



Photo: Lighthouse at Yuquot, courtesy of Canadian Coast Guard

Northwest Vancouver Island Tsunami Risk Assessment Phase II Final Report

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DISCLAIMER

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Georgina Amos, Elder	Ehattesaht First Nation
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Chief Tom Nelson, Elder	Quatsino First Nation
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EXECUTIVE SUMMARY

Characterized by its natural beauty, rich history, and open exposure to the Pacific Ocean, the northwest coast of Vancouver Island is also becoming known for its vulnerability to tsunami hazards. This idyllic region is directly exposed to both local tsunami sources, such as the Cascadia subduction zone¹, and distant tsunami sources, including the Aleutian subduction zone in Alaska. Recent major tsunamis around the world have demonstrated their potential for widespread destruction and danger, and this region is no exception.

In 2020, the Strathcona Regional District (SRD), in partnership with the Ka:'yu:'k't'h' / Che:k:tle7et'h' First Nations and the Nuchatlaht First Nation, commissioned a tsunami risk assessment for the region with funding from the Province of BC through the Union of BC Municipalities. This comprehensive study is the result of a collaboration between Northwest Hydraulic Consultants Ltd., Ocean Networks Canada Society, and Northwest Seismic Consultants Ltd.. The goal of this project was to better understand the tsunami hazard and risk along the northwest coast of Vancouver Island by using tsunami modelling and drawing upon community experience and Indigenous Knowledge.

The study area for this initial assessment is vast, extending 200 km from Gold River northward to Cape Scott (see figure below) and includes the communities of Gold River (waterfront), Tahsis, Zeballos, Port Alice, Winter Harbour, Quatsino, and Holberg, as well as several Indigenous communities, including the Ka:'yu:'k't'h'/Che:k:tle7et'h', Nuchatlaht, Ehattesaht Chinehkint, Mowachaht/Muchalaht, and Quatsino First Nations. Many historic community locations, sacred sites, fishing and hunting areas, shellfish harvesting sites, and old village sites are situated in this area.

Due to the large geographical area covered by the assessment, the project was divided into two phases. Phase I of the project included communities in Tahsis Inlet, Esperanza Inlet, and Kyuquot Sound and was completed in 2022. With funding provided by All One Fund, ONC engaged NHC to expand the risk assessment to communities in Nootka Sound and Quatsino Sound (Phase II). The second project phase also includes initiatives for increasing the public's awareness of tsunami hazards. This report summarized the work the study team undertook as part of Phase II.

¹ The place where two of Earth's tectonic plates collide, with one plate sinking into the Earth's mantle underneath the other plate.



Study area and project phases.

The project encompasses three main components, as summarized below:

1. **Community and Indigenous Engagement** – The study team produced a project webpage and completed a community survey during Phase I of the project. Phase II has involved developing an online story map to help concerned residents to better understand and contextualize the study findings. Several virtual public engagement meetings were held throughout the project to provide information and context by inviting community members to share experiences, knowledge, and lived experiences in local communities. The team conducted interviews with participating Indigenous Elders and Knowledge Holders, and a documentary film was produced to share these historical accounts with a wider audience. In addition, the study team consulted two advisory groups, one for each project phase, at various project milestones to disseminate information, provide guidance, and promote the exchange of knowledge. Educational modules were also delivered at schools in the study area to further increase awareness of tsunami risk.

2. **Tsunami Hazard Analysis and Mapping** – The study team simulated two tsunami sources: one from the nearby Cascadia subduction zone and another from the more distant Aleutian subduction zone in Alaska. The team then developed tsunami flood hazard or overland inundation maps for 50 priority areas within the Phase I and Phase II study areas. In response to these results, the SRD has designed and installed tsunami signage at key locations within SRD jurisdiction. In addition, overwater hazards, such as maximum tsunami wave amplitude and maximum tsunami-induced current speed, were mapped across the entire region.
3. **Risk Assessment** – Based on the tsunami hazard analysis and mapping, the study team completed a community-level risk assessment to identify potential risk to people, roads, and buildings, as well as several critical assets, and developed assets at risk maps to identify assets exposed to tsunami hazard.

General inundation levels for emergency planning were defined considering both present day and future sea levels and are presented in the table below. These inundation levels include a safety factor to account for the uncertainties in the analysis and are representative of one general area. This information should only be used for high-level planning, as tsunami inundation can vary over small distances as a function of local topography. Tsunami inundation levels corresponding to present-day sea level were mapped as part of this assignment as a starting point to understand tsunami risk to life safety. Model simulations including sea level rise were undertaken by the project team and are available to support longer-term development and planning, but the sea level rise simulations have not been mapped for this assignment.

General tsunami inundation level for emergency planning and arrival times at selected locations.

Area	Cascadia Tsunami			Alaska Tsunami		
	Arrival Time ¹	Inundation Level for Emergency Planning ² (CGVD2013)		Arrival Time	Inundation Level for Emergency Planning (CGVD2013)	
		Present day	Year 2100		Present day	Year 2100
Gold River Waterfront	0h59m	11.2 m	11.9 m	3h44m	6.8	8.0 m
Tlupana Inlet	0h50m	17.2 m	18.6 m	3h36m	4.4	5.6 m
Yuquot	0h28m	11.9 m	13.4 m	3h13m	2.9	4.2 m
Quatsino	0h38m	5.9 m	6.8 m	3h06m	3.6	4.8 m
Winter Harbour	0h35m	5.4 m	6.5 m	2h58m	4.1	5.0 m
Port Alice	0h57m	5.8 m	6.8 m	3h16m	3.6	4.8 m
Holberg	1h35m	3.3 m	4.5 m	3h45m	2.9	4.1 m
Coal Harbour	1h22m	2.3 m	3.6 m	3h37m	2.1	3.3 m

Notes:

1. Arrival time is defined as the time of the first maximum of the tsunami waves and flooding may begin before this moment is reached.
2. The inundation level for emergency planning includes a safety factor and accounts for the local subsidence associated to the triggering earthquake, as applicable. Freeboard is not included. The location where the inundation level was determined generally corresponds to the location of maximum runup.
3. CGVD2013 stands for the Canadian Geodetic Vertical Datum of 2013.

The outcomes of the risk analysis can strengthen hazard awareness and the four key components of emergency management: mitigation, preparedness, response, and recovery. Emergency management plans are discussed as well as the status of the above components in terms of best practices and regulations, progress achieved during this project, and possible paths forward for the region. Furthermore, various measures were suggested to reduce tsunami risk in conjunction with developing and updating tsunami emergency management plans. Notably, high-level evacuation recommendations are provided for higher risk areas, which include:

- Gold River Waterfront
- Yuquot
- Hamlet of Quatsino
- Winter Harbour
- Port Alice
- Holberg

Such recommendations are only meant to support reviews of existing evacuation plans and are by no means final or official, as more assessment and public engagement is required to carefully develop evacuation plans for each community.

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 are often carried in the water during such event. While studies exist to evaluate human safety in flood conditions as a function of flow depth and velocity, as well as age and body characteristics, 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 experience extreme risk of survival if unable to evacuate safely. Overland tsunami hazard varies across the study area depending on the tsunami source, whereas tsunamis pose a risk anywhere near the shoreline as well as overwater.

No specific site reconnaissance was performed as part of this assignment and no structural nor seismic assessment of buildings and infrastructure was performed in the study area. Nevertheless, it is assumed for this relatively remote region that buildings exposed to direct tsunami inundation would be severely damaged and lose their function.

The study results are based on a limited number of tsunami scenarios for subduction earthquakes with specific seismic parameters. Tsunami hazards and effects can vary for different earthquakes that may occur. The Cascadia earthquake and tsunami scenario analysed correspond to a severe event according to the paleoseismic record of past earthquakes and is known to be the worst scenario readily available for analysis. However, this record suggests that at least one stronger earthquake occurred in the past 10,000 years. Including a safety factor for the inundation mapping reduces the residual risk associated to a stronger event but may not eliminate it. Hazards from tsunamis generated by landslide (subaerial or submarine) have not been assessed as part of this project. Such landslide may be triggered by both crustal² and subduction earthquakes.

² An earthquake generated at a zone of relatively shallow fractures that separate different blocks of the earth's crust where tectonic forces concentrate.

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ABBREVIATIONS

Acronym / Abbreviation	Definition
ASCE	American Society of Civil Engineers
BC	British Columbia
CCG	Canadian Coast Guard
CDEM	Canadian digital elevation model
CGVD2013	Canadian Geodetic Vertical Datum of 2013
CHS	Canadian Hydrographic Service
DEM	digital elevation model
EMBC	Emergency Management BC
FEMA	(US) Federal Emergency Management Agency
FSR	forestry service road
GIS	geographic information system
HHWLT	higher high water, large tide
HHWMT	higher high water, mean tide
LIDAR	light detection and ranging
MHW	mean high water
MHHW	mean higher high water
NHC	Northwest Hydraulic Consultants Ltd.
NOAA	National Oceanographic and Atmospheric Administration
NRCan	Natural Resources Canada
NSC	Northwest Seismic Consultants Ltd.
NTHMP	United States National Tsunami Hazard Mitigation Program
ONC	Ocean Networks Canada Society
RCP	representative concentration pathways
RDMW	Regional District of Mount Waddington
SLR	sea level rise
SRD	Strathcona Regional District
TRSI	Terra Remote Sensing Inc.
TVE	tsunami vertical evacuation
US	United States
WGS84	World Geodetic System of 1984

SYMBOLS AND UNITS OF MEASURE

Symbol / Unit of Measure	Definition
km	kilometre
km ²	square kilometre
m	metre
m/s	metres per second
m ²	square metre
Mw	earthquake moment magnitude

GLOSSARY

Term	Definition
alluvial fan	An accumulation of sediments at the mouth of fast-moving mountain streams where sediments deposit as the water slows down.
astronomical forcing	Influence driven by astronomical forces associated with the movement of celestial bodies.
atmospheric forcing	Influence by forces associated with atmospheric phenomena.
barometric pressure	The measurement of air pressure in the atmosphere.
bathymetry	The measurement of water depth in oceans, rivers, or lakes.
Boussinesq model	A model that solves the Boussinesq equations, which comprise a set of nonlinear, partial differential equations that describe the behaviour of fluids.
Canadian Geodetic Vertical Datum of 2013 (CGVD2013)	Reference standard for heights across Canada; replaced the Canadian Geodetic Vertical Datum of 1928; defined by a surface of equal gravitational potential (equipotential surface), which represents, by convention, the coastal mean sea level for North America.
chart datum	For navigational safety, depths on a chart are shown from a low water surface or a low water datum. Chart datum is selected so that the water level will seldom fall below it and rarely with less depth available than what is portrayed on the chart. On most Canadian coastal charts, the surface of lower low water, large tide (also known as LLWLT) has been adopted as chart datum.
core sample	A cylindrical section of overburden material, such as sediment, ice, or rock, obtained by drilling with special drills that lift out an intact part of the material.
crustal velocity model	A digital representation of the rate and direction of the Earth's crustal movement over time.

digital elevation model	A digital representation of the Earth’s surface both above and below water.
fault line	A planar fracture or discontinuity across a volume of rock with significant displacement from mass movement of the rock.
freeboard	A vertical distance added to the actual calculated flood level to accommodate for underlying uncertainties in the analysis; selection of this distance also includes consideration of the risks and implications associated with the water level exceeding the flood level.
full feature point	A LiDAR survey point that is not classified in terms of the type of surface it relates to (e.g., bare Earth, vegetation, building, water).
global SLR (sea level rise)	An increase in the average height of the entire ocean surface.
higher high water, large tide (HHWLT)	The average of the yearly highest high tides predicted from each year over a tidal epoch, as defined by the Canadian Hydrographic Service (CHS) in Canada.
higher high water, mean tide (HHWMT)	The average of the higher high-water height of each tidal day observed over a tidal epoch, as defined by the CHS in Canada.
LiDAR (light detection and ranging)	An aerial survey method to infer surface elevation by using a laser to target from the air and measuring the time for the reflected light to return to a receiver on an airborne craft (i.e., airplane, drone).
liquefaction	A phenomenon in which earthquake shaking or other rapid loading reduce the strength and stiffness of soil .
mean high water (MHW)	The average of all the high-water heights observed over a tidal epoch, as defined by the US National Oceanic and Atmospheric Administration (NOAA).
mean higher high water (MHHW)	The average of the higher high-water height of each tidal day observed over a tidal epoch, as defined by the NOAA; similar to the HHWMT level defined by the CHS in Canada.
megathrust	A very strong earthquake that occurs at a subduction zone.
microfossil assemblages	Samples containing the tiny remains of bacteria, protists (single cell organisms), fungi, animals, and plants that are useful in age-dating.
ortho imagery	Aerial photographs or satellite images that have been geometrically corrected to produce a uniform scale, enabling the use of the image(s) with a specified map projection; can be used to measure true distances due to the ortho image’s accurate representation of the Earth’s surface.
paleoseismic	Earthquakes that have been recorded geologically, most of them unknown from human descriptions or seismograms. Geologic records of past earthquakes can include faulted layers of sediment and rock, injections of liquefied sand, landslides, abruptly raised or lowered shorelines, and tsunami deposits (Ferguson et al., 2022).

percentile	Each of the 100 equal groups into which a statistical population (i.e., a sample) can be divided according to the distribution of values of a particular variable.
post-event time interval	The time difference between one event and the next.
radiative forcing	The amount of solar energy that enters the Earth’s atmosphere in comparison to the amount of energy that leaves it.
relative sea level rise (SLR)	The increase in the sea level relative to the elevation of the land at one location.
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.
resonance	Caused by waves entering a semi-enclosed waterbody (e.g., harbour, fjord, inlet) within a similar period as the natural high-tide period of the waterbody; can cause amplification of the wave height and extend the duration of the wave activity within the waterbody.
Ring of Fire	A path around the Pacific Ocean that is characterized by active volcanoes and frequent earthquakes where several subduction zones are also present.
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.
subaerial	Something that is existing, occurring, or formed in the open air or on the Earth’s surface, not underwater or underground.
subsidence	The downward vertical movement of the Earth’s surface, which can be caused by both natural processes and human activities.
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.
tidal epoch	A 19-year period established for collecting information on water levels and calculating tidal datum values.
tidal heights	The vertical distances rising or falling water due to the tide. Standard heights are published by the CHS in Canadian waters, which are established statistically.
time series	Data measured over time at evenly spaced intervals.
topography	The study of the forms and features of land surfaces, which provides measurements of land elevation.
tsunami	A series of travelling ocean waves of extremely long length and period that have been triggered by a large earthquake occurring near or under the ocean or by a volcanic eruption, submarine landslide, or onshore landslide.

tsunami arrival time	The time when the first maximum tsunami wave arrives; flooding may begin before this moment is reached.
tsunami drawdown	The period before the arrival of a first tsunami wave, when the sea level recedes, moving the shoreline seaward and exposing fish, rocks, and the sea bottom; a natural warning sign of an approaching tsunami; a function of physical processes related to tsunami propagation that may not occur before the arrival of the first tsunami wave.
tsunami inundation depth	The measurement of the depth or height of a tsunami above ground level at a specific location.
tsunami runup	The highest upland elevation reached by a tsunami when compared to a reference plane (i.e., vertical datum).
tsunami vertical evacuation	Evacuation above rising waters into buildings or other structures that have the needed strength and resilience to resist tsunami loads and effects.
tsunami wave amplitude	The vertical distance between the crest of a tsunami wave and a reference plane consisting of the still water level (i.e., the water level without the influence of the tsunami).
tsunami wave height	The vertical distance between the crest and the trough of a wave.
tsunami wave velocity	The speed of a wave form as it propagates across a water body (not related to how fast the water itself moves).
turbidites	Sea-bottom deposits formed by massive slope failures in response to excessive sedimentation load and sometimes earthquake shaking, which cause the sediments to slide down to the ocean bottom, creating a turbidite.
uplift	Upward vertical movement of the Earth's surface, which can be caused by both natural processes and human activities.
wavelength	The distance between two identical points on successive waves, e.g., from crest to crest or trough to trough.
wave shoaling	Occurs when surface waves enter shallower water, causing an increase in wave height and a change in the wave's behaviour.
World Geodetic System of 1984	The reference standard for world coordinates (latitude and longitude) used in cartography and navigation.

1 INTRODUCTION

Characterized by its natural beauty, rich history, and open exposure to the Pacific Ocean, the northwest coast of Vancouver Island is also becoming known for its vulnerability to **tsunami** hazards. This idyllic region is directly exposed to both local tsunami sources, such as the Cascadia **subduction zone**, and distant tsunami sources, including the Aleutian subduction zone in Alaska. Recent major tsunamis around the world have demonstrated their potential for widespread destruction and danger, and this region is no exception.

In 2020, the Strathcona Regional District (SRD), in partnership with the Ka:'yu:'k't'h' / Che:k:tles7et'h' First Nations and the Nuchatlaht First Nation, commissioned a tsunami risk assessment for the region with funding from the Province of BC through the Union of BC Municipalities. This comprehensive study is the result of a collaboration between Northwest Hydraulic Consultants Ltd. (NHC), Ocean Networks Canada Society (ONC), and Northwest Seismic Consultants Ltd. (NSC). The goal of this project was to better understand the tsunami hazard and risk along the northwest coast of Vancouver Island by using tsunami modelling and drawing upon community experience and Indigenous Knowledge.

The study area for this initial assessment is vast, extending 200 km from Gold River northward to Cape Scott (Figure 1.1) and includes the communities of Gold River (waterfront), Tahsis, Zeballos, Port Alice, Winter Harbour, Quatsino, and Holberg, as well as several Indigenous communities, including the Ka:'yu:'k't'h'/Che:k:tles7et'h', Nuchatlaht, Ehattesaht Chinehkint, Mowachaht/Muchalaht, and Quatsino First Nations. Many historic community locations, sacred sites, fishing and hunting areas, shellfish harvesting sites, and old village sites are situated in this area.

Due to the large geographical area covered by the assessment, the project was divided into two phases. Phase I of the project included communities in Tahsis Inlet, Esperanza Inlet, and Kyuquot Sound and was completed in 2022. With funding provided by All One Fund, ONC engaged NHC to expand the risk assessment to communities in Nootka Sound and Quatsino Sound (Phase II). The second project phase also includes initiatives for increasing the public's awareness of tsunami hazards.

The community-level risk assessment undertaken as part of this project focuses on life safety and uses scenario-based tsunami hazard analysis and mapping to identify potential risks to people and assets. These risk analysis outcomes can strengthen hazard awareness while supporting the four pillars of emergency management: mitigation, preparedness, response, and recovery. The information from this investigation is expected to support development and planning decisions and improve existing emergency and evacuation planning processes.



Figure 1.1 Study area and project phases.

1.1 Tsunami Exposure

As with many other areas along the British Columbia (BC) coast, Vancouver Island is exposed to tsunamis originating along the Pacific Ocean's **Ring of Fire**, a nearly continuous series of tsunamigenic³ subduction zones surrounding the ocean (Figure 1.2).

Several major subduction earthquakes have occurred globally 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

³ Definition of tsunamigenic: capable of generating a tsunami.

the town of Port Alberni, BC, during the night of March 27, 1964. According to the United States Geological Survey (USGS, n.d.), this tsunami was generated south of the Alaskan coast by a subduction earthquake with a moment magnitude (M_w) of 9.2. It reached Vancouver Island approximately 3 to 4 hours after the earthquake.



Source: Adapted from Atwater et al. (2005).

Figure 1.2 Subduction zones around the Pacific Ocean and locations of several major tsunamigenic earthquakes. This area is referred to as the Ring of Fire. The proximity of the Cascadia subduction zone makes Vancouver Island susceptible to potentially large tsunami waves, providing a short warning time between an earthquake and the arrival of a tsunami on the open coast – less than 30 minutes in some areas. Geological studies, historical records from Japan, and oral history from Indigenous people 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., 2015). The earthquake associated with this tsunami is estimated to have had an M_w of approximately 9.0 (Witter et al., 2013).

Based on the assessment of other large historical tsunamis in the Pacific Ocean, Ferguson et al. (2022) determined that future tsunamis along the Cascadia and Alaska subduction zones (similar to the 1700 and 1964 tsunamis, respectively) present the greatest risks to the BC coast and thus merit a hazard assessment.

1.2 Approach and Methodology

The project focuses on the importance of making space for everyone to participate and communicate when identifying, assessing, reducing, and managing disaster risk. The study team actively sought input from people in communities throughout the study area – in particular, from Indigenous community members living at the forefront of tsunami risk who have fostered disaster resilience and acquired

knowledge over millennia. The study approach for this risk assessment leverages input from Indigenous Knowledge Holders and community engagement participants with information produced from scientific tsunami modelling and mapping. This synergetic approach seeks to strengthen outcomes by better informing communities and thus better enabling community members to understand and adopt study recommendations.

The project is divided into three components, which are summarized below:

4. **Community and Indigenous Engagement** – The study team produced a project webpage and completed a community survey during Phase I of the project. Phase II has involved developing an online story map⁴ to help concerned residents to better understand and contextualize the study findings. Several virtual public engagement meetings were held throughout the project to provide information and context by inviting community members to share experiences, knowledge, and lived histories in local communities. The team conducted interviews with participating Indigenous Elders and Knowledge Holders, and a documentary film was produced to share these historical accounts with a wider audience. In addition, the study team consulted two advisory groups, one for each project phase, at various project milestones to disseminate information, provide guidance, and promote the exchange of knowledge. Educational modules were also delivered at schools in the study area to further increase awareness of tsunami risk.
5. **Tsunami Hazard Analysis and Mapping** – The study team simulated two tsunami sources: one from the nearby Cascadia subduction zone and another from the more distant Aleutian subduction zone in Alaska. The team then developed tsunami flood hazard or overland inundation maps for 50 priority areas within the Phase I and Phase II study areas. In response to these results, the SRD has designed and installed tsunami signage at key locations within SRD jurisdiction. In addition, overwater hazards, such as maximum **tsunami wave amplitude** and maximum tsunami-induced current speed⁵, were mapped across the entire region.
6. **Risk Assessment** – Based on the overland inundation mapping, the project team conducted a community-level risk assessment to identify potential risks to people, roads, and buildings, as well as risks to other assets identified in the critical infrastructure sectors defined by the National Strategy for Critical Infrastructure (Public Safety Canada, 2009). Maps showing assets at risk were also developed to identify assets exposed to tsunami hazards.

The outcomes of the risk analysis can strengthen both hazard awareness and the four key components of emergency management: mitigation, preparedness, response, and recovery. Accordingly, this study touches on emergency management plans as well as the status of these four emergency management components in terms of aligning with best practices and regulations, achieving progress throughout both project phases, and informing the path forward. This information is expected to support development and planning decisions and improve existing emergency and evacuation plans. Lastly, this

⁴ A story map is an interactive web application that enables sharing of geographic information in the context of narrative text and other multimedia content. The story map integrates maps, legends, text, photos, and video and provides functionality that helps users explore and better understand the issues under study.

⁵ Tsunami-induced current speed is the velocity of the water being displaced when tsunami waves propagate.

study provides recommendations for measures that can reduce tsunami risk in conjunction with developing and updating tsunami emergency management plans.

1.3 Report Structure

This document forms the main report for Phase II of the project. It follows a similar structure to the main Phase I report (NHC, 2022), focuses on communities within the Phase II study areas, and summarizes the project team’s initiatives to increase the public’s awareness of tsunami hazards. The main steps of the community and Indigenous engagement activities conducted for this project are described in Section 2, and the results of the tsunami modelling and mapping are summarized in Section 3. The report emphasizes the outcomes of the risk assessment, which are presented in Section 4, while Section 5 discusses emergency management plans and recommendations for reducing tsunami risk.

In addition, this report includes a series of appendices that present records of Indigenous engagement, summarize results of the community survey, and present the technical details of the study. Also provided in the appendices are the many maps that were produced or updated as part of this second phase of the project. The use and limitations of these maps are discussed as part of this main report in Section 3.4.

1.4 Project Team

This project is the result of a collaboration between many individuals of various backgrounds, including risk assessment and disaster management specialists, Indigenous community liaison partners, coastal engineers, tsunami scientists, and geographic information system (GIS) specialists. While NHC and ONC undertook the analysis for Phase II, community members, municipal officials, and personnel from the SRD and Regional District of Mount Waddington (RDMW) provided valuable contributions. This report also relies on the emergency management details provided by NSC during Phase I of the project.

Following are brief background descriptions of the team from NHC and ONC, including their respective responsibilities during the second phase of this project.

NHC

NHC is a private employee-owned Canadian firm that was incorporated in 1972. NHC’s engineers and scientists are focused on and passionate about assessing, measuring, designing, and supporting water-related projects. Working extensively in local communities across BC, as well as supporting large-scale international projects, NHC’s experts are world leaders in assessing flood hazards and reducing flood risk in coastal and inland communities. Serving as a subconsultant to ONC during this second project phase, NHC has led community engagement activities, developed the project’s online story map, performed engineering reviews of the modelling work by ONC, produced maps, conducted the risk assessment, and provided risk reduction recommendations.

ONC

Formed from an initiative of the University of Victoria, ONC monitors the Pacific, Atlantic, and Arctic coasts of Canada and continuously delivers real-time data for scientific research that helps communities, governments, and businesses make informed decisions for the future. ONC's scientific expertise is grounded by a deep respect for the perspectives and values held by members of coastal Indigenous communities. By collaborating and engaging with local leaders and Knowledge Holders, ONC is gaining collective knowledge and experience along the northwest coast of Vancouver Island while building long-standing relationships, in turn deepening our collective understanding of past tsunami events and increasing community awareness and consideration of tsunami risks. As the prime consultant for this second phase of the project, ONC developed the project's **digital elevation model** (DEM) used for tsunami modelling, conducted the tsunami model simulations, coordinated community engagement activities, delivered the educational modules at schools within the study area, produced the project's documentary film, and assisted the SRD in installing tsunami signage.

1.5 Glossary of Terms

To support reader comprehension, a glossary of specialized terms is provided at the front of this report, which provides term definitions and accurate descriptions of the coastal processes described throughout the report. Please note, glossary terms are set in bold when they first appear in the text.

2 COMMUNITY AND INDIGENOUS ENGAGEMENT

A key component of the risk assessment process, community engagement focuses on informing and engaging with community members to discuss how to reduce risk and better protect community members against tsunami hazards. Community engagement also identifies collective priorities and values and provides greater insight into community preparedness, risk perception, and resilience to tsunamis. Furthermore, community engagement can strengthen study outcomes and support communities in adopting study recommendations. The engagement conducted for this study is further enhanced by collaboratively sharing scientific information in conjunction with traditional Indigenous Knowledge on tsunami hazards. This knowledge sharing further substantiates the study outcomes and will help participating communities make important decisions on reducing tsunami risks in the future.

During the 1980s, scientists began studying tsunamis on the west coast of Vancouver Island in earnest; however, the history and impacts of tsunamis date back much longer, as exemplified by the ancient Nuu-chah-nulth story of mountain dwarves and the earthquake foot legend. These and other historical accounts passed down from one generation to the next highlight the Traditional Knowledge and Indigenous teachings about earthquakes and tsunamis on the northwest coast of Vancouver Island. The First Nation communities in the study area share multi-generational experience connecting their people to the land as they coped with environmental change and survived natural disasters. By engaging with local Indigenous community members and learning more about these ancient accounts, the study authors have strived to work closely with people in all participating communities to capture and incorporate their ideas, history, and recommendations. To accomplish this objective, the team has connected the study results to these shared local histories to provide a more fulsome historic context and understanding of past tsunami events and their effects across the northwest coast of Vancouver Island.

This section summarizes the engagement activities that have been conducted to support this project, which include the following:

- assembly of an advisory group for each project phase to guide the project team and promote the exchange of knowledge
- research on Indigenous Knowledge to better understand and contextualize the experience, knowledge, and history provided by Knowledge Holders in local Indigenous communities
- community touchpoints, including online resources and meetings, to engage with members of the public and invite additional community participation in the project.

2.1 Advisory Group Involvement

During each project phase, the project team assembled distinct advisory groups with representation from communities within each respective study area. The purpose of the advisory groups was to combine expertise and counsel with community representatives to communicate, explain, and promote study findings while supporting an ongoing exchange of knowledge between communities and collaboration toward the collective goal of reducing tsunami risks. Throughout both phases, the project

team worked with specific advisory groups to collect background information and review preliminary findings. The advisory group for Phase II of the project included representatives from the following communities and organizations:

Regional Districts

- SRD
- RDMW

First Nations

- Mowachaht/Muchalaht First Nations
- Quatsino First Nation

Communities

- Village of Port Alice
- Hamlet of Quatsino
- Village of Gold River
- Winter Harbour

Other Organizations

- Canadian Coast Guard (CCG)
- BC Parks
- Epic Exeo
- Western Forest Products

In addition to providing background information about each jurisdiction and community and identifying areas of interest within the region, members of the advisory group were also instrumental in prioritizing areas for inundation mapping, as further discussed in Section 3.3. Table 2.1 provides an overview of the three advisory group meetings that were held virtually as part of the project's second phase. Each advisory group meeting was opened by an Indigenous Elder.

Table 2.1 Summary of Phase II advisory group meetings.

Meeting	Date	Aspects Discussed
1	May 5, 2022	<ul style="list-style-type: none"> • Project overview • Priority areas for tsunami inundation mapping and risk assessment • Collection of background information
3	February 16, 2023	<ul style="list-style-type: none"> • Project overview • Presentation of draft mapping results • Identification of community assets at risk • Plans for first round of public meetings • Summary of initiatives for increasing public awareness
3	April 13, 2023	<ul style="list-style-type: none"> • Presentation of risk assessment results • Plans for second and final round public meetings

2.2 Collection of Background Information

The project study team gathered background information from communities and other sources located within the Phase II study area, as well as from publicly available sources. The following list identifies the main information sources consulted for this study.

Strathcona Regional District

- Village of Gold River Community Wildfire Protection Plan 2020 Update (SuavAir, 2020)

Regional District of Mount Waddington

- North Island Regional Emergency Plan (RDMW, 2015)
- Holberg high-water danger zone map (Strategic Forest Management Inc., 2006a)
- Holberg campsite map (Western Forest Products Limited, n.d.)
- Quatsino high-water danger zone map (Strategic Forest Management Inc., 2006b)
- Quatsino park options and active transportation improvements (RDMW, 2009)
- Winter Harbour high-water danger zone map (Strategic Forest Management Inc., n.d.)
- Winter Harbour cadastral map (RDMW, 2005)

Village of Port Alice

- Village of Port Alice Emergency Plan (Mid Island Emergency Coordinators and Managers Association, 2011)
- Cadastral map showing community assets and 10 m tsunami zone

Canadian Coast Guard

- Maps with markups showing location of CCG resources and commentary from CCG personnel

Epic Exeo

- Points of interest on North Vancouver Island

2.3 Indigenous Knowledge Research



Earthquake Foot Legend

This legend is a rendition of a Mowachah/Muchalaht story

“A man was going through the mountains in Yuquot (Friendly Cove) and stumbled on across the home of two dwarves. They were very happy and outgoing. They greeted him with every respect and invited him into their home. They invited the man to perform, to dance and sing around their great drum in the house. This went on all day and all night until the man tired and stumbled into that drum. It was then that he became afflicted with an earthquake foot, and every time he took a step, tremors occurred. The whole world began to shake and quake. This is a family cultural teaching that is a true history from Friendly Cove.”

—Shake Up interview with renowned Artist and Knowledge Holder A-nii-sa-put (Tim Paul), 2020

The image above is a detail in a silkscreen print from 1977 called Earthquake Foot, created by artist A-nii-sa-put (Tim Paul), who spent his youth with his grandmother in Chinehkint (Queens Cove) in Esperanza Inlet. The image depicts the moment that Yahlua tires, kicks the drum, and becomes afflicted with the disease Earthquake Foot, as one of the dwarves looks on.

Indigenous peoples along the northwest coast of Vancouver Island have been living at the forefront of tsunami risk for millennia. Each First Nation has multiple generations of shared experience connecting their people to the land as they coped with environmental change and survived natural disasters. As a result, each First Nation holds deep understanding within their knowledge systems of tsunami risk and occurrence in their territories – knowledge gained through thousands of years of lived experience on their land and waters. This project uses a framework of “two-eyed seeing,” where different ways of knowing are used simultaneously to benefit all instead of one way being incorporated into the other. This collective tsunami risk assessment draws from and incorporates Indigenous Knowledge and modern risk assessment tools such as computer modelling to result in a more robust risk assessment. This project has provided all participants with a unique opportunity to showcase the resiliency of leveraging what is now being referred to as “knowledge coexistence” to support disaster management planning and risk assessment.

The following sections describe ONC’s work to gather and document the Indigenous Knowledge used in this investigation.

2.3.1 Interviews

As part of Phase I, the project team worked closely with the advisory group members to identify Elders and Knowledge Holders from within the study area. The team then connected with each person to inquire if they would be interested in participating in the study and contributing their experience to the growing body of knowledge. Between September 2020 and March 2021, individuals who agreed to be interviewed shared stories, teachings, and oral histories of past tsunamis, including the 1700 and 1964 tsunamis. The study team collected details from these interviews with Elders and community members and combined them with the details gathered during background research from publicly available sources. The knowledge shared through community participant interviews illuminated the immense history shared about earthquakes and tsunamis on the northwest coast of

Vancouver Island. These accounts also provided insight during the hazard mapping component of this risk assessment. Elders, Knowledge Holders, and community members shared first-hand experiences and ancestral stories, which validate many of the results shown in the tsunami maps produced as part of this project. First-hand accounts and Traditional Knowledge from these interviews have been shared across the advisory group and project team, and these details have been correlated to the modelling results, which are presented in Section 3.2.3.

The full report summarizing the interviews and additional research regarding Indigenous Knowledge of tsunamis and earthquakes in the study area is attached to this report as Appendix A.

2.3.2 Documentary Film

As part of Phase I of the project, ONC's Indigenous engagement team conducted Indigenous tsunami research with Indigenous Knowledge Holders through phone interviews, as in-person meetings were restricted due to the Covid-19 pandemic. During Phase II, the team went back to the Knowledge Holders and filmed a documentary to preserve the shared tsunami knowledge for future generations. Throughout the project, three elders passed away, highlighting the urgency to record this important history.

Thanks to funding provided by the SRD and Union of BC Municipalities (UMBC), in May 2023 the documentary team toured several communities in the study area to show the documentary as part of BC's Emergency Preparedness Week.

2.4 Community Touchpoints

The project team engaged with communities throughout both phases of the project via several touchpoints, not only to raise awareness about earthquakes and tsunamis but also to ensure that local knowledge is represented in the project. These touchpoints include the following:

- **project webpage** (<https://srd.ca/nwvi-tsunami-risk-project/>) and a community survey (Table 2.2, Appendix B), prepared and communicated in collaboration with the SRD
- **online, virtual community meetings** enabling project team members to engage directly with participating members of the public
- **online story map** developed by NHC to describe the overall project and disseminate key information gathered during the study
- **educational modules** delivered by ONC at several schools within the study area
- **tsunami signage**, designed and installed by the SRD based on study results

2.4.1 Project Webpage

Developed by the project team and hosted by the SRD, the project webpage provides an overview of the project, presents background information on tsunami hazards in the region, and is used to provide updates and inform the public about project-related events. The SRD has also published a webpage with

information about tsunami safety and links to the resources produced for the project, including project maps and reports (www.srd.ca/tsunami-mapping).

2.4.2 Community Survey

During Phase I of this project, residents in the study area were surveyed to build community preparedness. Study participants were asked to:

- share experiences and knowledge between communities to help reduce tsunami risk
- assess community evacuation and shelter-in-place preparedness levels
- help communities understand where they can access emergency programs

During the winter of 2021, the SRD oversaw the compilation of the community survey and promoted it by producing and circulating a media release, mailing out hard copies of the survey to households in the study area, sending emails, and sharing project and survey details on community-specific social media sites. Survey respondents were invited to mail in their surveys or submit them electronically. The SRD then oversaw the assessment of 282 responses in total and conducted follow-up discussions with respondents who provided permission by sharing their contact information.

Complete results of the survey are presented in Appendix B. Survey questions were prepared by the project team in collaboration with the SRD and are provided in Table 2.2. Responses were also assessed on a community basis; the distribution of respondents per community is shown in Figure 2.1.

Table 2.2 Community survey questions.

General questions
Which community/location are you providing information on?
<ul style="list-style-type: none">What concern do you have about a tsunami occurring in your community?
"Yes" or "no" questions on preparedness
Do you and your family have enough disaster supplies in case your community is cut off for two weeks and you have to shelter in place?
Are your supplies portable, such as in a backpack or suitcase with wheels?
Do you know your community's tsunami meeting points?
Do you know your community's tsunami evacuation routes?
Do you know how your community will alert you if there is a tsunami threat?
Do you know how the Canadian Coast Guard broadcasts tsunami alerts to mariners?
Do you know that the immediate signs of an approaching local tsunami are: <ul style="list-style-type: none">a strong ground shakinga rapid and unexpected recession of water levels, and a loud roaring sound coming from the ocean?
Do you know that the immediate signs of an approaching distant tsunami are: <ul style="list-style-type: none">a rapid and unexpected withdraw of water levela loud roaring sound coming from the ocean?
Do you know that a tsunami can also be triggered by landslides?
Are you a certified Amateur Radio Operator?
Are you interested in receiving information about how to achieve an Amateur Radio Certification to help disaster communications of your community?
Do you have a satellite communication device (Spot X, In Reach)?
Open-ended questions (responses vary)
Do you have personal experience of a tsunami event in northwest Vancouver Island? <ul style="list-style-type: none">If yes, which year/specific location?Can you provide details (impacts/damage, physical observations, personal response, etc.)?Would you be willing to share your contact information to provide further details to us? If so, please enter it below. This personal information will be kept confidential by the SRD and the project team.
Do you have any recommendations or feedback you would like passed along to emergency planners?
Anything else you would like to share with us?

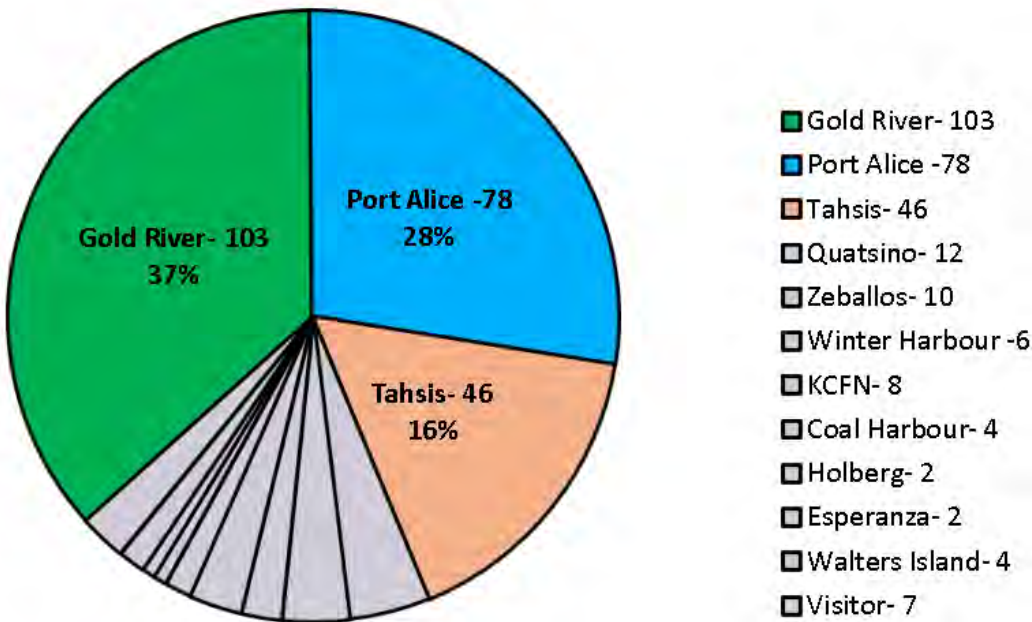


Figure 2.1 Total survey respondents per community.

2.4.3 Public Meetings

The project team organized two rounds of public meetings during each project phase to meet two objectives:

7. Share preliminary results of tsunami modelling and mapping with communities and collect community inputs for the risk assessment.
8. Share finalized information about the tsunami hazard and risk assessment results to help communities prepare for the next steps in reducing tsunami risks.

For Phase I, the first round of meetings took place in August 2021; the second and final round occurred in April 2022. The first round of meetings for Phase II took place in February 2023, and the second and final round was completed in April 2023. Each public meeting was opened by an Indigenous Elder and included a presentation by the project team followed by an interactive question-and-answer period.

Due to the COVID-19 pandemic, all Phase I meetings were conducted online. For Phase II, the first round of meetings was conducted online while the second and final round of meetings was conducted in person in the municipalities of Gold River, Port Alice, Quatsino (hamlet), and Coal Harbour.

2.4.4 Online Story Map

NHC developed an online and interactive story map to facilitate the communication of study results with the public and increase tsunami hazard awareness. The story map main objectives are to:

1. introduce and describe the overall project

2. share Indigenous Knowledge related to tsunamis
3. educate the public on tsunamis and tsunami safety

NHC developed the story map using the Environmental Systems Research Institute’s *ArcGIS StoryMaps* online tool and transferred control of the story map to the SRD at the end of the project. The SRD is responsible for any future maintenance or updates to the story map.

2.4.5 Education Modules

Ocean Networks Canada (ONC) implemented tailored educational programming in May and June 2022 to support project objectives. The ONC education team, consisting of K-12 Education Coordinators and an Indigenous Community Learning Coordinator, visited four communities and delivered presentations to students from Pre-Kindergarten to Grade 11. The program was conducted in four schools within School Districts 84 and 85, including K’ak’ot’lats’i School in Coal Harbour, Ray Watkins Elementary School in Gold River, Sea View Elementary & Junior Secondary in Port Alice, and Captain Meares Elementary Secondary School in Tahsis. In total, 78 students and 20 educators were reached through these presentations.

The primary aim of this initiative was to engage community youth through educational outreach conducted in schools. The ONC team developed grade-appropriate content for different grade bands and incorporated hands-on activities to enhance the learning experience, as shown in Photo 2.1. The topics covered included earthquakes, tsunamis, and ocean observing technologies, from both scientific and Indigenous knowledge perspectives.



Photo 2.1 Students participating in hands-on activities as part of the “Prepare and Take Care” presentations (Photo credit Lauren Hudson, ONC)

2.4.6 Tsunami Signage

To enhance safety in high-risk coastal communities, a series of outdoor tsunami inundation maps and assembly signs were developed by Strathcona Regional District as part of the project deliverables. The tsunami assembly signs have been or will be installed in the following locations: Oclucje, Zeballos, Tahsis, Hamlet of Quatsino, Port Alice, Fair Harbour, and Holeberg.

These signs play an instrumental role in ensuring the safety of residents during a potential tsunami event by clearly marking designated evacuation routes. The tsunami inundation map signs serve as informational resources, offering insights into areas susceptible to tsunami inundation, as well as providing details about local and distant tsunami alerts, evacuation locations, and tsunami signs and warnings. By empowering residents with this valuable information, they are better equipped to make informed decisions and comprehend the potential impact during emergencies. An example of an evacuation map for Oclucje is provided in Figure 2.2.

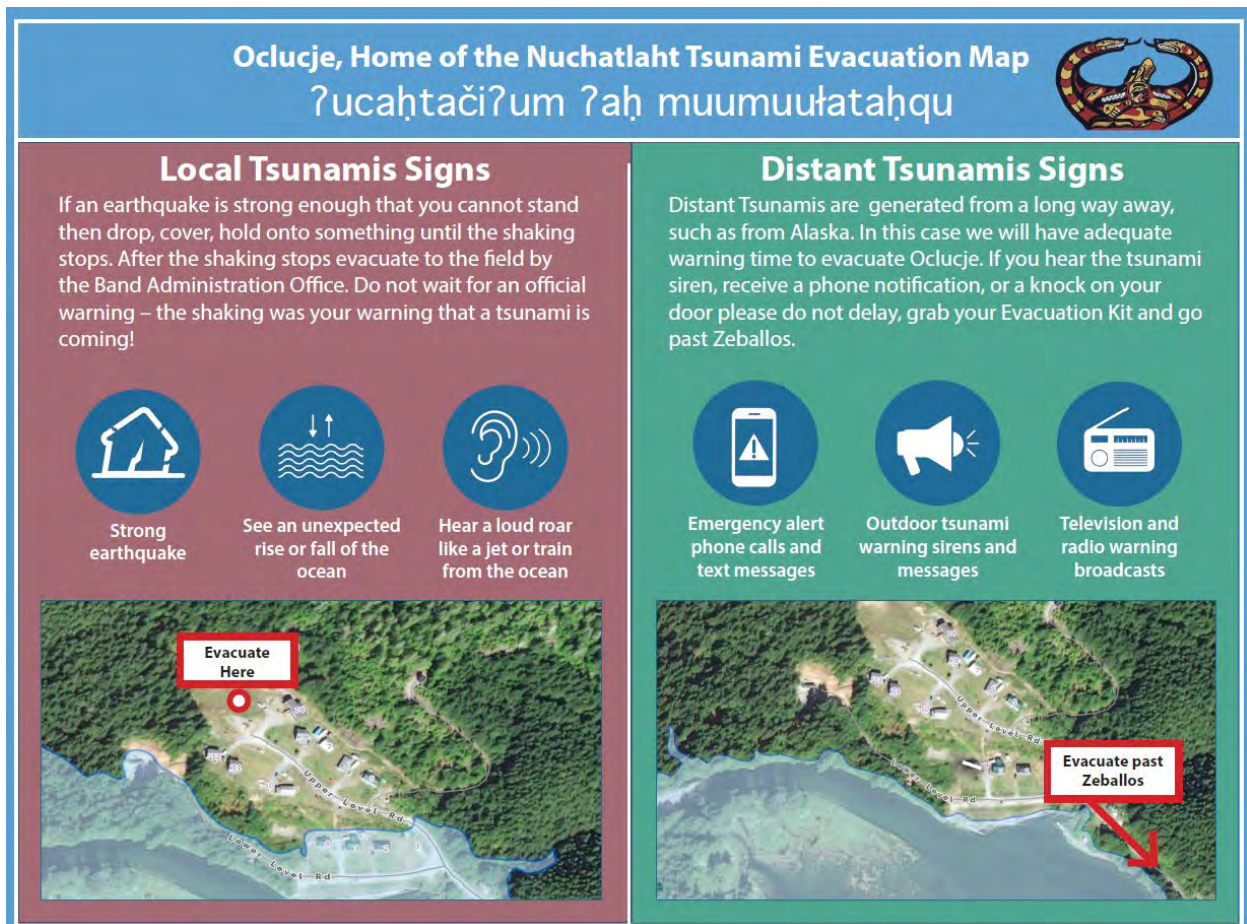


Figure 2.2 Tsunami evacuation map developed for Oclucje

3 TSUNAMI HAZARD ANALYSIS AND MAPPING

This section presents details on the tsunami hazard analysis and mapping completed for this project. It begins with a description of the DEM and provides a discussion of the elevation data and light detection and ranging (**LiDAR**) sources and collection, as well as the **bathymetry** survey conducted to develop the DEM. This section also provides details on the tsunami hazard modelling and includes descriptions of the tsunami model and tsunami scenarios developed, as well as a discussion of the modelling results. In addition, this section describes the hazard mapping conducted after analyzing the model results, discusses the coordinate reference system and how model results were processed, and provides details on the overwater hazard maps and the overland inundation or flood maps developed to inform community risk management planning.

One prerequisite to any risk assessment is defining the exposure hazards in a study area. According to the United Nations International Strategy for Disaster Reduction, a hazard is a potentially damaging physical event, phenomenon, or human activity that may cause loss of life or injury, property damage, social or economic disruption, or environmental degradation (UNISDR, 2009). For this study, the project team defined the hazards related to tsunamis using computer simulations and numerical modelling to estimate and predict the complex, nonlinear behaviour of tsunami waves as they propagate toward the coast and interact with the geographical features of the coastline.

A DEM is required for this modelling and represents the Earth's surface, both above the water (**topography**) and below the water (bathymetry). The quality of the tsunami modelling and mapping depends on the quality of the DEM developed: a high-quality DEM requires accurate elevation data and detailed spatial resolution (i.e., density of data points) in a specified study area. The study team maximized the quality of the data collected for this project by adopting a nested approach to data analysis; first, the team developed a broader, coarser model to accommodate all data collected within the study area boundary, then developed successively smaller models based on available higher data resolution, embedding these smaller, more detailed models into the broader, coarser model. In addition to maximizing the quality of the data provided for the project, this approach enabled the study team to focus the analysis on areas of interest, which reduces computation time.

The tsunami hazards analyzed in this study include the flood or overland inundation hazards in priority areas, as well as overwater hazards across the broader study area caused by maximum tsunami amplitude and maximum tsunami-induced current velocity. Other overwater hazards, such as shallow navigation depths during **tsunami drawdown**, sustained **flow eddies**, and impacts with floating debris, were not included in 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.

3.1 Digital Elevation Model

A DEM is generated by including elevation information with variable spacing onto grid points with constant spacing. ONC created several DEMs of varying resolutions to support tsunami modelling, and NHC developed a 2 metre (m)-resolution topographic DEM to support local-scale tsunami inundation mapping in key locations (see Section 3.3).

Development of the DEMs for tsunami modelling in the project study area followed a nested modelling approach, which is further described in Section 3.2.2. The resolution of these DEMs changes from a coarse resolution of approximately 1,500 m in the northeast Pacific Ocean to a finer resolution of 10 m in the regions of interest. Data sources and a summary of DEM development methods are presented below. Additional details on DEM development for tsunami modelling are provided in Appendix C.

3.1.1 Elevation Data Sources and Collection

The project study team developed DEMs specific to the study area using both pre-existing datasets and datasets collected for this project, including LiDAR topographic data, and bathymetric survey data. Data collection campaigns undertaken as part of this study are summarized below. Table 3.1 presents all datasets used for DEM development during the project's second phase. In places where datasets overlap, they are listed from top to bottom in terms of their priority over other datasets.

Table 3.1 Elevation datasets used for development of the project’s DEM.

Dataset	Date of Survey	Data Type	Spatial Resolution ¹
Commissioned LiDAR data collected by McElhanney	2020	Topographic LiDAR survey	Minimum of 1 point per square metre (m ²)
GeoBC LiDAR	2019	Topographic LiDAR survey	1 m
Commissioned multi-beam and single-beam bathymetric survey performed by Terra Remote Sensing Inc. (TRSI)	2020 - 2021	Multi-beam survey interpolated onto DEM surface, single-beam survey tracks	1 m for DEM surface, 0.1 – 0.3 m along survey tracks ~50 m apart
Multi-beam bathymetry data obtained from the Canadian Hydrographic Service (CHS)	2000 – 2020	Bathymetric data	2 – 5 m
Bathymetric survey points obtained from the CHS	1934 – 2010	Bathymetric data	Varies
Canada West Coast topo-bathymetric DEM (Fisheries and Oceans Canada/Natural Resources Canada)	Varies	Topographic and Bathymetric DEM surface	10 m
CHS non-navigational (NONNA-10) bathymetric data	2018 – 2020	Bathymetric DEM surface	10 m
Canadian DEM	1945 – 2011	Topographic DEM surface	0.75 arc-second (~20 m)
Bathymetric DEM of BC from the National Oceanographic and Atmospheric Administration (NOAA)	1930 – 2011	Bathymetric DEM surface	3 arc-seconds (~93 m)

Notes:

- The spatial resolution of DEM surfaces relates to the constant spacing between adjacent points onto which underlying elevation information is interpolated. The resolution of a DEM may not necessarily reflect the actual resolution of the underlying elevation information.
- The *Federal Airborne LiDAR Acquisition Guidelines* (NRCan and Public Safety Canada, 2022) specify a density of 4 to 10 full feature points per m² for LiDAR data to support inundation mapping in high flood risk areas (all urban areas and rural areas that are protected by diking) down to 2 full feature points per m² for low flood risk areas (sparsely populated areas).

3.1.2 LiDAR Collection

Prior to this project, LiDAR topographic data was non-existent for most of the study area. Initially, McElhanney Consulting Services Ltd. was engaged as part of this project to collect high-resolution topographic data, which has served a crucial role in this project as these data enable detailed inundation mapping.

The project team collected LiDAR by plane in August 2020 and planned flight paths to maximize the survey of intertidal zones at lower tides in specific areas of interest. Flights were performed over a total distance of 1,800 kilometres (km), covering a total area of approximately 765 square kilometres (km²). The coverage of the LiDAR data collected for the project is shown in Figure 3.1. Not all shorelines could be surveyed at lowest tide conditions due to the time-varying nature of the tides in relation to the duration of the flights. Flight paths were established to maximize the coverage of intertidal areas during low-water conditions. A minimum survey point density of one **full feature point** per square metre (m²) was adopted to maximize the coverage of the survey, while a density up to approximately three full feature points per square metre (m²) was achieved in inhabited areas. Raw LiDAR data were processed to remove vegetation, buildings, and bridges to represent a **bare-earth** surface only. This process resulted in an average density of approximately 1.5 bare-earth points per m² in inhabited areas.

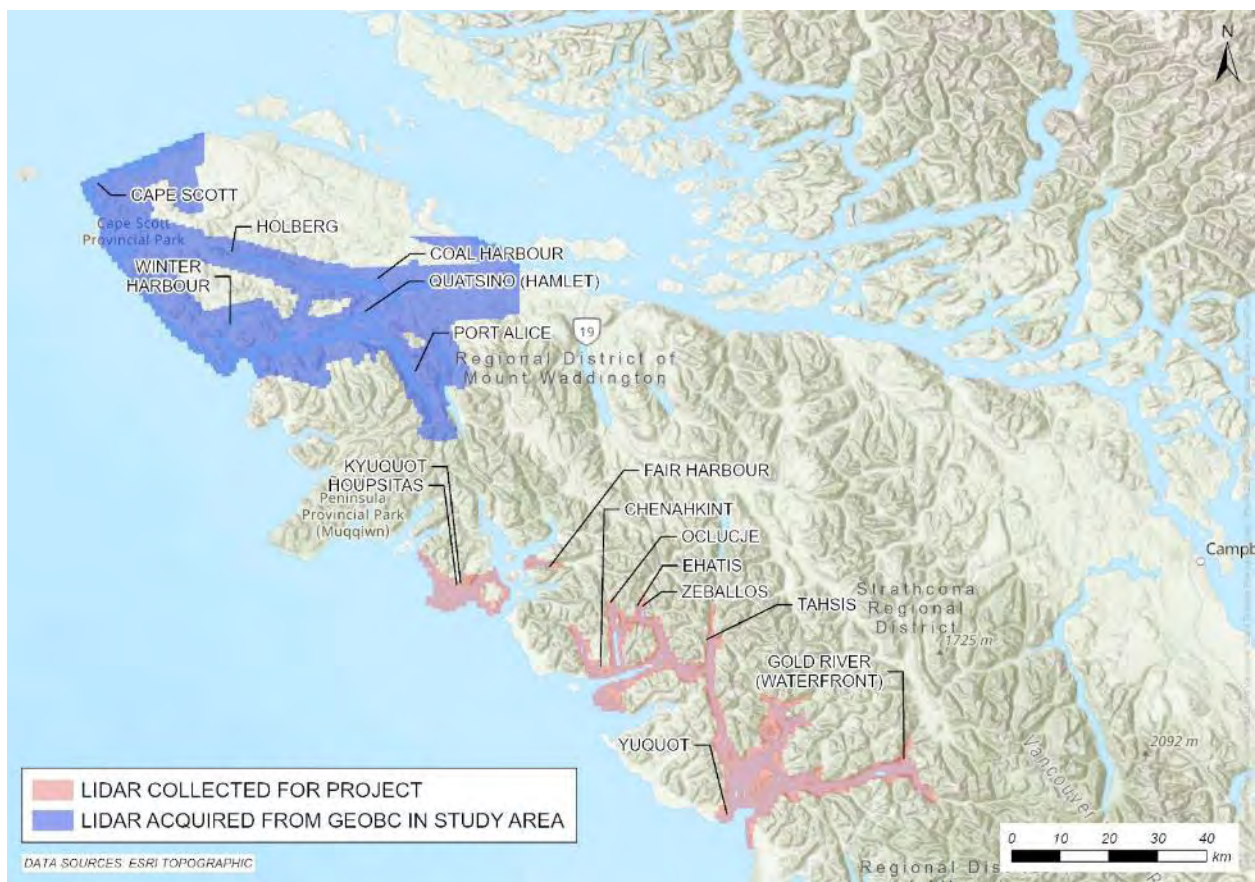


Figure 3.1 Coverage of LiDAR collected as part of the project.

3.1.3 Bathymetric Survey

Terra Remote Sensing Inc. (TRSI) was engaged as part of this project to conduct multi-beam and single-beam bathymetric surveys at several sites across the study area (Figure 1.1). Survey locations were prioritized to fill in gaps identified based on a review of available government data. TRSI conducted

surveys between August 12 and August 15, 2020, as well as between September 27 and November 18, 2021. The locations surveyed include Strange Island, Tahsis, Zeballos Inlet, Quatsino, Holberg Inlet, Winter Harbour, and Gold River, as shown in Figure 3.2. A single-beam echosounder was used to survey perpendicular profiles along the shoreline with a maximum distance of 50 m between each profile, and a multi-beam system was used to collect data in the remainder of the survey areas. TRSI processed the raw multi-beam data to produce a 1 m resolution surface of the seabed, which ONC subsequently used to develop the DEM for Phase II of the project.

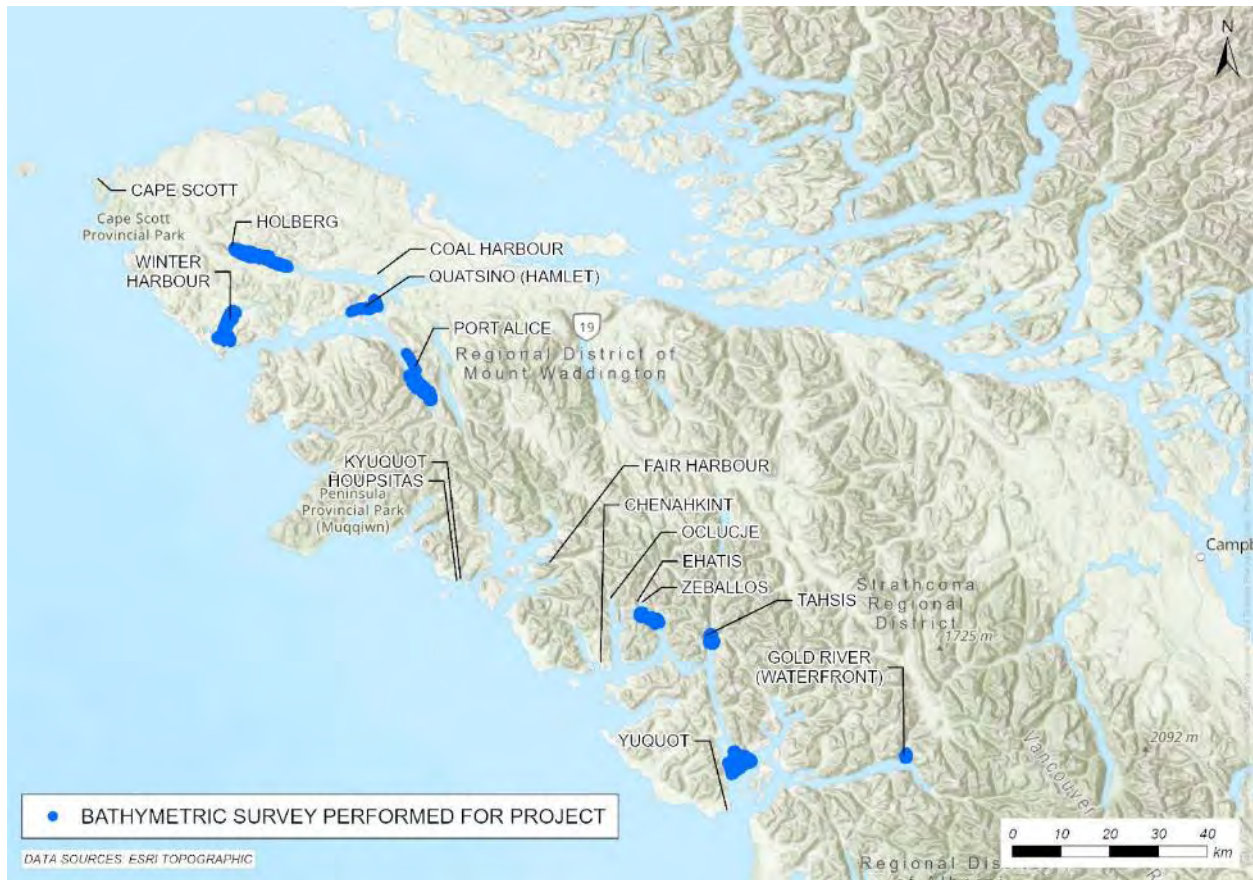


Figure 3.2. Approximate coverage of bathymetric survey conducted as part of the project.

3.1.4 DEM Development

ONC developed three DEMs for specific use in this Phase II of the study:

- 60 m resolution DEM to represent the northwest coast of Vancouver Island
- 10 m resolution DEM to represent Nootka Sound
- 10 m resolution DEM to represent Quatsino Sound

Broader, previously developed, ocean-scale DEMs (i.e., 240 m and over) were also included in the study but are not presented in this report. The geographical extents of the project-specific DEMs, which integrate both topographic and bathymetric information, are shown in Figure 3.3.

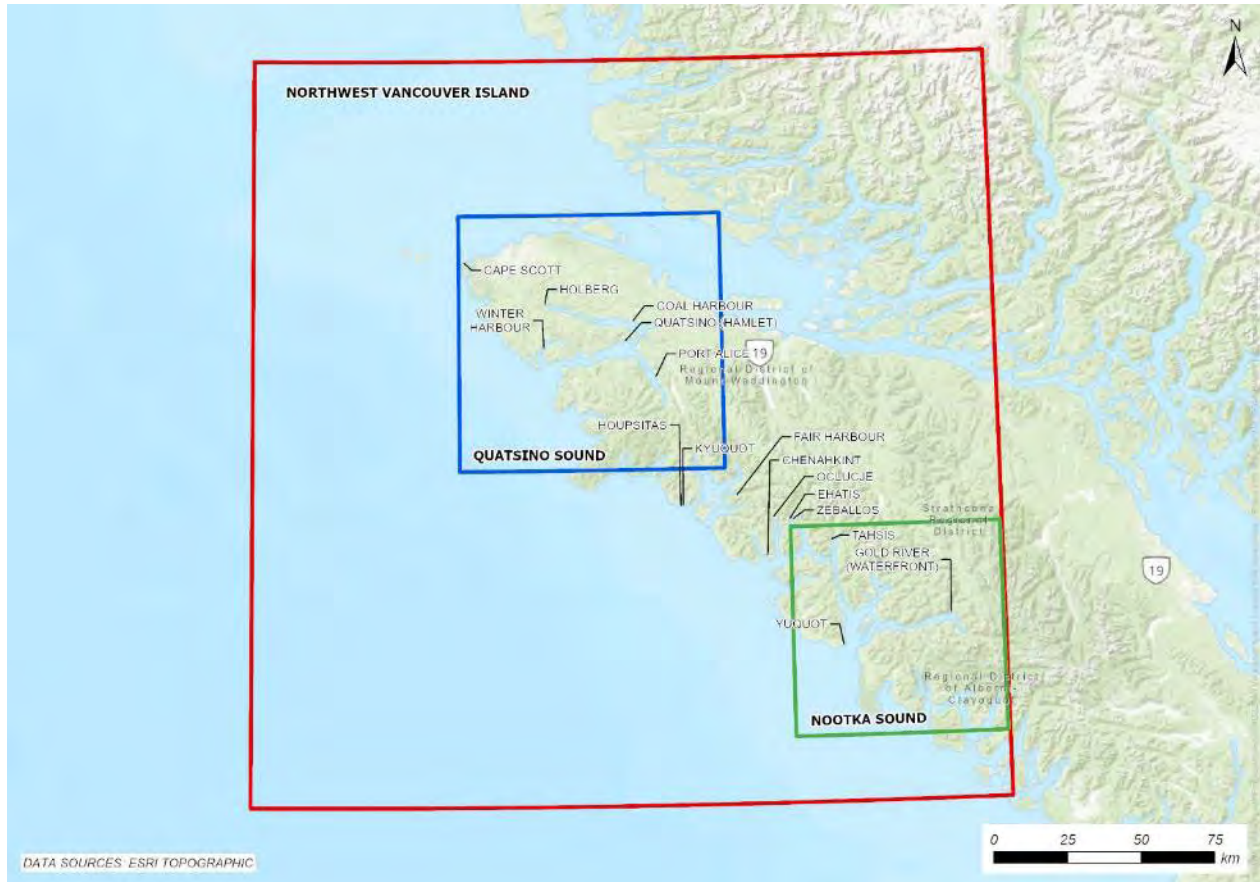


Figure 3.3 Geographical extents of DEMs developed to support tsunami modelling during Phase II of the project.

ONC developed the DEMs based on the following approach:

1. Convert source datasets (listed in Table 3.1) to a common geographic coordinate system (latitude and longitude) with the **World Geodetic System of 1984 (WGS84)** as horizontal datum and the **Canadian Geodetic Vertical Datum of 2013 (CGVD2013)** as vertical datum.
2. When assembling the DEMs, prioritize finer-resolution and more recent data where datasets overlap. Use interpolation methods to convert the elevation data to a gridded surface.
3. Use information from the Canadian Hydrographic Service (CHS) to delineate the coastline in areas where the resolution of the source elevation data is not sufficient (e.g., Canadian Digital Elevation Model [CDEM] and National Oceanographic and Atmospheric Administration [NOAA] datasets, as per Table 3.1).

The study team conducted quality assurance and control by visually comparing the shaded relief of the DEMs with satellite imagery on land and depth contours with CHS navigational charts underwater. When developing and reviewing DEMs, the team solely focused on tsunami modelling in the areas of interest. As a result, the DEMs produced as part of this project may not be suitable for other uses, unless confirmed through review and assessment.

Inherent limitations exist in how the DEMs reflect reality due to the vast geographical extent of the study area, in conjunction with the relatively sparse availability of elevation data. Such limitations can also translate into limitations in subsequent tsunami modelling and mapping, as further discussed in Section 3.4.

The DEMs for this phase of the project are limited by the following factors:

- The spatial resolution of a DEM surface relates to the constant spacing between adjacent points onto which underlying elevation information is interpolated or added. The resolution of a DEM may not necessarily reflect the actual resolution of the underlying elevation data. For example, to follow federal guidelines (NRCan and Public Safety Canada, 2022), detailed overland inundation mapping is not possible outside of the area covered by LiDAR (Figure 3.1). Where LiDAR coverage is not available, the study team used the CDEM with a resolution of 20 m (see Table 3.1). The constant 10 m resolution across the DEMs does not reflect this variation in the source elevation data.
- Several data gaps exist throughout the large study area that could not be covered in the project's data survey campaign. These areas include remote inlets and estuaries, but mostly they consist of intertidal zones, which are logistically more challenging to survey. For instance, intertidal zones may have been submerged at the time LiDAR data were collected. Also, shallow water depths can impede a typical boat survey unless survey trips are specifically planned, which explains why depths in intertidal zones are seldom reported on CHS navigational charts. As a result, the DEM surface in intertidal zones results from interpolating between topographic and bathymetric datasets where gaps exist, which can introduce inaccuracies in those areas.
- Aside from Gold River, no bathymetric data were available for rivers located in the Phase II study area. Hence, other rivers are represented based on the interpolation of topographic data only; therefore, the riverbeds generally appear to have elevations matching the adjacent riverbanks.

3.2 Tsunami Hazard Modelling

When an offshore subduction earthquake occurs, the quick **uplift** motion of the seafloor vertically displaces a large volume of water, which then induces a rapid and localized change in sea level. This change results in tsunami waves propagating in opposite directions, perpendicular to the earthquake's **fault line**. These waves can propagate thousands of kilometres away from their generating source at considerable speeds. In deep water, these waves will have a relatively small amplitude (often less than 1 m), but their **wavelength** often extends hundreds of kilometres. As these waves propagate into coastal waters, they experience an increase in amplitude, as well as a deceleration and shortening of their wavelength due to the compressing effect of an up-sloping seafloor and decreasing water depth. As

tsunami waves approach a shoreline and intrude over land, their behaviour will be mainly influenced by local geographical features and may vary considerably from one location to another.

Although most often triggered by subduction earthquakes, tsunamis can also be generated due to the sudden displacement of water induced by **subaerial** and submarine landslides, volcanic eruptions, and meteor impacts. Hazards associated with tsunamis triggered by mechanisms other than subduction earthquakes are beyond the scope of this assignment. A geological and geotechnical assessment is required to determine if risks associated with landslide-generated tsunamis exist in the study area.

The general physical processes of tsunamis described above are complex and difficult to predict without the use of numerical models. In simple terms, numerical models are a mathematical representation of a physical phenomenon based on relevant hypotheses and simplifying assumptions that are often derived from laboratory experiments. This mathematical representation essentially consists of a set of governing equations, which, when solved over the time and space domains, estimates the movement of water – in this case, the propagation of tsunamis. High-performance computers are used to undertake the many calculations performed at each grid point on defined computational grids covering the study area.

In general, inputs required for tsunami modelling include a representation of the Earth’s surface, such as a DEM as previously described in Section 3.1, as well as an estimation of the seafloor displacement resulting from an earthquake. The tsunami scenarios considered for this study are presented below, in addition to providing a technical overview of the tsunami model used for this study and a summary of the model results. Additional details on the tsunami modelling work performed to support this study are provided in Appendix D.

3.2.1 Tsunami Scenarios

According to the United States (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 1 hour of the triggering event. The effects of the triggering event may also be felt at the site, such as ground shaking when a tsunami is triggered by an earthquake. A distant tsunami originates from a source that is far away from the site of interest and takes 3 hours or longer to arrive following the triggering event.

This assessment distinguishes between local and distant tsunamis, as the associated risks differ considerably. A local tsunami arrives sooner and has more adverse effects in comparison to a distant tsunami; however, a distant tsunami still poses considerable risks and occurs more frequently because it can originate from any of the several subduction zones around the Pacific Ocean (see Figure 1.2). Furthermore, an earthquake associated with a distant tsunami would not be felt, and a community will need to rely entirely on warning systems to notify residents and visitors of the incoming threat, which may be challenging in remote areas. As further discussed in Section 5.2 tsunami risk reduction measures are generally recommended to distinguish between local and distant tsunamis.

Accordingly, two tsunami sources were considered for this study: a local tsunami from the Cascadia subduction zone (or a Cascadia tsunami) and a distant tsunami from the Aleutian subduction zone (or an

Alaska tsunami). These two tsunami sources are further described below and are considered the most hazardous to the BC coast (Ferguson et al., 2022).

The study team simulated two sea levels when assessing the impacts of a Cascadia or Alaska tsunami, resulting in a total of four tsunami scenarios being modelled. These sea levels include a present-day sea level and a future sea level based on sea level rise (SLR) predictions published by Natural Resources Canada (NRCan), as described explained below.

The following tsunami scenarios were modelled in this study:

1. present-day Cascadia tsunami
2. present-day Alaska tsunami
3. Cascadia tsunami with SLR
4. Alaska tsunami with SLR

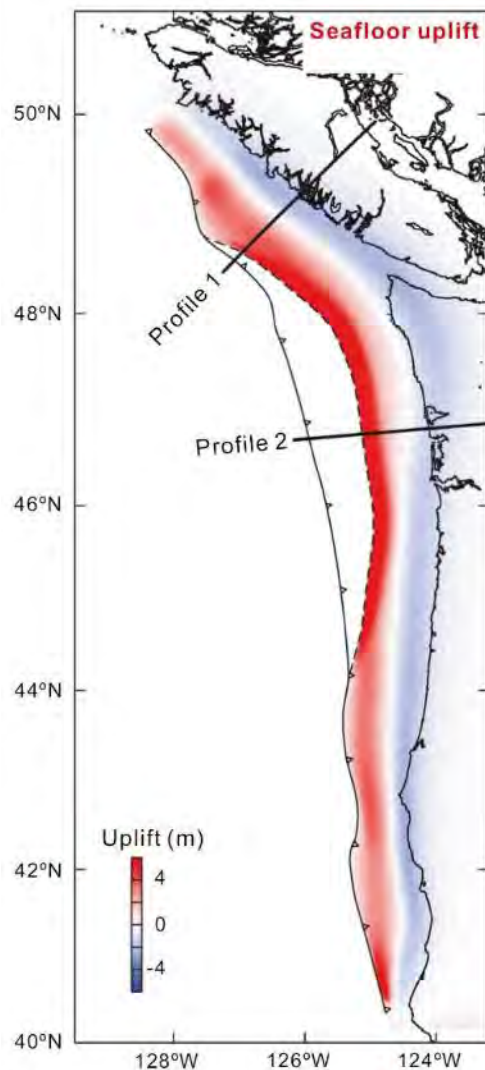
The study team defined general flooding or inundation levels for emergency planning by considering both present-day and future sea levels, as further discussed in Section 4.3. The team mapped only the inundation corresponding to present-day sea level as a starting point to understand the present-day tsunami risk to life safety. Model results including SLR are available for further mapping and assessment to support longer-term development and planning.

3.2.1.1 Tsunami Sources

This section presents details on the tsunami sources analyzed for simulating tsunamis in the project study area, including the Cascadia subduction zone and the Aleutian subduction zone.

Cascadia Subduction Zone

The tsunami source used to simulate 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). After acquiring this tsunami source information from NRCan, ONC included the rupture of the explorer segment of the Cascadia subduction zone for the simulation. This whole-margin **megathrust** scenario is appropriate for tsunami hazard assessments in the northernmost portion of the Cascadia margin. Figure 3.4 shows the estimated uplift (upward motion, red shade) and **subsidence** (downward motion, blue shade) of the Earth's surface associated with this rupture. The rupture zone extends south from California to Brooks Peninsula in the north and corresponds to an approximate 9.0 Mw earthquake. This scenario is generally considered similar to the historical tsunami of January 26, 1700, although it is believed to be stronger than the historical event, as further explained below.



Source: Image from Gao et al., 2018)

Figure 3.4 Vertical displacement of the Earth's surface associated with a modelled Cascadia tsunami.

The following scientific background information further supports the team's consideration of the tsunami source at the Cascadia subduction zone. Witter et al. (2013) simulated Cascadia tsunamis to characterize the associated hazard on the Oregon coast for megathrust earthquake scenarios. In that study the simulations were developed based on the following available information:

- knowledge of the structure of the Cascadia megathrust
- onshore and offshore **paleoseismic** evidence
- theoretical understanding of how megathrust ruptures deform the seafloor
- observations after historical megathrust earthquakes

Witter et al. (2013) established four earthquake size categories with respective mean inter-event time intervals based on the paleoseismic record of previous earthquakes going back approximately 10,000 years. These categories were defined as small (S), medium (M), large (L), and extra-large (XL) with mean **post-event time intervals** of 300 years, 425 to 525 years, 650 to 800 years, and 1,050 to 1,200 years, respectively. A fifth extra-extra-large (XXL) hypothetical scenario was also defined to simulate a maximum tsunami to guide evacuation planning in Oregon (Witter et al., 2013).

From this paleoseismic record the team determined that a total of 19 Cascadia earthquakes have occurred over the last 10,000 years (Table 3.2), with magnitudes that may have ranged from 8.7 to 9.2. According to the classification of Witter et al. (2013) in conjunction with rupture parameters, the 1700 Cascadia earthquake may be associated with the M category (Mw 8.9 – 9.0), and 10 earthquakes are believed to have occurred in the same category over the record. The earthquake scenario of Gao et al. (2018) that was simulated for this study can be associated with the L category (Mw 9.0 – 9.1), with three earthquakes of such magnitude occurring over the record. Only one earthquake associated with the XL category (Mw 9.1 – 9.2) is believed to have occurred over the record. Accordingly, while the Cascadia tsunami modelled in this study can be considered a severe event, it may technically not be the worst-case scenario, and some residual risk remains.

Table 3.2 Paleoseismic record of past Cascadia earthquakes based on turbidite⁶ analysis.

Event No.	Estimated Age ¹	Post-event Interval ²	Inferred Earthquake Size Category
T1 ³	271	-	M
T2	466	200	SM
T3	802	340	M
T4	1,254	450	SM
T5	1,566	310	M
T6	2,564	1,000	L
T7	3,051	490	M
T8	3,472	420	M
T9	4,131	660	M
T10	4,778	650	M
T11	5,924	1,150	XL
T12	6,404	480	SM
T13	7,164	760	L
T14	7,624	460	M
T15	8,177	550	M
T16	8,853	680	L
T17	9,109	260	SM
T17a	9,221	110	SM
T18	9,816	600	M

Source: Witter et al. (2013)

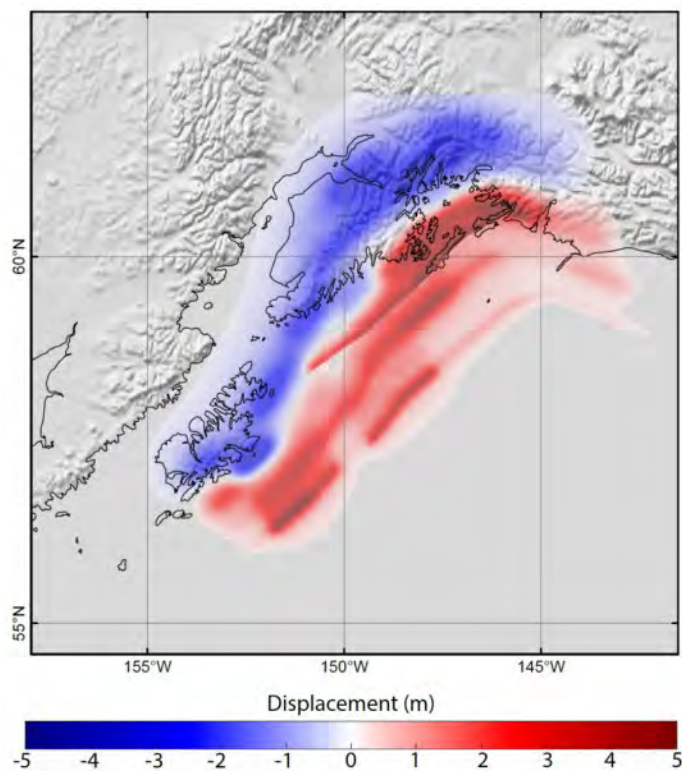
Notes:

1. Estimated age is the estimated turbidite age in calibrated radiocarbon years before 1950.
2. Post-event interval is the time difference between an event and the next subsequent event rounded to the nearest decade.
3. Event corresponding to the tsunami of 1700 as estimated by radiocarbon dating.

⁶ **Turbidites** are sea-bottom deposits formed by massive slope failures. These slopes fail in response to excessive sedimentation load and sometimes earthquake shaking, sending the sediments sliding down to the ocean bottom to create a turbidite. Carbon dating of turbidites has been shown to provide a good method of determining the date of very old earthquakes (USGS, n.d.).

Aleutian Subduction Zone

The numerical simulations of the 1964 Alaska tsunami are based on the seafloor displacement defined by Suleimani and Freymueller (2020). This displacement is associated with the Mw 9.2 earthquake that generated the tsunami and is shown in Figure 3.5. ONC acquired this tsunami source information from University of Alaska Fairbanks.



Source: Image from Suleimani and Freymueller (2020).

Figure 3.5 Vertical displacement of the Earth's surface associated with the Alaska tsunami modelled for the study. Uplift is represented by shades of red, and subsidence is represented by shades of blue.

3.2.1.2 Water Levels

This section provides details and background information on water levels, including present-day tide levels and future water levels caused by SLR due to climate change. This section also presents details on land subsidence estimates due to a local Cascadia earthquake.

Tide Level

Tides are driven by **astronomical forcing**, the gravitational forces applied on sea water by celestial bodies such as the Moon and the Sun. Since the rotation of the Moon and the planets is a cyclic and repeated phenomenon, the variation of the water level generated by the astronomical tide alone can be

predicted accurately. On the other hand, **storm surges** are driven by **atmospheric forcing**, which combines the effects of the wind and the **barometric pressure**. Because the probability of a tsunami occurring during an intense storm is low (although not impossible), no storm surge is included in the numerical simulations⁷.

The US National Tsunami Hazard Mitigation Program (NTHMP) recommends development of tsunami inundation maps based on simulations performed with a tide level corresponding to, at a minimum, the **mean high water** (MHW) of a specific region (NTHMP, 2010). As per the NOAA's definition of **tidal heights** in the US, 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, 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 1.4 to 1.6 m with respect to CGVD2013, so the study team used an average value of 1.5 m for the area covered by the model. The tide level was kept constant in the numerical simulations, which, for the purpose of inundation mapping, is considered a conservative simplification.

The selection of HHWMT as tide level for the simulations instead of a higher tide level such as **higher high water, large tide** (HHWLT) implies that some residual risk remains. HHWLT corresponds to the average of the annual highest high water heights over a tidal epoch. This high tide level generally only occurs approximately every 2 years at Winter Harbour on average, and the probability of a coinciding tsunami is low. In the study area HHWLT varies from 2.0 to 2.4 m with respect to CGVD2013 (or 0.6 to 0.8 m higher than HHWMT).

The tide levels stated above are based on information provided in the Canadian Tide and Current Tables (Fisheries and Oceans Canada, 2022), with data converted to CGVD2013 based on the Continuous Vertical Datum for Canadian Waters dataset developed by the CHS. This dataset constitutes a surface relating **chart datum** to the national geodetic reference frame with the year 2010 serving as baseline⁸.

Sea Level Rise

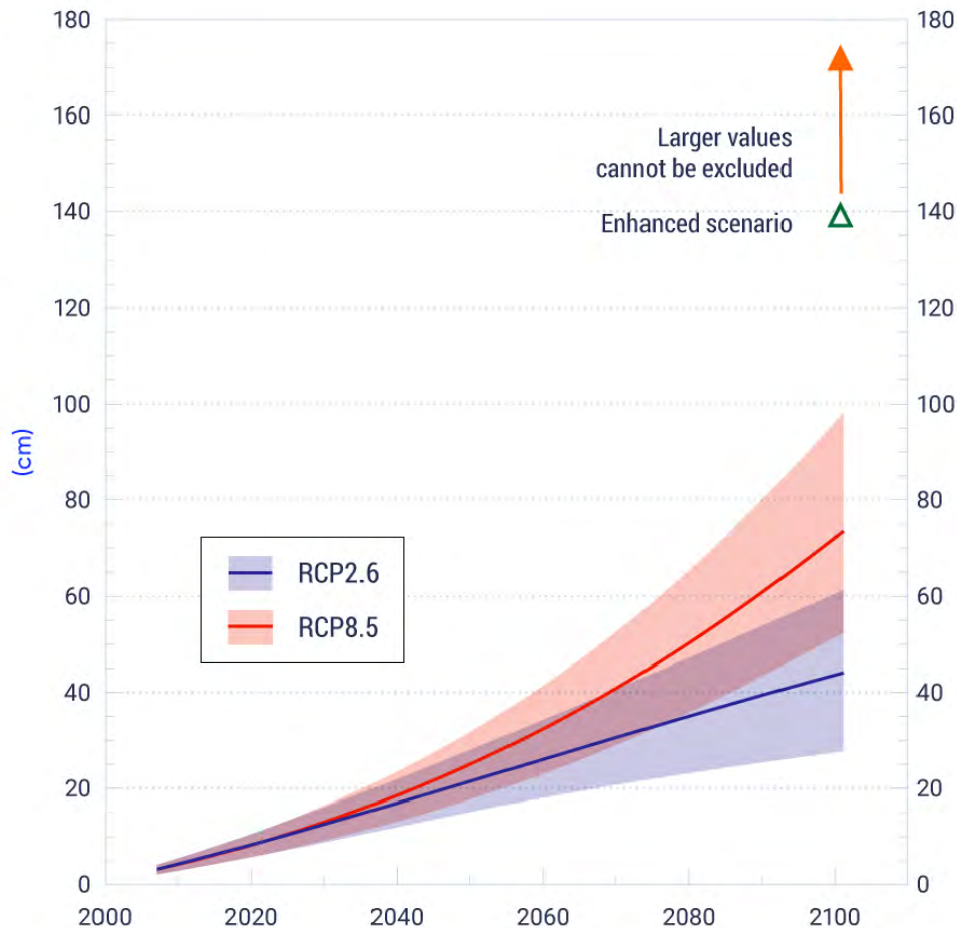
Sea levels around the world have been rising and are projected to continue to rise because of climate change and its associated increase in average temperatures. **Global SLR** is caused by melting glaciers, ice caps, and ice sheets, but increased ocean volume is also due to thermal expansion from higher water temperatures. Scientists have collected data and used modelling to estimate future sea levels, but the rate of continued SLR is subject to considerable uncertainty. This section presents a discussion of the existing projections and provides the sea level estimates used for the tsunami simulations with SLR.

Figure 3.6 shows projections of global SLR 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

⁷ The study authors note that regularly occurring storm surge in the region is between 0.3 and 0.7 m.

⁸ CHS, 2022. Email communication between Philippe St-Germain (pstgermain@nhcweb.com) and Mike Morley (mike.morley@dfo-mpo.gc.ca) on March 18, 2022.

fifth assessment report of the Intergovernmental Panel on Climate Change (International Panel on Climate Change, 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, respectively. The lines in Figure 3.6 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.



Source: Image adapted from Greenan et al. (2018).

Figure 3.6 Projected global SLR.

The BC provincial Flood Hazard Area Land Use Management Guidelines (Government of BC, 2018) recommend that projects consider 1.0 m of global SLR 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 global SLR 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 SLR during both the twenty-first and the twenty-second centuries.

In comparison to global SLR, the **relative SLR** observed in one location accounts for long-term vertical movements of the earth's surface at that location, 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 SLR, while subsidence will accelerate it. NRCan published relative SLR predictions at Canadian shorelines (James et al., 2021). These projections are based on the fifth assessment report of the Intergovernmental Panel on Climate Change (International Panel on Climate Change, 2014), as discussed above, in conjunction with a national **crustal velocity model**, which describes changes in ground elevation over time. The most adverse scenario analyzed by James et al. (2021) corresponds to a relative SLR of approximately 1.2 m on the northwest coast of Vancouver Island by 2100, which relates to the enhanced scenario and accounts for greater amounts of ice melting from Antarctica,

To err on the conservative side, the study team adopted NRCan's relative SLR projection of 1.2 m by 2100 for the tsunami simulations with SLR.

Earthquake Land Subsidence

For this study, the land subsidence associated with a local Cascadia earthquake is accounted for by lowering the ground elevation in the numerical model according to the spatially varying ground displacement estimated by Gao et al. (2018), which is shown by the blue shading in Figure 3.4. This essentially instantaneous subsidence is greater on the open coast and diminishes further inland. For example, the estimated subsidence from a local Cascadia earthquake corresponds to a lowering of the ground by approximately -1.0 m at Kyuquot and -0.4 m at Tahsis (the negative sign indicates downward movement). The land subsidence associated with a distant Aleutian subduction zone earthquake in Alaska does not affect the study area.

When considering the scenario involving a Cascadia tsunami with SLR, it is assumed that the land displacement associated a Cascadia earthquake in the far future is equivalent to the displacement associated with a Cascadia earthquake occurring in the near future.

3.2.2 Tsunami Model Description

This section provides a technical description of the numerical model used to simulate tsunami propagation and potential overland flooding or inundation, based on the scenarios described above. ONC performed tsunami simulations using version 3.4 of the fully nonlinear **Boussinesq**-based wave computer model FUNWAVE, which was developed and is maintained by the University of Delaware (Shi et al., 2016). The model solves governing equations for propagating long waves and has been benchmarked against other tsunami models as part of the US NTHMP 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.

The project study team 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. This nesting is performed at various levels, starting with a larger computational grid in the open ocean and moving into gradually smaller nested grids toward the area of interest, in this case the northwest coast of Vancouver Island. The geographical extent of the computational grids computing the tsunami results is shown in Figure 3.7. A coarser resolution of 60 m was used over the study area, while a higher resolution of 10 m was used in regions where areas of interest were identified for Phase II of the project. These areas of interest are situated in Nootka Sound and Quatsino Sound (refer to Figure 1.1 for the areas covered under the scope of Phase II). Broader grids of lower resolution were used in the Pacific Ocean but are not discussed in this report.

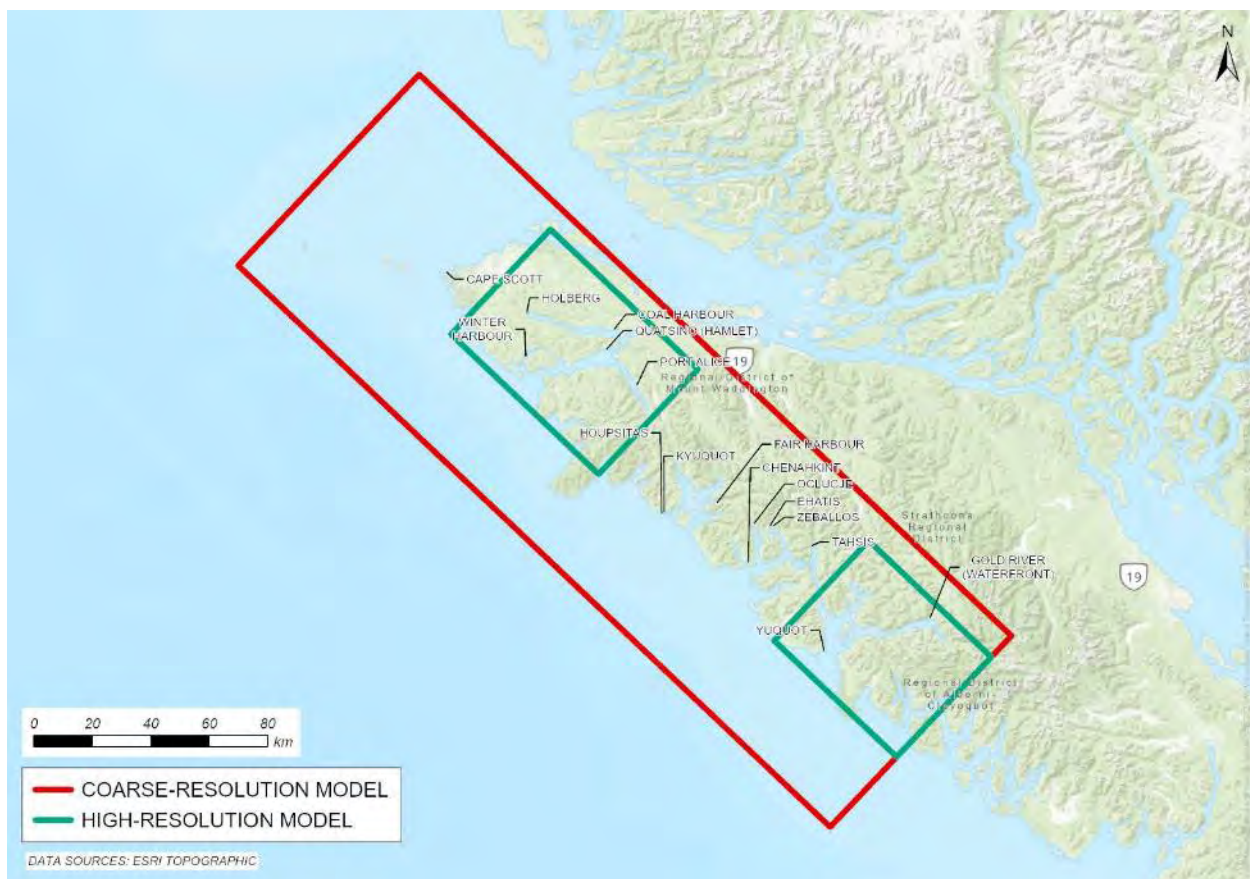


Figure 3.7 Extents of modelling grids used to simulate tsunami propagation and inundation, as part of Phase II of the project.

While coarser simulations enable the study team to identify overwater hazards from forces such as maximum tsunami amplitude and maximum tsunami-induced current velocity, this resolution is not sufficient to adequately simulate overland flooding or inundation. Hence, inundation mapping can only take place in areas modelled at a higher resolution, where high-resolution topographic information (i.e.,

LiDAR) is also available and integrated into the model's underlying DEM. The development of the DEM and the coverage of LiDAR for this project is discussed in Section 3.1. Additional details on the tsunami model and its results are provided in Appendix D.

3.2.3 Model Results

This section presents the general results of tsunami modelling for scenarios involving the generation of a Cascadia or Alaskan tsunami, along with the resulting influence of SLR in both tsunami scenarios.

Tsunami events generally consist of a series of waves that can affect coastal areas for several hours and even days after an associated earthquake. The tsunami model computes the changes in the water surface elevation across the modelled areas, as well as the current velocities induced by these relatively rapid changes, averaged over the depth of water. The study team used this information to derive the maximum tsunami wave amplitude and maximum tsunami-induced current velocities that may occur at any moment during a tsunami event. Tsunami-induced currents can be superimposed on tidal currents; in the numerical model developed for this project tidal currents were not included. Currents induced by a tsunami 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 (i.e., the water level without the influence of the tsunami). This term should not be confused with **tsunami wave height**, which is the vertical distance between the crest and trough of a tsunami wave.

Section 3.2.3.1 and Section 3.2.3.2 provide a general overview of the results for maximum tsunami wave amplitude and maximum tsunami-induced current velocities for a Cascadia and an Alaska tsunami, respectively. The results shown are limited to the extent of the overwater hazard maps produced as part of this study. The layout of these maps is shown in Figure 3.20, and the maps themselves are provided in Appendix E. **Tsunami arrival times**, which are also indicated on the overwater hazard maps, are presented in Section 4 as part of the risk assessment.

The extent of tsunami flooding or inundation is derived by post-processing the water surface elevation predicted by the model. Details of the methodology followed to derive the extent of inundation are presented in Section 3.3.4. The areas that were mapped and used to derive inundation extents are presented in Figure 3.21 and Figure 3.22 for Nootka Sound and Quatsino Sound, respectively. These areas were selected based on the areas of interest identified by the advisory group. Associated inundation maps are provided in Appendix F.

Other parameters were not directly included in this report but can be obtained from the model results, including **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.

3.2.3.1 Cascadia Tsunami

What makes Vancouver Island particularly susceptible to potentially large tsunami waves is the proximity of the Cascadia subduction zone, which is located approximately 100 km offshore and runs parallel to the west coast of North America. Figure 3.8 shows the influence of a Cascadia tsunami in the Pacific Ocean, directly affecting the west coast of Vancouver Island. 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 results in a reduction of their amplitude. This explains why areas such as the island of Haida Gwaii on the northern BC coast are less affected by tsunamis from the Cascadia subduction zone in comparison to Vancouver Island.

Oral History of the 1700 Tsunami

As told by Chief Louie Nookmiis (1881 – 1964) and recorded by anthropologist Eugene Arima:

“The Pachena Bay people were lost... But (for those) who lived at maat’caas ‘House Up Against Hill’, the wave did not reach (them) because they were on high ground right against a cliff. Because of that they came out alive. They did not drift out to sea along with the others.”

Although Pachena Bay, located near Bamfield, BC, is outside of the project study area, it is geographically relevant, and its mention in shared Indigenous Knowledge accounts provide a local example of the devastation caused by tsunamis on the west coast of Vancouver Island.

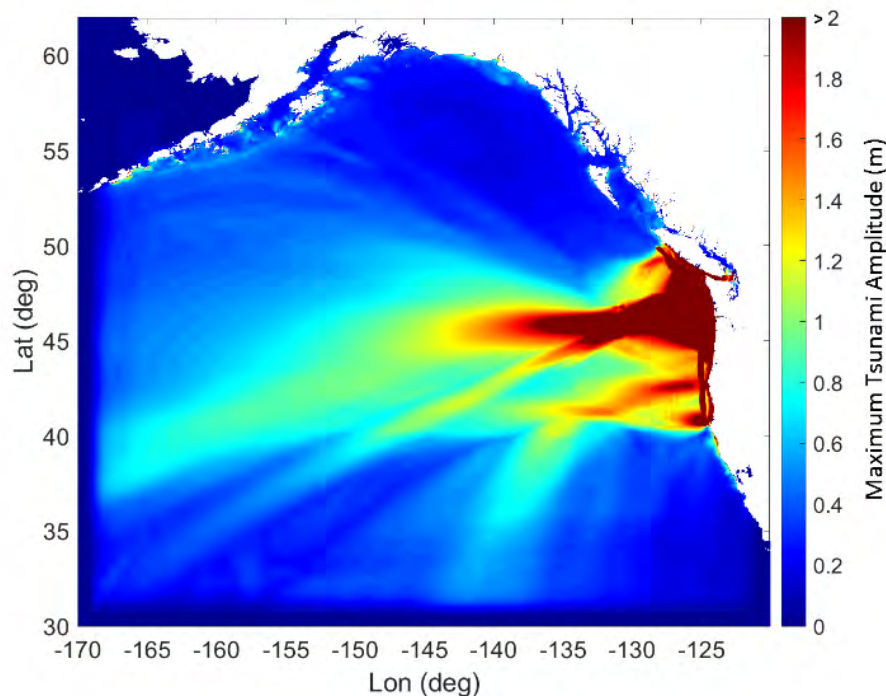


Figure 3.8 Maximum amplitude of Cascadia tsunami in the northeast Pacific Ocean.

Tsunami Wave Amplitude

Figure 3.9 illustrates the maximum tsunami amplitude from a Cascadia tsunami and the resulting effects on the northwest coast of Vancouver Island. This region is characterized by many narrow inlets and sounds where tsunami waves can be amplified, increasing their potential to cause adverse impacts to communities. This amplification can be the result of several physical factors, such as constricting topography, a decrease in water depth that induces **wave shoaling**, and/or **resonance**. No detailed assessment was performed to further characterize the physical factors that amplify tsunami waves.

The largest tsunami amplitude would generally occur along the open coast south of Brooks Peninsula, where amplitudes exceed 6 m (and up to 10 m on the west coast of Nootka Island). Results show that tsunami amplitude would be smaller in areas north of Brooks Peninsula. These areas are beyond the northern limit of the Cascadia subduction zone identified for this study (see Figure 3.4); consequently, they would not be affected by tsunami waves directly approaching them.

At the northern end of Vancouver Island near Cape Scott, the tsunami amplitude in the open ocean near the coast is expected to reach 2 m and can potentially be larger in embayments. These modelled results are less than the estimates originally predicted during Phase I of the project in response to further refinement of the tsunami model during the Phase II study.

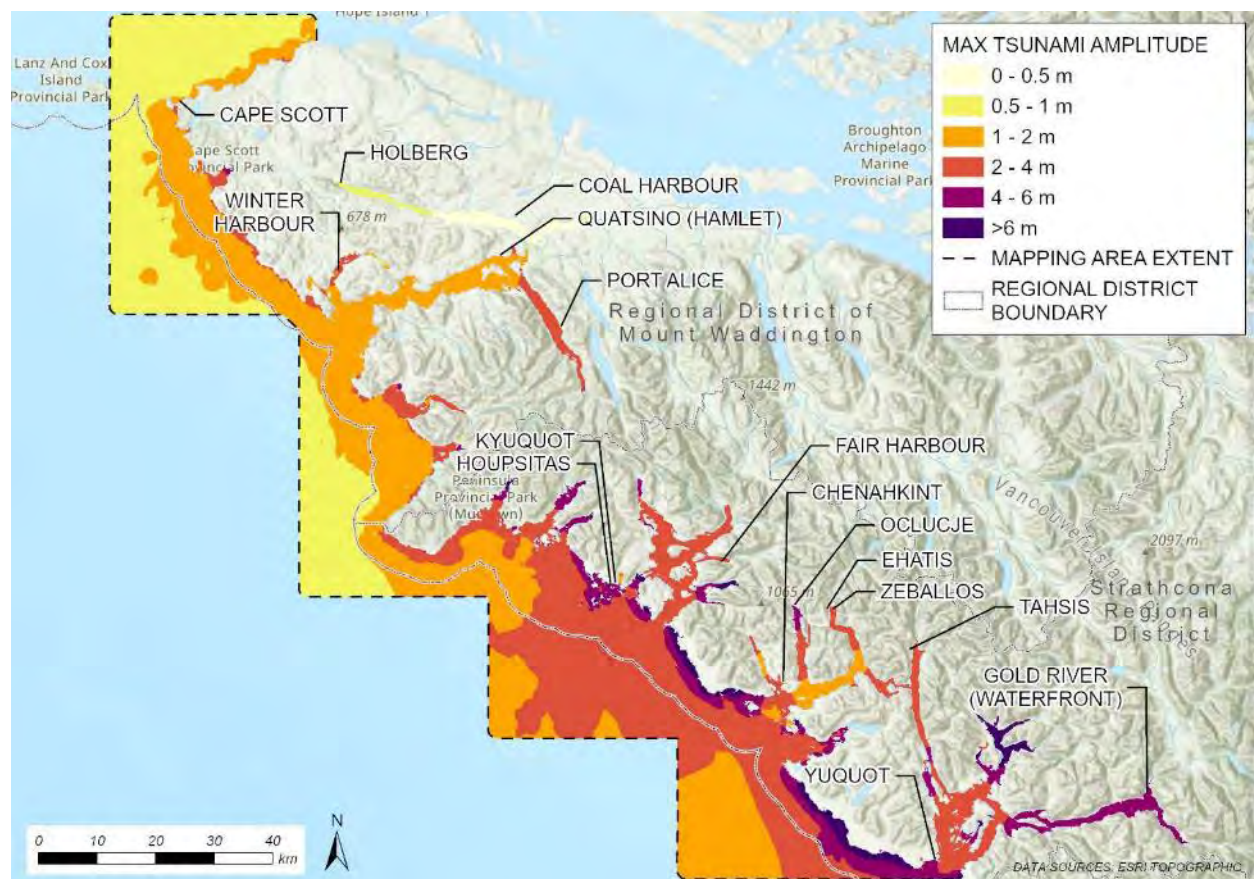


Figure 3.9 Maximum Cascadia tsunami wave amplitude modelled in the broader study area.

Results of the assessment of maximum tsunami amplitude in Nootka Sound and Quatsino Sound are shown in Figure 3.10 and Figure 3.11, respectively. Results for Tahsis Inlet, Esperanza Inlet, and Kyuquot Sound are discussed in the project's Phase I report (NHC, 2022).

Yuquot, which is located at the entrance of Nootka Sound on Nootka Island, has been occupied for at least the last 5,000 years, although stratigraphic evidence suggests the area was abandoned following the 1700 Cascadia tsunami. Exposed to the open ocean, this location is subjected to large tsunami waves with amplitudes ranging from 3.0 m in Friendly Cove directly north to 6.1 m on the open coast west of Yuquot Point (see Figure 3.10). These model predictions are consistent with the Indigenous oral history gathered as part of this study.

Oral History of the 1700 Tsunami

As told by Ray Williams

(Mowachaht/Muchalaht First Nations):

"In 1700 the tsunami washed pebbles into their lake at Yuquot because there is about 300 feet between the ocean and the lake."

At the head of Hisnit Inlet, the tsunami amplitude is expected to reach up to 6 m and overflow into Deserted Lake, which is located approximately 1 km north, past the inlet's head. Hutchinson et al. (2000) collected **core samples** in the lake and discovered three different layers of sand in the sediment profile. The sand and **microfossil assemblages** of these layers were consistent with deposition from tsunamis. Radiocarbon dating puts the tsunamis generated from earthquakes at the Cascadia subduction zone at approximately 2,600, 1,600, and 300 years ago. Cross-referencing these findings with the paleoseismic record of past Cascadia earthquakes presented in Table 3.2 suggests that the lake would not be affected by tsunamis generated by smaller earthquakes (e.g., less than category M).

Located at the head of Nootka Sound, Tlupana Inlet is particularly exposed to tsunami hazard with amplitudes exceeding 8 m (up to 10 m up the Sucwoa River, Canton Creek, and Conuma River). The area at the mouth of Gold River, where important infrastructure is located, would also be subjected to considerable tsunami amplitudes ranging from 4 to 6 m.

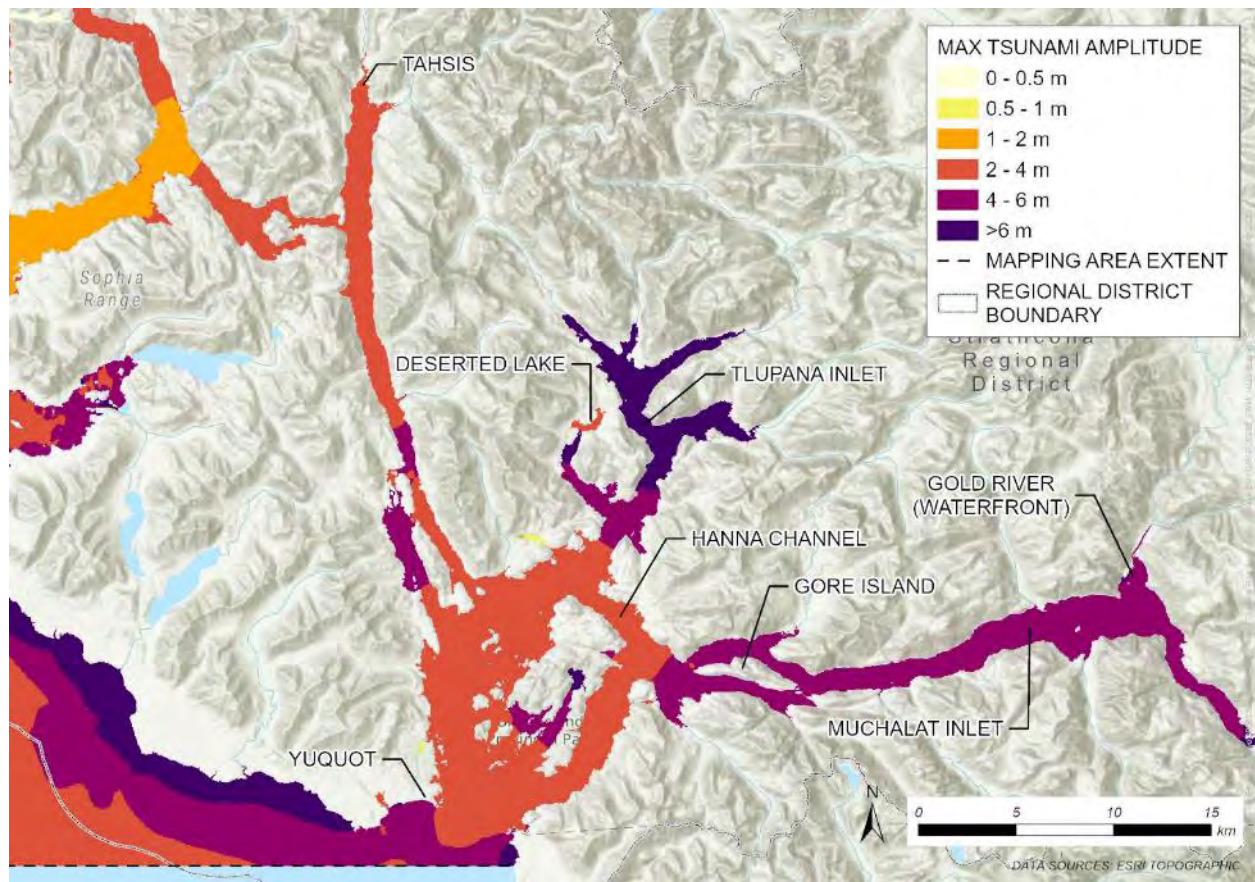


Figure 3.10 Maximum Cascadia tsunami wave amplitude in Nootka Sound.

Holberg Inlet is connected to Quatsino Sound through Quatsino Narrows and is where Holberg and Coal Harbour are located. This inlet is not expected to be greatly affected by tsunami waves in comparison to other areas in Quatsino Sound (see Figure 3.11). Nevertheless, detailed model results obtained as part of Phase II of this project reveal that some amplification of tsunami waves can occur toward the western end of the inlet, with wave amplitudes exceeding 1 m at Holberg.

At Port Alice and Winter Harbour, the tsunami wave amplitudes are expected to range between 2 m and 4 m. Along the open shores of the Hamlet of Quatsino, wave amplitudes are expected to reach up to 2 m but are expected to be higher in Hecate Cove (up to 2.8 m). The amplitudes of tsunami waves at Coal Harbour are not expected to exceed 0.5 m.

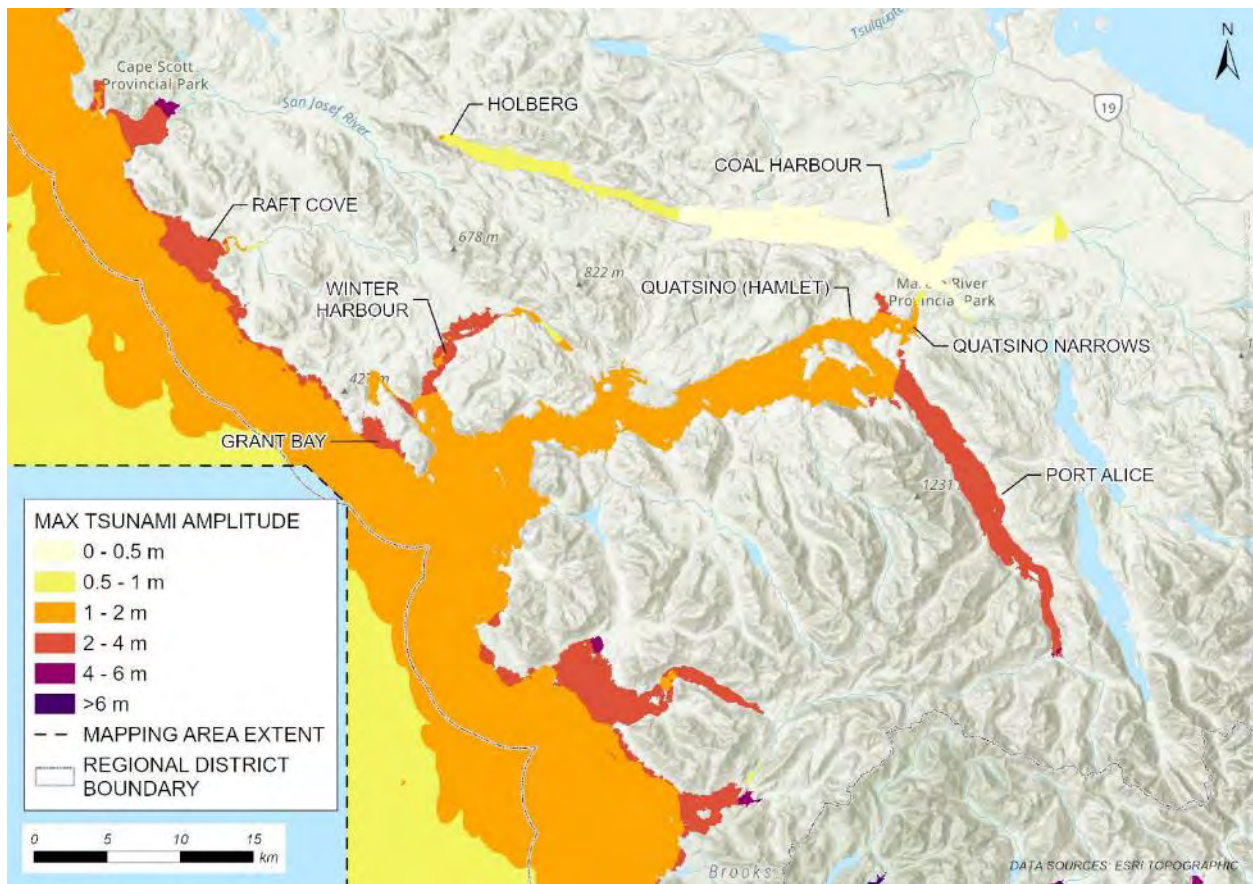


Figure 3.11 Maximum Cascadia tsunami wave amplitude in Quatsino Sound.

Tsunami-induced Current Velocity

Results of maximum current velocities induced by a Cascadia tsunami in Nootka Sound and Quatsino Sound are shown in Figure 3.12 and Figure 3.13, respectively.

Fast current velocities are hazardous to navigation (e.g., greater than 3 knots) and are predicted along the open coast of Nootka Island. Fast, hazardous currents are also predicted in the entrance of Nootka Sound due to relatively shallower water depths (e.g., less than 100 m) in conjunction with the constricted topography. Passages in the vicinity of Gore Island in Muchalat Inlet, Hanna Channel, and Tlupana Inlet are other areas where particularly fast currents are expected. Overall, tsunami-induced current velocities are expected to be strong over most of Nootka Sound. Because of the cyclic and reversing nature of tsunami waves, which may last several hours or even days, these currents will pose unusual and hazardous conditions that will be difficult, if not impossible, to predict.

Further inside Muchalat Inlet toward Gold River, tsunami-induced current velocities would be slower due to increased water depths (e.g., greater than 100 m). The water depth in this area can reach down to 360 m.

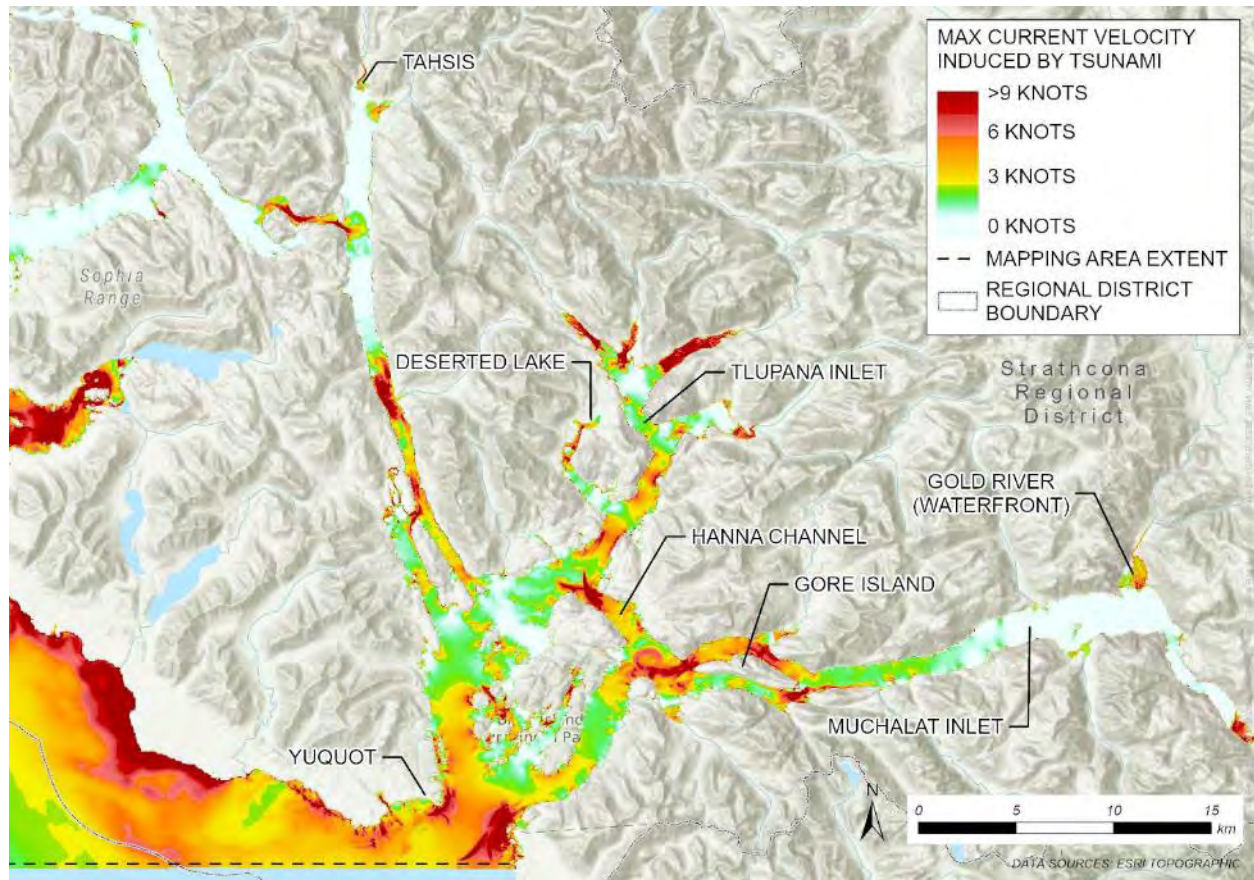


Figure 3.12 Maximum current velocity in Nootka Sound induced by a Cascadia tsunami.

In Quatsino Sound (Figure 3.13), current velocities would be generally slower compared to velocities in Nootka Sound, mainly due to the smaller tsunami amplitude in this region, in conjunction with increased water depths in some areas. Nevertheless, fast currents could occur at narrow constrictions, such as Quatsino Narrows leading into Holberg Inlet, as well as in the vicinity of islands within the sound. Very hazardous currents can be expected at Winter Harbour due to its narrowing topography and relatively shallower water depths.

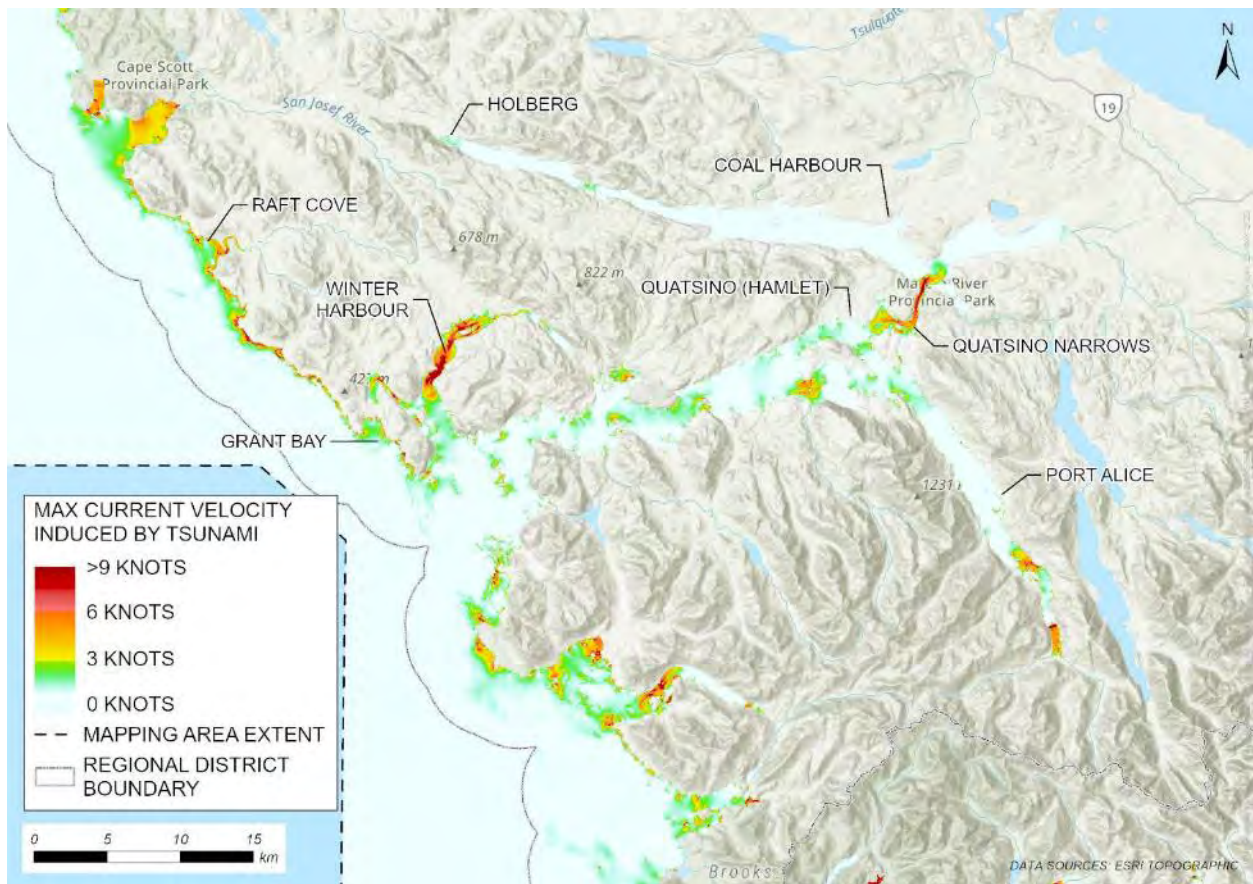


Figure 3.13 Maximum current velocity in Quatsino Sound induced by a Cascadia tsunami.

3.2.3.2 Alaska Tsunami

Figure 3.14 shows the general influence in the Pacific Ocean of a tsunami originating from the Aleutian subduction zone in Alaska. The orientation of this fault results in the main direction of the tsunami waves aimed toward the BC coast and the west coast of the US. The earthquake that generated the Alaska tsunami on March 27, 1964, occurred at approximately 6:30 pm Pacific Daylight Time (3:30 a.m. Greenwich mean time on March 28, 1964) and reached Vancouver Island within approximately 3 to 4 hours after the earthquake. At the time of arrival of the tsunami waves, the stage of the tide was approximately 3.0 m chart datum, which is approximately 0.5 m lower than HHWMT in the study area.

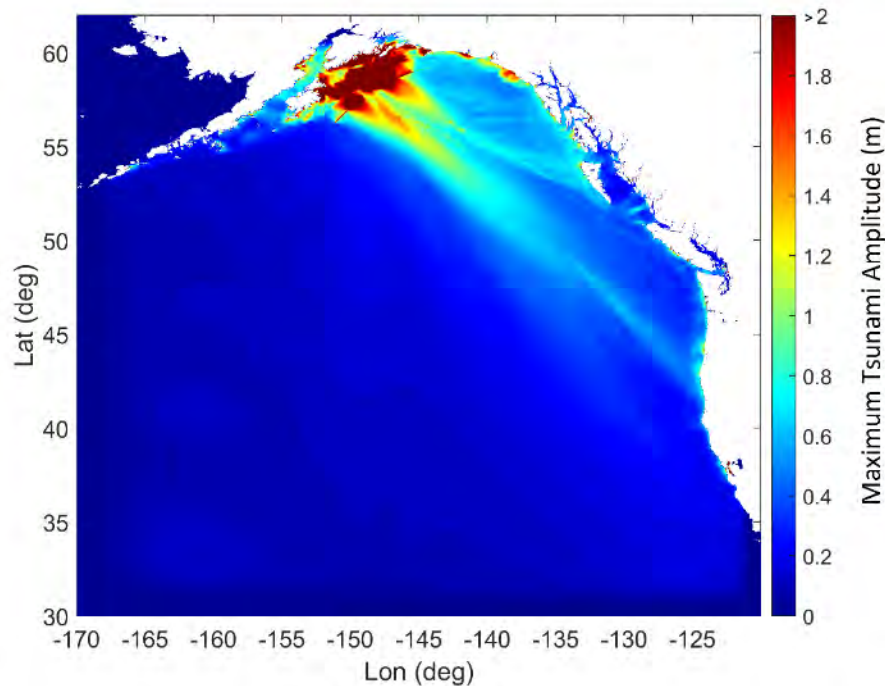


Figure 3.14 Maximum amplitude of Alaska tsunami in the northeast Pacific Ocean.

Tsunami Wave Amplitude

There are no records of observed water levels (e.g., **time series**) within the study area at the time of the 1964 Alaska tsunami, making it impossible to directly compare the tsunami amplitude predicted by the numerical model against the actual measurements. The tidal gauge at Tofino was operational at the time of the tsunami, recording a maximum wave amplitude of approximately 1 m (Rabinovich et al., 2019). However, since the tsunami occurred outside of the study area for this project, the model results computed at that location are too coarse to enable any meaningful comparison. Instead, model results are substantiated by consulting Indigenous community members who have first-hand experiences of the event. Details are presented below.

Modelling results of the maximum tsunami amplitude associated with an Alaska tsunami affecting the northwest coast of Vancouver Island are shown in Figure 3.15. In contrast to the Cascadia tsunami, for which the largest amplitude is generally predicted on the open coast, the largest amplitude in the case of an Alaska tsunami would occur at the heads of inlets. This is particularly observed at Tahsis, Gold River waterfront, and at the head of Neroutsos Inlet, past Port Alice. The larger amplitude at Gold River waterfront, in conjunction with the stage of tide, corroborates with first-hand experiences.

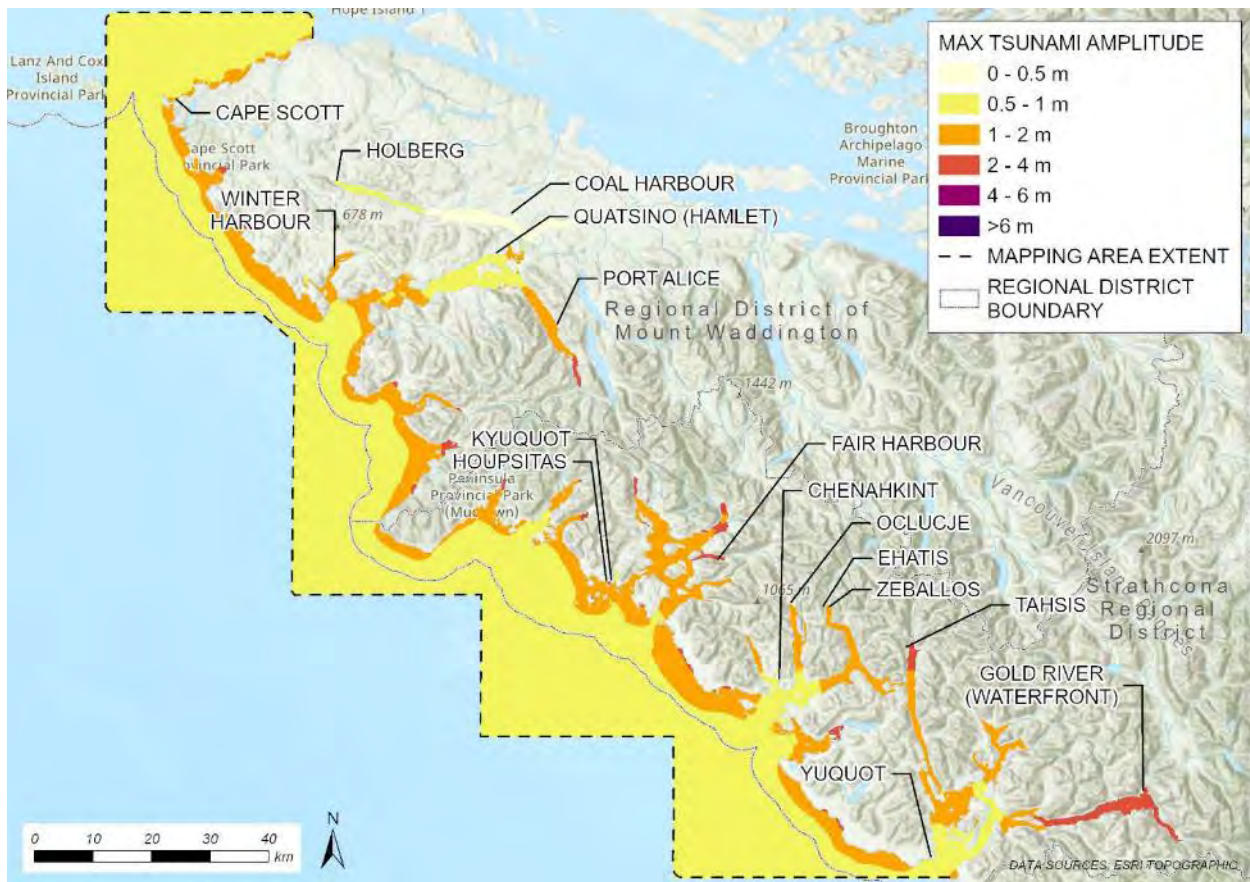


Figure 3.15 Maximum Alaska tsunami wave amplitude modelled in the broader study area.

Results of modelled maximum tsunami amplitude in Nootka Sound and Quatsino Sound are shown in Figure 3.16 and Figure 3.17, respectively. Results for Tahsis Inlet, Esperanza Inlet, and Kyuquot Sound are discussed in the project’s Phase I report (NHC, 2022).

In Nootka Sound, these results show that areas in Muchalat Inlet could be significantly affected by a distant tsunami, with wave amplitudes reaching up to 3.5 m at the mouth of Gold River. In Tlupana Inlet and west of Bligh Island, which is located in the centre of the sound, wave amplitudes would be milder (i.e., up to 2 m) but would remain considerable. Wave amplitudes at Yuquot would be relatively small (i.e., less than 1 m), and the overland area is less prone to be affected, depending on the tide levels coinciding with the tsunami.

First-hand Experience

From an interview with late Ray Williams, Mowachaht/Muchalaht First Nations:

(Ray was 80 years old when he was interviewed for the project.) During the 1964 Tsunami, Ray was working as a logger in Gold River and Yuquot. The waves bypassed Yuquot and shot up the inlet toward Tahsis. The bunkhouses, which were on 4-foot spruce logs, got engulfed in water in Gold River. He was 14 at the time.

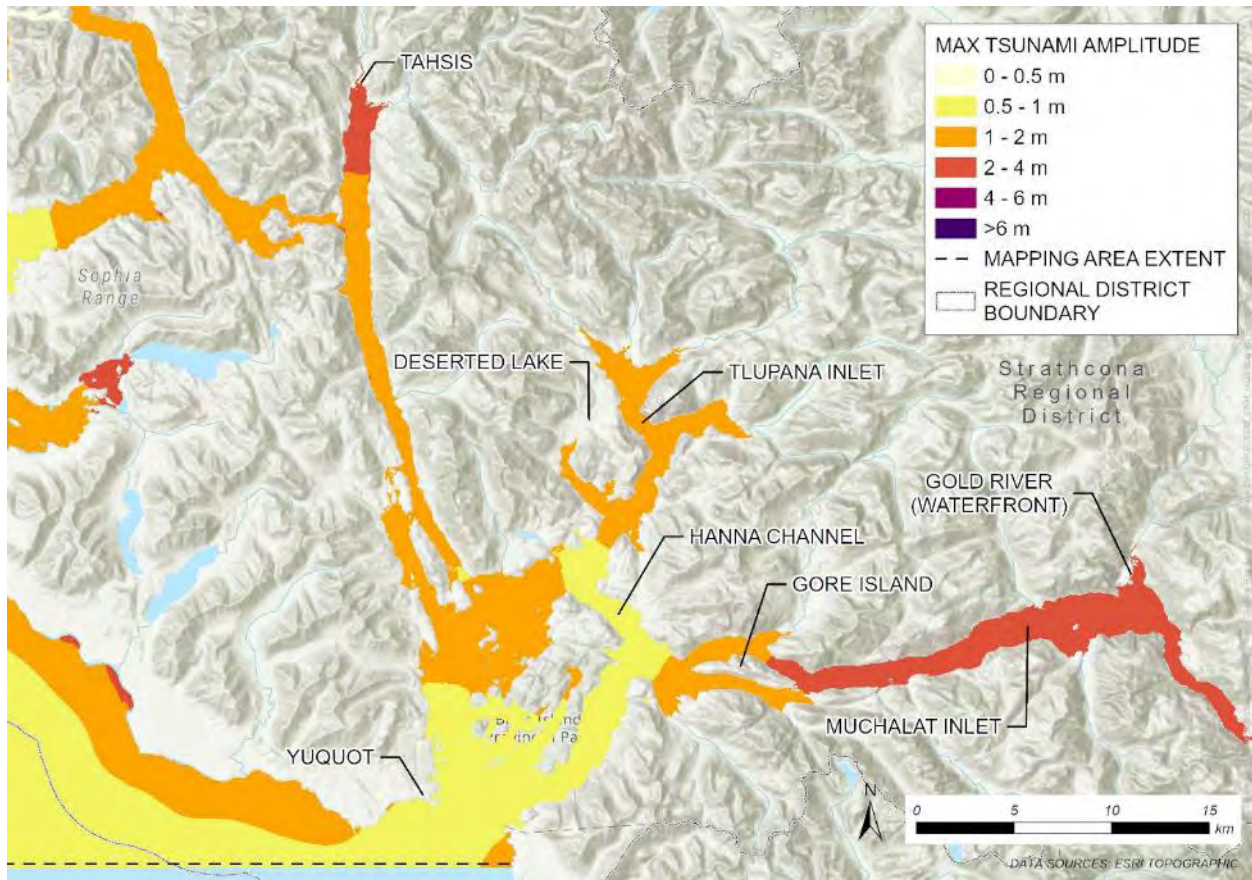


Figure 3.16 Maximum Alaska tsunami wave amplitude in Nootka Sound.

In comparison to other areas in Quatsino Sound, such as Holberg Inlet and the Hamlet of Quatsino, where the tsunami waves are not expected to exceed 1 m in amplitude, Port Alice and Winter Harbour could be more affected by an Alaska tsunami (Figure 3.17). At those locations, wave amplitudes are predicted to range from 1 to 2 m, and they could exceed 2 m at the head of Neroutsos Inlet. The amplitudes of tsunami waves at Coal Harbour are not expected to exceed 0.5 m.

First-hand Experience

From an interview with Chief Tom Nelson (Quatsino First Nation): *Tom's friend had a cabin near Port Alice, which had been moved 200 feet from its original location. He said his father's boat broke loose from where it was moored and was lifted by the wave and landed on a piling, putting a hole in the hull. There was damage to other boats and infrastructure like docks in Port Alice, but nobody was hurt from what he remembers. Tom would have been around 18 when the tsunami hit Port Alice.*

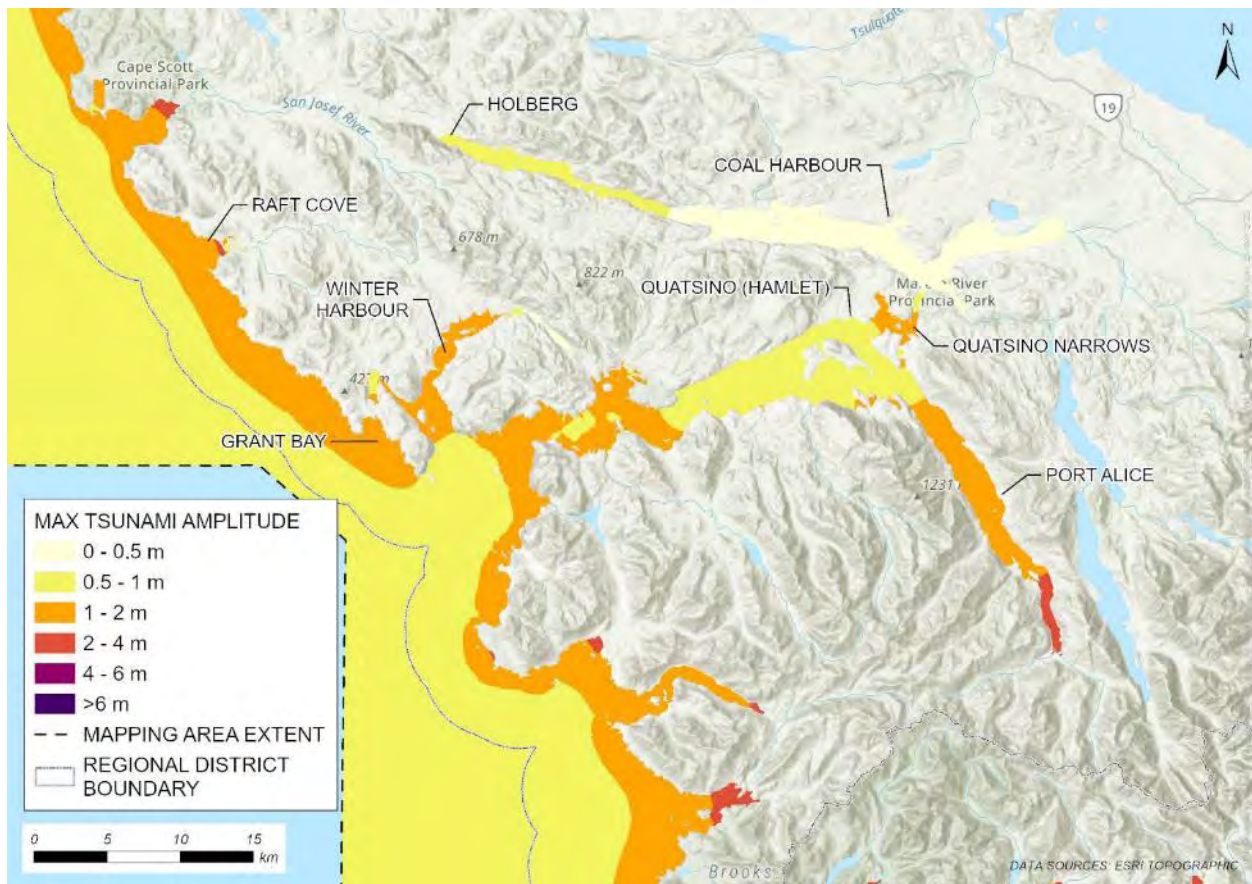


Figure 3.17 Maximum Alaska tsunami wave amplitude in Quatsino Sound.

Tsunami-induced Current Velocity

Results of maximum current velocities induced by an Alaska tsunami in Nootka Sound and Quatsino Sound are shown in Figure 3.18 and Figure 3.19, respectively. While considerably slower than the velocities predicted for a Cascadia tsunami (e.g., Figure 3.12), fast and hazardous velocities can still occur with an Alaskan tsunami, especially in constrictions, such as surrounding Gore Island in Muchalat Inlet and Quatsino Narrows; in areas of relatively shallower depths such as Winter Harbour; and in the passages between islands.

In addition to putting mariners at risks, fast current speed also places marina users at risk as marine infrastructure can be damaged. Currents could also affect anyone close to the water's edge who may fall into the moving water.

First-hand Experience

From an interview with Tim Paul (Ehattlesaht First Nation):

Tom was loading a boat at the time the 1964 tsunami hit. The lines got tight and broke a few things off the dock.

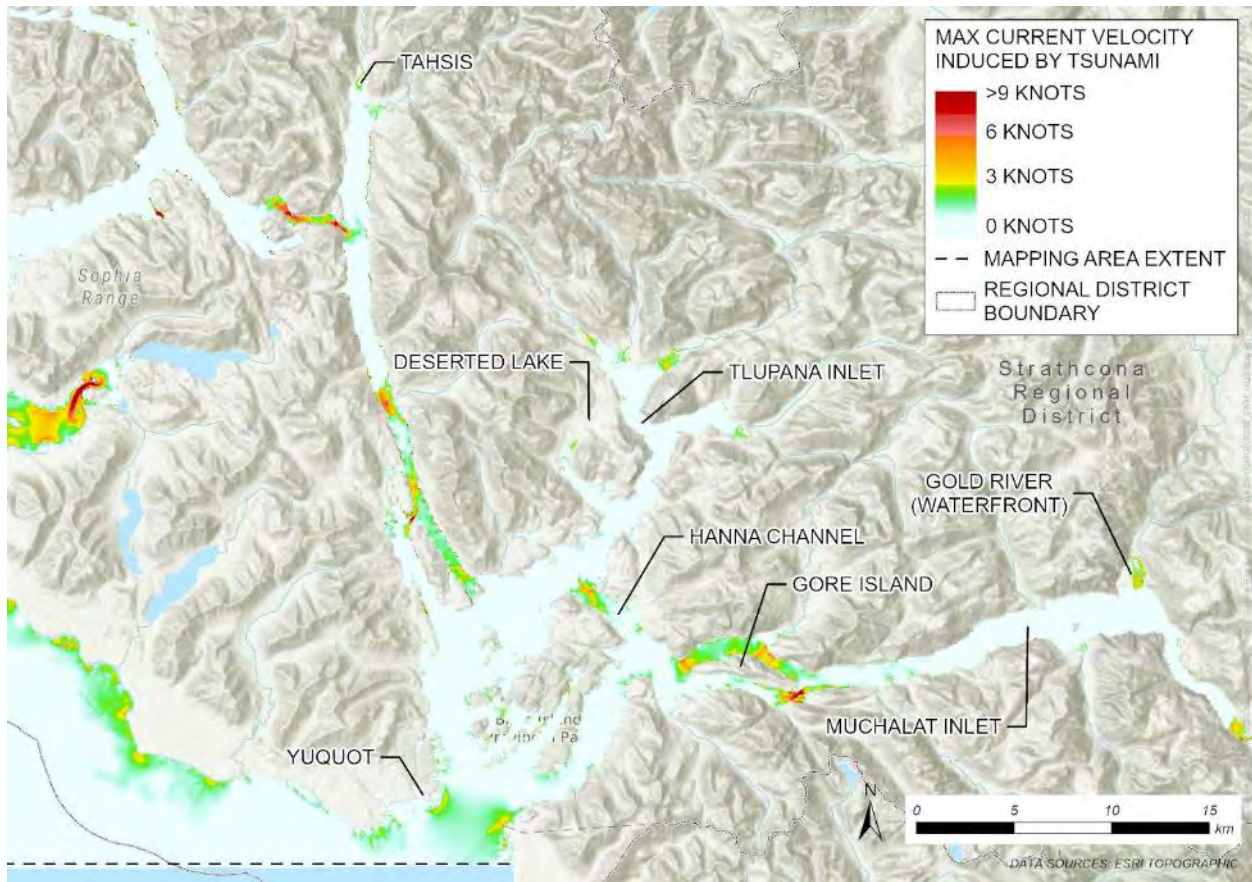


Figure 3.18 Maximum current velocity in Nootka Sound induced by an Alaska tsunami.

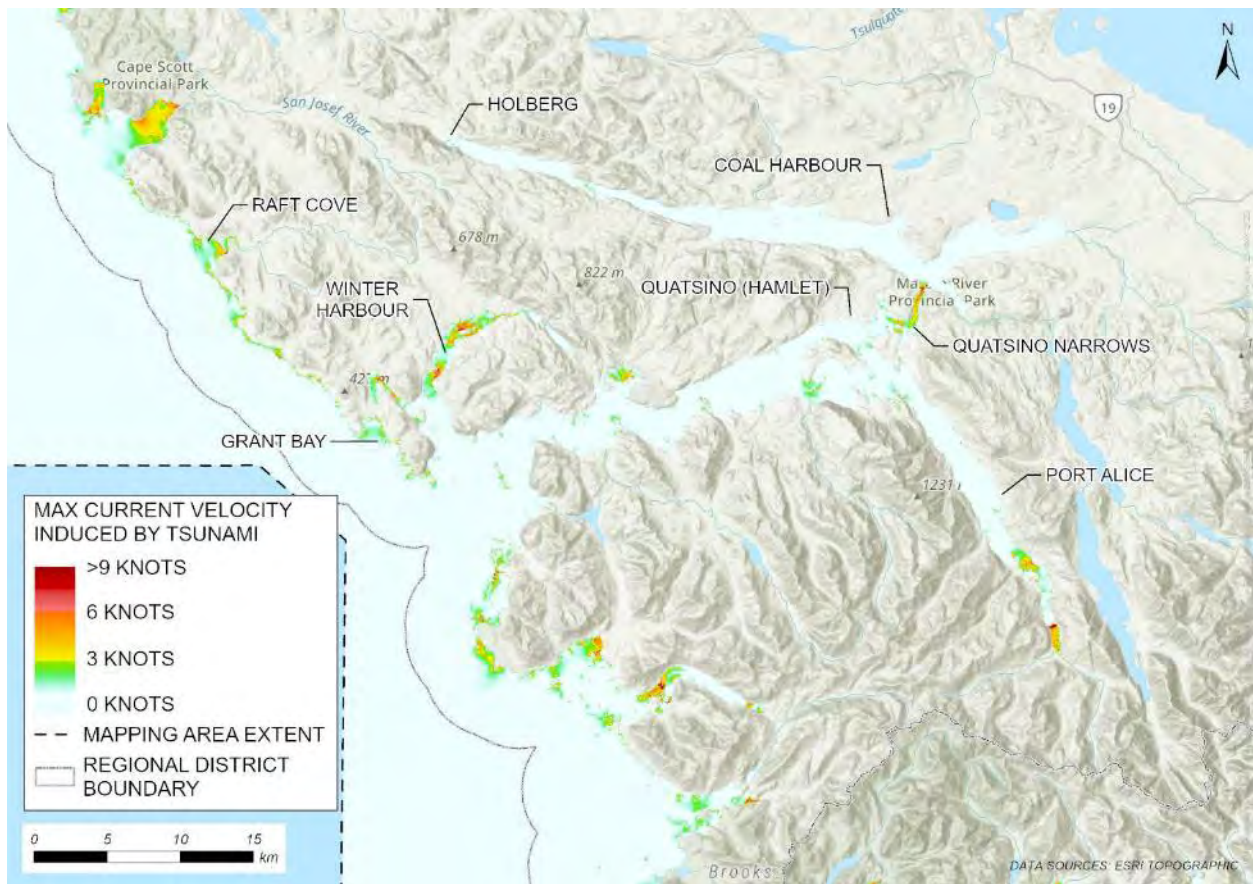


Figure 3.19 Maximum current velocity in Quatsino Sound induced by an Alaska tsunami.

3.2.3.3 Influence of Sea Level Rise

Additional modelling results (see Appendix D) suggest that SLR will not meaningfully influence the offshore propagation of tsunamis, since tsunami wave amplitudes are expected to be similar in the future, even with SLR. Greater inundation depths are associated with SLR, however, which can influence the behaviour of tsunami waves as they propagate overland. Analysis of the model results for a Cascadia tsunami at discrete locations in selected communities shows an increase in future inundation levels that will be, on average, similar to the increase expected for SLR, although there will be some variability from one location to another. Model results for the Alaska tsunami indicate the increase in future inundation levels will be more consistently similar to the anticipated SLR.

The overwater current velocities induced by a tsunami are not expected to be considerably affected by SLR, although deeper water tends to reduce current velocities. The influence of SLR on flow velocities inland was not included in the scope of this hazard analysis.

3.3 Hazard 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, these data were not collected and compiled; therefore, this information was not explicitly mapped.

The project team considered two scales for the tsunami mapping: a regional 1:100,000 scale (i.e., approximately 26 km X 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. The team mapped overwater hazards at the 1:100,000 scale and overland inundation at the 1:5,000 scale. Maximum tsunami-induced current velocity was also mapped at the 1:5,000 scale to inform boaters of associated hazards in navigable waters closer to shore. All maps produced as part of this project have been provided in PDF format for printing on an 11" x 17" page.

All information visible on the maps produced as part of this project are presented as GIS data layers. Maps can be found in the following appendices to this report:

- Appendix E – Overwater Tsunami Hazard Maps
- Appendix F – Overland Tsunami Inundation Maps
- Appendix G – Assets at Risk Maps (described in Section 4.1 of this report)

3.3.1 Coordinate Reference System

The project team used the North American Datum 1983 Canadian Spatial Reference System as the projection and horizontal coordinate systems for all GIS information and maps produced as part of this project. While the vertical datum for the project is CGVD2013, the tsunami amplitudes presented on the maps and in this report are based on a reference plane that corresponds to the individual water levels considered for the tsunami simulations.

3.3.2 Processing of Model Results

ONC provided model output data in geographic coordinates (i.e., latitude and longitude). The team predicted both maximum water surface elevation in metres above the model's reference plane (or still water level) and maximum tsunami-induced current velocity at any given moment in each simulation. The team imported these data to a GIS platform for map production and use in other GIS applications. Tsunami wave amplitude being 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), it is equivalent to the elevation of the water surface above this same reference plane.

As part of their analysis, the team converted coordinates to the Universal Transverse Mercator map projection; filtered out null data points; and removed points or grid cells where the increase in the water surface elevation induced by a tsunami is less than 0.001 m, as well as points where the calculated current velocity is less than 0.001 metres per second (m/s). Prioritizing higher-resolution data, the team interpolated point data to a gridded raster format and clipped the processed results to avoid overlap between information of different resolutions.

Additional adjustments were required to ensure a smooth transition between data layers. The team reviewed processed results at the appropriate mapping scale to remove information at locations with a lower confidence in modelled results. This data exclusion typically included remote areas where topographic or bathymetric information is insufficient to adequately model tsunami propagation.

Final raster GIS data layers include maximum tsunami amplitude in metres and maximum tsunami-induced current velocity in knots for all tsunami scenarios modelled. Additional data processing was required to estimate the extent of inundation based on the model results, as described in Section 3.3.4.1.

3.3.3 Overwater Hazard Maps

NHC produced maps showing maximum tsunami amplitude and maximum tsunami-induced current velocity for tsunamis originating in both the Cascadia and Alaska subduction zones. The maps correspond to present-day sea level. Map sheets at a 1:100,000 regional scale depict the entire study area (Figure 3.15). Map sheets at a 1:5,000 local scale provide more detailed information on predicted tsunami-induced current velocities closer to shore at identified priority areas. The regional maps also provide the tsunami arrival time at several point locations within the project area.

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 3.3.4.1 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.

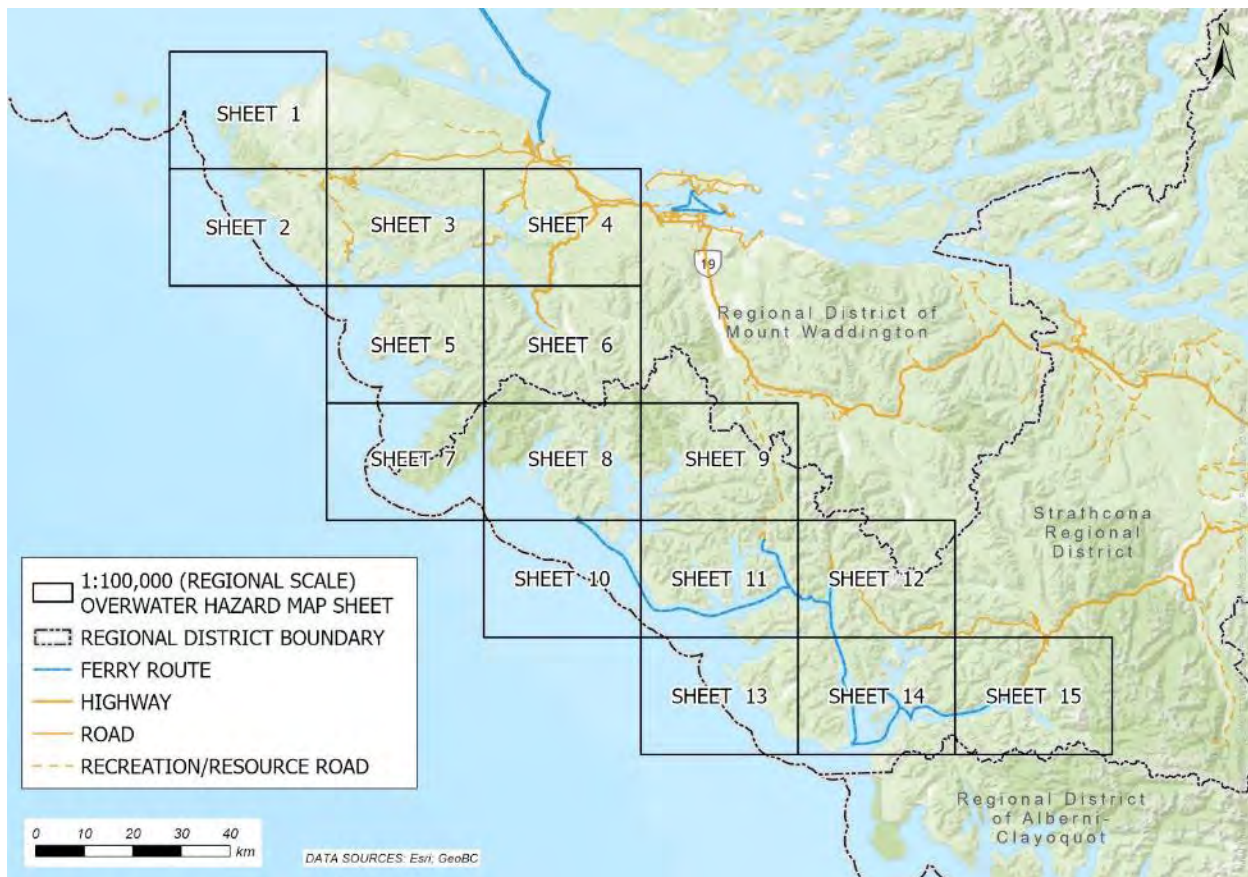


Figure 3.20 Layout of tsunami hazard map sheets showing regional-scale (1:100,000) t.

3.3.4 Overland Inundation Maps

NHC produced overland inundation (i.e., flood) maps for both Cascadia and Alaska tsunamis to show the extent of the inland tsunami hazard. The extent of inundation shown on the maps corresponds to the present-day sea level. While simulations were undertaken that consider SLR, the inundation associated with this sea level has not been mapped. Model results including SLR are available for further mapping and assessment to support longer-term development and planning.

NHC mapped inundation for priority areas selected during consultation with the project’s advisory group. These areas are displayed in Figure 3.21 and Figure 3.22, along with their identifying names for Nootka Sound and Quatsino Sound, respectively. The procedure followed to define the extent of inundation is presented below, as well as a discussion on the safety factor included in the analysis. All inundation maps were produced at a local scale of 1:5,000.

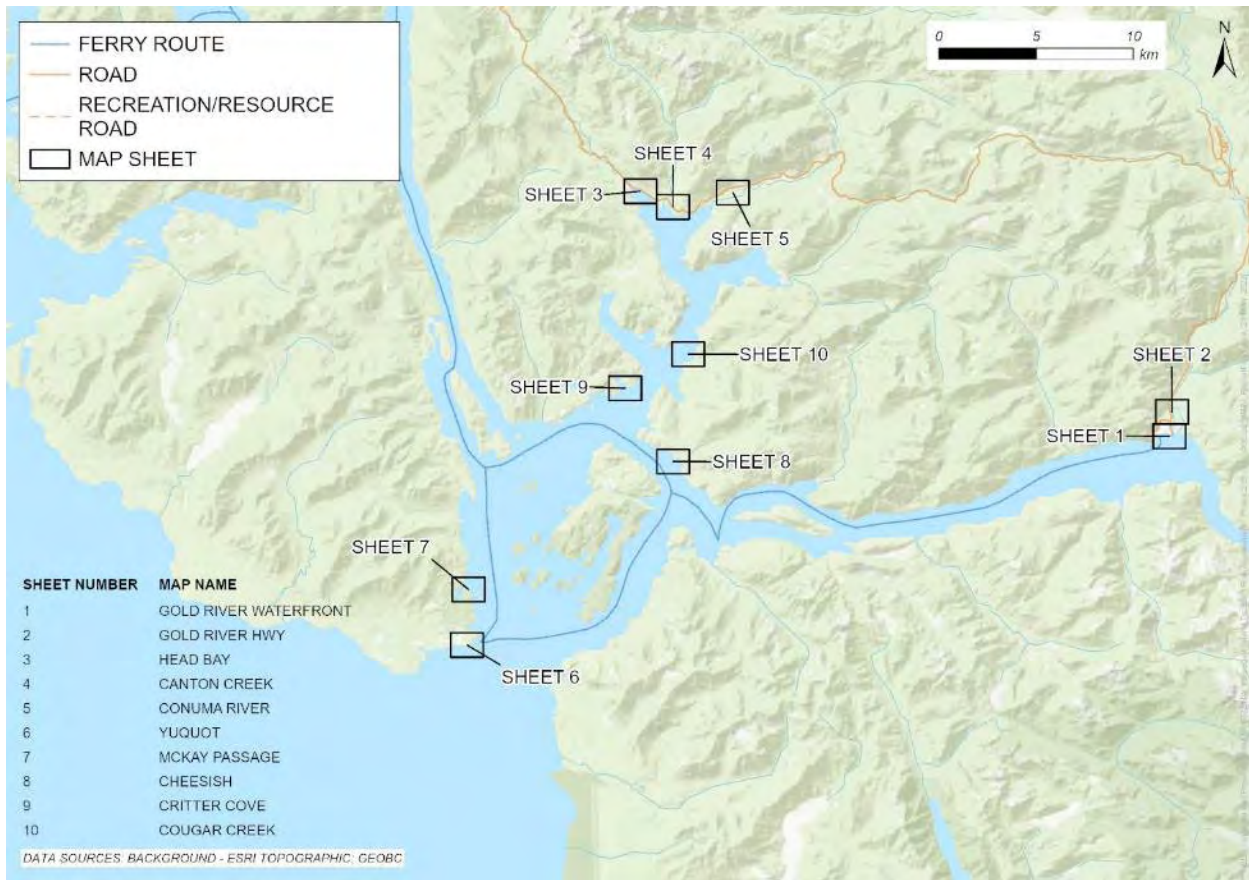


Figure 3.21 Layout of local-scale (1:5,000) tsunami inundation map sheets in Nootka Sound.

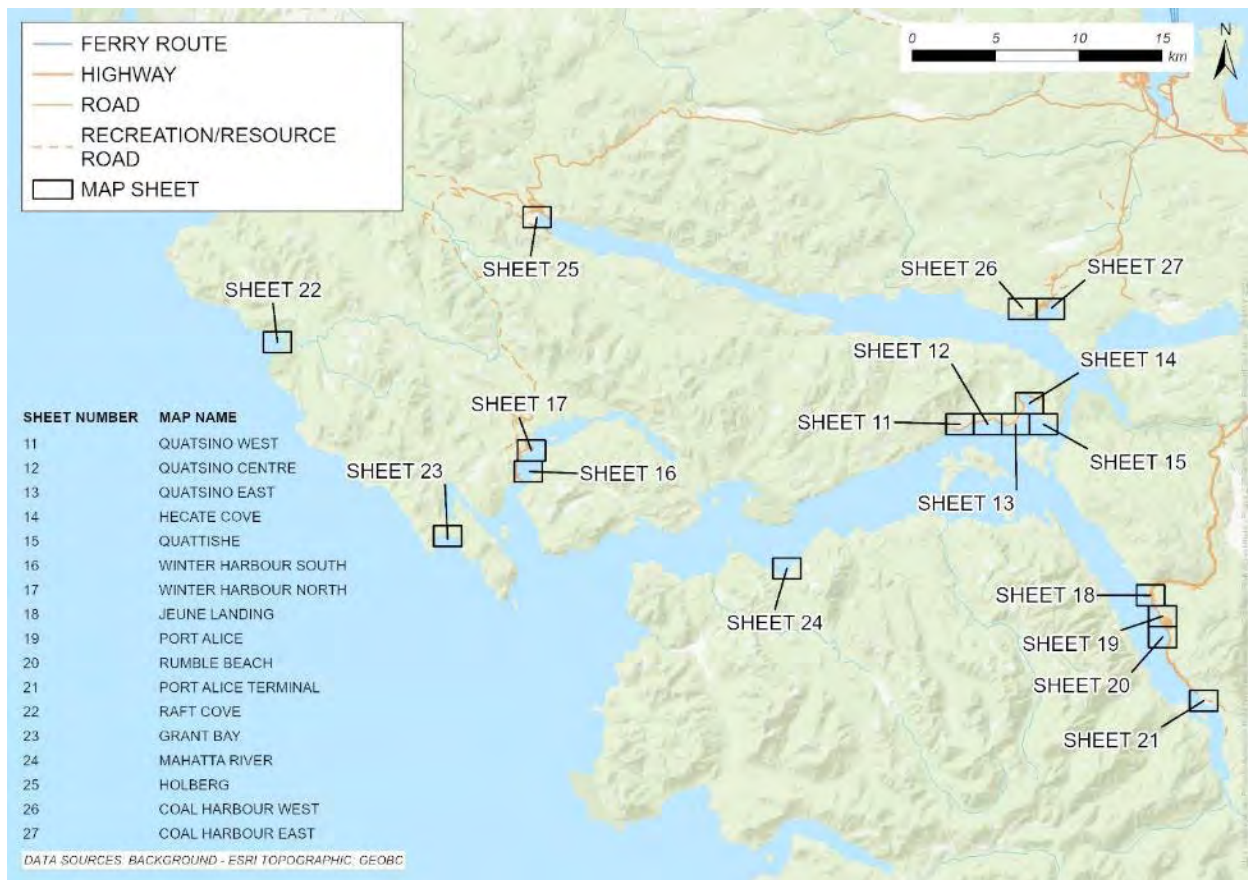


Figure 3.22 Layout of local-scale (1:5,000) tsunami inundation map sheets in Quatsino Sound.

3.3.4.1 Inundation Extents

The project team defined inundation extents based on model results of maximum water surface elevation in conjunction with a topographic DEM with a 2 m resolution specifically developed for this purpose. This DEM was developed using the bare-earth LiDAR data collected as part of this project and only covers the areas selected for inundation mapping. In the case of a Cascadia tsunami, this DEM was adjusted to account for the spatially varying ground displacement associated with the earthquake (e.g., subsidence).

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.

Inundations extents corresponding to the model results without any safety factor were developed following steps no. 2 to 5 described above; these extents are also shown on the inundation maps .

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. Chapter 6 of the American Society of Civil Engineers' (ASCE's) *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 specifies that refuge floors shall be located not less than the greater of 3.1 m (10 ft.) or a one-storey height above the design tsunami inundation elevation. Such a 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. In flatter areas this same increase in the tsunami inundation level will result in flooding of a relatively larger area. 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 be based on the estimated extent of the hazard but also on other factors established during public engagement.

The ASCE/SEI 7 standard stipulates that critical infrastructure located in the tsunami inundation zone must be designed to resist tsunami loads and effects. For residential buildings, the requirement for buildings to resist tsunami loads and effects is optional and left to jurisdictional authorities.

3.3.4.2 Safety Factor

A safety factor is included for mapping inundation extents and for defining inundation levels to support emergency planning. The safety factor accounts for uncertainties in the analysis, including the following:

- For either the Cascadia subduction zone or Aleutian subduction zone in Alaska, the analysis considers only one possible set of seismic parameters. Tsunami hazards and effects can vary for different earthquakes occurring 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. Detailed bathymetric data remain scarce in several locations within the project's large study area.
- The numerical model's underlying mathematical representation of tsunamis and associated model parameters remains an approximation of complex natural phenomena and carries some inherent uncertainties.

As discussed in Section 3.2.1.1, the Cascadia earthquake and tsunami scenario analyzed correspond to a severe event according to the paleoseismic record of past Cascadia earthquakes (Writter et al., 2013). However, this record suggests that at least one stronger earthquake occurred in the past 10,000 years. Including a safety factor in the inundation mapping reduces the residual risk associated with a stronger event but may not eliminate it.

The approach selected for the application of a safety factor consists of a 50% increase in the vertical distance of the maximum water surface above the level of the still water reference plane used in the numerical model (i.e., the 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 uncertain vertical components of a predicted inundation level. In this case, the uncertainties are associated with the numerical model predictions of the tsunami waves and not the astronomical tide level, which can be accurately defined. This approach aligns with Emergency Management BC's (EMBC's) stated intention to provide general guidance on recommended tsunami planning levels throughout coastal BC (EMBC, n.d.). This approach was also compared to other emergency planning approaches during Phase I of the study (NHC, 2022).

3.4 Modelling and Mapping Limitations

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

- 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 underlying base map vary from approximately 5 m up to 20 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.
- 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 to account for 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 the inundation maps includes the application of a safety factor and requires careful interpretation of the model results in conjunction with the local topography.
- 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.
- Service roads and/or resource roads shown on maps may be decommissioned and overgrown with vegetation, inhibiting their use. The status of such roads should be reviewed as part of evacuation planning. Furthermore, maps may not show all roads and pathways that can be considered for evacuation planning.

4 RISK ASSESSMENT

This section presents the results of the risk assessment conducted for the Project. It begins with a discussion of the process for mapping assets at risk and the potential tsunami-related impacts to life safety and infrastructure, then provides the risk assessment results for the Village of Gold River, Mowachaht/Muchalaht First Nations, Quatsino, Winter Harbour, the Village of Port Alice, and Holberg, as well as recreational and operational sites in the region.

With a focus on life safety, the community-level risk assessment conducted for this project leverages the results of the project's tsunami hazard analysis and mapping to identify potential risks to people and assets. The information from this risk assessment is intended to inform emergency managers, risk assessors, land use planners, residents, and visitors to help individuals understand the levels of personal and community risk from tsunamis and their impacts.

This risk assessment is limited to local-scale flood hazards, as presented in the 1:5,000 inundation maps prepared for the project (see Figure 3.21 and Figure 3.22 for an overview of the layout). Maps showing assets at risk highlight roads, buildings, and critical assets that would be exposed to tsunamis. Section 4.1 provides a summary of the risks associated with overwater tsunami hazards identified in this study, although these risks are not discussed in detail. Also briefly discussed where applicable are any high-level risks to navigation and marine infrastructure. Section 4.2 provides context to help better understand the destructive nature of tsunamis and their potential for endangering human life, describing the effects of tsunamis on structures and people caught in a tsunami's flow.

Results of the risk assessment are presented in Section 4.3. As explained above in Section 3.2.1.1, residual risk remains based on paleoseismic evidence that suggests that the Cascadia subduction zone has the potential to generate stronger earthquakes than the event considered for this study. Furthermore, this risk assessment is based on the tsunami flood hazard associated with the present-day sea level, and the mapped flood extents correspond to an inundation level to support emergency planning. Model simulations, including SLR, were performed as part of this study, although these results have not been mapped at this stage.

Tsunami risks will increase in the future as sea level rises, which should be considered for longer-term development and emergency planning. Inundation levels for emergency planning considering SLR are reported for general guidance only.

4.1 Mapping Assets at Risk

Maps showing assets at risk form the basis of the risk assessment and have been produced to identify the potential risk to people, roads, and buildings. Also presented on the maps are assets that are critical for response and recovery, which were selected based on the critical infrastructure sectors defined by the National Strategy for Critical Infrastructure (Public Safety Canada, 2009). Critical assets considered for this assessment correspond to the transportation, health, safety, energy and utilities, water, and government sectors. Assets categorized within those sectors are presented in Figure 4.1, along with the symbols used to identify them on the maps.

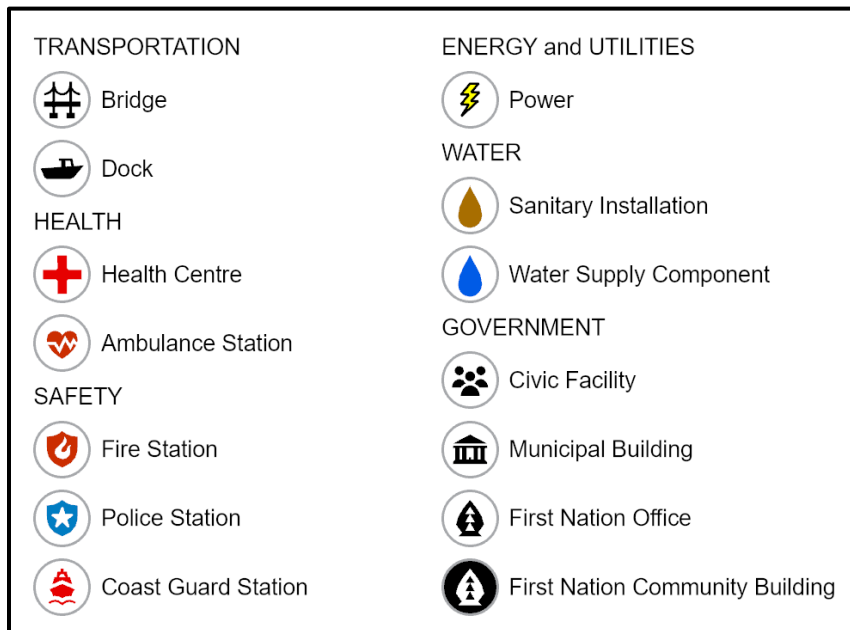


Figure 4.1 Categories of critical assets considered for the project's risk assessment.

The location of roads, buildings, and assets is based on publicly available spatial datasets from the provincial (GeoBC) and federal governments. The project team reviewed these details against the background information collected as part of the project. The location of buildings was also supplemented and checked against the full-feature LiDAR survey that was conducted as part of this study. The datasets used for the risk assessment are listed as follows:

- Digital Road Atlas
<https://www2.gov.bc.ca/gov/content/data/geographic-data-services/topographic-data/roads>
- Open Database of Buildings
<https://www.statcan.gc.ca/en/lode/databases/odb>
- Groundwater Wells
<https://catalogue.data.gov.bc.ca/dataset/groundwater-wells>

Maps showing assets at risk are provided in Appendix G. These maps may not identify all buildings and assets that are exposed to tsunami hazards, and they identify only those docks that are public, dedicated to residents, or that can be helpful in an emergency. Privately owned or privately operated docks are generally not shown on the maps. While schools, if located sufficiently away from the flood hazard, may be important assets to provide shelter following a tsunami, they are not considered as critical infrastructure according to the National Strategy for Critical Infrastructure. For this reason schools are not identified with a symbol on the maps, but they are labelled. Other infrastructure labelled on the maps include boat ramps and helipads.

4.2 Tsunami Impacts on Life Safety and Infrastructure

This section presents the potential tsunami scenarios that can occur at any time along the northwest coast of Vancouver Island. These details are provided to enable individuals and community leaders to better understand and anticipate the harmful, often devastating effects of tsunamis in coastal areas.

Following the arrival of the first wave, the flooding caused by a tsunami will appear as rapidly increasing water levels as the tsunami propagates inland, followed by rapidly decreasing water levels as the tsunami recedes. These rapid changes in 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 triggering earthquake, and the time between successive tsunami waves is generally in the order of 1 hour but can also be shorter.

For a person caught in 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 an event. While existing studies evaluate human safety in flood conditions as a function of flow depth and velocity, as well as age and body characteristics (e.g., Cox et al., 2010), it is conservative to consider that anyone caught in tsunami flow is likely to become a casualty.

The damage caused to buildings and infrastructure depends on the tsunami's flow characteristics in conjunction with structural considerations. The 2011 Tohoku tsunami in Japan brought to light the potential of such events for causing severe damage to inland buildings and endangering human lives. This tsunami also demonstrated how multiple-storey, engineered, concrete, and steel buildings can also be severely damaged or destroyed (Earthquake Engineering Research Institute, 2011b) despite previous beliefs that these structures would be tsunami resistant.

Figure 4.2 (top left) shows an example of a steel frame building damaged by the 2011 Tohoku tsunami, which also caused the complete failure of heavy coastal protection structures specifically designed to resist tsunamis (Figure 4.2, bottom left). Unfortunately, these structures gave people a false sense of safety, resulting in higher casualties (Earthquake Engineering Research Institute, 2011a).

Before a Cascadia tsunami arrives, bridges and roads may be damaged or weakened by the initial earthquake; they are also at risk of being damaged by a subsequent tsunami. Such transportation infrastructure can be affected by extreme forces induced by tsunami flow as well as impacts with floating debris such as boats, cars, building debris, etc. For example piers and abutments could be damaged or weakened by scour, and asphalted road surfaces could be washed out. Piers, docks, bridges, and other marine infrastructure are particularly exposed to damage from tsunamis due to their location along the water's edge and their exposure to a tsunami's full force.



Photos: Philippe St-Germain (2012)

Figure 4.2 Damaged infrastructure in the City of Miyako, Japan following the 2011 Tohoku tsunami. Top photos show damage to inland buildings, bottom left photo shows remains of tsunami protection wall, and bottom right shows damage to port installations.

No site reconnaissance was performed as part of this assignment, and no structural or seismic assessment of buildings and infrastructure was performed in the study area. Nevertheless, for this relatively remote region buildings exposed to direct tsunami inundation are expected to be severely damaged and would lose their function.

The study area also includes several bridges and roads that provide access to communities and serve as links between parts of these communities. No assessment was performed as part of this study to determine if this infrastructure would withstand the initial shaking and potential effects (e.g., **liquefaction**) associated with a Cascadia earthquake, or if they could potentially be affected by any landslide or rockslide that could be caused by such an earthquake.

4.3 Risk Assessment Results

This section presents the results of the risk assessment for the following groups of communities and areas:

- Mowachaht/Muchalaht First Nations and Village of Gold River
- Quatsino
- Winter Harbour
- Village of Port Alice
- Holberg
- Recreational and operational sites

The risk assessment for each group includes an assessment of the exposure to Cascadia and Alaska tsunamis and a tabulated summary of exposure for buildings and roads. The total number of buildings reported corresponds to the total number of buildings on a particular map sheet and may not represent the total buildings in a community or area. Also, the impact to pedestrian walkways and trails is not discussed.

Table 4.1 presents a summary of the general tsunami inundation levels and tsunami arrival times at main areas to support emergency planning discussions. The inundation levels reported for emergency planning represent one general area in a specific community and include a safety factor to account for uncertainties in the analysis. This general information should only be used for high-level planning, as tsunami inundation levels can vary over small distances due to changes in local topography. In addition, reported inundation levels do not include any freeboard. Inundation levels for emergency planning that account for SLR are also reported and should be considered as general guidance only. For Tlupana Inlet, the location of the inundation level for emergency plannings was identified as the place where maximum runup is expected in Canton Creek.

The tsunami arrival time presented in Table 4.1 is defined as the time when the first maximum tsunami waves arrive (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 4.1 General tsunami inundation level for emergency planning and arrival times at selected locations.

Area	Cascadia Tsunami			Alaska Tsunami		
	Arrival Time ¹	Inundation Level for Emergency Planning ² (CGVD2013)		Arrival Time	Inundation Level for Emergency Planning (CGVD2013)	
		Present Day	Year 2100		Present Day	Year 2100
Gold River waterfront	0h59m	11.2 m	11.9	3h44m	6.8 m	8.0
Tlupana Inlet	0h50m	17.2 m	18.6	3h36m	4.4 m	5.6
Yuquot	0h28m	11.9 m	13.4	3h13m	2.9 m	4.2
Quatsino	0h38m	5.9 m	6.8	3h06m	3.6 m	4.8
Winter Harbour	0h35m	5.4 m	6.5	2h58m	4.1 m	5.0
Port Alice	0h57m	5.8 m	6.8	3h16m	3.6 m	4.8
Holberg	1h35m	3.3 m	4.5	3h45m	2.9 m	4.1
Coal Harbour	1h22m	2.3 m	3.6	3h37m	2.1 m	3.3

Notes:

1. 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.
2. The inundation level for emergency planning includes a safety factor (see Section 3.3.4.2) and accounts for the local subsidence associated with the triggering earthquake, as applicable. Freeboard is not included. The location where the inundation level was determined generally corresponds to the location of maximum runup.

4.3.1 Mowachaht/Muchalaht First Nations and the Village of Gold River

Located in Muchalat Inlet and the Gold River Valley, the Mowachaht/Muchalaht First Nations are an amalgamation of four groups: the Mowachaht (Tahsis and Tlupana Inlet communities) and the Muchalaht (Cheeshish and Ahaminaquus) who were once whalers. Together, the members of these communities number 613, control 18 reserves totalling approximately 388 hectares of territory, and belong to the Nuu-Chah-Nulth Tribal Council. The Mowachaht/Muchalaht First Nation traditional territory includes all of Nootka Sound, extending from Gold River westward to Tahsis and expanding south from Yuquot to Tlupana Inlet to the north. One of the most famous places in this traditional territory is Yuquot, known for “where the wind blows from all directions.” The centre of both the government and the spiritual and ceremonial world for the Mowachaht/Muchalaht people, Yuquot is also the longest continuously occupied site on the west coast of Vancouver Island and one of the largest and deepest archaeological deposits in BC. Today, the Mowachaht/Muchalaht First Nation members live in the village of Tsa Xana, 10 minutes from Gold River (<https://www.yuquot.ca/center-of-the-world/>).

The Village of Gold River is located approximately 90 km west of the City of Campbell River on Highway 28. The village is situated at the confluence of the Heber and Gold Rivers approximately 13 km upstream of the Golder River mouth in Muchalat Inlet. Highway 28 is the primary access route in and out of the village. A secondary route on gravel roads connects the village with the community of Woss

and Highway 19 to the north. Head Bay Forest Service Road (FSR) connects the village with the Village of Tahsis, 65 km to the west. Water-based access by boat or float plane is possible at the head of Muchalat Inlet.

The village’s jurisdiction includes the waterfront area, which is commonly referred to as the old mill site, where a dry land sort, deep seaport, and residual mill infrastructure such as settling ponds and water treatment facilities are located. This area is connected to the village via Mill Road (Highway 28), which runs next to the river. Also located at the waterfront is Ahaminaquus, where the Mowachaht/Muchalaht First Nations plan for some development, including a waterfront welcome house and recreational site.

Risk Analysis

Assets at risk for the Village of Gold River and Mowachaht/Muchalaht First Nations land in Nootka Sound are located in the five map sheets listed in Table 4.2, which also provides a summary of the number of buildings and lengths of road estimated to be exposed to tsunamis.

Table 4.2 Summary of buildings and roads exposed to Cascadia and Alaska tsunamis in Mowachaht/Muchalaht First Nation communities and Gold River.

Map Sheet	Total Buildings on Map Sheet	Cascadia Tsunami		Alaska Tsunami	
		Buildings Exposed	Length of Road Exposed (km)	Buildings Exposed	Length of Road Exposed (km)
1. Gold River Waterfront	18	18	2.12	16	2.11
2. Gold River Highway	12	12	2.51	0	0.32
3. Head Bay	2	1	3.37	1	1.61
6. Yuquot	7	4	0.00	1	0.00
8. Cheesish	0	0	0.03	0	0.00

In Gold River the effects of a Cascadia tsunami are expected to reach up to approximately 4 km upstream of the river mouth. While the main village is not expected to be exposed to tsunami hazard, the entirety of the waterfront area is at risk of being flooded during such an event. Marine infrastructure such as the public dock, deep seaport, float plane terminal, and boat ramp may be severely damaged, which may limit the access to the village centre by road or air only. The extent of flooding would be limited to the area south of Ahaminaquus and west of Mill Road.

At the mouth of the Sucwoa River in Head Bay, the road on the north shore is expected to be flooded by both Alaska and Cascadia tsunami scenarios, which may affect road travel between Gold River and Tahsis.

At Yuquot, the majority of the low-lying area is at risk of being inundated during a Cascadia tsunami, which would isolate the Coast Guard station. In addition, marine infrastructure may be damaged by the

strong current velocities expected in such event. The wave amplitude associated with an Alaska tsunami is not expected to exceed 1 m (Figure 3.16); therefore, the risk to people and upland infrastructure has been identified as low with a distant tsunami.

At Cheesish, for both Cascadia and Alaska tsunami scenarios, tsunami inundation would be limited to areas close to the shoreline due to the steep local topography. However, the Hanna Channel Recreational Site next to the mouth of the neighbouring stream is located in a low-lying area that would be susceptible to tsunami flooding, particularly from a Cascadia tsunami.

4.3.2 Hamlet of Quatsino

The Quatsino First Nation includes five Kwakwaka'wakw tribes: T'latsinuxw (Klaskino), Huyalas (Hoyalas), Gusgimukw (Koskimo), Gob'inuxw (Giopino), Qwat'sinuxw (Quatsino) tribes. Their collective traditional territory comprises all Quatsino Sound, including Holberg Inlet and open-ocean waters spanning south from Brooks Peninsula past Cape Scott to the north. Before being relocated near Coal Harbour, the Quatsino First Nation was based at the historic site of Xwatis (Quattishe), just west of Quatsino Narrows. The Quatsino First Nation also administers areas in Winter Harbour (e.g., Grass Point) and near Port Alice (e.g., Cayuse).

The Hamlet of Quatsino is a small community just west of Xwatis, which is only accessible by boat. The hamlet is approximately 20 minutes by boat from Coal Harbour and 35 minutes from Port Alice. Approximately 26 properties are year-round residences, and 50 properties provide summer homes; the rest of the land comprises either undeveloped properties, wood lots, or Crown land leases held by private companies (www.quatsino.org).

Risk Analysis

Assets at risk for Quatsino and Xwatis were identified from the five map sheets listed in Table 4.3, which also includes a summary of the number of buildings and lengths of road estimated to be exposed to tsunamis.

Table 4.3 Summary of buildings and roads exposed to Cascadia and Alaska tsunamis in Quatsino.

Map Sheet	Total Buildings on Map Sheet	Cascadia Tsunami		Alaska Tsunami	
		Buildings Exposed	Length of Road Exposed (km)	Buildings Exposed	Length of Road Exposed (km)
11. Quatsino west	29	7	0.99	2	0.25
12. Quatsino centre	34	14	0.90	2	0.04
13. Quatsino east	22	18	0.14	4	0.00
14. Hecate Cove	16	8	0.37	6	0.08
15. Xwatis	0	0	0.00	0	0.00

In the event of a Cascadia tsunami, several waterfront residences in Quatsino are at risk of flooding. The fire station and school are not expected to be affected by the tsunami, although parts of the main road connecting the community are expected to be inundated. The risk associated with an Alaska tsunami is lower, with only a few residences affected; however, some low-lying areas that are still prone to flooding, and sections of the main road are still expected to be inundated.

At Xwatis, no building or infrastructure remain following the relocation of the Quatsino First Nation remains, except for one access dock. For both Cascadia and Alaska tsunami scenarios, tsunami inundation is limited to areas close to the shoreline due to the steep local topography. Nevertheless, current velocities induced by either scenario are expected to be strong in the area due to the presence of constrictions between small islands.

4.3.3 Winter Harbour

A sheltered haven for boaters, Winter Harbour is in the traditional territory of the Quatsino First Nation and is the most western settlement on Vancouver Island. Since the 1800s, Winter Harbour has been a refuge for commercial fishing boats during storms and bad weather, and the community has a rich history of salmon sales to fish buyers. Today, the community is a flourishing sport fishing destination. Winter Harbour is mainly accessed by boat, although vehicles can gain access from Holberg along approximately 20 km of FSRs.

Risk Analysis

Assets at risk in Winter Harbour are presented in the two map sheets listed in Table 4.4, which also summarizes the number of buildings and lengths of road estimated to be exposed to tsunamis.

Table 4.4 Summary of buildings and roads exposed to Cascadia and Alaska tsunamis in Winter Harbour.

Map Sheet	Total Buildings on Map Sheet	Cascadia Tsunami		Alaska Tsunami	
		Buildings Exposed	Length of Road Exposed (km)	Buildings Exposed	Length of Road Exposed (km)
16. Winter Harbour South	52	30	0.46	23	0.19
17. Winter Harbour North	42	19	0.80	15	0.42

Several buildings situated along the shoreline of Winter Harbour are expected to be impacted during both a Cascadia and an Alaska tsunami. The extent of flooding is expected to be relatively limited to areas closer to shore, except for Grass Point, where inundation could reach further inland. The fire station is not expected to be affected by tsunami flooding. As a result of the narrow channels east of Grass Point and near the mouth of Galato Creek further north, extremely strong, dangerous currents are expected to affect the entire area and potentially cause considerable damage to marine infrastructure.

4.3.4 Village of Port Alice

Port Alice is located in the traditional territory of the Quatsino First Nation on Neroutsos Inlet. The pulp mill operated by Whalen Pulp and Paper Mills of Vancouver was the village’s main economy until it closed permanently in 2015, after 97 years of operation. Today, the community is known for its natural environment and saltwater fishing. It is also known as the Sea Otter Capital of Canada.

Risk Analysis

The mapping of assets at risk in Port Alice covers the four map sheets listed in Table 4.5, which also provides a summary of the number of buildings and lengths of road estimated to be exposed to tsunamis.

Table 4.5 Summary of buildings and roads exposed to Cascadia and Alaska tsunamis in Port Alice.

Map Sheet	Total Buildings on Map Sheet	Cascadia Tsunami		Alaska Tsunami	
		Buildings Exposed	Length of Road Exposed (km)	Buildings Exposed	Length of Road Exposed (km)
18. Jeune Landing	33	13	1.10	7	0.49
19. Port Alice	250	18	0.05	0	0.02
20. Rumble Beach	118	5	0.60	0	0.34
21. Port Alice Terminal	13	8	0.49	6	0.21

Several waterfront residences and buildings in Port Alice are at risk of being impacted by flooding from a Cascadia tsunami. Most of the village’s critical assets are located on elevated ground and are not at risk, except for the health centre, which is located near the shoreline. The distance separating this building from the estimated extent of flooding is relatively short. In the Rumble Beach area Marine Drive could be damaged, which would complicate response efforts in and out of the industrial area further south. In addition, most of the shoreline is expected to be exposed to strong currents associated with a Cascadia tsunami.

Fewer buildings are expected to be impacted from an Alaska tsunami; nevertheless, many buildings are located close to the edge of estimated inundation. Several reaches of the shoreline could be exposed to strong currents.

The industrial site south of the village is expected to experience considerable flooding from a Cascadia tsunami, unless future development increases the land elevation in that area. Furthermore, extremely strong and dangerous currents are expected to affect the entire area due to the constriction in the waterway between land and Ketchen Island. The site is also at risk of flooding during an Alaska tsunami, and strong currents are expected in the area.

4.3.5 Holberg

Located in the traditional territory of the Quatsino First Nation and accessed by 50 km of gravel road from Port Hardy, the small community of Holberg sits at the most westerly end of Holberg Inlet. The community mainly serves as a logging camp and is the last stop for backpackers set to tackle the Cape Scott Trail and the North Coast Trail.

Risk Analysis

Assets at risk in Holberg are shown on the map sheet included in Table 4.6, which also provides a summary of the number of buildings and lengths of road estimated to be exposed to tsunamis.

Table 4.6 Summary of buildings and roads exposed to Cascadia and Alaska tsunamis in Holberg.

Map Sheet	Total Buildings on Map Sheet	Cascadia Tsunami		Alaska Tsunami	
		Buildings Exposed	Length of Road Exposed (km)	Buildings Exposed	Length of Road Exposed (km)
25. Holberg	65	9	1.53	1	0.54

The tsunami hazard in Holberg Inlet is relatively low as demonstrated by the tsunami wave amplitude shown in Figure 3.11 and Figure 3.17 for the Cascadia and Alaska tsunami, respectively. However, because of the long, narrow geography of the inlet, the tsunami amplitude is expected to be greater at the head of the inlet. Because of the low-lying topography of the Goodspeed River delta, some flooding can be expected at the community of Holberg under both tsunami scenarios.

In the case of a Cascadia tsunami, flooding is expected to affect considerable parts of the community that are situated near the water. All buildings on the west side of the river are expected to be affected, and Northeast 60 Road is expected to be completely overtopped on that side of the river. Critical assets that would be impacted include the health clinic, fire station, and power station. Doch Road, which leads to the community’s dock along the shallow intertidal area, is also expected to be inundated, which could potentially limit access to deeper navigable waters following the tsunami event. Furthermore, the community’s drinking water source is also expected to be affected, as it is located at the mouth of the river and would be fully exposed to the effects of the tsunami.

In the case of an Alaska tsunami, the risk to the community is similar in nature, although it is relatively less. While the area on the west side of the river is not expected to be flooded in this case, it may become isolated depending on any effects from the tsunami on the bridge connecting this area to the rest of the community. Several buildings, including the health centre, are located close to the estimated edge of inundation.

4.3.6 Recreational and Operational Sites

The study area includes several recreational and operational (e.g., commercial) sites where people could be present and would at risk of being affected by a tsunami. Table 4.7 provides a summary of the number of buildings and lengths of road estimated to be exposed to tsunamis at those sites.

Table 4.7 Summary of buildings and roads exposed to Cascadia and Alaska tsunamis at recreational and commercial sites.

Map Sheet	Total Buildings on Map Sheet	Cascadia Tsunami		Alaska Tsunami	
		Buildings Exposed	Length of Road Exposed (km)	Buildings Exposed	Length of Road Exposed (km)
4. Canton Creek	20	18	2.35	9	1.07
5. Conuma River	16	16	1.50	0	0.00
7. McKay Passage	11	9	0.00	8	0.00
9. Critter Cove	11	11	0.01	11	0.00
10. Cougar Creek	0	0	0.50	0	0.01
22. Raft Cove	0	0	0.00	0	0.00
23. Grant Bay	0	0	0.00	0	0.00
24. Mahatta River	5	0	0.54	0	0.37

The tsunami inundation level in Tlupana Inlet is expected to be particularly high. With a Cascadia tsunami, most of the buildings at the Mucha Bay Resort are expected to be affected by the tsunami due to their proximity to the water, although two storage buildings are located on elevated ground and are not expected to be affected. Inundation is not expected to reach Head Bay FSR above the resort; however, the lower section of the road to the west is expected to be inundated as it crosses Canton Creek. The bridge at that location may be severely impacted due to the high water level and strong current velocities induced by the tsunami. At Conuma River, the fisheries facility operated by Fisheries and Oceans Canada is expected to be completely flooded by a Cascadia tsunami, as well as the nearby segment of the Head Bay FSR. The facility is located approximately 2 km upstream of the river mouth.

Fewer effects are expected from an Alaska tsunami in Tlupana Inlet; nevertheless, the tsunami is still expected to pose considerable risk in the area. Several buildings at Mucha Bay Resort would be inundated, and the bridge over Canton Creek and the low-lying segment of the road to the west would also be impacted. The fisheries facility up the Conuma River is not expected to be affected by an Alaska tsunami.

In Nootka Sound, the tsunami hazard associated with the Cascadia tsunami is expected to be considerably high across the sound. At McKay Passage just north of the Santa Getrudis-Boca del Infierno Provincial Park, several buildings are expected to be affected by the tsunami. At Critter Cove, where a fishing lodge operates, the floating buildings are particularly at risk, given that they are directly on the water. In addition, the low-lying area of the recreational campsite at Cougar Creek on the west side of Galiano Road is expected to be inundated. While most of the road in the area is not expected to be affected by the tsunami, the segment crossing the creek as well as the bridge would be impacted. In the

case of the Alaska tsunami, these areas in Nootka Sound are expected to be similarly affected, although Galiano Road at Cougar Creek site is not expected to be inundated from an Alaska tsunami.

Located on the open coast, Raft Cove and Grant Bay recreational areas are particularly exposed to tsunami hazard, and the challenge associated with alerting people in this remote area amplifies the risk. Large upland extents are expected to be inundated from a Cascadia tsunami, including where an emergency cabin is believed to be located. The hazard from an Alaska tsunami is mainly limited to the high-water mark, although some flooding may occur in localized, low-lying areas, depending on the water level at the time of the tsunami. At Grant Bay under both tsunami scenarios, flooding is expected to propagate up the stream and discharge at the west end of the beach. While the flooding is not expected to affect the parking area at the southern end of the access road, the beach access trail may be inundated.

The exposure to the tsunami hazard at Mahatta River is relatively low, with no buildings expected to be impacted from either a Cascadia or an Alaska tsunami. Some localized areas closer to the shoreline are at risk of being inundated, and marine infrastructure may be damaged, complicating access and egress, as well as resupply and recovery efforts.

5 EMERGENCY MANAGEMENT AND RISK REDUCTION

The outcomes of the risk analysis can strengthen hazard awareness and the four key components of emergency management: mitigation, preparedness, response, and recovery. Section 5.1 discusses the status of emergency management planning in various communities in terms of compliance with best practices and regulations, progress achieved during this project, and proposed paths forward. This information is expected to support development and planning decisions and improve existing emergency and evacuation plans. Section 5.2 briefly introduces various measures that can be adopted to reduce tsunami risk, in conjunction with developing and updating tsunami emergency management plans.

5.1 Community Emergency Management

This section of the report summarizes the relevant best practices and regulations in place for each phase of emergency management. These best practices have been published in key guidance documents (see list provided below), which have been developed to support updates to emergency management plans and new emergency management legislation in BC. This section also includes details on existing emergency management plans to provide additional context.

The BC *Emergency Program Act* (RSBC 1996, c. 111) requires local authorities to direct and control emergency response in an emergency and prepare plans for response and recovery. While current regulations cover two phases of the emergency management cycle, EMBC plans to modernize emergency management legislation to bring it in line with the Sendai Framework for Disaster Risk Reduction (UNISDR, 2015), which emphasizes strengthening all four phases of emergency management.

EMBC plans to repeal and replace the *Emergency Program Act* and introduce new legislation (EMBC, 2022). In preparation for this new legislation, several documents have been developed that outline new standards and best practices, including the following:

- Sendai Framework for Disaster Risk Reduction (UNISDR, 2015)
- UN Declaration on the Right of Indigenous Peoples (United Nations, 2007)
- Draft Principles that Guide the Province of British Columbia's Relationship with Indigenous Peoples (Province of British Columbia, 2017)
- Addressing the New Normal: 21st Century Disaster Management in British Columbia (BC Flood and Wildfire Review, 2018)

New legislation means that while existing community management plans are expected to include the phases of response and recovery, they should be revised to also include the phases of preparedness and mitigation.

5.1.1 Existing Emergency Management Plans

Coastal communities in the study area understand how to work together to plan for disaster events. Legislated regulations and established governance structures are in place to enable rugged, remote, and

rural communities to undertake planning before, during, and after a disaster event. Planning efforts are driven by self-determined risk management priorities and are based on a community's tolerance for acceptable and unacceptable levels of risks. The drivers of risk tolerance are dynamic and often dramatic for a low-probability, high-consequence event such as a major tsunami.

Global tsunamis showcase the potential extent of a coastal disaster, driving community leadership teams to develop plans for providing continuity of critical infrastructure and services, such as housing, roads, bridges, water systems, utilities, first responder and health facilities, and communication systems during a tsunami. For this study, some communities provided documents, plans, and procedures that are relevant to a tsunami risk assessment. The project study team gathered information on existing planning efforts and community preparedness levels through engaging with the advisory group and Indigenous knowledge holders, documenting oral histories as permitted, and conducting the public survey, as presented in Section 0. Together, these voluntary community contributions clearly demonstrate strong and resilient communities, whose members share an abundance of knowledge and experience about the risks posed by both local and distant tsunamis.

In high-risk communities, opportunities exist to accelerate planning for a major tsunami scenario. To further engage community members and partners in tsunami resilience and risk reduction activities, communities are encouraged to support future tsunami planning, evacuation, and public readiness efforts following the completion of this project. As we have determined from the results of this study, a large tsunami event will overwhelm critical systems and impact lives and livelihoods in high-risk areas, so timely emergency planning and implementation are vital.

5.1.2 Preparedness

This section presents a discussion of preparedness activities being conducted in the communities participating in this project. In addition to summarizing best practices and regulations in place to guide community tsunami preparedness, this section also includes a summary of preparedness efforts and activities conducted to date and an overview of the path forward to strengthen local tsunami preparedness.

5.1.2.1 Best Practices and Regulations

Preparedness reflects the collective knowledge and readiness capacity to effectively respond to events and achieve an orderly transition from response to sustained recovery efforts (United Nations Office for Disaster Risk Reduction, 2017). Effective preparedness is based on a sound analysis of disaster risk and is rooted in evolving community development, emergency planning, and health and wellness activities.

Basic preparedness for tsunami hazards involves knowing and practicing how to safely respond to a tsunami alert (from a distant event) or to strong ground shaking (from a local event). Also part of basic preparedness is for everyone in the community to know how to effectively evacuate to a safe location until the tsunami threat has ended, which can be hours and even days after the arrival of the first wave. Preparedness also includes planning for the recovery process by identifying at-risk people, assets,

services, and supply chains, and developing recovery plans with key organizations, government, and not-for-profit and private-sector partners.

Public awareness and community building activities are motivators to empower preparedness and promote an agency-based approach to tsunami risk. Community preparedness efforts underway in the study area include the *Master of Disaster* program being delivered in several schools; the use of tsunami hazard signage on roadways, trails, and various public locations; visitor education materials; and community participation events to participate in earthquake and tsunami drills, such as the *Great BC ShakeOut* and *Hike to High Ground*.

This study is an example of a preparedness activity that shares knowledge to support communities at risk, including preparedness champions, first responders, and community leaders at all levels.

5.1.2.2 Progress

Indigenous communities living along the coast since time immemorial are most familiar with the risks of tsunami to their land, people, and infrastructure. Oral histories outlined in previous sections (e.g., Section 2.3, provide witness accounts of previous major tsunami events and offer wisdom to incorporate disaster preparedness and mitigation into daily life. For example, Nuu-Chah-Nulth and Kwakwaka'wakw stories speak of the importance for humans to be humble and respect our place on the land that we rely on for subsistence and survival. They advise to heed the guidance of those who speak of future disaster and to prepare, each and every one of us, as if a disaster could happen at any time.

In response to the tsunami warning issued for Vancouver Island on January 23, 2018, Nuchatlaht Tribe staff and partners prepared a Tsunami Preparedness Strategic Plan. This plan includes an analysis of strengths, weaknesses, opportunities, and challenges, a list of 10 strategic objectives, and plans to link to existing community strategies. Following is Nuchatlaht Tribe's vision statement for the plan:

"Nuchatlaht Tribe's tsunami preparedness and response is very quick, well equipped, well informed, communicates with the necessary people and organizations, organized, and most importantly, results in everyone surviving tsunamis."

This vision statement focuses on a critical detail: survival from a major tsunami event should be the expectation of every prepared community member and visitor on Northwest Vancouver Island. Opportunities exist in high-risk communities to improve preparedness through enhanced tsunami awareness, education, and evacuation exercises.

5.1.2.3 Path Forward

The path to tsunami preparedness is for all community members to adopt an 'all-of-society' responsibility that is both collaborative and community driven.

At the neighbourhood level, action-based approaches are recommended that support overall community development and create safe spaces for difficult conversations about tsunami risk. Preparedness activities can be promoted at community gatherings and can enhance existing volunteer

group capability while linking efforts with local schools, mariners, cultural groups, businesses, and other communities in the area, province, and across the globe. This cross promotion, linking with all groups in a community, and sharing knowledge from local to global will enable communities around the world to share tsunami experience and better prepare for effective local tsunami response and recovery. Preparedness efforts often lead to the identification of new risk management strategies, secure buy-in and funding for risk reduction efforts, and empowerment to create and implement community-led resilience solutions where they are most needed.

5.1.3 Response

This section presents a discussion of tsunami response activities in the communities participating in this project. In addition to summarizing best practices and regulations in place to guide community tsunami response, this section also includes a summary of local tsunami response efforts conducted to date and an overview of the path forward to strengthen local tsunami response efforts.

5.1.3.1 Best Practices and Regulations

The focus of emergency response is on taking direct action immediately before, during, and after a disaster to save lives, reduce health impacts, ensure public safety, and meet the basic subsistence needs of all people affected (United Nations Office for Disaster Risk Reduction, 2017). The current regulations state that a local authority is responsible at all times for the direction and control of the local authority's emergency response (Province of British Columbia, 1996). In addition, a local authority must have a local emergency plan in place that includes establishing and maintaining exercises and training for emergency response staff.

In the context of a tsunami, effective, efficient, and timely response depends on a community's level of preparedness against tsunami risk. During a tsunami event, communities will need to rely on their own response capacity, as well as on emergency services. Public assistance during a tsunami event can be provided by the public and private sector. Communities also need to be able to count on broader community and volunteer participation.

While this section focuses on community response, the distinction between response and recovery is not always clear. For example, emergency utilities services are sometimes set up as part of emergency response and continue to be used into the recovery phase due to the timelines required to rebuild infrastructure.

5.1.3.2 Progress

Directly addressing emergency response for tsunamis was not part of the scope for this project, although the study outcomes do support risk-informed planning for response efforts. For example, the project study team conducted a risk assessment for two key tsunami scenarios, providing more information and awareness to people in the areas most likely to be affected by both scenarios. This means that response training exercises can be tailored to different tsunami sources, which would facilitate a more efficient and effective response.

Current emergency management plans exist at a regional district, municipal, and tribal council level. Most communities have some guidance on emergency management generally, and other have tsunami specific plans. Several false alarms or near-miss tsunami events have occurred, with warning systems being activated, but no inundation was experienced. Nonetheless, these situations have served as an opportunity for community leaders to analyze tsunami preparedness and the response to tsunami warnings.

5.1.3.3 Path Forward

Response planning is already well established across the study area, as it is an existing requirement of the current emergency management regulations. Even so, there are more ways that communities can enhance their tsunami response based on the outcomes of the risk assessment, by examining specific systems, tools, response times, and attitudes in play in each community, such as:

- early warning systems
- risk-informed response for Cascadia and Alaska tsunami sources
- inclusion of all community members in response planning and preparation

5.1.4 Recovery

This section presents a discussion of tsunami recovery activities being conducted in the communities participating in this project. In addition to summarizing best practices and regulations in place to guide community tsunami recovering planning, this section also includes a summary of local tsunami recovery preparation efforts conducted to date and an overview of the path forward to strengthen local tsunami recovery preparedness efforts.

5.1.4.1 Best Practices and Regulations

As per the Sendai Framework (United Nations Office for Disaster Risk Reduction, 2017), recovery following a disaster means restoring or improving livelihoods, and health, as well as the economic, physical, social, cultural, and environmental assets, systems, and activities of a disaster-affected community. This approach aligns with the principles of sustainable development and ‘build back better’ to avoid or reduce future disaster risk. The principle of building back better is central to effective recovery and a core principle of the Sendai Framework, since recovery would be particularly difficult for any marine community that has damaged or lost docks and vessels.

The *BC Emergency Management Act* recommends recovery planning as part of the full cycle of emergency management. Immediate recovery actions include initiating business continuity plans for organizations as well as providing emergency support services for impacted community members. For most perils, including for earthquakes, insurance is an important part of community recovery; however, insurance coverage is not readily available for tsunami events. Medium and long-term recovery includes strengthening financial supports, equipment supply, and humanitarian activities from provincial, federal, and international agencies in impacted communities.

5.1.4.2 Progress

This tsunami risk study did not focus on recovery, but study results can support risk-informed recovery planning. For example, now specific communities along Vancouver Island’s northwest coast know which areas and assets are likely to be most affected by a tsunami, which can help leaders identify the highest-priority areas for recovery planning. Informed by this knowledge, communities can begin identifying recovery goals, as well as investment options in critical infrastructure, supply chains, mutual aid planning, and future needs for emergency social services and humanitarian assistance.

Recovery funding is not often identified prior to a disaster event taking place. However, pre-disaster communities can explore opportunities for recovery funding by pursuing government grant opportunities, private or public insurance and re-insurance expansions, and disaster aid through non-governmental organizations, as well as investing in catastrophic bonds, and advanced private-sector recovery projects.

5.1.4.3 Path Forward

Recovery planning should be proactive and include everyone in discussions on topics that include the following:

- trauma from injury and loss, and recognition of the importance of community wellness after a disaster
- repair and reconstruction of critical infrastructure
- support principles to build back better
- support business continuity and recovery
- include and welcome all community perspectives

5.1.5 Mitigation

This section presents a discussion of tsunami mitigation being discussed or implemented in the communities participating in this project. In addition to summarizing best practices and regulations in place to guide post-tsunami mitigation, this section also includes a summary of local tsunami mitigation efforts conducted to date and an overview of the path forward to strengthen local tsunami mitigation capabilities.

5.1.5.1 Best Practices and Regulations

Disaster mitigation means to lessen or minimize the adverse impacts of a hazardous event (United Nations Office for Disaster Risk Reduction, 2017). Mitigation is often described as either behavioural or structural in nature. While the physical impacts of a worst-case tsunami event cannot be fully prevented, the scale and severity of the impacts can be reduced through several types of pre-disaster actions. Mitigation has a record of being cost effective, enhancing existing capacities and spurring further actions that improve overall community safety, health, and wellness.

Regulatory actions that will mitigate tsunami risk include zoning actions that prevent or limit the construction of new residential and commercial buildings in flood hazard areas. They may also include updated building code adoption to ensure infrastructure built within the hazard areas is able to withstand tsunami forces.

A best practice for mitigating tsunami hazard is adoption of education materials and evacuation training for a community to inform the public about appropriate responses to a tsunami warning. Another best practice for mitigation is to ensure a community has emergency response capabilities and a safe evacuation facility with adequate supplies to support the community.

5.1.5.2 Progress

The community risk assessments have identified the highest risk areas prone to tsunami risk. By establishing and engaging with the project advisory group, the study team anticipates that present and

future community development decisions in marine and coastal areas will utilize the tsunami risk assessment results to inform and influence community land use decisions in high-risk areas. Through the second phase of this project, mitigation activities took place to increase public awareness. For example, ONC delivered education modules at several schools in the study area, and the SRD installed tsunami hazard signs, as described in Sections 2.4.5 and 2.4.6 respectively.

Meanwhile, progress is being made on key tsunami risk mitigation opportunities that stem from enhancing earthquake and tsunami monitoring and updating local communications infrastructure. In the near future, advance technologies are expected to come online in some areas, such as improved early warning systems for approaching earthquakes and the ability to share real-time tsunami observations at the local and individual level to help people respond more quickly and effectively to approaching hazards.

In a structural sense, tsunami mitigation is also happening as communities develop and upgrade marinas, roadways, and critical infrastructure, re-supply emergency equipment, and re-enforce tsunami evacuation routes. These activities are part of overall emergency management and community development.

5.1.5.3 Path Forward

Each at-risk community in the study area will want to consider tsunami mitigation activities that reflect local risk management decisions. Following are general recommended mitigation strategies for at-risk communities:

- Consider tsunami risk when revising development, emergency, and evacuation plans, and in decisions to upgrade critical infrastructure and services.
- Provide signage for hazard areas, community assembly areas, and evacuation routes.
- Evaluate tsunami evacuation routes and upgrade, as needed.
- Promote use of and expand existing tsunami alerting capacities such as Coast Guard VHF 16 and weather radio, along with local mobile-based alerting systems and tsunami sirens.
- Expand tsunami response processes and systems to include use of new technologies.
- Strengthen local and regional mutual aid agreements and supply chains.
- Expand household-level risk reduction (e.g., hazard hunts and family emergency plans that include tsunami evacuation procedures) plans and activities.
- Explore insurance, re-insurance, and other financial risk distribution methods.

Some of these risk and additional reduction measures are further discussed in Section 0.

5.2 Recommendations for Reducing Tsunami Risk

Everyone who may be affected by a tsunami is responsible for reducing tsunami risk. In the is and priorities of the Sendai framework (UNISDR, 2015), the first step in informing action is to understand

risk. While the scope of this study does not include the detailed elaboration of risk reduction measures and plans, this section provides an overview of possible options.

The development of formal risk mitigation plans is specific to each community and requires more than just government action. Participation and support are needed from all levels in communities, including local governments, First Nations, the provincial and federal governments, community members, business owners, property owners, and visitors. In the event of a Cascadia earthquake and tsunami, disastrous impacts would not be limited to Vancouver Island, but also to BC's Lower Mainland because of the strong shaking. In this scenario the provincial and federal emergency response may be overwhelmed, and it could take time before help arrives to remote, less populated areas such as the northwest coast of Vancouver Island. This scenario highlights the importance for local government to take the matter of tsunami risk reduction into their own hands and promote self-reliance as much as possible.

Risk reduction plans should follow a road map that includes short-term, medium-term, and long-term actions. The short-term plan would cover the next two years following a tsunami event; during this time, recommended steps should be identified to take early action. The medium-term plan would involve the next two to five years and would include details on opportunities for additional input. Finally, the long-term plan is intended to guide communities on a path over the next 5 to 10 years and provides a vision for what the work being conducted could achieve during this period. Such plans should also highlight measures that can meaningfully reduce risk with relatively modest resources and identify funding opportunities and strategies. Clear objectives and evaluation criteria specific to each community should be established early on to support decision making.

The sections below briefly introduce the different categories of measures that can be developed to reduce tsunami risk, in conjunction with developing tsunami emergency management plans. An example of a tsunami risk reduction plan specific to the District of Tofino on Vancouver Island can be found at <https://tofino.civicweb.net/document/107147/> (Northwest Hydraulic Consultants et al. 2020).

5.2.1 Public Awareness

Public awareness is a key component of any tsunami risk reduction plan. Involving people on specific ways they can reduce their own risk and educating them to know how to physically remove themselves from the hazard zone may be the most effective measure to reduce tsunami risks.

Evacuation Signage

Tsunami signage improves way finding during a tsunami event and is a key tool for providing educational awareness to visitors and community members on a daily basis. Multiple signs should be posted around a community at risk and along major routes, providing directional guidance that shows inundation zones, evacuation routes, high-ground areas, and designated refuge areas. While these signage measures are generally targeted at visitors who are not familiar the area's geography or the spatial extent of a community's tsunami hazard, these signs also serve as reminders for locals to be prepared to evacuate for several days or longer.

Annual Community and Neighbourhood Evacuation Drills

An annual evacuation drill can help ensure tsunami preparedness remains top of mind in a community while encouraging and reminding people to be prepared to evacuate immediately when they first receive notice. Each year, a different preparedness focus can be highlighted to help people freshly engage with the process. In addition, as evacuation route planning evolves in a community, people from different neighbourhoods or regions may be better off evacuating to different refuge areas and using different evacuation routes. These scenario examples clearly demonstrate the need for holding yearly (or more often) evacuation drills on a neighbourhood-by-neighbourhood basis.

Visitor Education and Staff Training

A tsunami event is not the time to start preparing for a tsunami. Life safety during a major tsunami event depends on advance development, distribution, and delivery of tsunami educational material that addresses local risk, advises on alerts, and provides detailed response procedures. Visitors in particular are especially vulnerable due to their limited understanding of tsunami risk, their potential disconnection from social networks and information sources, and their lack of awareness of appropriate response procedures. Local government and emergency management staff training is also critical to ensure sufficient people are able to support up-to-date tsunami response in each community.

The safety of visitors and staff is a shared responsibility with, among others, local accommodation providers, tour operators, and other businesses. For example, resort operators should post specific tsunami evacuation routes at common places around the resort, include tsunami evacuation information in each room, and have a plan for staff to guide guests to safety during a tsunami. Visitor-specific tsunami education material can capture attention, raise awareness, and be designed to empower self-reliance rather than induce fear.

5.2.2 Public Alerting

The SRD receives distant tsunami notification via EMBC and the US National Tsunami Warning Center. If a tsunami threat is identified, EMBC will activate the Provincial Emergency Notification System and Alert Ready, which notifies residents and communities through email, phone calls, social media, texts or short messaging systems (SMS). The Environment and Climate Change Canada Alert Me platform and Channel 16 marine radio will also be activated with information provided on alert levels for the province's five tsunami zones (GeoBC, 2015), namely:

- Zone A – north coast and Haida Gwaii
- Zone B – central and northeast Vancouver Island coast
- Zone C – outer west coast of Vancouver Island
- Zone D – Strait of Juan de Fuca
- Zone E – Strait of Georgia

The SRD also receives tsunami alerts directly from the US National Tsunami Warning Center via text and NOAA weather radio. During a distant event, the SRD will make every effort to broadcast official tsunami alerts and information by email, telephone, and text message via the Alertable system. The SRD will also

post on social media, make radio announcements, and contact people door to door if possible. Most notification systems activated during a tsunami event are expected to malfunction or fail despite rigorous pre-event testing; communities have several opportunities to improve local public alerting to further reduce tsunami risks, especially for visitors.

Tsunami Sirens

The communities of Ka:'yu:'k't'h'/Che:k:les7et'h' First Nation, Ehattesaht First Nation, Gold River, Tahsis, and Zeballos all have their own tsunami sirens. Improvements to existing systems may include additional testing and upgrades, and expansion based on the assessment of sound levels and reach. Other areas where modern tsunami sirens could be deployed include the Village of Port Alice, the Hamlet of Quatsino, Winter Harbour, Holberg, and Cougar Creek, where campsite users may not be aware of a distant tsunami approaching. A local Cascadia tsunami alert for evacuation should always be considered as a natural or environmental warning, such as strong ground shaking. In such an event, sirens may not be heard due to other noises associated with the earthquake, or the siren system may become damaged during the earthquake.

Alerts by Last Mile Public Distributors

Last mile public distributors⁹ rely on redundant tools for public communications, including weather radios, sirens, traditional and social media, and cell phone alerts. Each method has advantages and limitations, and each requires ongoing education, training, and practice to ensure that alerting tools meet expectations, and people respond appropriately to the alerts.

Last-mile public alerting is designed to directly improve the likelihood of at-risk populations receiving timely information on an advancing distant tsunami, and appropriate response actions are taken. Generally, tsunami alerting is designed specifically for distant tsunami events (i.e., > 3 hours to arrival) where there is no warning from earthquake ground shaking. Local tsunamis have shorter arrival times, and communications infrastructure can potentially be damaged by significant ground shaking, so last mile public alerts may not be possible. During a local earthquake or tsunami, people should consider groundshaking as the only alert they will receive.

Radio Training

Results of the 2021 community survey summarized in Appendix B suggests that only 8% of survey respondents are certified amateur radio operators, but 32% would be interested in obtaining such certification to help with alerting their fellow community members. Facilitating and further promoting this training could be an effective way to reduce tsunami risk, since many remote areas do not have phone or internet connections.

Weather radios are robust, effective, and inexpensive. They are designed to send an alert for multiple hazards, including extreme weather and storm surge. They deliver authoritative, regionally specific alert

⁹ According to publicsafety.gc.ca/cnt/mrgnc-mngmnt/mrgnc-prprdncss/npas/rchvd/fls/clf-lng-11-en.pdf, a last mile distributor is "A party that presents audience alert messages to the public through one or more media., e.g. radio, television, search engine provider, SMS text message service, etc."

information and are both transportable and intrusive in nature. These attributes make them especially effective for nighttime and indoor alerting. Weather radios do have limitations; they can be a challenge to program, they can have reception issues, and they may deliver information more slowly, and in some conditions less reliably, than other alerting tools. However, if no other communication means are available and if sufficient people in a community are trained, they can serve as a crucial tool to alert people of a hazard.

5.2.3 Evacuation Planning

This section presents a discussion of evacuation planning, including the critical issues to consider when planning evacuation routes along with both short- and long-term refuge spaces. Before identifying preliminary, site-specific considerations for areas at higher risk of being impacted by tsunamis, this section first discusses the critical considerations needed when evacuation planning, including a tsunami's source and the anticipated means of transportation to both short-term and long-term safe locations (refugia).

The survival rate of a large tsunami depends on a community's evacuation success. Careful planning and assessment is required when designating and developing tsunami evacuation routes and refuge areas. People must be able to quickly and effectively exit tsunami inundation zones through evacuation routes and find their way to safe designated spaces. Routes should be developed based on the characterization of a tsunami hazard and should consider the time required for evacuees to leave the evacuation zone (e.g., evacuee travel speed) under circumstances imposed by an earthquake and tsunami.

During evacuation planning, it is important to distinguish between a short-term tsunami refuge for people to survive tsunami flooding and a longer-term shelter that would house people for a longer stay, as these functions have varying requirements. Short-term tsunami refuge is generally sufficient for people to survive the tsunami itself; however, tsunami effects can last several hours to several days. Some people may not survive extended periods without supplies, medical aid, and protection from the elements. The assessment of the time available for evacuation should include consideration of the duration of any ground shaking associated with a triggering earthquake, the time required for people to evacuate after the ground shaking stops, and the time needed to exit buildings that may be damaged by the earthquake.

The designation of tsunami refuge areas should prioritize naturally elevated ground areas. In some cases, such areas can be located on privately owned or otherwise publicly inaccessible land. Community agreements can be developed to respect private property rights and privacy, while providing community members and visitors with a safe evacuation location.

If a tsunami's arrival time does not provide sufficient time for people to reach safe higher ground, it may be warranted for a community to construct a **tsunami vertical evacuation (TVE)**, as further discussed in Section 5.2.5. Existing buildings sufficiently tall and robust can also serve as TVE structures, although their capacity to withstand tsunami loads and effects must be carefully assessed. Evacuation planning for a local tsunami in comparison to a distant tsunami differs greatly, which also affects the means of

transportation during evacuation. Local geography is another factor influencing evacuation routes and refuges.

Although any evacuation planning needs to be developed in close collaboration with the public, preliminary site-specific considerations are provided below for areas more impacted by tsunamis.

5.2.3.1 Tsunami Source

Designating a single tsunami inundation source or zone offers the advantage of simplicity during evacuation planning and facilitates public awareness and understanding. However, a single zone must also accommodate a larger range of tsunami scenarios, which could result in relatively frequent over-evacuation of a larger area than necessary when a community is faced with responding to smaller-scale, more frequent events (i.e., distant tsunamis). Since over-evacuation can cause inconvenience and create stress for many people in a tsunami risk zone, levels of community trust in and compliance with emergency response arrangements may subsequently decrease following multiple over-evacuations in a community. On the other hand, differentiating inundation zones requires greater mapping resources and greater levels of coordination in planning and managing responses for each threat or event. This greater level of complexity can lead to some people misunderstanding what they need to know and must do in each situation. The project team recommends identifying two inundation zones – one for local tsunamis and one for distant tsunamis – in communities where inundation extents are significantly different.

Since distant tsunamis will provide more time for evacuation and road infrastructure would not be damaged by the distant earthquake, residents should be evacuated to shelters rather than short-term refuge areas, if possible. This longer-term sheltering plan could take the form of a community ‘buddy system’ where neighbours on elevated ground shelter those evacuating from low-lying areas.

5.2.3.2 Means of Transportation

In addition to understanding and planning for local and distant tsunami sources, evacuation planners must also consider the means of transportation required and whether the transportation will be over land or water.

Evacuation by Land

Deciding on the specific means of transportation for land evacuation requires careful assessment in conjunction with considering the tsunami source. While many people are tempted to evacuate by car, this method of transportation is generally not recommended as it is likely to lead to road congestion and potential accidents, which can also slow down pedestrian travel, depending on a community’s road and sidewalk configuration. Particularly for a Cascadia tsunami with a shorter arrival time, road infrastructure may be damaged by the earthquake, or some roads may be obstructed by fallen trees or downed powerlines.

Evacuation over Water

Evacuation planners should use the results of the hazard assessment to specifically address the option of evacuation in overwater areas and islands. The overwater hazard maps showing tsunami-induced current velocity can provide some guidance for evacuating boaters on the water being notified of an approaching tsunami. The NTHMP and US Coast Guard (2017) provide additional guidance by including safe minimum offshore depths for boaters evacuating during a tsunami, as summarized in Table X below.

Table 5.1 Guidance to evacuating boaters during local vs. distant tsunami.

Local Cascadia Tsunami	Distant Alaska Tsunami
<ul style="list-style-type: none"> If you are on land or tied up at the dock, do not attempt to take your vessel offshore. Leave your boat and go to elevated ground on foot as soon as possible. 	<ul style="list-style-type: none"> If you are on land, DO NOT use your vessel to evacuate before or during a tsunami. Leave your boat and go to elevated ground on foot.
<ul style="list-style-type: none"> If you are in deep water or close to deep water, take your vessel beyond a depth of at least 100 m. 	<ul style="list-style-type: none"> If you are on the water consider taking your boat offshore, and consider the following: <ul style="list-style-type: none"> the time available before the tsunami arrives the preparedness of the boat and captain’s experience to stay offshore for 12 – 24 hours or travel to a safe, undamaged harbour the weather at sea could be as or more dangerous as the tsunami itself.
<ul style="list-style-type: none"> If you are on the water but close to shore, use your best judgement to decide between safely beaching/docking the vessel and evacuating to elevated ground, or attempting to get beyond a depth of at least 100 m. <ul style="list-style-type: none"> Beaching a vessel and running to elevated ground entails numerous risks. A skilled vessel operator is required with knowledge of the upland area (forest undergrowth can be extremely difficult to climb through), and all party members must be physically fit. 	

The above general guidance is based on typical US coastlines, which may vary from the northwest coast of Vancouver Island. While the rapid fluctuations in water level (i.e., tsunami amplitude) would pose a limited risk to most boaters, the highest risk is the strong current velocities and the waves breaking in shallower areas or in narrow passages. More assessment is required to define minimum safe water depths and safe overwater areas.

In the case of inhabited islands at *higher* elevation than the estimated inundation level, residents are not advised to leave the island. If an island is *below* the estimated inundation level, residents are advised to leave the island only in the case of a *distant* tsunami, and only if they can reach a safe location before the arrival of the tsunami. In the case of a *local* tsunami, island residents are advised to stay on the island unless they are confident they can navigate to safety before the tsunami arrives. If leaving the island is judged unsafe or not possible, residents may have a better chance of survival if they go the highest location on the island, as the local tsunami may be smaller than the one analyzed in this study. While a smaller local tsunami may result in lower inundation levels, it can potentially induce dangerous currents and breaking waves for boaters.

5.2.3.3 Preliminary Considerations for Site-specific Evacuations

Following are high-level evacuation considerations the study team has developed based on the results of the risk assessment conducted for this project. *Such considerations are only meant to support the review of existing evacuation plans and are not final or official. More assessment and public engagement are required to carefully develop evacuation plans.*

The high-level evacuation considerations provided below are based on the premise that if people are safe where they are and they have access to shelter and supplies (e.g., in their homes), they should not evacuate.

Please refer to the maps showing assets at risks provided in Appendix G for a better understanding of the zones affected by either a local Cascadia tsunami or distant Alaska tsunami.

5.2.3.3.1 Gold River Waterfront

This section presents the recommendations for reducing tsunami risk along the Gold River waterfront. It includes details on the existing tsunami evacuation plan and provides recommendations for reducing risk from both a local and a distant tsunami.

Existing Tsunami Evacuation Plan

According to information shared in conversations between the project team and the advisory group, Gold River's tsunami evacuation plan is to evacuate the entire waterfront area using Mill Road (Highway 28) and travelling north.

Bounded by steep cliffs to the west, the relatively flat and low-lying area of the Gold River waterfront is typical of a river delta. The road leaving the area (Mill Road/Highway 28) runs directly parallel to the river at a relatively constant elevation until the route travels uphill, approximately 2 km past the northern end of the river's **alluvial fan** (Figure 5.1). The approximate distance to reach the elevated road from the waterfront (e.g., Air Nootka terminal) is approximately 4 km.

In the case of a Cascadia tsunami, the entire area is expected to be inundated, and tsunami effects are expected to reach the confluence with the Ucona River. The stretch of straight road before it begins its uphill ascent is deemed hazardous, given its proximity to the river. Evacuation plans should require people to either reach the elevated road or travel uphill through vegetation to the hillside on the eastern side of the road, if possible.



Source: Aerial imagery from Global Mapper.

Figure 5.1 Approximate locations of elevated ground at Gold River waterfront (red dots). The project’s risk assessment results identify as hazardous the stretch of straight road before Mill Road (Highway 28) ascends uphill. Both the river and road would be fully inundated from a local tsunami, given the road’s proximity to this stretch of the river.

FEMA (2012) indicates that the average healthy person can walk approximately 4 miles per hour (1.8 m/s), and the travel speed of a mobility-impaired person is assumed to be about 2 miles per hour (0.9 m/s). Travelling speed is expected to be slower at night, although few individuals are anticipated to be present in the area at that time, since it is mainly used for industrial and commercial purposes. This situation may change however, if a recreational site is developed on Ahaminaquus lands, as is currently being planned. Computer modelling suggests that the first wave from a Cascadia tsunami would arrive

within about 1 hour after the earthquake¹⁰. Considering the approximate travel speed of the average healthy person, it may take up to 20 minutes to exit the estimated inundation zone; it would then take another 20 minutes to reach the elevated road past the straight stretch of road next to the river (Figure 5.1). Considering that the ground shaking caused by the earthquake may last up to five minutes and people may have to exit boats and potentially damaged buildings, it only leaves a 15-minute buffer before the arrival of the first tsunami wave, which does not leave much time for other aspects that may complicate evacuation (e.g., decision time, injury, pathway obstructions, etc.).

While the whole area could technically be evacuated relatively quickly by car, this means of transportation is generally not recommended when evacuating in response to a Cascadia tsunami (see Section 5.2.3.2 above). The decision to evacuate by car in such a scenario should be carefully reviewed and should consider the number of vehicles present in the area, the traffic capacity of the roads, and ideally should be based on a seismic hazard assessment of the area to evaluate to risk of road damage and obstruction by falling debris (e.g., landslides, power lines, trees, building materials).

Local Tsunami

Additional assessment is required (and beyond the scope of this study) to carefully identify a safe evacuation plan for the area in advance of a local Cascadia tsunami mainly because of the complexity of several factors that affect evacuation, in conjunction with the generally steep bounding topography. Evacuation planning may consider the elevated ground located at the western end of the road leading to the industrial area directly west of Ahaminaquus (Figure 5.1). In comparison to other elevated ground nearby, access to this elevated location is not excessively steep, and the location is centrally located, allowing people to reach it on foot relatively quickly from anywhere in the general area. However, establishing this area as a refuge would isolate evacuees for some time. In addition, fences may limit direct access to this area.

As an alternative to using natural elevated ground as refuge area, a TVE structure may also be considered. A separate structure could be built to serve the single purpose of a tsunami refuge, but a TVE could also be a multi-purpose building, which could provide opportunity for future development. See Section 5.2.5 for additional discussion of this risk mitigation option.

Distant Tsunami

In the case of a distant tsunami, evacuating the Gold River waterfront area by car may be appropriate, as the area would not be subjected to the effects of the triggering earthquake, so there would be no damage to the road and no fallen debris obstructing the road. There would also be enough time to coordinate traffic control to facilitate the evacuation.

¹⁰ Arrival time is defined as the time of the first maximum of the tsunami waves (Intergovernmental Oceanographic Commission, 2019); flooding may begin before this moment is reached.

5.2.3.3.2 Yuquot

The project team is not aware of any formal evacuation plan for Yuquot. Following are general recommendations for evacuation in the event of a local Cascadia tsunami and a distant Alaska tsunami.

Local Tsunami

A local Cascadia tsunami is expected to inundate a large extent of the peninsula (Figure 5.2). Most of the coast guard station buildings are located on elevated ground and thus provide ideal refuge and shelter. This location, however, is isolated on steep cliffs, and not everyone on the peninsula may have time to reach it as the first tsunami wave will arrive in less than half an hour from the seismic event at the Cascadia Subduction Zone. Access is currently possible by boat, unless other land-based means are developed (e.g., stairs or trestle). As general guideline, people should not get in their boats if elevated ground is accessible by foot. Therefore, people on the peninsula are recommended to evacuate to the nearby hill to the northwest. Development of a trail and a shelter with supplies on this hill would facilitate evacuation.

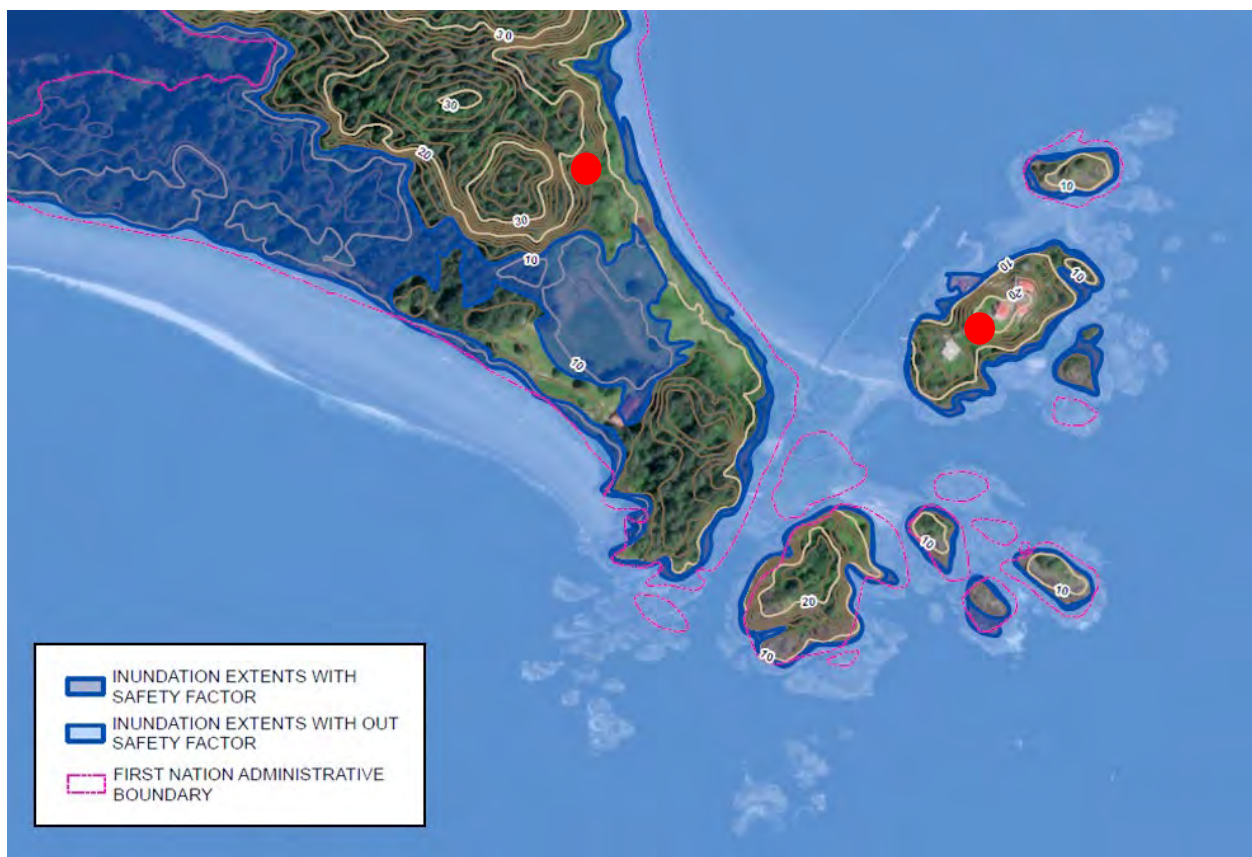


Figure 5.2 Estimated extent of inundation in Yuquot due to a Cascadia Tsunami. Data excerpted from inundation maps developed for this project. Red dots show safe areas above tsunami for recommended evacuations.

Distant Tsunami

In the event of an Alaska (distant) tsunami, inundation at Yuquot is expected to be limited as a result of the relatively small tsunami wave amplitude expected (0.5 to 1 m). Accordingly, evacuation may be limited to areas lower than 10 m with respect to CGVD2013. For the total of seven buildings identified in the area, three are known to be below that elevation.

People should not leave the area by boat during any tsunami.

5.2.3.3.3 Hamlet of Quatsino

This section presents the recommendations for reducing the tsunami risk in the Hamlet of Quatsino. It includes details on the existing tsunami evacuation plan and provides recommendations for reducing risk from both a local and a distant tsunami.

Existing Tsunami Evacuation Plan

The project team understands and assumes that evacuation planning for the Hamlet of Quatsino was being developed independently during the preparation of this report. To further support this critical planning process, general recommendations are provided in this section for evacuation in advance of a local Cascadia tsunami and a distant Alaska tsunami.

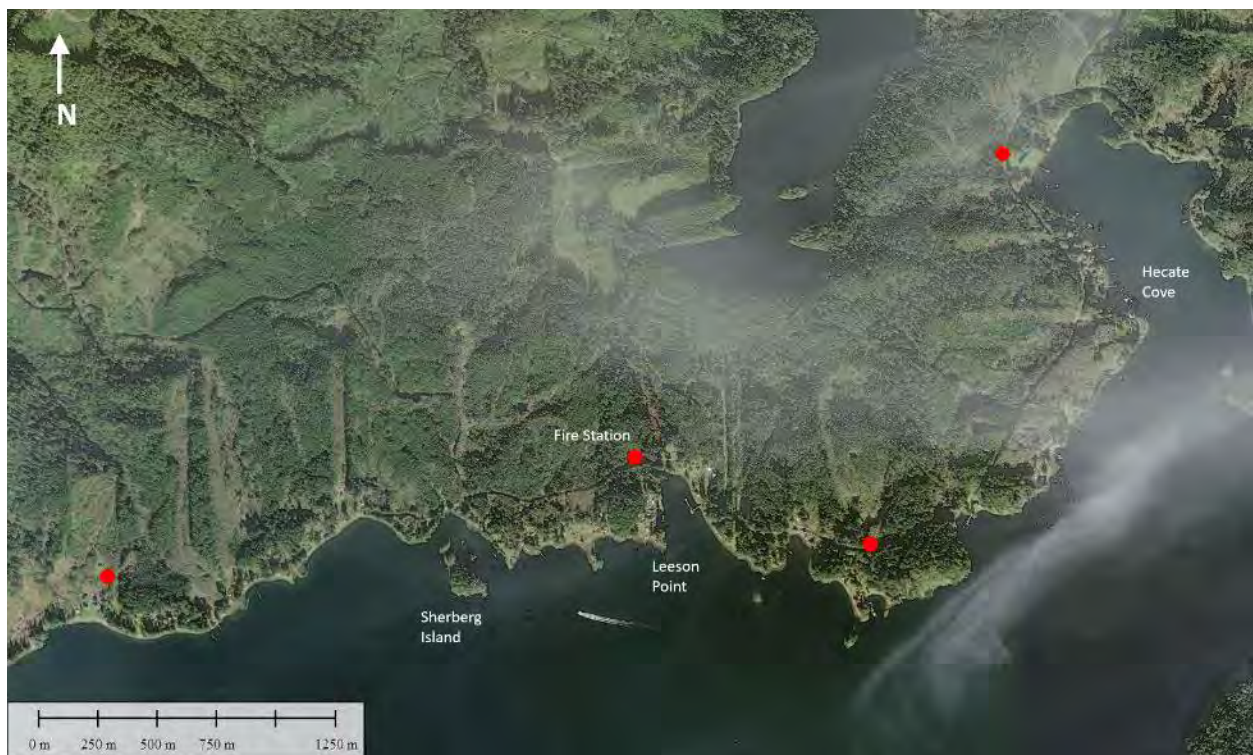
Local Tsunami

The first tsunami wave of an approaching local Cascadia tsunami would arrive at Quatsino within 40 minutes. Different parts of the community would be separated due to the expected inundation of several low-lying segments of the main road. Since the area is residential, it is possible that evacuation would occur at night, which would slow the pace of evacuating people. Figure 5.3 shows potential tsunami refuge locations for Quatsino that are identified based on travel distance (or time) and hazard zone along evacuation route. People located outside of the hazard zone should avoid re-entering or crossing the hazard zone to access any refuge location.

The fire station and adjacent yard would serve as a good location for a tsunami refuge as this emergency response facility is located on elevated ground and offers space. While the nearby school is not expected to be inundated, it is located relatively close to the hazard zone. The study team recommends that people located east of Sherberg Island and surrounding the bay at Leeson Point evacuate to the fire station, and people located west of Sherberg Island should evacuate to the elevated ground at the western end of the main road. This area is known for generating landslides, however, so this risk should be assessed before confirming any refuge area locations. In addition, people evacuating to this western location would be travelling alongside the water's edge, rather than away from it; they should be aware of the time they have left to reach the refuge area and be ready to travel directly uphill through vegetation if they are running out of time. Tsunami inundation is expected to occur rapidly and, people may not have time to evacuate safely. The study team recommends not using any routes that run parallel to the water's edge as evacuation routes; instead, we recommend the hamlet develop a new evacuation route/trail along elevated ground.

When designating tsunami refuge areas, evacuation planners in Quatsino should prioritize naturally elevated areas. In some cases, refuge areas and access routes may be located on privately owned land. Community agreements can be developed to respect private property rights and privacy, while ensuring community members and visitors have access to a safe evacuation route.

The study team strongly discourages anyone from evacuating Quatsino by boat to Coal Harbour in advance of a Cascadia tsunami, even if the tsunami hazard is expected to be relatively lower beyond Quatsino Narrows. Considering the duration of the ground shaking, the time needed to exit a damaged building, reaction/decision time, and the strong counter-currents in the narrows that may be induced by tsunami drawdown immediately after the earthquake, it would be extremely hazardous to evacuate the area by boat.



Source: Aerial imagery from Global Mapper.

Figure 5.3 Potential tsunami refuge locations for the Hamlet of Quatsino (red dots).

Distant Tsunami

Most of the community's main road would not be exposed to tsunami flooding from a distant Alaska tsunami, with the exception of relatively short, localized segments. The longer tsunami arrival time (e.g., 3 hours) would allow for a safer and more coordinated evacuation of the areas close to the water's edge.

While the arrival time of a distant tsunami may be technically sufficient to evacuate by boat to Coal Harbour, the study team does not recommend evacuation by boat as this means would potentially risk people's safety and lives. While isolation from health care services and supplies during and after a distant tsunami may also pose some risk, planning preparedness measures to mitigate this impact would reduce the risk to a manageable level.

5.2.3.3.4 Winter Harbour

The project team is not aware of any formal evacuation plan for Winter Harbour. General recommendations for evacuation in the event of a local Cascadia tsunami and a distant Alaska tsunami are provided below.

Local Tsunami

Tsunami inundation at Winter Harbour is expected to be mostly limited to waterfront areas where buildings and marine facilities on the waterfront would need to be evacuated. Fortunately, the land topography allows for quick access to elevated ground throughout the community. Since the main road is not expected to be inundated, evacuees could assemble at the southern end of the community up Croft Street, where there is more space and potential shelter.

Areas that are more affected include Grass Point, where the inundation would reach further inland, as well as near mouth of Galato Creek, where the land elevation next to shore is relatively lower. People located north of the intersection between S Road and Winter Harbour Road should not evacuate to the south as inundation is expected to reach Winter Harbour Road, approximately 250 m south of the intersection where a small stream flows nearby.

Distant Tsunami

The impacts of an Alaska tsunami at Winter Harbour are similar to the ones of a Cascadia tsunami. Therefore, the evacuation plan for a distant tsunami could be the same as a local tsunami.

5.2.3.3.5 Village of Port Alice

This section presents the recommendations for reducing the tsunami risk in the Village of Port Alice. It includes details on the existing tsunami evacuation plan and provides recommendations for reducing risk from both a local and a distant tsunami.

Existing Tsunami Evacuation Plan

To the project team's knowledge, Port Alice's tsunami evacuation plan consists of evacuating areas lower than 20 m and using the school building as shelter. No distinction has yet been made between local or distant tsunamis. General recommendations for evacuation in the event of a local Cascadia tsunami and a distant Alaska tsunami are provided below.

Local Tsunami

Port Alice is fortunate to have elevated ground that is readily accessible to evacuees, as well as good transportation connectivity throughout the community on paved surfaces. Inundation from a Cascadia tsunami is expected to be limited to the waterfront areas lower than the village's main road, except for a segment of the main road located south of the stream crossing that is close to the public dock. Any damage to this stream crossing may isolate the southern end of the village from road access.

Of particular importance is the village's health centre, which is located close to the extent of inundation. The study team recommends evacuating this facility in advance of a Cascadia tsunami. Although the arrival time of the tsunami allows for up to 1 hour to evacuate, this effort may require additional support if patients with limited mobility are being treated and if medical equipment and supplies need to be transported.

Distant Tsunami

Although most waterfront buildings located seaward of the main are not expected to be affected by the Alaska tsunami, their evacuation is still recommended as they are located relatively close to areas that would be flooded.

5.2.3.3.6 Holberg

The project team is not aware of any formal evacuation plan for Holberg. General recommendations in the event of a local Cascadia tsunami and a distant Alaska tsunami are provided below.

Local Tsunami

For the purpose of evacuation planning, the community of Holberg is situated in two areas: the main community center on the eastern shore of the Goodspeed River and the area on the western shore of the river. The community centre area has sufficient elevated ground nearby, and the school may offer suitable shelter for evacuees. The study team recommends evacuating the area south of E Hardy Way and Winter Harbour Road, since this area is not much higher than the estimated inundation level and the area is relatively flat; a small increase in the inundation level could lead to a larger extent of flooding. The dock area should also be evacuated, along with the community's health centre, which is located within the estimated inundation zone. Although the arrival time of a local tsunami allows for more than 1 hour to evacuate, additional efforts may be required if patients with limited mobility are being treated and if medical equipment and supplies need to be transported.

The evacuation route for people located on the western shore of the river depends on the state of the bridge following the earthquake. If the bridge is safe, people should evacuate to the eastern shore of the

river. If the bridge is not safe to cross and if the other bridge crossing the river further north along San Joseph Road is damaged by the earthquake, people should evacuate west on NE 60 Road and reach elevated ground. This latter scenario is less ideal as evacuees may be isolated in a wooded area.

Distant Tsunami

While the extent of inundation is less severe from an Alaska tsunami in comparison to a Cascadia tsunami, the study team recommends the community consider a similar or the same evacuation plan for both tsunami scenarios. With a distant tsunami, the earthquake generating the tsunami would not be felt and the bridge connecting both side of the river would remain operational. As a result, people located on the western shore should evacuate toward the community centre area.

5.2.4 Land Use Planning

One approach to reduce tsunami risk is to minimize the assets that are exposed to the hazard through land use planning. Based on flood-related regulations in BC and best practice examples globally, three main land use planning tools can be used to reduce tsunami exposure:

- Restrict critical infrastructure and facilities in hazard areas through zoning. Identify a hazard area where critical infrastructure and facilities cannot be built. When any existing critical infrastructure or facilities in a hazard area need renovations or upgrades, use the opportunity to relocate the infrastructure. This measure would significantly improve the recovery process as damages to key infrastructure would be limited.
- Use development permit areas in hazard zones to specify development conditions. For buildings in hazard areas, changes in development permit requirements could be applied to new developments or major renovations requiring a permit.
- Designate hazard areas as open space areas, or restrict density through zoning. In areas where a tsunami hazard exists, a additional risk further accommodation or facilities.

5.2.5 Structural Mitigation

Structural mitigation options are also available to help communities reduce their tsunami hazard. This section summarizes two options – developing and improving evacuation pathways and identifying, designating, and building Tsunami Vertical Evacuation (TVE) structures to enable people to reach high ground with less risk.

Develop and Improve Evacuation Pathways

Improving evacuation pathways can significantly help save lives during a tsunami by removing evacuation bottlenecks and improving evacuation speeds. Routes should be accessible to all, including people with mobility challenges who would otherwise face evacuation barriers. Access should be clearly marked, and the route should support effective egress through wide, smooth, low-angle pathways that are lighted to facilitate evacuation at night.

Figure 5.4 shows as example of an evacuation ramp to access higher ground in a community in Japan, which was affected by the 2011 Tohoku tsunami.

In the case of a Cascadia tsunami, people may also be injured during the earthquake which would hinder their ability to evacuate in rugged terrain. Furthermore, evacuation by car in such event is generally not recommended as road infrastructure may be damaged by the earthquake and there is a higher chance for blockage due to traffic. Evacuation pathways can also consist of multi-use recreational trails.



Photo: Philippe St-Germain (2012)

Figure 5.4 Evacuation pathway in the City of Miyako, Japan. A refuge is visible further in the distance up the hill, while the foundations of a destroyed building are visible in the foreground.

Identify and Establish Tsunami Vertical Evacuation Structures

A TVE structure provides an elevated evacuation location where high ground is either nonexistent or it is located too far away for people to reach before a tsunami arrives. By creating artificial high ground through building a TVE, refuge can be created closer to where people live and recreate. For these structures to save lives, they must be designed to withstand effects associated with earthquake shaking as well as tsunami loads and effects. To reduce construction costs, they are often designed as short-term tsunami refuge for occupants to survive tsunami flooding, in contrast to a shelter that would house occupants for a longer stay. An example of a simple, single-purpose TVE is shown in Figure 5.5.



Photo: Philippe St-Germain (2018)

Figure 5.5 Tsunami vertical evacuation tower near Kamakura, Japan.

If designed and planned appropriately, TVE structures can also serve as multi-purpose buildings, such as recreational and community centres, exhibition and cultural centres, information offices, schools, etc. An advantage of a multi-purpose TVE structure is the possibility for a return on investment through daily community or commercial use when the structure is not needed as a refuge. Since a Cascadia tsunami would be an extremely rare event, a TVE structure would be rarely, if ever, used over its refuge-based service life. A multi-purpose facility has the co-benefit of providing additional community space and benefits. A scoping study to develop a potential TVE in Tofino is presented in NHC's 2020 Tsunami Risk Reduction Plan, which is available at <https://tofino.civicweb.net/document/107147/> (NHC, 2019).

Most communities and areas that were assessed for risk during the second phase of this study have high ground relatively close by, allowing for the potential development of refuge areas on natural ground, resulting in reduced development costs. In the case of the Gold River waterfront, however, more assessment is required to understand the benefits of a TVE structure, since the extent of inundation from a local Cascadia tsunami would be relatively large. This type of assessment generally falls under the process of evacuation planning.

6 CONCLUSION

The northwest coast of Vancouver Island is particularly exposed to tsunami hazards from local sources, (e.g., Cascadia subduction zone) and distant sources (e.g., Alaska’s Aleutian Islands subduction). By conducting tsunami modelling and drawing additional details from Indigenous Knowledge and personal experience of community members about past tsunami events, this project provides a sound understanding of the tsunami hazard in this region and the associated risks in the communities under study. This information is intended to support development and planning decisions and improve existing emergency and evacuation plans.

Due to the large geographical area covered by the assessment, which extends 200 km from Gold River northward to Cape Scott, the study team divided the project into two phases. During Phase I of the project, communities in Tahsis Inlet, Esperanza Inlet, and Kyuquot Sound were the focus; Phase II focused on communities in Nootka Sound and Quatsino Sound and was completed in 2023. The second project phase also includes initiatives for increasing the public’s awareness of tsunami hazards. This report summarized the work the study team undertook as part of Phase II.

The project focused on the importance of making space for everyone to participate and contribute in disaster risk reduction and management, and the study team actively sought input from communities in the study area. Guided by this perspective, the study team divided the project into three components, as summarized below:

1. **Community and Indigenous Engagement** – The study team produced a project webpage and completed a community survey during Phase I of the project. Phase II has involved developing an online story map to help concerned residents better understand and contextualize the study findings. Several virtual public engagement meetings were held throughout the project to provide and seek information and context by inviting community members to share their tsunami stories, knowledge, and lived experiences. The team conducted interviews with participating Indigenous Elders and Knowledge Holders, and a documentary film was produced to share these historical accounts with a wider audience. In addition, the study team consulted two advisory groups, one for each project phase, at various project milestones to disseminate information, provide guidance, and promote the exchange of knowledge. Educational modules were also delivered at schools in the study area to further increase awareness of tsunami risk.
2. **Tsunami Hazard Analysis and Mapping** – The study team simulated two tsunami sources: one from the nearby Cascadia subduction zone and another from the more distant Aleutian subduction zone in Alaska. The team then developed tsunami flood hazard or overland inundation maps for 50 priority areas within the Phase I and Phase II study areas. In response to these results, the SRD has designed and installed tsunami signage at key locations within SRD jurisdiction. In addition, overwater hazards, such as maximum tsunami wave amplitude and maximum tsunami-induced current speed, were mapped across the entire region.
3. **Risk Assessment** – Based on the tsunami hazard analysis and mapping, the study team completed a community-level risk assessment to identify potential risk to people, roads, and buildings, as well as several critical assets, and developed assets at risk maps to identify assets exposed to tsunami hazard.

The risk assessment identified the following communities as higher risk areas::

- Gold River Waterfront
- Yuquot
- Hamlet of Quatsino
- Winter Harbour
- Port Alice
- Holberg

The outcomes of the risk analysis can strengthen hazard awareness and the four key components of emergency management: mitigation, preparedness, response, and recovery. This report discusses emergency management plans as well as the status of the key components in terms of best practices and regulations, progress achieved during this project, and possible paths forward for the region. In addition, various measures have been identified to reduce tsunami risk, in conjunction with developing and updating tsunami emergency management plans. Recommendations for Future Assessment

The information developed as part of this assessment is anticipated to be useful in informing participating communities of their existing tsunami risk, since the first step in developing mitigation actions is to understand hazards and associated risks. This study also highlights some aspects that would benefit from additional assessment, as listed below.

- The communities participating in the project are closely connected to the ocean, and marine activities are an integral part of daily life for many members. Furthermore, several at-risk islands are inhabited. Guidance that is specific to overwater evacuation is scarce and has generally been developed for coastal geographies that are different than the areas under study. Marine evacuation planning is recommended in specific areas, in collaboration with local mariners, to enable development of new guidelines specific to overwater evacuation plans and routes and designated marine refuge areas (i.e., waters considered safe for boaters, remote elevated land where safe emergency landing is possible).
- The risk assessment performed as part of this regional study covered aspects related to life safety and physical assets critical to response and recovery. Community-specific assessments are recommended to identify and analyze other elements at risk, such as social, economic, environmental, cultural, and economic aspects.
- While many of the communities in the study area have elevated ground nearby that can be used as refuge areas, some of these areas may be considered too far for people to safely reach them before the arrival of a local tsunami. Site-specific evacuation assessments are recommended that would consider travel speed, population demographics, seasonality, and time of day to help determine whether the development of TVE structures is warranted in specific locations.
- The inundation mapping undertaken as part of this study is limited to priority areas; people may be exposed in other areas where only overwater tsunami amplitude has been defined. Additional inundation mapping is recommended as one way to address this information gap in communities where both LiDAR and higher-resolution modelling information was not available

at the time of this study. Alternatively, site-specific desktop assessments comparing tsunami amplitude results with local topography can help identify safe refuge areas for these areas (such as at specific commercial/industrial or recreation sites).

- The response and recovery to both local and distant tsunamis depend on the ability of certain infrastructure to withstand the effects induced by a local preceding earthquake and/or the tsunami. This is particularly the case for bridges, which provide access to communities and key areas within those communities. A structural and geotechnical assessment would confirm whether existing infrastructure should be relied upon in emergency planning or if structural upgrades are required. Unless marine structures have been specifically designed to withstand tsunami forces, planners should assume that wharves, docks, bridges and other marine infrastructure exposed to a tsunami would be damaged and inoperable.
- The tsunami inundation extents and levels developed as part of this assignment are for emergency planning and do not constitute flood construction levels, as they do not include any vertical freeboard or horizontal setback. No clear guidance exists at present for defining the parameters that are specific to a tsunami hazard; community leaders are recommended to consult with members to establish community-specific guidance that reflects each community's tolerance for risk.
- Tsunami inundation levels for emergency planning, including SLR effects, were defined for general areas and should be considered as high-level guidance only. The associated model results may be used to update inundation maps to further inform longer-term land use and development planning.
- The scientific community is constantly refining both SLR predictions and the prevailing understanding of the Cascadia subduction zone and its associated tsunamis. Longer-term land use and development planning can benefit from assessing future revisions and updates to tsunami information, guidelines, and legislation, then adapting plans, actions, and activities to address and accommodate these changes.
- This study is limited to tsunami hazards generated by earthquakes. Tsunamis may also be generated by subaerial and submarine landslides, which may occur in the study area with its many hillsides, fjords, and river deltas. A geological and geotechnical assessment would determine if hazards associated to landslide-generated tsunamis exist in the study area.
- Evacuation routes in the study area may be affected by landslides triggered by a Cascadia earthquake. Evacuation planning efforts should include a geotechnical assessment to identify these hazards.

These recommendations are intended to support reviews of existing evacuation plans and are by no means final or official. More assessment and public engagement is required to develop specific evacuation plans for each community.

It is noted that this study is limited to the analysis of tsunami hazards from deterministic earthquake sources. It is also recommended to undertake a Probabilistic Tsunami Hazard Analysis (PTHA) for the study area. PTHA estimates the likelihood that the tsunami wave amplitude (or inundation depth) at a particular location will exceed a given level within a certain period of time. While deterministic tsunami

hazard has provided crucial information for immediate emergency planning and preparedness, PTHA will offer a more comprehensive assessment of long-term tsunami hazards through the consideration of a broader range of potential sources, their probabilities of occurrence, and the associated uncertainties.

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APPENDIX A

DIGITAL ELEVATION MODEL DEVELOPMENT

June 28, 2023



Northwest Vancouver Island Tsunami Risk Assessment - Phase 2

Digital Elevation Models Metadata Report

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1.0 Summary

Ocean Networks Canada (ONC) joined Northwest Hydraulic Consultants Ltd. (NHC) to aid in emergency preparedness for communities on northwest Vancouver Island, British Columbia. ONC's role in this project was to create integrated topographic bathymetric digital elevation models (DEMs) and tsunami models, as well as to undertake community engagement and public awareness. This report will specifically discuss the creation of DEMs to support risk and vulnerability assessment, as well as improve collective resiliencies of these coastal communities.

Throughout April to December of 2022 ONC developed the DEMs, which included areas of the Strathcona Regional District (SRD) and Regional District of Mount Waddington. The purpose of these DEMs was to provide support for modelling and mapping of Tsunami inundation and hazards due to potential earthquakes from the Alaska-Aleutian and Cascadia Subduction Zones as part of the Northwest Vancouver Island Tsunami Risk Assessment project for SRD, in partnership with NHC, and several communities and First Nations.

DEMs were created by implementing strategies using international standards developed by the National Center for Environmental Information (NCEI), and National Ocean and Atmospheric Administration (NOAA). ONC participated in several workshops in 2019 as part of a cross-border collaboration effort to develop these DEM standards. DEM creation is a complex process which aims to create a representation of the surface of the earth from multiple bathymetric and topographic data sources. A high-quality DEM is imperative to this work as even minor artifacts and errors can significantly affect the quality of the tsunami and flood hazard modelling.

DEM products for the study area include two low resolution grids at 240m and 60m horizontal resolution. These were used to inform the modelling for two higher resolution 10m grids, referred to as the "Quatsino" and "Nootka" grids (Figure 1). The DEMs were created from a variety of datasets and sources, including recently captured bathymetry and LiDAR data, acquired to support this project. The extents of these DEMs, data sources, as well as data conversion and DEM creation process will be described in this document.

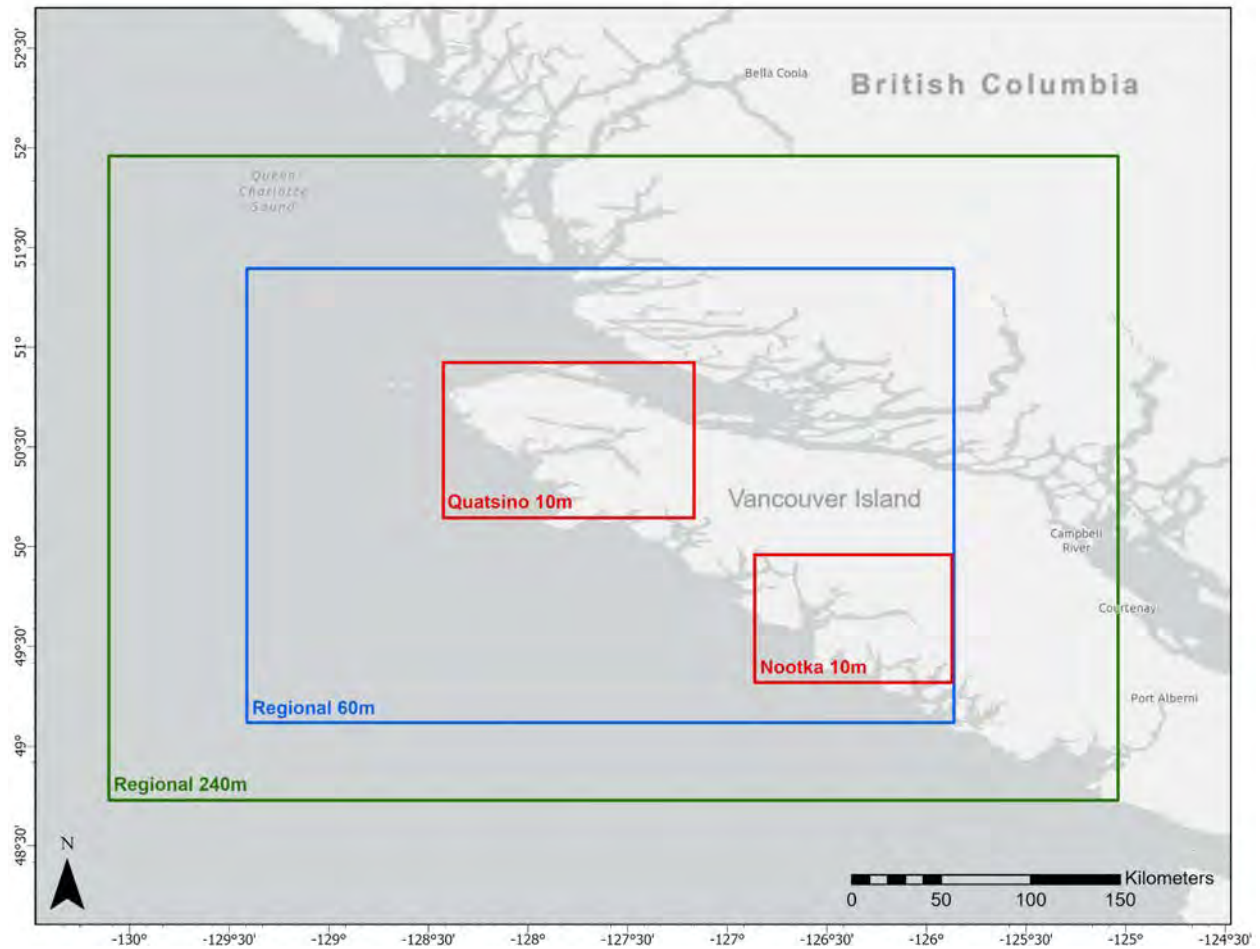


Figure 1. Map showing the extents of the two low and two high resolution DEMs created for this project.

2.0 DEM Specifications

The DEMs were built to the specifications listed in Table 1.

Table 1. Specifications for the DEMs				
Grid	Regional 240m	Regional 60m	Nootka	Quatsino
Grid Area	Northwest Vancouver Island encompassing Cape Scott to Clayoquot Sound	Northwest Vancouver Island encompassing Cape Scott to Clayoquot Sound	Northwest Vancouver Island encompassing the areas around Nootka Sound	Northwest Vancouver Island encompassing Cape Scott to Brooks Peninsula
Coverage extent (west/east/south/north)	-130.103772/-125.039247/48.727714/51.960117	-129.411/-125.862/49.117/51.395	-126.86255/-125.872144/49.31847/49.959422	-128.308306/-127.15308/50.122475/50.859865
Spatial Resolution	240m	60m	10m	10m
Coordinate System	Geographic Coordinate System World Geodetic System of 1984 (GCS WGS-84)			
Horizontal Datum	World Geodetic System of 1984 (WGS-84)			
Vertical Datum	Canadian Geographic Vertical Datum of 2013 (CGVD2013)			
Vertical Units	Metres			
Data Format	TIFF			

3.0 Data Sources

The DEMs consist of 11 different data sources (Table 2) that were integrated into one continuous DEM surface. The Canadian Hydrographic Service (CHS) coastline polyline feature class was used to clip the lower resolution Canada DEM and National Oceanic and Atmospheric Administration (NOAA) data sources so that only the land and bathymetric values, respectively, were preserved as DEM inputs for each. Please refer to pages 37-42 for maps of the datasets in Table 2.

Table 2. Data Sources

Source/Title	Date	Data Type	Resolution	Horizontal Datum	Vertical Datum
Commissioned Bathymetry (Terra Remote Sensing Inc.)	2020, 2022	Bathymetric Survey	1m and variable	NAD83 ¹ UTM ² 9N, EPSG ³ : 3156	CGVD2013 ⁴
Commissioned LiDAR (McElhanney)	2020	Topographic LiDAR Survey	1m	NAD83 UTM 9N, EPSG: 3156	CGVD2013
LiDAR (GeoBC)	2019	Topographic LiDAR	1m	NAD83 UTM 10	CGVD2013
Multibeam Bathymetry (CHS)	2000 - 2020	Bathymetric Survey	2-5m	WGS ⁶ 1984	Chart Datum (LLWLT ⁷)
Singlebeam Bathymetry (CHS)	1934 - 2010	Bathymetric Survey	Varies	WGS 1984	Chart Datum (LLWLT)
Canadian Hydrographic Service Non-Navigational (NONNA-10) Bathymetric Data (comprised of many data sources in the CHS catalogue)	2018 - 10 - 01	Bathymetric Surface	10m	WGS 1984	Chart Datum (LLWLT) for most but no official unified vertical datum
Canada West Coast Topo-Bathymetric DEM (DFO/NRCan)	2021	DEM Surface	10m	WGS 1984	Chart Datum (LLWLT)
Canadian Digital Elevation Model (NRCan)	1945 - 2011	DEM Surface	0.75 arc-second (~20m)	NAD83 (CSRS)	MSL ⁸ (NAD83)
Bathymetric DEM of British Columbia, Canada (NOAA)	1930 - 2012	Bathymetric Surface	3 arc-second (~93m)	WGS 1984	MSL
Simulated Points (ONC)	2022	Bathymetric and Topographic Points	Variable	WGS 1984	CGVD2013
High Water Line for	2013	Coastline	N/A	NAD83	N/A

British Columbia (CHS)		Shapefile			
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¹ North American Datum

² Universal Transverse Mercator

³ European Petroleum Survey Group

⁴ Canadian Geodetic Vertical Datum

⁵ Canadian Spatial Reference System

⁶ World Geodetic System

⁷ Lower Low Water Large Tide

⁸ Mean Sea Level

4.0 DEM Processing and Development

Each data source went through a variety of processes to convert the horizontal and vertical datums, coordinate systems, data format, and spatial resolutions, in order to incorporate into the DEMs and meet the specifications in Table 1. Processing of the data and DEM surfaces was accomplished on Linux machines using a number of tools and scripts.

Software, scripts, and programs used:

- Generic Mapping Tools (GMT)
- LAStools
- MB-System & MB-Grid
- Geospatial Data Abstraction Library (GDAL)
- Bathymetry smoothing python script
- ArcGIS Pro
- Global Mapper
- CHS vertical datum conversion grid

This section is a summary of the processes to prepare each data source listed in Table 2 for integration into the DEM surfaces. All input data was required to be in XYZ format, meaning that each dataline had a longitude, a latitude, and an elevation value.

4.1 Data Conversion

Commissioned Bathymetry, 2020 & 2022 (Terra Remote Sensing Inc.)

Geospatial data acquisition company Terra Remote Sensing Inc. (TRSI) was contracted to capture bathymetry data for the Zeballos Inlet, Tahsis Inlet, Strange Island vicinity, Gold River, Quatsino, Winter Harbour, Port Alice, and Holberg, due to previously poor data availability in those key areas. The 2020 multibeam data for Phase I was delivered in four XYZ files at 1m horizontal resolution and singlebeam data was delivered in two XYZ files with variable resolution. The data delivered from 2022 for Phase II contained four XYZ files that were a combination of multibeam and singlebeam, and one variable resolution XYZ singlebeam for Gold River.

- Horizontal Datum: NAD83
- Horizontal Units: Geographic coordinates, Latitude and Longitude in decimal degrees
- Projection: UTM Zone 9 North
- Vertical Datum: CGVD2013
- Vertical Units: Metres

The data was then processed into the format required for DEM integration.

1. Converted the horizontal datum from NAD83 UTM Zone 9N to WGS-1984 in decimal degrees, and XYZ format, using the cs2cs tool from LAStools.
2. Split the larger XYZ files into more manageable data chunks using the GMT block median tool.
3. Generated .inf files for each XYZ file.
4. Created a datalist for the processed bathymetry files.

Commissioned LiDAR (McElhanney)

As part of Phase I of the project, the multi-disciplinary survey company McElhanney was contracted to capture LiDAR data throughout the study area as no publicly available data existed in the key areas. Data was delivered in 436 .las format files at a horizontal resolution of 1m.

- Horizontal Datum: NAD83
- Horizontal Units: Geographic coordinates, Latitude and Longitude in decimal degrees
- Projection: UTM Zone 9 North
- Vertical Datum: CGVD2013
- Vertical Units: Metres

The points classified as bare earth (ground only, vegetation and buildings removed) were extracted and the data were converted to XYZ for integration into the DEM. However, some additional processing was necessary to remove some erroneously classified bare earth points over areas of water before the datasets underwent processing for the DEM integration. This step was accomplished by viewing the LiDAR points in Global Mapper and deleting swaths of erroneous points that remained over known deep water areas. In addition, some points were deleted near Gold River that appeared to be from buildings and tall trees that were incorrectly classified as bare earth.

After the bare earth data was verified, the remaining points were processed and converted into the format required for the DEM.

1. Extracted the bare earth points using the las2txt tool from LAStools.
2. Converted the horizontal datum from NAD83 UTM Zone 9N to WGS-1984 in decimal

- degrees, and in XYZ format, using the cs2cs tool from LAStools.
- 3. Generated .inf files for each of the XYZ files.
- 4. Created a datalist for the processed LiDAR dataset.

LiDAR (GeoBC)

GeoBC Topographic LiDAR is publicly available and was obtained from the GeoBC portal¹. Data was obtained as .laz files and covers a large swath of area spanning the majority of the Quatsino grid, and a small portion of the southeast of the Nootka grid. This dataset consisted of 1169 .las format files at a horizontal resolution of 1 metre.

- Horizontal Datum: NAD83
- Horizontal Units: Geographic coordinates, Latitude and Longitude in decimal degrees
- Projection: UTM Zone 10 North
- Vertical Datum: CGVD2013
- Vertical Units: Metres

The points classified as bare earth (ground only, vegetation and buildings removed) were extracted and the data were converted to XYZ for integration into the DEM. However, some additional processing was necessary to remove some erroneously classified bare earth points over areas of water before the datasets underwent processing for the DEM integration. This step was accomplished by viewing the LiDAR points in Global Mapper and deleting swaths of erroneous points that remained over known deep water areas. The incorrectly classified points covered a significant amount of area in much of the Quatsino grid and some of the Nootka grid.

After the bare earth data was verified, the remaining points were processed and converted into the format required for the DEM.

1. Extracted the bare earth points using the las2txt tool from LAStools.
2. Converted the horizontal datum from NAD83 UTM Zone 9N to WGS-1984 in decimal degrees, and in XYZ format, using the cs2cs tool from LAStools.
3. Generated .inf files for each of the XYZ files.
4. Created a datalist for the processed LiDAR dataset.

Multibeam Bathymetry (CHS)

Through a data agreement with CHS, multibeam bathymetry within the study area was obtained. The data was delivered in .CSAR format in two files; one for 2m resolution surfaces, and the second for 5m resolution.

- Horizontal Datum: WGS-1984

¹<https://governmentofbc.maps.arcgis.com/apps/MapSeries/index.html?appid=d06b37979b0c4709b7fcf2a1ed458e03>

- Horizontal Units: Geographic coordinates, Latitude and Longitude in decimal degrees
- Projection: GCS_WGS_1984
- Vertical Datum: Chart Datum (LLWLT)
- Vertical Units: Metres

The data was processed and converted into the format required for the DEM.

1. CARIS Easy View software was used to read the .CSAR format and export the multibeam surfaces as a tab-delimited text file with the data in geographic coordinates in decimal degrees.
2. Converted the data to XYZ format
3. Converted the vertical datum from chart datum to CGVD2013 using a conversion grid provided by CHS.
4. Split the converted XYZ files into more manageable data chunks using the GMT block median tool.
5. Generated .inf files for each XYZ file.
6. Created a datalist for the processed CHS multibeam dataset.

Singlebeam Bathymetry (CHS)

Through the same data agreement with CHS mentioned above, singlebeam bathymetry within the study area was obtained. The data was delivered in .CSAR format. This was a very large point dataset that varied in resolution across the entirety of the study area, with the highest resolution in the inlets and concentrated around communities, and the lowest in the open ocean offshore.

- Horizontal Datum: WGS-1984
- Horizontal Units: Geographic coordinates, Latitude and Longitude in decimal degrees
- Projection: GCS_WGS_1984
- Vertical Datum: Chart Datum (LLWLT)
- Vertical Units: Metres

The data was processed and converted into the format required for the DEM.

1. CARIS Easy View software was used to read the .CSAR format and export the singlebeam points as a text file, tab-delimited, with the data in geographic coordinates in decimal degrees.
2. Converted the data to XYZ.
3. Converted the vertical datum from chart datum to CGVD2013 using a conversion grid provided by CHS.
4. Generated .inf files for the 1 XYZ file.
5. Created a datalist for the processed CHS singlebeam dataset.

However, during the course of this project it was discovered that the singlebeam points were also integrated into the multibeam package that was delivered by CHS. This made the use of the singlebeam dataset in the DEMs unnecessary.

Non-Navigational (NONNA-10) Bathymetric Data (CHS)

CHS has publicly available Non-Navigational (NONNA) bathymetric data from their data portal in both 10m and 100m horizontal resolution (<https://data.chs-shc.ca/map>). The NONNA-10 (10m resolution) for the study area was downloaded from the CHS data portal in ASCII text format.

- Horizontal Datum: WGS-1984
- Horizontal Units: Geographic coordinates, Latitude and Longitude in Degrees, Minutes, Seconds
- Projection: GCS_WGS_1984
- Vertical Datum: Chart Datum (LLWLT)
- Vertical Units: Metres

The data was processed and converted into the format required for the DEM.

1. Converted geographic coordinates to decimal degrees, rearranged from YXZ to XYZ, and removed extraneous characters from datalines using a custom python script built in-house. Below is an example of this conversion:
 - a. Original data: 49-00-00.712N 126-02-57.407W 60.09020.
 - b. Converted data: -126.079182778 49.0997838889 60.09020.
2. Converted the data to XYZ text format from ASCII .txt.
3. Converted the vertical datum from chart datum to CGVD2013 using a conversion grid provided by CHS.
4. Split the converted XYZ files into more manageable data chunks using the GMT block median tool.
5. Generated .inf files for each XYZ file.
6. Created a datalist for the processed CHS NONNA-10 dataset.

Canada West Coast Topo-Bathymetric DEM (DFO/NRCan)

A joint partnership with Fisheries and Oceans Canada (DFO) and NRCan resulted in a derived DEM with the best data available from multiple sources with a horizontal resolution of 10m. This data is publicly available through the Government of Canada². Data was obtained in geodatabase raster format, and was used as a background dataset to fill data gaps between the more reliable and higher resolution datasets. Only the bathymetric data (below 0m) was used in DEM generation due to the topographic areas being well covered by LiDAR throughout the study area.

² <https://open.canada.ca/data/en/dataset/e6e11b99-f0cc-44f7-f5eb-3b995fb1637e>

- Horizontal Datum: WGS-1984
- Horizontal Units: Geographic coordinates
- Projection: GCS_WGS_1984
- Vertical Datum: Chart Datum (LLWLT)
- Vertical Units: Metres

The data was processed and converted into the format required for the DEM.

1. Converted the GDB raster into .tif in WGS84 using ArcGIS Pro
2. Ran tif2chunks2xyz script to convert .tif to XYZ
3. Converted grid from Chart Datum to cgvd2013 using conversion grid provided by CHS
4. Split the converted XYZ files into more manageable data chunks using the linux split command
5. Clipped data to obtain only values less than 0m
6. Generated .inf files for each XYZ file
7. Created a datalist for the processed west coast DEM dataset

Additional processing:

This dataset was produced with data from many sources and the quality of all the inputs and quality assurance is unknown. Some areas of this dataset were trimmed, particularly along the coasts in key areas of the Nootka DEM, and obvious outliers were removed before it was integrated into the DEMs as part of this project.

Canadian Digital Elevation Model (CDEM)(NRCan)

Data was downloaded via FTP in GeoTIFF format, courtesy of the Government of Canada - Natural Resources Canada³. This data acquisition resulted in 9 GeoTIFFs (the number of CDEM grids that intersected the study area) with a grid resolution of 0.00020833333 degrees (approximately 20 Metres).

- Horizontal Datum: NAD83
- Horizontal Units: Geographic coordinates, Latitude and Longitude in decimal degrees
- Projection: GCS_North_American_1983_CSRS
- Vertical Datum: CGVD28
- Vertical Units: Metres

Linux tools and scripts were used to process the CDEM into elevation subsets and convert datums.

1. Removed cells with a standard “no data” value of -32767 from all files.

³ ftp.geogratis.gc.ca/pub/nrcan_rncan/elevation/cdem_mnec

2. Split the 9 GeoTiffs into subsets called 'chunks', 500 row by 500 column data files, and then to XYZ files, using a tif2chunks2xyz script from GDAL.
 - a. This resulted in 1174 text file format XYZ files, tab delimited, which were organized into 9 folders, one for each of the original GeoTIFFs.
 - b. It was decided that the vertical and horizontal datums did not need to be converted to WGS-1984 and CGVD2013, as the difference would be negligible at the desired DEM surface resolution (Natural Resources Canada, 2020).
3. Generated .inf files for each XYZ file in every subset folder.
4. Created a datalist for each of the subset folders for a total of 9 datalists.
 - a. CADEM092C
 - b. CADEM092E (later reprocessed, see note below)
 - c. CADEM092F
 - d. CADEM092K
 - e. CADEM092L (later reprocessed, see note below)
 - f. CADEM092M
 - g. CADEM092N
 - h. CADEM102I (later reprocessed, see note below)
 - i. CADEM102P

Additional processing:

It was noticed in preliminary test DEM surfaces that there was some issue in higher resolution surfaces (2m) in the overlapping areas between the CDEM and the LiDAR. To remedy this issue, the CDEM subsets that overlapped with the LiDAR in key locations of the study area were clipped to remove any overlap with the LiDAR. The newly clipped subsets and the corresponding datalists were used to replace the originals listed above.

In addition, subset 092E was suspected to have unreliable values at Canton Creek. Therefore, a small area of unrealistically high elevations within the creek area were removed from the dataset.

Bathymetric DEM of British Columbia, Canada (NOAA)

Bathymetric data at 3 arc-second resolution (approximately 90m) was obtained as a netCDF from the National Geophysical Data Center⁴, courtesy of NOAA. This dataset was used to fill in the data gaps between the higher resolution bathymetric data in the lower resolution DEM grids.

- Horizontal Datum: WGS-1984
- Horizontal Units: Geographic coordinates, Latitude and Longitude in decimal degrees
- Projection: GCS_WGS_1984
- Vertical Datum: MSL
- Vertical Units: Metres

⁴ <https://catalog.data.gov/dataset/british-columbia-3-arc-second-bathymetric-digital-elevation-model>

Linux tools and scripts were used to process the NOAA netCDF into a format suitable for DEM integration.

1. Converted to GeoTIFF format using the `grdconvert` tool from GMT.
 - a. It was decided not to convert the MSL to CGVD2013 since the original data resolution of ~90m is very coarse and conversion would have negligible impact on the final DEM. The difference between the two datums is 1-3 metres.
2. Clipped the GeoTIFF to the coarsest extents of the study area, -129.8/-125.2/51.3/48.4.
3. Split and converted the clipped GeoTIFF into 'chunks', 500 row by 500 column data files, and then to XYZ files using GDAL tool `tif2chunks2xyz`.
4. Generated `.inf` files for each XYZ file.
5. Created a datalist for the processed NOAA dataset.

Additional processing:

It was noticed in preliminary test DEM surfaces that there was an issue with the coarse resolution of the ~90m NOAA data in resolving the depths in the narrow coastal inlets. The inlets, some as narrow as 300m, resulted in few data points from the NOAA dataset (3-4 in the narrowest areas) with values that were vastly different from reality, as evidenced by the higher resolution multibeam and singlebeam bathymetric values in the same areas. This was likely due to data being averaged from a large range of values due to the steep nature and sudden depth changes over small horizontal distances in these coastal fjords. Since these values were not reliably representing the inlets, the NOAA dataset was clipped so that only the open ocean and other wider coastal areas were preserved. This clipped dataset then underwent steps 3-5 above and was used for integration into the lower resolution DEM surfaces.

Simulated points from ONC

Gold River

Simulated points were created at Gold River to mitigate issues observed in the DEM during the modelling process. Observed issues, such as large vertical variations and inconsistencies in the river bed, were caused by sparsely populated LiDAR (likely due to heavy vegetation coverage hindering canopy penetration) along the shoreline upriver from the industrial terminals at Muchalat Inlet. This was remedied by creating a small simulated point file along the river edge, with the most points added along the south bank. Values for the simulated elevations were estimated based on the nearby LiDAR that did capture the river bank elevations. Points were created manually using Global Mapper. Figure 2 shows the segment of Gold River before and after the addition of manual points to the model. This image also shows the result of removing LiDAR (McElhanney) points that were erroneously classified as ground, but were likely representing tall vegetation values.

1. Evaluated where there were gaps in the LiDAR data in problem areas

2. Used Global Mapper to create a new XYZ point file
3. Added points and assigned elevation values
4. Exported as an XYZ file
5. Generated .inf file and created datalist for the simulated Gold River points

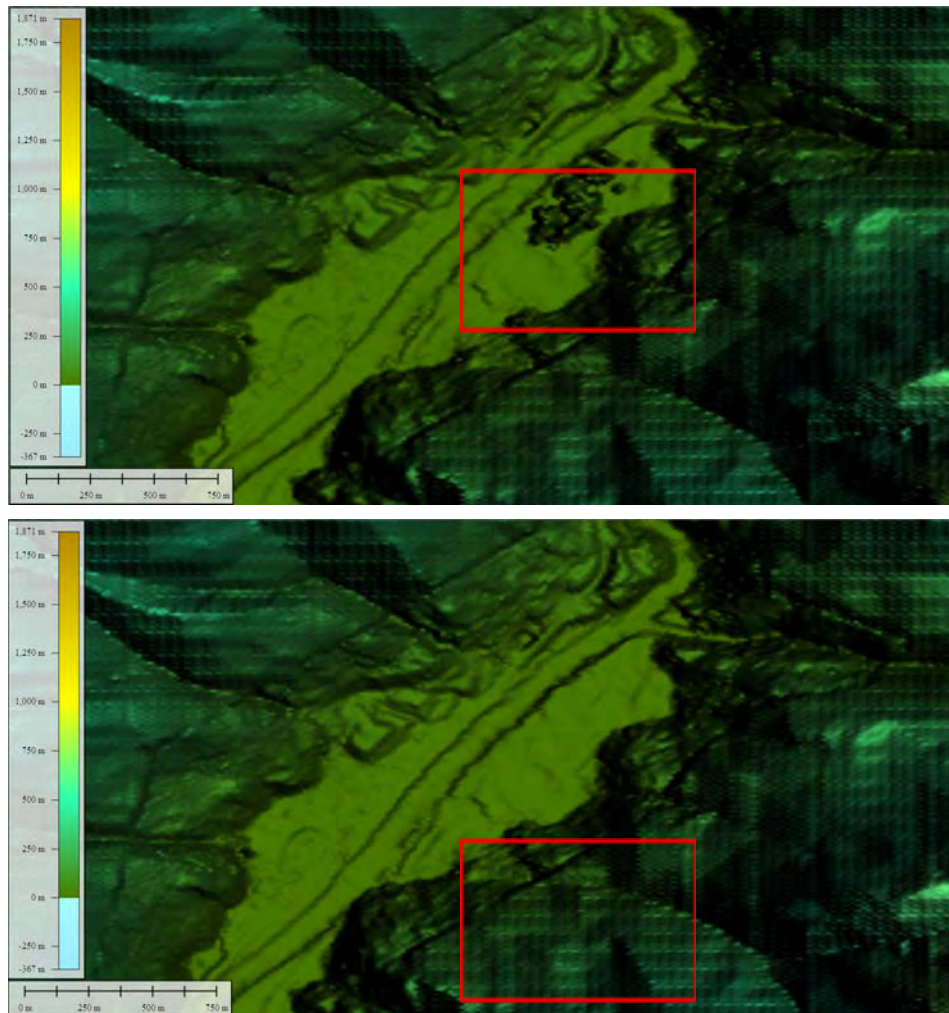


Figure 2. Comparison of the Nootka 10m DEM before and after simulated points were added along the river bank to supplement sparse lidar. The image above shows the DEM prior to the removal of erroneous lidar points and the addition of the simulated points while the image below is the DEM after the modifications.

Critter Cove

A narrow passageway connecting a small body of water to Critter Cove was not able to be resolved in the 10m Nootka DEM due to a lack of high resolution bathymetry data availability. Simulated points were added in the passageway and along the coastline in order to improve the model in this area. A value of -3.5m was chosen for these simulated points and was based on

the depth of the few bathymetry data points available in the narrow channel. Points were created manually using Global Mapper. Refer to Figure 3 to see the difference before and after the simulated points were added at Critter Cove.

1. Evaluated where there were gaps in the bathymetry
2. Used Global Mapper to create a new XYZ point file
3. Added points and assigned elevation values
4. Exported as an XYZ file
5. Generated .inf file and created datalist for the simulated Critter Cove points

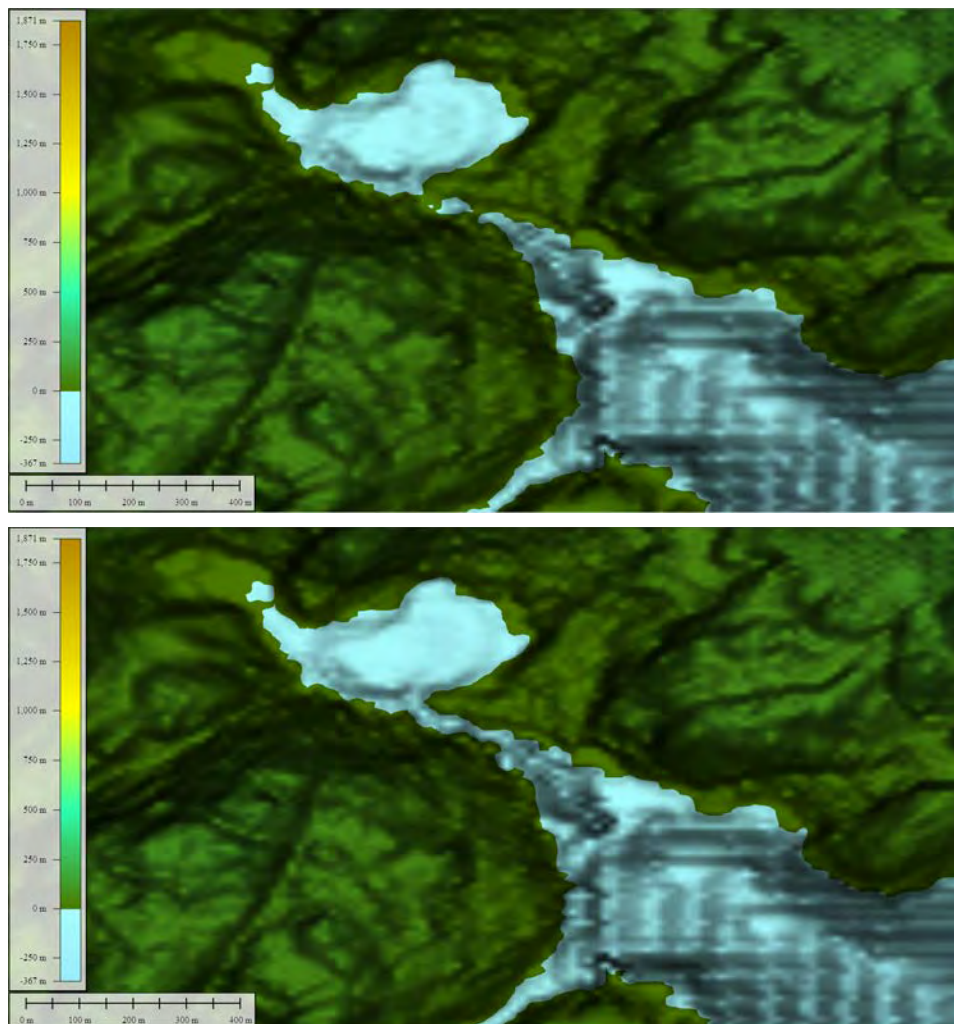


Figure 3. Comparison of the Nootka 10m DEM before and after simulated points were added at Critter Cove. The image above shows the DEM prior to the addition of the simulated points while the image below is the DEM after the modifications.

Cougar Creek

A bridge feature was removed from the McElhanney LiDAR, but without any ground points for the creek below the bridge, the DEM model produced an obstruction in Cougar Creek in the Nootka 10m DEM. To remedy this, simulated points were added along the creek and under the bridge with a value of 2.5m determined based on nearby LiDAR points. The addition of these points significantly lowered the vertical obstruction at this location. Points were created manually using Global Mapper. Figure 4 provides a visual comparison of Cougar Creek before and after the addition of the simulated points.

1. Evaluated where there were gaps in the LiDAR data in problem areas
2. Used Global Mapper to create a new XYZ point file
3. Added points and assigned elevation values
4. Exported as an XYZ file
5. Generated .inf file and created datalist for the simulated Cougar Creek points

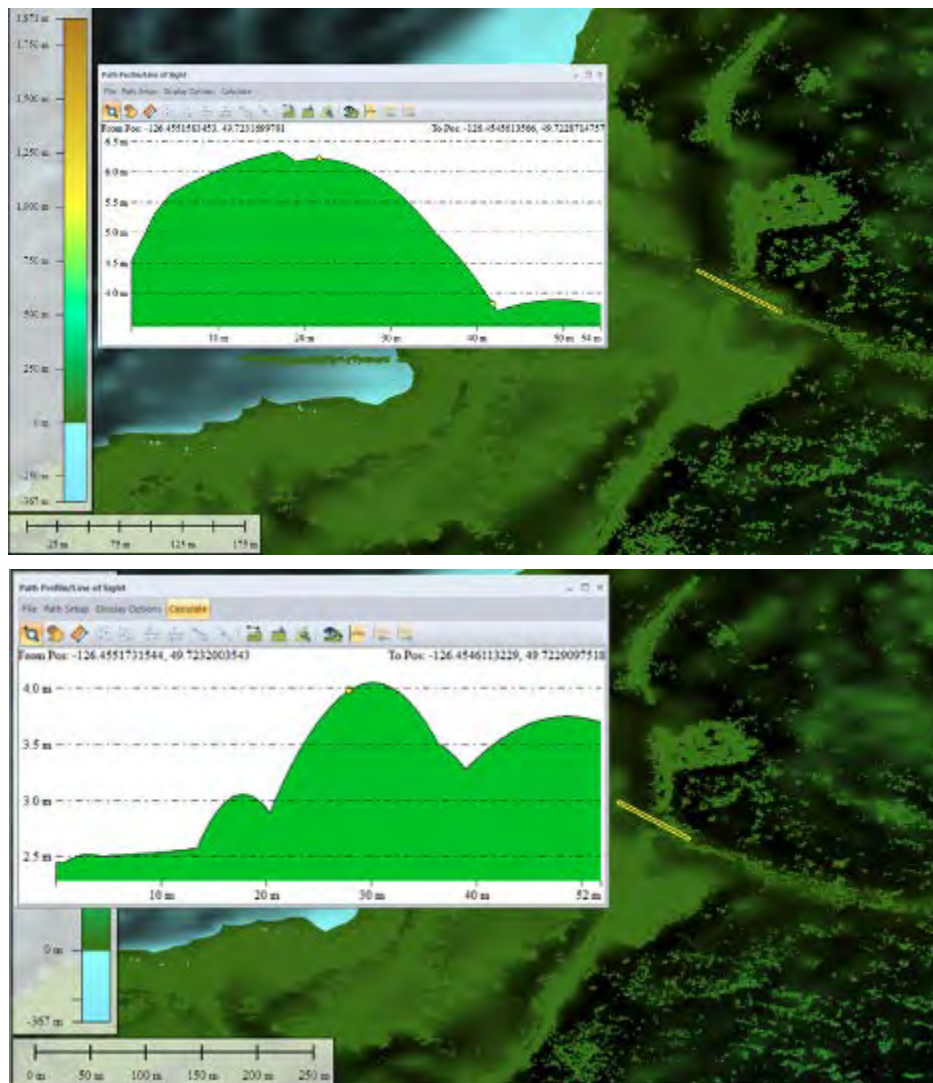


Figure 4. Comparison of the Nootka 10m DEM before and after simulated points were added along Cougar Creek. The image above shows the DEM, with a cross-section along the creek at the bridge, prior to the addition of the simulated points while the image below is the DEM and cross-section after the modifications.

Santa Boca Inlet

A narrow passageway connecting a small body of water at Santa Boca Inlet was not able to be resolved in the 10m Nootka DEM due to the lack of high resolution bathymetry data available. Simulated points were added in the passageway and along the coastline, including some topographic elevations, in order to improve the model in this area.

Bathymetric simulated points were created by using ArcGIS Pro to draw a polygon containing the narrow passage and then utilizing the 'Create Random Points' tool to generate dense points within the polygon. A value of -1.0 metres was chosen for the bathymetric simulated points and was based on the depth of the few bathymetry data points available in the narrow channel. The point feature class was exported as a .txt, which was then converted to XYZ.

Elevation values for the topographic simulated points were selected based on the nearest surrounding LiDAR and points were created manually using Global Mapper. The addition of topographic elevations was necessary in this area due to sparse LiDAR coverage on the southern slope bordering the passage, which was contributing to the challenges in modelling this narrow inlet. Refer to Figure 5 to see the difference before and after the simulated points were added at Santa Boca Inlet.

1. Evaluated where there were gaps in the bathymetric and topographic data
2. Used Global Mapper and ArcGIS Pro to create new XYZ point files (bathymetric and topographic)
3. Added points and assigned elevation values
4. Exported as, or converted to, XYZ files
5. Generated .inf files and created datalists for the simulated Santa Boca Inlet points

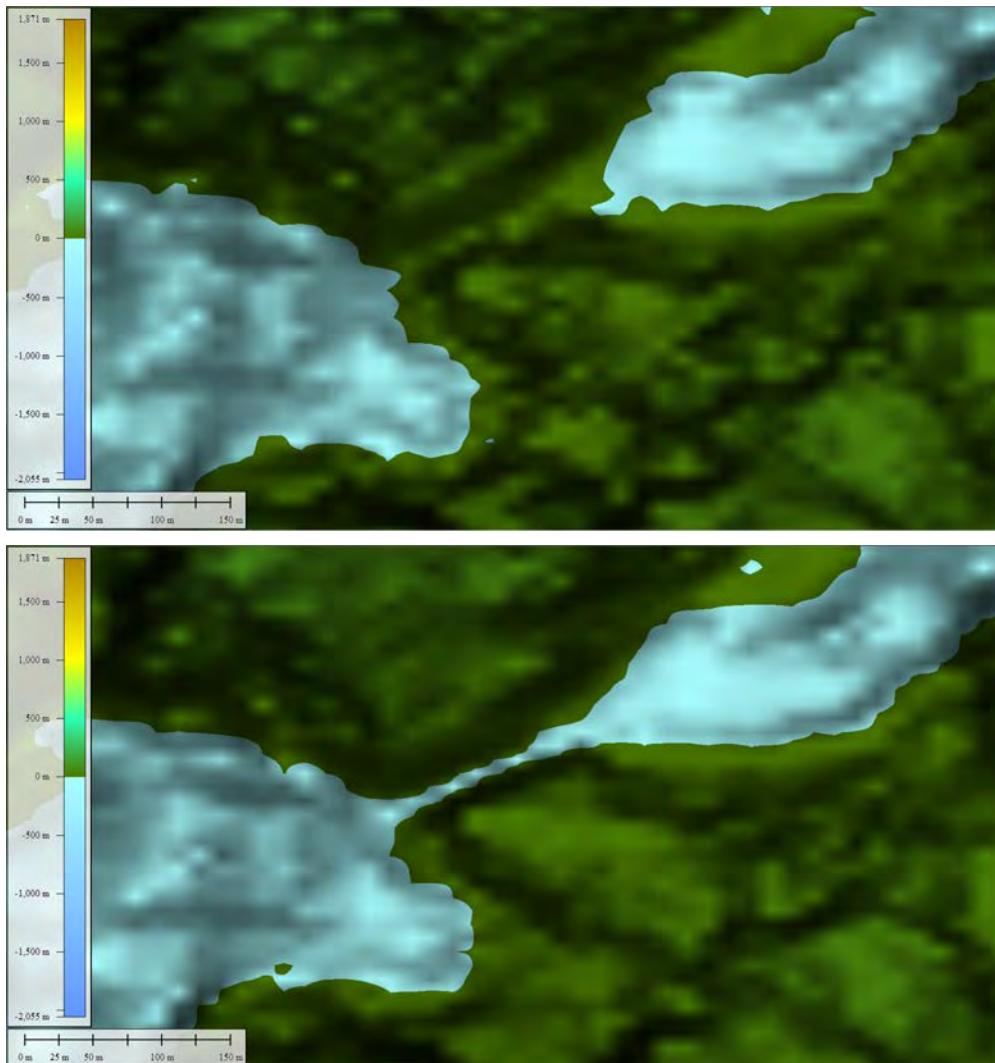


Figure 5. Comparison of the Nootka 10m DEM before and after simulated points were added at Santa Boca Inlet. The image above shows the DEM prior to the addition of the simulated points while the image below is the DEM after the modifications.

Deserted & Yoquot Lakes

Bathymetric data for lakes was not available in the study area which led to lakes within the Nootka DEM extent that contained elevation spikes and bumpy surface texture. The non-flat nature of two of these lake surfaces was identified as having potential impact on the tsunami modelling, therefore, a hydro-flattening process using simulated points was undertaken. The hydro-flattening process involved accessing a provincial freshwater lakes atlas shapefile⁵, and extracting only the two lakes of interest. ArcGIS Pro tool 'Create Random Points' was then used

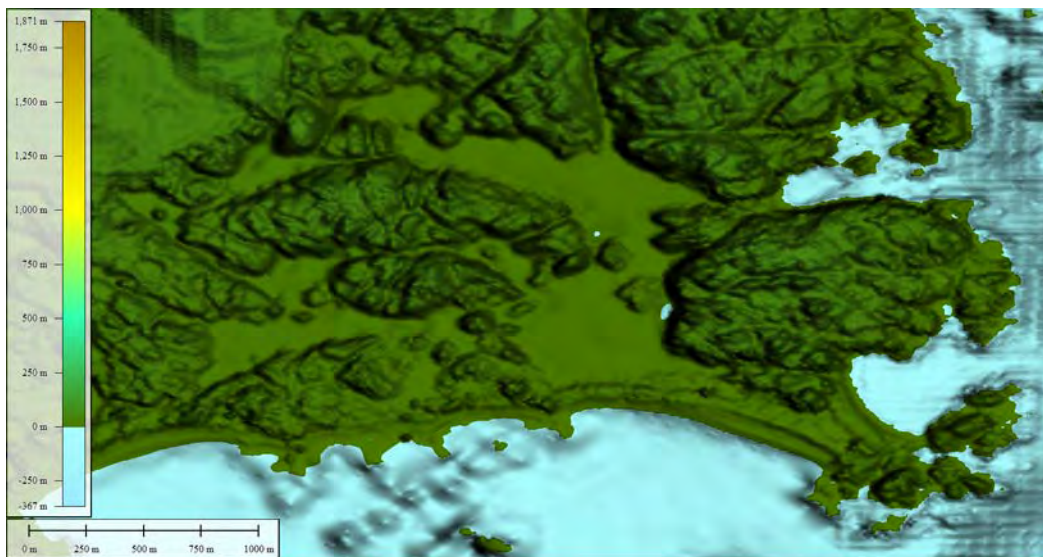
⁵

<https://catalogue.data.gov.bc.ca/dataset/freshwater-atlas-lakes/resource/be0fa7e3-75d1-4514-8148-30bd110c6179>

to fill the lake polygons with dense points. A point density of 20,000 points was used as this provided an average of 5m separation between the points.

The selection of elevation values to apply to the points was accomplished by creating a buffer of 1m around the lakes polygons, and then selecting the McElhanney LiDAR points that were within that buffer zone. The elevation values of the LiDAR within the buffer were sorted, and the average of the 10 lowest elevation points of each lake were calculated. The 10 lowest points were also plotted over satellite imagery to ensure they were not outliers before the values were applied to the simulated points. See Figure 6 for a comparison of Yoquot Lake before and after the application of the simulated points.

1. Extracted lake polygons from provincial atlas
2. Used “Create Random Points” tool in ArcGIS Pro to fill the polygons with dense points
3. Added XY coordinates to the points and applied elevation values
4. Exported as .txt and then converted to XYZ
5. Generated .inf files and a datalist for the simulated lake points



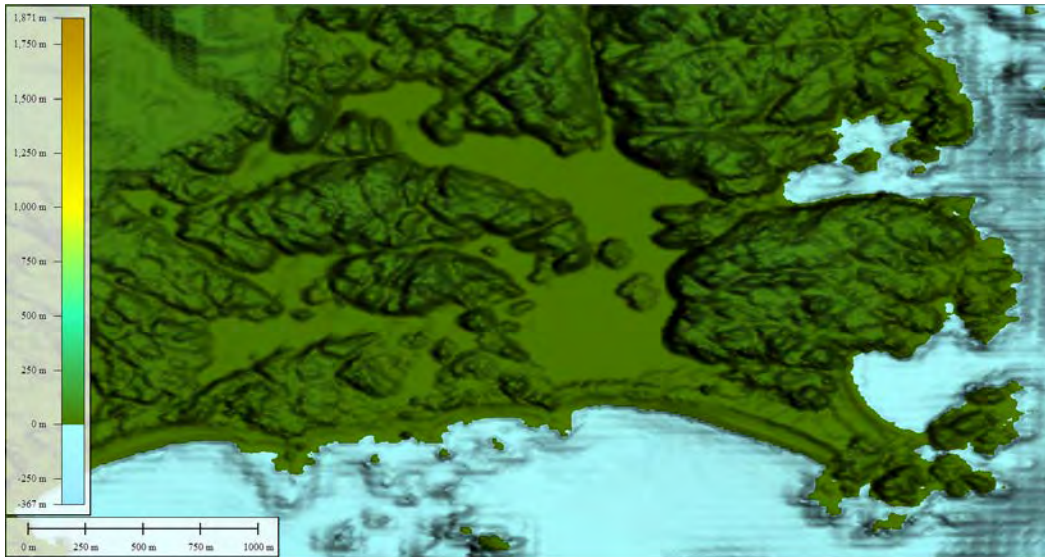


Figure 6. An example comparison for before (above) and after (below) of the hydro-flattening performed at Yoquot Lake.

Ahwhichaolto Inlet

Located near Winter Harbour, Ahwhichaolto Inlet had no high resolution bathymetry data, despite it being connected to the ocean and an area that experiences tidal flooding. While this area is not of high importance in this project, it was decided to hydro-flatten the inlet to improve the visual aesthetic of the DEM, and mitigate any issues the original elevation discontinuities and spikes in this area could have on further use of the Quatsino DEM. Similar to the method for the lake simulated points above, hydro-flattening involved creating simulated points in the inlet. Bathymetric values of -1.0m were applied to these simulated points based on the nearest CHS dataset values and examination of the underlying charts.

1. Created a polygon encompassing Ahwhichaolto Inlet
2. Used “Create Random Points” tool in ArcGIS Pro to fill the polygon with very dense points (over 1,000,000 at 1m spacing)
3. Added XY coordinates to the points and applied an elevation value
4. Exported as .txt and then converted to XYZ
5. Generated .inf files and a datalist for the simulated Ahwhichaolto Inlet points

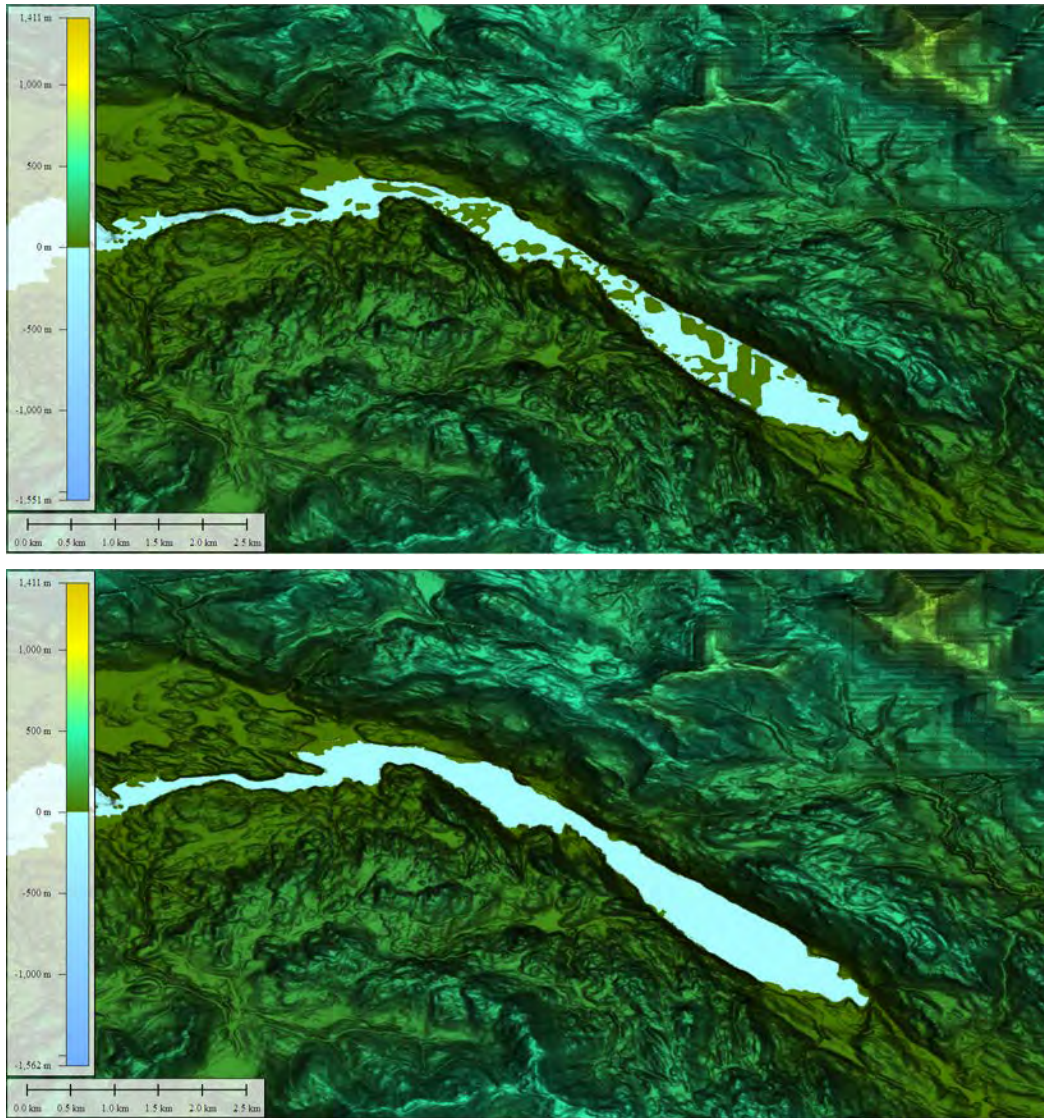


Figure 7. An example comparison for before (above) and after (below) of the hydro-flattening performed at Ahwhichaolto Inlet.

High Water Line for British Columbia (CHS)

A polyline vector feature class used by CHS that defines the coastline at the Higher High Water Large Tide mark in BC's tidal waters. This dataset is derived from numerous sources including satellite imagery and other CHS data products. No processing was necessary for this dataset.

4.2 DEM Surface Processing

Before the DEMs were created, all the data needed to be prepped into XYZ files with accompanying .inf files for each as well as a datalist for each dataset. The .inf file provides an

overview of the XYZ files and is a necessary input for the MB Grid program. The .inf contains the amount of points, the dataset extent, and the maximum/minimum values. The datalist is a text file that contains the file names for each of the XYZ files. There is a unique datalist for each input dataset folder that contains XYZ and .inf files.

Once all of the unique datalists were generated, one master datalist was created so that each of the unique datalists can be referenced and given a proper weight. In the master datalist, individual datasets can be commented out, which means that when the DEM grid is generated, these datasets won't be used. This is a useful function to have in order to test DEM creation and was used to evaluate individual dataset contributions to the final integrated DEM grids.

There were 12 datasets, generated from the input data sources in Table 2, in the master datalist for this project. With MB-Grid, the weights of each dataset in the master datalist determine which dataset gets the highest priority when determining the value of each point in the DEM surface. Therefore, the higher resolution and the most reliable datasets were assigned the highest weights for this project. Table 3 below lists the datasets in the master datalist for each high resolution DEM, and the weights assigned to each for this project. Lower resolution DEMs used the same weights as the Nootka DEM.

Table 3. Dataset weights in Nootka and Quatsino Datalists		
Dataset Name	Weight (Nootka)	Weight (Quatsino)
Commissioned LiDAR (McElhanney)	20	N/A
LiDAR (GeoBC)	15	50
Commissioned Bathymetry, 2020 & 2022 (TRSI)	20	30
Gold River Bathymetry 2022 (TRSI)	50	N/A
Multibeam Bathymetry (CHS)	15	20
Singlebeam Bathymetry (CHS) (Excluded from high resolution DEMs)	15	15
Non-Navigational (NONNA-10) Bathymetric Data (CHS)	3	10
Canada West Coast Topo-Bathymetric DEM (DFO/NRCan)	1	1
Bathymetric DEM of British Columbia, Canada (NOAA) (Excluded from high resolution DEMs)	0.1	0.1

CDEM (NRCan)	1	1
CDEM-Clipped to LiDAR (NRCan)	1	1
Simulated Points - Bathymetric (ONC)	150	150
Simulated Points - Topographic (ONC)	100	N/A

An MB-Grid function was used to integrate all of the above processed and weighted datasets into the final DEMs. For each DEM grid, the extents and resolution were specified when running the tool.

The MB-Grid program is used to grid bathymetry in the hydrography industry and it is part of the MB System program, an open source seafloor mapping system developed by the Monterey Bay Aquarium Research Institute (MBARI). MB Grid uses a thin plate spline interpolation to create a grid using a gaussian weighted average. Users can specify the grid extent and resolution, as well as other parameters. The program outputs a netCDF GRD file, which can then be converted to a more user-friendly GeoTIFF format using the GDAL tools. To create the grid, the same interpolation methods were used for both topographic and bathymetric data.

Due to the sparse nature of the bathymetry data throughout most of the study area, some of the bathymetric areas of the DEMs contain visible artifacts as a result of stitching together the various data sources, particularly those of differing resolutions. There is a smoothing script available from NOAA that can be used to mitigate the abrupt features at the edges of the differing input sources. This script implements a user-specified smoothing factor to smooth only the bathymetric values of the DEM surface (values below 0m). However, it was decided not to apply the smoothing to any of the grids in this project.

5.0 Quality Checks, DEM Usage & Limitations

5.1 Quality Checks

In order to evaluate and check results of the DEM models, a number of visual inspections were performed. The software programs ArcGIS Pro and Global Mapper were used for most of these checks. For the first inspections, Global Mapper was used to visualize the DEMs with hillshades and colour shading to determine the elevation and depth changes, and compare these with satellite imagery of the area to determine if the model was a reasonable representation of reality. These comparisons aided in finding some of the initial issues that led to the abovementioned reprocessing for some of the input datasets.

Next, the DEM models were compared with the CHS navigational charts. CHS charts were used to examine the elevation of the seafloor in the DEMs to ensure that the models produced reliable and realistic results, especially in the narrow inlets and along the coastline. Elevation contours at the -2, -5 and -10 metre intervals were used to confirm elevation in the DEM and ensure that the model was a reasonable representation of reality. Charts also confirmed deeper seafloor depths where data can be sparse.

Following the depth comparisons between the charts and the DEM models, satellite imagery was used to compare the coastlines between the models and reality (Figure 8). The remotely sensed imagery was also used to determine whether small islands and coastal rocks modelled in the DEM were an accurate representation of reality by checking if these features were also visible in the imagery. The imagery inspections ensured that islands in the DEMs are real, rather than artifacts in the DEMs. It should be noted that the CHS charts were also used to confirm that rocks and islands in the DEM were realistic. Additionally, this imagery allowed for confirmation of road placement in the DEM to ensure that these important infrastructure features were accounted for in the models. Furthermore, the imagery was used to evaluate the representation of key rivers in the models. This was an important step because the interaction of a tsunami with a river impacts the inundation modelling results, which is of particular concern near communities and infrastructure.

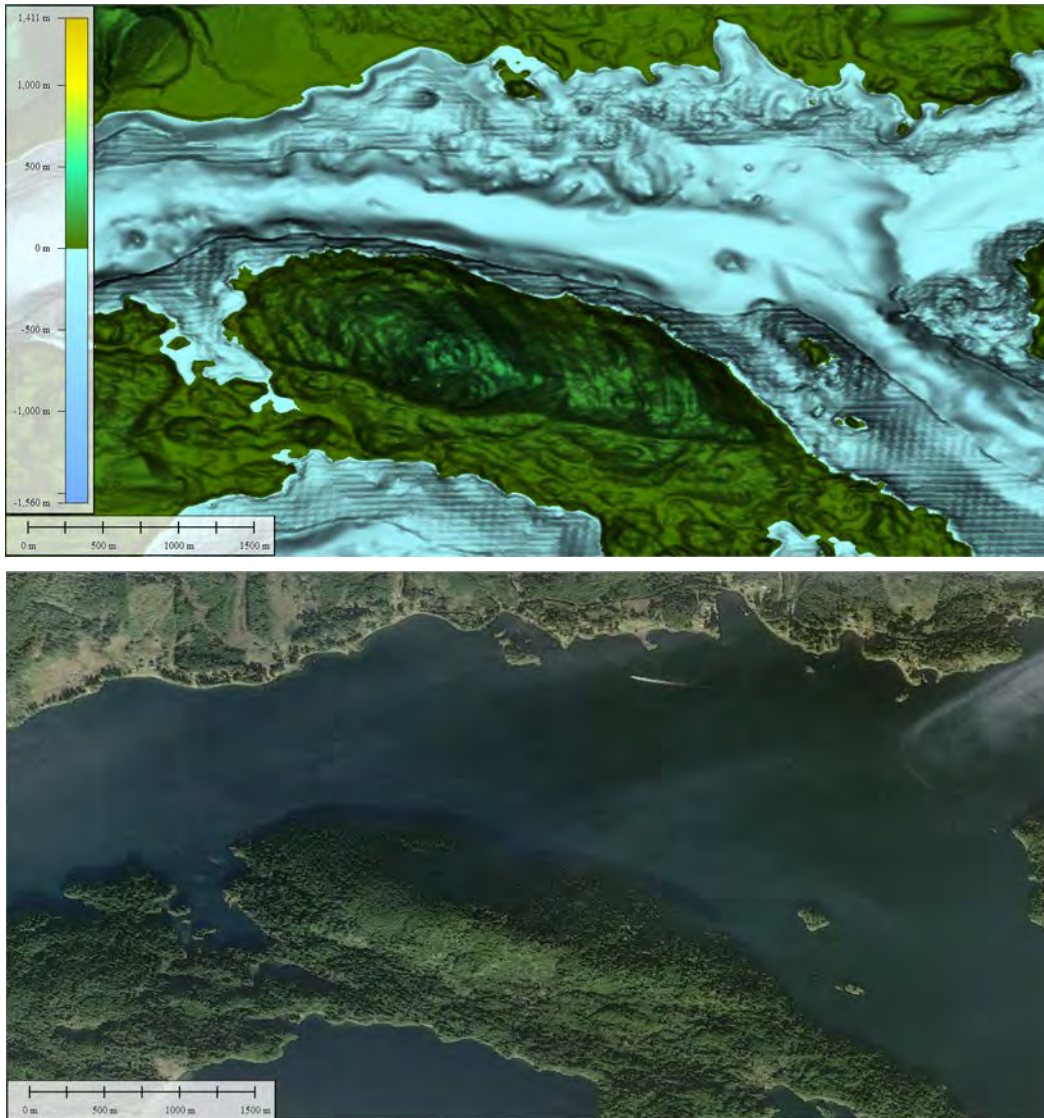


Figure 8. Image comparing a segment of the Quatsino 10m DEM with satellite imagery in Global Mapper.

In addition to the above mentioned methods, the DEM elevations were also compared to the high resolution raw data inputs to ensure that the best available data was accurately integrated and represented in the final products.

5.2 Dataset limitations

Due to the sparse coverage of high resolution data in some parts of the study area, lower resolution datasets were used to fill the gaps where there was no high resolution data available. For example, NOAA's Bathymetric DEM of British Columbia was used to fill the gaps in the open ocean for lower resolution DEMs. However, due to the low resolution of this dataset, it was

excluded from the inland coastal areas due to the narrow inlets and fjords being poorly represented at this resolution.

Another dataset used to fill bathymetric gaps was the Canada West Coast DEM. This proved to be an essential piece in some areas, such as parts of Muchalat Inlet and King Passage (Figure 9) where CHS data was unavailable. However, this dataset created barrier issues at the boundaries where the West Coast DEM met with the higher resolution datasets (Figure 10). Additionally, it is unknown exactly what data was used to create this dataset, or how it was integrated and quality checked. There were a few instances where parts of the West Coast DEM had to be edited before it was integrated into the high resolution DEMs for this project. These edits were made to remove suspicious rocks and shallow depths that did not match with what was seen in co-located higher resolution data, or was not noted in the charts. Despite some of the drawbacks to using this dataset, it filled necessary inshore gaps where the CHS data was significantly sparse, or lacking entirely, and the NOAA data was excluded nearshore due to the abovementioned low resolution.

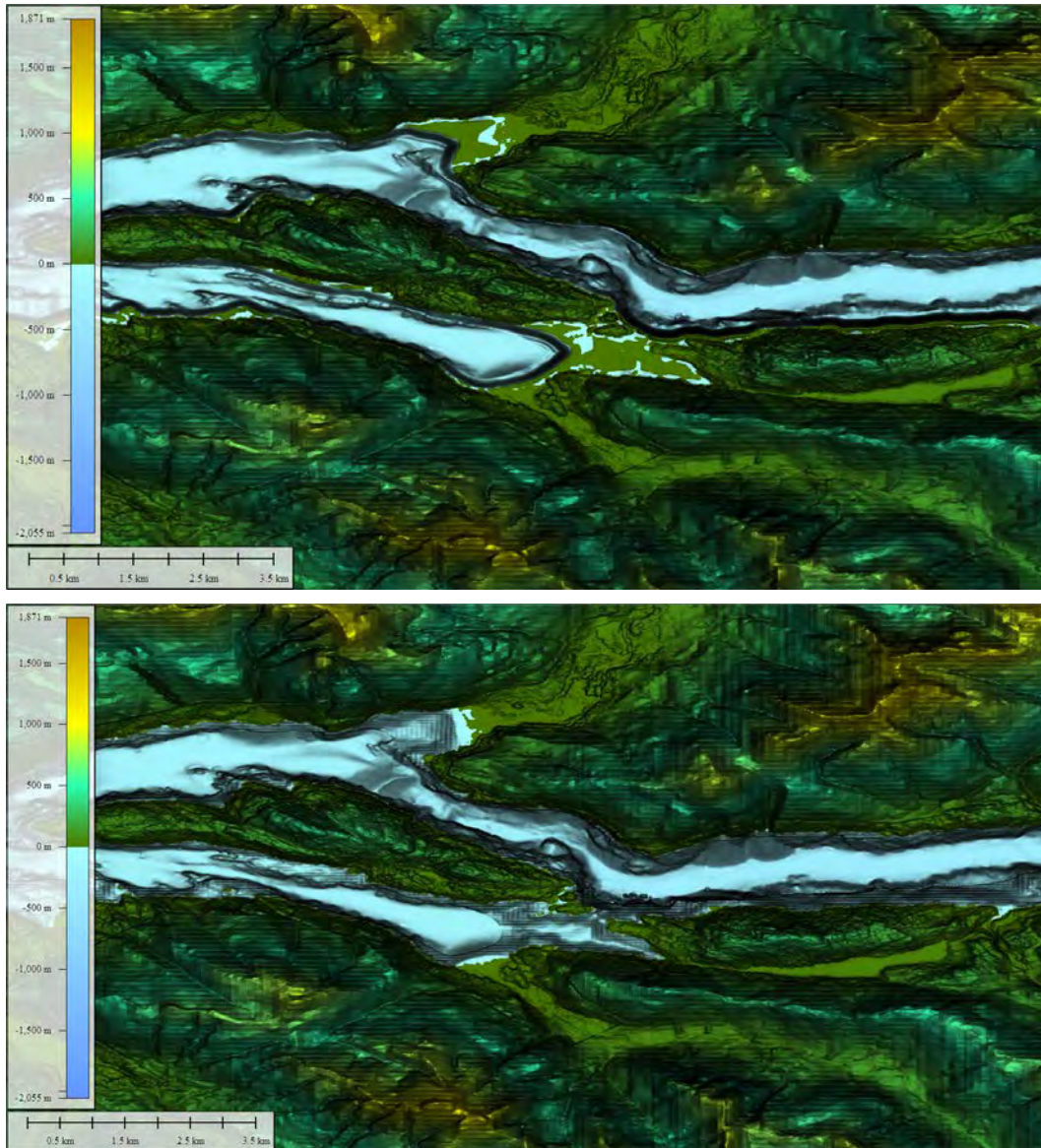


Figure 9. King Passage without the inclusion of Canada West Coast DEM (above) and the same area with it included (below).

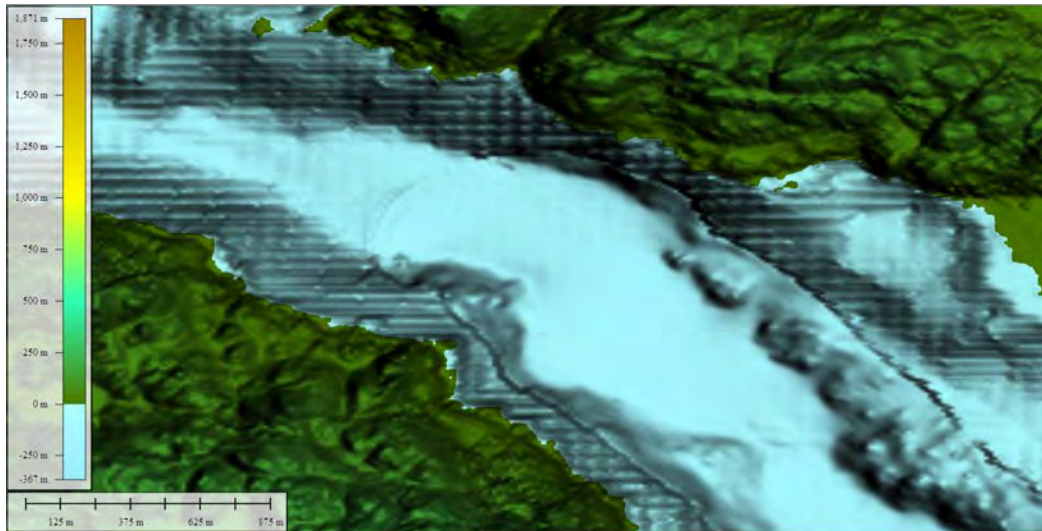


Figure 10. Example of a barrier effect where the Canada West Coast DEM converges with the higher resolution CHS multibeam.

Similarly, to fill the sparse coverage over the land topography, the lower resolution Canadian Digital Elevation Model (CDEM) was used. Figure 11 shows the accuracy of the CDEM, as specified by NRCan, to be between 0-20 metres throughout most of the study area. This product is reasonably reliable for most mapping uses, but there were instances where the roads, coastline, and other important finer details were not accurately represented in the models due to the lower resolution. Fortunately, the high resolution 1m LiDAR datasets covered most of the study area at the lower elevations, so the CDEM was only used to model higher elevations where the LiDAR was not captured. However, there was a low elevation area upstream of Canton Creek, not far from the outflow into Tlupana Inlet, that showed irregularities in the CDEM and was not covered by high resolution LiDAR. The suspected erroneous CDEM data in the area was removed from the project, but it should be noted that this area has additional uncertainties.

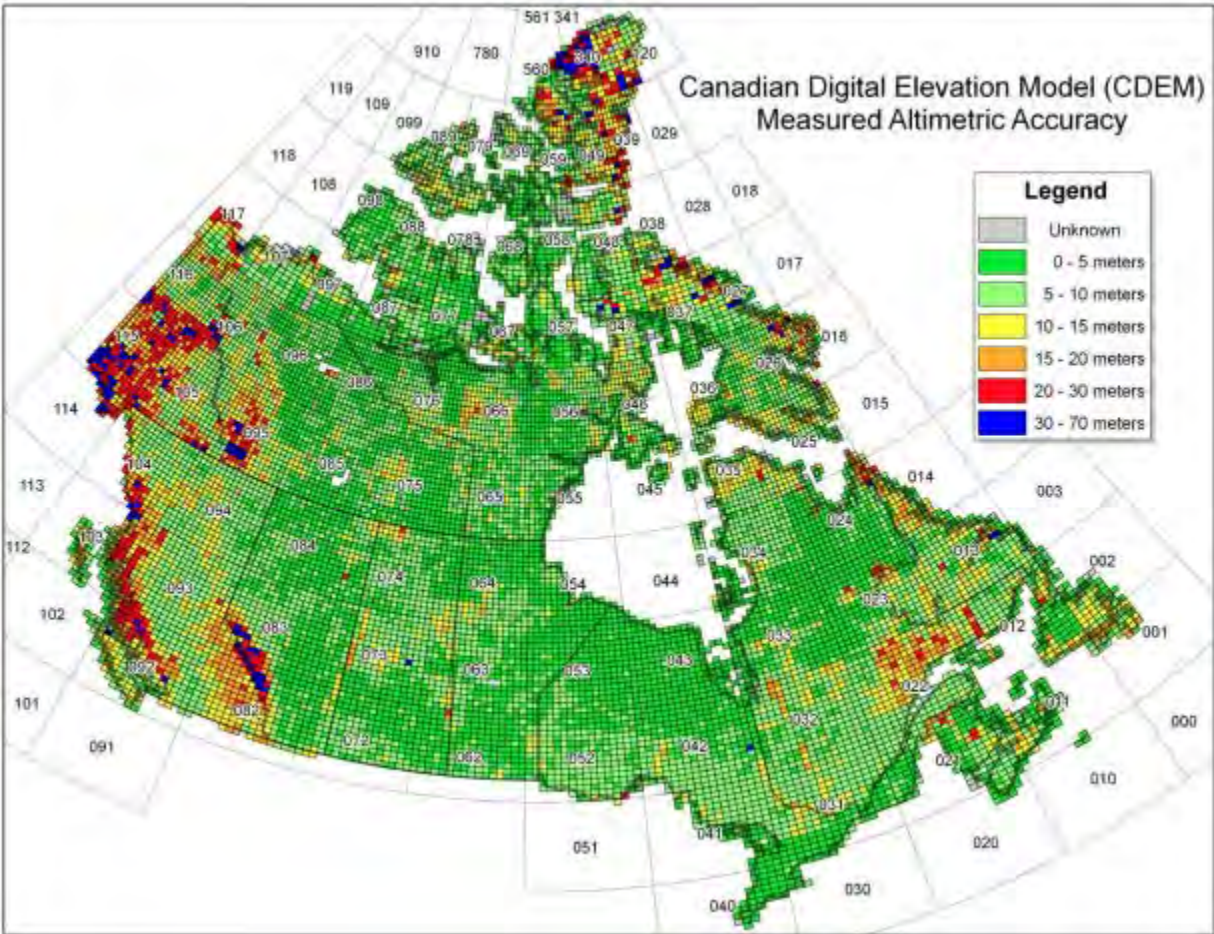


Figure 11. Natural Resources Canada map showing CDEM altimetric accuracy from the Canadian Digital Elevation Model Product Specifications report.

Additionally, it was found that some finer features, such as rivers and streams, can be poorly represented in the output DEMs due to some of the lower resolution datasets and a lack of freshwater bathymetry. In areas without adequate coverage of high resolution data, these smaller features may not be accurately represented. In this project, Gold River received enhanced scrutiny due to the proximity of major infrastructure. Improvements to this area included the capture of bathymetric data at the river mouth, and thorough quality checks of the resultant DEM. However, the additional bathymetry only extends a short distance upriver due to the challenges capturing river bathymetry with traditional methods. In order to aid with modelling this area, simulated points were added to an upriver portion of Gold River. It must be noted that these simulated points are only estimations, and this can introduce additional uncertainties to this area. Therefore, without additional field data to confirm estimated elevation values, caution should be exercised when using these DEMs for additional modelling and mapping purposes at Gold River, as well as other areas where simulated points were used.

As mentioned previously, some of the GeoBC LiDAR were found to have incorrectly classified some of the LAS files, so manual fixes were implemented in order to remove the misclassified data from the final DEM models. There were 341 LAS files included in this project where land values were incorrectly classified over known deeper bathymetric areas and this led to some unrealistic flat plateaus in the open ocean and inland fjords in the initial DEM models. These incorrect points in the LAS files were identified and then manually removed. The DEM was recreated with the fixed LAS files so that the final models no longer included these false shallow ocean plateaus (Figure 12).

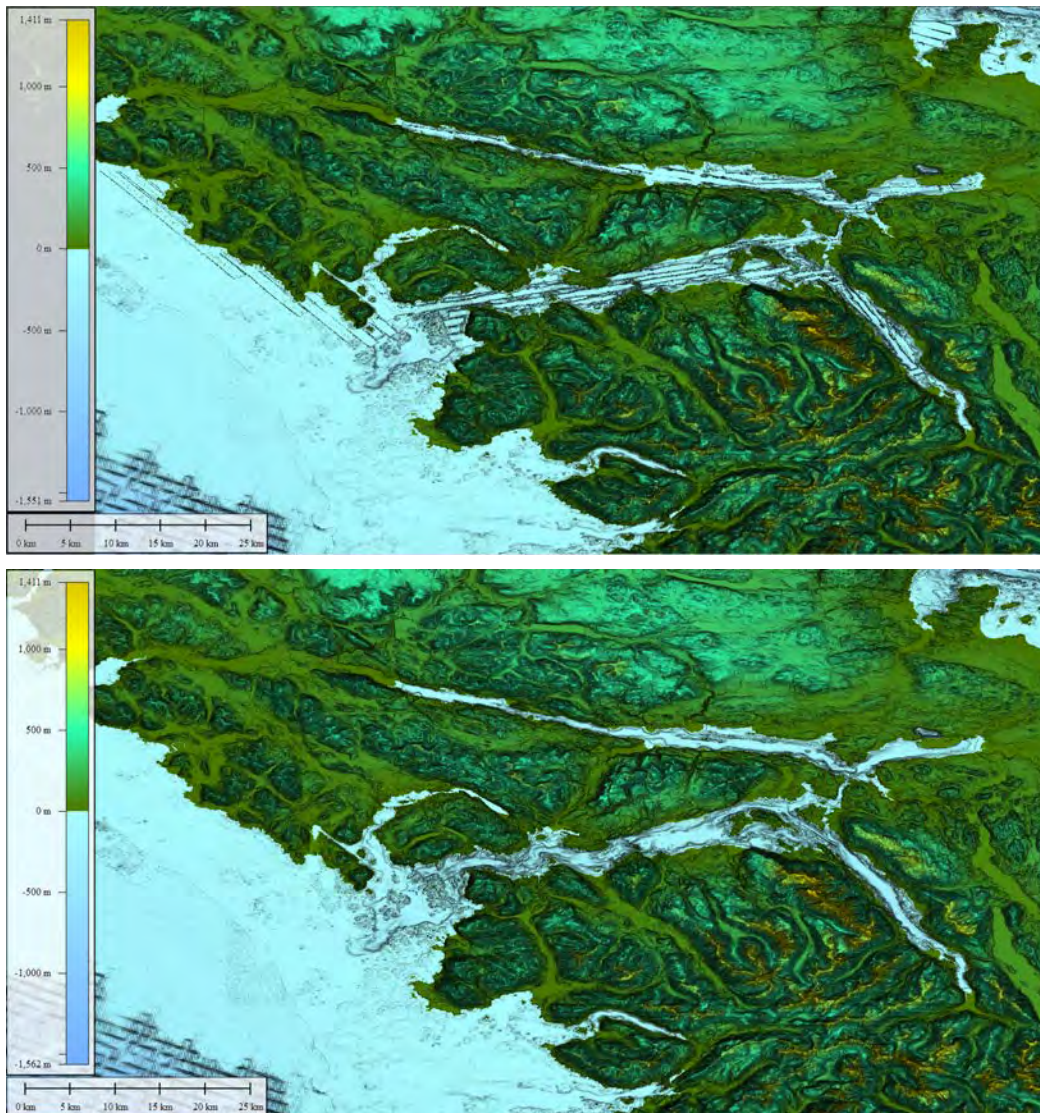


Figure 12. Comparison of the Quatsino DEM before and after removal of misclassified GeoBC LiDAR points. The top image is before alteration and shows significant shallowing of ocean areas throughout, and the bottom image is after alteration.

Some less extensive modifications to McElhanney LiDAR and CHS data were also made based on examination of high resolution data, as well as comparisons with navigational charts and satellite imagery. In addition, it was awkward that the CHS singlebeam points were integrated into the multibeam package that was received. Some of the CHS singlebeam points were deleted from this dataset as they did not match with the co-located modern multibeam. Though these modifications and deletion of erroneous points from the included datasets improved the output DEM, without further ground control points or field data, the accuracy of these modifications can't be confirmed.

5.3 DEM Usage and Limitations

DEMs can be used for a variety of purposes. Slope maps, hillshades, and viewsheds created from DEMs can be useful for fire forecasting and emergency response planning, just as a small example of how DEMs can be used. However, the DEMs developed as part of this project were not reviewed for uses other than tsunami modelling. Caution should be taken when using these DEMs as they are models and are only a representation of reality, generated using multiple datasets that originated from numerous sources and were produced with significant interpolation due to the nature of the sparse high resolution data in some of these remote areas.

Both the topography and bathymetry in these DEMs is only as good as the input data, and some of the areas where the input data was knit together by the DEM grid algorithm, and areas of sparse data, show minor artifacts that may impact other uses of the DEMs. These grids can be used to get a good estimation of overall elevation, but CHS charts should be used to confirm elevation for navigation. In addition, although the DEMs are modelled at 10m resolution, that does not mean that all the input datasets used were 10 metre resolution or better, and interpolation was necessary to generate a continuous surface with a grid spacing of 10m.

Intertidal zones, coastal rivers, and estuaries are also inherently challenging to model due to the difficult nature of data collection in the transition zone between bathymetric and topographic data and the complexity of modelling these evolving coastal zones. While it is possible to collect topographic data using LiDAR at low tide, and bathymetric data by boat at high tide, or commission bathymetric LiDAR that can penetrate shallow depths, the study area of this project is vast and this method of data collection in the intertidal zone was cost prohibitive. Therefore, these intertidal areas of the DEM models may only be an approximation of reality.

Another limitation of the grids is the coordinate system conversions between datasets. The McElhanney LiDAR, GeoBC LiDAR, and TRSI bathymetry, originally came in a UTM coordinate system and these coordinates had to be converted to WGS84 horizontal datum in decimal degrees for the modelling process. The conversion can result in shifts in the data, but is thought to be negligible for this use.

Also, while most of the data was converted to the CGVD2013 vertical datum, some datasets were left in their original datum due to the lower resolution of these datasets. It was decided that converting the datums of these lower resolution datasets would have little to no influence on improving the DEMs and the resulting tsunami models. For example, NOAA's Bathymetric DEM was originally in mean sea level and due to the low resolution of this dataset it was not converted to CGVD2013 and instead left in its original datum.

Due to the above mentioned factors, these models should not be used for navigation purposes, or other uses requiring high accuracy, especially those requiring accuracy of greater than 10m. Proceed with caution and take into account these limitations when sharing and using these models.

Finally, in past projects the DEMs underwent a smoothing process on the bathymetric portions under 0m depth. The process smooths out small pockets and rigid features such as artifacts modelled into the DEMs due to interpolation and the stitching together of various data sources. However, it was decided not to apply this process during this project in order to maintain a surface that is truer to the input data.

6.0 References

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Natural Resources Canada. Height Reference System Modernization. 2020-10-21. [https://www.nrcan.gc.ca/sites/nrcan/files/files/pdf/Height_reference_system_modernization_\(EN\).pdf](https://www.nrcan.gc.ca/sites/nrcan/files/files/pdf/Height_reference_system_modernization_(EN).pdf)

Annex A: Maps of Data Extents

This section contains the maps of the extents for the high resolution datasets used for this project. The coverage of each dataset is shown with the extents of the final 10m DEM grids overlaid on top.

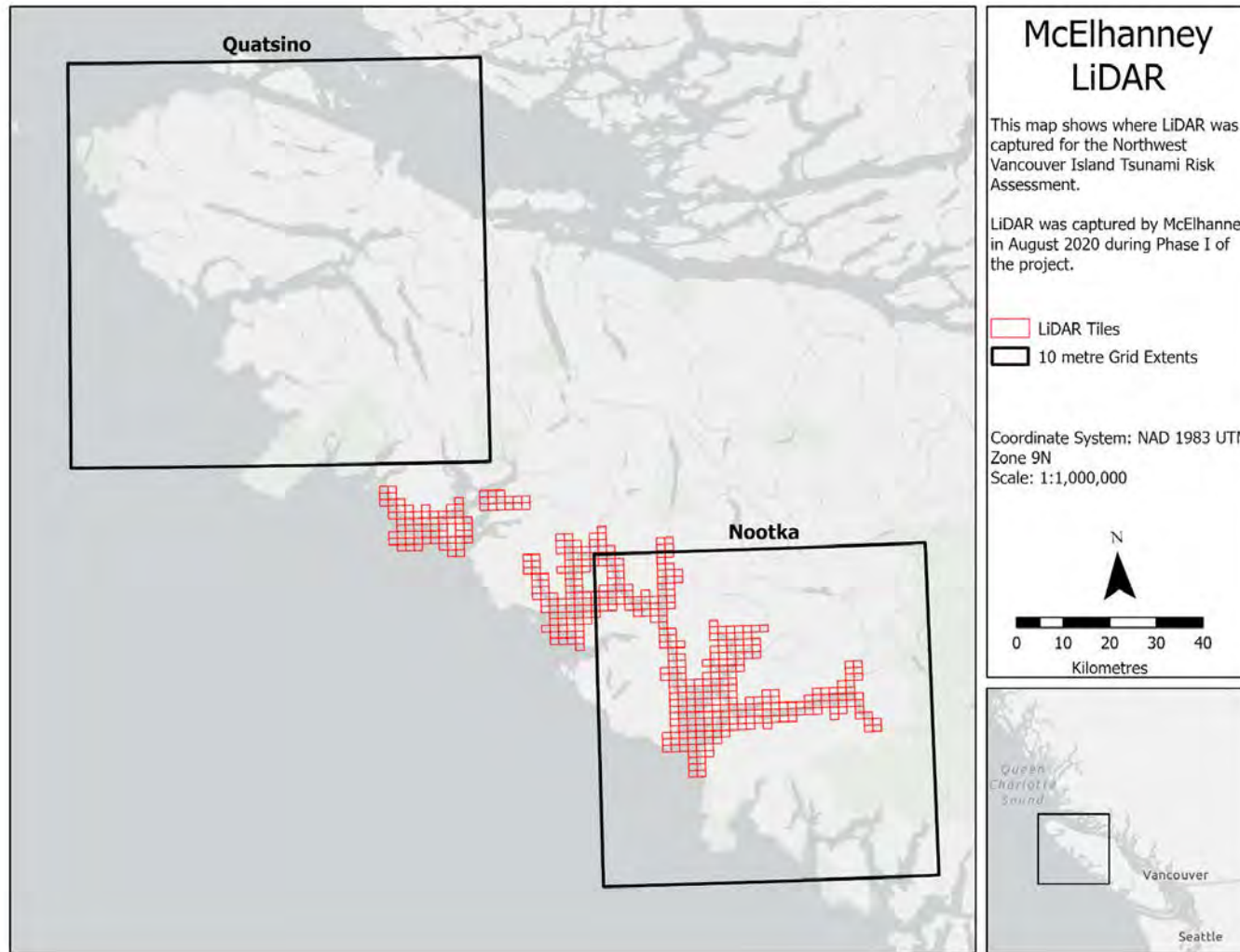


Figure 13. Map of commissioned McElhanney LiDAR extent.

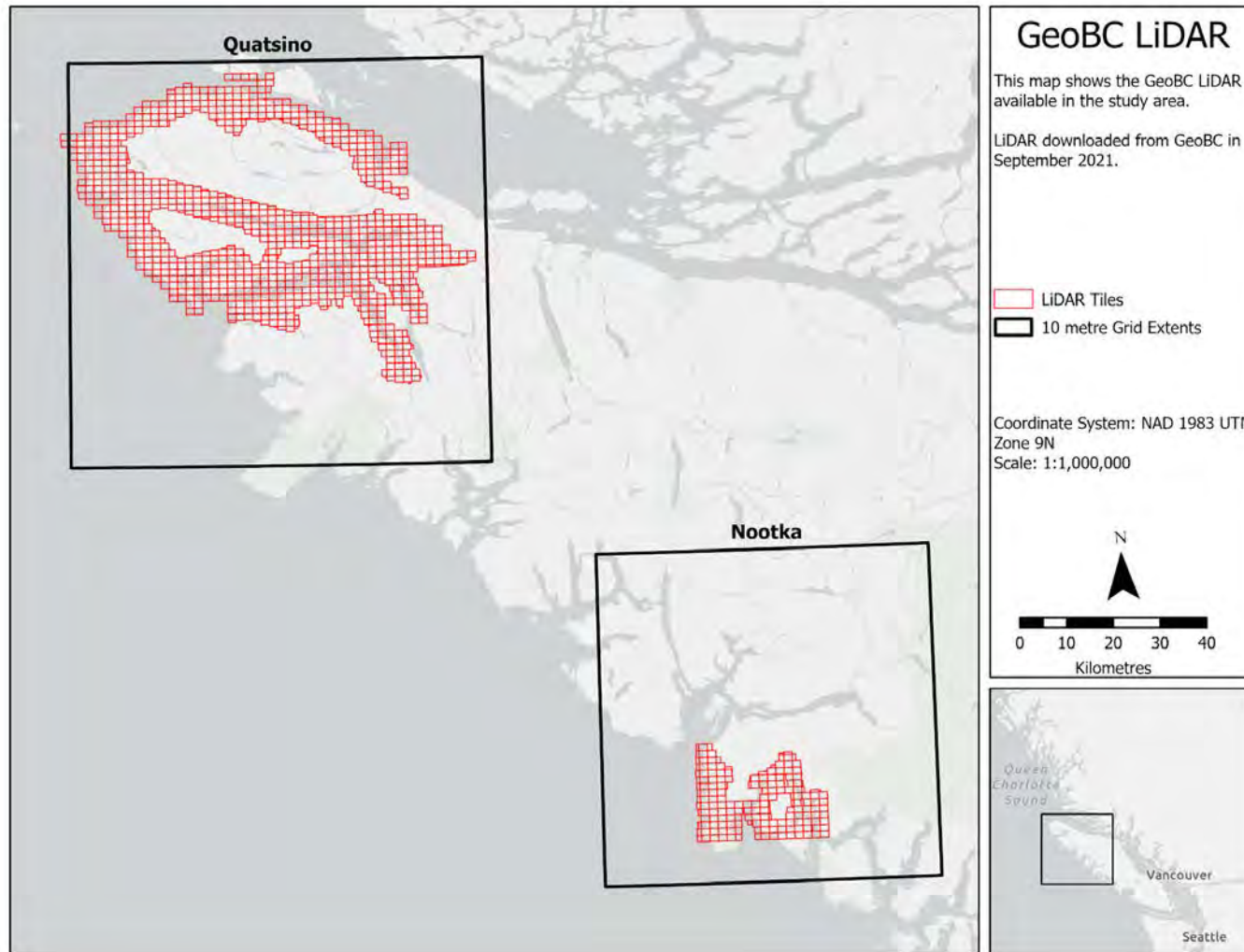


Figure 14. Map of GeoBC LiDAR extent.

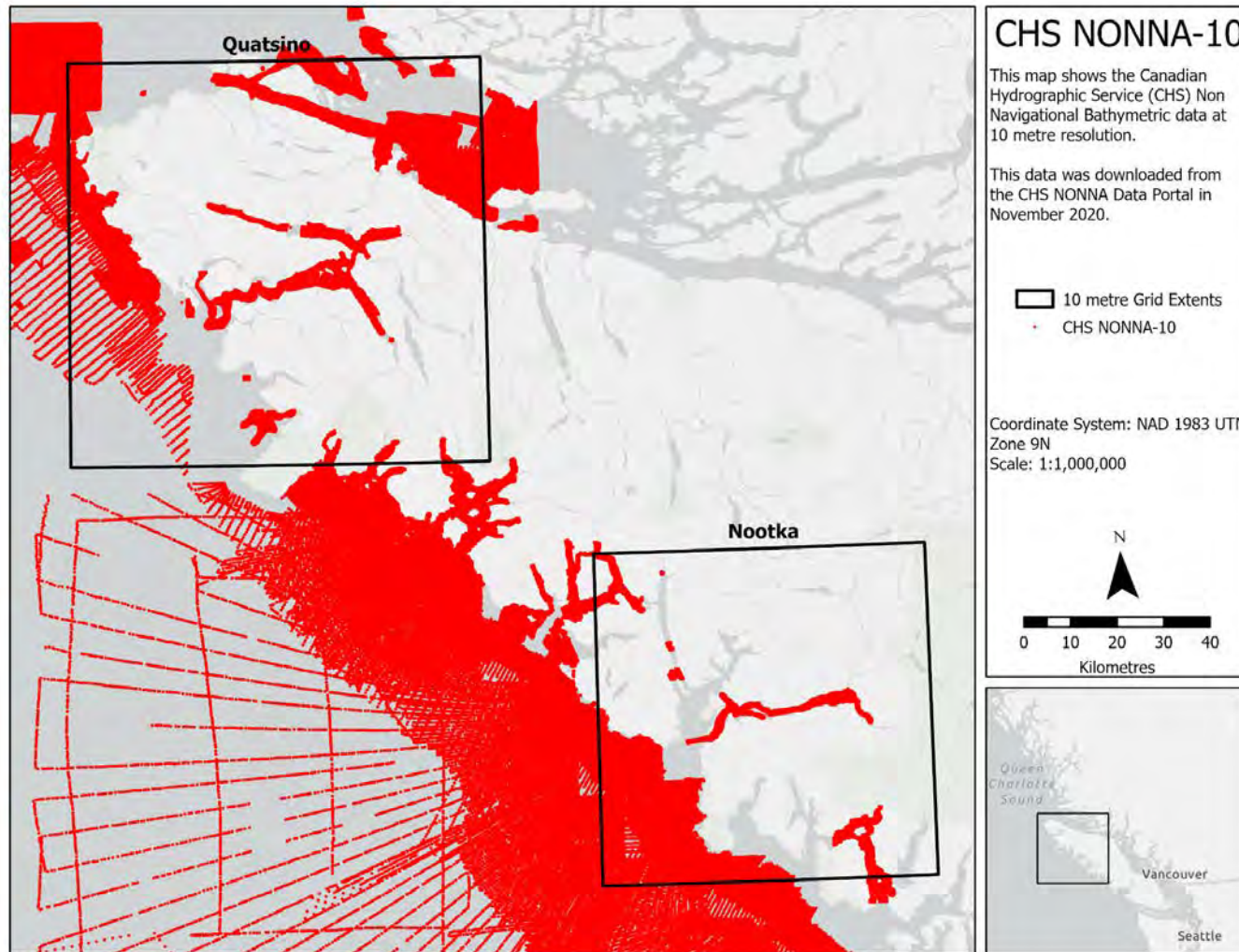


Figure 15. Map of CHS NONNA-10 extent.

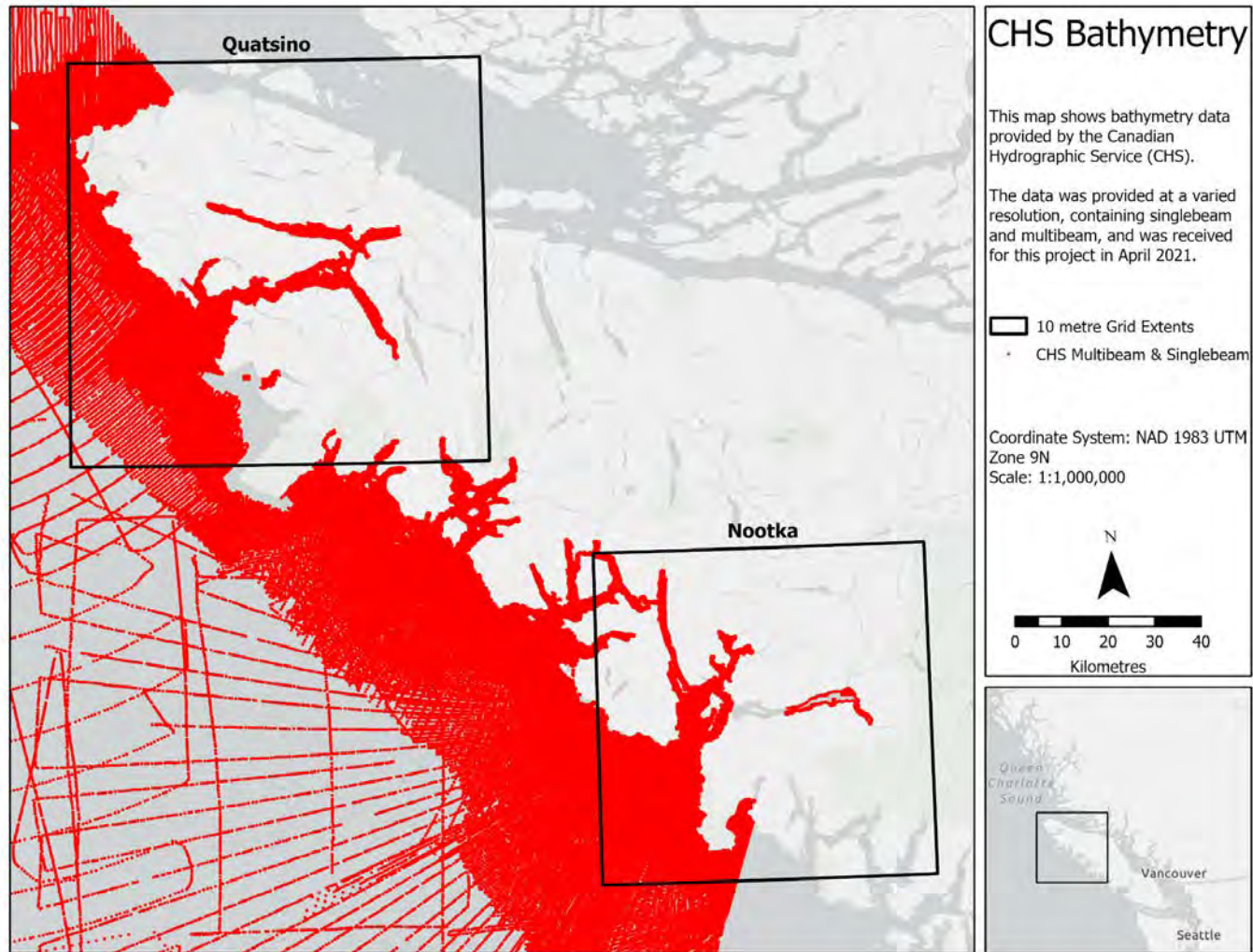


Figure 16. Map of CHS bathymetry extent.

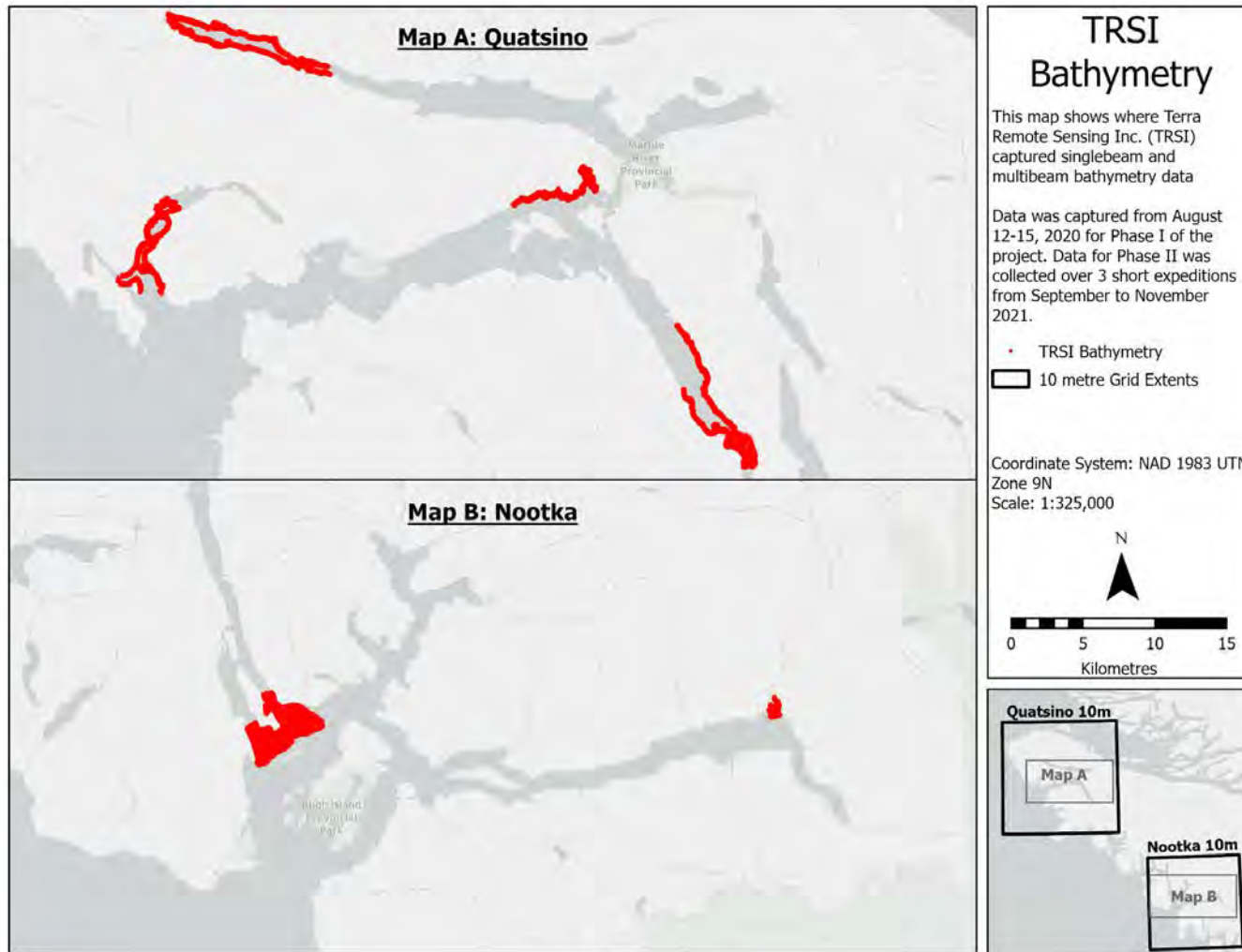


Figure 17. Map of commissioned TRSI bathymetry extent.

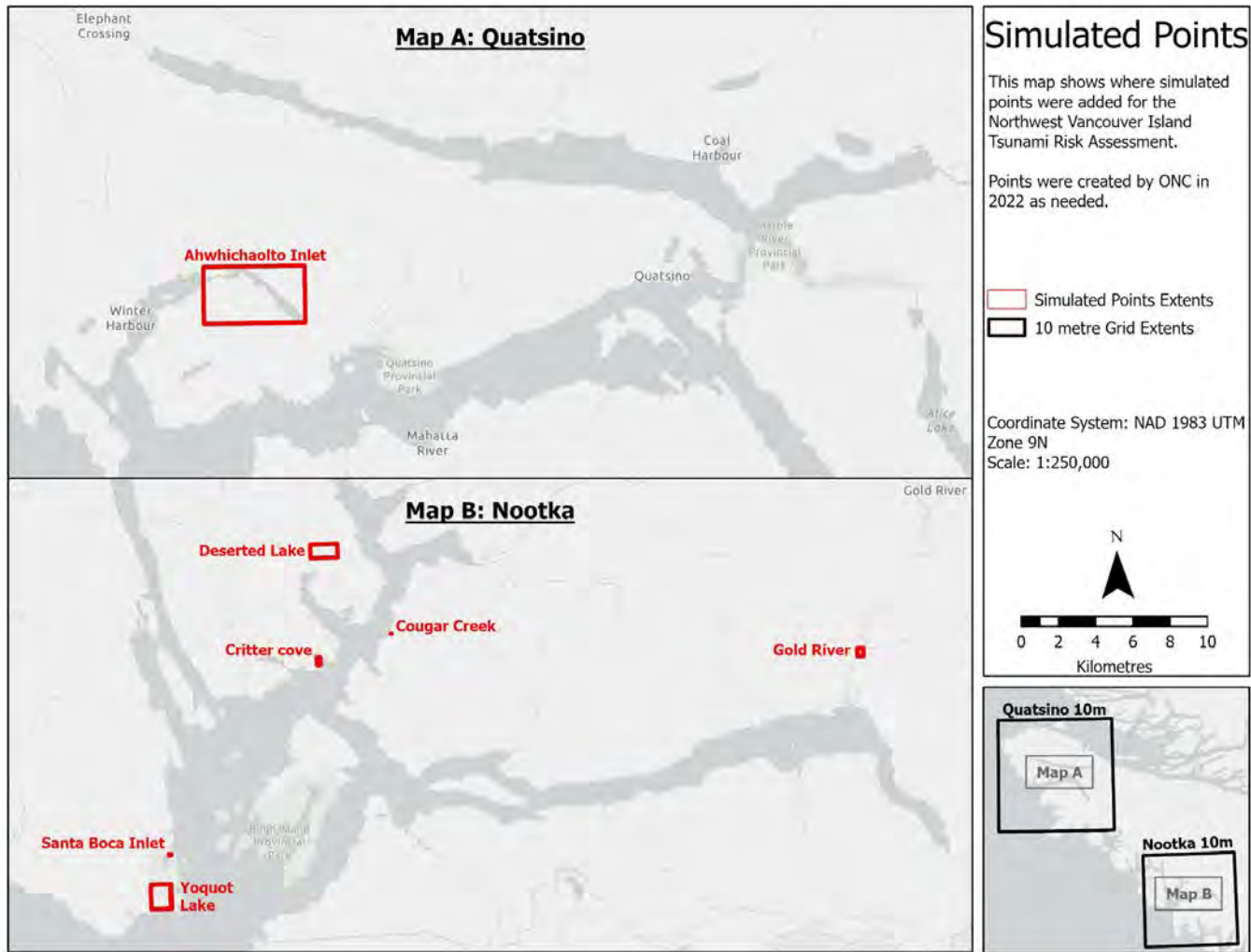


Figure 18. Map of simulated points extents for Quatsino and Nootka 10m grids.

APPENDIX B

TSUNAMI MODELLING



OCEAN
NETWORKS
CANADA

Co-seismic Tsunami Hazard Assessment for Northwest Vancouver Island - Phase II

Sep 2023

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Report

This report was prepared by Ocean Networks Canada (ONC), as part of the Northwest Vancouver Island Tsunami Risk Assessment project, in collaboration with Northwest Hydraulic Consultants Ltd. (NHC), and in partnership with Strathcona Regional District (SRD). The objective of this report is to present the tsunami modelling methodology and results performed for the study area. For more details regarding the tsunami mapping and risk assessment, refer to the project's final report prepared by NHC.

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1. INTRODUCTION

Most large tsunamis are triggered by subduction earthquakes beneath the Pacific Ocean, mainly off southern Alaska and along the Cascadia Subduction Zone. Geological evidence of recent large tsunamis has been found in tidal marshes and coastal lakes on western Vancouver Island (Benson et al., 1997, Clague et al., 1994, 2000). The most vulnerable areas to future tsunamis of this type are the outer coasts and inlets of Vancouver Island, where damage to coastal communities would be large according to the outcome of computer tsunami models based on hypothetical bottom motions (Dunbar et al., 1989, 1991). Several studies have investigated the tsunami hazard along the west coast of Canada from both distant sources (e.g., Alaska-Aleutian) (Rabinovich et al., 2019) and local sources (e.g., Cascadia Subduction Zones) (Hebenstreit et al., 1989, Murty et al. 1989). The focus of most of these studies has been on Victoria (Fine et al., 2018a, Associated Engineering, 2021), Boundary Bay (Fine et al., 2020, ONC, 2022), and southern parts of Vancouver Island, for instance, Port Alberni (Barua et al., 2007), while less work has been performed for the Northwest Vancouver Island.

The Strathcona Regional District (SRD) commissioned a tsunami risk study for the region in 2020 with funding from the Province of BC through the Union of BC Municipalities in collaboration with the Ka:'yu:'k't'h' / Che:k'tles7et'h' and the Nuchatlaht First Nation. The collaboration between Northwest Hydraulic Consultants Ltd. (NHC), Ocean networks Canada Society (ONC), and Northwest Seismic Consultants Ltd. (NSC) produced this comprehensive study. The purpose of this project was to better understand tsunami hazards and risk on the northwest coast of Vancouver Island by using tsunami modelling, community experience, and Indigenous Knowledge.

The study area for this assessment is broad, spans about 200 km from Nootka Sound northward to Cape Scott and includes the communities of Gold River, Tahsis, Zeballos, Port Alice, Winter Harbour, Quatsino, and Holberg, as well as several Indigenous nations including the Ka:'yu:'k't'h'/Che:k'tles7et'h' First Nations and Nuchatlaht First Nation, Ehattesaht/Chinehkint First Nations, Quatsino First Nations, Mowachaht/Muchalaht First Nations. Therefore, the project was split into two phases: Phase I of the project included Tahsis Inlet, Esperanza Inlet, and Kyuquot Sound, and was completed in 2022. The project resources and inundations maps for Phase I are published and now available online (www.srd.ca/tsunami-mapping). In Phase II, ONC partnered with NHC to expand the risk assessment to communities in Nootka Sound and Quatsino Sound, with the funding provided by The Lake Family's All One Fund. This report focuses on tsunami modeling of Phase II of the project.

In this report, detailed tsunami simulations were carried out to quantify the coastal tsunami hazard posed by local and distant sources using FUNWAVE-TVD model, a well-established tsunami prediction tool with demonstrated accuracy. In the following sections, the study area and tsunami sources are firstly described. The modelling details and tsunami scenarios will be discussed next, and finally, the model results will be presented.

2. STUDY AREA

Northwest Vancouver Island is renowned for its natural beauty and rich historical significance. Located along the western coast, this region faces potential tsunami hazards from both local sources like the Cascadia Subduction Zone and distant sources like the Aleutian Islands in Alaska. The area encompasses parts of the Strathcona Regional District (SRD) and Regional District of Mount Waddington (RDMW). Phase II of the project includes several communities, namely Gold River (waterfront), Port Alice, Winter Harbour, Quatsino, Holberg, as well as the Quatsino First Nation and Mowachaht/Muchalaht First Nation. Notable provincial parks in the region include Raft Cove and Cape Scott. Please refer to Figure 1 for the visual representation of the study area.



Figure 1: Northwest Vancouver Island study area. The blue shades on the map indicate the area covered in Phase I, while the dotted lines represent the extent of Phase II.

3. CO-SEISMIC TSUNAMI SOURCES

Multiple approaches can be employed to evaluate the tsunami hazard, such as the deterministic method (e.g., Wronna et al., 2015) and the probabilistic method (e.g., Geist and Parsons, 2006; Goda, 2022). For this particular project, we utilize a deterministic approach, wherein we identify and analyze the most substantial tsunami scenarios for the study area. The subsequent sections will elaborate on these selected scenarios.

3.1. Cascadia Subduction Zone

Great megathrust earthquakes occur in the Cascadia Subduction Zone roughly once every 500 years (Goldfinger et al., 2012). The last great Cascadia earthquake occurred in 1700, and while there is no written record of the impact along the eastern Pacific, it was recorded in oral history (e.g., Ludwin et al., 2005) as well as in the coastal and offshore stratigraphy at sites from northern California to Vancouver Island (e.g., Atwater et al., 1995; Goldfinger et al., 2012).

For the Cascadia Subduction Zone tsunami source, the splay-fault rupture model developed by Gao et al. (2018) was selected from three types of rupture scenarios including buried rupture, splay-faulting, and trench-breaching. The low-resolution tsunami simulation indicated that the splay faulting rupture (Mw=9.0) can generate higher wave surface elevation compared to other rupture scenario (e.g., 50-100% higher compared to buried rupture scenario) (Gao et al., 2018). This suggests that splay-faulting scenario has the greatest potential impact on the BC west coast and SRD. The low-resolution tsunami simulation performed by ONC for the City of Prince Rupert also confirmed the higher surface elevation from a splay-fault rupture compared to other Cascadia fault ruptures (ONC, 2019). Figure 2 shows the initial vertical displacement of the Cascadia Subduction Zone rupture based on this scenario.

3.2. Alaska-Aleutian Subduction Zone

The Alaska-Aleutian Subduction Zone is the origin of numerous significant earthquakes of magnitude 8 and more (e.g., Mw 8.3 in 1938, 1946 Mw 8.6, 1957 Mw 8.6, 1964 Mw 9.2, 1965 Mw 8.7; see Dunbar and Weaver (2008) and Nelson et al. (2015)). The largest of the recent earthquakes, namely, the 1964 Alaska earthquake produced the largest instrumentally recorded tsunami waves to date on the British Columbia coast (Wigen and White, 1964), and this event represents a realistic proxy for similar large events generated by the subduction zone.

Numerical simulation of the 1964 tsunami in this study is based on the most recent co-seismic slip distribution for the Alaska 1964 rupture (Suleimani et al., 2020), constructed on the model of Suito and Freymueller (2009) (Figure 3). The authors applied the inversion-based model by Johnson et al. (1996) as a basis for their co-seismic slip model, adjusting it to an updated geometry. The revised model includes contributions from co-seismic horizontal displacements into the initial tsunami wave distribution through the component of the sea surface uplift due to horizontal movement of the steep sea floor slopes. Inclusion of deformation due to horizontal displacements can increase the far-field tsunami wave amplitudes in tsunami simulations.

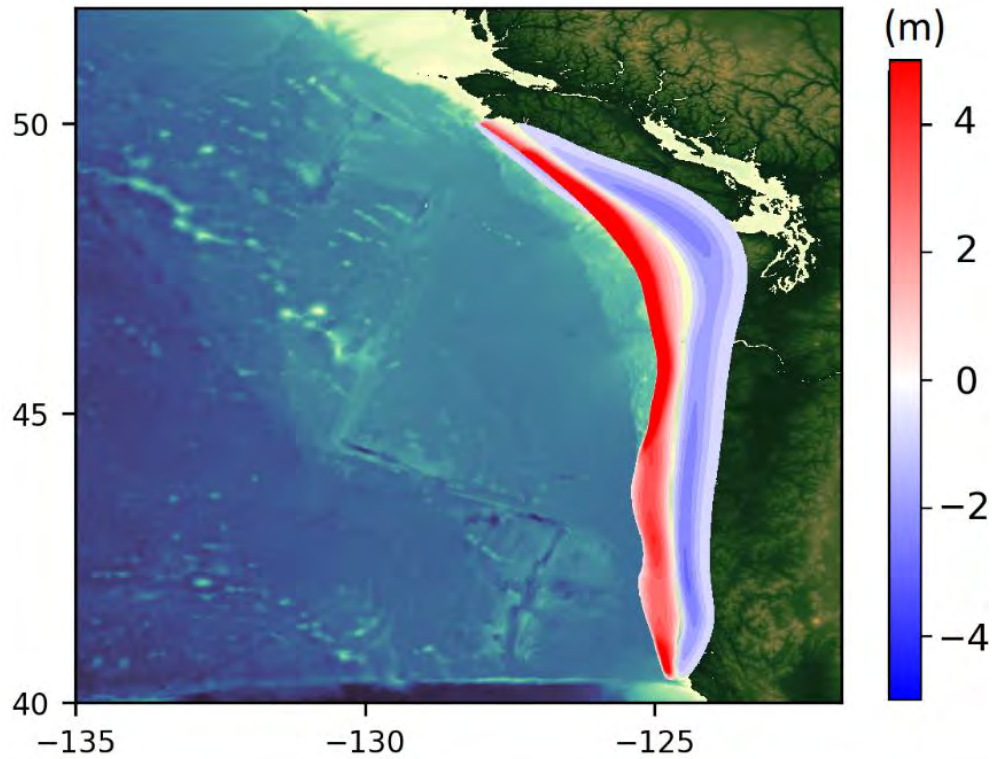


Figure 2: Seafloor vertical displacement (m) for the Cascadia Subduction Zone earthquake based on the splay faulting rupture model. Image was replotted from the provided data by Natural Resource Canada (NRCan) corresponding to Gao et al. (2018) where blue color shows the seafloor/topography subsidence and red color indicates seafloor uplift.

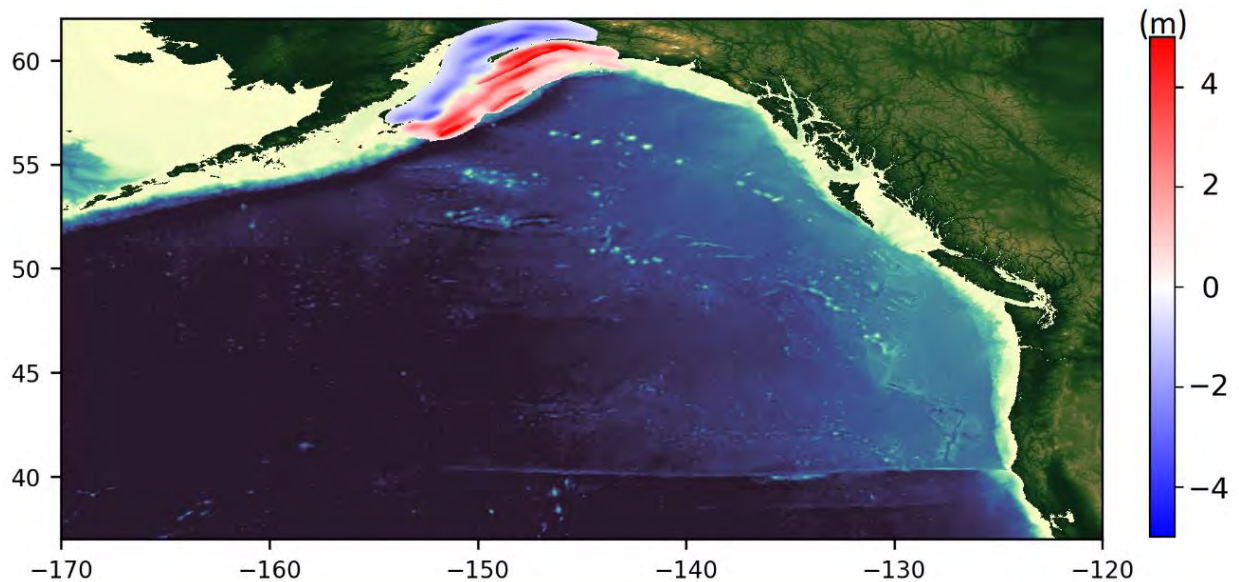


Figure 3: Seafloor vertical displacements (m) at the source region for the Alaska 1964 earthquake. Image was replotted from the provided data by University of Alaska Fairbanks corresponding to Suleimani et al. (2020) where blue color shows the seafloor/topography subsidence and red color indicates seafloor uplift.

4. HYDRODYNAMIC METHODOLOGY

Tsunami wave generation, propagation and inundation are commonly modelled using the 2D non-linear shallow water equations (SWE) and non-hydrostatic models. The non-linear shallow water equations can be derived in a number of methods, but all of them fundamentally arise from an integration of the Euler or Navier-Stokes equations with the assumption of vertically invariant horizontal velocity and hydrostatic pressure. These assumptions are usually correct for seismically generated tsunamis as the horizontal wavelength of tsunamis is much larger than the water depth scale. TUNAMI, COMCOT, and MOST are popular models based on the SWE which have been validated successfully through benchmarks using water level records from historical tsunami events (Imamura et al., 1988; Liu et al., 1994; Titov and Synolakis, 1998).

However, the SWE models lack the capability of simulating dispersive waves, which is the dominating features in landslide-generated tsunamis (Lynett and Liu, 2002) and is important for far-field tsunamis travelling a long distance (Grilli et al., 2012). Correspondingly, Boussinesq-type models represent an extension to SWE to better describe the wave dispersions, and multiple numerical models have been developed based on these equations, for instance, FUNWAVE-TVD a fully nonlinear Boussinesq wave model (Kirby et al., 1998 and Wei et al., 1995) or COULWAVE (Lynett and Liu, 2002). NEOWAVE (Non-hydrostatic Evolution of Ocean WAVES) (Yamazaki et al., 2010) and NHWAVE (Non-Hydrostatic Wave Model) (Ma et al., 2012) are also 3D non-hydrostatic models that have been widely used for the generation and propagation of seismic and landslide-generated tsunamis.

Although nonlinear non-hydrostatic models can simulate complicated physics associated with wave dispersion, they are computationally more demanding. The numerical model FUNWAVE TVD used to examine the propagation of the tsunami waves is described in the following section.

4.1. Model description

The propagation and inundation of tsunamis induced by seismic events were modelled using the FUNWAVE-TVD model, a long wave propagation model that solves fully non-linear and dispersive Boussinesq wave propagation equations (Wei et al., 1995). This model employs a hybrid finite-volume and finite-difference scheme and has been developed both as a fully nonlinear version in cartesian coordinates (Shi et al., 2012) and a weakly nonlinear approximation in spherical coordinates (Kirby et al., 2013).

FUNWAVE-TVD has been benchmarked against other models and reference data in the U.S. as part of the National Tsunami Hazard Mitigation Program (NTHMP) (Horrillo et al., 2014), for hazard mapping along the U.S. coastline. The FUNWAVE-TVD model has been extensively used for tsunami modelling worldwide, for instance, modelling of a potential flank collapse of the Cumbre Vieja Volcano in the Atlantic Ocean, submarine mass failures along the US east coast (Grilli et al., 2015), interactions with tides (Shelby et al., 2016), tsunami hazard in the Mediterranean (Nemati et al., 2018), and recently co-seismic tsunami hazard assessment for Prince Rupert undertaken by ONC in collaboration with NHC (ONC, 2019, 2022a, 2022b, 2023a).

4.2. Grid nesting

Accurate numerical simulation of tsunami waves in rapidly shoaling coastal regions requires setting up the model domain as a series of grids of finer spatial and temporal resolution. The use of nested grids makes it possible to resolve tsunami wave configurations as they propagate into increasingly shoaling coastal regions.

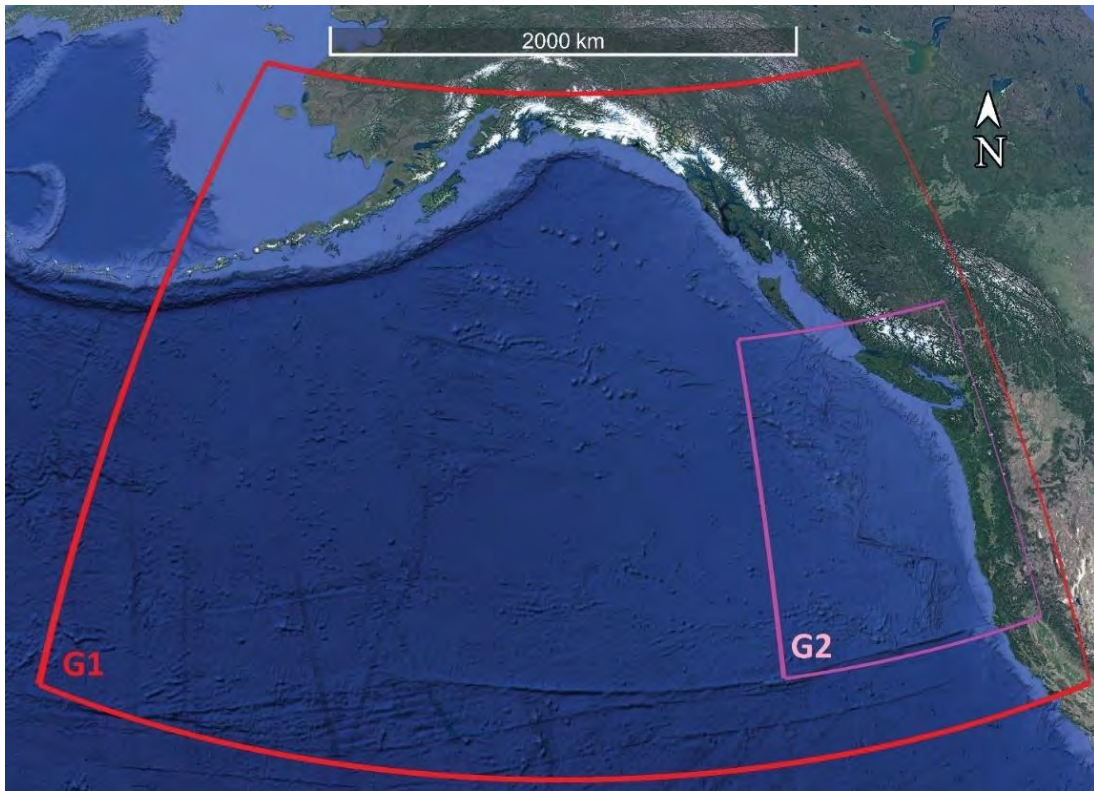
The use of nested grids for numerical modelling has several principal requirements: (1) grid cell sizes are obtained by dividing the initial, large-scale coarse numerical grid by an integer, typically 3 to 6. Integers larger than this can lead to grid interface problems. (2) nested grids are needed in near-coastal areas and the coarse “parent” grid should be of sufficient extent to resolve possible feedback effects that the nested grid may have on the parent grid during the simulation time. (3) high-resolution bathymetry, external forcing, and observations are needed for model domain setup, initialization, and validation at each domain level.

For this study, a series of nested grids (G1, G2, G3, G4, G5A, and G5D) was used to simulate the propagation of the potential tsunamis from the source regions to north coasts of Vancouver Island (Figure 4). It should be noted that grids G5B and G5C are specifically associated with Phase I of the project (ONC, 2022b). The resolution increases from the outer grid to the inner grid and is reported in Table 1. The wave elevations and horizontal water velocities are transferred from the coarser resolution to finer resolution grids at the boundaries.

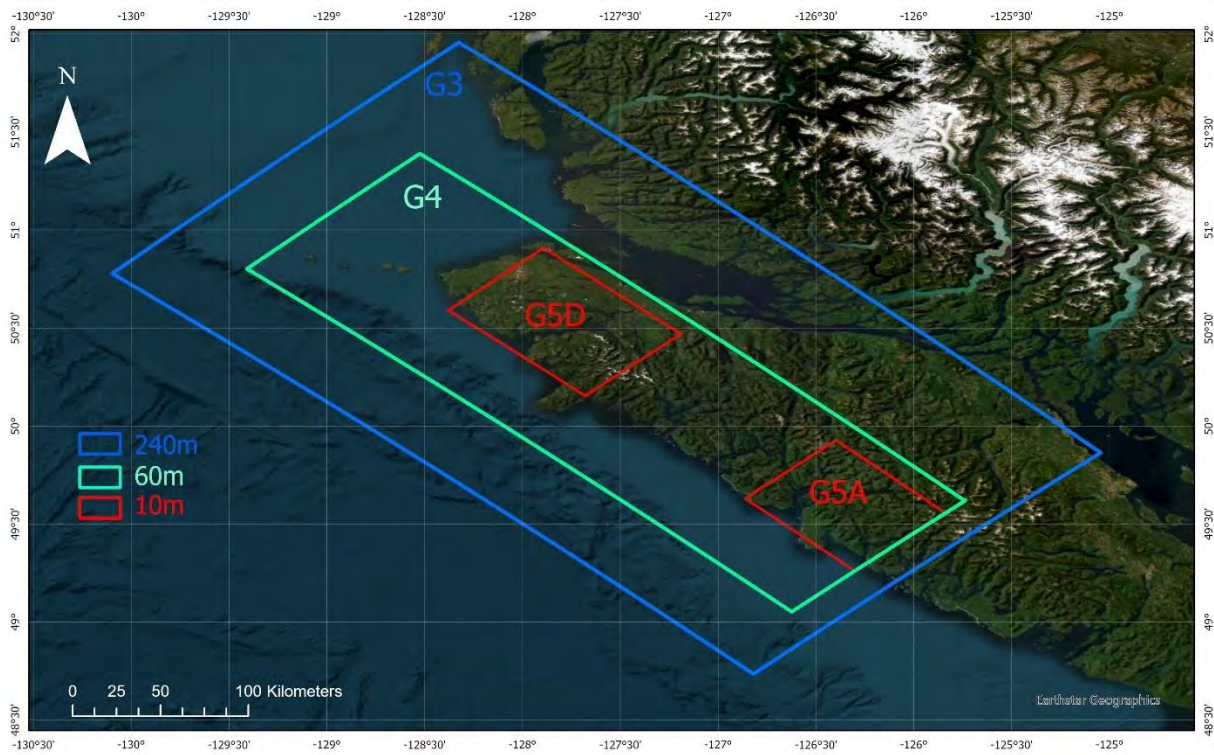
The initial grid in spherical coordinates (G1) with a horizontal resolution of 2 arc-minutes is used for the initial source generation, which is necessary to reproduce tsunami waveforms in the Pacific with the FUNWAVE-TVD model (e.g., Kirby et al., 2013). To avoid non-physical reflections from boundaries of G1, an absorbing sponge layer of 200 km were applied to all boundaries. G1 is the coarsest numerical grid that covers the north pacific and includes the Alaska tsunami source region. As waves approach the area of interest, a second coarse resolution spherical mesh of 30 arc-seconds is used for the area covering most of the BC coastline encompassing the Cascadia Subduction Zone.

Table 1: Information of the numerical grids for the tsunami modelling.

Grid	Latitude	Longitude	Resolution
G1: Northeast Pacific	37° to 62°N	170° to 120°W	2 arc-min (~3000 m)
G2: Cascadia	40° to 52°N	135° to 121.76° W	30 arc-sec (~ 700 m)
G3: Vancouver Island	48.74° to 51.96° N	130.1° to 125.04° W	240 m
G4: Local region	49.05° to 51.39° N	129.41° to 125.74° W	60 m
G5A: Nootka Sound	49.26° to 49.93° N	126.86° to 125.84° W	10 m
G5D: Quatsino Sound	50.15° to 50.91° N	128.38° to 127.19° W	10 m



(a)



(b)

Figure 4: The arrangement of the nested grids: (a) spherical grids G1 and G2 with 2' and 30" resolutions, respectively; (b) cartesian grids G3, G4, G5A and G5D with 240 m, 60 m, 10 m, and 10 m, respectively. Note: grids G5B and G5C are specifically associated with Phase I of the project (ONC, 2022b).

In order to generate the Cartesian grids (Figure 4b), the spherical coordinates were projected on Cartesian coordinates using a Mercator projection. This projection is similar to UTM projection, with an origin located at 50° N and 127° W between the high-resolution grids (G5A and G5D), to minimize distortion to the grid as the wave propagates toward the shore. Moreover, in order to better align the higher resolution mesh with Vancouver Island coastlines and continental shelf, a 45° counter-clockwise rotation relative to the horizontal geographical coordinates at the region were applied to all cartesian grids. This rotation was also applied to the calculated output of the G2 results to accurately produce the boundary conditions at G3 boundary nodes.

G3 has an intermediate resolution of 240 m and can capture the energy exchange between the deep waters and shallower coastal zone. The nested grids are then refined to higher resolutions on the Cartesian grid, first to a 60m resolution grid (G4) and lastly to two 10 m resolution grids (G5A and G5D) covering the key study areas shown in Figure 1. G4 covers the waters surrounding Northwest Vancouver Island to account for wave transformation along the outer coast of the island. G5A and G5D have the highest spatial resolution of 10m, designed for the tsunami inundation modelling of the region.

The Manning coefficient $n = 0.025 \text{ s/m}^{1/3}$ was assumed over the entire domain for all tsunami grids. This coefficient varies based on the roughness of the seabed, however, significant reduction in tsunami amplitudes may occur by using higher values of n in finer resolution grids (Schambach et al., 2018). Therefore, in the absence of land use data, they recommended using the conservative manning n coefficient $n=0.025$ for coarse sand.

4.3. Bathymetry and topography assimilation

Multiple bathymetric and topographic data were integrated to develop required high-resolution DEMs for the tsunami modeling. Topographic data was collected from the Light Detection And Ranging (LiDAR) survey for this study. Bathymetric data was mainly provided by the Canadian Hydrographic Service (CHS) in various resolutions. High-resolution multibeam existed for some inlets and coasts, however, to accurately model these areas, additional data was required for the high-resolution modelling which was acquired from surveying the areas that were not covered by the CHS data.

DEM development included data collection and review, DEM generation, and quality assurance and quality control (QAQC). Additional details of the topographic and bathymetric datasets used to develop the high-resolution DEM is reported in the DEM development appendix associated with this project, prepared by Ocean Networks Canada in collaboration with NHC (ONC, 2023).

4.4. Model vertical reference level

The US National Tsunami Hazard Mitigation Program (NTHMP, 2010) recommends to capture the contribution of high tide conditions, the inundation modelling takes place at a minimum of the US Mean High Water (MHW) level for a specific region. However, it is common to use US standard Mean Higher High Water (MHHW) as a more conservative tidal reference in such tsunami

modelling studies (Suleimani et al., 2013). The US standard Mean Higher High Water (MHHW) corresponds to Canadian standard Higher High Water Mean Tide (HHWMT), which has been used for various tsunami modelling projects in BC regions, for example, Victoria (AECOM, 2013), Seal Cove (Fine et al., 2018b), and Boundary Bay (Fine and Thompson, 2020). Accordingly, in this work, the tsunami modelling was performed with respect to the HHWMT, as the initial tide level.

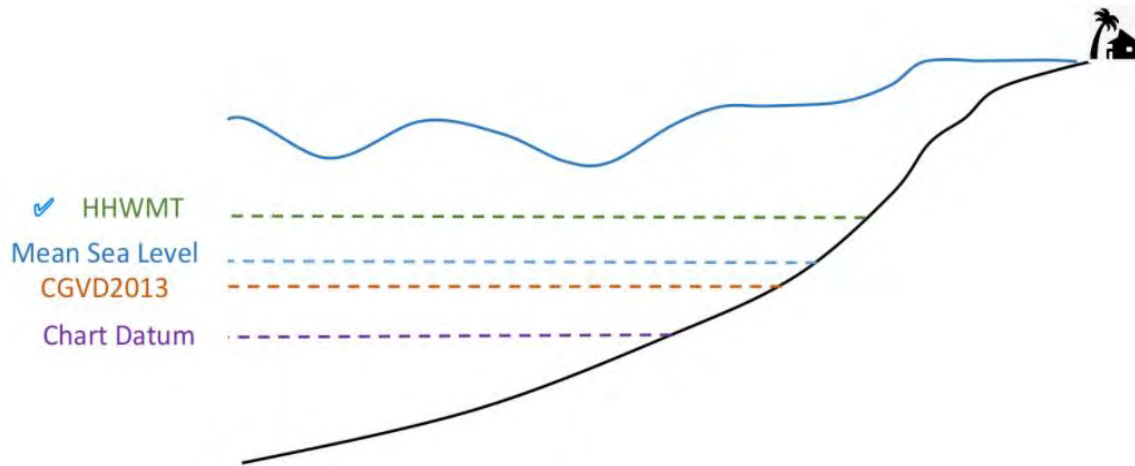


Figure 5: Schematic of vertical elevation references at the study area. HHWMT was used for tsunami modelling.

Figure 5 demonstrates the schematic of the vertical elevation references at the study area. The vertical reference of the DEMs developed for the tsunami modelling was relative to the Canadian Geodetic Vertical Datum (CGVD) 2013, which was translated to HHWMT for the modelling. To undertake this conversion, the HHWMT relative to Chart Datum (CD) were obtained for a number of key communities from the Canadian Tide and Current Tables (Fisheries and Oceans Canada, 2023).

CGVD2013 vertical reference levels with respect to CD along the BC coast were provided by CHS directly to ONC and is plotted in Figure 6. The conversion from CD to CGVD2013 were extracted from the CHS dataset and used to obtain values of HHWMT with respect to CGVD2013, as listed in Table 2 for the locations within the study area. Lastly, values of HHWMT with respect to CGVD2013 were averaged and presented in the last column of Table 2. For example, the Nootka Sound (G5A) which includes Saavedra Islands and Gold River, the HHWMT level on average is 1.5m above CGVD2013. Similarly, the HHWMT on average is 1.5m above CGVD2013 for Quatsino Sound (G5D) grid (see Table 2).

As a result, for modelling purposes at HHWMT, the DEM of these two grids (which were developed relative to CGVD2013) were uniformly lowered by 1.5m. Similarly, for 60m resolution grid, the averaged value of 1.5 m was applied for modelling. It should be noted for the first phase of the project, 1.5m was similarly calculated as the conversion value for modelling of G5B (Nuchatlitz) and G5C (Kyuquot) grids as well.

Table 2: Conversion of CGVD2013 to HHWMT by averaging the corresponding values for each grid of the study area. The listed CGVD2013 and HHWMT are relative to Chart Datum (CD).

Grid	Location	HHWMT (m, CD)	Elevation Datum Conversion (CD to CGVD2013)	HHWMT (m, GVD2013)	Averaged HHWMT for simulation (m, CGVD2013)
G5A	Saavedra Islands	3.6	-2.1	1.5	1.5
	Gold River	3.6	-2.1	1.5	
G5D	Hunt Islets	3.5	-2	1.5	1.5
	Port Alice	3.6	-2	1.6	
	Bergh Cove	3.5	-2	1.5	
	Kwokwesta Creek	3.6	-2.2	1.4	
	Makwazniht Island	3.4	-1.9	1.5	
	Coal Harbour	3.5	-1.9	1.6	

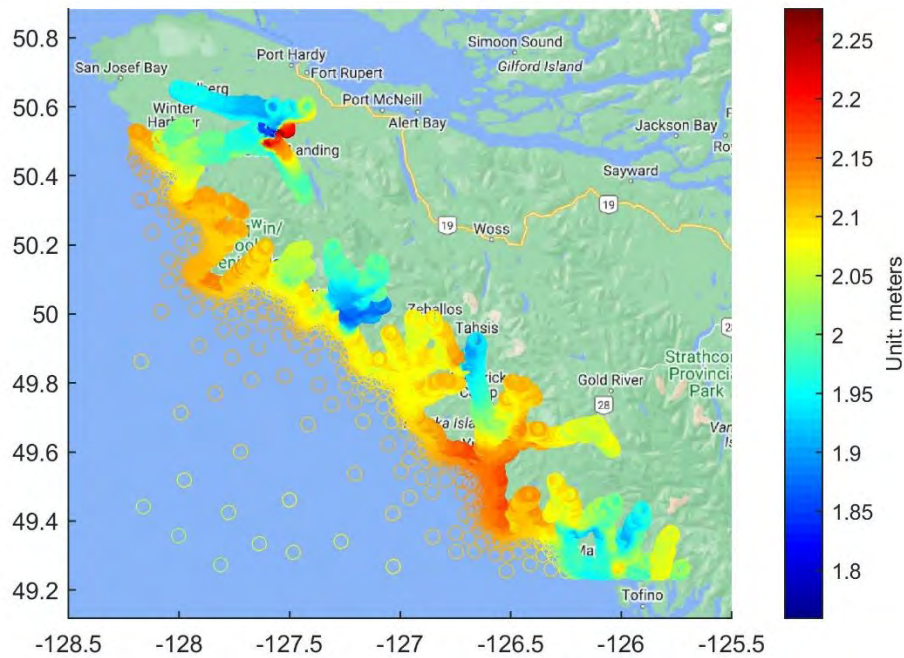


Figure 6: CGVD2013 spatial variation over the study area with respect to CD, provided by CHS directly to ONC.

4.5. Land subsidence/uplift

When considering tsunami impacts, land subsidence actively acts to increase the water elevation due to tsunamis and the subsided land will be more at risk to tsunami inundation. Subsidence within the study area is spatially variable, which is greater along the open coast and reduces further inland. It should be noted Nootka Sound would be relatively more affected by land subsidence due to its proximity to Cascadia subduction zone compared to Quatsino Sound. To account for the land deformation (subsidence/uplift) in the modelling process, the vertical deformation is simply superimposed to the underlying DEM.

4.6. Future sea level rise inclusion

Sea-level rise can noticeably increase the tsunami hazard, and even minor sea-level rise, can pose greater risks of tsunamis for coastal communities worldwide (Li et al., 2018). The sea level rise policy for the BC Ministry of Environment (Sandwell, 2011) recommends using 1.0 m rise in global mean sea level between the year 2000 and 2100 for planning purposes. In a recent study by NRCan (James et al., 2021), several average and enhanced SLR scenarios were studied for the water bodies surrounding Canada, which are based on different pathways of greenhouse concentration through the 21st century. For this project, the worst-case scenario of Projected Relative Sea-Level Change for Enhanced Scenario at 2100 was used for which additional meltwater from Antarctica is considered (Figure 7). This Enhanced SLR scenario predicts a maximum of 1.2 m of relative SLR along the coasts of Northwest Vancouver Island. For simulation of SLR scenarios in this project, the underlying DEM was lowered by 1.2 m for each tsunami scenario.

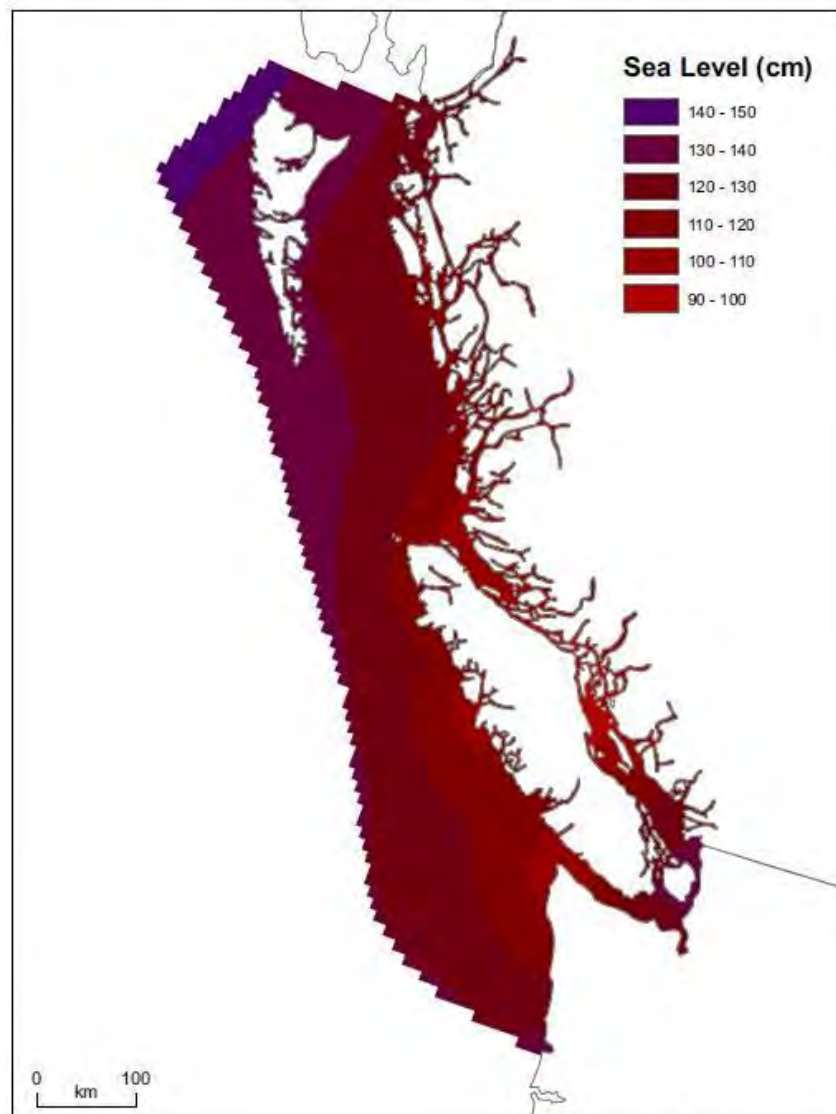


Figure 7: Projected Relative Sea-Level Change for Enhanced Scenario at 2100 along BC West Coast (James et al., 2021).

4.7. Modelling scenarios

A total of four tsunami scenarios were modelled which corresponding to present and future tsunami events. These scenarios include a local source event (Cascadia Subduction Zone) and distant source event (Alaska-Aleutian Subduction Zone) described in Sections 3.1 and 3.2, respectively under both present and future sea-level conditions:

- Scenario 1: Cascadia Subduction Zone, current-day sea-level conditions
- Scenario 2: Alaska-Aleutian Subduction Zone, current-day sea-level conditions
- Scenario 3: Cascadia Subduction Zone, future sea-level conditions
- Scenario 4: Alaska-Aleutian Subduction Zone, future sea-level conditions

The results of the 60m simulation were used to provide hazard information including wave amplitude, time of arrival, and tsunami-induced current velocities. The results of the high-resolution 10 m modelling were utilized for detailed inundation mapping for key study areas shown in Figure 1.

5. RESULTS

The following sections present the results of the tsunami simulation for three grids: the 60m grid, and the two high-resolution 10m grids, G5A (Nootka Sound) and G5D (Quatsino Sound). The outputs from the 60m simulation were used for overwater hazard mapping in the broader study area as well as the boundary conditions for the 10m modelling in Nootka Sound and Quatsino Sound. The results obtained from the 10m simulations was also utilized for inundation mapping. It is important to note that in this report, we provide the model outputs for the entire extent of each grid. For more detailed information on localized hazards and inundation mapping, please refer to the "Northwest Vancouver Island Tsunami Risk Assessment Final Report" prepared by NHC.

It is worth mentioning that in this study, the 240m and 60m resolution grids have been redesigned with larger extents compared to the grids used in the first phase of the project. This redesign was necessary to improve accuracy observed at the northern tip of Vancouver Island. The updated grid extents were expanded towards the north and west to overcome these issues.

To ensure the reliability and accuracy of the results, the consistency between the 240m and 60m resolutions at boundaries and offshore locations was first verified using the model results from the updated grid extents.

Additionally, as part of the quality assurance measures, the time series of water surface elevation obtained from the 60m and 10m model results were compared at various numerical gauge points. This comparison demonstrated a good agreement in the majority of the gauge points, further confirming the credibility of the model outputs.

The report utilizes various tsunami terminologies with the following definitions:

- 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.
- The arrival time is defined the time of the first maximum of the tsunami waves (Intergovernmental Oceanographic Commission, 2019) following the trigger event. Flooding may begin before this moment is reached.
- Tsunami-induced currents are only generated by tsunami, and the tidal currents are not considered in modelling.
- Tsunami run-up is the highest vertical elevation upland reached by a tsunami with respect to a reference plane. This parameter is not directly reported in this document but can be obtained from the model results.
- For simplicity, Cascadia Subduction Zone and Alaska-Aleutian Subduction Zone tsunami sources are briefly referred as 'Cascadia' and 'Alaska', respectively.
- The simulation time for the Cascadia and Alaska scenarios were 6 and 9 hours, respectively. Tsunami wave parameters includes tsunami wave amplitude, tsunami wave arrival time, and tsunami-induced currents. In the case of the Cascadia scenario, which is in close proximity to the study areas, a test run revealed that a simulation time of 6 hours is adequate to capture the maximum wave parameters. On the other hand, for the Alaska scenario, it was determined that a minimum simulation time of 9 hours is necessary to account for the maximum tsunami wave parameters. It is important to note that longer simulation times could be employed for each scenario; however, this would increase computational costs without yielding significant additional benefits for the purpose of estimating the maximum tsunami wave parameters.

For better understanding of the tsunami impacts, the estimated amplitudes of the leading and maximum waves, as well as corresponding arrival times, were identified from the time series of water surface elevation at several numerical gauge points (GP). The location of the gauge points (GPs) is depicted in Figure 8 and listed in Table 3. The corresponding time series data obtained at these gauge points can be found in Annex A

It is important to mention that the numerical gauge points are situated a few meters away from the shoreline in deeper water. This placement allows for the representation of wave amplitudes over the water. However, it should be noted that when waves interact with the shoreline and propagate inland, they can cause water to surge to higher elevations, leading to the creation of an inundation zone. For detailed information regarding the levels of inundation for emergency planning, please refer to the main report of the project.

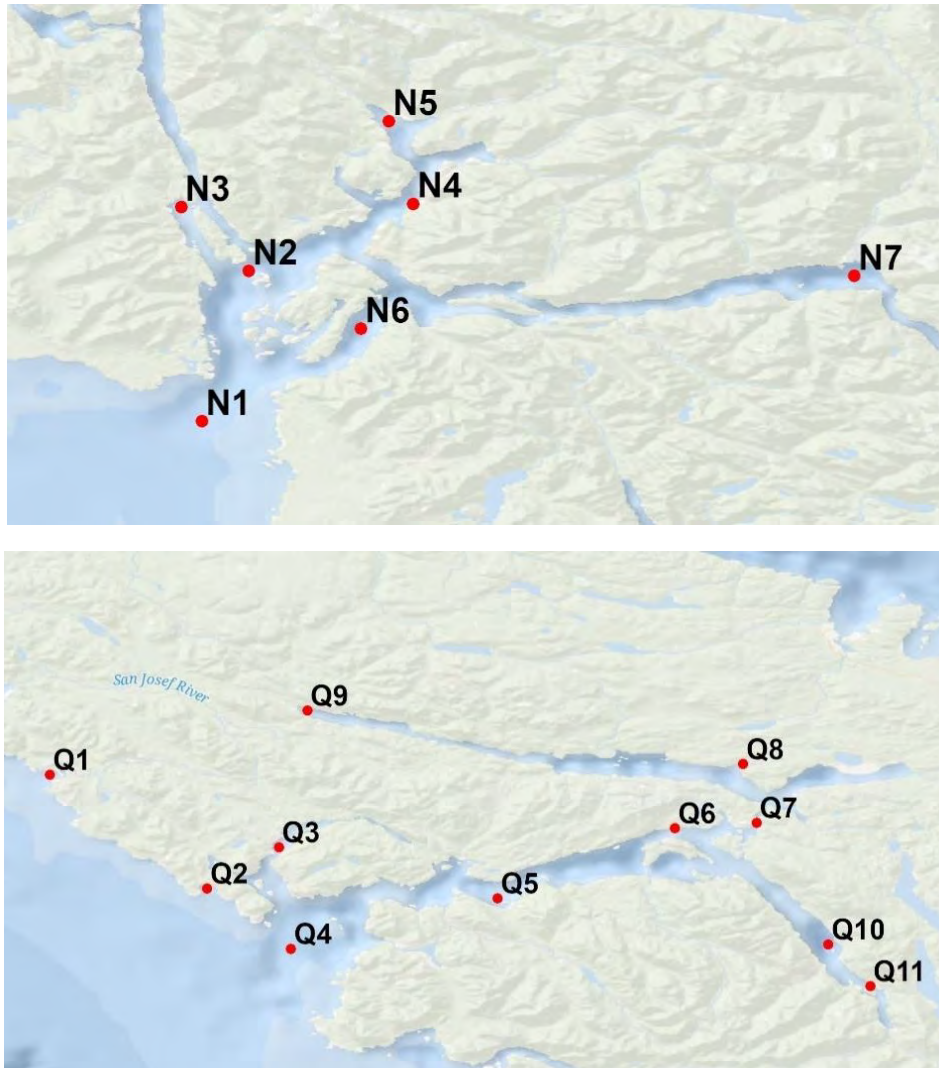


Figure 8: The location of several numerical gauge points (GPs) specified over the study area to obtain the time series of wave amplitude, top) Nootka Sound and bottom) Quatsino Sound See Table 3 for more details.

Table 3: The information of several numerical gauge points (GP) specified over the study area. See Figure 8 for the location of the GPs on the map.

GP	Location	Longitude	Latitude	GP No.	GP	Longitude	Latitude
N1	Nootka Sound entrance	-126.6231	49.5563	Q3	Winter Harbour	-128.0231	50.5158
N2	Eliza Passage	-126.5868	49.6724	Q4	Quatsino Sound entrance	-128.0115	50.4187
N3	Kendrick Inlet	-126.6391	49.7216	Q5	Mahatta River mouth	-127.8134	50.4669
N4	Cougar Creek mouth	-126.4594	49.7243	Q6	Quatsino	-127.6435	50.5339
N5	Head Bay	-126.4785	49.7881	Q7	Quatsino Narrows	-127.5653	50.5392
N6	Zucariate Channel	-126.4999	49.6277	Q8	Coal Harbour	-127.5781	50.5953
N7	Gold River waterfront	-126.1181	49.6685	Q9	Holberg	-127.9958	50.6466
Q1	Raft Cove	-128.2427	50.5853	Q10	Port Alice	-127.4965	50.4228
Q2	Grant Bay	-128.0921	50.4763	Q11	Port Alice terminal	-127.4564	50.3827

5.1. Cascadia Subduction Zone

5.1.1. Tsunami wave amplitude

The spatial distributions of maximum tsunami wave amplitudes from Cascadia event are illustrated in Figure 9. As a result of proximity to the Cascadia Subduction Zone, the tsunami amplitudes are generally higher toward the southern parts, in particular, from Brooks Peninsula toward south with the highest wave amplitude in Nootka Sound. In contrast, from Brooks Peninsula to Cape Scott in the northmost of Vancouver Island, including Quatsino Sound, the wave amplitudes reduce along the coast by distancing from the Cascadia subduction zone. More details about the maximum wave amplitude and arrival time of a Cascadia tsunami in Nootka Sound and Quatsino Sound are discussed in the next sections.

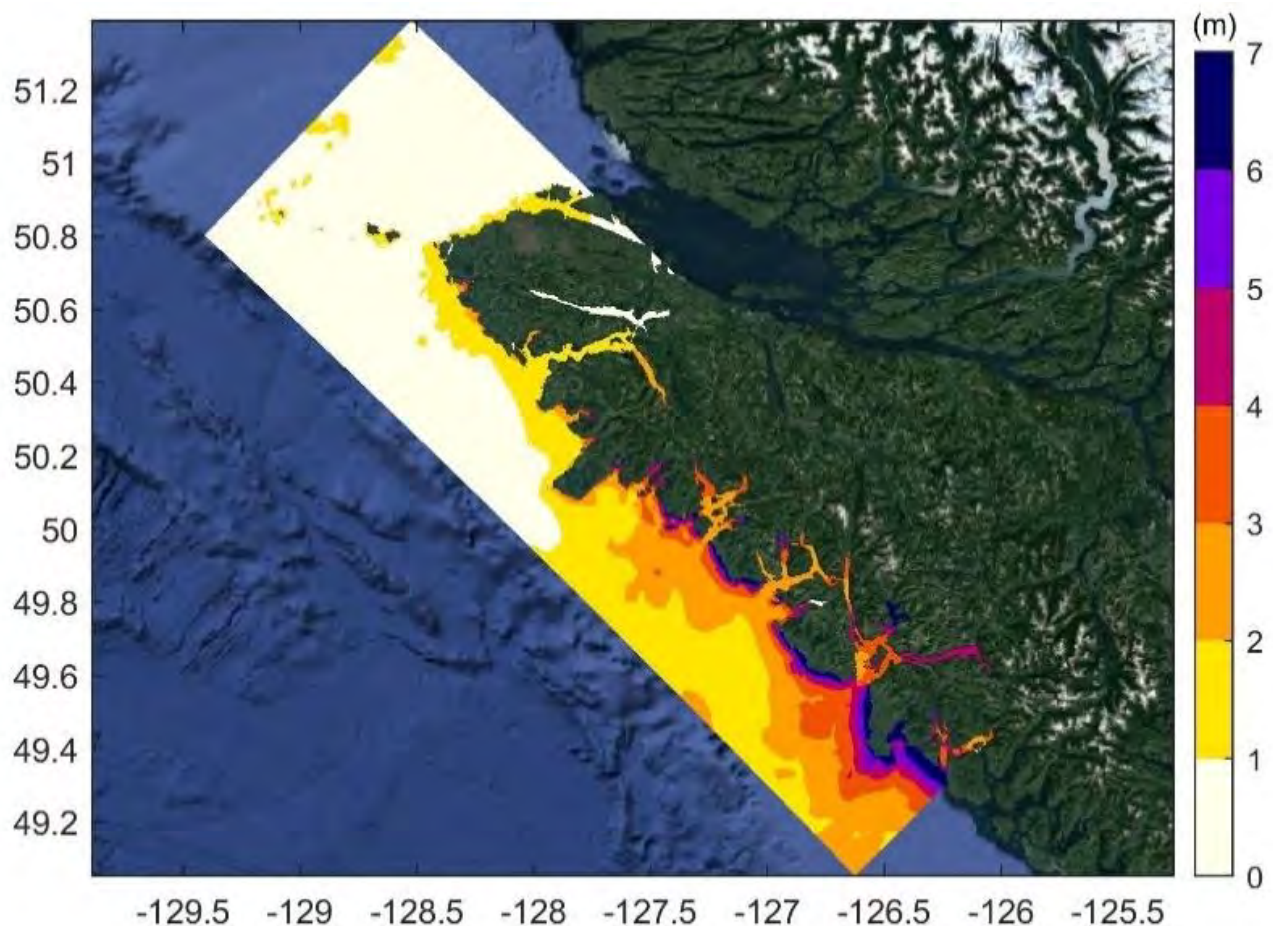


Figure 9: Maximum tsunami wave amplitude along Northwest Vancouver Island coasts for Scenario 1: Cascadia Subduction Zone current-day resulted from the 60 m resolution simulation.

Nootka Sound

Figure 10 shows the maximum wave amplitudes from the high-resolution simulation (10m) in Nootka Sound. The predicted amplitudes of the leading and maximum waves, as well as

corresponding arrival times were obtained from the time series of the water surface elevation (See Annexe A.1) at selected GPs (N1 – N7) and are listed in Table 4.

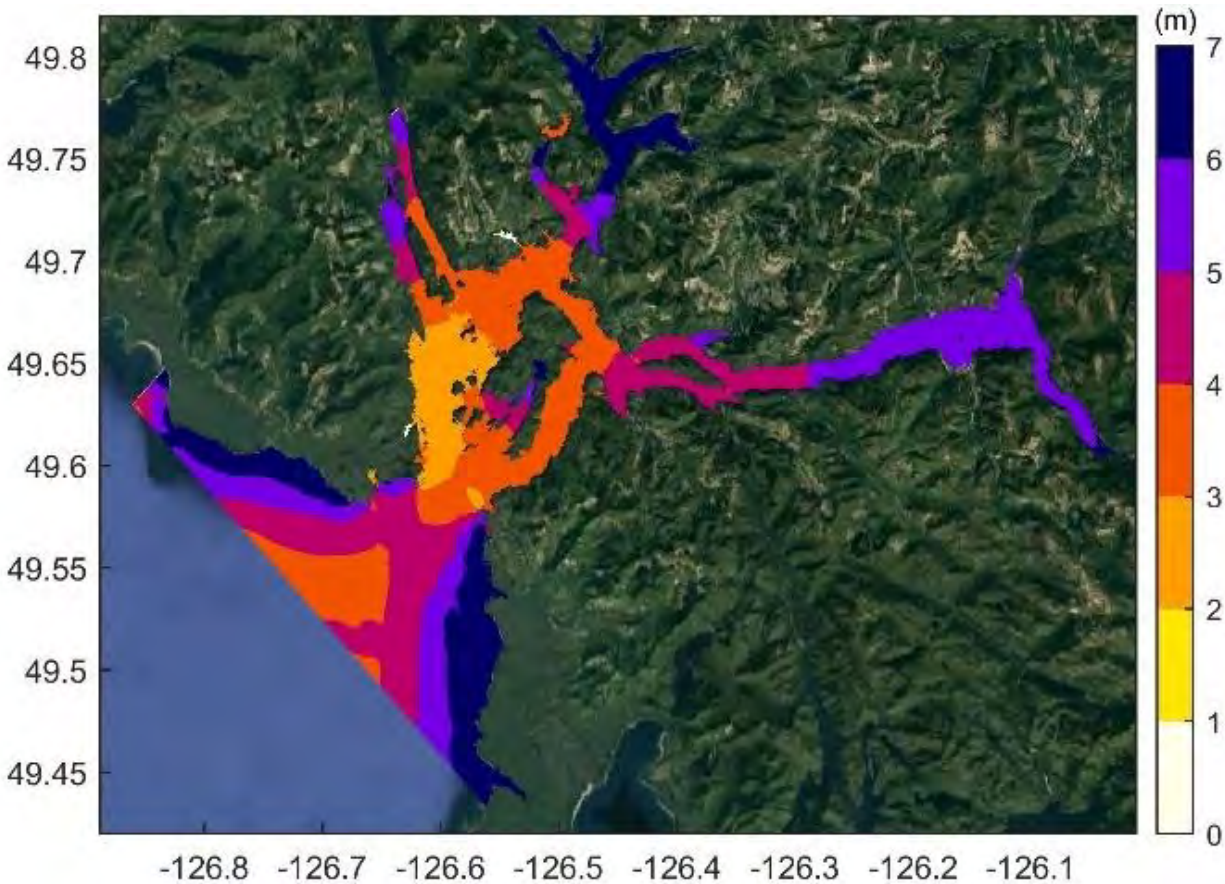


Figure 10: Maximum tsunami wave amplitude in Nootka Sound for Scenario 1: Cascadia Subduction Zone current-day resulted from the 10 m resolution simulation.

The wave amplitude at Nootka sound entrance (about 100 m depth) is about 4 m, where the funnel shape with shallower depths at the sides amplifies the wave to larger than 7 m. The wave would be dissipated as travelling into the sound (2 - 4 m), for instance to 2.9 m in Eliza passage (N2) before entering Tahsis inlet and 3.6 m in Zucariate Channel (N6) before entering the Muchalat Inlet. Inside Tahsis inlet and near to Strange Island the wave amplitude would be greater between 4-5m, for instance, it reaches 5.3 m at the end of Kendrick inlet (N3).

Similarly, at Gold River waterfront close to the end of Muchalat Inlet wave amplitudes of 5.5 m is predicted (N7). In this region, the model result from a 10m simulation predicts greater wave amplitude compared to 60m resolution (5.5m vs. 4.5m), as the higher resolution resolve the amplification more accurately, which may be the results of the resonance and reflection from the end of Muchalat Inlet. This pattern was also observed in the results of the Phase 1 of the project in this area.

As the tsunami waves propagating towards Tlupana Inlet, the tsunami wave is amplified to 5.6 at the mouth of Cougar Creek and when it reaches to Head Bay (N5), it exceeds 8m as the result of

the shoaling and potential resonance. It is also estimated that the tsunami wave amplifies at the end of Hisnit Inlet up to about 7m and spill over into Deserted Lake.

For the Cascadia tsunami in the Nootka Sound, the time series show that the first tsunami wave (peak) has the largest wave amplitude as a result of proximity to the subduction zone. The arrival time of the first maximum wave is estimated less than an hour from the earthquake occurrence, except at the Gold River waterfront which experiences the first maximum wave amplitude after about 1hr:15min.

Table 4: Tsunami maximum wave amplitudes and arrival times of Nootka Sound for Cascadia Subduction Zone current-day scenario at selected numerical gauge points (GP) displayed in Figure 8.

GP	Location	First wave		Maximum wave	
		Arrival time HH:MM	Amplitude (m)	Arrival time HH:MM	Amplitude (m)
N1	Nootka Sound entrance	00:28	4.2	00:28	4.2
N2	Eliza Passage	00:43	2.9	00:43	2.9
N3	Kendrick Inlet	00:45	5.3	00:45	5.3
N4	Cougar Creek mouth	00:47	4.5	00:51	5.6
N5	Head Bay	00:50	8.2	00:50	8.2
N6	Zucariate Channel	00:36	2.6	01:06	3.6
N7	Gold River waterfront	00:59	4.3	01:15	5.5

Quatsino Sound

Figure 11 shows the maximum wave amplitudes resulted from the high-resolution simulation (10m) in Quatsino Sound for a Cascadia tsunami. The predicted amplitudes of the leading and maximum waves, as well as corresponding arrival times at selected GPs (Q1 – Q11) are listed in Table 5. This information was obtained from the time series of the water surface elevation (See Annexe A.2).

The tsunami wave amplitude is between 2-3 m along the coasts of the Northwest of Vancouver Island. Offshore of the Raft Cove (Q1) and Grant Bay (Q2), the wave amplitude can reach to 3m.

The wave amplitude is estimated between 1-2m entering the Quatsino Sound (about 1.4 m at Q4). The maximum wave amplitude at Winter Harbour area predicted up to 3 m, although at the selected GP, it is about 1.9m (Q3). The wave has an of amplitude of 1.4 m at the mouth of Mahatta River (Q5) which increases to 1.7m at Hamlet of Quatsino (Q6), while at Hecate Cove the wave estimated to increase further to about 2.7m due to the shape of the cove.

The tsunami wave reaches up to 2 m at Quatsino Narrows (Q7), but dissipated as the wave passes through this narrow and shallow passage (reaches to about 200 m in width and as low as 30m in depth) to wider and deeper area (about 100m depth) towards Rupert and Holberg Inlets. Maximum wave amplitude would be smaller than 0.5m in these inlets (e.g., 0.4 m at Coal Harbour (Q8)), although at the end of Holberg inlet (Q9) the wave amplitude increases up to about 1 m.

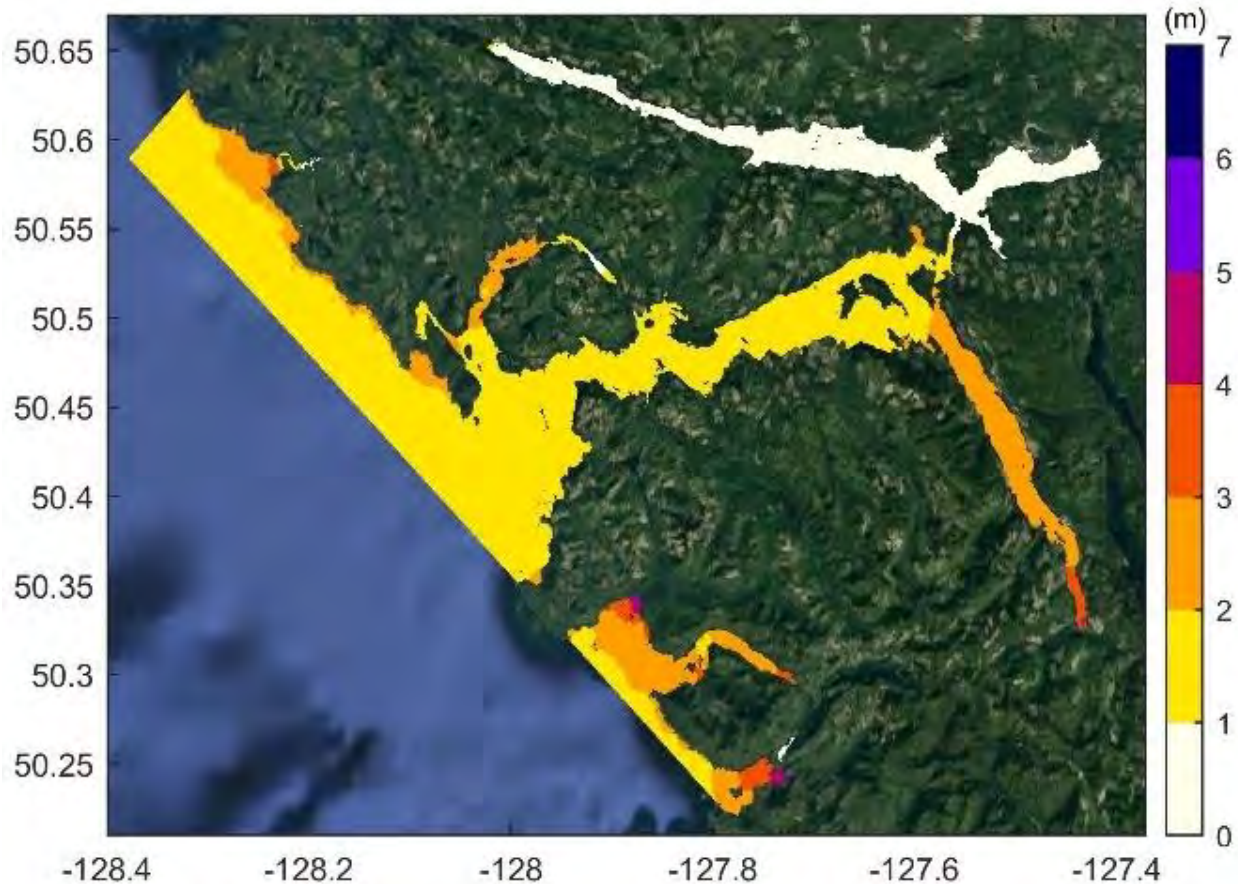


Figure 11: Maximum tsunami wave amplitude in Quatsino Sound for Scenario 1: Cascadia Subduction Zone current-day resulted from the 10 m resolution simulation.

In contrast, the wave which travels from Drake Island towards Port Alice through Bochholz Channel and Neroutsos Inlet is estimated 2.6 m at Port Alice (Q10) and its terminal (Q11). The wave would be amplified up to 4 m at the end of the Neroutsos Inlet due to shoaling in the shallower depths.

The first tsunami wave arrives to Quatsino Sound entrance in about 18 minutes. The arrival time of the first maximum wave for most gauges occur in less than an hour from the earthquake. However, the areas located in Holberg Inlet, Rupert Inlet, experience the first tsunami wave after about 1hr:30min from the earthquake (see Q8 and Q9). In Port Alice, the first maximum wave amplitude arrives about 1 hour from the earthquake (Q10 and Q11).

The time series also show that in most gauges the first tsunami wave (peak) is not the largest wave amplitude. For example, the first tsunami wave with 1m amplitude arrives to Port Alice after about 1 hour, whereas the largest wave with 2.6 m amplitude arrives about 3 hours from the earthquake (see Q10). It should be noted, however, for Nootka grid (presented in previous section), the first tsunami wave was the largest compared to the trailing waves at most gauges, as a result of proximity to the Cascadia tsunami source. According to the time series, the largest peak occurs within 1.5 hour inside Nootka Sound while within 5 hours in Quatsino Sound.

Table 5: Tsunami maximum wave amplitudes and arrival times of Quatsino Sound for Cascadia Subduction Zone current-day scenario at selected numerical gauge points (GP) displayed in Figure 8.

GP	Location	First wave		Maximum wave	
		Arrival time HH:MM	Amplitude (m)	Arrival HH:MM	Amplitude (m)
Q1	Raft Cove	00:26	2.2	02:18	2.9
Q2	Grant Bay	00:22	2.1	03:25	2.8
Q3	Winter Harbour	00:35	1.1	03:34	1.9
Q4	Quatsino Sound entrance	00:18	0.7	03:29	1.4
Q5	Mahatta River mouth	00:30	0.7	02:45	1.4
Q6	Quatsino	00:38	0.5	02:54	1.7
Q7	Quatsino Narrows	00:45	0.8	04:51	1.4
Q8	Coal Harbour	01:22	0.3	01:40	0.4
Q9	Holberg	01:35	0.5	03:28	0.8
Q10	Port Alice	00:57	1.4	03:02	2.7
Q11	Port Alice terminal	01:00	2.1	03:05	2.6

5.1.2. Tsunami-induced current velocities

The maximum tsunami-induced currents for Cascadia event is shown in Figure 12. As a result of proximity to the Cascadia Subduction Zone, the tsunami-induced currents are generally higher toward the southern parts of the broader study area, in particular, from Brooks Peninsula toward south, including Nootka Sound. In contrast, from Brooks Peninsula to Cape Scott in the northmost of Vancouver Island, including Quatsino Sound, tsunami-induced currents reduce along the coast by distancing from Cascadia tsunami source. On average, tsunami-induced currents offshore of Nootka Sound entrance is up to 2m/s while offshore of Quatsino Sound is lower than 1m/s. Quantitative tsunami-induced currents of Nootka Sound and Quatsino Sound from Cascadia event are discussed below.

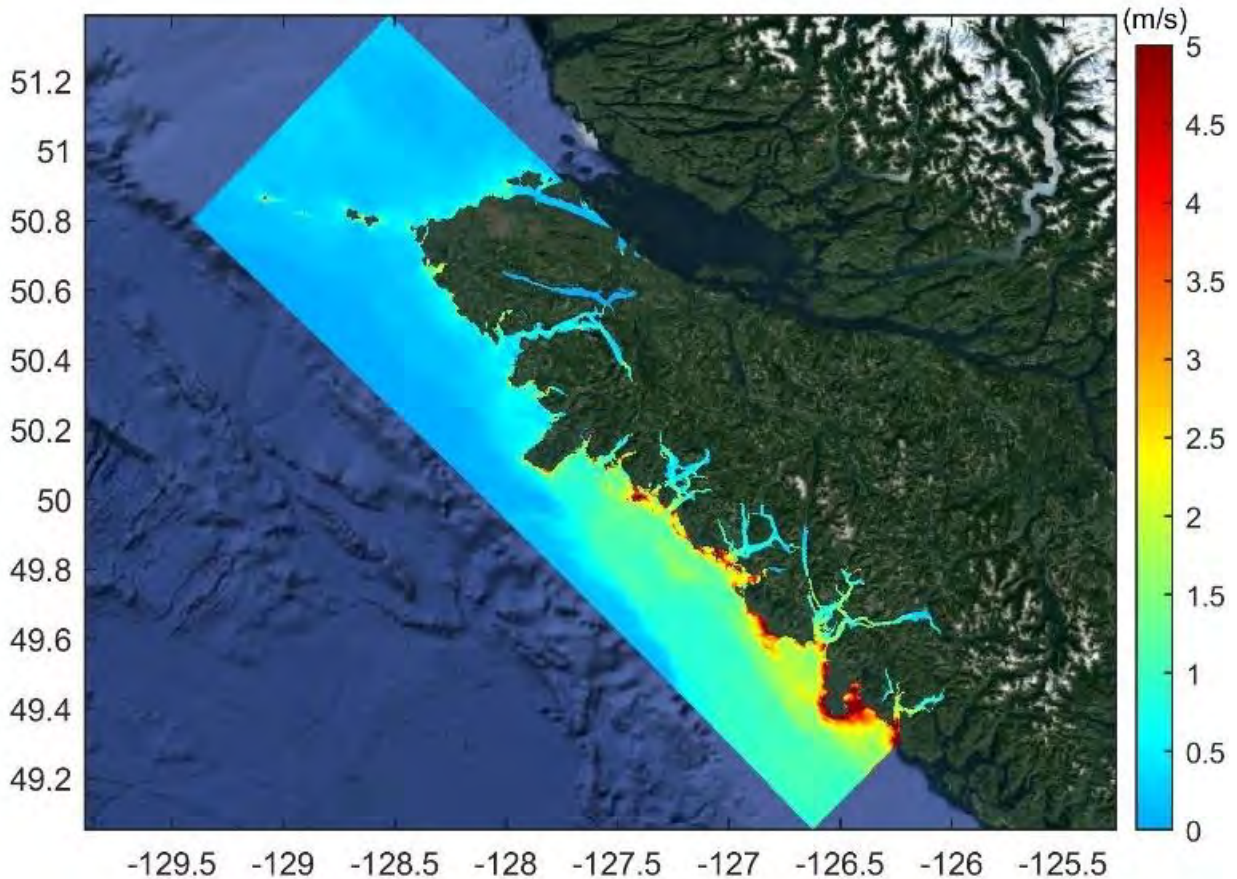


Figure 12: Maximum tsunami current velocities along Northwest Vancouver Island coasts for Scenario 1: Cascadia Subduction Zone current-day resulted from the 10 m resolution simulation.

Nootka Sound

The maximum tsunami-induced currents of the Cascadia tsunami simulation for Nootka Sound grid are shown in Figure 13. At entrance of Nootka Sound in deeper water, the tsunami currents of between 1.5 - 3 m/s estimated. However, at the sides of Nootka entrance due to its funnel shape and shallow depth the strong currents may exceed 5 m/s which, consistent with higher wave amplitude at these locations.

Within Nootka Sound tsunami-induced currents predicted in the range of 1-2 m/s at many regions. The tsunami currents, however, are stronger close to small island and narrow waterways. For example, in Hanna Channel close to Beligh Island tsunami-induced current of up to 5m/s are predicted. Similarly, at King and Williamson Passages in Muchalat Inlet in the vicinity of Gore Island where the tsunami wave propagates towards Gold River the tsunami-induced current larger than 5m/s are estimated.

In deep area of Gold River Terminal (i.e., greater than 100m), tsunami-induced currents less than 1m/s are predicted, however in shallower area and close to Gold River Highway larger tsunami currents about 2m/s are expected. In contrast, in Head Bay and Nesook Bay strong tsunami currents larger than 5m/s is estimated as the result of the shallower depth and wave runup over land. Please refer to the tsunami-induced current maps for additional details at specific areas of interest.

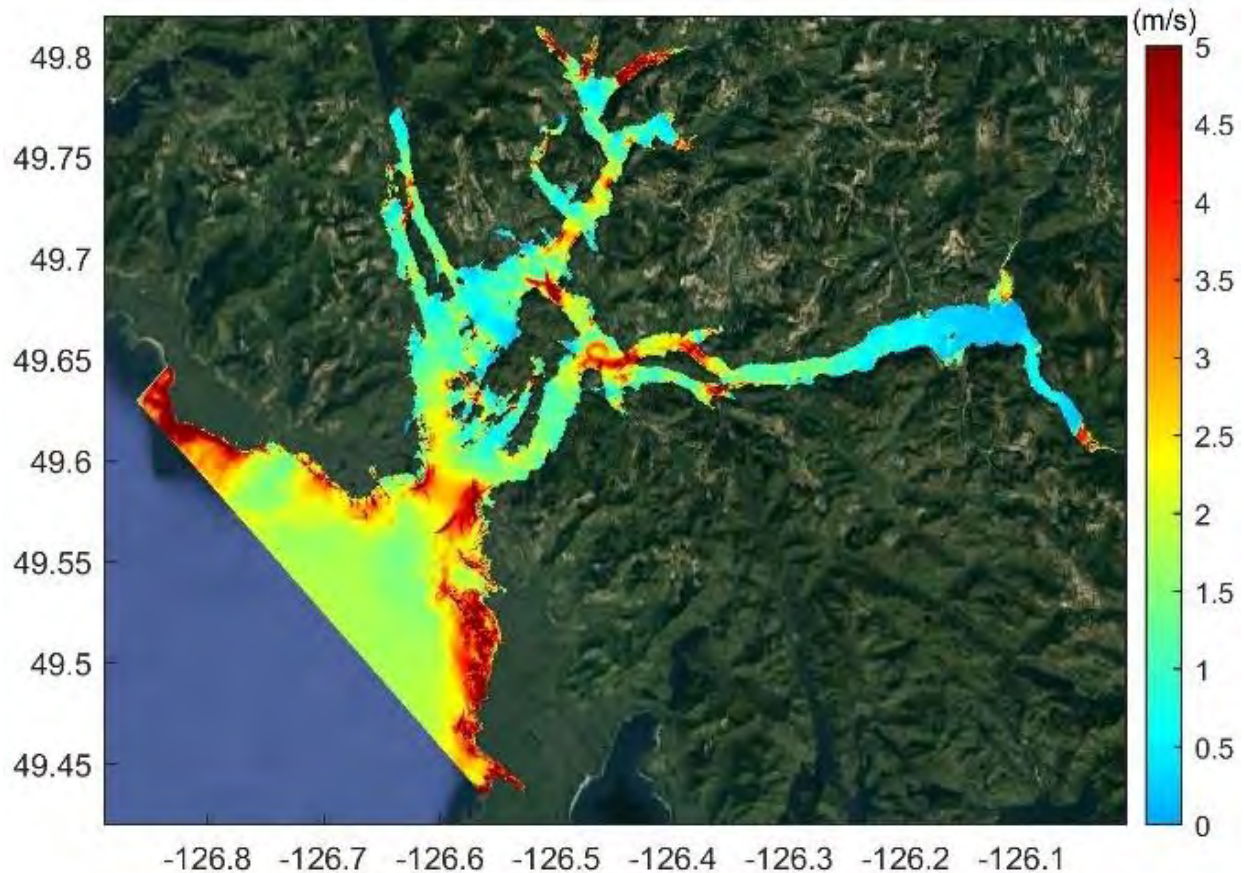


Figure 13: Maximum tsunami current velocities in Nootka Sound for Scenario 1: Cascadia Subduction Zone current-day resulted from the 10 m resolution simulation.

Quatsino Sound

The maximum tsunami-induced currents of the Cascadia tsunami in the Quatsino Sound is shown in Figure 14. In general, tsunami-induced currents in Quatsino Sound would be slower than Nootka Sound, as the result of the proximity with the Cascadia subduction zone and greater tsunami amplitude in Nootka Sound.

At northwest coast of Vancouver Island from Grant Bay toward north, the tsunami currents between 1.5 - 5 m/s is estimated, where recreational areas such as at Raft Cove are located. At entrance and inside the Quatsino Sound the tsunami currents of up to 1 m/s estimated. However, in narrow waterways, channels and close to small islands stronger tsunami currents are expected. For example, close to Quattische Island and Quatsino narrows tsunami currents larger than 3 m/s are estimated. Similarly, in Forward Inlet at Winter Harbour where the geometry is constricted and the depth is relatively shallow (e.g., about 20 m) strong currents larger than 5 m/s are simulated.

In Holberg Inlet, tsunami currents are small; for instance, in Coal harbour tsunami-induced currents are very small (less than 0.5 m/s), however, at the end of the inlet at Holberg it can exceed 1m/s. In Neroutsos Inlet where the tsunami wave propagates towards Port Alice,

tsunami-induced currents are up to about 0.5m/s, while in Port Alice terminal which has shallower depth the currents may exceed 3 m/s.

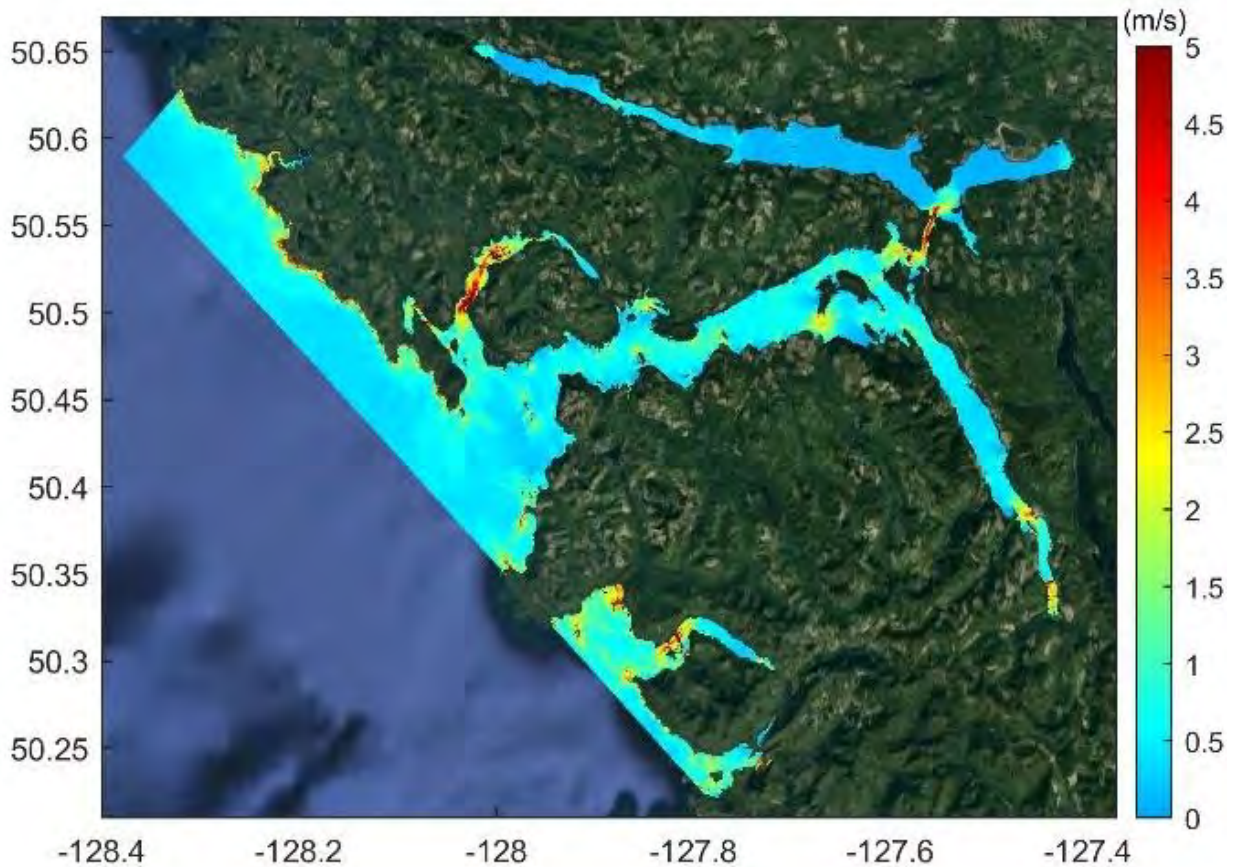


Figure 14: Maximum tsunami current velocities in Quatsino Sound for Scenario 1: Cascadia Subduction Zone current-day resulted from the 10 m resolution simulation.

5.2. Alaska-Aleutian Subduction Zone

5.2.1. Tsunami wave amplitude

The maximum tsunami wave amplitudes from Alaska event are illustrated in Figure 15. Unlike the Cascadia scenario, the maximum tsunami amplitudes are almost uniform in the range of 1 to 2 m along the western coast of Vancouver Island. This is due the tsunami propagation from a distant source, maintaining the physical characteristics of the waves almost unchanged along Vancouver Island coasts. More details regarding the maximum tsunami wave amplitude and arrival time of Nootka Sound and Quatsino Sound from Alaska event are discussed below.

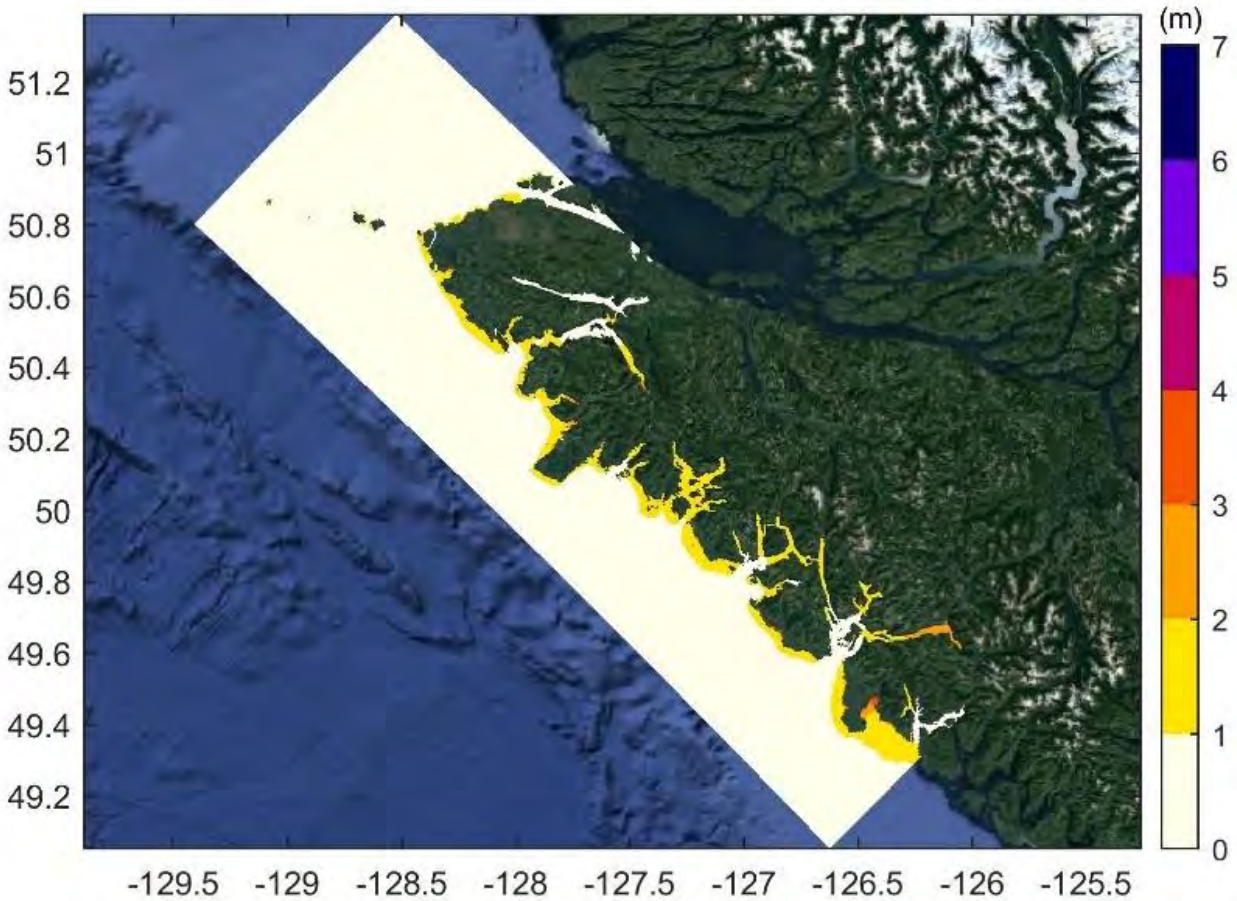


Figure 15: Maximum tsunami wave amplitude along Northwest Vancouver Island coasts for Scenario2: Alaska-Aleutian current-day resulted from the 60 m resolution simulation.

Nootka Sound

Figure 16 shows the maximum wave amplitudes resulted from the high-resolution simulation (10m) in Nootka Sound for an Alaska tsunami. The predicted amplitudes of the leading and maximum waves, as well as corresponding arrival times at selected GPs (N1 – N7) are listed in Table 6. This information was obtained from the time series of the water surface elevation (See Annexe A.3)

The wave amplitude at Nootka sound entrance (N1) is estimated up to 1m at the inner parts of the passage and up to 2 m at the sides of the passage. The wave amplitude will remain up to 1m at Yuquot, McKay Passage, Cheesish, and Critter Cove as well as at Eliza Passage (N2). While it amplifies to 1.2 m at Kendrick Camp (N3) and Cougar Creek (N4).

As the tsunami waves propagate towards the end of the inlets, the tsunami waves are amplified due to shoaling and potential resonance. At Head Bay (N5), the maximum wave amplitude of about 1.6m and at Gold River waterfront (N7), an amplitude of 3.2m is predicted. Similar to Cascadia tsunami in Muchalat Inlet, 10m resolution model results predict larger wave amplitude compared to 60m resolution model results.

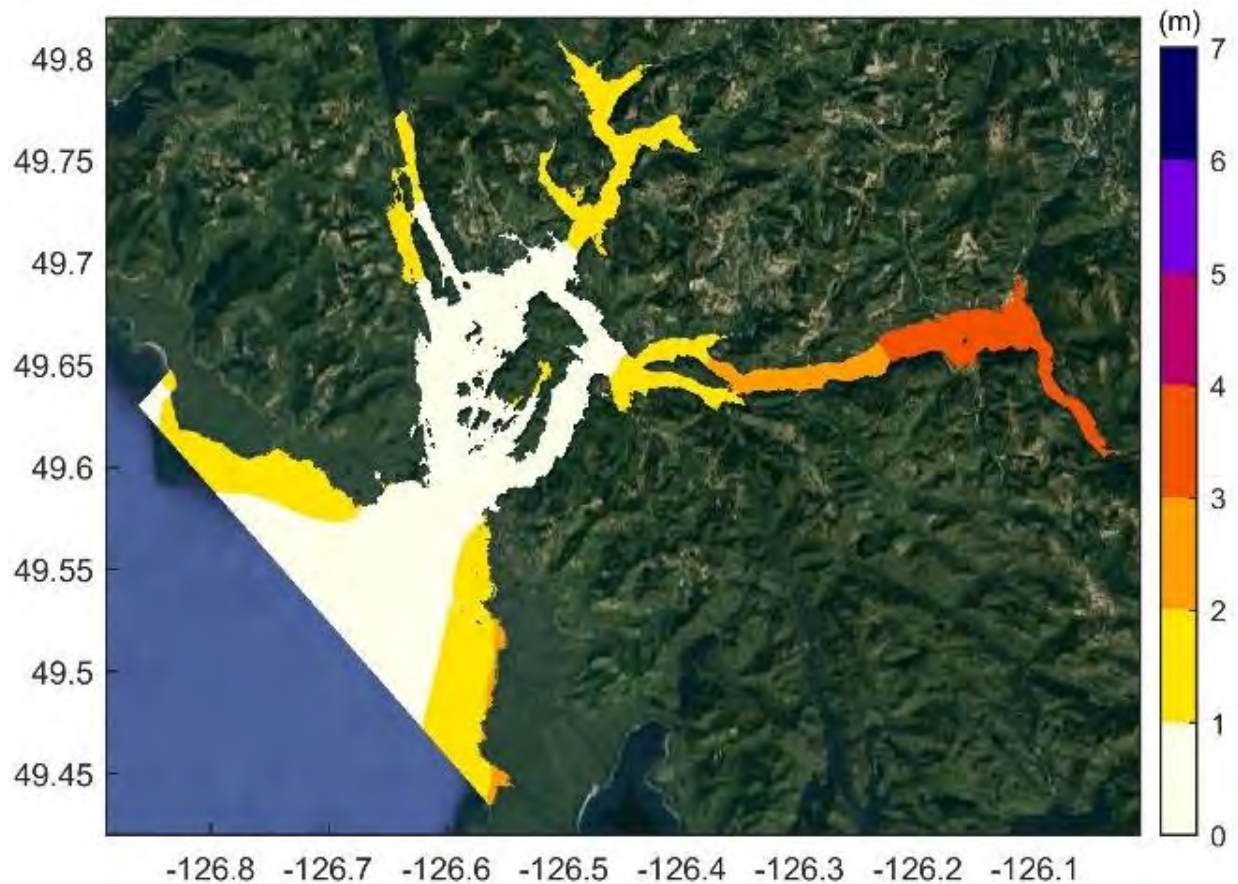


Figure 16: Maximum tsunami wave amplitude in Nootka Sound for Scenario2: Alaska-Aleutian current-day resulted from the 10m resolution simulation.

It is expected the first tsunami wave to arrive to all GPs after about 3 hours. The trailing waves may be larger compared to the first tsunami wave. For example, Gold River waterfront (N7) experiences a maximum wave amplitude of 3.2 m after about 7hr:12min.

Table 6: Tsunami maximum wave amplitudes and arrival times of Nootka Sound for Alaska-Aleutian current-day scenario at selected numerical gauge points (GP) displayed in Figure 8.

GP	Location	First wave		Maximum wave	
		Arrival time HH:MM	Amplitude (m)	Arrival time HH:MM	Amplitude (m)
N1	Nootka Sound entrance	03:13	0.8	07:38	0.9
N2	Eliza Passage	03:27	0.7	06:52	0.9
N3	Kendrick Inlet	03:29	1	06:55	1.2
N4	Cougar Creek mouth	03:32	0.9	05:33	1.2
N5	Head Bay	03:36	1.5	05:35	1.6
N6	Zucariate Channel	03:21	0.6	06:56	0.8
N7	Gold River waterfront	03:44	1.1	07:12	3.2

Quatsino Sound

Figure 17 shows the maximum wave amplitudes resulted from the high-resolution simulation (10m) in Quatsino Sound for an Alaska tsunami. The predicted amplitudes of the leading and maximum waves, as well as corresponding arrival times at selected GPs (Q1 – Q11) are listed in Table 6. This information was obtained from the time series of the water surface elevation (See Annexe A.4).

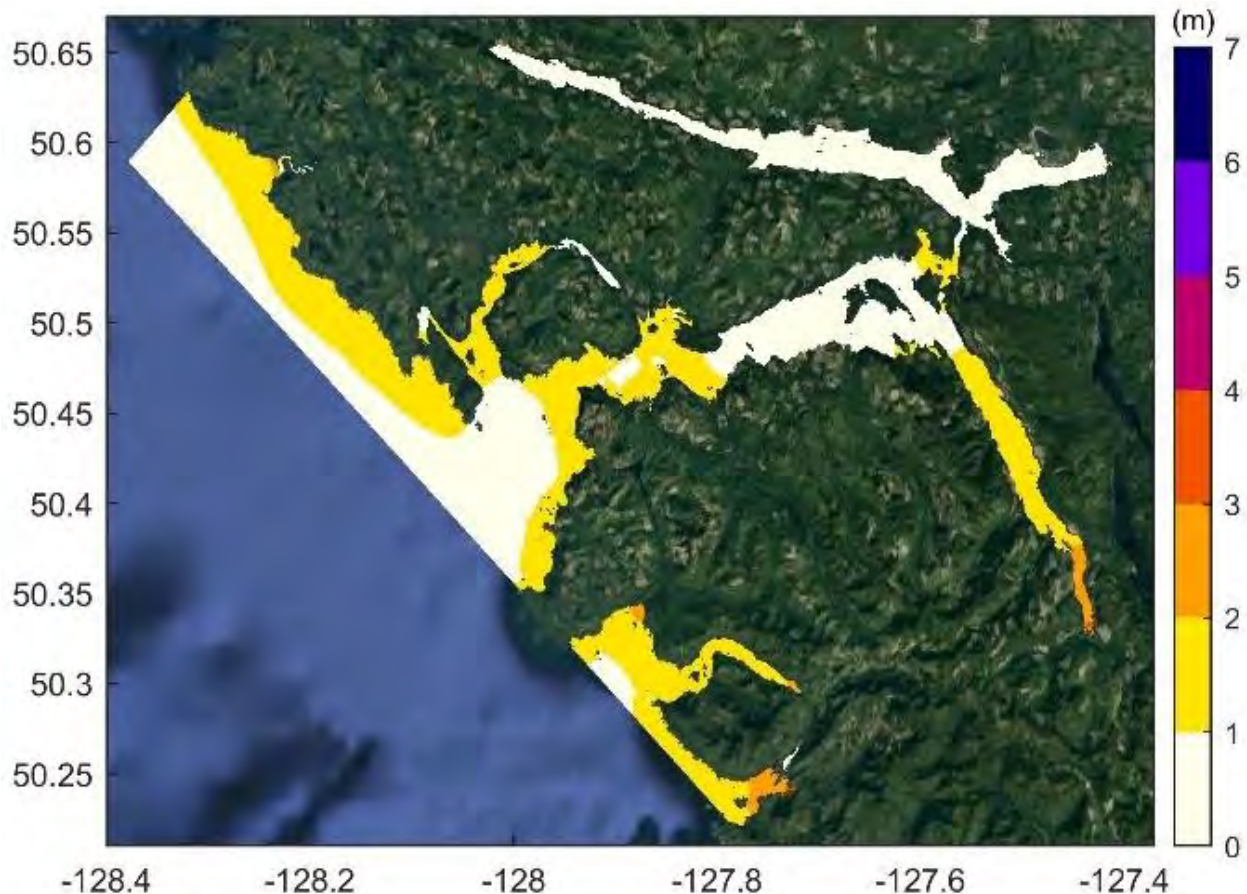


Figure 17: Maximum tsunami wave amplitude in Quatsino Sound for Scenario2: Alaska-Aleutian current-day resulted from the 10m resolution simulation.

Near to the coastlines of Northwest Vancouver Island the wave amplitude estimated to be between 1-2 m, for example, offshore of Raft Cove (Q1) and Grant Bay (Q2), the wave amplitude is estimated 1.8 m.

At the entrance the Quatsino Sound, wave amplitude is estimated up to about 1m for the Alaska tsunami (e.g., 0.8 m at Q4). The tsunami wave amplitudes are relatively consistent between 0-1 m at both 'Nootka Sound' and 'Quatsino Sound' entrances due to distance from the seismic source. Moving inside the sound, at Winter Harbour where the geometry is constricted and the depth is relatively shallow (e.g., about 20m) the wave amplitude of up to 2 m is estimated (e.g., 1.2 m at Q3). The wave amplitude at the Hamlet of Quatsino is about 0.9 m (Q6).

Within Holberg Inlet, the wave amplitudes are attenuated after passing through Quatsino Narrows. The wave amplitude at Coal Harbour (Q8) would be about 0.4m. At Holberg (Q9), the

10m resolution grid predicts larger wave amplitude (0.8 m) compared to 60m resolution grid, as the Quatsino Narrows is resolved more accurately with the higher resolution grid (10m).

The wave which travels from Drake Island towards Port Alice through Bochholz Channel and Neroutsos Inlet would be amplified due to shoaling in the shallower depths at the end of the Inlet. The maximum wave amplitude at Port Alice (Q10) and its Terminal (Q11) is estimated about 1.3 m and 1.8 m, respectively.

The first tsunami wave will arrive the entrance of Quatsino Sound after about 2hr:50min from the earthquake (Q4). While the first tsunami wave predicted to reach other gauges between 3-4 hours from the earthquake. The time series shows that the amplitude of the first tsunami wave is larger compared to the amplitude of the trailing waves at most gauges. However, Holberg (Q9) and Port Alice terminal (Q11) experience their largest amplitudes as trailing waves between 8-9 hours after the earthquake. Nevertheless, the difference between first wave and the maximum wave is not considerable, and the first wave arrival time may be used for emergency management and preparedness purposes in this case.

Table 7: Tsunami maximum wave amplitudes and arrival times of Quatsino Sound for Alaska-Aleutian current-day scenario at selected numerical gauge points (GP) displayed in Figure 8.

GP	Location	First wave		Maximum wave	
		Arrival time HH:MM	Amplitude (m)	Arrival time HH:MM	Amplitude (m)
Q1	Raft Cove	02:46	1.8	02:46	1.8
Q2	Grant Bay	02:48	1.8	02:48	1.8
Q3	Winter Harbour	02:58	1.2	02:58	1.2
Q4	Quatsino Sound entrance	02:47	0.8	02:47	0.8
Q5	Mahatta River mouth	02:58	1	02:58	1
Q6	Quatsino Hamlet	03:06	0.9	03:06	0.9
Q7	Quatsino Narrows	03:12	1	03:12	1
Q8	Coal Harbour	03:37	0.2	08:37	0.4
Q9	Holberg	03:45	0.3	09:04	0.8
Q10	Port Alice	03:16	1.3	03:16	1.3
Q11	Port Alice terminal	03:24	1.7	08:11	1.8

5.2.2. Tsunami-induced current velocities

The maximum tsunami-induced currents for Alaska event are illustrated in Figure 18. The distribution of tsunami-induced currents along the western coast of Vancouver Island due to the long distance from Alaska source is weaker and more uniform compared to the tsunami currents from Cascadia source when comparing Figures 18 and 12, for Alaska and Cascadia events, respectively. Although the predicted tsunami currents from Alaska event are considerably slower than Cascadia event, the behaviour of the current velocities is similar to those of the Cascadia event within Nootka Sound and Quatsino Sound. For instance, stronger current velocities at shallower, narrower, and constricted waterways and passages are estimated. This indicates that although the tsunami-induced currents of Alaska event are typically slower compared to Cascadia

event, hazardous velocities can still occur. Quantitative tsunami-induced currents of Nootka Sound and Quatsino Sound from Alaska event are discussed below.

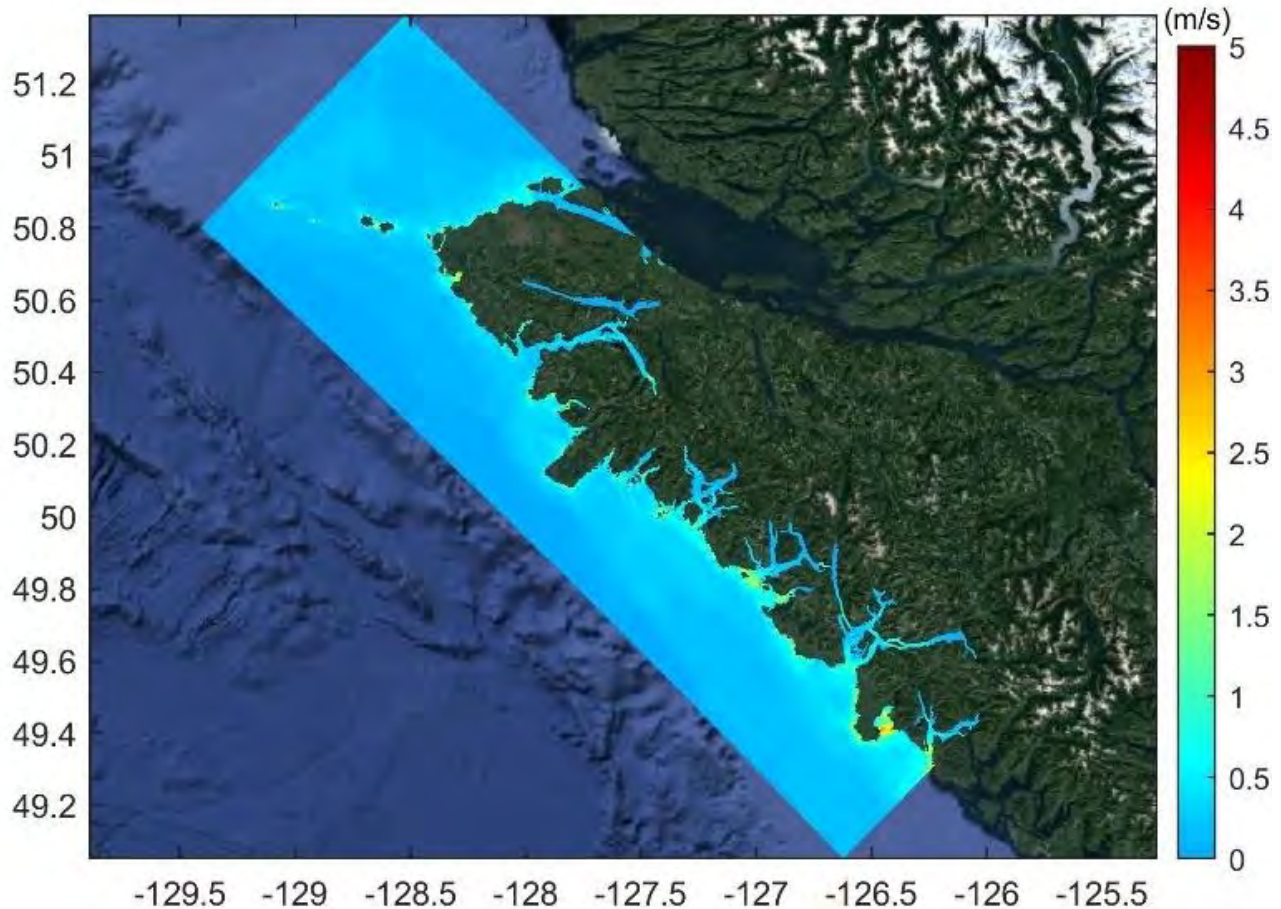


Figure 18: Maximum tsunami current velocities in Northwest Vancouver Island coasts for Scenario2: Alaska-Aleutian current-day resulted from the 60m resolution simulation.

Nootka Sound

The maximum tsunami-induced currents of the Alaska tsunami simulation for Nootka Sound grid is shown in Figure 19. At entrance of Nootka Sound in deep water (e.g., about 100m) the tsunami currents of up to 1 m/s estimated. However, at the sides of Nootka entrance due to its funnel shape and shallow depth the strong currents would reach up to 2 m/s which is consistent with the amplification of wave amplitude at these locations.

Within Nootka Sound tsunami currents of up to 1 m/s is estimated. For instance, in Critter cove, Cougar Creek, and Cheesish. While in Head Bay tsunami currents up to about 2m/s is estimated, as a result of shallower depth.

The tsunami currents are typically stronger close to small island and narrow waterways. For example, in Hanna Channel next to Beligh Island and Williamson Passage in Muchalat Inlet tsunami current of up to 2 m/s is predicted. In deep area of Gold River Terminal (e.g., greater

than 100m) tsunami currents less than 1m/s predicted, however, in shallower water at Gold River waterfront tsunami currents of up to 2 m/s are expected.

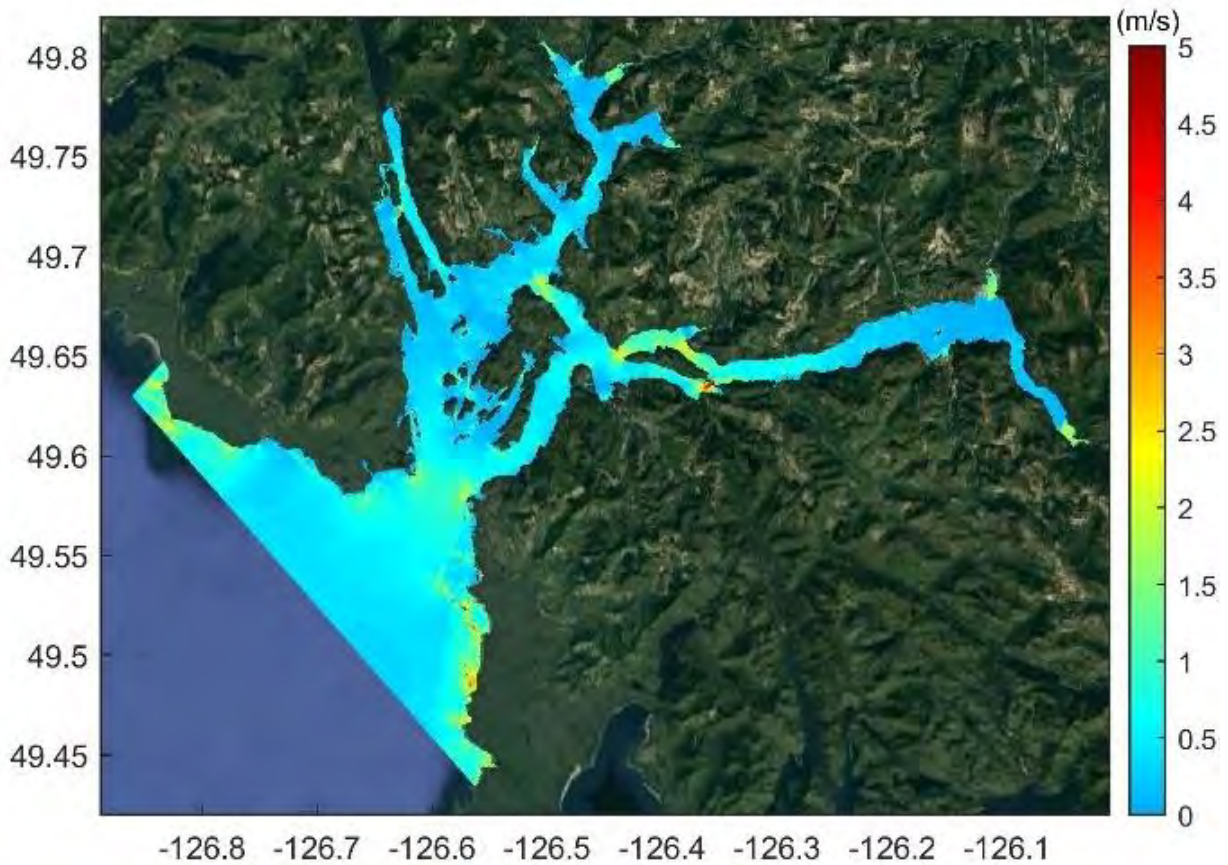


Figure 19: Maximum tsunami current velocities in Nootka Sound for Scenario2: Alaska-Aleutian current-day resulted from the 10m resolution simulation.

Quatsino Sound

The maximum tsunami-induced currents of the Alaska tsunami simulation for Quatsino Sound is shown in Figure 20. On the northwest coast of Vancouver Island from Grant Bay to toward north, the tsunami-induced currents between 1-3 m/s are estimated, where recreational areas such as Raft Cove are located. At the entrance of Quatsino Sound in deeper water (i.e., about 100m) the tsunami currents of about 0.3m/s are estimated. Inside Quatsino Sound tsunami currents are mainly in the range of 0-1 m/s. However, in narrow waterways, channels and close to small islands stronger tsunami currents are expected. For example, in the vicinity of Quattische Island and in Quatsino narrows tsunami currents exceed 2 m/s. Similarly, in Forward Inlet at Winter Harbour South where the geometry is constricted and the depth is relatively shallow (e.g., about 20m) strong currents up to and greater than 3 m/s are predicted.

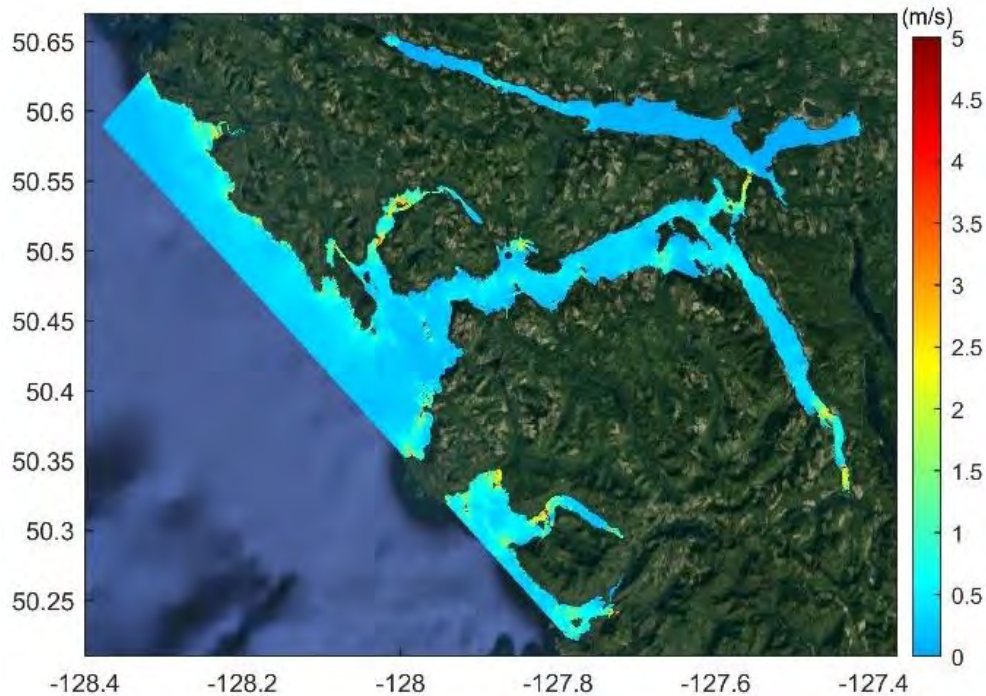


Figure 20: Maximum tsunami current velocities in Quatsino Sound for Scenario2: Alaska-Aleutian current-day resulted from the 10m resolution simulation.

In Holberg Inlet, tsunami-induced currents are small (e.g., less than 0.5 m/s in Coal harbour) and at the end of the inlet at Holberg, it can reach to 1 m/s. In Neroutsos Inlet where the tsunami wave propagates towards Port Alice tsunami-induced currents may exceed 0.5m/s, while in Port Alice terminal with shallower depth the currents would reach up to 3 m/s.

5.3. Future sea level rise

As discussed in Section 4.6, 1.2m of relative Sea Level Rise (SLR) was applied for tsunami modelling for both local and distant tsunami sources. Tsunami modelling results for SLR scenario from Cascadia and Alaska events are presented in Annexes B and C, respectively.

The results show that the inclusion of SLR scenarios (1.2 m) has little influence on the amplitude of the tsunami waves at offshore locations compared to present-day scenario (i.e. no SLR included). Also, the rise in sea level will only weakly change the distribution of tsunami induced currents at offshore locations, although deeper water (SLR scenario) has a tendency to reduce tsunami-induced currents.

Although the SLR does not appear to change the offshore tsunami wave amplitudes substantially, it can cause larger inundation extents and impact communities, specially, in low-lying areas of the region.

For detailed comparison of the water surface elevations from SLR scenario with present-day scenario of the Cascadia and Alaska events, offland numerical gauge points within each high-resolution grid were selected from Table 3. Comparison of the time series of water surface elevation for those gauge points for both Cascadia and Alaska events are presented in Annexes B.3-4, and C.3-4, respectively. The comparison indicates that the tsunami parameters including wave amplitudes and their arrival time for a future tsunami (i.e., 1.2m SLR) are almost similar regardless of minor differences compared to the present-day condition.

5.4. Limitations

The main source of uncertainties in tsunami modelling are due to the tsunami seismic source including uncertainties associated with the structure and vertical displacements of a future subduction zone earthquake scenario.

While Boussinesq models consider physical wave dispersion, they are computationally more demanding compared to SWE models. Furthermore, addressing numerical instabilities in Boussinesq models, which often stems from sharp changes in bathymetry, can be challenging. To address such issue, wave dispersion was neglected in the 10 m simulations, and the modelling was effectively performed based on the nonlinear shallow water equations. As tsunami waves are mainly comprised of long waves, this simplification is not expected to have a considerable influence on the results.

6. SUMMARY

This report was prepared by Ocean Networks Canada (ONC) as part of the Northwest Vancouver Island Tsunami Risk Assessment project for the Strathcona Regional District (SRD) in collaboration with Northwest Hydraulic Consultants (NHC). The project was divided into two phases due to the extensive geographic area of Northwest Vancouver Island. The first phase, completed in 2022, focused on communities in Kyuquot Sound, Tahsis Inlet, and Esperanza Inlet. This report specifically covers phase II of the project and presents tsunami modelling results for Nootka Sound and Quatsino Sound. The study area within phase II includes the communities of Gold River (waterfront), Port Alice, Winter Harbour, Hamlet of Quatsino, Holberg, as well as the Quatsino First Nation and Mowachaht/Muchalaht First Nations.

In this work, high resolution tsunami modelling was performed to assess the tsunami hazard for two earthquake events: Cascadia Subduction Zone (Mw: 9.0) and Alaska Subduction Zone (Mw: 9.2). Both earthquake scenarios were simulated corresponding to current-day sea level and 1.2 m future relative Sea Level Rise (SLR).

The simulations were conducted using FUNWAVE-TVD version 3.4, a fully nonlinear and dispersive Boussinesq wave model, on a nested grid with resolutions of 2 arcminutes, 30 arcseconds, 240m, 60m, and 10m. Digital elevation models (DEMs) were developed for the study area at resolutions of 240m, 60m, and 10m, relative to the Canadian Geodetic Vertical Datum CGVD2013, using various available or collected bathymetric and topographic data sources. All simulations were performed at the High High Water Mean Tide (HHWMT) level, which was determined to be 1.5m above the CGVD2013 level.

The results indicated that tsunami waves generated by the Cascadia earthquake event are larger, particularly within Nootka Sound, and have a more significant impact on the study area compared to the Alaska tsunami. The first tsunami wave would reach most study sites between 30 min to 1 hour for the Cascadia earthquake and between 2h:46min to 3h:30min for the Alaska earthquake. The following sections provide a summary of the modelling results for the study areas during the Cascadia and Alaska events.

Cascadia Subduction zone

The maximum tsunami wave amplitudes within Nootka Sound range from 2-4 m in most areas, with amplification occurring towards the end of the inlets. The Gold River waterfront and Head Bay encounter elevated wave amplitudes, reaching up to 6m and exceeding 8 m, respectively. The first tsunami wave arrives at Nootka Sound communities in less than an hour from the earthquake.

In Quatsino Sound, tsunami wave amplitudes vary between 1-2 m, while along the open coasts of the Northwest of Vancouver Island, they range from 2-3 m. Semi-enclosed bays and inlets experience increased amplitudes such as Grant Bay, Winter Harbour and Port Alice Terminal having maximum amplitudes of up to 3 m.

Tsunami-induced currents are stronger from Brooks Peninsula towards Nootka Sound, exceeding 5 m/s at the open coast of Nootka Sound entrance, while currents at Quatsino Sound entrance are less than 2 m/s. Within Nootka Sound, currents range from 1-2 m/s, with stronger velocities exceeding 5 m/s in some of the narrower waterways and passages. In Quatsino Sound, currents are generally slower, ranging from 0-1 m/s, with stronger currents exceeding 5 m/s in specific areas like Quatsino Narrows and Winter Harbour.

Alaska-Aleutian Subduction Zone

The maximum tsunami wave amplitudes along the western coast of Vancouver Island range from 1-2 m. Within Nootka Sound, the maximum wave amplitudes are generally around 1 m, but they amplify at the Muchalat Inlet up to 4 m and Tlupana Inlet up to 2 m. The first tsunami wave is expected to reach Nootka Sound communities within 3-4 hours.

In Quatsino Sound, the maximum wave amplitudes predicted up to 1 m, but they increase in semi-enclosed bays and inlets such as Grant Bay and Neroutsos Inlet up to and above 2 m. The first tsunami wave would reach most Quatsino Sound communities approximately 3 hours after the Alaska event, and the initial peak wave is larger compared to trailing waves in most locations. Tsunami-induced currents along the coast are weaker for the Alaska event compared to the Cascadia event, but they still pose hazards in areas with shallower depth, narrower topography, and constricted passages.

Within Nootka Sound and Quatsino Sound, tsunami-induced currents range from 0-1 m/s, but higher velocities are estimated in specific locations such as William passage in Nootka Sound and Quatsino narrows and Winter Harbour in Quatsino Sound.

The study also suggests that sea level rise scenarios may not significantly alter tsunami wave amplitudes offshore and near the shoreline, but they can increase wave run-up and inundation extents during future tsunamis.

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ANNEXE A: TIME SERIES OF WATER SURFACE ELEVATION
A.1 Cascadia subduction zone, Nootka Sound

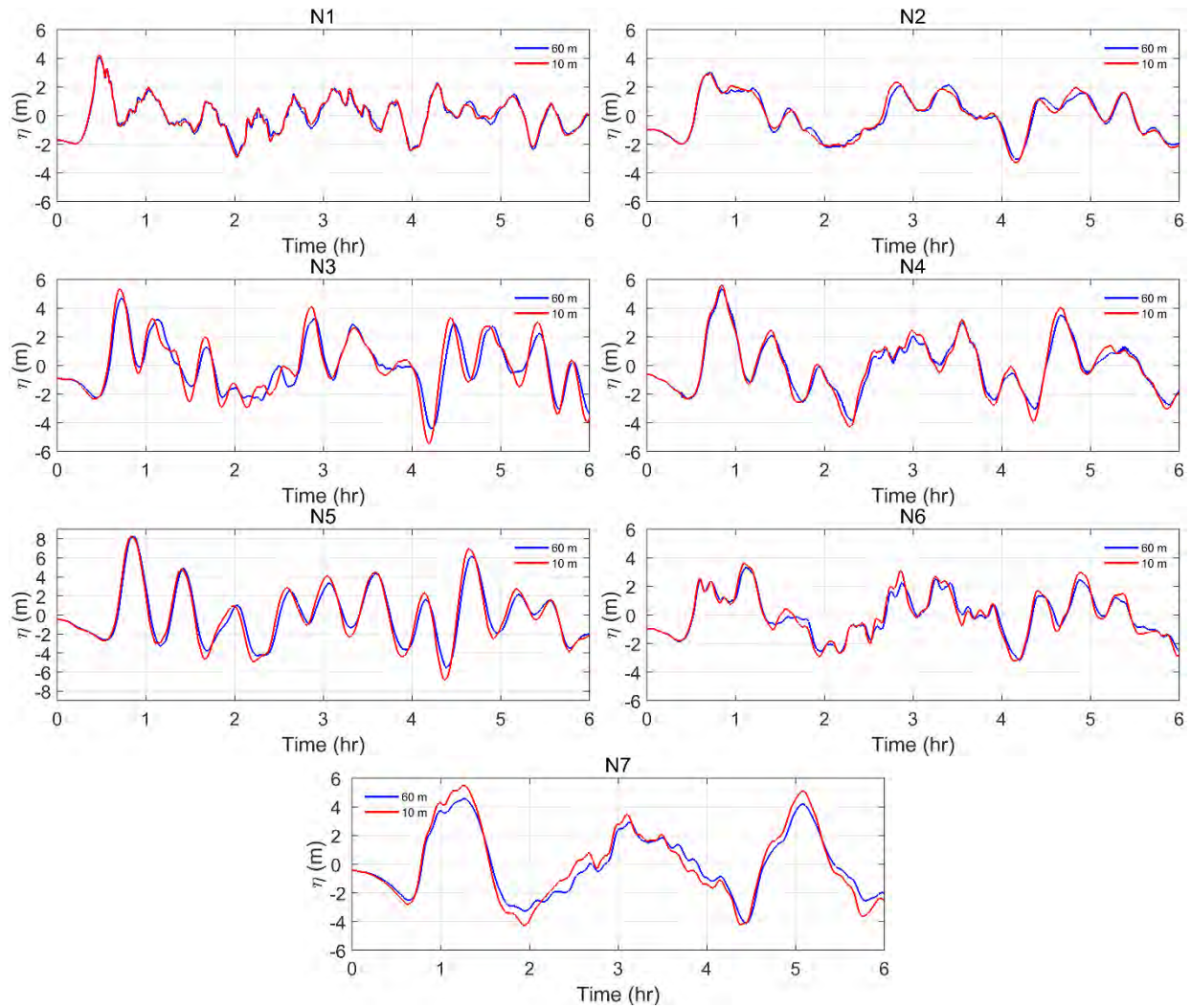


Figure A.1. Time series of water surface elevation for selected numerical gauge points of Nootka grid from Cascadia tsunami source using 60m and 10m resolutions. The water surface elevation (η) is with respect to HHWMT.

A.2 Cascadia subduction zone, Quatsino Sound

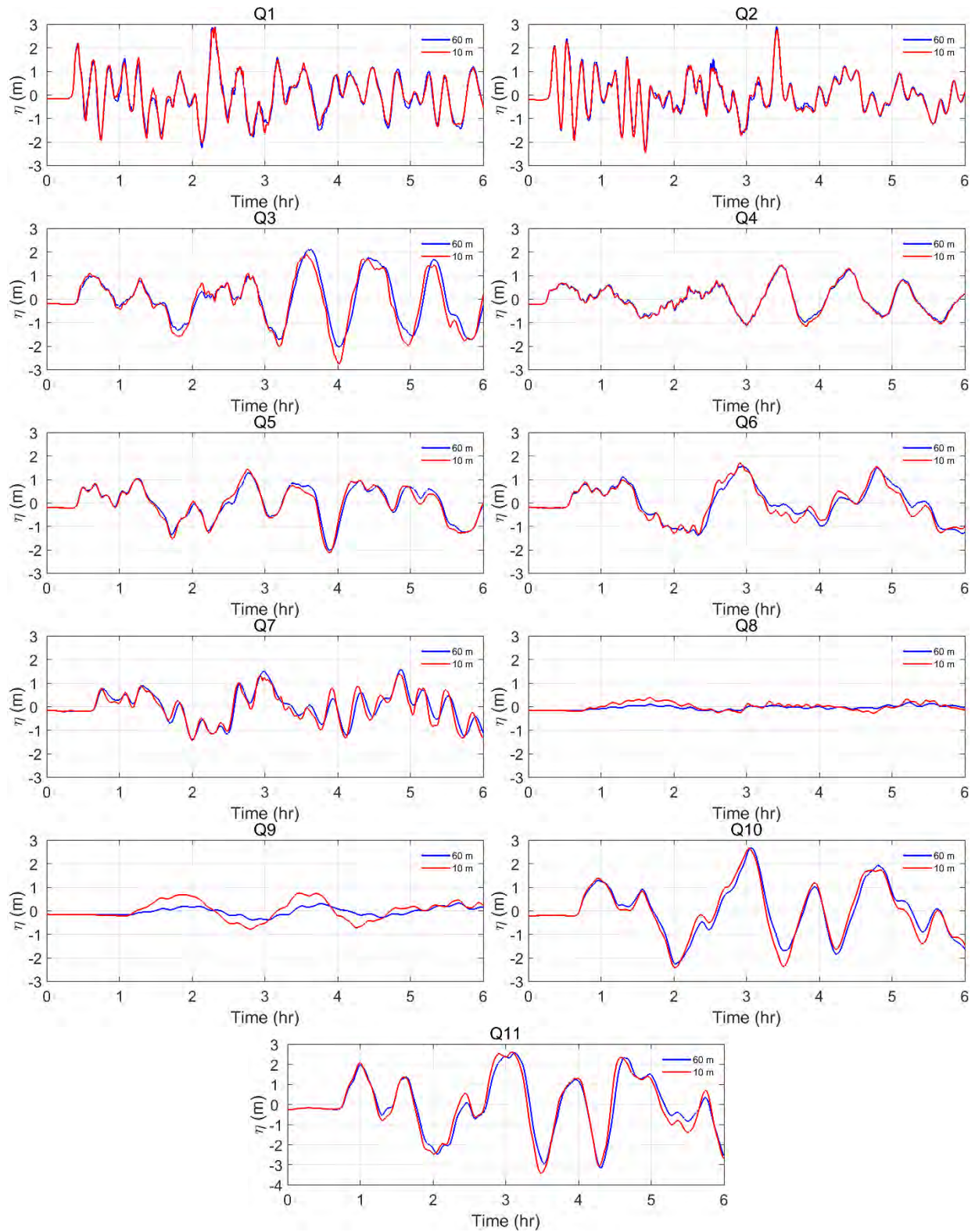


Figure A.2. Time series of water surface elevation for selected numerical gauge points of Quatsino grid from Cascadia tsunami source using 60m and 10m resolutions. The water surface elevation (η) is with respect to HHWMT.

A.3 Alaska-Aleutian subduction zone, Nootka Sound

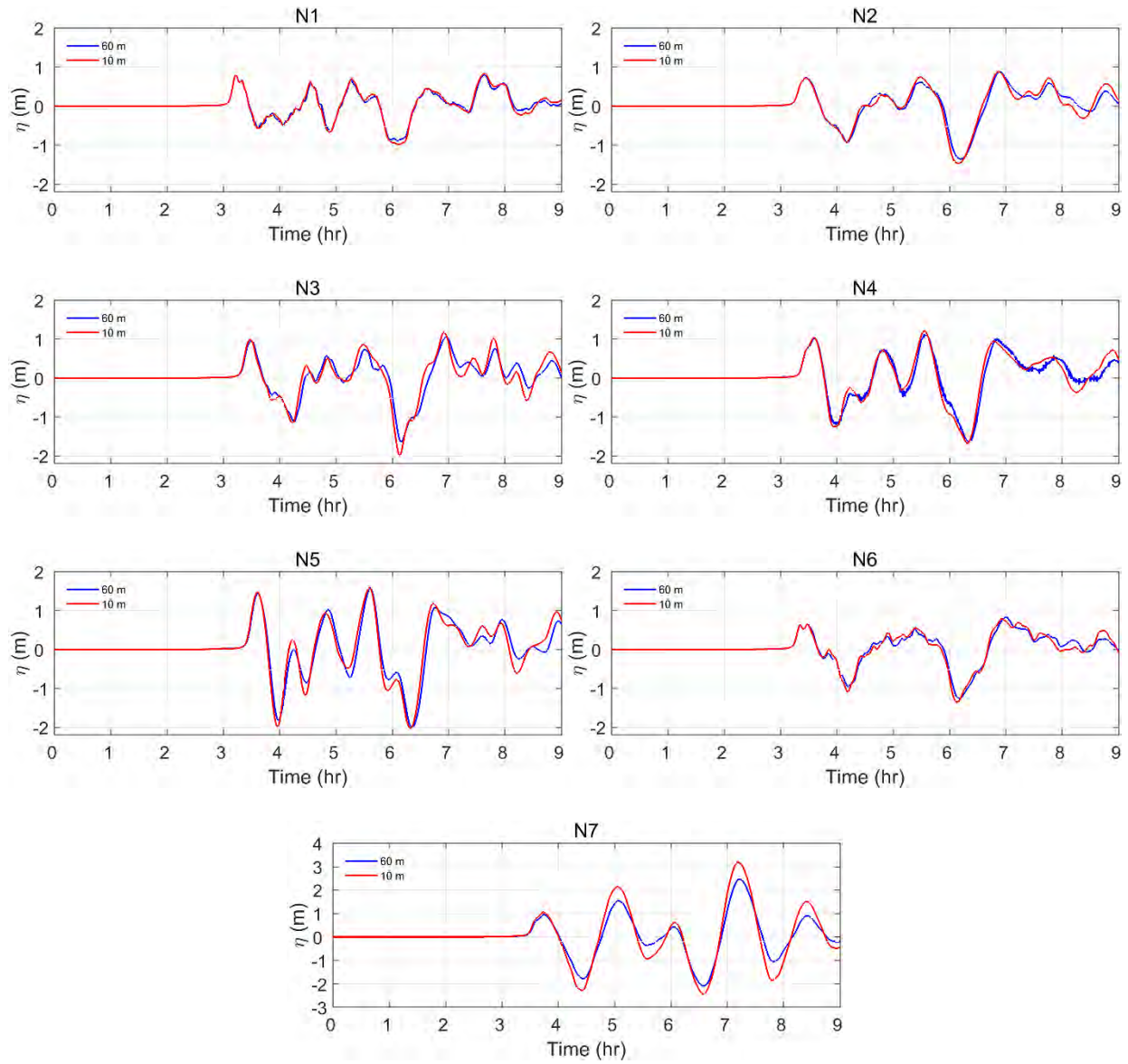


Figure A.3. Time series of water surface elevation for selected numerical gauge points of Nootka grid from Alaska tsunami source using 60m and 10m resolutions. The water surface elevation (η) is with respect to HHWMT.

A.4 Alaska-Aleutian subduction zone, Quatsino Sound

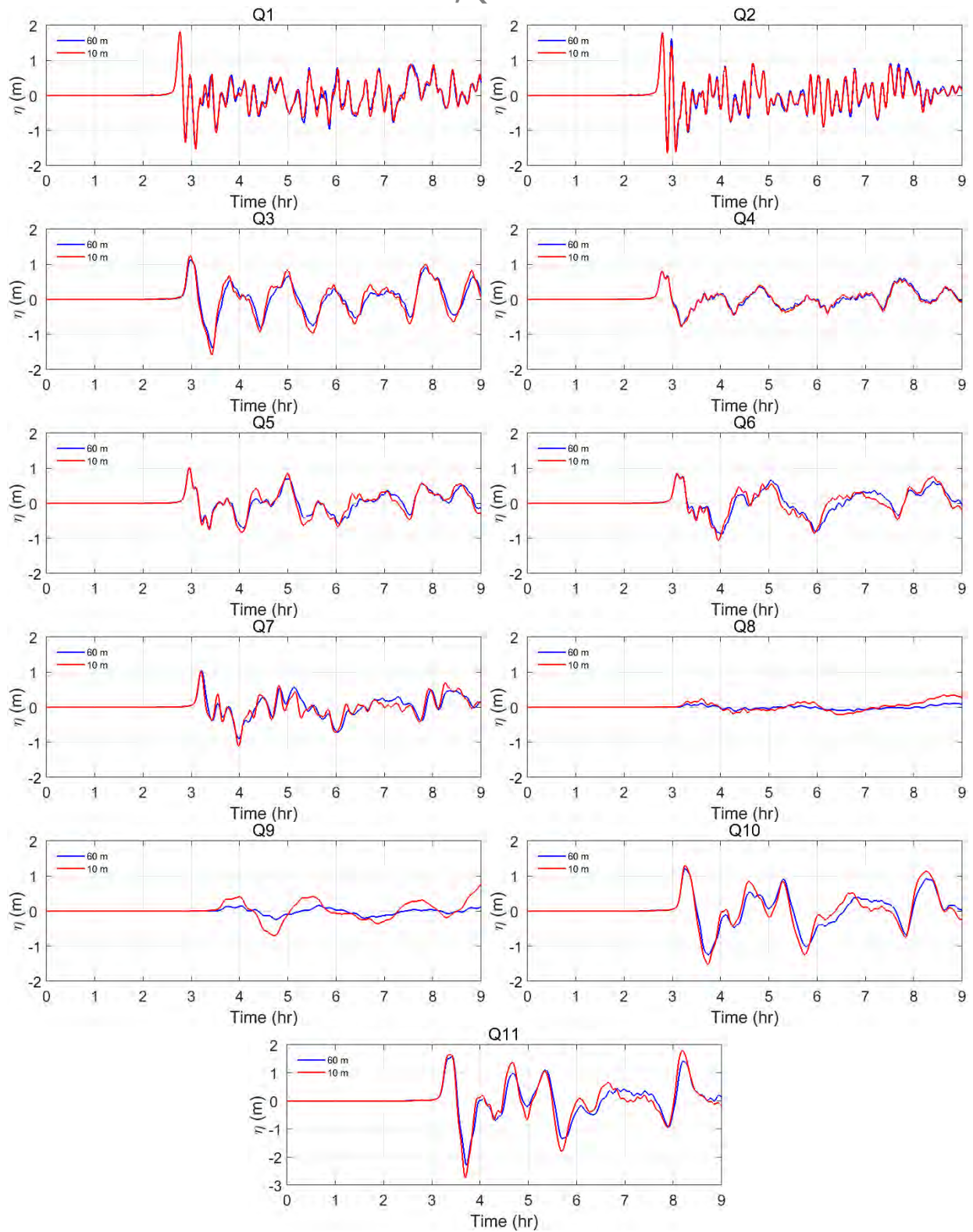


Figure A.4. Time series of water surface elevation for selected numerical gauge points of Quatsino grid from Alaska tsunami source using 60m and 10m resolutions. The water surface elevation (η) is with respect to HHWMT.

ANNEXE B: CASCADIA SUBDUCTION ZONE, SEA LEVEL RISE RESULTS

B.1 Tsunami wave amplitude

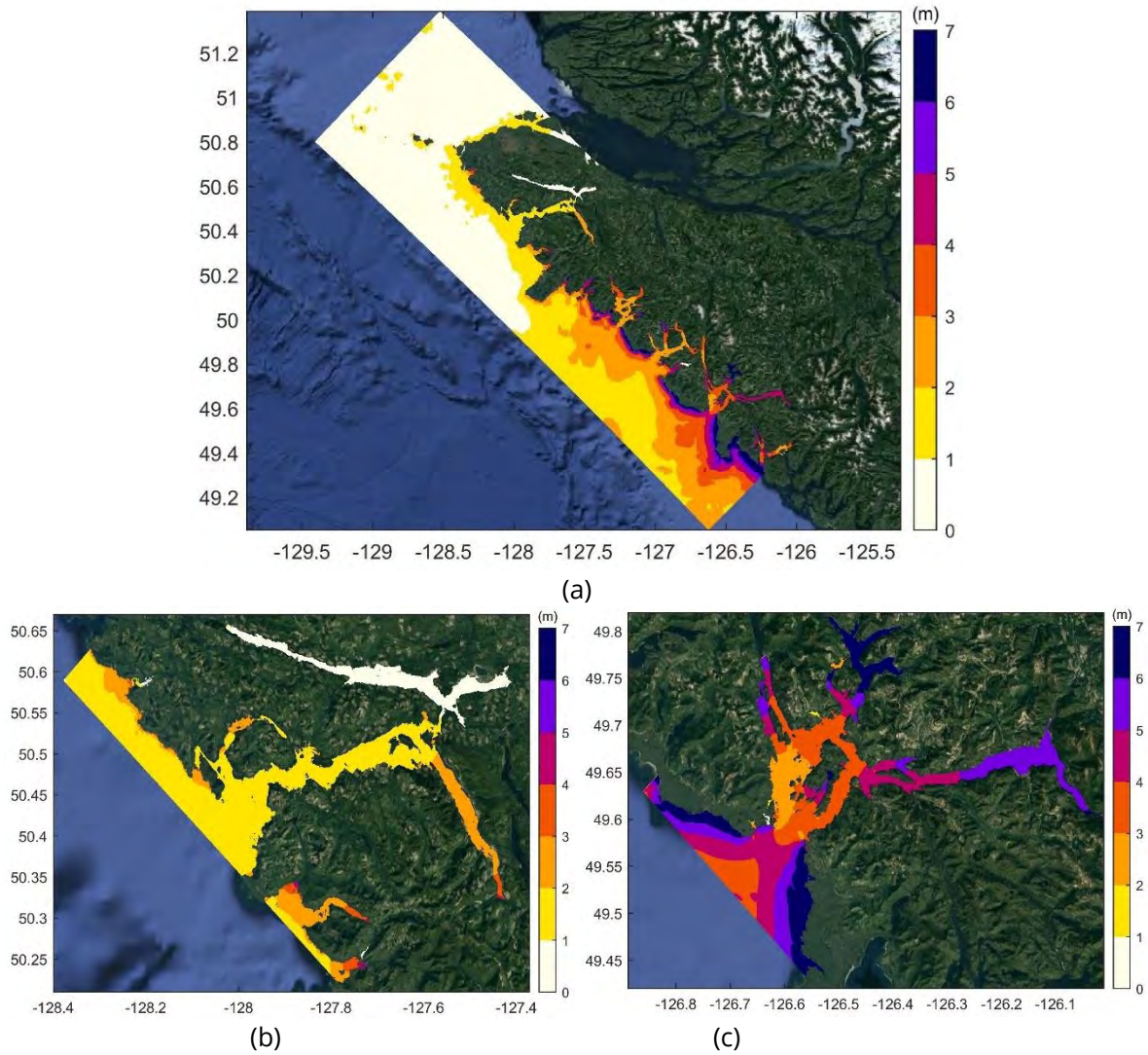


Figure B1: Maximum tsunami wave amplitudes for Scenario3: Cascadia Subduction Zone with 1.2m SLR a) 60 m resolution grid, b) 10m resolution grid of Quatsino, and c) 10m resolution grid of Nootka.

B.2 Tsunami-induced currents

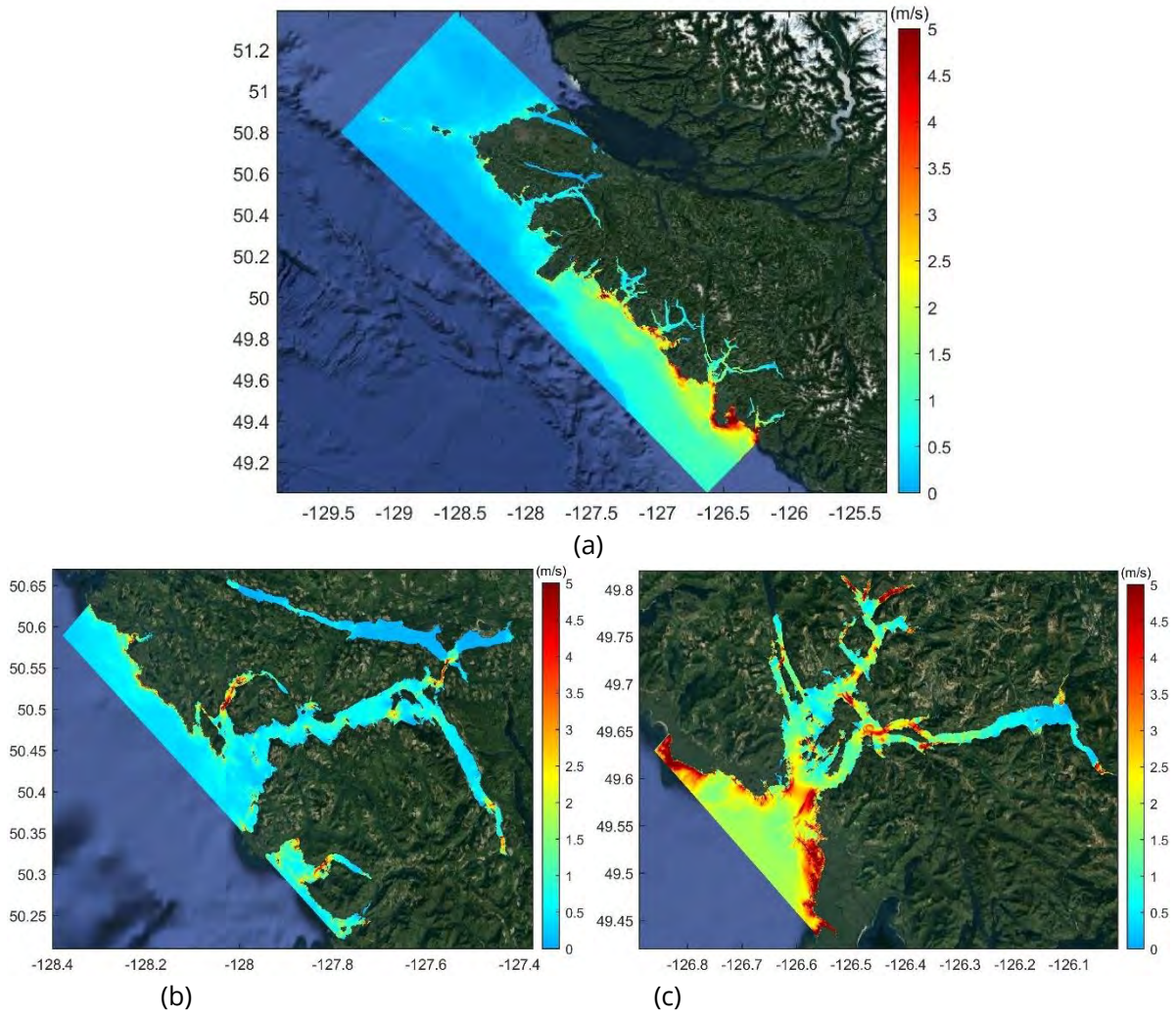


Figure B2: Maximum tsunami current velocities for Scenario3: Cascadia Subduction Zone with 1.2m SLR a) 60 m resolution grid, b) 10m resolution grid of Qautsino, and c) 10m resolution grid of Nootka.

B.3 Time series of water surface elevation, of Nootka Sound (0m, 1.2m SLR comparison)

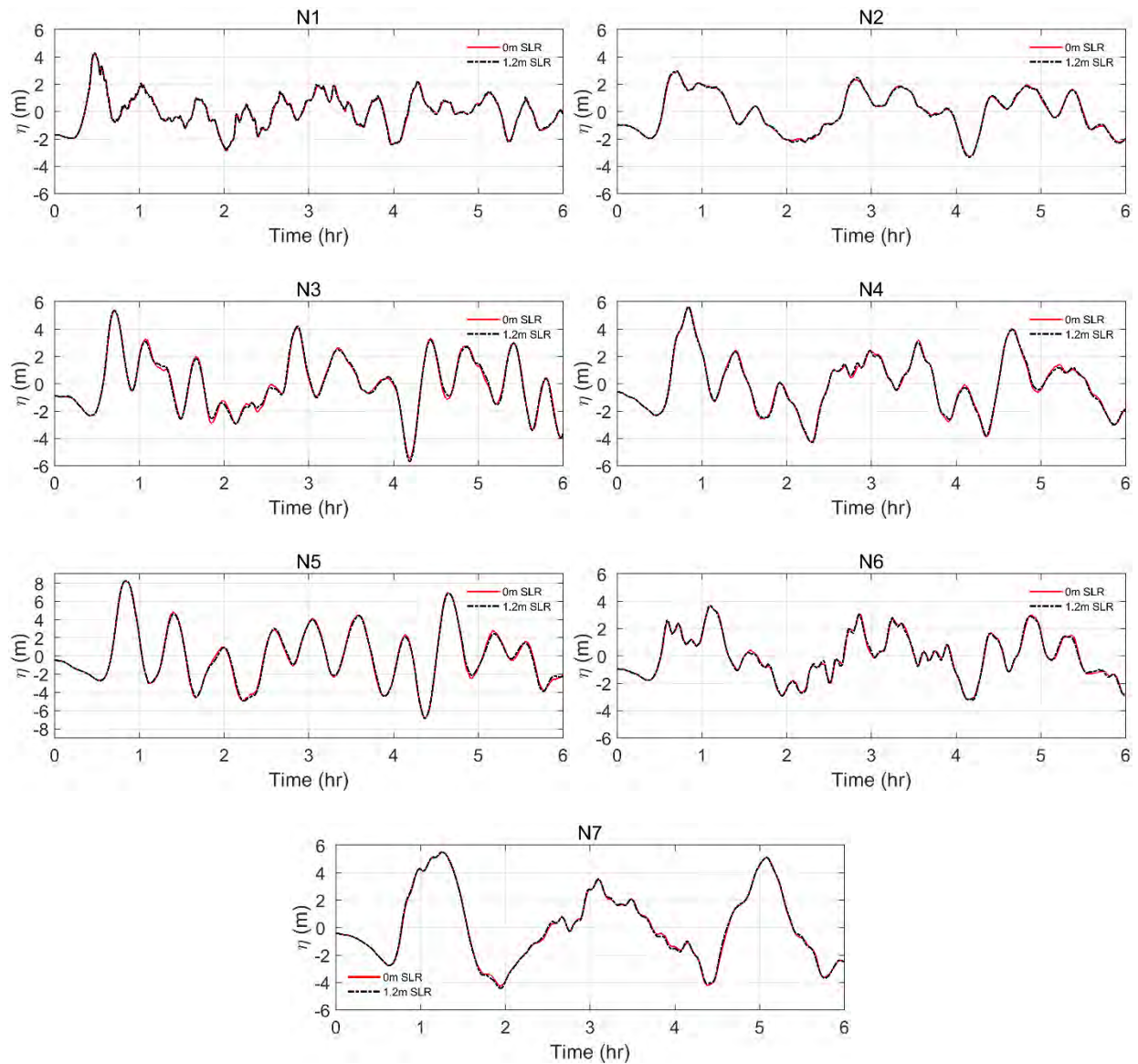


Figure B.3: Time series of water surface elevation for selected numerical gauge points of Nootka grid for present-day (0m SLR) and future scenario (1.2m SLR) from Cascadia tsunami source. The water surface elevation (η) is with respect to HHWMT.

B.4 Time series of water surface elevation, of Quatsino Sound (0m, 1.2m SLR comparison)

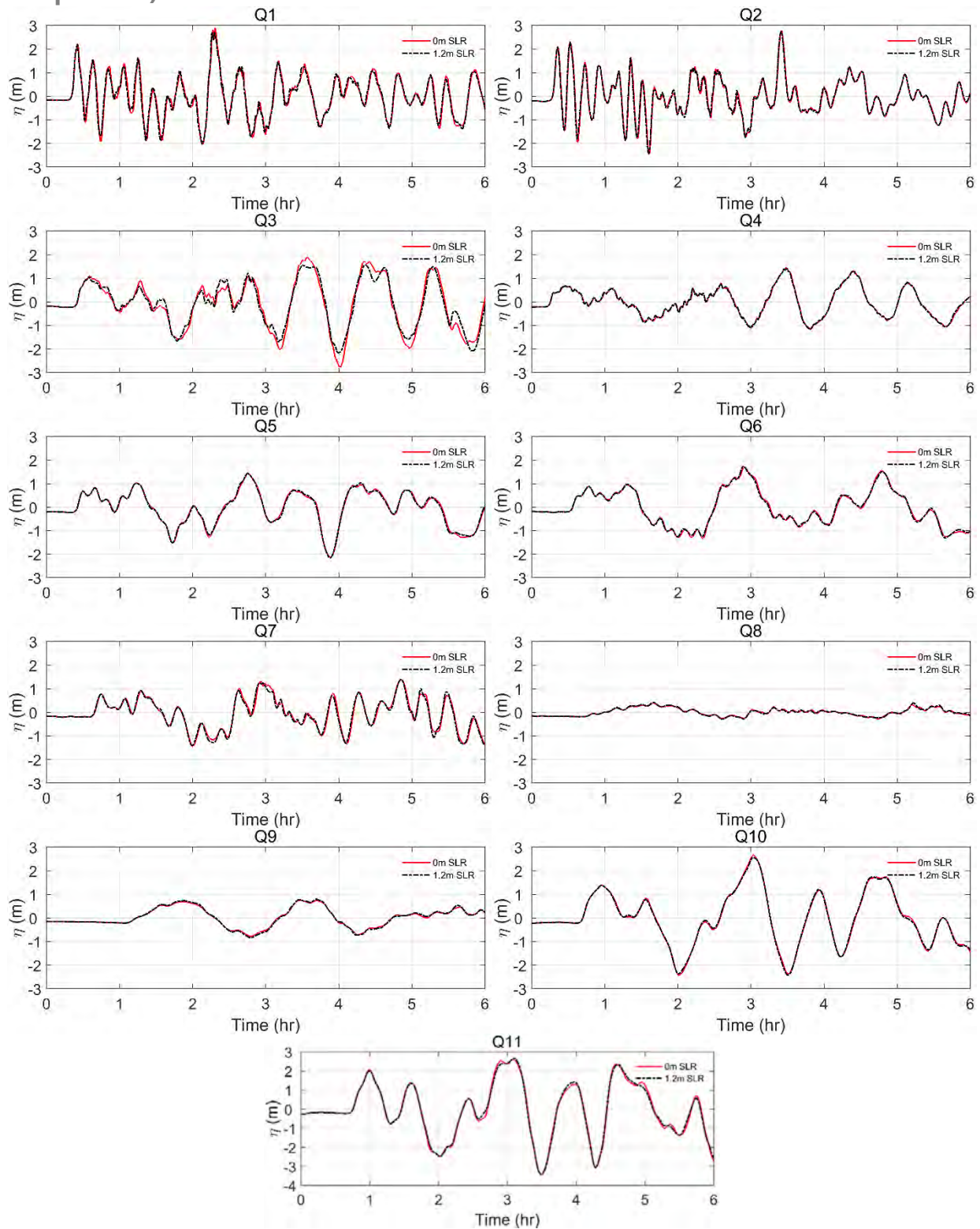


Figure B.4: Time series of water surface elevation for selected numerical gauge points of Quatsino grid for present-day (0m SLR) and future scenario (1.2m SLR) from Cascadia tsunami source. The water surface elevation (η) is with respect to HHWMT.

ANNEXE C: ALASKA-ALEUTIAN SUBDUCTION ZONE, SEA LEVEL RISE RESULTS

C.1 Tsunami wave amplitude

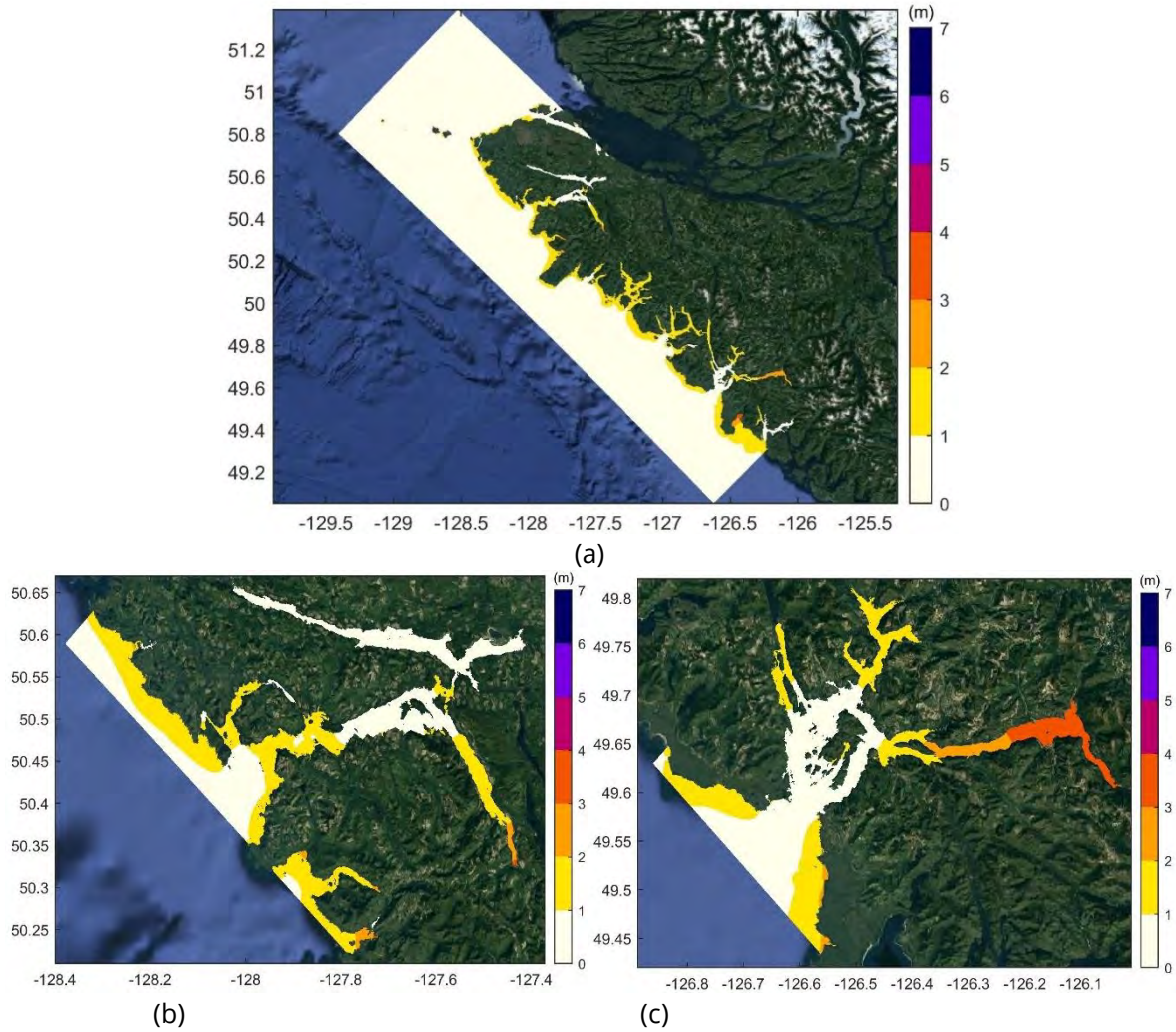


Figure C1: Maximum tsunami wave amplitudes for Scenario4: Alaska-Aleutian Subduction Zone with 1.2m SLR a) 60 m resolution grid, b) 10m resolution grid of Quatsino, and c) 10m resolution grid of Nootka.

C.2 Tsunami-induced currents

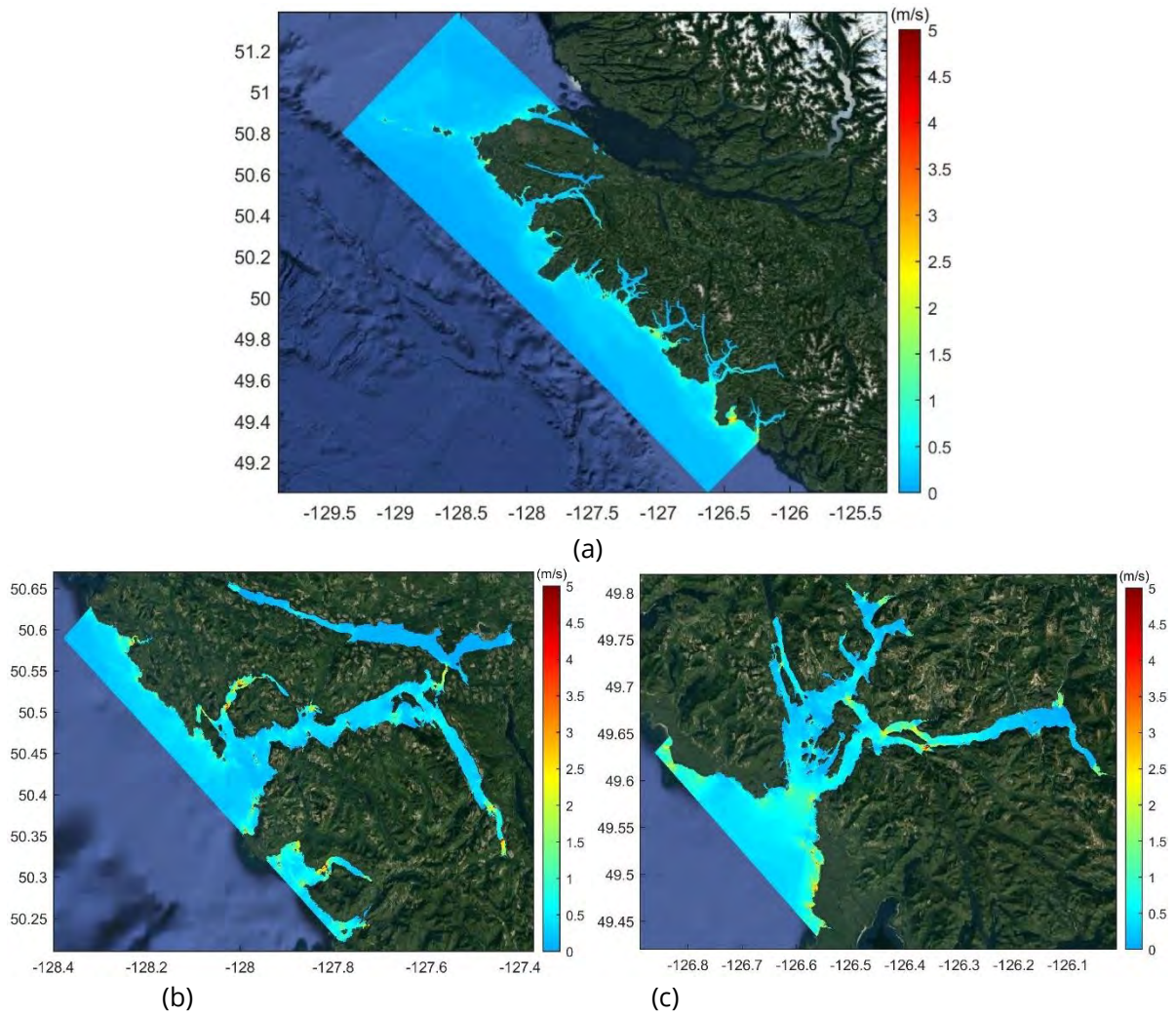


Figure C2: Maximum tsunami current velocities for Scenario4: Alaska-Aleutian Subduction Zone with 1.2m SLR a) 60 m resolution grid, b) 10m resolution grid of Quatsino, and c) 10m resolution grid of Nootka.

C.3 Time series of water surface elevation, of Nootka grid (0m, 1.2m SLR comparison)

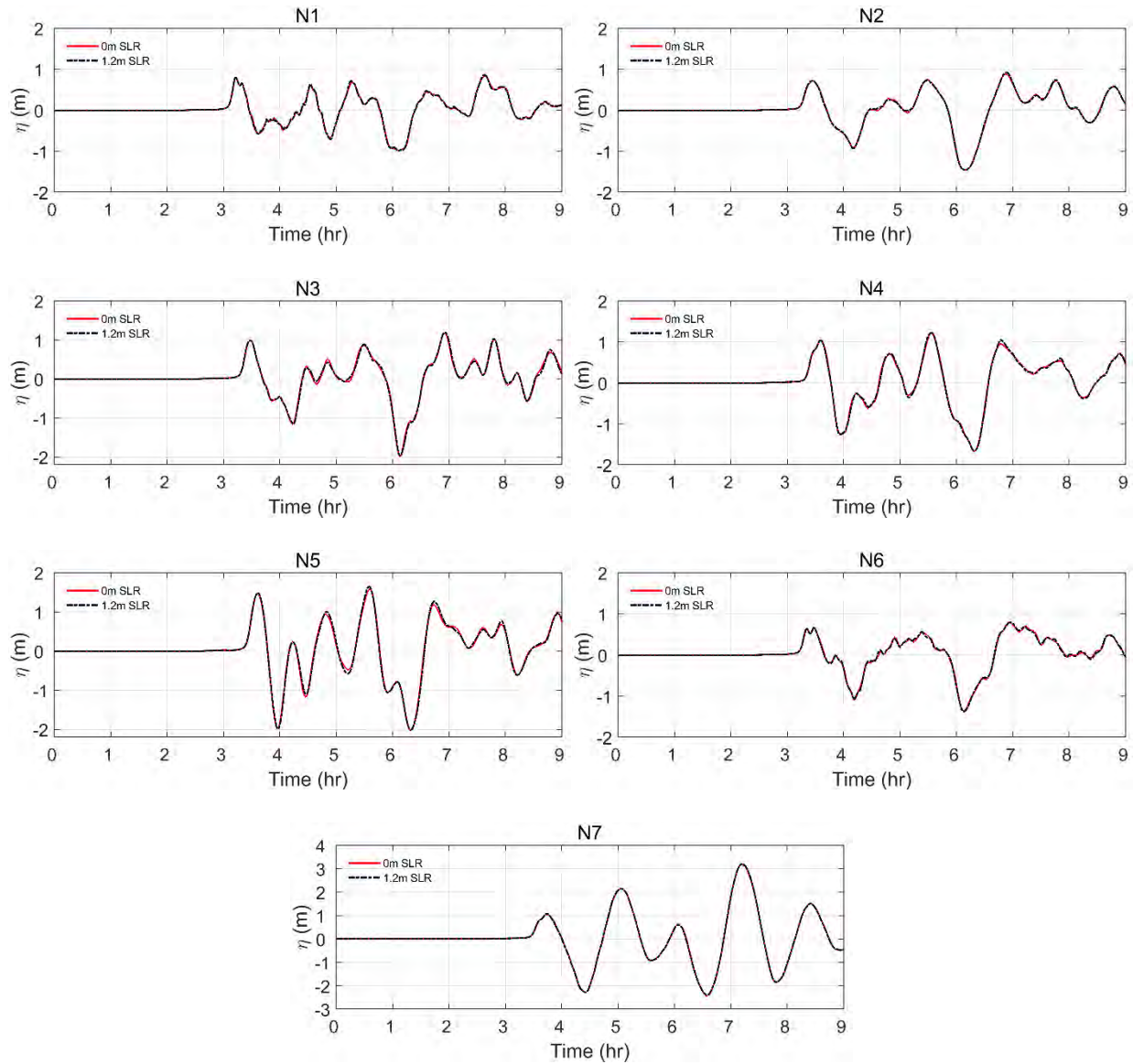


Figure C.3: Time series of water surface elevation for selected numerical gauge points of Nootka grid for present-day (0m SLR) and future scenario (1.2m SLR) from Alaska tsunami source. The water surface elevation (η) is with respect to HHWMT.

C.4 Time series of water surface elevation of Quatsino Sound (0m, 1.2m SLR comparison)

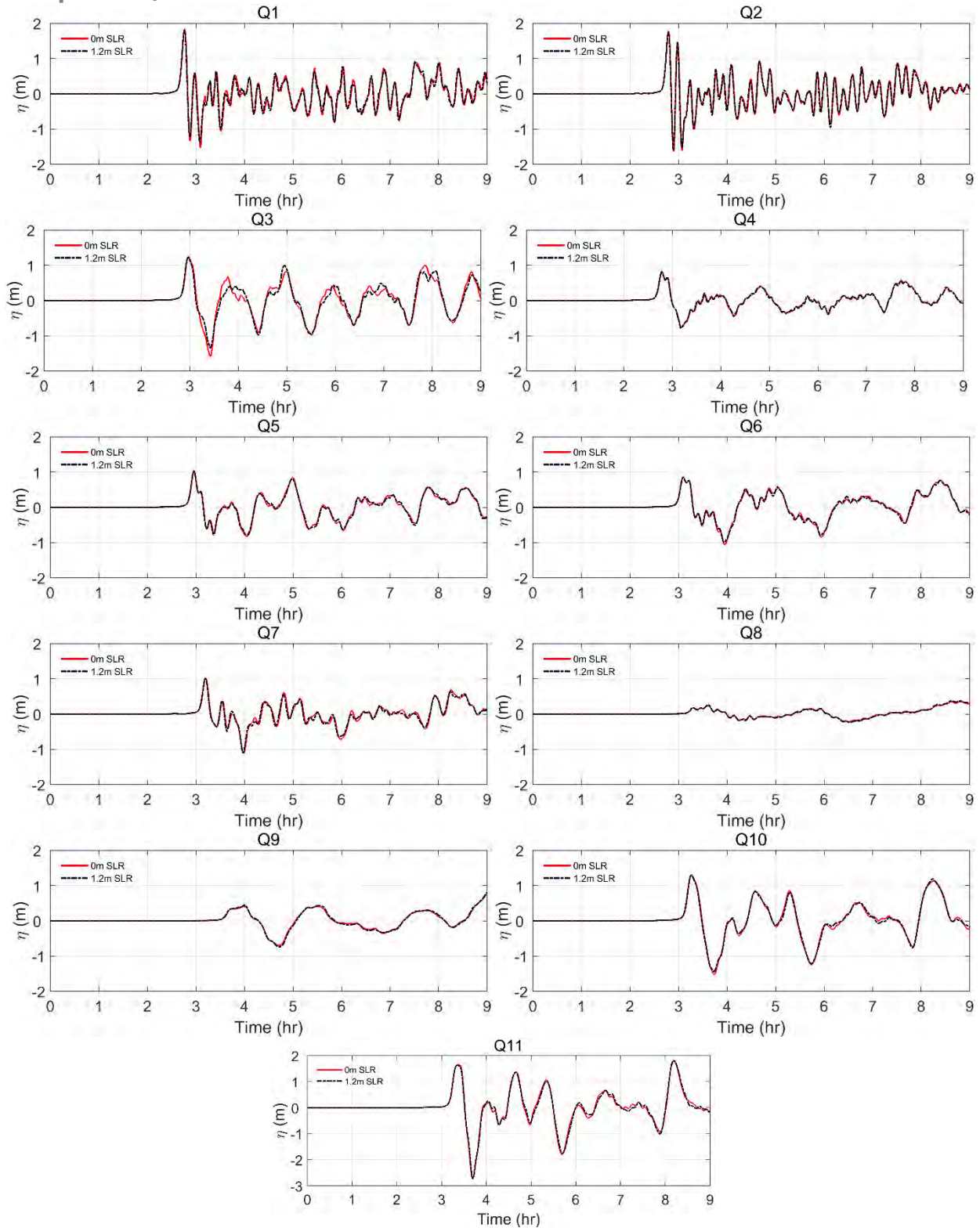


Figure C.4: Time series of water surface elevation for selected numerical gauge points of Quatsino grid for present-day (0m SLR) and future scenario (1.2m SLR) from Alaska tsunami source. The water surface elevation (η) is with respect to HHWMT.

APPENDIX C

OVERWATER TSUNAMI HAZARD MAPS

(Separate PDF file due to size)

APPENDIX D

OVERLAND TSUNAMI INUNDATION MAPS

(Separate PDF file due to size)

APPENDIX E

ASSETS AT RISK MAPS

(Separate PDF file due to size)