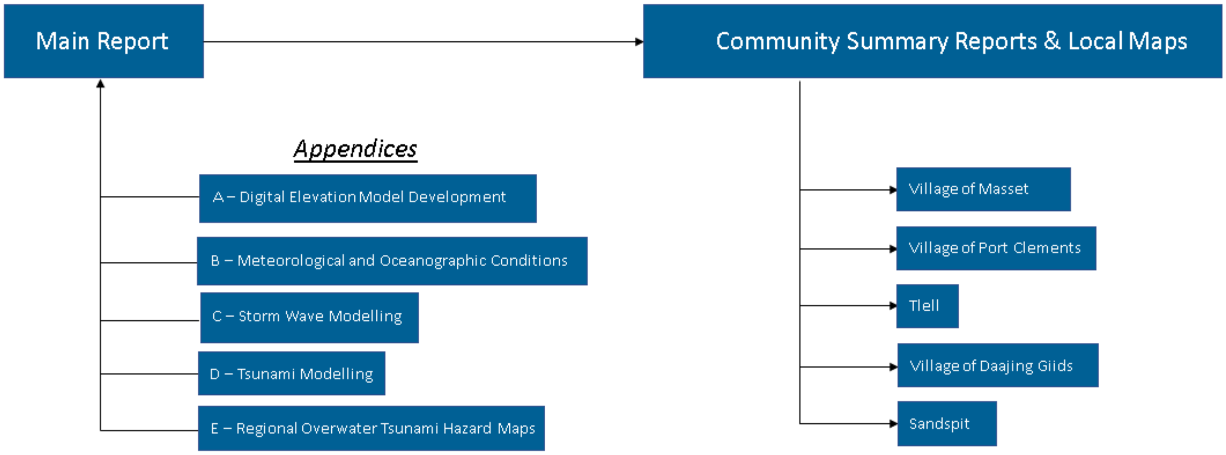

Figure 1-4. Project reporting structure.

1.6 Project Team

This project is the result of a collaboration between many individuals of various backgrounds, including coastal engineers, geomorphologists, tsunami scientists, and geographic information system (GIS) specialists. While NHC and ONC are the main firms undertaking the analysis, NCRD personnel and municipal officials also made valuable contributions to this project.

Following are brief background descriptions of NHC and ONC, including their respective responsibilities on this project.

Northwest Hydraulic Consultants Ltd.

NHC is a private Canadian firm, incorporated in 1972 and wholly owned by its managing principals. NHC's engineers and geoscientists are focused on and passionate about water-related projects, and the firm has become renowned as a world leader in flood hazard assessments and risk reduction initiatives. NHC brings extensive local and provincial experience, as well as in-depth experience supporting a variety of international projects. As the prime consultant on this project, NHC assessed coastal storm flood hazards and erosion susceptibility, performed engineering reviews of the modelling work conducted by ONC, produced the maps, and presented the results to the public.

Ocean Network Canada Society

Established as part of an initiative of the University of Victoria, ONC monitors the Pacific, Atlantic, and Arctic coasts of Canada to deliver continuous, real-time data for scientific research, which helps communities, governments, and businesses make informed decisions for the future. On this assignment ONC developed the project's digital elevation models (DEMs) used for tsunami modelling, reviewed the tsunami sources that are potentially affecting Haida Gwaii, and conducted the tsunami model simulations.

1.7 Glossary of Terms

A glossary of terms, which are specialized to the coastal processes area of practice, but essential to preserve accuracy in description, is provided at the front of this report. The terms included in the glossary are set in bold when they first appear in the text.

2 METHODOLOGY AND APPROACH

The focus of this project is on identifying, characterizing, and better understanding the coastal hazards affecting communities on Haida Gwaii and how such hazards will worsen as sea levels rise. The findings described in this report are intended to inform local governments as they develop and implement land use management plans and embark on emergency planning.

This section describes the data, methods, and analytical approach used to conduct this study and provides an overview of the mapping approach used to communicate hazard information. In addition, this section describes the limitations of the analysis, which should be considered when interpreting study findings and acting on study recommendations.

2.1 Pillars of Analysis

The analysis undertaken for this project combines three pillars to provide a sound and robust foundation for this study. This project has been informed by new and historic data collected from the study areas, numerical modelling developed to help characterize and interpret hazardous conditions at the study areas, and interpretive geomorphology to explain the significance of the data analysis and modelling results and assess the susceptibility of shorelines to erosion.

2.1.1 Data Collection

The data required to support this study were collected both in the field by the project team and via governmental agencies. Data for this study originated from the following sources:

- Field observations of shoreline conditions
- **Topographic** information describing the elevation of the ground
- **Bathymetric** information describing the elevation of the seabed
- Tsunami sources describing the earthquake-induced vertical motion of the seabed, which displaces water and in turn generates tsunamis
- Wind, wave, and water level information to describe the meteorological and oceanographic (**metocean**) conditions affecting the shorelines of Haida Gwaii

Derek Ray, PGeo, and Logan Ashall, coastal specialist, both from NHC, visited the project study areas in May 2021 to survey each area and observe the shoreline. The survey data collected during the visit was then used to ground truth the digital topographic datasets that would later be used for numerical modelling. NHC's visual observations informed the subsequent interpretation of the geomorphological processes shaping the shorelines of the study areas. Detailed observations and results of the site visit are presented in the individual companion reports specific to each of the study areas.

NHC acquired topographic **LiDAR** datasets from GeoBC[4] and the BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development[5] to define ground elevation. The team acquired several bathymetric datasets from the Canadian Hydrographic Service (CHS) to define the elevation of the seabed as well as the ground above water in areas where topographic LiDAR data were not available. Datasets provided by the CHS include bathymetric LiDAR, which involves a technology that penetrates the water surface to measure the elevation of the intertidal areas and the seabed (down to a certain depth), as well as the elevation of upland areas. However, this dataset needed to be processed to represent **bare earth**, which represents the earth's bare surface, free of vegetation, buildings, and other structures.

The team assembled the elevation data collected into a series of DEMs to obtain a digital representation of the earth's surface both above water **(topography)** and below the water surface (**bathymetry**). The team used these DEMs as the basis when conducting numerical modelling of waves (both wind waves and tsunamis), and when mapping inundation extents. Details regarding the data sources and methodology used to develop the DEMs for wave modelling are provided in Appendix A, while details regarding the DEMs used for inundation mapping are provided in Section 2.3.

2.1.2 Numerical Modelling

For this study, the hazards related to coastal storms and tsunamis are defined using computer simulations, or numerical modelling. These computer simulations are needed to estimate the complex and nonlinear behaviour of waves as they propagate toward the coast and interact with the geographical and topographical features of the coastline. Waves generated by the wind during storms and tsunamis exhibit fundamentally different characteristics and behaviour, so the team used two types of modelling analyses to help characterize their different features and effects, as further described below.

2.1.2.1 Wind Waves

Winds blowing over water generate waves by transferring energy to the water surface through friction. When wind combines with high sea levels, wind waves result, potentially advancing further up the shoreline and inducing flooding. Additional force is also act on structures in coastal areas from increased wave action and collisions with floating debris.

An important step in estimating **wave effects** at the shoreline is to define offshore metocean conditions. Factors that influence the assessment of wave effects in the study area include the winds blowing over the water bodies connected to Haida Gwaii, the wind-generated waves propagating through these water bodies, and coinciding water levels. Details of the offshore metocean analysis performed as part of this

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[4] GeoBC is a provincial government agency that creates and manages geospatial information and products to help better manage natural resources in BC.

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

study are provided in Appendix B. The methods for analyzing wave conditions approaching the shoreline and wave effects are discussed below.

Incident Wave Conditions

Described as waves moving toward the shore, incident waves may cause wave effects and potentially result in erosion. Estimates are needed to understand how offshore waves propagate toward the shore. The study team used the SWAN numerical model to simulate the action of waves near shore (Booij et al., 2004). A **phase-resolving** wave model, SWAN (version 41.31) computes the generation and propagation of waves in coastal regions and enclosed bodies of water such as Masset Inlet. The model accounts for the physical processes associated with waves such as wave generation and propagation, interactions between waves, **wave transformation**, and wave dissipation due to white-capping, **wave breaking**, and bottom friction.

NHC followed a nested approach when conducting numerical wave modelling. Results from a broader and coarser modelling grid were considered as boundary conditions and passed into successively smaller grids with higher resolution that were embedded into the broader grid. This type of nested approach focuses the analysis to areas of interest and reduces computation time. Figure 2-1 shows the extents and spatial resolution of the modelling grids employed to simulate wind waves that propagate toward Haida Gwaii shorelines. Inputs required for this type of modelling include wind conditions over water, **swell** conditions coming from the open ocean, and a digital representation of the seabed.

Additional details of the numerical modelling of incident waves are provided in Appendix C.

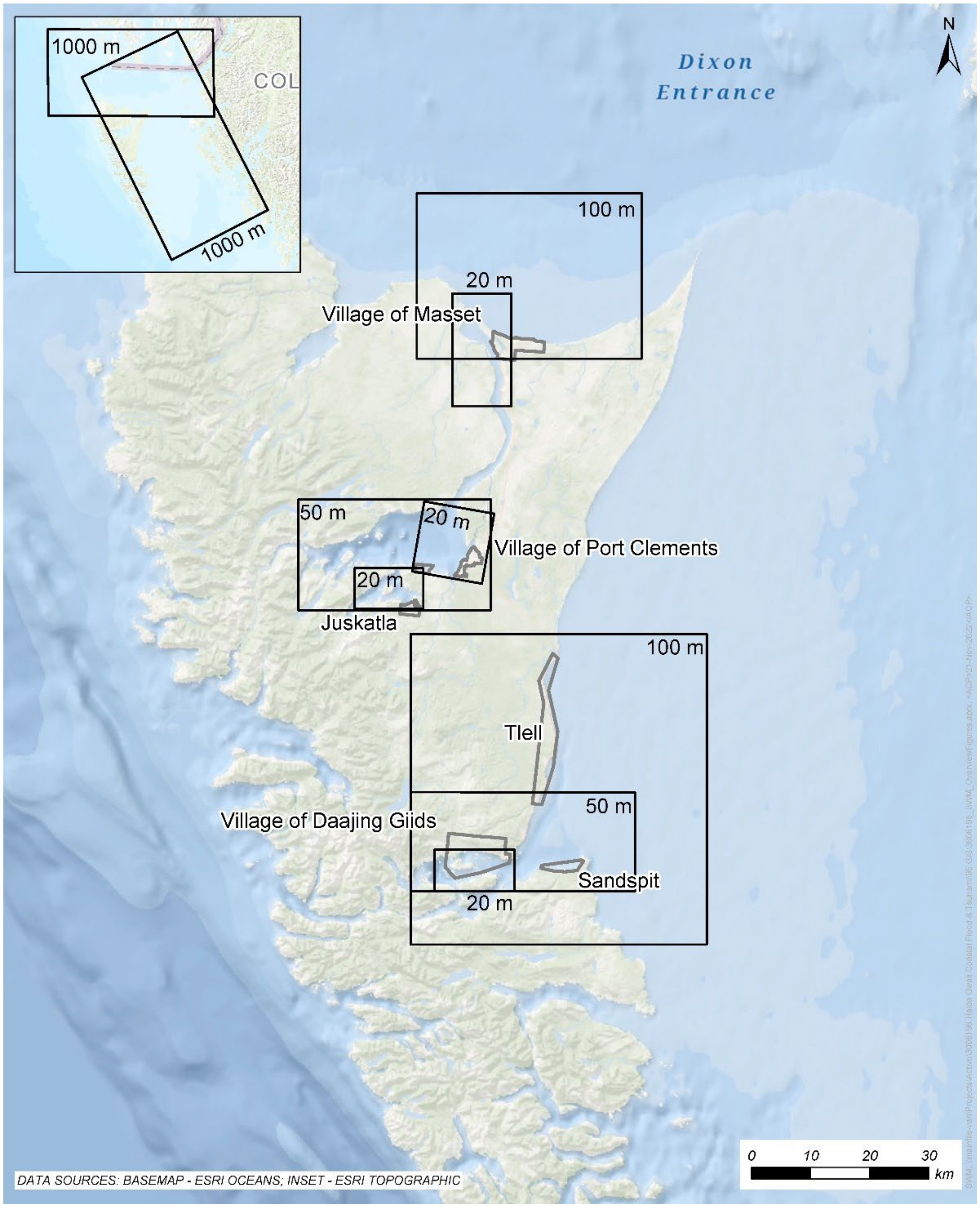

Figure 2-1. Extents of modelling grids employed to simulate wind waves approaching Haida Gwaii shorelines. Labels show the spatial resolution of the grids, and the insert at the top left of the figure shows the broader grids considered for Dixon Entrance and Hecate Strait.

Wave Effects

NHC used both empirical and numerical approaches to estimate wave effects induced by coastal storms along the Haida Gwaii shorelines. **Wave runup** was estimated using the **empirical methodology** presented in the EurOtop (2018) manual, which provides technical guidance for designing and assessing coastal structures. Specific methodological approaches depend on the geometry of the shoreline and on any coastal protection structures present.

Due to the highly variable nature of wave effects, empirical methods are not accurate tools for estimate wave runup in all circumstances; for this project, numerical simulations were utilized to check the empirical estimates for areas with shoreline geometries that did not confirm to the uniform slope assumptions, or areas with low crest elevations and structures. The study team simulated wave runup onshore using the SWASH (version 5.01) **time-resolving wave model** (Zijlema et al., 2011).

Inputs required for estimating wave effects include incident wave conditions, as well as a representation of the shoreline geometry and its roughness characteristics. Additional details on the estimation of wave effects are provided in Appendix C.

2.1.2.2 Tsunamis

Translated from Japanese as a wave (*nami*) in a harbour (*tsu*), a tsunami is a series of travelling waves of extremely long **wavelength** (hundreds of kilometres) and **wave period** (up to one hour). A tsunami is also referred to as a seismic sea wave, but it is different from a tidal wave, which is formed by the gravitational forces between celestial bodies (i.e., **astronomical tides**). A tsunami is usually generated by earthquakes occurring below or near the ocean floor. Tsunamis can also propagate from the sudden displacement of water induced by subaerial and submarine landslides, volcanic eruptions, and meteor impacts, although hazards associated with tsunamis triggered by mechanisms other than earthquakes are beyond the scope of this assignment.

The team also followed a nested approach when conducting tsunami modelling, passing the results from a broader and coarser modelling grid as boundary conditions to successively smaller grids with higher resolution and embedded into the broader grid. The geographical extent of the computational grids over which tsunami results were computed for this study are shown in Figure 2-2. A coarser resolution of 160 m was used over Haida Gwaii, and a resolution of 40 m was used over the most part of Graham Island, while a higher resolution of 10 m was used in regions where study areas are located.

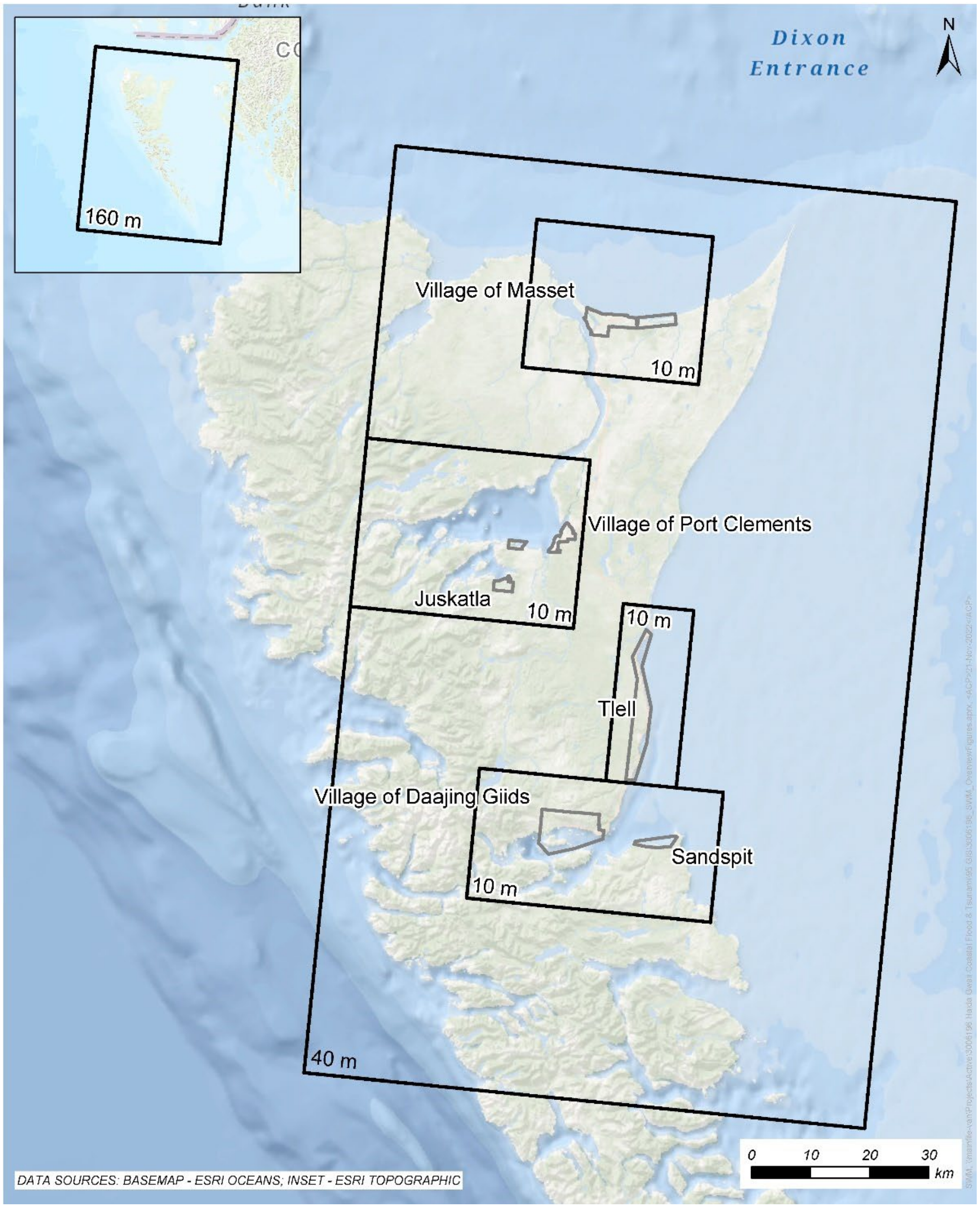

Figure 2-2. Extents of modelling grids employed to simulate tsunami propagation and inundation. Labels show the spatial resolution of the grids, and the insert at the top left of the figure shows the broader grid considered for Haida Gwaii.

In general, inputs required for tsunami modelling include a series of DEMs, as well as a definition of the seafloor displacement resulting from an earthquake (i.e., a tsunami source). The tsunami scenarios considered for this study are discussed in Section 3.4, which also includes a regional summary of the model results. ONC performed tsunami simulations using version 3.4 of the fully nonlinear **Boussinesq**-based wave computer model FUNWAVE, developed at and maintained by the University of Delaware

(Shi et al., 2016). The model, which solves governing equations for propagating long waves, has been benchmarked against other tsunami models as part of the United States (US) National Tsunami Hazard Mitigation Program to confirm its strength and accuracy (Horrillo et al., 2014). As a Boussinesq model, FUNWAVE accounts for **wave frequency dispersion**, which is important when simulating the propagation of tsunamis over long distances.

Additional details on ONC's tsunami modelling work to support this study are provided in Appendix D.

Effects of tsunamis in coastal areas can last several hours and even days after the associated earthquake. Information computed by the tsunami model includes the changes in the elevation of the water surface across the modelled areas, as well as the current velocities induced by these relatively rapid changes, averaged over the depth of water. From this information the maximum **tsunami wave amplitude** is derived as well as the maximum tsunami-induced current velocities that may occur at any moment during the event. Tsunami-induced currents can be superimposed to tidal currents, which were not included in the numerical model and should not be confused with **tsunami wave velocity**, which relates to how fast tsunami waves propagate across the water surface, and not how fast the water itself moves.

Tsunami wave amplitude is defined as the vertical distance between the crest of a tsunami wave and a reference plane consisting of the **still water level** (e.g., water level without the influence of the tsunami). Tsunami amplitude should not be confused with tsunami **wave height**, which consists of the vertical distance between the crest and the trough of a tsunami wave.

Other parameters not directly reported herein but that can be obtained from the model results include **tsunami runup** and **tsunami inundation depth**. Tsunami runup is defined as the highest elevation upland reached by a tsunami with respect to a reference plane (i.e., vertical datum), and inundation depth is defined as the depth of water above ground at a specific location.

2.1.3 Interpretive Geomorphology

Geomorphology considers the physical landscape features in the context of past and contemporary processes that created the form and maintain it in its present shape. Processes to be considered include relative sea level changes, wind-generated waves, storm surge, freshwater runoff, hillslope processes, past glacial processes, and geologic processes such as tectonics. As such, the landscape is considered a dynamic feature that changes in response to both short- and long-term forcings. For instance, features formed during the most recent glacial period are readily evident in the landscape, and the landscape continues to evolve in response to glacial melting, even though Haida Gwaii has been ice free for approximately 10,000 to 15,000 years. In contrast, short-term changes occur in response to individual storm events, which can be viewed as part of the long-term processes but must be assessed carefully to avoid over-estimating the magnitude and rate of change when scaling up to longer time periods.

The approach to interpreting geomorphic features and processes for this study relies on a combination of field-based observations and measurements, landscape interpretation from aerial imagery and LiDAR, and previous studies, including those published in scientific literature. Shorelines within each of the areas included in this study (see Figure 1-1) were inspected on foot to provide an overview survey of the dominant coastal processes as well as more detailed inspections focusing on key shoreline segments where erosion has been of recent concern. Observations were recorded in the form of written notes and geotagged field photographs.

2.2 Approach to Analysis

The findings from data collection, numerical modelling, and interpretative geomorphology were interpreted holistically to arrive at the conclusions of this study. This combined approach strengthens outcomes and reinforces a community's ability to adapt and manage risk over the long term.

A building block in this assessment of flood hazards from coastal storms is examining the probability of multiple oceanographic parameters occurring simultaneously, referred to as **joint probability**. In a coastal environment, water level and wave height are both factors in how a coastline can be damaged. The extent of damage may vary, depending on the combinations of these two parameters. For example, a smaller wave height combined with a higher water level may be more hazardous than a larger wave height combined with a lower water level, or vice versa, depending on local **foreshore** and backshore characteristics. For this reason, NHC assessed various combinations of water level and wave height with an equal joint **annual exceedance probability** (AEP) to identify the most adverse conditions at a particular shoreline.

This section provides an overview of the existing guidelines for mapping coastal storm flood and tsunami inundation hazards, as well as how these guidelines relate to the approach followed for this study.

2.2.1 Coastal Storm Flood Hazard

The BC Ministry of Land, Water, and Resource Stewardship (MLWRS)[6] presents two methods for determining coastal storm FCLs (BCMFLNRD, 2018): the **combined method** and the **probabilistic method**. The combined method involves superimposing a **higher high-water large tide** (HHWLT) with relative sea-level rise, **storm surge**, wave effects, and **freeboard** and applying an AEP of 0.5%[7] (1:200) for the storm surge magnitude and wave effects individually. This method is considered conservative as it assumes that the peak of a storm coincides with high tide and does not consider the probability that the peak of a storm may occur at a lower tide. The probabilistic method involves superimposing a high-water level – comprised of both a high tide and a storm surge with an overall AEP of 0.5% established by probabilistic analysis – with relative sea-level rise, wave effects, and freeboard, where the wave effects have an AEP of 0.5% irrespective of the water level.

For both methods, the event inducing the wave effects for a designated AEP is referred to as the **designated storm** and is established in a similar way. Within the context of managing flood hazards with land use, this coastal event is analogous to a **designated flood** in a river environment. First, a **designated flood level** (DFL) is established, which is the observed or calculated water surface elevation for the

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[6] This ministry was created in April 2022 along the Ministry of Forests following the dissolution of Ministry of Forests, Lands, Natural Resource Operations and Development.

[7] While a 0.5% AEP is the minimum provincial standard, local governments may decide to adopt more stringent criteria for heavily populated and built-up areas (BCMFLNRD, 2018).

designated storm and is used to determine the FCL (MWLAP, 2004). The DFL for both methods includes combining tide and storm surge with an allowance for sea-level rise.

In an environment governed by fluvial (river) processes, a **flood plain** is established in an environment by incorporating both the (designated) flood profile plus the freeboard allowance onto the base maps, which then enables the production of finished flood plain maps (MWLAP, 2004). In a coastal environment, the flood plain is delineated by intersecting the FCL with ground topography, as reported by the Ministry of Forests, Lands and Natural Resource operations (2011).

Study Approach

The methodology adopted to determine the FCLs for this study expands on the probabilistic method presented above. In addition to capturing the probability of the storm surge to occur with the high tide to form the DFL, the methodology used for this study accounts for the probability of the wave effects coinciding with such DFL. The resulting combinations of tide, storm surge, and wave effects are established by conducting a full joint probability analysis and have an overall combined AEP of 0.5%. This method is referred to hereafter as the **fully probabilistic method** and requires investigation of which combination of equal probability would induce the most adverse conditions for a particular shoreline.

In relatively steep areas, defining the coastal flood plain by determining the intersection of the FCL with ground topography is appropriate; however, in flat areas, applying this approach may lead to overly conservative flooding scenarios, as overland wave effects are expected to dissipate with the distance away from the shoreline and have a reduced influence on the inundation level. For the purposes of this study, the flood plain is separated into two zones:

1. The zone with wave effects present and included in the FCL
2. The zone with wave effects that would have dissipated and are thus not included in the FCL.

For the second zone, the FCL is based on a DFL with a tide and storm surge combination with an overall AEP of 0.5%, irrespective of wave conditions, as well as added freeboard.

Details of the analysis performed to determine the FCLs for the study areas are presented in Appendix C. Due to the lack of long-term wind and water level data in Masset Inlet, it was not possible to apply the fully probabilistic method to this region of the project area; instead, the combined method was considered for determining the FCLs within the jurisdiction of Port Clements.

2.2.2 Tsunami Inundation Hazard

Following the arrival of the first wave, the flooding caused by a tsunami will consist of rapidly increasing water levels as the tsunami propagates inland, as well as rapidly decreasing water levels as the tsunami recedes. These rapid changes in the water level will create strong and extremely dangerous moving waters and will undergo cycles, since a tsunami event generally consists of several waves. These effects can last several hours and even days after the earthquake, and the time between successive tsunami waves is generally in the order of one hour but can also be shorter.

For a person caught in a tsunami flow the chance of survival is low, mainly due to the strong flow momentum and the floating debris that is often carried in the water during such event. The damage caused to buildings and infrastructure depends on tsunami flow characteristics in conjunction with structural considerations. The 2011 Tohoku tsunami in Japan brought to light the potential for such events to cause severe damage to engineered buildings and endanger human life (Earthquake Engineering Research Institute, 2011). Bridges and roads can be affected by extreme forces induced by tsunami flow as well as impacts with floating debris such boats, cars, building debris, etc. Other effects include scour of piers, abutments, and foundations as well as the wash-out of asphalted surfaces. Marine infrastructure is particularly exposed to damage from tsunamis due to the proximity to the water's edge and the exposure to the full force of the tsunami.

The BC MLWRS (MFLNRO, 2011) states that where the tsunami hazard level exceeds the coastal storm hazard level, the tsunami elevation governs the FCL. In areas where this situation applies, implementing such a tsunami FCL may be prohibitive to development because of the considerable structural requirements that buildings need to fulfill to keep their occupants safe during a tsunami. From a risk mitigation perspective on the other hand, limiting development in tsunami inundation zones is an effective measure to increase safety.

Chapter 6 of the American Society of Civil Engineers' (ASCE) *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* design standard (ASCE/SEI 7), titled *Tsunami Loads and Effects* (ASCE, 2016), provides provisions for the design of buildings exposed to tsunamis. The standard categorizes buildings by their level of importance in determining design criteria against failure and the risk associated with unacceptable structural performance. These risk categories are listed below, in general terms.

- Risk Category I – Buildings and other structures that represent a low hazard to human life in the event of failure (e.g., agricultural facilities, storage facilities)
- Risk Category II – Buildings and other structures not included in Risk Categories I, III, and IV
- Risk Category III – Buildings and other structures that represent a substantial hazard to human life in the event of failure, including but not limited to:
    - buildings whose primary function is public assembly
    - schools and daycare facilities
    - buildings in which care or supervision is provided to people who are or are not capable of self-preservation without physical assistance, or in which people are detained for penal or correctional purposes, or in which the liberty of the occupants is restricted
    - power-generating stations, water treatment facilities for potable water, wastewater treatment facilities, and other public utility facilities not included in Risk Category IV
    - any other building with a large occupancy (e.g., greater than 5,000)

- Risk Category IV – Buildings and other structures designated as essential facilities, including but not limited to:
    - fire, rescue, ambulance, and police stations and emergency vehicle garages
    - designated earthquake, tsunami, hurricane, or other emergency **refuges** and **shelters**
    - designated emergency preparedness, communications, operations centres, and other facilities required for emergency response
    - power-generating stations and other public utility facilities are required as emergency backup facilities for Risk Category IV structures

The ASCE/SEI 7 standard stipulates that Risk Category IV and Risk Category III buildings located in the tsunami inundation zone shall be designed to resist tsunami loads and effects. For Risk Category II, which includes residential buildings, the requirement for buildings to resist tsunami loads and effects is optional and left to jurisdictional authorities.

Study Approach

In comparison with coastal storm flood hazard, official federal or provincial guidance for estimating tsunami hazard is limited. Consequently, there are no consistent approaches for establishing levels for tsunami inundation mapping or for defining tsunami FCLs. Some of the parameters that need to be elaborated for the assessment of tsunami hazards, but often vary from one study to another, include:

- tsunami sources and their representation in any modelling
- the tide level considered for the tsunami assessment
- application of a safety factor to account for the uncertainties in the analysis
- any freeboard and **setback** to separate people and assets from hazards

The approaches taken to address each of these parameters are provided in the following paragraphs, respectively.

The BC MLWRS stipulates that, “at a minimum, buildings conditions should protect […] from a tsunami of equal magnitude to the March 28, 1964 tsunami that resulted from the Prince William Sound, Alaska earthquake and a possible Cascadia Subduction Zone earthquake” (BCMFLNRD, 2018). The team considered these two sources for this study, as they pose the highest risk at the study areas located on the northern and eastern coasts of Haida Gwaii. Local tsunamis originating from the Queen Charlotte fault or nearby **crustal faults** were not simulated but are briefly discussed. The numerical simulations of the 1964 Alaska tsunami are based on the seafloor displacement defined by Suleimani and Freymueller (2020). The tsunami source used for the simulations of a Cascadia tsunami corresponds to the splay-fault rupture of the Cascadia subduction zone developed by researchers from NRCan and the University of Victoria (Gao et al., 2018). Additional information regarding tsunamis affecting Haida Gwaii is provided in Section 3.4.

The US National Tsunami Hazard Mitigation Program (NTHMP, 2010) recommends that tsunami inundation maps be developed based on simulations performed with a tide level corresponding to, at a minimum, the **mean high water** (MHW) of a specific region. As per the NOAA's definition of **tidal heights** in the USA, MHW corresponds to the average of all the high-water heights observed over a **tidal epoch**. **Mean higher high water** (MHHW), which is higher than MHW and corresponds to the average of the higher high-water height of each tidal day observed over a tidal epoch. Based on the CHS definition of tidal heights in Canada, MHHW is similar to **higher high-water mean tide** (HHWMT). In the study area HHWMT varies from 0.3 to 2.6 m with respect to the **Canadian Geodetic Vertical Datum of 2013** (CGVD2013). The tide level was kept constant in the numerical simulations, which for the purpose of inundation mapping is a conservative simplification. The selection of HHWMT instead of HHWLT for the simulations implies that some residual risk remains. HHWLT corresponds to the average of the annual highest high-water heights over a tidal epoch and the probability of a coinciding tsunami is low. In the study area HHWLT varies from 0.7 to 3.7 m with respect to CGVD2013 (or 0.4 to 1.1 m higher than HHWMT). Water levels in the study area are further discussed in Section 3.3.

The safety factor applied to estimate the tsunami inundation levels and extents accounts for the uncertainties in the analysis, including the following.

- For either the Alaska-Aleutian Islands or the Cascadia subduction zone tsunami, the analysis considers only one possible set of seismic parameters. Tsunami hazards and effects can vary for different earthquakes that may occur at these subduction zones.
- Uncertainties associated with the scientific understanding of subduction zone earthquakes and their rupture mechanisms may influence the size of the tsunami waves they generate.
- The accuracy of model results is limited by the accuracy of the available bathymetric and topographic data available for this assessment.
- The numerical model's underlying mathematical representation of tsunamis and associated model parameters remains an approximation of a complex natural phenomena and carries some inherent uncertainties.

The approach selected for the application of a safety factor consists in a 50% increase of the vertical distance of the maximum water surface above a reference plane corresponding to the still water level of the numerical model (i.e., water level without any effects induced by the tsunami). NHC adopted this approach based on the rationale that a safety factor should be practically applied to the vertical components of an inundation that contain uncertainty. In this case, the uncertainties are associated with the numerical model predictions of the tsunami waves and not the astronomical tide level, as the latter can be accurately defined. This approach is in line with the one adopted by Emergency Management BC (EMBC) to provide general guidance on recommended tsunami planning levels throughout coastal BC (EMBC, n.d.).

Neither a vertical freeboard nor horizontal setback were applied to the tsunami inundation estimated as part of this study. No official guidance exists in defining such distances, which are meant to physically separate people and assets from hazards, and which will influence individual life-saving decisions. The ASCE/SEI 7 design standard specifies that refuge floors shall be located not less than the greater of 3.1 m (10 ft.) or one-storey height above the design tsunami inundation elevation. Such vertical distance accounts for localized tsunami effects as well as the reach of larger floating debris. In steeper areas, the setback can be less because an increase in the tsunami inundation level will result in a limited advancement of the water; however, in a flatter area this same increase in the tsunami inundation level will result in a relatively larger area being flooded. NHC recommends selecting freeboard and setback as part of evacuation planning, mainly because the decision to evacuate an area and what elevation to evacuate to should not only be based on the estimated extent of the hazard, but also on other factors established as part of public engagement and risk analysis.

2.2.3 Erosion Susceptibility Hazard

Erosion and **accretion** are natural processes that occur within the near-shore sediment transport system, resulting in shoreline retreat and advance, respectively. While shoreline retreat is a natural process, accelerated erosion can be induced by human activities, including changes to the sediment transport system from shoreline armouring, construction of infrastructure on the foreshore, and changes to upland land use. Larger-scale processes relating to the changing climate can also have a profound effect on shoreline erosion. Erosion can be particularly problematic where shoreline retreat threatens infrastructure or important habitat.

A shoreline erosion susceptibility rating system was developed for this study to provide additional context to the coastal storm hazard maps, highlighting the degree to which the relative rate of shoreline retreat may exacerbate the flood hazard. Various shoreline rating and classification systems were reviewed to determine if existing systems could be readily adapted to this assessment. This is not intended to offer a broad review but rather to describe the range of spatial focus and detail that various shoreline classification systems have been applied.

Physical Shore-Zone Mapping System for British Columbia (Howes et al., 1996) provides a highly systematic basis for classifying shorelines. The shoreline is considered in terms of shore units that are mapped based on a large number of factors, including exposure and shoreline materials. The approach is highly detailed and considers up to four cross-shore zones within each shoreline segment (backshore, intertidal, shallow sub-tidal, and deep sub-tidal). The general framework was adopted, though it was found that the level of detail exceeded the needs of the present study.

Technical Guide for Great Lakes – St. Lawrence River Shorelines (Anon., 1997) offers a similar approach to the mapping system for British Columbia described above. While somewhat simpler, it requires the collection of detailed information at a high spatial resolution, and the focus is highly descriptive rather than deterministic, meaning that there is no mechanism for relating the information from the shoreline descriptions to an expected outcome.

Shoreline Classification and Coastal Erosion, Southern and Central Labrador (Catto, 2019) is a descriptive classification system that was developed, in part, to evaluate the vulnerability of shoreline segments to contamination from oil spills. As with the other classification systems reviewed, it is based on a systematic approach to describing the shoreline, but the necessary scale and resolution of data collection exceeds the needs of the present study.

The methodology adopted for this classification system allows for relatively rapid classification of extensive segments of the shoreline, grouping similar shoreline types into reaches, and avoiding the need to sub-divide the shoreline to accommodate highly localized changes in conditions. The system is not a predictor of future conditions, yet it must consider the time scales associated with future sea level changes. It is understood that large-scale geomorphic processes will adjust to the gradual increase in sea level in the future, which in many cases drastically alter the shoreline system. A conservative approach to classifying erosion susceptibility was taken to avoid the potential for present-day erosion rates to have an undue influence on the assessment. Table 2-1 below summarizes the classification system for application to this study.

Table 2-1. Shoreline erosion susceptibility classification system.

Rating	Description
Low	Shoreline types that are classified as having a low potential for erosion are typically dominated by highly resistant materials or have very low exposure to coastal processes (wind driven waves). Examples include shorelines exhibiting a rock shelf in the foreshore, having a rocky backslope (even if the foreshore is erodible material), and those that face into a body of water with a short fetch or are otherwise protected from the direct influence of storm waves. The presence of shoreline protection structures does not generally place the shoreline in the low category. Often the presence of such structures is indicative of past erosion activity that required active intervention.[1] *Low* does not mean non erodible, nor does it mean that the shoreline will not be modified by large storms in the future.
Medium	The *medium* designation is applied to shorelines that dominantly display characteristics of either *high* or *low* susceptibility shorelines but with one or more key characteristics that indicate the classification needs to be lowered or raised, respectively. Features that might mitigate the severity of a *high* designation include, exposure to lower energy coastal processes or modification of those processes due to the presence of a nearby headland, offshore rocks, or high rates of sediment inputs from a nearby rivers discharging to the coastal zone. Conversely, features that might increase the susceptibility of a shoreline from a *low* designation include, exposure to higher energy coastal processes compared to similar nearby shorelines, presence of a very low backshore area (resulting in less material for coastal processes to transport to achieve shoreline retreat), shoreline comprised of smaller calibre material compared to similar nearby shorelines.
High	Shoreline types that are classified as having a high potential for erosion are typically dominated by small-calibre or loose materials that area easily transported by coastal processes and are exposed to highly energetic coastal processes. Typically, there are no mitigating features at the shoreline or backshore to slow the rate of shoreline erosion. Examples include sandy or gravel beaches with backshores that can be overtopped by waves during very large storms or at extreme high tides.

Notes

1. An exception was applied in Daajing Giids where segments of shoreline were designated with low susceptibility to erosion within the main village area because of a combination of bedrock and heavily managed shoreline (riprap, marina breakwater, etc.). In this case it is assumed that the shoreline will continue to be managed to control erosion.

2.3 Hazard Mapping

This section describes the mapping products produced as part of this study and provides guidance on their interpretation. The hazard mapping completed as part of this project includes two categories of maps: coastal storm flood and erosion susceptibility maps, and tsunami maps. The use and limitations of these maps are covered in Section 2.4.

Coastal storm flood and erosion susceptibility maps provide FCL information and indicate the likelihood or susceptibility of each shoreline segment to erosion. Tsunami maps consist of two subcategories of maps that show flood hazards (i.e., areas of overland inundation) and overwater hazards: maximum tsunami amplitude and maximum tsunami-induced current velocity. Additional details on the two main map categories are provided in the subsections below.

NHC produced both coastal storm flood and erosion susceptibility maps, and tsunami inundation maps at a local scale of 1:5,000 (i.e., approximately 1.8 km x 3.1 km on each map sheet). Additional details regarding the coverage of these maps (i.e., map sheet layout) specific to each community's study area are presented in the associated community summary report. The team also defined inundation extents, whether induced by coastal storms or tsunamis, based on topographic DEMs with a 2 m resolution specifically developed for this purpose. These DEMs were developed based on bare earth LiDAR information and cover only the areas selected for inundation mapping.

All maps produced as part of this project are provided in PDF format with a size of 11” x 17”, and all information visible on the maps produced for the project were delivered as GIS data layers. The projection and horizontal coordinate systems of all GIS information and maps are based on the BC Environment standard projection (e.g., Albers equal area conic projection). The horizontal datum is North American Datum 1983 Canadian Spatial Reference System, and the vertical datum for all elevations reported as part of this project is CGVD2013, unless indicated otherwise.

2.3.1 Coastal Storm Flood and Erosion Susceptibility Mapping

The coastal storm hazard and erosion susceptibility maps include flood hazard (e.g., localized flooding near to the shoreline and zones in which wave runup may occur) as well as indications of the susceptibility of the shoreline to erosion. The hazard maps are prepared at a local scale of 1:5000 (approximately 1.8 x 3.1 km on each map sheet) to show relevant details at the community level. Index sheets for each community show the spatial relationship between maps. In some cases, maps are arranged in a tile pattern, while in other cases (such as Tlell), they align with the shoreline.

2.3.2 Tsunami Mapping

The tsunami hazards mapped in this study include flood hazards (e.g., overland inundation) in localized areas, as well as overwater hazards, such as maximum tsunami wave amplitude and maximum tsunami-induced current velocity. Other overwater hazards such as shallow navigation depths (i.e., **tsunami drawdown**), sustained **flow eddies**, and impacts with floating debris were not assessed as part of this project's scope and therefore were not mapped. While model results obtained as part of this study can be used to estimate tsunami inundation depth and overland flow velocity, this information was not compiled and was therefore not mapped explicitly.

Two scales were considered for the tsunami mapping: a regional 1:100,000 scale (i.e., approximately 26 km by 34 km on each map sheet) to show general hazard information over a larger area and a local scale of 1:5,000 (i.e., approximately 1.8 km x 3.1 km on each map sheet) to show additional details. Overwater hazards were mapped at the 1:100,000 scale, and overland inundation was mapped at the 1:5,000 scale. Maximum tsunami-induced current velocity was also mapped at the 1:5,000 scale to inform boaters of the associated hazard in navigable waters closer to shore.

2.3.2.1 Overwater Tsunami Hazard Maps

NHC produced maps showing maximum tsunami amplitude based on results of simulations for tsunamis from both the Alaska-Aleutian and the Cascadia subduction zones. These maps correspond to 1 m of sea-level rise. The modelling results for this study show that the propagation of tsunamis offshore is not meaningfully influenced by sea-level rise. In other words, the amplitudes of the tsunami waves in the ocean are expected to be similar in the future, regardless of the overall sea level. However, the greater inundation depths associated with sea-level rise will cause variation in the behaviour of tsunami waves as they propagate over land.

As model results show that a tsunami from the Alaska-Aleutian subduction zone is more averse to the study areas in comparison to a tsunami from the Cascadia subduction zone, results of maximum tsunami-induced current velocity were only mapped for the former scenario. An overview of tsunami model results is presented in Section 3.4.1.

Neither a safety factor nor freeboard were applied to the results plotted on the overwater hazard maps. Any overland inundation or overland tsunami flow velocity visible on these maps or in the overlaid model results corresponds to information as approximated by the numerical model without any adjustment and should not be relied upon without additional site-specific assessment. Delineation of the flooding shown on the inundation maps introduced in Section 2.3.2.2 requires careful interpretation of the model results, as well as application of a safety factor. It should be noted, however, that the tsunami amplitudes reported on the maps and in this report are presented according to a reference plane that corresponds to the water level considered for the tsunami simulations; this water level varies across the study area and is noted on the various tsunami amplitude maps.

Four map sheets at a 1:100,000 regional scale depict the general study area (Figure 2-3). Seventy-five maps at a 1:5,000 local scale provide more detailed information on predicted tsunami-induced current velocities closer to shore in each study area. The regional maps also provide the **tsunami arrival time** at several point locations within the project area.

Regional overwater tsunami hazard maps are provided in Appendix E of this main report, while local current velocity maps are provided as an appendix to each community summary report.

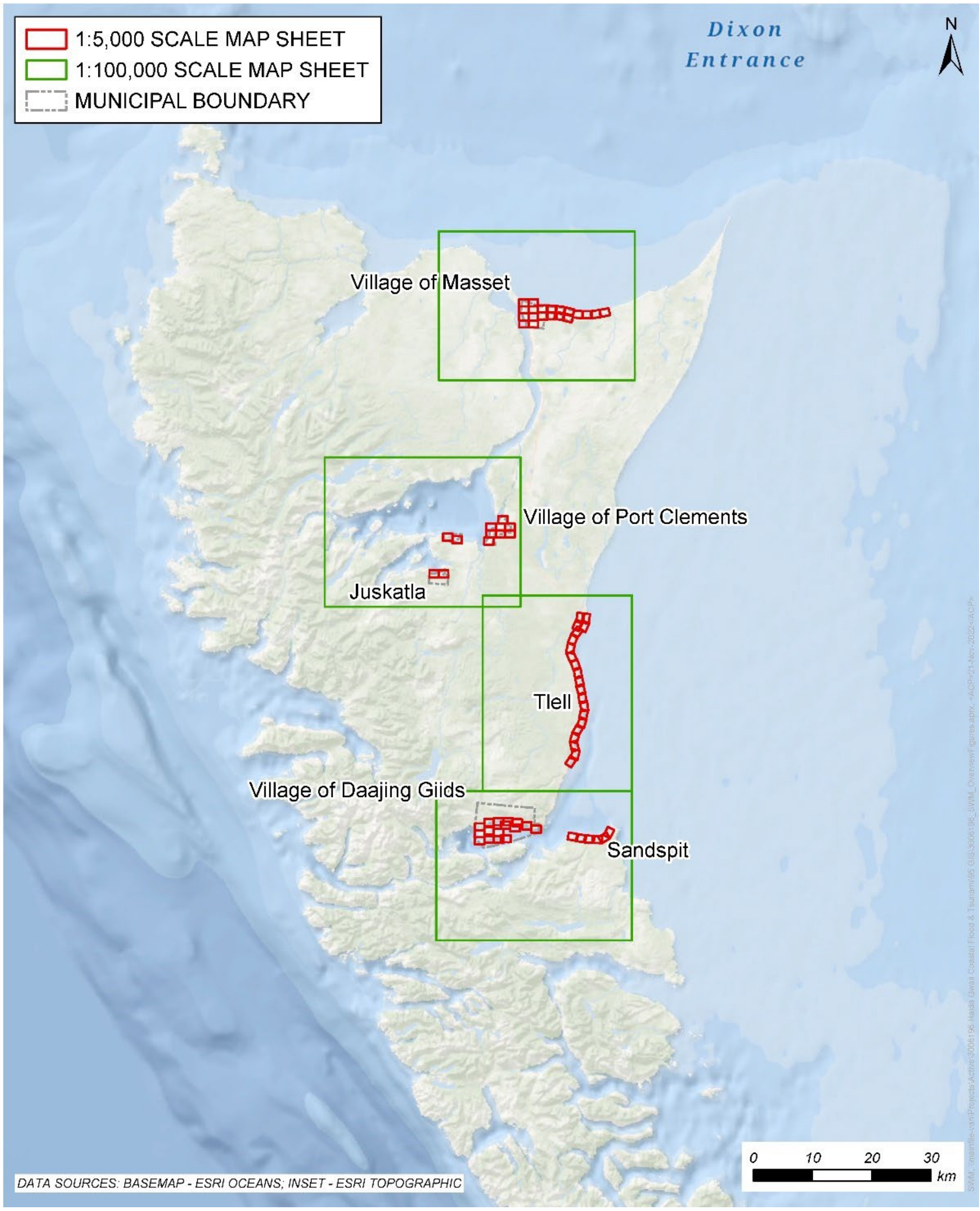

Figure 2-3. Layout of the regional (1:100,000)-scale tsunami overwater hazard map sheets. The smaller rectangles show the general layout of the local 1:5,000 scale maps showing tsunami-induced current velocities closer to shore at each community study area.

2.3.2.2 Overland Tsunami Inundation Maps

NHC produced overland inundation (i.e., flood) maps for the most adverse scenario between tsunamis originating from the Alaska-Aleutian and the Cascadia subduction zones. While both modelled tsunamis have similar effects in all study areas, a tsunami from the Alaska-Aleutian subduction zone is predicted to be more adverse with greater tsunami amplitude. The extent of inundation shown on the maps corresponds to 1 m and 2 m of relative sea-level rise. While simulations were undertaken for current-day sea level, the inundation associated to this sea level is not mapped.

NHC defined the inundation extents using the following general procedure:

1. Increase spatial results of maximum water surface elevation above the model's reference plane of HHWMT by a safety factor of 1.5 (i.e., a 50% increase).
2. Convert factored results of maximum water surface elevation to the CGVD2013 vertical datum based on the average height of HHWMT above CGVD2013 across the modelled area.
3. Define zones of approximately constant water surface elevation (rounded to the nearest 0.2 m) to advance the water surface further inland and intersect the 2 m resolution DEM.
4. Interpolate the inundation extents in a horizontal plane to obtain a smooth delineation of the estimated flooding.
5. Review and manually adjust inundation extents to ensure consistency with the local topography.

2.4 Study Limitations

It is important to consider the limitations of the technical analysis when interpreting the results of the hazard assessment performed as part of this study. These limitations can be addressed by adopting conservative mitigation plans and measures. The following considerations are important for interpreting the study findings.

General

- For local 1:5,000-scale maps, the mapping accuracy is limited by the accuracy of the available **ortho imagery** shown on the maps (i.e., the base map). Horizontal shifts between mapped information and the underlaying base map vary from approximately 2 m up to 10 m.
- The extent and level of flooding estimates conducted for this study and shown on the maps are limited by the accuracy of the topographic data and ortho imagery available.

Coastal Storm Flood Analysis and Mapping

- The study results for estimating wave effect on the shoreline are based upon a limited number of transects within each community area. Within the scope and budget of the project it was not possible to model wave effect at each individual property within a community. Shoreline zones were assigned for having similar exposure and backshore types, and within them a transect was selected that was expected to have higher than average wave effect to ensure a conservative estimate within a given zone.

- Wave effects can vary greatly over short distances and from one property to another depending upon the offshore and foreshore topography, shoreline elements such as vegetation and small structures, and alignment of the property to incoming waves. It is possible that a given property may experience wave effects (i.e., wave runup) that is higher than typical for a given zone on a map.
- Changes to properties such as construction of new seawalls will alter wave effects and could change the safe Flood Construction Level on a given property.

Erosion Susceptibility Assessment and Mapping

- As described in Section 2.2.3, erosion susceptibility describes the relative likelihood and severity of erosion in the future. The designation is not intended to be a predictor of conditions in the future, nor is it intended to offer assurance that erosion would be limited to the designation applied.
- The scale at which erosion susceptibility was mapped may necessarily overlook localized conditions that may not conform to the dominant conditions within the mapped segment. As such, the designation should not be relied on for site-specific assessment of shoreline erosion rates or erosion risk analysis.

Tsunami Modelling and Mapping

- The study results are based on a limited number of tsunami scenarios for subduction earthquakes with specific seismic parameters. While these scenarios are considered severe and known to be the worst scenarios readily available for analysis, the possibility of stronger earthquakes should not be ruled out unless supported by scientific research.
- Numerical simulations were undertaken at a resolution of 10 m; such simulations may not capture effects that would take place at a smaller scale (i.e., over distances shorter than 10 m). Such effects include localized runup, flow around obstacles, and overflow of solid features. The definition of any tsunami effects occurring at a scale smaller than the grid resolution of 10 m requires additional assessment.
- The tsunami inundation level is established by applying a safety factor to the non-tidal component in the sea surface predicted by the numerical model. Projecting this inundation level inland over long low-lying distances neglects some potential dissipation of the tsunami energy due to friction and other dissipative mechanisms. This simplified approach may yield conservative results in relatively flat coastal areas.
- No safety factor or freeboard was applied to the results plotted on the overwater hazard maps of maximum tsunami amplitude and maximum tsunami-induced current velocity. Any overland inundation or overland tsunami flow velocity visible on these maps or in the underlying data corresponds to information as estimated by the numerical model without any adjustment and should not be relied upon without additional site-specific assessment. The delineation of the flooding shown on inundation maps requires careful interpretation of the model results in conjunction with the local topography and includes the application of a safety factor.

- Tsunami simulations were performed for a constant tide level and therefore do not include the influence of tidal currents, which can be superimposed on the estimated tsunami-induced currents.
- The potential influence of stream flow on the propagation of tsunamis up rivers and creeks was not included in the numerical model.

3 GOVERNING PHYSICAL PROCESSES

Coastal flood and erosion hazards affecting the coastal areas of Haida Gwaii are influenced by the physical processes that are either ongoing or expected to occasionally occur. This section provides a general summary of the natural conditions associated with costal flood and erosion hazards, which are in part defined by the physical setting of the study area as well as its geological history. More detailed technical assessment of these conditions is presented in this report's appendices.

3.1 Physical Setting

Defined in Haida language as *X̱aaydag̱a Gwaay.yaay / X̱aayda gwaay*, which translates to "Islands of the Haida people," Haida Gwaii is an island archipelago located off the northern coast of BC. The overall land mass is primarily contained in the two largest of the approximately 150 islands that make up Haida Gwaii, namely Graham Island and Moresby Island, which are separated by the narrow Skidegate Channel that extends west from Skidegate Inlet. The total land area is approximately 9,945 square kilometres (km^2), of which Graham Island is approximately 6,436 km^2 and Moresby Island is 2,745 km^2. Located at the centre of Graham Island, Masset Inlet is a large saltwater bay. Approximately 30 km long and 15 km wide and with depths varying between 20 m and 100 m, the inlet is fed by several rivers and is connected to McIntyre Bay by the narrow Masset Sound. This channel is 38 km long and 1.5 km wide on average, with depths varying between 10 and 25 m.

The waters surrounding Haida Gwaii's shorelines are described as four separate bodies based on their physiological characteristics: Dixon Entrance to the north, Hecate Strait to the east, Queen Charlotte Sound to the south, and the Pacific Ocean to the west (Figure 3-1).

Figure 3-1. Ocean water bodies surrounding Haida Gwaii.

Dixon Entrance is an inlet approximately 140 km long by 80 km wide and forms part of the maritime boundary between Canada and the USA state of Alaska, with depths varying between 200 m and 500 m. Hecate Strait, which separates Haida Gwaii from the BC mainland, is a relatively wide, shallow water body, in which depths generally vary from 20 m to 100 m. The strait is approximately 260 km in length on a roughly north-south axis and is 140 km wide where it merges with Queen Charlotte Sound to the south and narrows to approximately 48 km where it meets Dixon Entrance to the north.

Queen Charlotte Sound is located between Vancouver Island to the south and Haida Gwaii to the north, which are approximately 200 km apart. The sound, which extends approximately 150 km offshore from the mainland, is bounded to the west by the outer fringe of the **continental shelf** where the water depth drops below 1,000 m.

Haida Gwaii has previously been divided into three physiographic zones by Sutherland Brown (1968), offering a useful way to describe the general landscape features: the Queen Charlotte Range, the Skidegate Plateau, and the Queen Charlotte Lowlands. The Queen Charlotte Range, which forms the west coast of the island chain contains the highest peaks of the Haida Gwaii and is characterized by steep rocky shorelines and is indented by deep inlets formed by glaciers. The Skidegate Plateau occupies the middle portion of the islands immediately to the east of the Queen Charlotte Range. It is comprised of generally flat- or round-topped ridges with much lower relief (reaching elevations of 300 m to 600 m), and thick deposits of sediment along the lower slopes, including the valley bottoms and coastal shorelines. The Plateau grades northeastward into the Queen Charlotte Lowlands, a 10 to 40 km wide coastal plain with elevations generally below 150 m. Daajing Giids is located within the Skidegate Plateau, while the other communities included in this study are located in the Lowlands with the exception of Sandspit, which is located on an accumulation of very low-lying sediments at the eastern margin of the Plateau.

3.2 Recent Geological History

Most of Haida Gwaii was covered by thick sheets of glacial ice during the **Pleistocene** epoch, often referred to as the Ice Age and lasting from approximately 2.5 million years ago to approximately 11,700 years ago. Glacial processes had a profound influence on the present-day landscape, and in particular, the areas of Haida Gwaii that are the subject of this study. The majority of the shorelines within the study areas are comprised of sediments that were deposited during the last glacial period and have been subsequently modified by ongoing changes in relative sea level during the **Holocene** that are directly related to the relatively recent effects of glaciation.

Holocene sea-level changes varied from elevations between 160 m and 16 m below and above current-day sea level, respectively (Walker and Barrie, 2006). The dominant trend has been a steady decline in sea level relative to the land over the last 8,000 years (Clague et al., 1982), which has left its mark on the landscape. The exposed rocky coastlines of Haida Gwaii, which are prevalent in the Queen Charlotte Ranges physiographic zone of the west coast and southern Haida Gwaii, are not particularly susceptible to changes induced by past and future sea levels. In contrast, on the north of Graham Island, a rocky coast transition to extensive Quaternary glacial sediment deposits provides a source for the wide, sandy beaches backed by coastal dunes to the east of Masset Sound (Shaw et al., 1998). **Relic shorelines** and nearshore sediment deposits such as beach ridges that move outward (i.e., prograde) into the ocean indicate a landscape response to sea-level changes along the eastern coast of Graham Island. However, there is ample evidence that many of these formerly prograding shorelines are experiencing active erosion and retreat in response to the relatively recent trend of rising sea levels (see Section 1.3).

3.3 Meteorological and Oceanographic Conditions

The shorelines of Haida Gwaii are influenced by the metocean conditions occurring in the open waters surrounding the island. These conditions include water levels, as well as winds that generate waves by transferring energy to the water surface through friction. The potential effects of waves on coastal areas will depend in part on the water level at the time they approach the shoreline. This section provides an overview of governing metocean conditions offshore of Haida Gwaii, which NHC used as inputs for the estimation of coastal flood hazards. Details of the analysis NHC performed to define these offshore conditions are provided in Appendix B. Nearshore conditions and coastal hazards specific to each of the study areas are presented in the separate community summary reports.

3.3.1 Water Levels

Coastal water levels are influenced by multiple variables such as astronomical tides, wind, atmospheric pressure, temperature, and salinity. The variables with the greatest influence are astronomical tides as well as wind and atmospheric pressure, which when the two are combined, produce storm surge. Excluding the local effect of storm waves (i.e., **wave setup**), the **total water level** near the coast during a storm is the addition of the astronomical tide with the storm surge. These two components are independent from one another since they are independently driven by distinct and unrelated forcing mechanisms. The total water level corresponds to the observed water level measured by tide gauges.

3.3.1.1 Astronomical Tides

Tides in Dixon Entrance and Hecate Strait are **mixed semidiurnal** and the **tidal range**, which corresponds to the difference in height between the highest high tide and lowest low tide, varies across the coastlines of Haida Gwaii. At Langara Point, located to the northwest of Graham Island, the tidal range is 5.2 m. At Daajing Giids in Skidegate Inlet, the tidal range is 7.7 m, which is the largest range recorded on Haida Gwaii.

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 due to the constricting physical characteristics of the sound’s channel. The tidal range at the entrance of Delkatla Inlet in the Village of Masset is 4.3 m in comparison to 6.0 m at Wiah Point, which is located just west of McIntyre Bay in Dixon Entrance. 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. The tidal ranges at Daajing Giids and the communities of Tlell and Sandspit are similar, varying from 7.4 to 7.7 m.

The CHS publishes tidal heights at several locations on the coastline of Haida Gwaii. Appendix B provides tidal heights for each of the areas under study.

3.3.1.2 Storm Surge

While tides are driven by **astronomical forcing**, storm surges occur because of **atmospheric forcing**, which combines the effects of the wind and atmospheric pressure related to storm systems. Storm surge is calculated based on the **residual water level**, which is the difference between the measured or observed water level and the predicted astronomical tide. For this study, NHC calculated long-term records of storm surge for Langara Island (Dixon Entrance) and the Village of Daajing Giids (Hecate Strait), based on measurement records kept over 49 and 58 years, respectively. Results are presented in Table 3-1 and show that storm surge in Hecate Strait tends to be higher than in Dixon Entrance.

Table 3-1. Storm surge of varying annual exceedance probability for Langara Island and the Village of Daajing Giids.

AEP (%)	Storm Surge (m)	
	Langara Island	Daajing Giids
0.5	0.78	1.40
1	0.73	1.33
2	0.69	1.26
5	0.63	1.17
20	0.53	1.03
Annual	0.40	0.82

3.3.2 Wind Regime

Winds blowing over water generate waves by transferring energy to the water surface through friction. It is therefore necessary to accurately characterize offshore winds to reliably estimate the wave climate in the study area.

Storm systems in this region of the northeast Pacific experiences seasonably opposed winds that are strongest in the winter months. According to Walker and Barrie (2006), the **Aleutian Low** develops and intensifies, causing a counter-clockwise circulation of low-altitude winds. From October through April, this low-pressure system brings southerly and southeasterly winds up Hecate Strait and over Haida Gwaii in general. With the arrival of spring, the Aleutian Low declines and retreats to the northwest, while the **North Pacific High** expands and intensifies, which shifts the dominant southeasterly winds to a northwesterly dominant direction in the summer.

Wind roses are diagrams used to show wind magnitude, direction, and frequency. Each stem characterizes the wind coming from the direction in which it expands outwards; the individual length of the coloured segments along a stem represents the frequency of the wind within a specific speed range. Figure 3-2 shows wind roses for overwater winds measured throughout the year (i.e., year-round) in Dixon Entrance (left) and Hecate Strait (right). The data show that the predominant winds are from the southeast in both water bodies, although strong winds (e.g., > 17.5 metres per second 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.

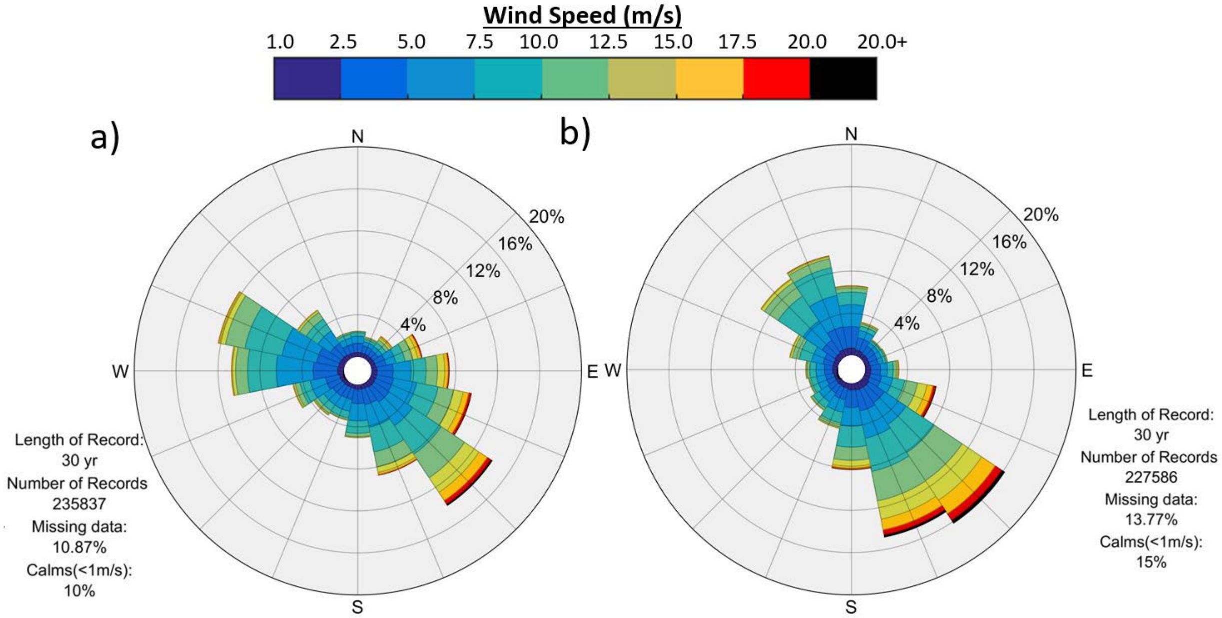

Figure 3-2. Wind roses for year-round wind measured at buoys in a) Dixon Entrance and b) Hecate Strait.

NHC analyzed historical winds measured at several land-based meteorological stations and offshore wave buoys to understand the nature of the wind regime that can affect the shoreline along the northern and eastern coasts of Graham Island. The areas of interest for this study are mainly exposed to waves coming from the general directional sectors shown Figure 3-3 and listed as follows:

- Dixon Entrance westerly sector
- Dixon Entrance easterly sector
- Hecate Strait northerly sector
- Hecate Strait southerly sector

These sectors are used to describe the scenarios considered for the analysis of coastal storm flood hazards.

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

Figure 3-3. General open-water exposure of study areas.

3.3.3 Offshore Wave Climate

NHC analyzed historical wave observations measured at several offshore wave buoys to characterize the general wave conditions inside Dixon Entrance and Hecate Strait. The analysis is based on wave measurements recorded at buoys operated by Fisheries and Oceans Canada. Such measurements 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. The wave conditions are analyzed further in

Appendix C, which presents the wave modelling undertaken to understand how offshore waves propagate toward and affect the shorelines of the study areas.

Waves generated locally by wind are known as **wind sea**. On large bodies of water, such as the open ocean, waves will travel beyond the area in which they are generated. Such waves are called swell. While the waves travel over long distances, their frequencies are reorganized, and the waves become more orderly, with the waves of similar frequency (i.e., wave period) being grouped together to form a **wave train**. Swell tends to have longer wave periods in comparison to wind sea, which means the energy associated with swell is greater, even for waves of equal height. A **transitional sea** is described as a swell over which locally generated wind waves are also present to some degree. NHC determined that westerly swell conditions for Dixon Entrance are predominant in comparison to wind sea conditions coming from the east. In Hecate Strait, the occurrence of wind sea from the northern sector is relatively rare in comparison to transitional sea coming from the southern sector.

General model results of the typical propagation of waves in Dixon Entrance and Hecate Strait are presented graphically in the figures below (Figure 3-4 to Figure 3-7). Wave height is shown by colour and wave direction by arrows. White rectangles show extent of regional 1 km resolution wave modelling.

Dixon entrance is notable for longer period ocean swell and large storm waves coming in from the northeast Pacific. Strong local winds can augment wave energy from the Pacific. That said, the very long fetch lengths to the northeast from the Masset area allows for large waves from an easterly and northeasterly direction to occur during periods of strong winds from these directions in the region.

In Hecate Strait, the largest waves occur from the southeast where there is a large fetch between the Sandspit/Tlell area to Vancouver Island. Wave modelling indicated insignificant amounts of ocean swell entering south Hecate Strait from the Pacific reach the community shorelines. However, the large fetches to the south and the occurrence of strong southeasterly winds causes high energy seastates with waves above 4 m in height and wave periods in excess of 8 seconds on a regular basis during winter storm periods. Such conditions, when coupled with high tides and storm surges, can lead to significant wave effects on shorelines. Storm events with easterly and northeasterly winds in Hecate Strait were also examined, but found to cause lower levels of coastal flood hazard than the southeasterly storms.

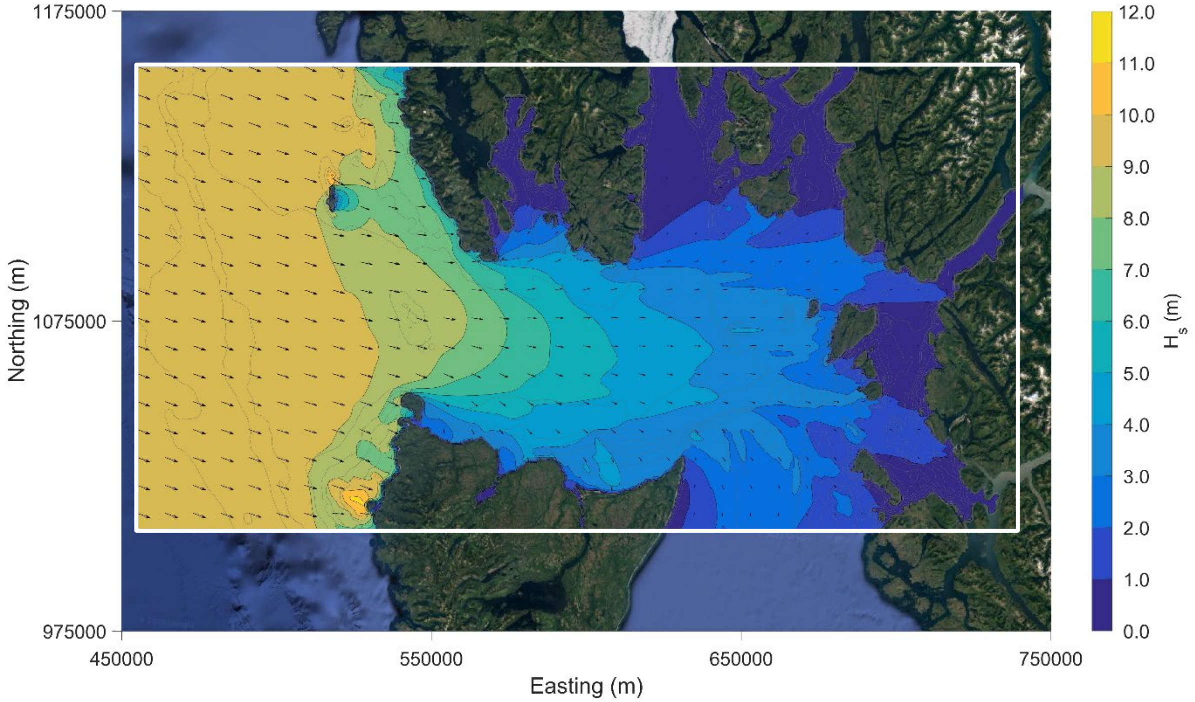

Figure 3-4. Typical pattern of wave propagation in Dixon Entrance during a westerly wave event.

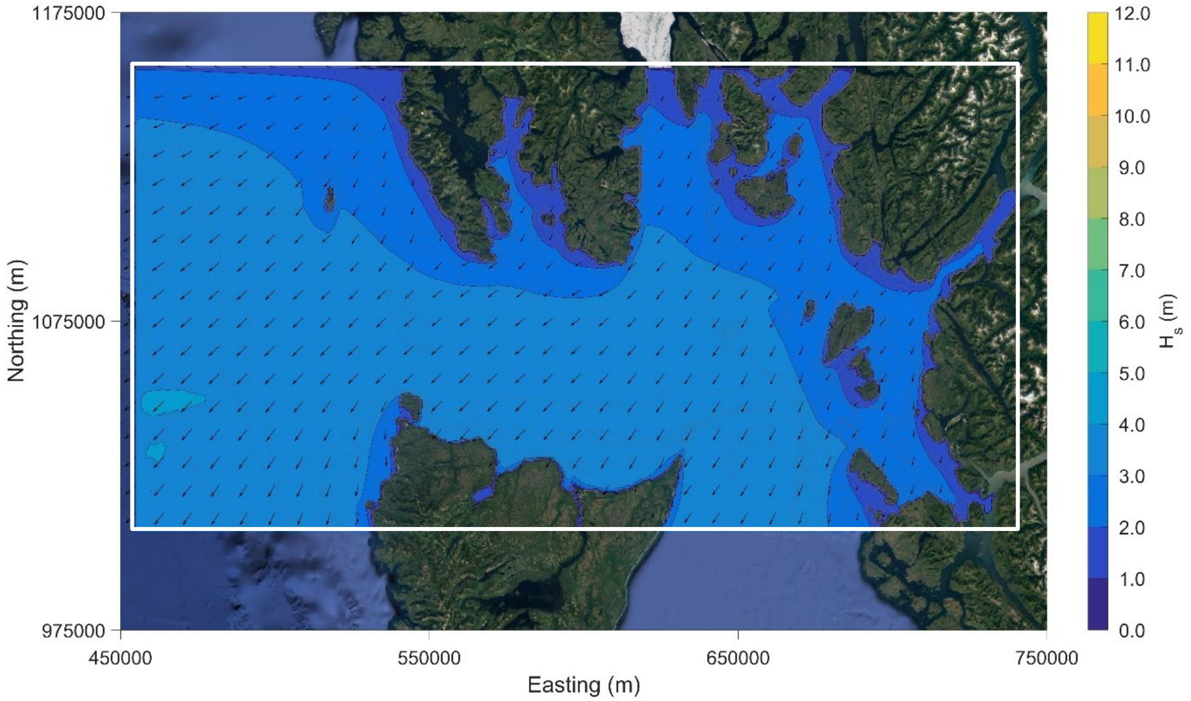

Figure 3-5. Typical pattern of wave propagation in Dixon Entrance during a northeasterly wave event.

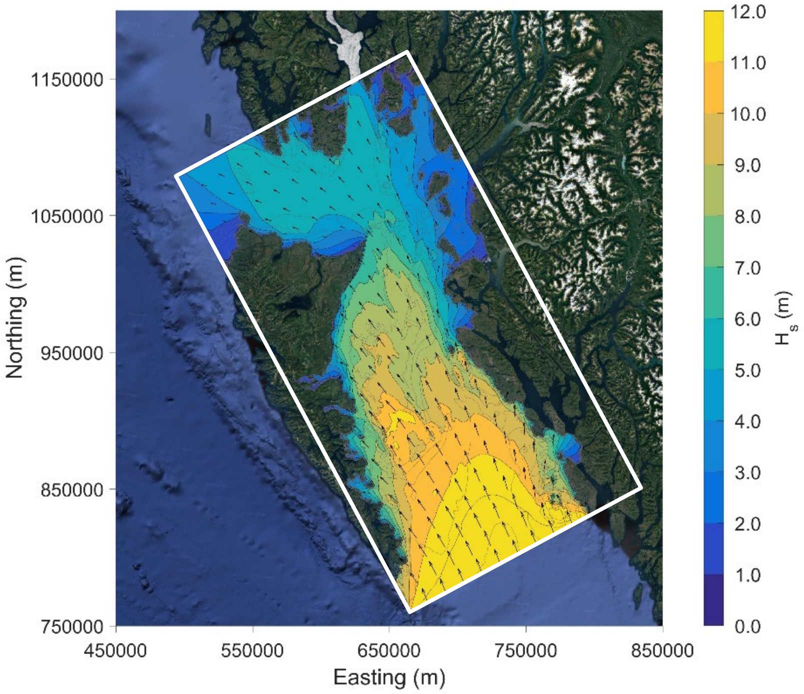

Figure 3-6. Typical pattern of wave propagation in Hecate Strait during a southeasterly wave event.

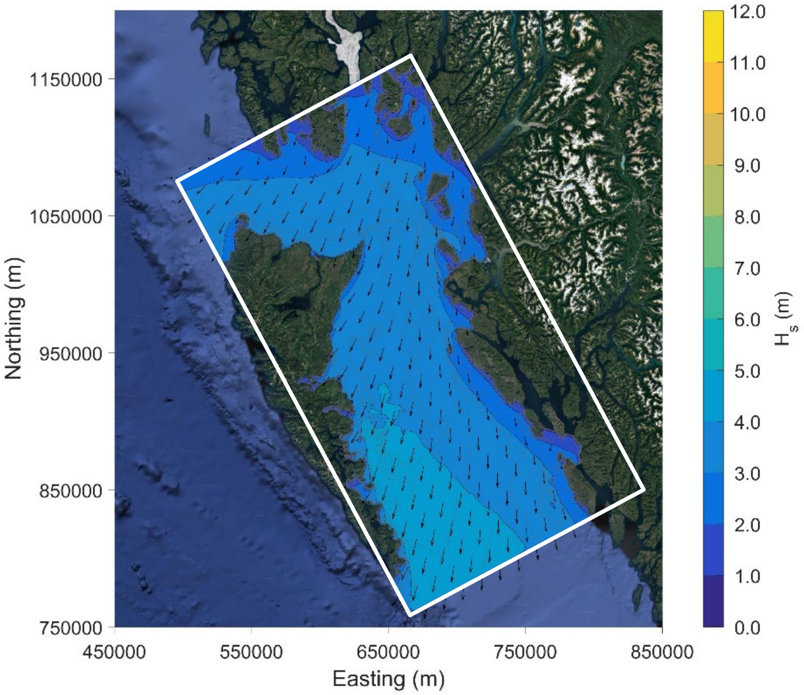

Figure 3-7. Typical pattern of wave propagation in Hecate Strait during a northeasterly wave event

3.4 Tsunamis

According to the US Federal Emergency Management Agency (FEMA, 2019), a local tsunami is one that originates from a source that is close to the site of interest and arrives within one hour of the triggering event. The effects of the triggering event may also be felt at the site, such as ground shaking in the case the tsunami is triggered by an earthquake. A distant tsunami is one that originates from a source that is far away from the site of interest and takes three hours or longer after the triggering event to arrive. This longer arrival provides an advantage for the evacuation of areas at risk. However, as the earthquake may not be felt, the notification of residents and visitors will rely entirely on warning systems, which may be challenging in remote areas.

This assessment focuses on distant tsunamis that pose the highest risk at the study areas located on the northern and eastern coasts of Haida Gwaii. Local tsunamis, which can originate from the Queen Charlotte fault just west of Haida Gwaii or potentially from crustal faults in Hecate Strait, are discussed but were not analyzed.

3.4.1 Distant Tsunamis

As with many other areas along the BC coast, Haida Gwaii is exposed to tsunamis originating along the Pacific Ocean's **Ring of Fire**, which consists of a nearly continuous series of tsunamigenic subduction zones surrounding the ocean Figure 3-8. Several major subduction earthquakes have occurred in recent history, exemplifying the tremendous impacts tsunamis can have on communities, even ones located far away from a tsunami source.

A geologically recent and well-known Canadian example is the tsunami that partially destroyed the town of Port Alberni, BC, during the night of March 27, 1964. This tsunami was generated by a **moment magnitude** (Mw) 9.2 subduction earthquake south of the Alaskan coast (United States Geological Survey, n.d.), which is the second largest earthquake ever recorded worldwide, following the Mw 9.5 earthquake in Chile in 1960 (United States Geological Survey, 2022). The earthquake occurred at approximately 6:30 p.m. Pacific daylight savings time (3:30 a.m. Greenwich mean time on March 28) and reached Haida Gwaii within approximately 2 to 3 hours after the earthquake. Although measurements of the tsunami on Haida Gwaii are scarce, Wigen and White (1964) reported that the maximum elevation of the tsunami in Shields Bay at the head of Rennell Sound reached up to 9.8 m above **chart datum** (CD) and that a logging camp was severely damaged. In Prince Rupert, the maximum elevation reached by the tsunami was 7.7 m above CD, which was approximately 1.5 m above the tide level at the time (Wigen and White, 1964).

Figure 3-8. Subduction zones around the Pacific Ocean and locations of several major tsunamigenic earthquakes (adapted from Atwater et al., 2005).

Earth tremors resulting from the 1964 Alaska earthquake were noticed in the northern part of BC. According to Wigen and White (1964), "Very noticeable motions in buildings and other structures were reported generally as far south as towns along the Canadian National Railroad east of Prince Rupert.". It is unclear if the earthquake was felt on Haida Gwaii, potentially providing a warning to the approaching tsunami, or if earthquakes that are smaller yet strong enough to generate dangerous tsunamis would be felt. Hence, it is conservative to assume that an Alaska earthquake generating a tsunami would not be felt on Haida Gwaii.

Haida Gwaii is also susceptible to tsunami waves originating from the Cascadia subduction zone, which is located approximately 100 km offshore, parallel to Vancouver Island. Geological studies, historical records from Japan, and oral history from Indigenous communities along the west coast of North America show that a major subduction earthquake occurred on January 26, 1700, followed by the generation of a large tsunami (Atwater et al., 2005). The earthquake associated with this tsunami is estimated to have had a moment magnitude of approximately Mw 9.0 (Witter et al., 2013). It is estimated that a tsunami of this magnitude would have reached Haida Gwaii approximately 2 to 3 hours after the earthquake.

The general characteristics of tsunamis arising from earthquakes along the Alaska-Aleutian and Cascadia subduction zones in the northeastern region of Haida Gwaii are presented below. Associated regional maps of overwater tsunami hazards, such as maximum tsunami wave amplitude and maximum tsunami-induced current velocity, are provided in Appendix E of this report. Details of the tsunami assessments specific to each study area are discussed in the associated community summary reports.

Alaska Tsunami

Figure 3-9 shows the general influence in the Pacific Ocean of a tsunami originating from the Alaska-Aleutian Islands subduction zone. The orientation of this fault results in the main direction of the tsunami waves aimed toward the BC coast and of the west coast of the USA.

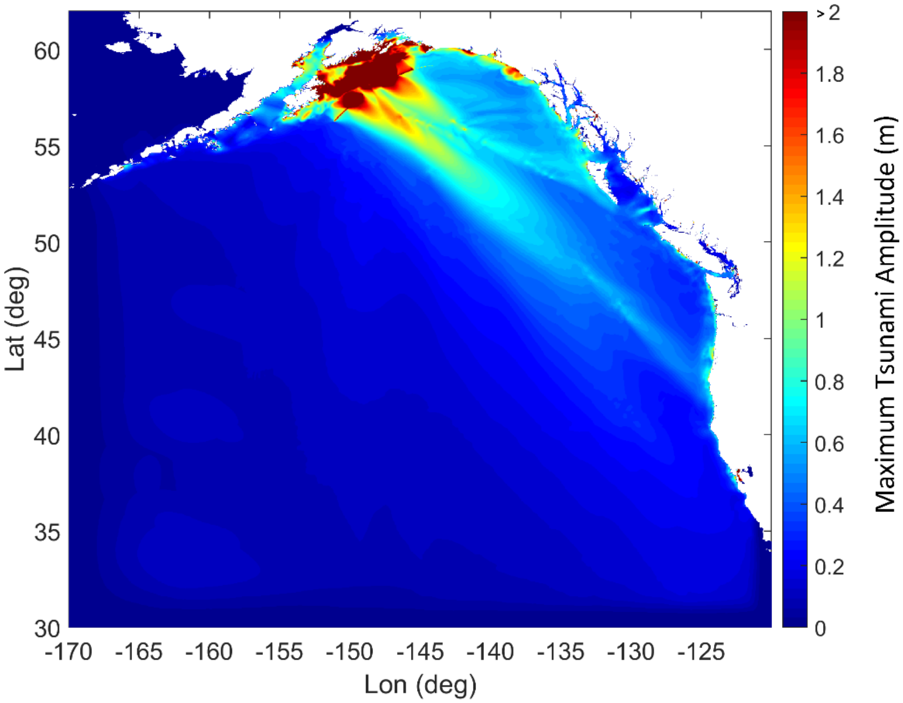

Figure 3-9. Maximum amplitude in the Northeast Pacific Ocean of a tsunami generated from the Alaska-Aleutian Islands subduction zone.

The maximum tsunami amplitude associated with an Alaska tsunami affecting the northeastern coast of Graham Island is shown in Figure 3-10. Between the study areas, the open coastline of Masset would be the most affected, where maximum tsunami amplitude offshore in McIntyre Bay could reach up to 4 m above the water level at the time of the tsunami. As the tsunami wave propagates toward Port Clements, the wave amplitude would be reduced as it exits Masset Sound and enters Masset Inlet. By the time it reaches Juskatla, the amplitude would be relatively small (e.g., <0.5 m). On the eastern shore of Graham Island, the tsunami would build up against the coastline, reaching amplitudes up to 2 m across the coastline, in comparison to amplitudes of less than 1 m in Hecate Strait. The tsunami would amplify as it propagates inside Skidegate Inlet and past Daajing Giids, reaching amplitudes of up to 4 m toward the end of the inlet. This amplification could be the result of several physical factors such as constricting topography, a decrease in water depth inducing **wave shoaling**, or resonance. No detailed assessment was performed to further describe the physical factors causing such amplification.

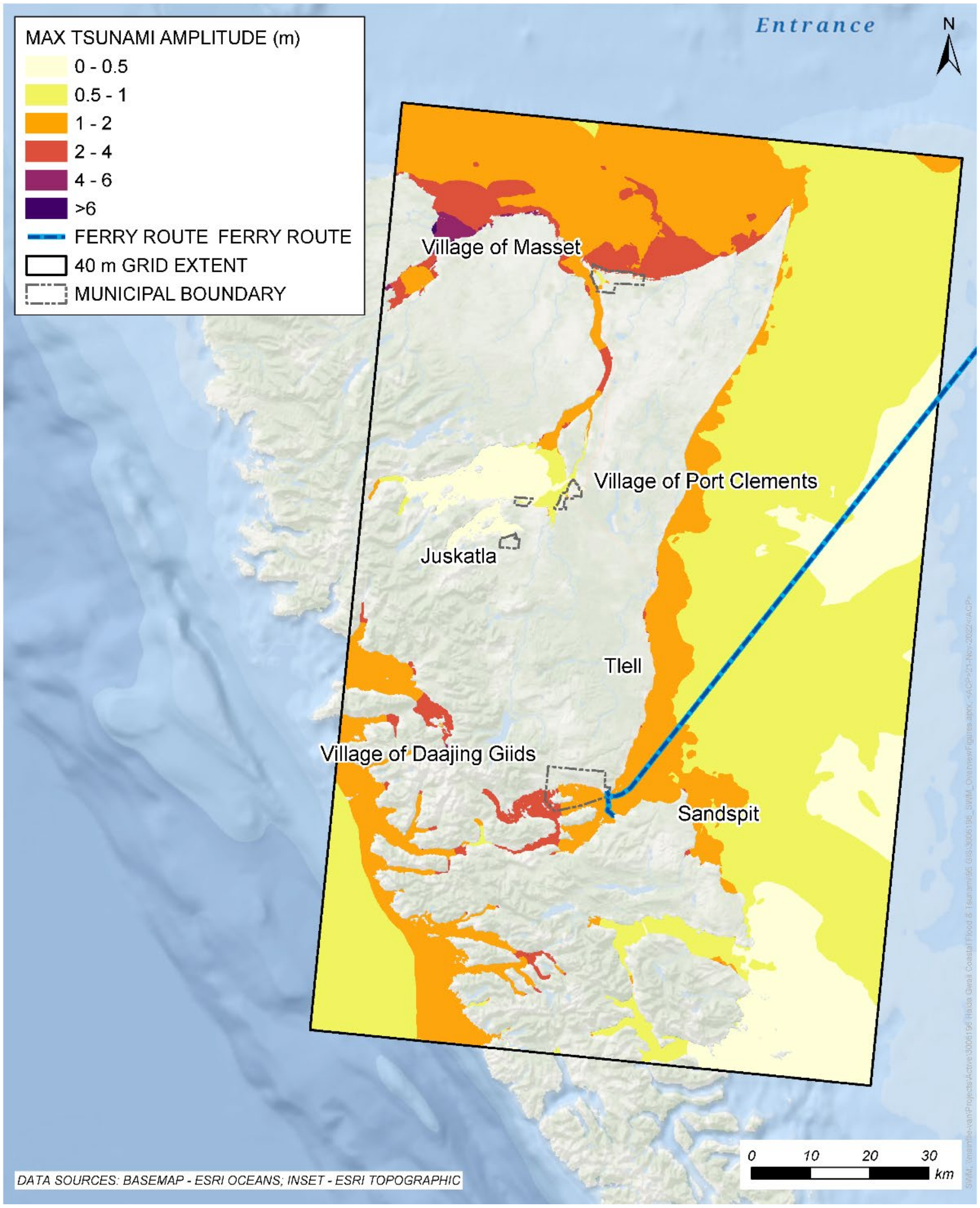

Figure 3-10. **Maximum tsunami amplitude in the broader study area of a tsunami generated from the Alaska-Aleutian subduction zone.**

In Shields Bay at the head of Rennell Sound on the west coast of Graham Island, which is not within one of the study areas of this study, the model results suggest a maximum tsunami amplitude varying between 3.3 and 4.3 m above the water level at the time of the tsunami, depending on the precise location of measurement within the bay. Wigen and White (1964) reported that the maximum elevation of the tsunami in that area reached up to 9.8 m above CD and damaged a logging camp. However, it isn't clear exactly where and how this value was measured, or if it relates to the height of the tsunami wave crest above the reference datum or to the maximum tsunami runup, which is the highest elevation reached by the tsunami overland. High tide at that location varies from 3.9 (HHWMT) to 4.6 m (HHWLT) CD. More assessment is required to understand what the water level was at the arrival of the tsunami and if any storm surge was in effect. Considering the largest modelled amplitude and the highest tide, model results suggest a tsunami height of 8.9 m above CD, which is below the reported value of 9.8 m. Shields Bay is away from the study areas, and higher-resolution modelling was not undertaken for that area (see Figure 2-2), thus limiting the accuracy of the model and its ability to simulate inundation, which may in part explain this difference. Nevertheless, this comparison with anecdotal information demonstrates that the numerical model reasonably simulates tsunamis, including their generation and propagation across the ocean and into coastal waters.

Cascadia Tsunami

Figure 3-11 shows the general influence in the Pacific Ocean of a tsunami originating from the Cascadia subduction zone. Tsunamis travel outward in all directions from the generating area, with the largest waves propagating perpendicular to the fault line and in opposite directions. Waves that propagate into the open ocean radiate laterally as they propagate away from their source, which result in a reduction of their amplitude. This explains why areas such as Haida Gwaii on the northern BC coast are less affected by tsunamis from the Cascadia subduction zone in comparison to areas on the western coast of Vancouver Island.

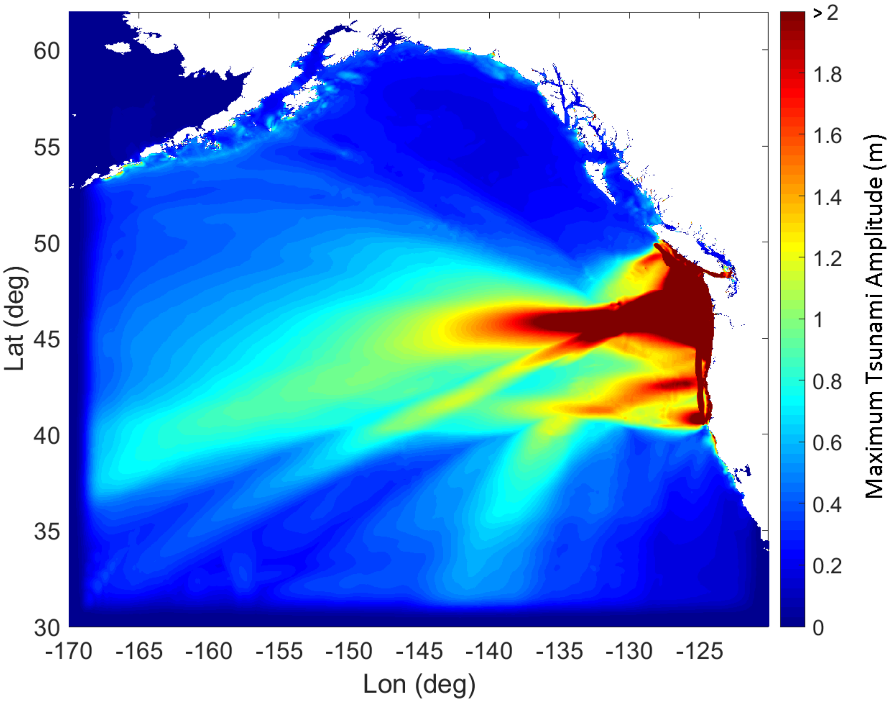

Figure 3-11. Maximum amplitude in the Northeast Pacific Ocean of a tsunami generated from the Cascadia subduction zone.

The maximum tsunami amplitude associated with a Cascadia tsunami affecting the northeastern coast of Graham Island is shown in Figure 3-13. Along the northeastern coast of Graham Island, the general characteristics of a tsunami originating from the Cascadia subduction zone are similar to the characteristics of an Alaska tsunami (Figure 3-10), although of lesser magnitude.

NHC focused the mapping of overland inundation to the case of a tsunami originating from the Alaska-Aleutian subduction zone, as model results show that the effects of a tsunami from the Alaska-Aleutian subduction zone would more adversely affect the study areas in comparison to a tsunami from the Cascadia subduction zone.

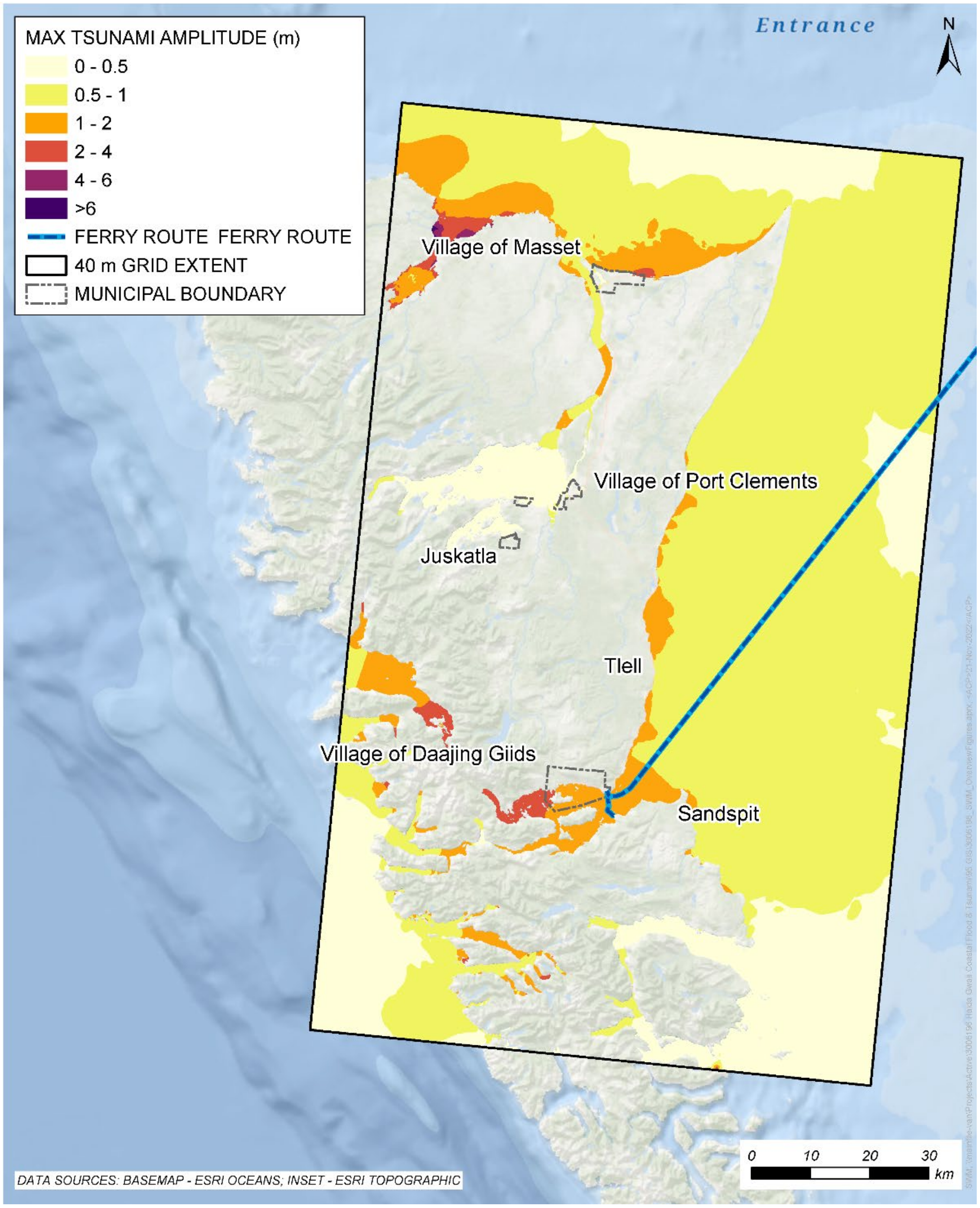

Figure 3-12. **Maximum tsunami wave amplitude in the broader study area of a tsunami generated from the Cascadia subduction zone.**

3.4.2 Local Tsunamis

Tsunamis originating closer to Haida Gwaii may be triggered by earthquakes from the nearby Queen Charlotte fault, or potentially from local crustal faults, as discussed below.

Queen Charlotte Fault

The Queen Charlotte fault separates the Pacific and North America tectonic plates and expands from Alaska to the southward to Queen Charlotte Sound. Figure 3-13 shows the location of the fault relative to Haida Gwaii. North of Haida Gwaii, the relative plate motion is essentially parallel to the plate boundary, and earthquakes are dominated by a motion from a **strike-slip fault**. In comparison to subduction earthquakes, which result in a motion from a **dip-slip fault**, little vertical movement of the seafloor occurs during a strike-slip earthquake, and the ensuing generation of a tsunami is less likely. The Mw 8.1 Queen Charlotte fault earthquake of 1949 that occurred west of Graham Island is Canada's strongest recorded earthquake (Cassidy et al., 2010), although it only resulted in a small tsunami in the ocean. Larger tsunami amplitudes were reported, but they are believed to have been generated by landslides triggered by the earthquake (Leonard et al., 2012).

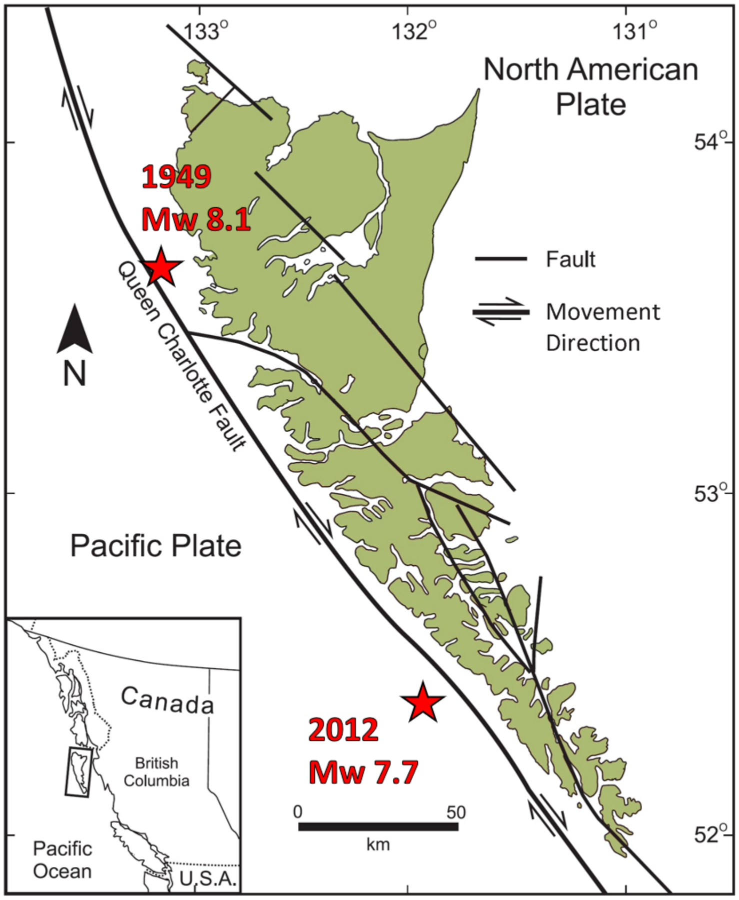

Figure 3-13.Queen Charlotte fault and location of significant earthquakes (adapted from Shellnutt and Dostal, 2019).

Further south along the Queen Charlotte fault, the relative motion of the plates becomes increasingly oblique to the plate boundary. Although a strike-slip motion still dominates, the plate motion can also include a vertical motion caused by a **thrust fault**, which has the potential of generating a tsunami. This fault produced another significant earthquake with a magnitude of Mw 7.7, which was the second strongest recorded earthquake in Canada. Because of its thrust motion, it was also the largest thrust earthquake recorded in offshore BC (Cassidy et al., 2014). The earthquake triggered a large tsunami with the wave runup reaching elevations up to 13 m above tide level on the western side of Moresby Island (Leonard and Bednarski, 2014). However, the amplitude of the tsunami was small on the northern and eastern coasts of Graham Island, as the propagation of the tsunami was mainly directed westward.

The 2012 Haida Gwaii earthquake involved a thrust rupture length of approximately 150 km. For a stronger earthquake occurring at that location along the Queen Charlotte fault, the rupture length could extend further north of Haida Gwaii (Leonard et al., 2012), and the potential thrust motion would generate a tsunami that would have a larger impact on the northern and eastern coasts of Graham Island. This study does not include a simulation of a tsunami generated by a thrust rupture extending to a location further north along the Queen Charlotte fault, but this simulation is recommended for further assessment.

Crustal Faults

Evidence of seismicity is also present in Hecate Strait between Haida Gwaii and the northern BC mainland where faults were identified to potentially result in a combination of both thrust and strike-slip faulting (Leonard et al., 2012). These faults include the Sandspit fault on the eastern side of Graham Island and other crustal faults to the east in Hecate Strait. The seismicity of these crustal faults is relatively low in comparison to other faults at tectonic boundaries where tsunamis have historically been recorded; therefore, crustal faults were not included in the analysis performed for this study. Nevertheless, given the more direct exposure of some of the study areas to potential tsunamis originating from crustal faults, NHC recommends additional assessments of crustal faults.

3.5 Expected Physical Effects of Climate Change

Climate change is expected to result in rising global sea levels stemming from melting ice and increased ocean volume due to increasing water temperature. Potential effects from climate change are discussed in more detail in Section 1.3.

According to Greenan et al. (2018), consistent, statistically significant trends in winds, storminess, and waves have not been found for most of the waters off Canada, in part due to limited data and strong effects of natural variability. However, off the Pacific coast, wave heights have been observed to increase in winter and decrease in summer, and these trends are projected to continue in future. Nevertheless, the uncertainty in past and future trends remains high, as it reflects the limited amount of published literature specific to winds and waves in the marine regions off Canada, the lack of high-quality historical data, and discrepancies in trends derived from different datasets.

Climate change is also expected to alter the oceans in ways that will have impacts on communities in Haida Gwaii that are outside the scope of this study. Changes in ocean acidification, change in the frequency and intensity of ocean heatwaves, and changes in ocean circulation patterns are just some that are noted in the recent scientific literature. Such changes could have notable effects on the shoreline and ocean ecosystems of Haida Gwaii.

The following sections provide some insights on the potential physical effects of climate change on the coastal areas of Haida Gwaii in relation to the hazards assessed as part of this study.

3.5.1 Effect on Coastal Storm Flooding

Future climate change is expected to increase the hazard from coastal storm flooding due to sea level rise and a possible increase in the frequency and intensity of coastal storms. Both of these may increase the hazard posed to communities as compared to present day conditions.

Most of the shorelines fronting the communities have intertidal zones which trigger wave breaking of longer period and larger waves offshore from the shoreline. With local sea level rise, less of this energy dissipation will occur before waves reach the shoreline. This effect has been modelled for 1 m and 2 m of local sea level rise on the shoreline and for this reason the hazard of coastal flooding is not entirely linear. For example, in some cases where wave breaking offshore causes notable attenuation of the incident wave heights on the shoreline, a 1 m increase in sea level causes more than a 1 m increase in the associated Flood Construction Level as the wave runup increases as a result of the deeper water immediately offshore of the shoreline.

3.5.2 Effects on Erosion

Rising sea levels and a possible increase in the frequency and intensity of coastal storms is generally expected to result in more frequent instances of storm events coinciding with tidal stages high enough to deliver waves to the upper shoreline. Where shorelines are comprised of readily erodible mobile materials, the response will likely be more rapid shoreline erosion and coastal retreat. Wave cutting into high banks and coastal bluffs will introduce sediments more rapidly into the coastal sediment transport system (including the onshore-offshore as well as alongshore transport systems) and so the response will not be consistent at all shoreline segments. More frequent incursions of marine water to the vegetation communities of the present-day backshore zone may induce short-term die-off in the transition to marine-type vegetation. This will likely initially destabilize surface sediments and initiate a cycle of relatively rapid shoreline adjustment.

Shoreline adjustments won’t occur in a consistent manner, even within similar shoreline types. The introduction of large amounts of new sediments to the coastal system will likely result in broader to the lower inter-tidal and shallow sub-tidal zone, which will in turn influence the wave processes at the upper shoreline. Effects on Tsunami Propagation

Modelling results obtained for this study suggest that the propagation of tsunamis off land is not meaningfully influenced by sea level rise. In other words, the amplitudes of the tsunami waves in the ocean are expected to be similar in the future. However, because of the greater inundation depth associated with sea-level rise, the behaviour of tsunami waves as they propagate overland will vary. Analysis of the model results at discrete locations in the study areas predicts that, in most locations, the increase in future inundation levels resulting from an Alaska tsunami would be approximately the same as the increase in sea level, except for Masset (village core) and Daajing Giids, where the increase in future inundation levels would be greater than the amount of sea-level rise itself. This prediction is further highlighted in Section 4.2 as general tsunami inundation levels for varying sea levels are presented (Table 4-2). The overwater current velocities induced by a tsunami are not expected to be considerably affected by sea level rise, although deeper water tends to reduce current velocities. The influence of sea level rise on inland flow velocities was not assessed.

4 MAIN FINDINGS

By providing a sound understanding of coastal hazards, a goal of this project is to provide information that will support risk assessments and improvements to existing emergency and evacuation plans, as well as inform the elaboration of future development plans. The following sections summarize the main findings of the study. Findings specific to each study area are presented in the associated community summary report.

4.1 Coastal Storm Flood Hazard

The coastal flood hazard varies along shorelines depending upon the exposure to ocean waves, the height of the shoreline, and the nature of the shoreline (i.e. steep riprap, mild slope beach, etc). Areas such as McIntyre Bay, facing Dixon Entrance, and Tlell are directly exposed to long period ocean waves, while more sheltered areas such as Port Clements have less exposure to coastal flood hazards.

BC guidance on the determination of the Flood Construction Level (FCL) is composed of three primary components: the Designated Flood Level (DFL), Wave Effects, and freeboard. The following table (Table 4-1) gives a summary of the DFL and associated FCL for both 1 m and 2 m of SLR.

Table 4-1. General Flood Construction Levels for planning purposes.

Area	DFL (1m SLR) [1] (m CGVD2013)	DFL (2m SLR) [1] (m CGVD2013)	Flood Construction Levels for Emergency Planning[2] (CGVD2013)	
			1 m SLR (m)	2 m SLR (m)
McIntyre Bay	4.1	5.1	7.7 – 8.6	8.8 – 10.5
Masset (Village Core)	4.0	5.0	5.2 – 5.7	6.2 – 6.7
Port Clements	3.1	4.1	4.7 – 5.5	5.3 – 6.4
Ferguson Bay	3.1	4.1	5.6	6.6
Juskatla	2.2	3.2	3.7	4.5
Tlell	5.1	6.1	8.1 – 9.6	12.2 – 14.4
Daajing Giids	4.9	5.9	6.0 – 8.2	7.0 – 9.2
Sandspit	4.9	5.9	7.4 - 9.6	8.5 – 11.1

Notes: SLR – sea-level rise

1. Designated Flood Level (DFL) is given for 1 and 2 metres of SLR. As per BC guidance, 1 m of SLR is for a planning window to year 2100, and 2 m of SLR is tentatively for a planning window of year 2150 to 2200. There remains high level of uncertainty as to the future timing of SLR so estimates of the timing of SLR should be considered accordingly. The DFL does not include any freeboard allowance.
2. The Flood Construction Level for emergency planning includes a freeboard allowance of 0.6 m. The FCL level varies spatially within an area and thus the range of FCL levels is noted.

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 allowing the backshore area to be dry in the absence of waves. Thus, when waves do occur, they 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. Inland from the breaking wave zone the overtopping water propagates as low bores over land. The profile view shown schematically in Figure 4-1 illustrates the segregation of the shoreline for consideration of the coastal flood hazard.

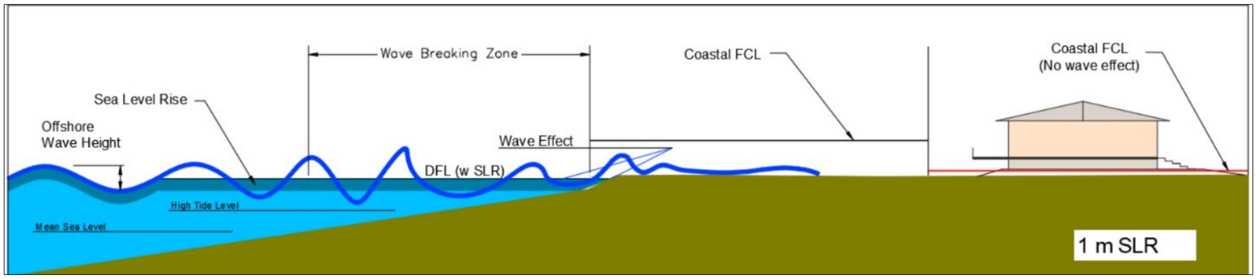

Figure 4-1. Profile view of FCL zones (not to scale). View shows project approach in which zone of wave breaking and runup on shoreline is estimated, and a lower in-land FCL zone is determined for a low area that could experience flooding from wave overtopping at the shoreline.

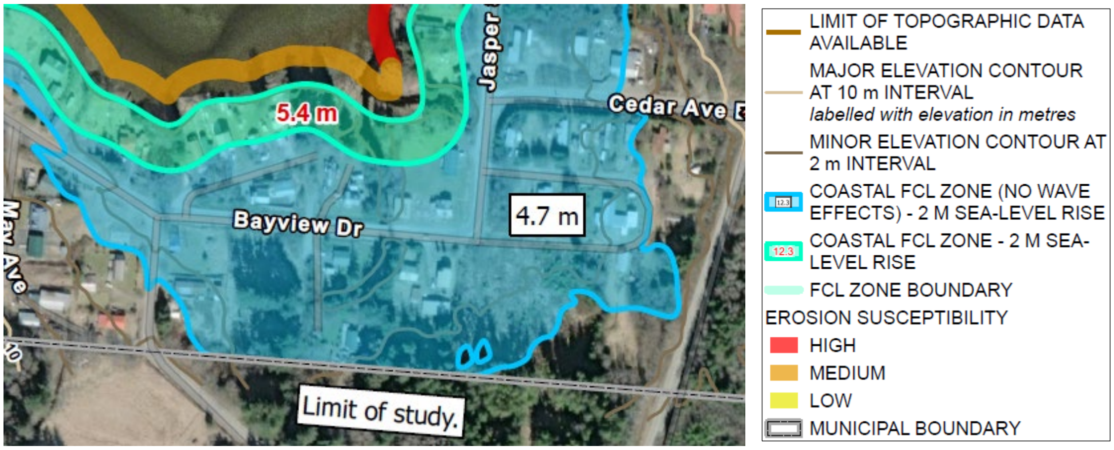

Figure 4-2. Example of a portion of a map view, showing the various coastal FCL zones. At the shoreline is the coastal FCL zone, while inland is a low lying area that is also at risk in a coastal flood event. The Coastal FCL zone (no wave effects) includes the highest DFL level for the area plus a 0.6m Freeboard allowance.

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.

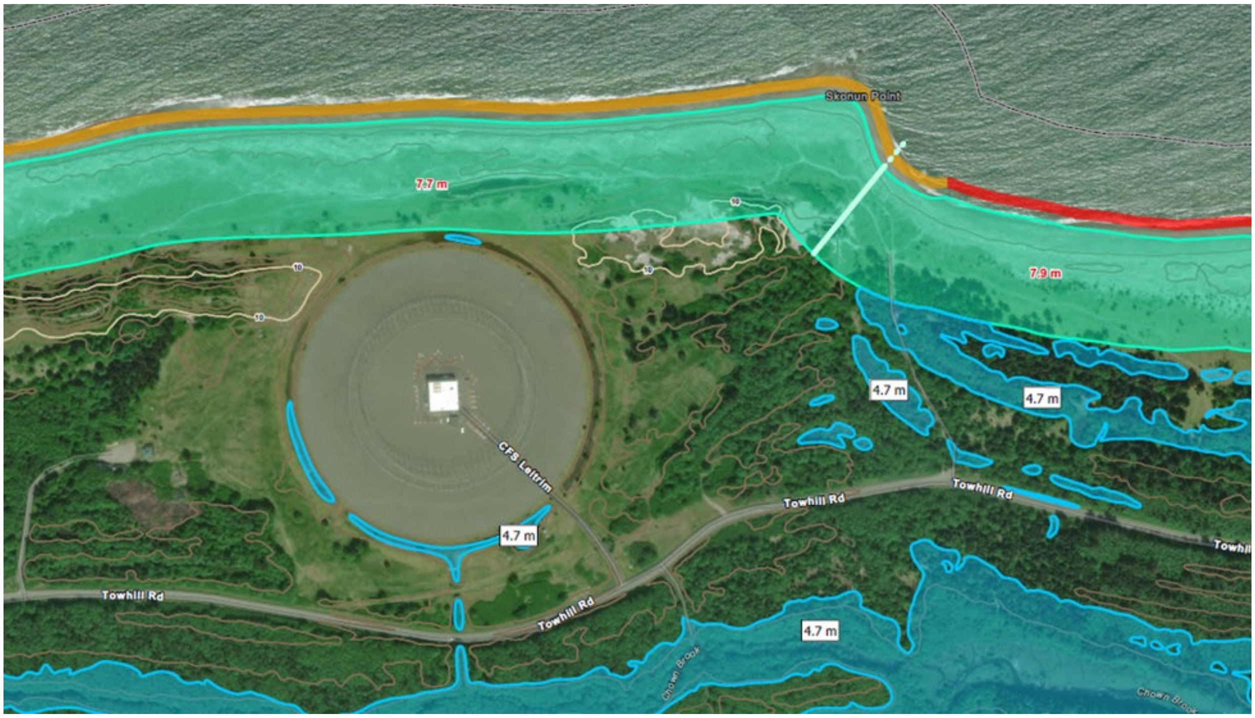

Figure 4-3. Example of a map view of 1 m SLR coastal flood hazard near Masset. The FCL zone is wider to account for the lack of shoreline erosion protection, and the potential for shoreline changes with 1 m of SLR. Backshore areas that are lowlying have an FCL that includes the DFL + Freeboard as small rivers and creeks can backwater in a extreme coastal flood event.

4.2 Tsunami Inundation Hazard

For a person caught in a tsunami the chance of survival is low, mainly due to the strong flow momentum and the floating debris that is often carried in the water during such an event. Studies have been conducted that evaluate human safety in flood conditions as a function of flow depth and velocity, as well as age and body characteristics; however, it is conservative to consider that anyone caught in tsunami flow is likely to become a casualty. For planning purposes, it is recommended to assume that people exposed to tsunami hazards will face an extreme risk of survival if they are unable to evacuate safely. Furthermore, the earthquakes associated with distant tsunamis, such as the ones considered for this study, may not be felt, and the ability to notify residents and visitors would rely entirely on warning systems, which may be challenging in remote areas of the island.

Tsunamis pose a risk anywhere near the shoreline as well as over water, whereas the overland tsunami hazard varies across the study area depending on local topography in conjunction with exposure to the incoming waves. Emergency managers, risk assessors, land use planners, and members of the public should consider this variability to help individuals understand their personal and their community's risk.

The Village of Masset and its jurisdiction are particularly susceptible to tsunami hazards due to the region's relatively low-lying topography in conjunction with its exposure to larger tsunami amplitudes. Located within Masset Inlet, the Village of Port Clements is relatively sheltered in comparison. Northern Tlell is also exposed to greater tsunami hazard due to its relatively lower topography, which is also is exacerbated by the proximity of the Tlell River, which can act as pathway for the inland propagation of tsunamis. The relatively steeper topography at the Village of Daajing Giids limits inland inundation and provides an opportunity for safe evacuation to elevated ground. The low-lying topography at the community of Sandspit exposes residents to large extents of inundation if the tsunami overflows the shoreline in Shingle Bay to the west, as well as the northern and eastern shorelines of the spit. Additional descriptions of the hazards at each study area are provided in the associated community summary report.

To support emergency planning, a summary of the general tsunami inundation levels and tsunami arrival times at the study areas are provided in Table 4-2. The inundation levels reported for emergency planning include a safety factor to account for the uncertainties inherent in the analysis and are representative of each general area. This general information should only be used for high-level planning, as tsunami inundation level can vary over small distances due to changes in local topography. Inundation levels reported do not include any freeboard to define safe refuge elevation. The inundation levels were established based on an Alaska tsunami, which was found to be more adverse than a Cascadia tsunami; however, since waves from a Cascadia tsunami are expected to arrive sooner following the triggering earthquake, the associated arrival times are recommended for emergency planning in the case of a distant tsunami, as reported below. The tsunami arrival time is defined as the time of the first maximum of the tsunami waves (Intergovernmental Oceanographic Commission, 2019), and flooding may begin before this moment is reached. Further assessment of the modelling results is required to better understand the progression of the estimated inundation over time.

Table 4-2. General tsunami inundation level for emergency planning and arrival times at selected locations.

Area	Arrival Time[1]	Inundation Level for Emergency Planning[2] (CGVD2013)		
		Current-day (m)	1 m SLR (m)	2 m SLR (m)
Masset Airport	2h 32min	6.9	7.6	8.6
Tow Hill	2h 37min	7.2	8.5	9.4
Masset (Village Core)	2h 38min	4.3	6.0	7.1
Port Clements	3h 31min	2.8	3.7	4.9
Ferguson Bay	3h 36min	1.8	2.9	3.8
Juskatla	4h 29min	0.4	1.4	2.4
Tlell	3h 49min	5.7	6.7	7.6
Daajing Giids	3h 52min	6.1	7.3	8.7
Sandspit	3h 43min	6.9	8.0	7.8

Notes: h – hour; min – minute; SLR – sea-level rise

1. Arrival time is defined as the time of the first maximum height of the first tsunami wave; flooding may begin before this moment is reached.
2. The inundation level for emergency planning includes a safety factor. Freeboard is not included. The location where the inundation level was determined generally corresponds to the location of maximum runup. The inundation level varies spatially within an area.

5 PLANNING FOR ADAPTATION AND SOLUTIONS

The following sections discuss general approaches for planning applicable to all communities. The reader is referred to community reports for further information specific to individual areas.

5.1 General Approaches

In recognition of the significant challenges that existing and potential future hazards pose to many coastal communities, five broad adaptation and mitigation approaches are commonly considered: (1) avoid, (2) accommodate, (3) retreat, (4) protect, and (5) advance (**Figure 5.1**). In practice, a combination of these approaches is often required as noted below.

AVOID

Avoid development in hazardous areas.

ACCOMODATE

Continue to use hazardous areas, but accommodate changes through alternative design practice or land-uses.

RETREAT

Relocate or abandon assets in hazardous areas. Allow natural systems to migrate inland.

PROTECT

Protect existing land-uses from hazards using ‘hard’ or ‘soft’ techniques.

ADVANCE

Extend land-use into hazardous areas. Frequently combined with ‘protect’ approaches.

Figure 5.1 Five main approaches to coastal flood and erosion hazard adaptation and mitigation.

Avoiding development in hazardous areas through ‘no-build’ areas is often the most effective approach to mitigating coastal flood and erosion hazards. Retreat involves the strategic relocation of people, buildings, and infrastructure outside of high-risk areas. Retreat has the benefit of making space for natural systems to migrate inland to match the pace of sea level rise (i.e. avoiding coastal squeeze), but frequently has perceived negative impacts to traditional, recreational, residential, or commercial uses of the land. Further, some community shoreline areas are already intensely utilized and require access to the shoreline (i.e. for marinas, fish processing, etc), meaning that this approach may not be feasible everywhere.

Advance involves strategically extending the land into the sea, creating trade-offs between sub-tidal, intertidal, and upland areas. Often, advance creates new ‘at risk’ land, but helps to protect existing inland areas from erosion and flooding. Protect, accommodate, and advance type approaches all typically involve implementing structural measures to mitigate flood or erosion risk and may have negative impacts on shoreline ecology and natural coastal processes. Protect and accommodate approaches may also be carried out in partial combination with the retreat approach. Protect and accommodate type approaches often include:

- Raising the elevation of low areas
- Building floodwalls (bulkheads, seawalls, revetments, Dikes)
- Groynes
- Headlands
- Offshore breakwaters and islands
- Beach nourishments
- Wetlands and salt marsh enhancements
- Building submerged reef

Accommodate and protect approaches may be split further into ‘reach-based’ and ‘site-based approaches’ as per **Figure 5.2**.

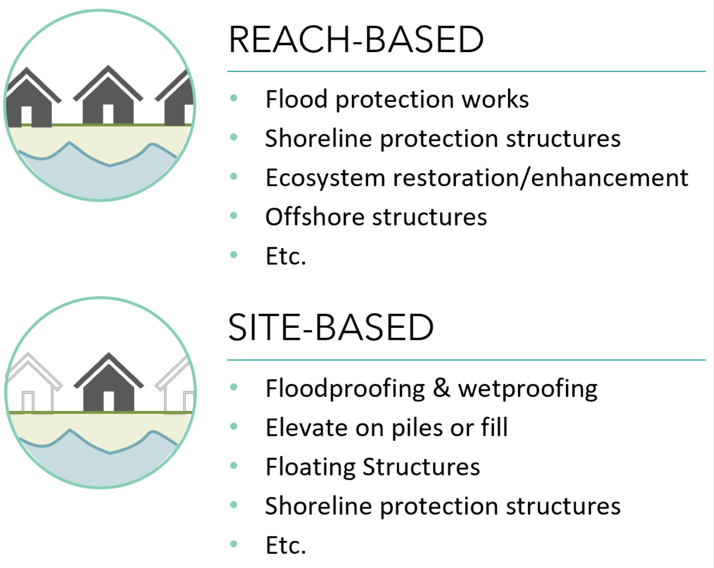

Figure 5.2 Site-based vs reach-based approaches to accommodate and protect coastal hazards.

Notably, many of these approaches can be constructed together to enhance benefits. For example, beach nourishment and headlands could be constructed to raise beach profiles and reduce wave runup. Additional elements may also be added to many of the approaches to enhance ecological, social and ceremonial, and recreational values. For example, benches can be added to a rock revetment to enhance intertidal habitat and buffers may be established at the crest of beach nourishments and rock revetments to provide space for riparian vegetation.

5.2 Timeline for Adaptation to SLR

Coastal Flood Hazards exist in low lying areas at present, and future SLR will increase the frequency at which coastal flooding occurs. However, SLR is a slowly occurring process and the hazards from 1 m and 2 m of SLR as depicted on the hazard maps will not occur for some time. This provides opportunities for community level planning and adaptation to occur to reduce the risks associated with the hazards.

The timing of when various levels of SLR will occur is highly uncertain. The latest science (IPCC WGI, 2021) suggests that 2 m of SLR could occur (low probability) as soon as year 2100 but is much more likely to occur sometime after 2150. Similarly, there is a high confidence that based upon present trends 1 m of SLR will occur, but again the timing is uncertain. There is no means at this time to provide more accurate estimates given the uncertainties in both the science and future anthropogenic behaviours. Planning must occur now with acceptance and understanding of the uncertainty.

From a discussion on planning opportunities, it is worth considering infrastructure and development as:

1. Critical Community Infrastructure (Key transportation networks, Emergency Services, water and sewer, utility corridors, etc.)
2. Residential and Commercial Development zones

3. Parks and community spaces

Critical community infrastructure is of high value to communities and deserves long range planning to ensure that future investments in upgrades support increased resiliency to climate change. Investments in new infrastructure should not occur in hazard zones if possible, while upgrades to existing infrastructure should consider the hazard exposure.

One example for discussion is the highway that is exposed to erosion and coastal flood hazards in the Tlell area. A decision will need to be made on whether to keep this infrastructure in its present alignment and protect against erosion and flood hazards, or to retreat to an alignment corridor that is removed from coastal flood hazards. This is not an easy decision and will involve many trade-offs given the existing infrastructure. The decision on whether to protect or retreat (or other options) requires community consultation and planning and coordination with other levels of government which will require time, and for that reason alone suggests planning studies to support such decisions should begin in the near future. Major infrastructure can take upwards of 10 to 20 years from initial planning to actual construction which would put the timeframe for mitigation of risk in the 2050 time horizon for project completion.

Residential and commercial infrastructure tends to have service lives on buildings of 30 to 80 years. One tool commonly used to reduce future risk from flood hazard is through zoning and building by-laws that discourage (or prevent) new development in hazardous areas. In this way, as existing infrastructure ages out and requires replacement over time there is a reduction in the general community risk. Such strategies can lead to a gradual retreat from shorelines and allow for community level benefits of increased shoreline access (flood prone areas can become public park spaces). However, such strategies can also have financial impacts to property owners who are in hazardous areas. Shoreline properties that will flood due to future SLR will not have future land value unless protected (either individually or at community scale), and for this reason property owners in hazardous areas typically advocate for protection of such properties. It is thus important at a community level that the trade-offs and economic benefits are considered against the long-term costs to the entire community of protection strategies.

In summary, we have the following high-level recommendations for planning:

<u>5-15 years (~ 2027-2042)</u>

- Undertake reviews of the viability of critical Infrastructure with respect to coastal flood and erosion hazards. For infrastructure at risk, or approaching end of service life, begin planning as required with other levels of government for replacements that will mitigate climate risks in the future.
- Update Community long-term plans.
- Refine zoning and development by-laws to encourage actions in future development that will reduce risk to coastal flood hazards.
- Undertake a coastal process study to provide a technical basis to support decision making related to future approvals of new seawalls and revetments to protect against coastal flooding and erosion. Depending upon the sediment transport processes and the complexity of the intertidal ecology, such structures may not work efficiently (cause scour and require significant

maintenance) or cause harm to the local environment. Such a study would help to inform decision making in specific areas on the viability of future adaptation pathways.

- Identify co-benefit projects that can reduce erosion and flood hazard risks while also improving habitat and intertidal ecology. Begin implementation as opportunity allows.
- Establish a climate adaptation working group specific to coastal flood hazards for Haida Gwaii communities to allow for sharing of ideas, and for coordination on regional issues with Provincial agencies (such as Ministry of Transportation and Infrastructure).

15-30 years (~ 2040-2055)

- Review and update flood hazard maps with latest SLR science predictions (i.e., is SLR occurring faster or slower than predicted at the time of this study?)
- Undertake projects to improve shoreline resilience to erosion as and where appropriate.
- Begin implementation of plans to mitigate the coastal flood hazard to communities for 1 m of SLR and continue long-term climate adaptation planning.

5.3 Tsunami Preparation

Tsunami hazards present a different risk in that there is a low probability of occurrence, but high consequence from an event. Further, the chance of occurrence does not change in time in the way that climate change will worsen in time. In this manner, tsunami present an immediate hazard.

Planning to mitigate consequences of tsunami should begin as soon as practical. In the short term:

- Update Emergency Management Plans to include tsunami response. Plans should address:
  - Planning and Community engagement
  - Notifications
  - Evacuation Routes & shelters.

The path to preparedness is an ‘all-of-society’ responsibility that is community driven and collaborative in nature.

At the neighbourhood level, recommendations for action-based approaches that support overall community development and create safe spaces for difficult conversations about tsunami risk. Preparedness activities can be promoted at community gatherings, enhance existing volunteer group capability, and be linked to local schools, mariners, cultural groups, and businesses as well as connecting with other communities across the globe with tsunami experience.

6 SUMMARY AND CONCLUSIONS

This study found that the shorelines of Haida Gwaii communities are exposed to coastal flood and erosion hazards from both extreme storm events and from tsunamis. The study involved extensive analysis to determine the spatial extents of the hazard areas. Maps showing the results of the analysis have been prepared to assist communities in developing plans to mitigate future risks. Main conclusions and recommendations are summarized as follows:

- Planning for adaptation to 1 m of future SLR is recommended and prudent based on the presently available science on climate change.
- The future rate of SLR and timing estimates on when various levels of SLR will occur in the future remain uncertain; however, 1 m of SLR at year 2100 is possible and may not be conservative depending on the rate of ice loss in Arctic regions of the planet (IPCC WGI, 2021).
- Low areas of Haida Gwaii shorelines are at risk of coastal flooding from both storm events and tsunamis, and this risk increases with SLR.
- Adaptation planning should begin soon to mitigate the risks of coastal flood hazards, as implementation of various adaptation pathways may take many years to undertake and complete.

It is important to consider that the risk of coastal flooding from storm events is an annual occurrence, and the likelihood of severe flooding that causes damages will increase over time as SLR increases. In contrast, the probability of a large tsunami is less likely to occur at any given time but may occur at any time. The planning and mitigation strategies for these flood events is thus different. Long-term community changes to improve resilience against coastal flooding can occur on a similar time scale to the rate of SLR. The slow pace of SLR currently allows for a planning and implementation response window. This pace allows time for design and construction of new infrastructure that is either more resilient or located in less hazardous areas to replace existing infrastructure as it reaches the end of its life. In contrast, tsunami hazards are immediate and represent a risk to life for people living and working near shorelines. Plans should therefore be developed for communication and evacuation procedures, safe refuge during a tsunami event and for a suitable period following the event, and for recovery operations. Of note for the entire Haida Gwaii community is that a major tsunami may cause significant damages to all major transportation infrastructure, including airports, harbours and marinas, ferry docks, and roadways near the coasts. Such damage will inhibit emergency response following a tsunami and subsequent recovery efforts and will require communities to be self-reliant for some time and capable of supporting their citizens. It is also noted that the hospital in Masset is located in a tsunami hazard zone and more detailed analysis of the level of potential risk to this specific structure is warranted as evacuation of medical facilities may pose greater harm than remaining in place if the flood level at the facility is very low.

Planning new developments in hazardous areas can create **infrastructure-traps** in which future generations are financially obligated to maintain protection works for these areas. The long-term costs of providing protection against coastal flooding in the context of rising sea levels can far exceed the initial capital costs of such projects. For this reason, community planning must consider the financial risks to protecting infrastructure and community assets in hazardous areas. In the very long term, strategies to avoid, accommodate, and retreat tend to yield the greatest overall benefit as they reduce the requirements for active protection and maintenance (such as for seawalls).

The community reports provide more specific analysis of results and findings for each individual community and should be referenced in addition to this main report.

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APPENDIX A

DIGITAL ELEVATION MODEL DEVELOPMENT

APPENDIX B

METEOROLOGICAL AND OCEANOGRAPHIC CONDITIONS

APPENDIX C

STORM WAVE MODELLING

APPENDIX D

TSUNAMI MODELLING

APPENDIX E

REGIONAL OVERWATER TSUNAMI HAZARD MAPS