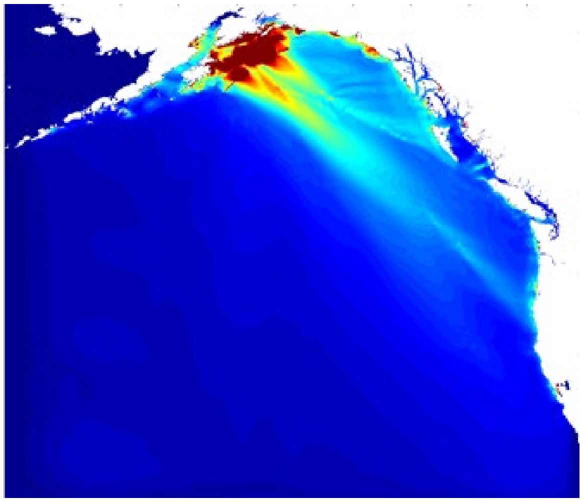
THE CITY OF PRINCE RUPERT
TSUNAMI FLOOD RISK ASSESSMENT



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Final Report: 21 June, 2019

NHC Ref. No 3003349

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OCEAN NETWORKS CANADA

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FINAL REPORT

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DISCLAIMER

This document has been prepared by **Northwest Hydraulic Consultants Ltd. (in collaboration with Ocean Networks Canada, Arlington Group Planning + Architecture Inc, Dr. John Clague, and Dr. Brian Menounos)** for the benefit of **The City of Prince Rupert** for specific application to the **Tsunami Flood Risk Assessment**. The information and data contained herein represent **Northwest Hydraulic Consultants Ltd.'s** best professional judgment in light of the knowledge and information available to **Northwest Hydraulic Consultants Ltd.** at the time of preparation, and was prepared in accordance with generally accepted engineering practices.

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EXECUTIVE SUMMARY

The City of Prince Rupert (the City) is located on Kaien Island within the coast mountains of Northwest British Columbia. The City is potentially vulnerable to a tsunami generated from either a seismic event in the Pacific or, conceivably generated from local landslides. As such, the City was granted funding through the National Disaster Mitigation Program (NDMP) to conduct a tsunami flood risk assessment to investigate the tsunami threat to the community and facilitate more extensive emergency planning. This report presents the results of studies undertaken by Northwest Hydraulic Consultants Ltd. (NHC) in collaboration with Ocean Networks Canada (ONC), Arlington Group Architects + Planners (Arlington Group), and Dr. John Clague and Dr. Brian Menounos (independent academics) to identify, select, and model inundation extents associated with tsunami events, as well as to provide recommendations for emergency management.

It was determined that the City is mostly vulnerable to seismic-generated tsunamis associated with Cascadia and Alaska-Aleutian subduction zones. The FUNWAVE-TVD model (Shi et al., 2012) was used to simulate the propagation and inundation of the tsunami induced by seismic events from these zones. Given that the inundation and damage due to tsunami events are greater if the waves arrive at high tide, it was assumed that the tsunami would occur at the time of high water slack tide (i.e. Higher High Water Mean Tide or HHWMT).

The results show that the maximum increase in water levels from the Alaska-Aleutian subduction zone seismic event are greater than those from the Cascadia subduction zone seismic event. The maximum water level occurred inside Tuck Inlet with decreasing height towards the City. Maximum wave level from the Alaska-Aleutian subduction zone seismic event was about 1.5 m at Tuck Inlet whereas the maximum water level from the Cascadia subduction zone seismic event was about 0.8 m. High velocities of 3 to 4 m/s were predicated in the channel north and east of Digby Island.

To account for future climate change impacts on tsunamis affecting the City, a separate simulation was conducted assuming a 1 m rise in global mean sea level. The results show that the addition of 1 m on sea level does not significantly impact the overall tsunami wave characteristic in the Prince Rupert region.

Landslides entering water may generate large waves that are extremely destructive near their source. A LiDAR (Light Detection And Ranging) survey and geomorphic analysis were conducted on both subaerial and subaqueous terrains using available data in the Prince Rupert area to identify sites potentially prone to landslides. The analysis shows that there is no evidence of recent or ongoing slope instability near Prince Rupert that might indicate that the region is presently at risk from landslides. However, for the purpose of exploring the potential inundation and impact due to landslide, landslide-generated tsunami simulations were conducted using a TELEMAC-3D model for two selected slide locations on steep, high slopes in the area:

- Landslide Site 1 is located approximately 4 km northeast of Seal Cove at the northeast tip of Kaien Island; and

- Landslide Site 2 is located on the west side of Kaien Island approximately 3 km south of the Prince Rupert Ferry Terminal to Digby Island Airport.

The results show that the maximum increases in water level and velocity near Slide 1 were 90 m and 50 m/s, respectively. The increase in water level was generally less than 3 m in the main channel 3.5 km away from the slide source. However, a large increase in water level was predicted 3.5 km away from the source in shallow ground areas and in an enclosed embayment where wave run-up is higher due to wave concentration and funnelling effects. This is most noticeable in Tuck Inlet and the area between Rushbrook Harbour and Cow Bay. The maximum increases in water level and velocity near Slide 2 were 110 m and 50 m/s respectively. The landslide rock mass pushed water to a height of 40 m above sea level on the opposite shore (Digby Island) of the channel. The increase in water level was generally less than 3 m in the main channel 4.5 km away from the slide source.

Similar to the findings from the seismic-generated tsunami, an increase of 1 m of sea level does not significantly impact the overall landslide-generated tsunami wave characteristic in the Prince Rupert region.

It should be emphasized that the landslide-generated tsunami analysis explores potential 'worst-case' scenario's for an event that could produce a damaging tsunami within the study area. Given the potential hazard from a landslide-generated tsunami wave, it is recommended that a geotechnical study be conducted to examine steep, high slopes in the region.

A risk assessment was conducted using inundation depth and velocity results from the seismic-generated tsunami modelling. No residential areas were exposed to the tsunami hazards under any of the seismic scenarios. Emergency services, critical community infrastructure and schools are all located away from the impacts of these tsunami scenarios. All road transportation corridors, BC Hydro corridors and substations, and the municipal water supply are outside of tsunami impact areas. Marine infrastructure and port facilities are the most exposed areas under seismic-generated tsunami scenarios.

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LIST OF ACRONYMS

ASL	Above Sea Level
BC	British Columbia
CCG	Canadian Coast Guard
CHS	Canadian Hydrographic Service
DEM	Digital Elevation Model
EDF	Electricité de France’s Research and Development Division
GD	Geodetic Datum(CVGD2013)
GNSS	Global Navigation Satellite System
HHWLT	Higher High Water Large Tide
HHWMT	Higher High Water Mean Tide
IMU	Inertial Measurement Unit
LiDAR	Light Detection And Ranging
LLWLT	Lower Low Water, Large Tide
LLWMT	Lower Low Water, Mean Tide
LNHE	Laboratoire National d’Hydraulique et Environnement
Mw	Moment magnitude
MWL	Mean Water Level
NHC	Northwest Hydraulic Consulting Ltd.
NTHMP	National Tsunami Hazard Mitigation program
ONC	Ocean Networks Canada
QLCP	Quality of Life Community Plan
RCMP	Royal Canadian Mounted Police
SFU	Simon Fraser University
SLR	Sea Level Rise
The City	The City of Prince Rupert
UNBC	University of Northern British Columbia
YPR	Prince Rupert Airport

DEFINITIONS

Bathymetry is the study of the underwater depth of the ocean floor or other water body. A bathymetric map measures the ocean floor and is the underwater equivalent of a topographic map.

Climate Change refers to the process by which the average weather becomes different over time. Aspects of climate include temperature, precipitation, wind speed and direction, sunshine, fog and frequency of extreme events. Climate has changed due to natural forces over the course of history (e.g., volcanoes, ocean currents) but human activity is now considered the cause of rapid and severe climate change. These changes include sea level rise, more intense and more frequent extreme weather events (e.g., storms, hurricanes, storm surge) and seasonal changes in precipitation.

Datum refers to any numerical or geometrical quantity or set of such quantities that may serve as a reference or base for other quantities. A horizontal datum forms the basis for computations of horizontal control surveys in which the curvature of the Earth is considered. A vertical datum refers to elevations.

Emergency Operations Centre refers to the designated location for emergency management where a local authority may declare a state of local emergency under the *Emergency Program Act.*

Geodetic Datum means a set of constants specifying the coordinate system used for geodetic control (i.e., for calculating the coordinates of points on the Earth). The Canadian Geodetic Vertical Datum is the current orthometric height reference in Canada.

Habitable Building means a building that is or can be used for human occupancy.

Headscarp refers to the upper part of a landslide zone at the area between the non-disturbed soil and the landslide.

High Water Mark means that part of the ocean shore to which the waves normally reach when the tide is at its highest point. It is often marked by a debris or wrack line along the shore.

Resilience means the capacity to anticipate, prepare for, respond to, and recover from the adverse effects of a tsunami, sea level rise, etc. with minimum damage to social well-being, the economy and the environment.

Risk means the likelihood of a negative event occurring (e.g., flooding due to a tsunami or sea level rise) combined with the magnitude of the potential consequences.

Sea Level Rise means an increase in the average level of the ocean in relation to the land level measured by the geodetic datum. Sea level rise is due to global factors such as an increase in water mass due to the melting of glaciers and ice caps on land and an increase in water volume, primarily due to increased temperature. Local conditions such as structural uplift and subsidence as tectonic plates collide also affect and can even reverse sea level rise.

Seismic event is commonly known as an earthquake, and is an event that generates seismic waves in the land. .

Subduction zone is a region of the Earth's crust where tectonic plates meet.

Subsidence refers to the sinking of the Earth's surface in response to geologic or human-induced factors and may occur through gradual settlement or sudden collapse, such as during a seismic event.

Tectonic plate or **plate** are massive pieces of the Earth's crust that interact with each other.

Tsunami is a long period ocean wave generated by an seismic event (earthquake), submarine landslide, landslide, or other disturbance (i.e impact by a large meteor, underwater volcanic eruption).

Vulnerability refers to the degree to which a system is susceptible to, or unable to cope with adverse effects such as a tsunami, sea level rise and climate change.

1 INTRODUCTION

The City of Prince Rupert (the City), a coastal city of about 13,000 people (as per BC Stats, July 2018), is located on Kaien Island on the coast of Northwest British Columbia. The City is separated from Digby Island and Metlakatla by water. The City's 22 km long harbour is one of the deepest, natural, ice-free harbours in the world that is able to accommodate large commercial vessels.

Being a coastal community bordering the Pacific Ocean and nestled at the base of a mountain, the City is susceptible to tsunamis[1] generated from seismic events in the Pacific and, conceivably, from local landslides. The City received funding through the National Disaster Mitigation Program to conduct a tsunami flood risk assessment to investigate the tsunami threat to the community and facilitate more extensive emergency planning. The City engaged Northwest Hydraulic Consultants Ltd. (NHC) to undertake a tsunami flood risk assessment to determine the potential levels of inundation and tidal velocities in the Prince Rupert Harbour area in the event of a tsunami.

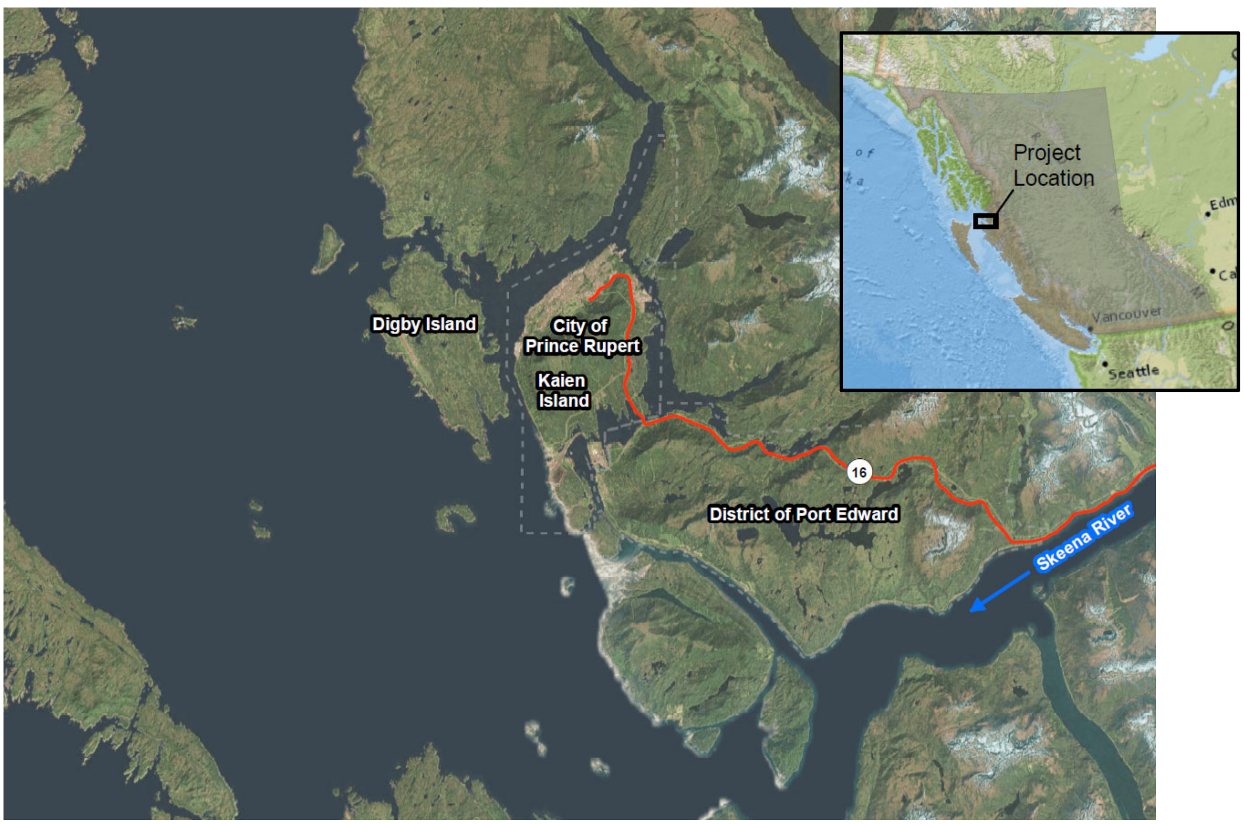


Figure 1-1 Prince Rupert, British Columbia, area map

[1] Tsunamis are sometimes referred to as tidal waves.

This report summarizes our work to identify, select and model inundation extents associated with seismic-generated tsunami and landslide-generated tsunami events, and provides recommendations for emergency management.

1.1 Study Objectives

The objectives of the study are to:

- Analyze data specific to the geography of the region and identify seismic-generated and landslide-generated tsunami hazards;
- Conduct flood modelling for most likely and worst-case tsunami hazard scenarios to determine potential inundation levels and velocities;
- Conduct a hazard, risk and vulnerability analysis that:
    - Indicates the level of hazard in the assessment area and the potential risks to affected communities;
    - Identifies areas in which the risk tolerance is unacceptable, and forms the basis for mitigative actions in the future; and
    - Identifies key infrastructure which is likely to be affected; and
- Incorporate findings into ongoing emergency preparedness, mitigation, planning and response initiatives.

1.2 Project Team

The project team includes professionals from NHC, Ocean Networks Canada (ONC), Simon Fraser University (SFU), University of Northern British Columbia (UNBC), and Arlington Group. The team brings together individuals with experience in tsunami hazard identification, tsunami modelling and inundation mapping, and risk assessment.

Table 1-1 Project Team

Organization	Team Member	Project Role
NHC	Grant Lamont, M.A.Sc., P.Eng.	Project Manager
NHC	Jose Vasquez, Ph.D., P.Eng.	Landslide-generated wave modelling
NHC	Edwin Wang, M.Eng., P.Eng.	Landslide-generated wave modelling
NHC	Sarah North	GIS Mapping
ONC	Reza Amouzgar, Ph.D.	Seismic-generated wave generation and modelling
ONC	Nathan Grivault	Seismic-generated wave generation and modelling
ONC	Jeffrey C. Harris, Ph.D.	Seismic-generated wave generation and modelling
SFU	John Clague, Ph.D.	Seismic hazard identification
UNBC	Brian Menounos, Ph.D.	Landslide hazard identification
Arlington Group	Graham Farstad, MA, RPP	Vulnerability and risk assessment
Arlington Group	Cathy Forbes	Vulnerability and risk assessment

The team would also like to acknowledge the contributions of Dr. Tania Insua (formerly at Ocean Networks Canada) for her contributions during the initial period of this study.

1.3 Report Organization

Chapter 1 and Chapter 2 present a description of the tsunami hazards identified in Prince Rupert. The study methodology including the numerical model and vulnerability analysis and assessment are presented in Chapter 3. Chapters 4 and 5 present the results from the seismic-generated tsunami event and landslide-generated tsunami event, respectively. Flood mapping are presented in Chapter 6. Vulnerability and risk assessment are discussed in Chapter 7 followed by conclusions and recommendations in Chapter 8.

Six appendices are also contained in the report:

- Appendix A – Landslide-generated tsunami source evaluation
- Appendix B – Digital Elevation Model (DEM) development
- Appendix C – Numerical modelling of seismic-generated tsunami wave
- Appendix D – Numerical modelling of landslide-generated tsunami wave
- Appendix E – Seismic tsunami flood maps
- Appendix F – Risk assessment
- Appendix G – Landslide tsunami flood maps

2 THE TSUNAMI HAZARD IN PRINCE RUPERT – BACKGROUND INFORMATION

Previously denoted as tidal waves, the Japanese term tsunami is now used to denote long period waves (5 to 60 minutes) that radiate out due to the rapid displacement of a large volume of water. The initial displacement can result from an earthquake, landslide, volcanic eruption, glacier calving, or impact from a meteorite. As Prince Rupert is located on the shores of the Pacific Ocean it is exposed to potential risk from tsunami events.

The sources of tsunami hazards considered in the study are discussed in the following sections. These sources were selected based on a literature review, previous studies of tsunamis in the Pacific Ocean, and a preliminary geomorphic analysis using available data.

2.1 Seismic-Generated Tsunami

The largest tsunamis in British Columbia result from great (magnitude 8 or larger) earthquakes at the Cascadia subduction zone (Clague, 1997). The British Columbia coast is also affected by tsunamis generated by more distant seismic sources in the Pacific (the subduction zones around the Pacific ocean are shown in **Figure 2-1**). Other subduction zones can generate far field tsunamis with lower impacts to Vancouver Island and west coast of BC. Tsunamis with source regions thousands of kilometres away historically have not been a hazard in west coast of Canada. Among the distant tsunamis, the largest tsunami to strike British Columbia was generated by the 1964 Alaska earthquake (Lander 1996).

Far-field tsunamis from pacific subduction zones and their tsunami hazard assessment are also presented by Leonard et al. (2014). They discussed that the 1964 Alaska tsunami (2.4 m peak to trough at Tofino) represents a near maximum, although previous Alaskan events may have involved longer ruptures (Shennan et al. 2009). Therefore, both Cascadia and Alaska-Aleutian subduction zones, more severe cases for seismic-generated tsunamis, are adopted in this study.

More precisely, off the BC coast, the Cascadia plate is bordered with several microplates, namely the Explorer Plate, Juan de Fuca Plate, and South Gorda Plate (**Figure 2-2**). These plates are local sources of earthquakes that may trigger a tsunami which may present a direct threat to Prince Rupert.

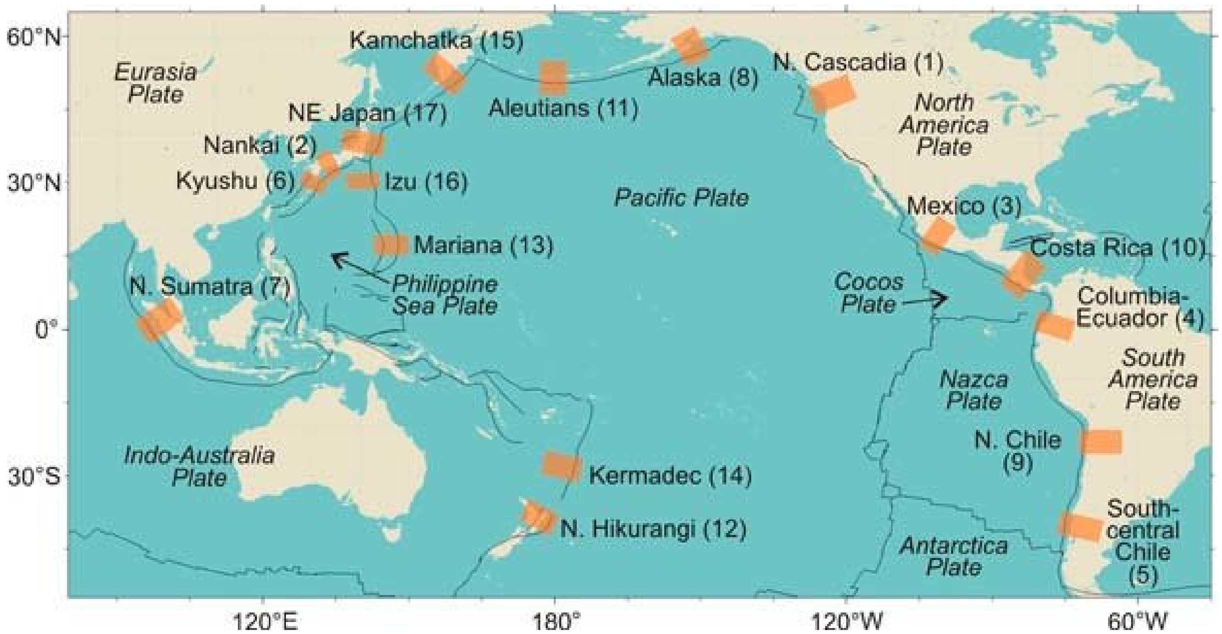


Figure 2-1 Map showing the locations of 17 subduction zones in the Pacific Ocean (orange areas) where the number in parentheses indicates the index number of the subduction zone (Wada and Wang, 2009)

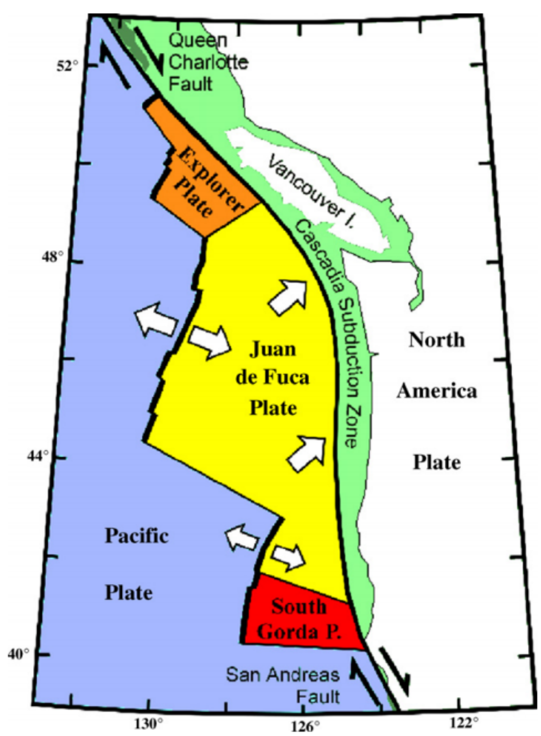


Figure 2-2 Tectonic plates off BC Coast (Koohzare at al.,2008)

2.1.1 Explorer-North America Plate

The Explorer-North America Plate has been recently studied by NRCan (Gao et al., 2017). The rupture of this thrust fault in 2012 generated a M_w[2] 7.8 earthquake and a large tsunami (Leonard and Bednarski, 2015). However, this tsunami caused only small waves at Prince Rupert (Fine et al., 2018a) and therefore was not considered further in this study.

2.1.2 Queen Charlotte Fault

The Queen Charlotte fault, which marks the boundary between the Pacific and North America plates, is seismically active and located about 250 km from Prince Rupert and Metlakatla. It was the source of Canada's largest earthquake, the M_w 8.1 Queen Charlotte earthquake in 1949. However, the Queen Charlotte fault north of Haida Gwaii, where it is nearest Prince Rupert, is a pure strike-slip (horizontal displacement) structure. Such faults are not generally considered to be tsunami generators and were not considered further in this study.

2.1.3 Cascadia Subduction Zone

The Cascadia subduction zone is a convergent plate boundary that stretches from northern Vancouver Island in Canada to Northern California in the United States. It poses the most significant and widespread tsunami threat to the BC coast because of its proximity and the expected magnitude of its earthquakes. Great megathrust earthquakes occur in the Cascadia subduction zone roughly once every 500 years (Goldfinger et al., 2012). The last great Cascadia earthquake was in 1700 and while there is no written history of this event, studies such as Witter et al. (2011) document the potential hazard.

Gao et al. (2018) identified four fault rupture scenarios for tsunami hazard associated with the Cascadia subduction zone: a splay-faulting rupture, buried or 'blind' rupture, full trench-breaching rupture and half trench-breaching rupture. The maximum uplift and subsidence for each scenario are summarized in **Table 2-1**.

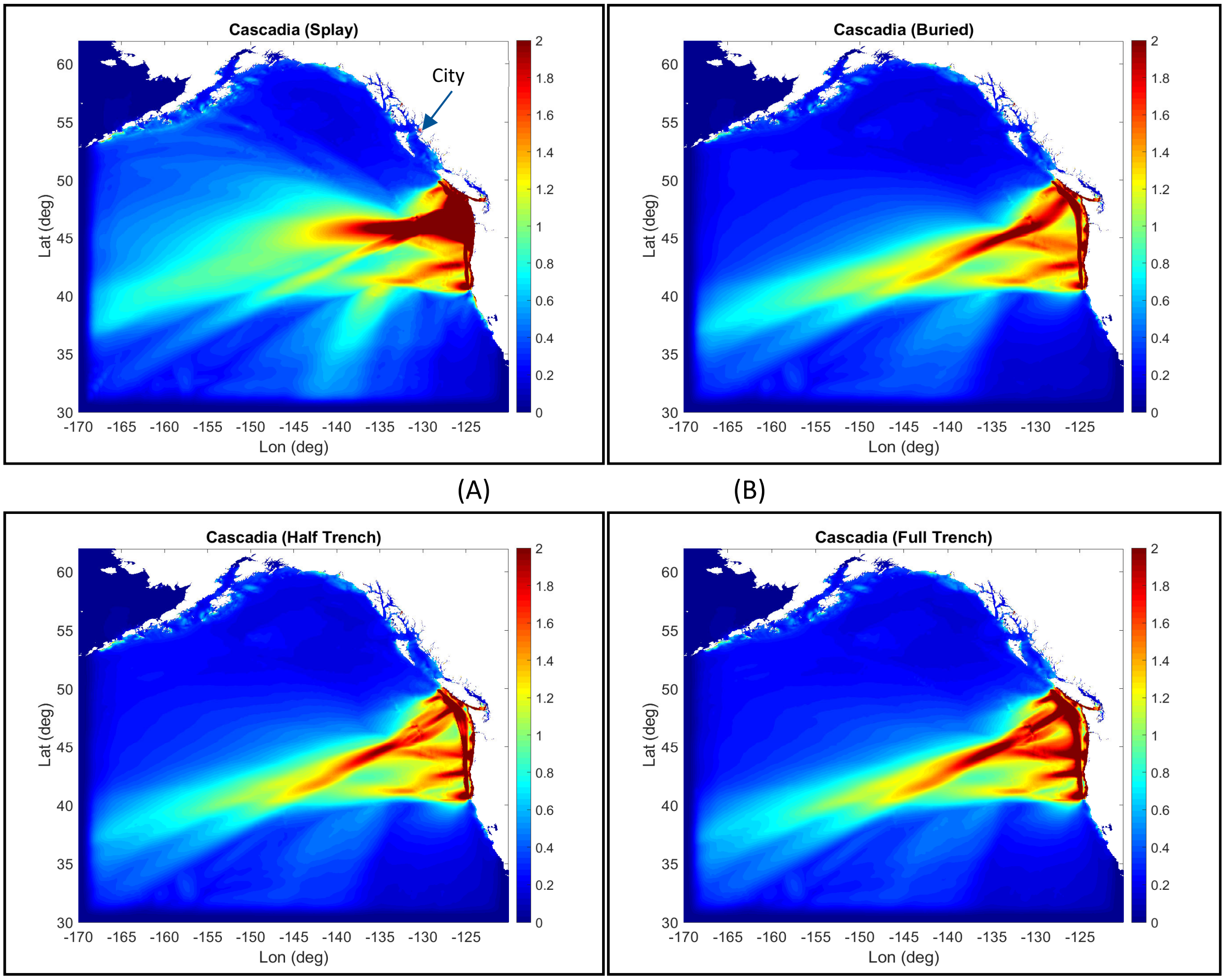
Table 2-1 Maximum uplift and subsidence for Cascadia subduction zone

Mechanism	Max Uplift (+)	Max Subsidence (-)
Splay rupture	9.76 m	-2.60 m
Buried rupture	5.13 m	-2.63 m
Full-trench rupture	9.80 m	-2.63 m
Half-trench rupture	8.62 m	-2.62 m

High-level tsunami modelling analysis was conducted using a coarse resolution model grid to examine the initial tsunami heights resulting from each rupture scenario (more detailed on tsunami modelling

[2] Moment magnitude, Mw, is a measure of an earthquake's energy release ("size" or strength) based on its seismic moment. It has supplanted the original and more familiar "Richter" magnitude.

methodology is provided in **Section 3.4.1**). The resulting tsunami heights are shown in **Figure 2-3**. The results show that the splay fault rupture (Panel A) generates higher waves (water surface elevation) than the other three scenarios. This scenario was adopted and examined further using the high resolution model (**Section 4**).



(C) (D)

Figure 2-3 Maximum tsunami height (m) based on low-resolution simulation of a large seismic event at the Cascadia subduction zone using four rupture scenarios: (A) Splay-faulting; (B) Buried rupture; (C) Half trench-breaching; (D) Full trench-breaching. (See Appendix C)

2.1.4 Alaska-Aleutian Subduction Zone

The Alaska-Aleutian subduction zone is a 4,000-km long convergence boundary between the North American and Pacific plates, that extends from the Alaska Range to the Kamchatka Peninsula. The Alaska-Aleutian subduction zone is at the origin of numerous earthquakes of magnitude 8 or more (e.g., 1938 M_w 8.3, 1946 M_w 8.6, 1957 M_w 8.6, 1964 M_w 9.2, 1965 M_w 8.7). The largest of the recent earthquakes, namely, the 1964 Alaska earthquake produced the largest tsunami waves to date on the

British Columbia coast (Wigen and White, 1964). This event represents a realistic proxy for similar large events at the subduction zone.

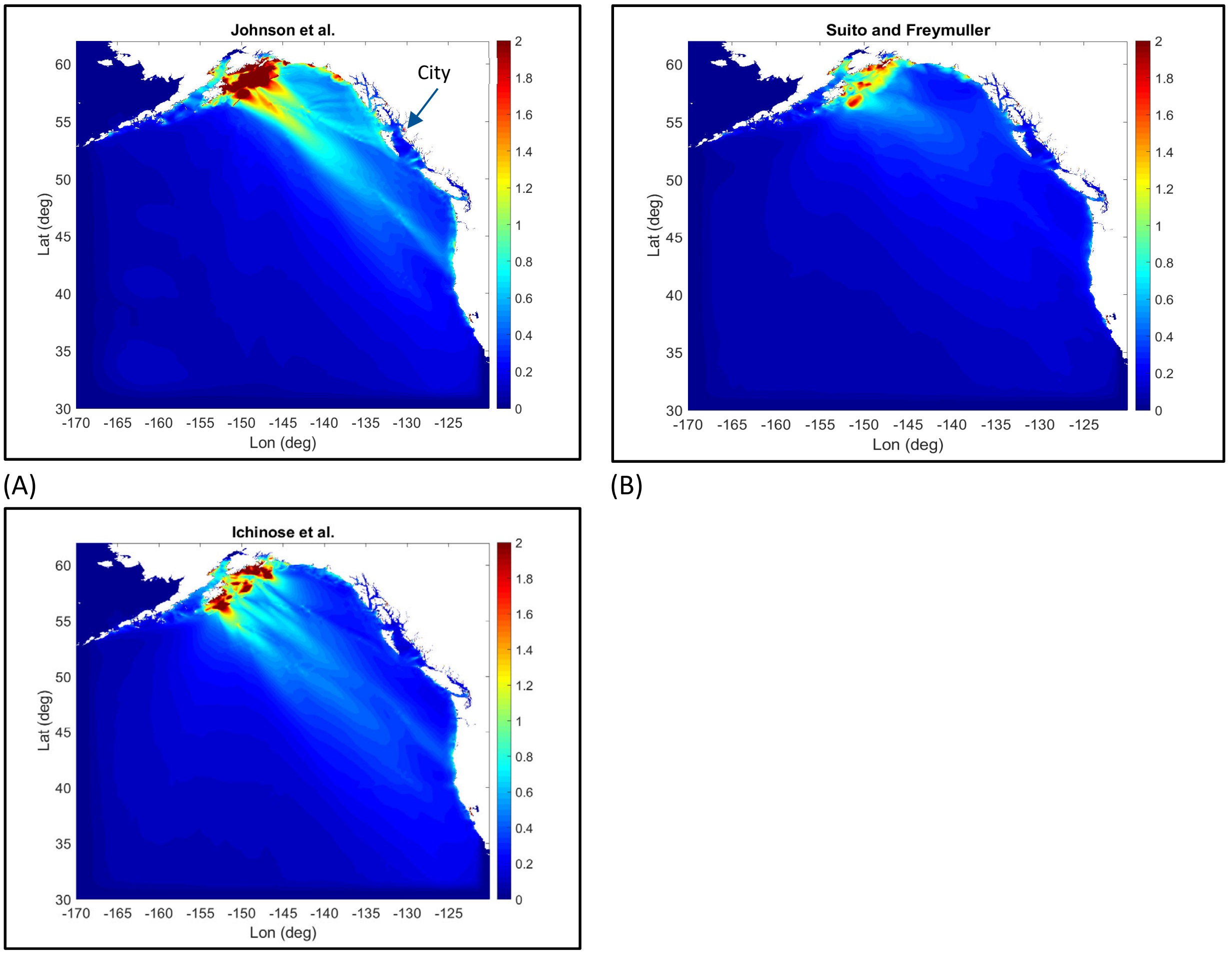
Three inversions[3] of the 1964 earthquake event were investigated based on information published in Johnson et al (1996), Ichinose et a. (2007), and Suito and Freymueller (2009). The maximum uplift and subsidence for these three inversions are shown in **Table 2-2**.

Table 2-2 Maximum uplift and subsidence for Alaska-Aleutian subduction zone

Mechanism Source	Max Uplift (+)	Max Subsidence (-)
Johnson et al. 1996	6.86 m	-5.47 m
Ichinose et al. 2007	8.60 m	-1.81 m
Suito and Freymuller 2009	2.78 m	-1.80 m

For this study, high-level tsunami modelling analysis was conducted using a coarse resolution model grid to examine the initial tsunami heights resulting by each inversion scenario (more detail on the tsunami modelling methodology is provided in **Section 3.4.1**). The resulting tsunami heights show that the inversion described by Johnson et al. (1996) generates higher surface elevation (Panel A) compared to the other two inversions (Figure 2-3). This scenario used a joint inversion of tsunami waveforms and geodetic data to determine a set of sub-faults for the detailed slip distribution that was an improvement on earlier tests (Christensen and Beck, 1994). This scenario was adopted and examined further using the high resolution model in the analysis (**Section 4**).

[3] Inversion is the methodology used to estimate the fault parameters and slip distributions of an earthquake. The slip distribution of the earthquake can be determined by geodetic and tsunami wave forms data. Then, providing sufficient information including the fault parameters and slip distributions, the vertical and horizontal displacements of the sea floor from a specific earthquake can be estimated (e.g., utilizing the Okada, 1985 model). This information about the seismic source is then coupled to the hydrodynamic tsunami model to predict the tsunami wave propagation and inundation.



(A)

(B)

(C)

Figure 2-4 Maximum tsunami height (m) based on low-resolution simulation for Alaska subduction zone using three different source models: (A) Johnson et al., 1996; (B) Suito and Freymueller, 2009; (C) Ichinose et al., 2007(See Appendix C)

2.2 Landslide-Generated Tsunami

Landslides entering water may generate large waves that are extremely destructive near their source. As an example, an earthquake in Alaska in 1958 triggered a rockslide that entered into Lituya Bay in Alaska The rock mass pushed water to a height of 525 m above sea level on the opposite shore of the fiord and generated a gravity wave that moved down the bay to its mouth at a speed of between 43 and 58 m/s.

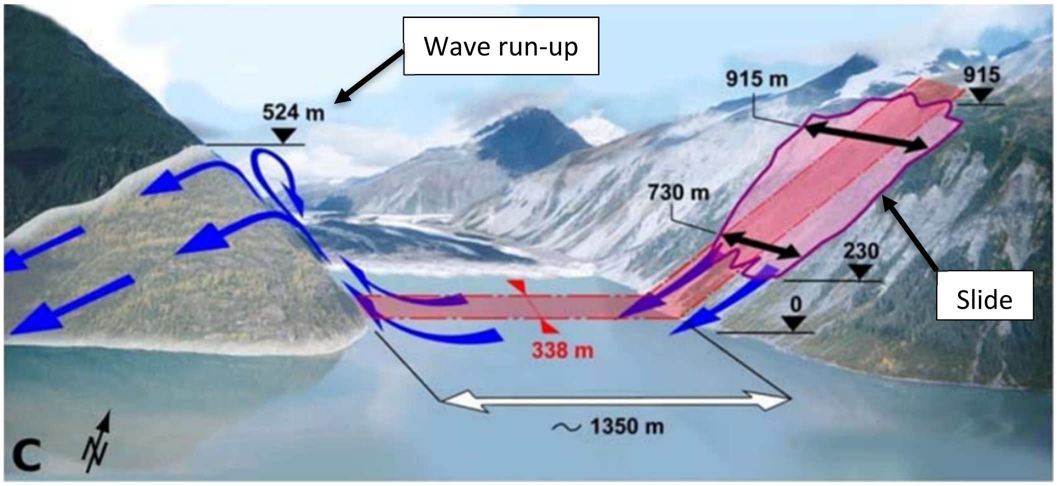


Figure 2 - The 1958 Lituya Bay landslide-generated tsunami wave (Fritz et al., 2001)

Submarine landslides can also produce large tsunamis. For example, an earthquake-triggered submarine landslide generated a devastating tsunami that killed more than 2200 people in Papua New Guinea in July 1998 (González, 1999, McSaveney, 1999, Tappin, 2001, Tappin et al., 2001). Tsunami-producing submarine landslides can be triggered by a variety of mechanisms, including earthquakes, undersea volcanic eruptions, and construction activity. Gases trapped under layers of sediment at the edge of a continental shelf could cause the sediments to fail and slide downslope, triggering a tsunami.

2.2.1 LiDAR surveys

A LiDAR (Light Detection And Ranging) survey and geomorphic analyses were conducted on both subaerial and subaqueous terrains using available data in the Prince Rupert area to identify sites potentially prone to landslides. Only the general results of this investigation are presented in this section. Further details on the evaluation of a landslide-generated tsunami source can be found in **Appendix A**.

LiDAR is a laser based remote sensing surveying technique that provides detailed geo-referenced models of Earth's surface and can help identify former landslides and landslide-prone terrain in densely-vegetated landscapes. This surveying technique has been recently used to identify landslide hazards near the community of Terrace, BC (Geertsema et al., 2018).

A LiDAR survey of the intertidal area and steep slopes in the vicinity of Prince Rupert (**Figure 2-6**) was completed over a two-day period in June 2018 which coincided with a low tide. The survey was conducted using a Riegl Q780 full waveform infrared scanner (1064 nm) with dedicated Applanix PosAV Global Navigation Satellite System (GNSS) Inertial Measurement Unit (IMU). The horizontal and vertical uncertainties of the measurements were typically ±0.15 m. The LiDAR data were classified into ground and non-ground laser returns, and the ground returns were gridded into 1 m bare earth GeoTiffs.

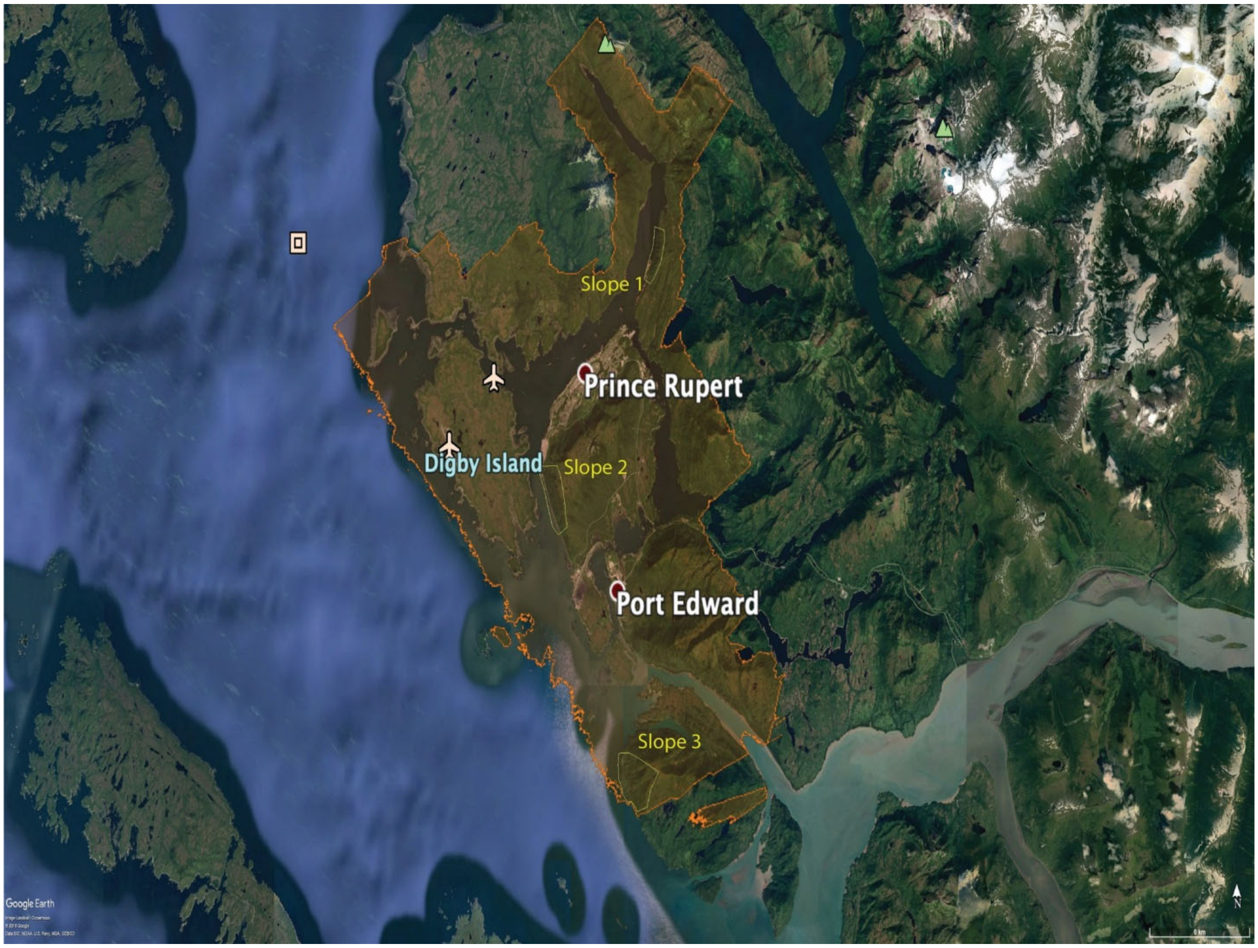


Figure 2-5 Area of LiDAR survey acquisition (orange polygon) and slopes identified for landslide assessment

2.2.2 Subaerial and Subaqueous Terrain Analyses

A preliminary geomorphic analysis of all slopes bordering the sea within 20 km of Prince Rupert was conducted using existing LiDAR imagery of Kaien and Digby islands, Google Earth satellite images and scanned aerial photographs of the Prince Rupert area. The analysis revealed that rock slopes border much of the coastline north and south of Prince Rupert. The shores of Digby Island have gentle slopes that border the shoreline and are generally too low to be of concern. Other shorelines in the region, however, have slopes that rise moderately to steeply, and have local relief of as much as 600 m. The slopes are forested and, with the exception of numerous shallow-seated debris slides and debris flows, bear no evidence of past instability (e.g., visible head and lateral scarps, bulging slope toes, and hummocky ground). Three slopes that are sufficiently steep to be of concern were identified (**Figure 2-6**):

- Site 1 (Slope 1 on **Figure 2-6**) is located approximately 4 km northeast from Seal Cove at the northeast tip of Kaien Island (where Seal Cove Seaplane Base, Coast Guard Heliport and Prince Rupert Marine Communications and Traffic Services are located).
- Site 2 (Slope 2 on **Figure 2-6**) is located on the west side of Kaien Island approximately 3 km south from Prince Rupert Ferry Terminal to Digby Island Airport. Site 2 is also located roughly 2 km south from Fairview Container Terminal and 4 km north from Ridley Terminals.
- Site 3 (Slope 3 on **Figure 2-6**) is located on Smith Island, approximately 16 km south from Prince Rupert.

These slopes were chosen for follow up analysis using the LiDAR data collected in June 2018 (**Section 2.2.1**).

Inspection of the bare-earth lidar data indicated that the lineaments associated with the three slopes previously identified on Google Earth satellite images were structural (joints or faults) and not the result of slope movements. The absence of instability at these sites was confirmed by noting that no anomalous lobes of rockslide debris are present on the seafloor at the base of the slopes. A geomorphic analysis of the nearshore seafloor in these areas was conducted using high-resolution bathymetric maps (**Figure 2-7**) acquired from Canadian Hydrographic Service (CHS). The results show that there are no unusual accumulations of debris on the seafloor that could have originated from rockslides or large rockfalls.

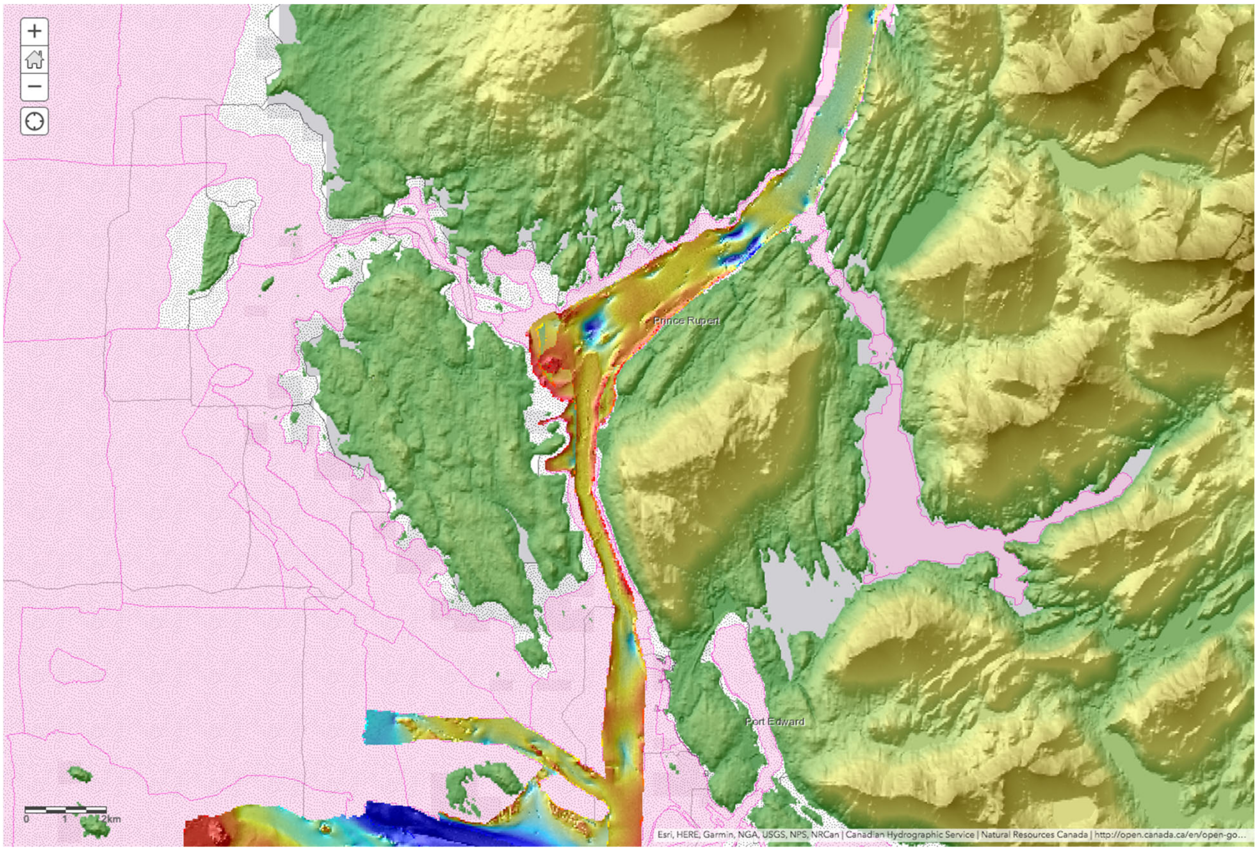


Figure 2-6 Area of bathymetric maps of the nearshore seafloor in the Prince Rupert area.

The analysis based on LiDAR and satellite images , the aerial photographs, and LiDAR data shows that there is no evidence of recent or ongoing slope instability near Prince Rupert that would pose an immediate hazard of landslide-generated tsunami for the region.

Nevertheless, landslide-generated simulations were conducted for large debris slides at sites 1 and 2 in this study for the purpose of illustrating inundation and impact due to landslide. Site 3 was not considered as it is located more than 16 km away from Prince Rupert and the preliminary modelling results indicate that this scenario would not produce significant waves at Port Edward or Prince Rupert.

3 TSUNAMI MODELING AND FLOOD HAZARD METHODOLOGY

The City is located on the coast of Northwest British Columbia. The City is separated from Digby Island and Metlakatla by Venn Passage. There are flow passages around two sides of Digby Island, as well as a flow channel on the east side of Kaien Island past Ridley Island and through Fern Passage. Due to the complex bathymetry of the region, it was expected when planning this project that a tsunami event could potentially cause complex wave patterns that would be difficult to predict without the use of advanced engineering tools and numerical models. The study region and modelling methodologies were adopted in light of this concern to examine flood inundation due to seismic-generated tsunami and landslide-generated tsunami and by necessity the model domains extend beyond the immediate areas of interest. The approach taken to set up the tsunami models is described in this section.

3.1 Study Region

The key outcomes of the study are:

- Flood maps illustrating potential levels of inundation and velocities associated with tsunami events; and
- Improved emergency preparedness, mitigation, planning and responses initiatives based on the hazard, risk and vulnerability analysis.

The solid blue line and the solid yellow line in **Figure 3-1** show the extents of the study areas for the flood mapping effort and the risk assessment respectively.

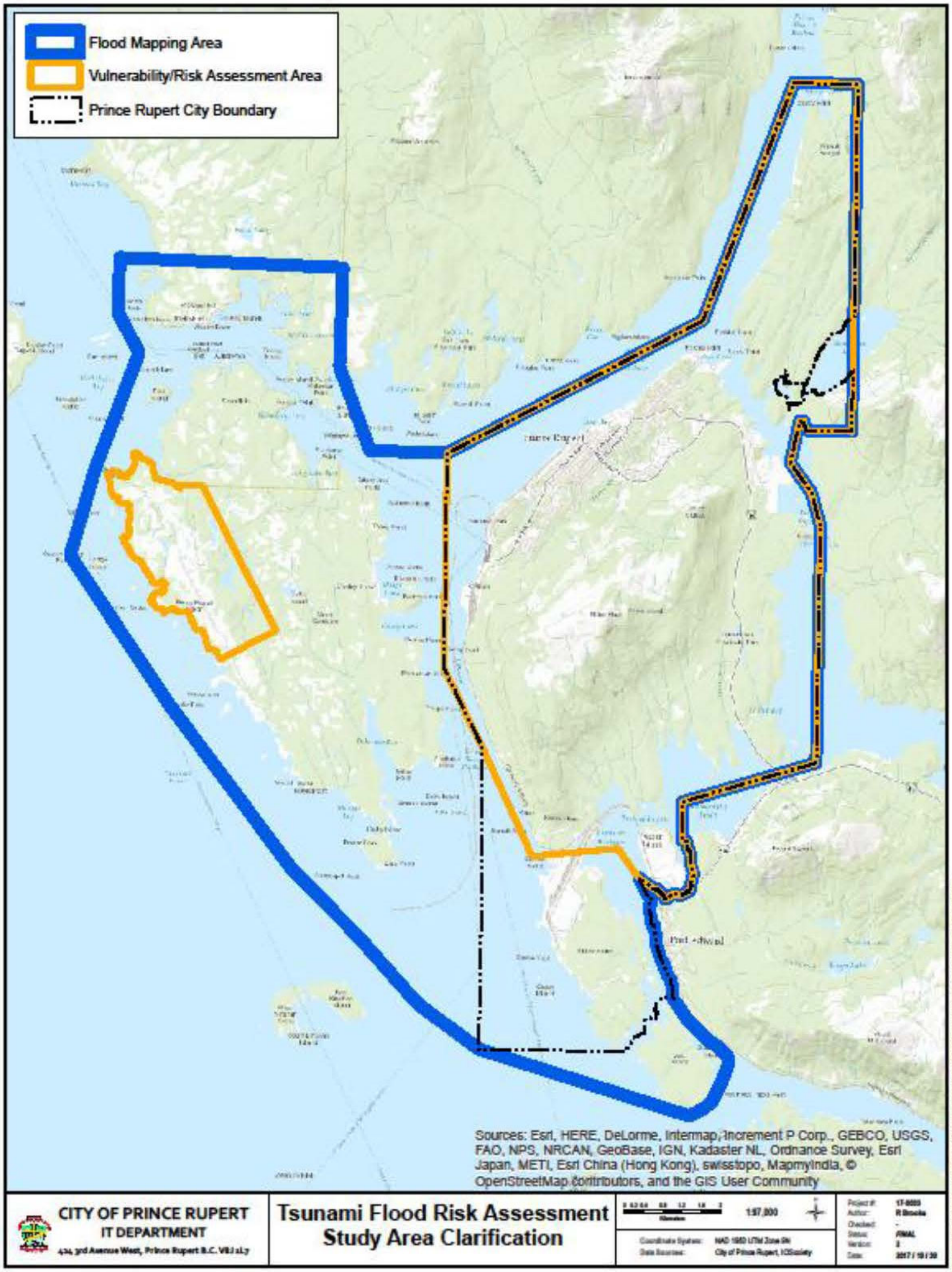


Figure 3-1 Flood map and risk assessment extents as defined by the re-issued RFP.

3.2 DEM Data Processing

In July of 2018, Northwest Hydraulic Consultants (NHC) developed a digital elevation model (DEM) of the Greater Prince Rupert Area, and surrounding areas encompassing both British Columbia, Canada and Alaska, United States. The development of the DEM was for the City of Prince Rupert, in connection with the Tsunami Flood Risk Assessment Project. The intent of this DEM is primarily to support computer modelling of inundation scenarios to create tsunami inundation maps, vulnerability maps, and hazard maps for the Project Area

The bathymetry and topography in the model were generated from several overlapping datasets, including the aerial LiDAR survey collected in June 2018. The DEM was produced from 8 different data sources (**Table 3-1**). Data sources were clipped to the red DEM extent boundary shown in **Figure 3-2**. The DEM coverage is 240,017 square kilometers (92,671 square miles) and data resolution was preserved closer to the Prince Rupert study area and along the shoreline between 0 and 50 meters CGVD2013.

Table 3-1 Summary of datasets used to develop model DEM

Dataset	Resolution
ETOPO1	1 arc-minute
British Columbia 3 arc-second Bathymetric Digital Elevation Model	3 arc-second
Southeast Alaska 8 arc-second MHHW Coastal Digital Elevation Model	8/15 to 8 arc-second
Canadian Digital Elevation Model	20 metre
Electronic Navigational Charts, Canadian Hydrographic Service	Various resolutions
Airborne Imaging of Calgary, Alberta, Canada, The City of Prince Rupert	1 metre
USGS NED Digital Surface Model AK Ifsar, United States Geological Survey	5 metre
Prince Rupert Area Intertidal LiDAR, University of Northern British Columbia	1 metre

The DEM was built to the specifications listed in **Table 3-2**.

Table 3-2 Specifications for the DEM

	Description
Grid Area	Greater Prince Rupert Area, and surrounding areas encompassing both British Columbia, Canada and Alaska, United States
Coverage Area	136.37° to 126.79° W, 50.10° to 57.38° N
Coordinate System	Universal Transverse Mercator (UTM), Zone 9 North
Horizontal Datum	North American Datum of 1983 (NAD 83)
Vertical Datum	Canadian Geographic Vertical Datum of 2013 (CGVD2013)
Vertical Units	Metres
Spatial Resolution	1, 5, 20, 40, 50, 93, 247, 500 - Various resolutions in metres
Data Format	XYZ Files

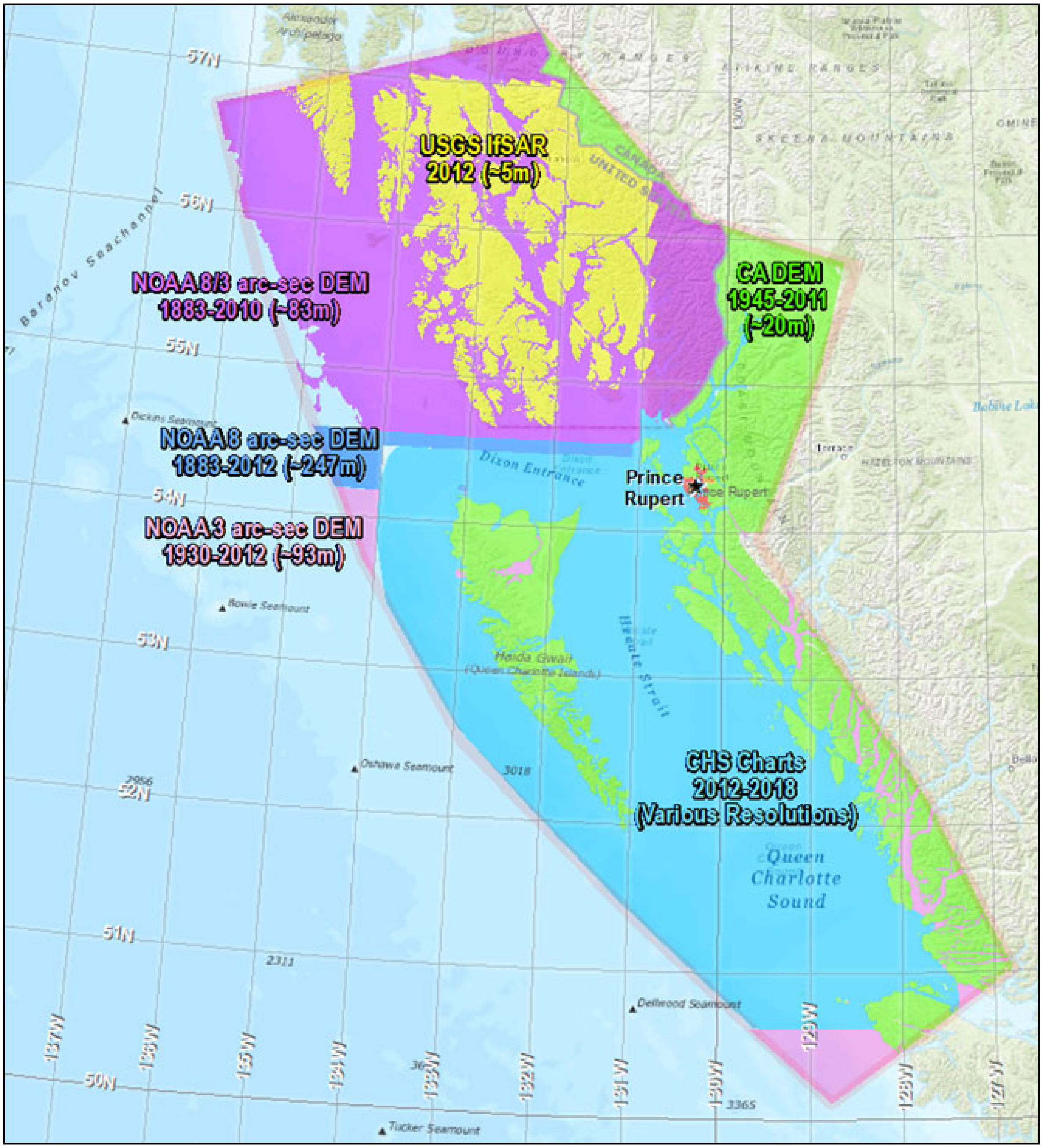


Figure 3-2 Map showing DEM data sources and extents

Details of the DEM data processing are provided in **Appendix B**.

3.3 Design Water Levels

The inundation and damage due to tsunami events are greater if the waves arrive at high tide. Canadian Tide and Current Tables Volume 7 (**Table 3-3**) presents the local tidal water levels at Prince Rupert.

Table 3-3 Summary of Prince Rupert Tide elevations

Sea State	Tide Elevation (m Chart Datum)	Tide Elevation (m Geodetic Datum)
Higher High Water, Large Tide (HHWLT)	7.4	3.6
Higher High Water, Mean Tide (HHWMT)	6.1	2.3
Mean Water Level (MWL)	3.8	0.0
Lower Low Water, Mean Tide (LLWMT)	1.3	-2.5
Lower Low Water, Large Tide (LLWLT)	0.0	-3.8

For the “present day” risk assessment, it is assumed that the tsunami wave arrives at the time of high tide. Ocean Networks Canada followed the recommendations for tsunami simulations in the United States, according to National Tsunami Hazard Mitigation program(NTHMP), to use mean higher high water (or higher high water, mean tide in Canadian terminology). Thus, a HHWMT water level of 2.3 m still water level above mean sea level is applied for the Prince Rupert seismic tsunami modelling. Tsunami modeling was undertaken at a high water slack condition to explore the potential hazard at the highest tide levels. No storm surge was included in the modeling and the hazard assessments include a freeboard allowance to account for this.

NHC utilized a Higher High Water Large Tide design water level for the landslide-tsunami simulations to remain consistent with exploring “worst-case” scenarios.

Climate change will have an important role in tsunami vulnerability analysis in the near future. Based on worldwide tide gauge records, global sea level has risen more than 0.2 m since the late 19th century (Thomson et al., 2008) and global mean sea levels are rising at approximately 3 mm/yr. The rate of sea level rise is expected to increase in the future although projections of sea level rise are highly uncertain. The sea level rise policy for BC (BC Ministry of Environment, 2011b) recommends using a 1.0 m rise in global mean sea level between the year 2000 and 2100 for planning purposes (**Figure 3-3**).

For the “future climate change” risk assessment, it is assumed that 1.0 m of local relative sea level rise has occured. This study makes no allowance for vertical land movement as vertical land motions over the next century are expected to be much less than 1.0 m in general within the study area. Instead, a full 1.0 m of increased water level has been simulated to examine the behavior of tsunami waves in the region to these higher water depths. As such, the scenario allows for 1.0 m of local sea level rise irrespective of land movement. However, as the future timing of SLR itself is uncertain, this is deemed a reasonable approach for examination of whether increased sea levels will affect tsunami hazards.

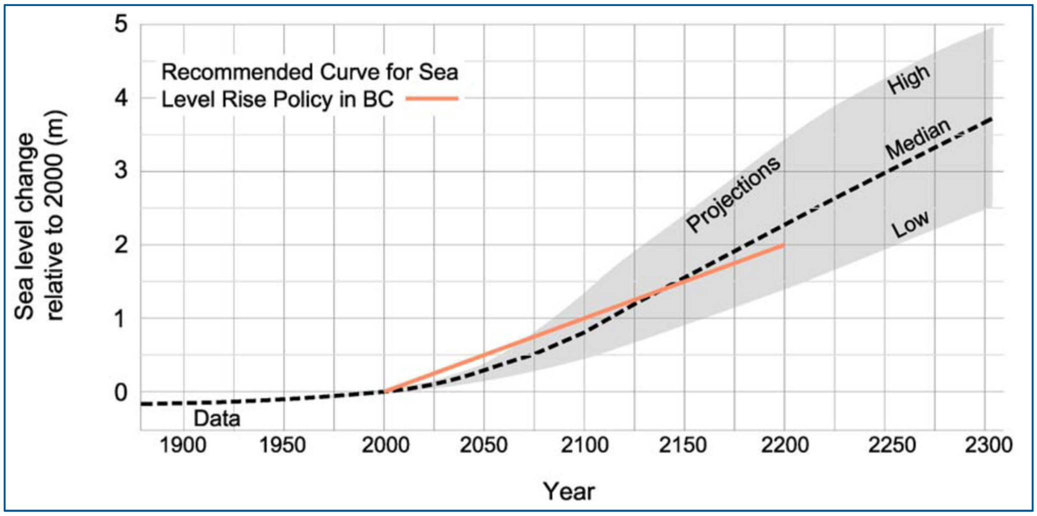


Figure 3-3 Projections of global sea level rise (BC Ministry of Environment, 2011b)

3.4 Numerical Models

Numerical modelling tools used to examine the propagation and inundation of the tsunami induced by seismic event and landslide events are described in the following sections.

3.4.1 Seismic-Generated Tsunami Model

The propagation and inundation of tsunamis induced by seismic events were modelled using the FUNWAVE-TVD model (Shi et al., 2012). FUNWAVE-TVD is a long wave propagation model that solves fully non-linear and dispersive Boussinesq wave propagation equations (Wei et al., 1995). FUNWAVE-TVD has been benchmarked against other models and reference data as part of the U.S. National Tsunami Hazard Mitigation Program (NTHMP). The FUNWAVE-TVD model has been used extensively for tsunamis around the world, including 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), and tsunami hazards in the Mediterranean (Nemati et al., 2018).

Tsunami generation, propagation and inundation were resolved through five levels of nested and linked grids with increasing higher resolution from 2 arc-minute (about 3,600 m) for the northeast Pacific Ocean, 30 arc-second (about 900 m) for the BC Coast, 240 m for the Haida Gwaii region, 60 m for the local region and 10 m in the vicinity of Prince Rupert (**Table 3-4** and **Figure 3-4**).

Table 3-4 Seismic-generated tsunami model grid information

Model grid	Model grid resolution	Model grid dimensions
Northeast Pacific (G0)	2 arc-minute	1621 x 1081
British Columbia (G1)	30 arc-second	1201 x 1201
Haida Gwaii (G2)	240 metres	901 x 1301
Local region (G3)	60 metres	1209 x 1701
Prince Rupert (G4)	10 metres	2371 x 2911

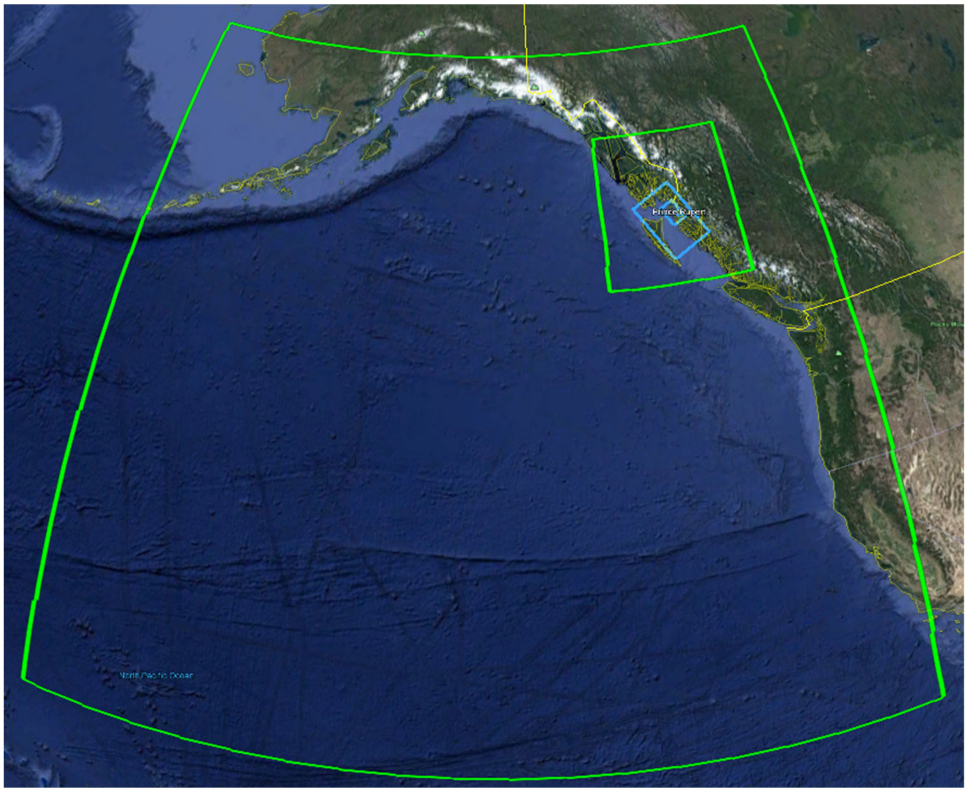


Figure 3-4 The view of nested grids for seismic-generated tsunami model

For each subduction zone seismic event, modelling simulations were conducted under high water slack water level conditions for the following two scenarios:

- Present day - equal to HHWMT (2.3 m GD).
- Future sea level rise (approximately year 2100) - equal to HHWMT (2.3 m GD) plus 1 m sea level rise.

3.4.2 Landslide-Generated Tsunami Model

The propagation and inundation of the tsunami induced by landslide events were modelled using TELEMAC-3D, developed by the Laboratoire National d'Hydraulique et Environnement (LNHE), a department of Electricité de France's Research and Development Division (EDF). TELEMAC-3D is a threedimensional model that solves the Reynolds-Averaged Navier-Stokes equations in unstructured meshes obtained by superimposition of two-dimensional meshes of triangles. The TELEMAC model was first used to used to simulate landslide induced waves in 1998 (Viard, 2017). Independent verification of the model's ability to simulate landslide induced waves was conducted by NHC. Further details on the validation of the model can be found in **Appendix D**.

The landslide location, geometry and impact velocity are summarized in **Table 3-5**.

Table 3-5 Landslide location, geometry and impact velocity

Slide	Location	Angle	Length (m)	Width (m)	Thickness (m)	Velocity (m/s)
1	54.3656 N -130.2569 E	32	580	150	20	20
2	54.2654 N -130.3542 E	32	1,240	1,000	10	10

It must be emphasized that this analysis provides a 'worst-case' scenario for landslides that could produce damaging tsunami within the study area. The analysis considers the sudden failure of a large mass of material on a steep, high slope with the material sliding in a manner that enters the water at high speed. The analysis also assumed that the landslides initiated with headscarps near the top of the slopes, a situation that results in the highest impact velocities of the sliding mass. Because no geomorphic evidence was found for such failures, either on rock slopes or on the seafloor below, it is assumed that none has happened within the past 12,000 years, i.e., since the study area was deglaciated at the end of the last 'Ice Age'. The possibility that such a landslide might happen within the next several hundred years cannot be totally ruled out, but is extremely unlikely. Thus, the tsunami wave heights resulting from these events are not only the maximum possible, but also have a likely average annual probability of 1 in 10,000 (0.001). Smaller landslides within a 20-km radius of Prince Rupert are much more likely, but they would produce correspondingly smaller tsunamis. It is likely that landslides with average annual probabilities of 1 in 100 (0.01) would have little or no effect on Prince Rupert or Port Edward.

Two model meshes (**Figure 3-5** and **Figure 3-6**) were developed for the study to simulate the tsunami propagation and inundation induced from the landslides, one for Slide 01 and the other Slide 02 (**Figure 2-6**). The element lengths vary from approximately 50 m in the Pacific Ocean to about 3 m near the slide source.

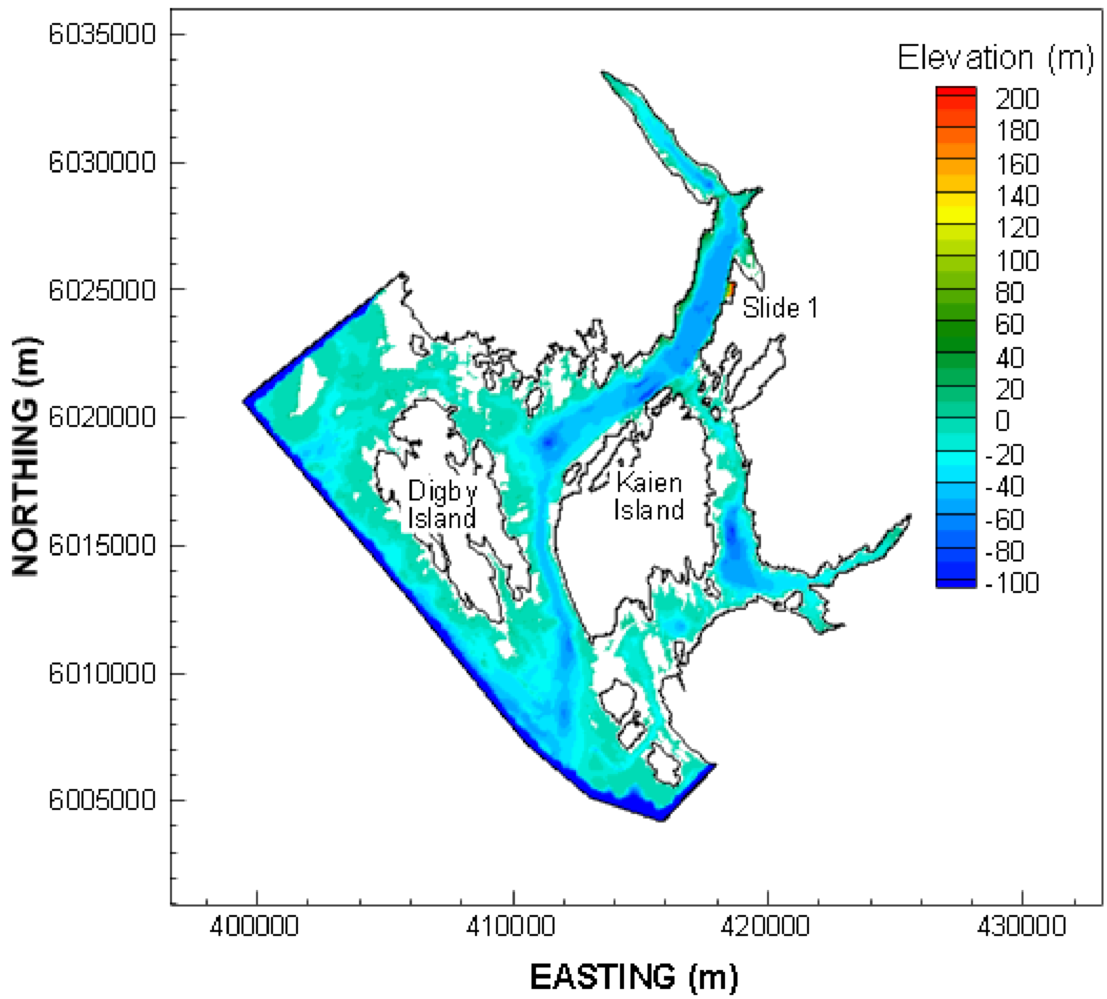


Figure 3-5 Slide 1 model mesh extent (UTM coordinates, zone 9 North)

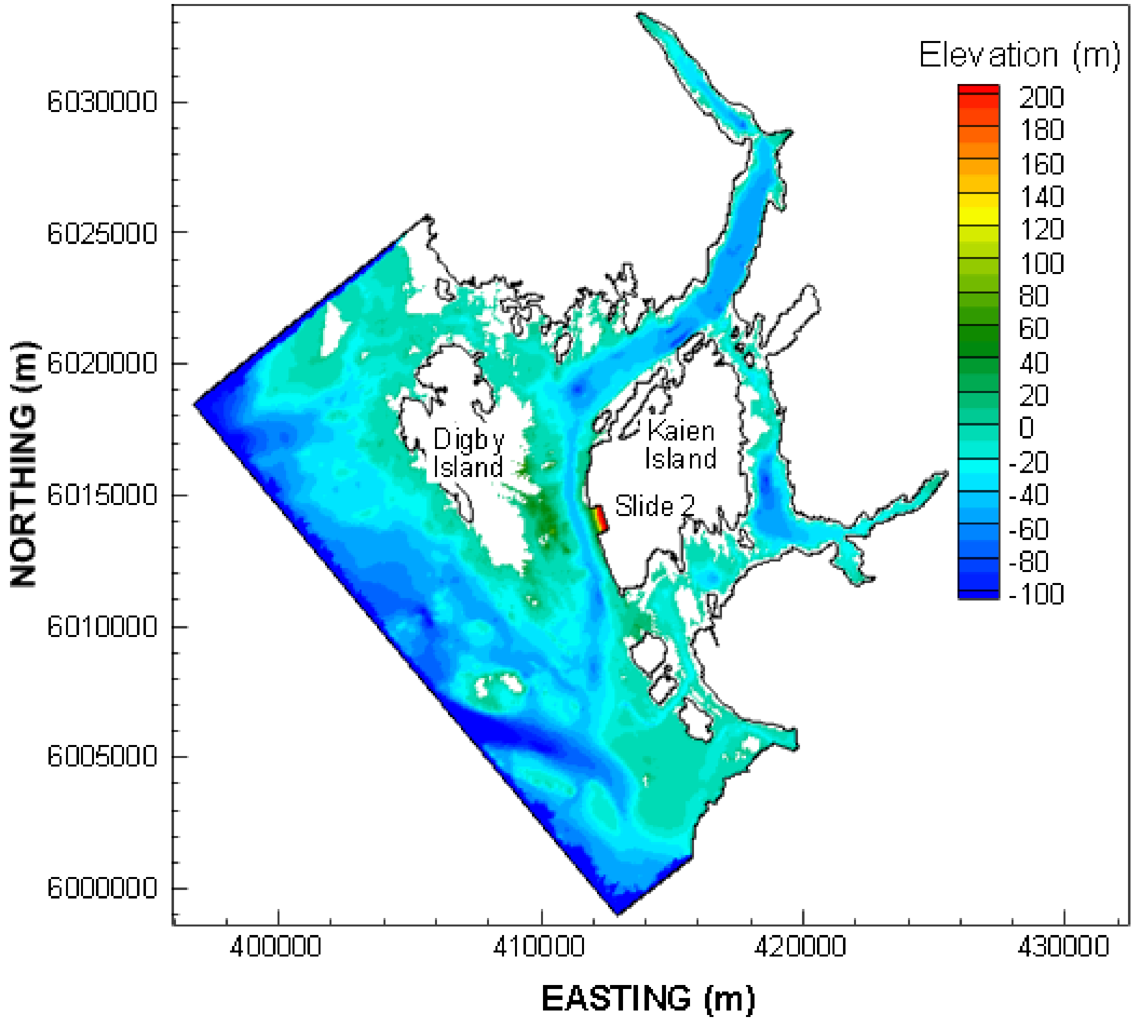


Figure 3-6 Slide 2 model mesh extent (UTM coordinates, zone 9 North)

For each landslide, modelling simulations were conducted under two static water level conditions:

- Present day - assuming that prevailing tide was static (no flow) and equal to HHWLT (3.6 m GD).
- Future climate change - assuming that prevailing tide was static (no flow) and equal to HHWLT (3.6 m GD) plus 1 m sea level rise.

The same bathymetry and topography datasets (**Table 3-1**) used to develop the model surface for the seismic-generated tsunami model were used for the landslide-generated tsunami model.

4 SEISMIC-GENERATED TSUNAMI MODELLING ANALYSIS

Seismic-generated tsunami modelling analysis was conducted to evaluate inundation extent and velocities associated with the tsunami hazard. Only the modelling results are presented in this section. Further details on the development, calibration, and validation of the numerical model can be found in **Appendix C**. A summary and discussion of the areas within the City affected by tsunami is provided in detail in the Risk Assessment (**Section 7**). Maps showing the extents of flood hazard zones are provided in **Appendix E**.

4.1 Present Day

Figure 4-1 shows changes in surface water elevation over a period of 12 hours at Cow Bay Marina for the Cascadia subduction zone seismic event (pink line) and for the Alaska-Aleutian subduction zone seismic event (blue line). The figure shows that the initial tsunami waves arrived about 100 minutes and 120 minutes apart for the Cascadia and Alaska-Aleutian subduction zone seismic events, respectively. First wave amplitudes and maximum crest elevations with arrival times are presented in Table 5 of Appendix C.

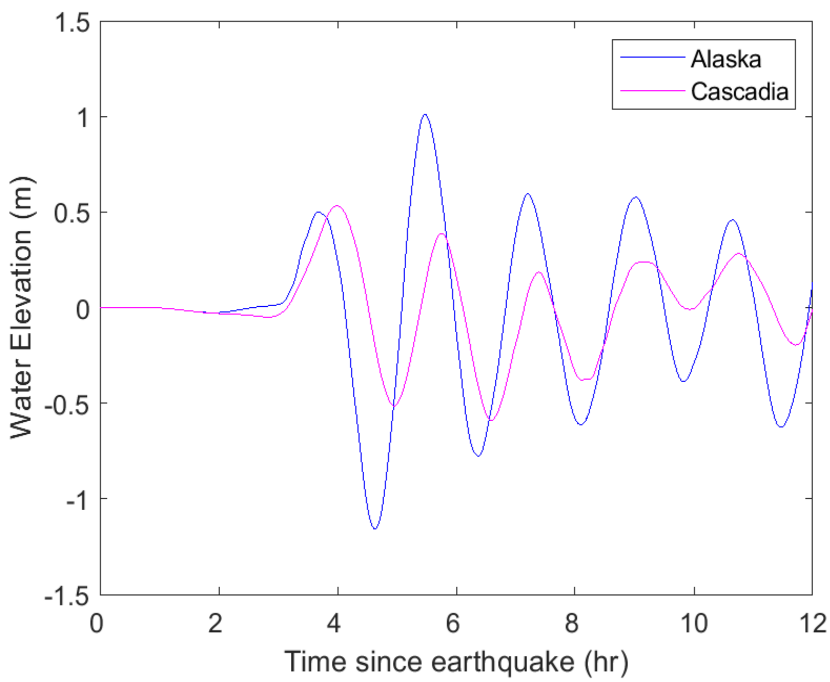


Figure 4-1 Time series of changes in surface water elevation at Cow Bay Marina for Alaska-Aleutian subduction zone seismic event (blue line) and Cascadia subduction zone seismic event (pink line)

The Cascadia subduction zone seismic event generated an initial tsunami wave height of about 0.5 m and it reached Cow Bay Marina about four hours after the initial seismic event. This was the maximum increase in water surface elevation at this location for the Cascadia subduction zone seismic event. **Figure 4-2** shows the distribution and change in water surface elevation in the Prince Rupert region 4, 5, 6 and 8 hours after the seismic event.

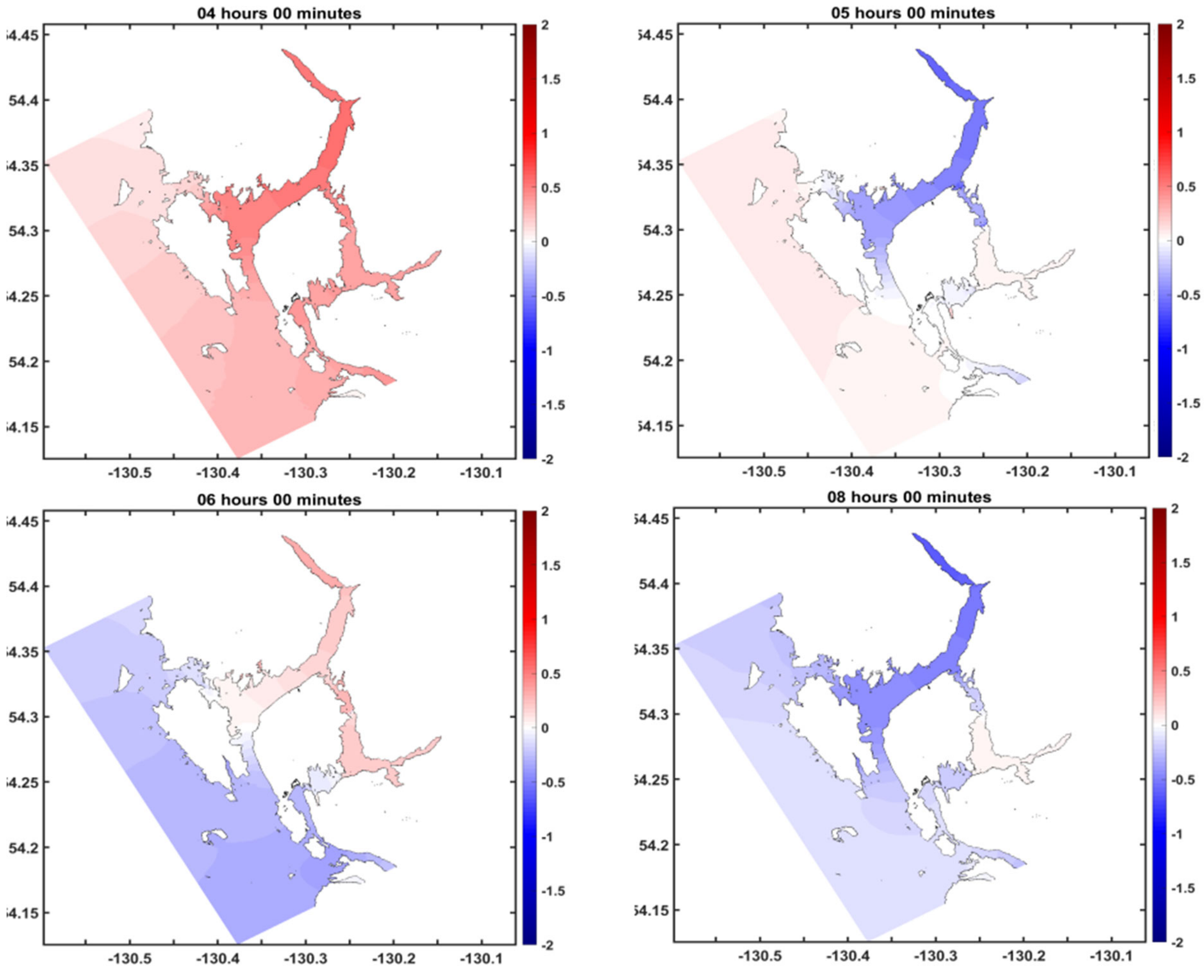


Figure 4-2 Changes in surface water elevation for the Cascadia event

The Alaska-Aleutian subduction zone seismic event also generated an initial tsunami wave height of about 0.5 m and it reached Cow Bay Marina about three hours and forty minutes after the seismic event. It is noted that the first wave from the Alaska-Aleutian subduction zone seismic event did not result in the maximum increased in water surface elevation at this location. Rather, it is the second wave that results in the maximum increased in water surface elevation of 1 m at this location[4]. **Figure 4-2** shows

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[4] The sequencing of tsunami waves and why the first wave is not always the largest might be related to several factors. This behaviour could be explained from frequency dispersion, as the width of wave spectrum in the primary wave packet becomes dispersed in time comparable to dominant wave period, which is controlled by a combination of source size and ocean depth, and influence of the fault width on the distribution of sequencing is more important than the fault length. Further discussions can be found at Okal and Synolakis (2016). The authors also simulated two largest recent transoceaninc tsunamis (2010 Chile and 2011 Japan). Based on the distribution of sequencing, for most DART buoys they showed that the delayed arrival time of the maximum wave are not (or at least not entirely) due to site effects involving the nonlinear response of bays and harbours. From an operational perspective, this supports the precautionary attitude in emergency management

the map of distribution and change in surface water level in the Prince Rupert region 4, 5, 6 and 7 hours after the seismic event.

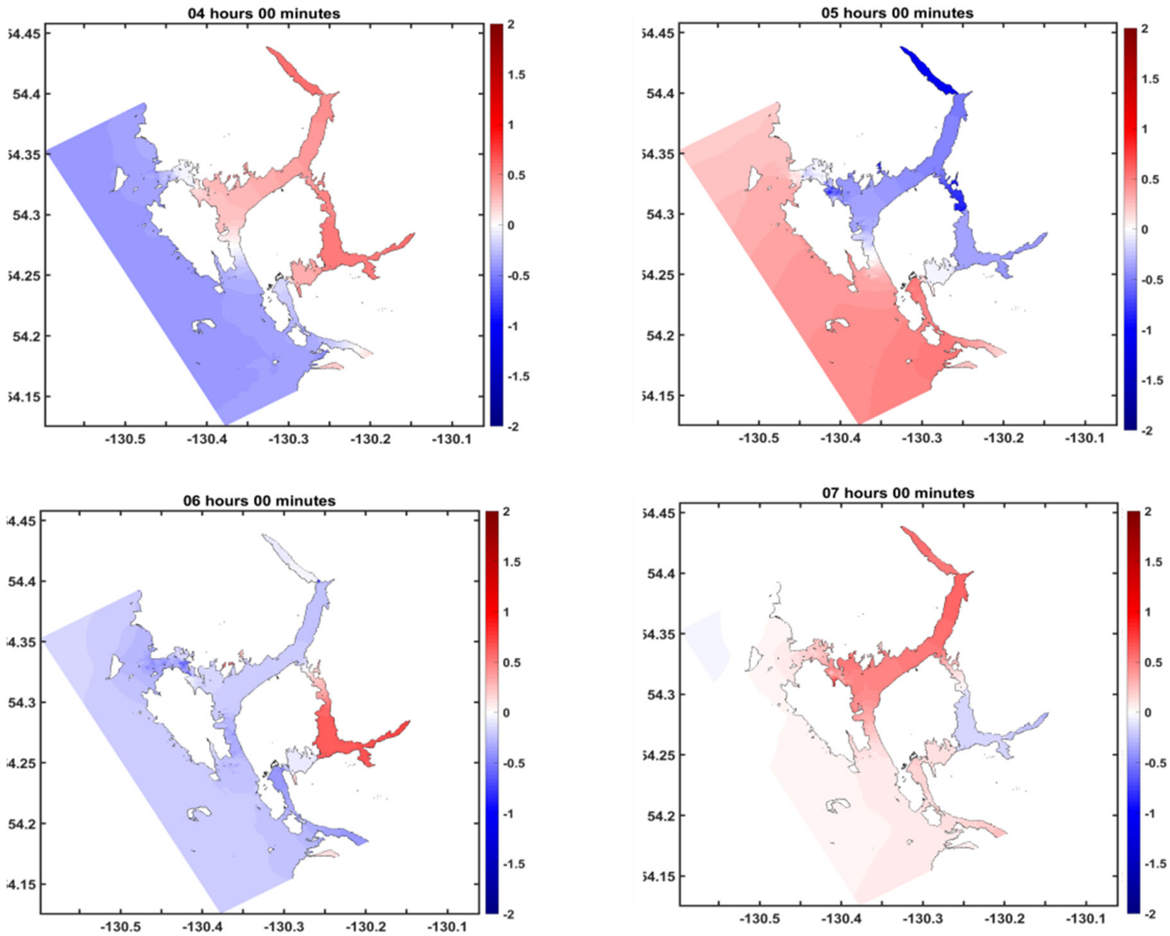

Figure 4-3 Changes in surface water elevation for the Alaska-Aleutian subduction zone event

Figure 4-4 shows the distribution of maximum increase in water surface elevation over the course of 12 hours after the Cascadia subduction zone seismic event (left panel) and Alaska-Aleutian subduction zone seismic event (right panel). The figure shows that maximum increase in water level from the Alaska-Aleutian subduction zone seismic event is greater than that from the Cascadia subduction zone event. The maximum water level occurred at the north end of Tuck Inlet, with a maximum water level elevations decreasing towards the City. Maximum wave level from the Alaska-Aleutian subduction zone

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highlighting that tsunami arrival time refer to initiation of the phenomenon, while its full development may delay the most dangerous parts of the wave for a few hours. (from: Okal, E. A., and Synolakis, C. E. (2016). Sequencing of tsunami waves: Why the first wave is not always the largest. *Geophysical Journal International, 204*(2), 719–735.)

seismic event is about 1.5 m at Tuck Inlet whereas the maximum wave height from the Cascadia subduction zone event is about 0.8 m.

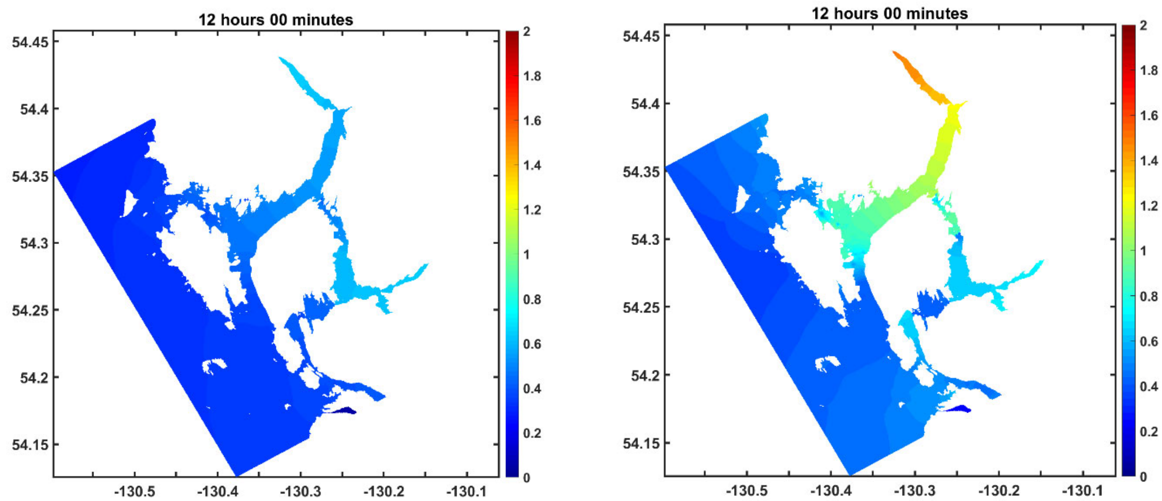


Figure 4-4 Maximum wave heights (m) for a period of 12 hours for the Cascadia subduction zone seismic event (left panel) and Alaska-Aleutian subduction zone seismic event (right panel)

Figure 4-5 shows the distribution of maximum water velocity over a period of 12 hours after a Cascadia subduction zone seismic event (left panel) and Alaska-Aleutian subduction zone seismic event (right panel). Maximum velocities generated from the Alaska-Aleutian subduction zone seismic event are greater than the velocities from the Cascadia subduction zone seismic event.

Due to the surface water gradient (as shown in **Figure 4-2** and **Figure 4-3**), high velocities are predicted in the channel north and east of the Digby Island. Under the Cascadia subduction zone seismic event, the velocities in these two channels are about 1 m/s and 2 m/s, respectively. Under the Alaska-Aleutian subduction zone seismic event, the velocities are about 3 m/s and 4 m/s, respectively.

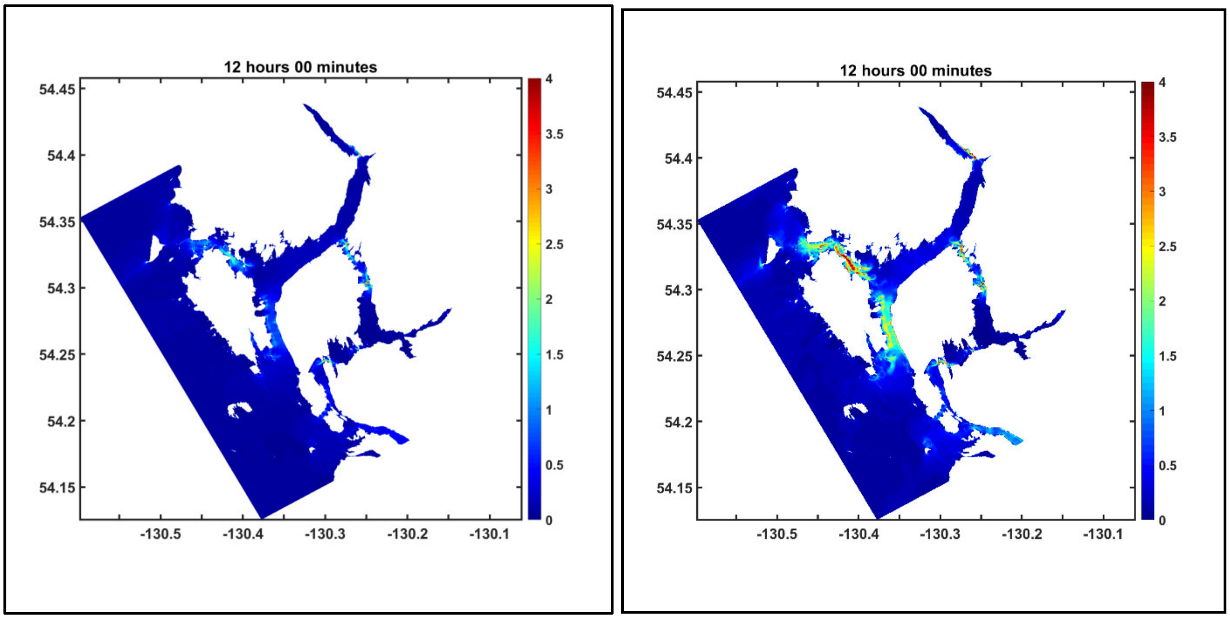


Figure 4-5 Maximum velocity over a period of 12 hours for the Cascadia subduction zone seismic event (left panel) and Alaska-Aleutian (right panel) subduction zone seismic event

Maximum increases in surface water level and maximum velocity at selected locations from the Alaska-Aleutian subduction zone seismic event are summarized in the table below (**Table 4-1**).

Table 4-1 Maximum increase in surface water level and maximum velocity [5]

Location	Increase in water level (m)	Maximum velocity (m/s)
Metlakatla Marina	0.5	0.85
Digby Island Ferry	0.8	3.1
Airport Ferry	0.8	0.62
Cow Bay Marina	0.95	0.38
Hays Cove	1.1	0.85
Lax Kw'Alaams Ferry	1.5	0.07

The overall distributions of changes in water surface elevations and maximum velocities are consistent with Fine et al. (2018a) and Fine et al. (2018b). Changes in water surface elevations and maximum velocities at selected locations were about 20% and 35% lower than the values presented in the Fine et al (2018a, 2018b) studies. The differences are likely due to a difference in the bathymetry and topography data as well as the different model resolution and model selected. For this study a full Boussinesq model was employed for seismic wave propagation modeling.

[5] The first wave will arrive after about 3.5 hours. See Appendix C-Figure 13 in section 4.4.2 (specific locations of high interest) where the wave time-series for these locations are plotted.

Given the limitations of this study, a safety factor such as that proposed by Fine et al. (2018a, 2018b) of 50% is reasonable when planning for possible future tsunami hazards, as we did not study the full range of potential slip distributions off of the Alaska subduction zone. Therefore, our numerical experiment shows a maximum of 1.1 m tsunami at Seal Cove. We recommend a maximum realistic tsunami safe height of 1.65 m over HHWLT and a storm surge allowance should be considered, with the inclusion of a 50% safety factor. This maximum safe height after the addition of 1 m sea level rise (to represent future conditions in the region) corresponds to a safe height of 2.65 m above HHWLT and a storm surge allowance.

4.2 Future Climate Change

The results from the present day simulation show that the Alaska-Aleutian zone seismic event resulted in higher increase of water level and tidal velocity than from a Cascadia Subduction zone seismic event. Therefore, the discussion presented in this section focuses only on the Alaska-Aleutian zone seismic event.

Figure 4-6 shows map distribution of maximum increase in water level over a period of 12 hours after the Alaska-Aleutian subduction zone seismic event under the present day condition (left panel) and in the future with 1 m of sea level rise (right panel). **Figure 4-7** shows map distribution of maximum velocity during the first 12 hours after the Alaska-Aleutian subduction zone seismic event under the present day condition (left panel) and under the future climate change condition (right panel).

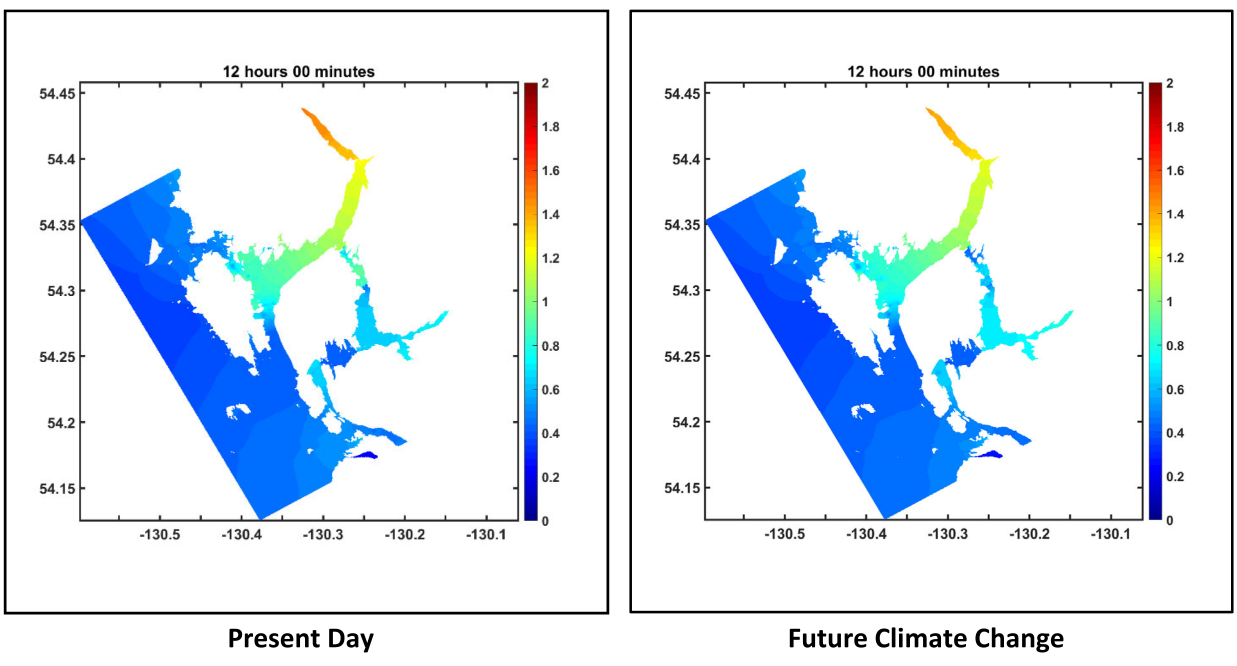
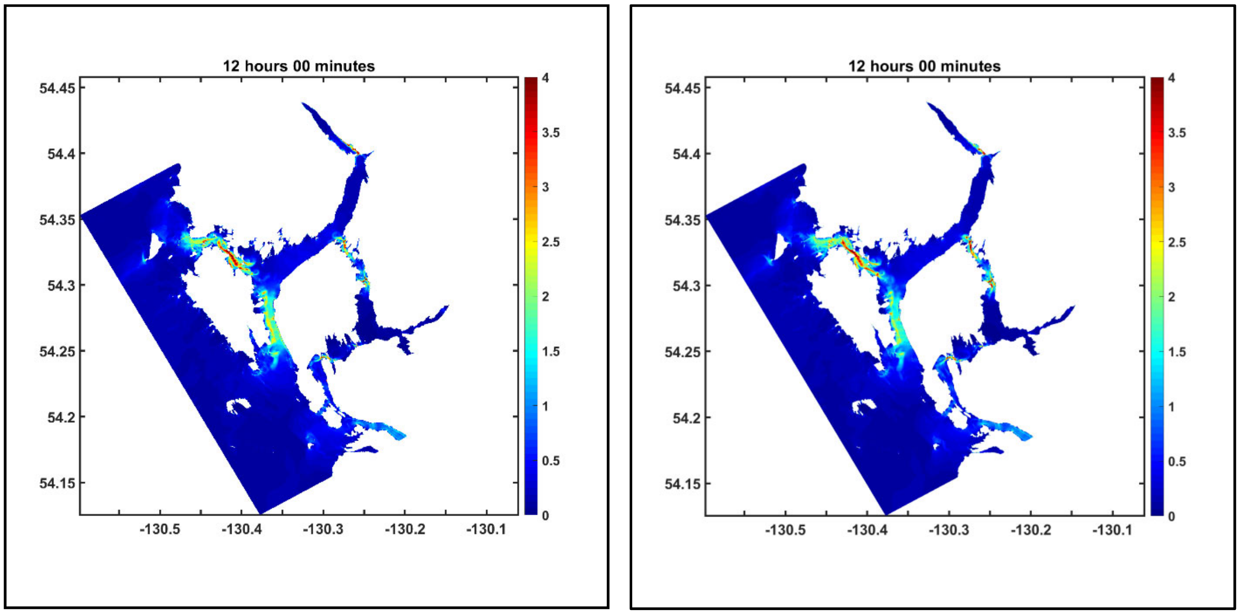


Figure 4-6 Maximum increased in water level (m) during 12 hour period following seismic event for present day (left panel) and with 1 m of sea level rise (right panel)



Present Day **Future Climate Change**

Figure 4-7 Maximum velocities (m) during 12 hour period following seismic event for present day (left panel) and with 1 m of sea level rise (right panel)

The results show that the addition of 1 m of sea level due to climate change does not significantly impact the overall tsunami wave characteristics in the Prince Rupert region. Maximum increases in surface water level and velocities at selected locations from the Alaska-Aleutian subduction zone seismic event are summarized in **Table 4-2** below. It is observed that in some cases the tsunami wave height (increase in water level) is less with SLR than at present day and this is attributed to the increased water depths and widths of the inlets at higher water resulting in a slightly lower wave height. Similarly, variability in channel geometry and nearshore water depths accounts for variability in maximum flow velocity in the model.

Table 4-2 Maximum increase in surface water level and maximum velocity

Location	Increase in water level (m)		Maximum velocity (m/s)	
	Present	1 m SLR	Present	1 m SLR
Metlakatla Marina	0.5	0.5	0.85	0.45
Digby Island Ferry	0.8	0.8	3.10	1.80
Airport Ferry	0.8	0.8	0.62	0.54
Cow Bay Marina	1.0	0.8	0.38	0.35
Hays Cove	1.1	1.0	0.85	1.00
Lax Kw'Alaams Ferry	1.5	1.3	0.07	0.06

5 LANDSLIDE-GENERATED TSUNAMI MODELLING ANALYSIS

Landslide-generated tsunami modelling was conducted to evaluate inundation extent and velocities associated with the potential tsunami hazard from very large landslides in the region. The modelling methodology and results are presented in the sections below. Further details on the development, calibration, and validation of the numerical models can be found in **Appendix C**.

As discussed in **Section 2.2.2**, the preliminary geomorphic analysis was based upon inspection of LiDAR, satellite images , and historical aerial photographs. The LiDAR data revealed no evidence of recent or ongoing slope instability near Prince Rupert that might generate a tsunami. The landslide-generated simulations were conducted to examine the possible tsunami inundation from a "worst-case' landslide scenario .

5.1 Present Day

Figure 5-1 shows changes in surface water elevation over 30 minutes at the Cow Bay Marina for Slide 1 (pink link) and for Slide 2 (blue line). The first wave from Slide 1 arrived at Cow Bay Marina about five minutes after the initial slide and resulted in an increase in water surface level of 1.3 m. Slide 2 is located farther from Cow Bay Marina than Slide 1. The first wave from Slide 2 arrived at Cow Bay Marina about six minutes after the initial slide and resulted in an increase in surface water level of 0.9 m. The landslide-generated tsunami waves have shorter wave periods than seismic-generated tsunami waves. Instead of successive waves with lower amplitudes as seen in **Figure 4-1**, the water level oscillates back and forth with irregular patterns throughout the simulation. These irregular oscillations are in part due to waves reflecting from the irregular coastline and prolongs the duration of the tsunami wave on people and infrastructure.

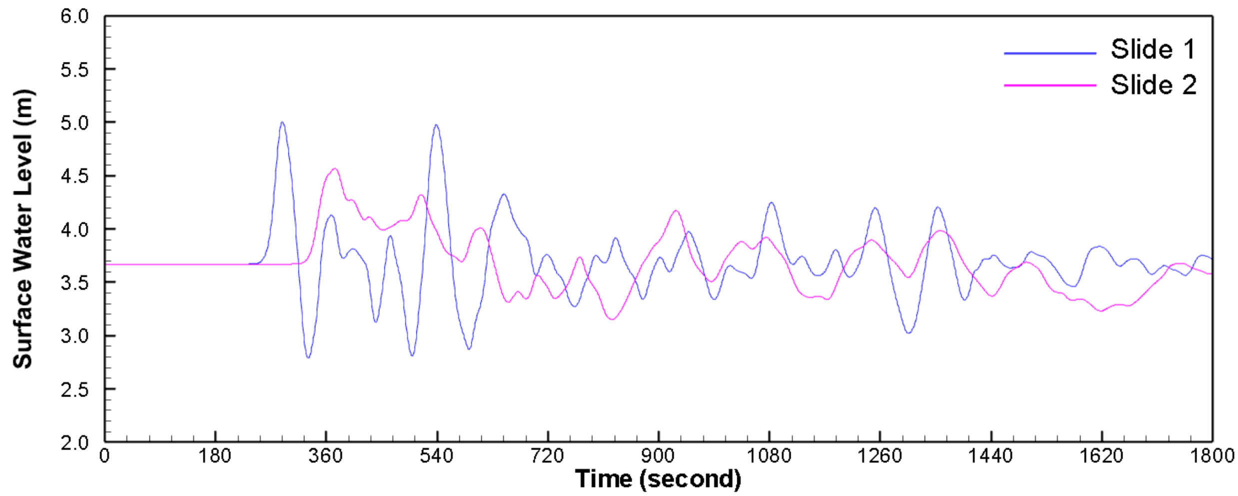


Figure 5-1 Time series of changes in surface water elevation at the Cow Bay Marina for Slide 1 (blue line) and for Slide 2 (pink line)

Figure 5-2 and **Figure 5-3** shows the distribution of maximum increases in surface water elevation over the course of 30 minutes after the Slide 1 and Slide 2 events, respectively. **Figure 5-4** and **Figure 5-5** show the distribution of maximum velocities over the course of 30 minutes after Slide 1 event and Slide 2 event, respectively.

As described in **Section 2.2**, landslides entering water generate large waves that are extremely destructive near their source. The results show that maximum increase in water level and velocity near Slide 1 were 90 m and 50 m/s, respectively. Increases in water level are generally less than 3 m in the main channel at the Prince Rupert downtown waterfront 3.5 km away from the slide source. However, large increases in water level values were predicted in shallow water areas and in enclosed embayments where tsunami run-up is higher due to wave concentration and funnelling effects. This is most noticeable near Hays Cove and the area between Rushbrook Harbour and Cow Bay as illustrated in **Figure 5-6**. Maximum increase in water level and velocity near Slide 2 were 110 m and 50 m/s respectively. The rock slide mass pushes water to a height of 40 m above sea level on the opposite shore (Digby Island) of the channel. Increases in water level are generally less than 3 m in the main channel at the Prince Rupert downtown waterfront 4.5 km away from the slide source.

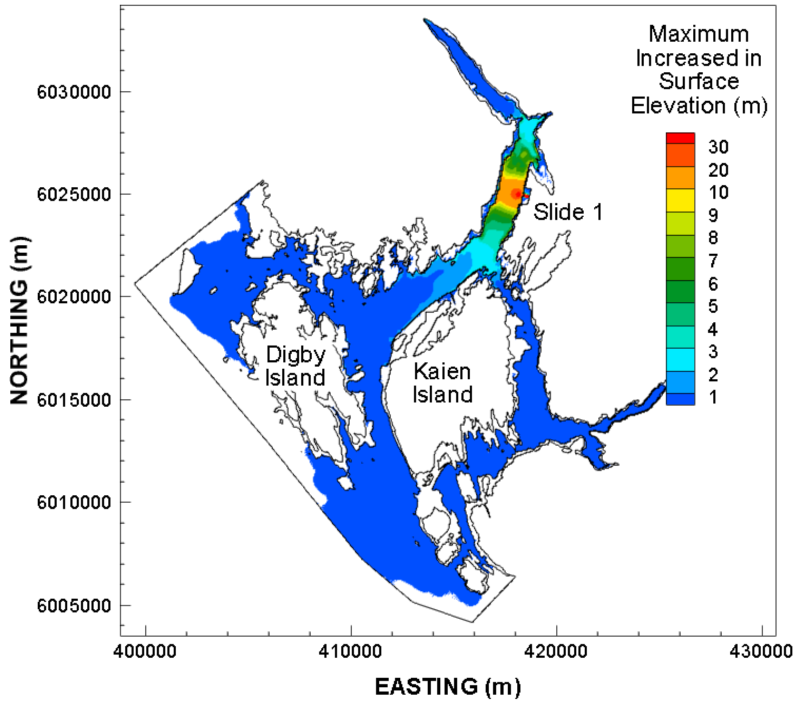


Figure 5-2 Maximum increase in water surface elevation over the course of 30 minutes for Slide 1

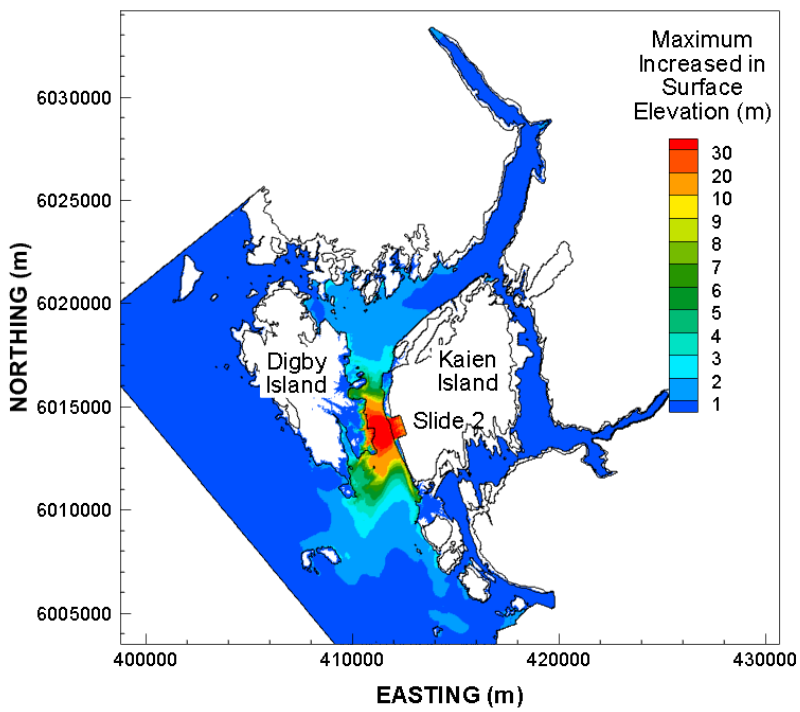


Figure 5-3 Maximum increase in water surface elevation over the course of 30 minutes for Slide 2

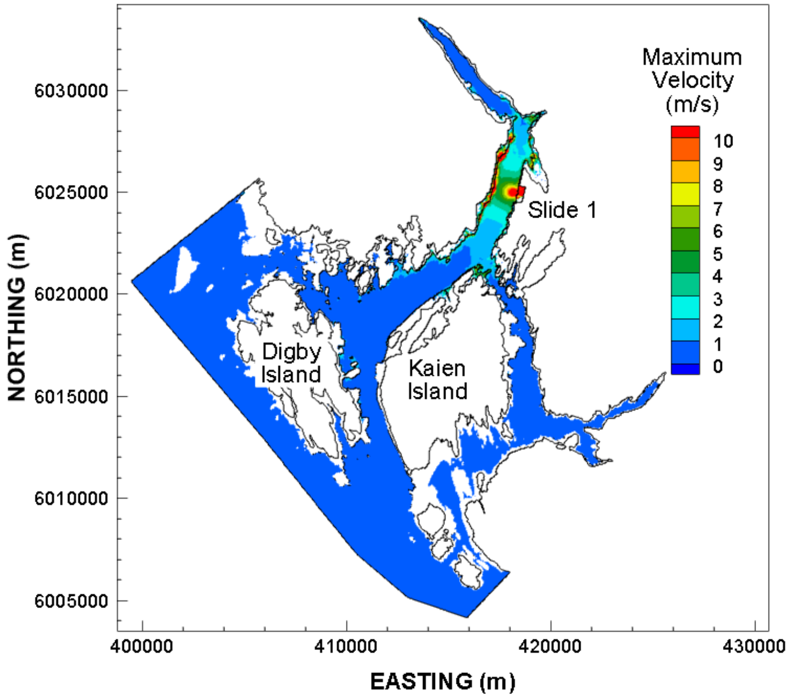


Figure 5-4 Maximum velocities over 30 minutes for Slide 1

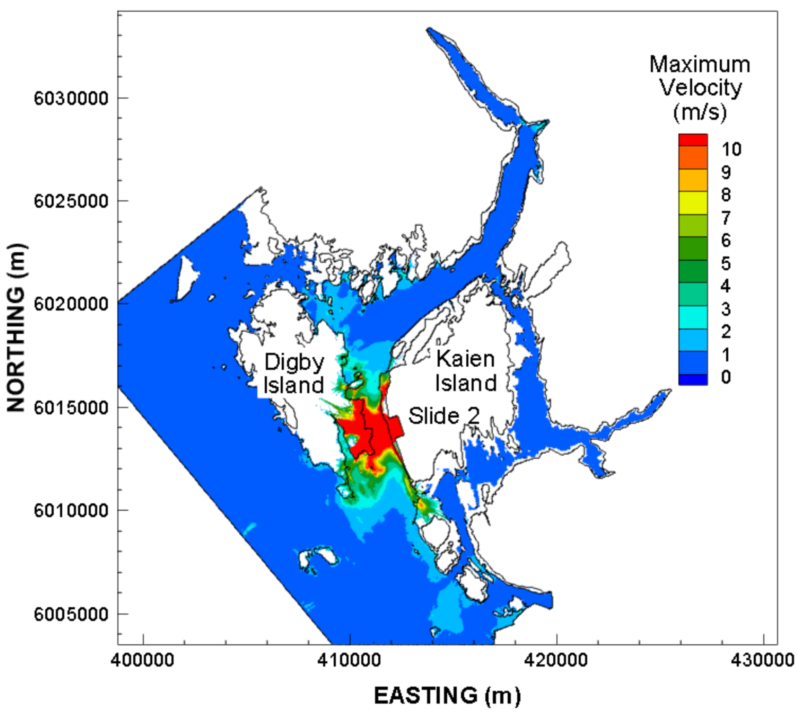


Figure 5-5 Maximum velocities over 30 minutes for Slide 2

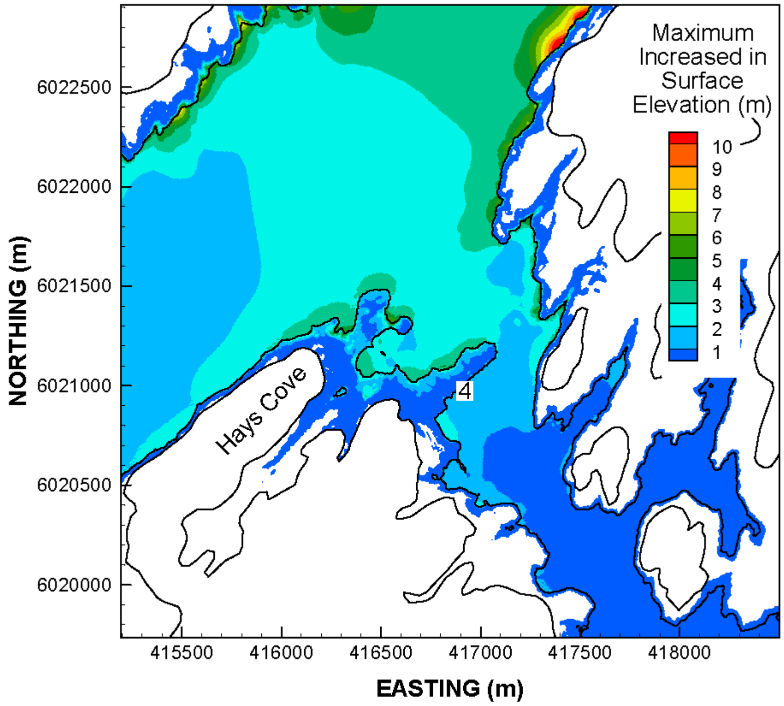


Figure 5-6 Maximum increase in water surface elevation near Hays Cove over a period of 30 minutes for Slide 1

Maximum increase in water level and maximum velocity at selected locations from Slide 1 and Slide 2 events over a period of 30 minutes following the landslide event are summarized in **Table 5-1**.

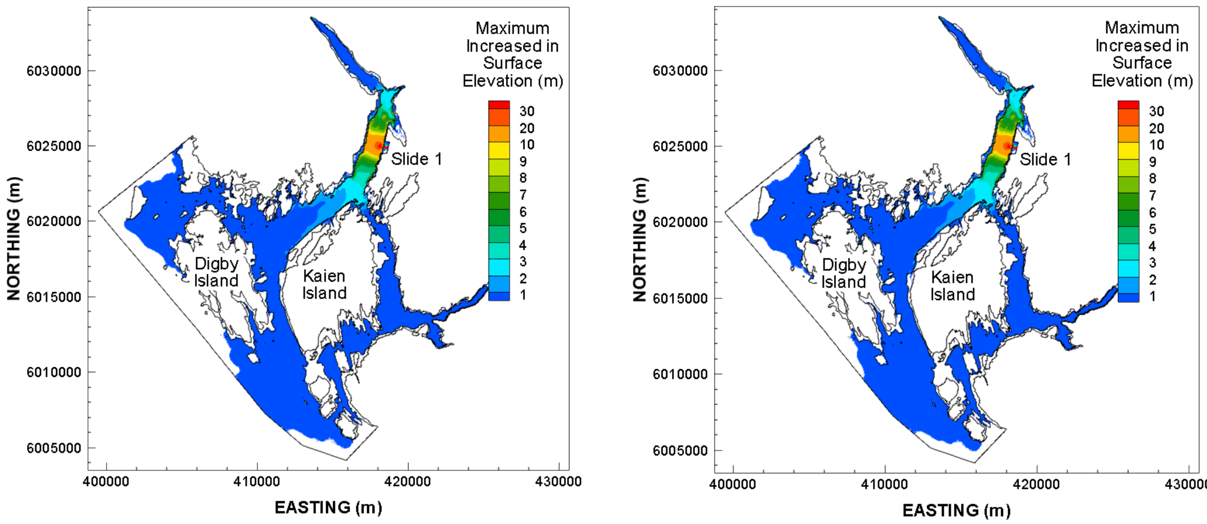
Table 5-1 Maximum increase in surface water level and maximum velocity

	Slide 1		Slide 2	
Location	Increase in water level (m)	Maximum velocity (m/s)	Increase in water level (m)	Maximum velocity (m/s)
Metlakatla Marina	0.1	0.2	0.4	0.3
Digby Island Ferry	0.4	0.5	1.3	1.8
Airport Ferry	1.0	0.7	2.6	1.4
Cow Bay Marina	1.3	0.7	0.9	0.5
Port Simpson Ferry	3.0	7.3	0.9	0.4
Lax Kw'Alaams Ferry	0.7	0.4	0.6	0.5

5.2 Future Climate Change

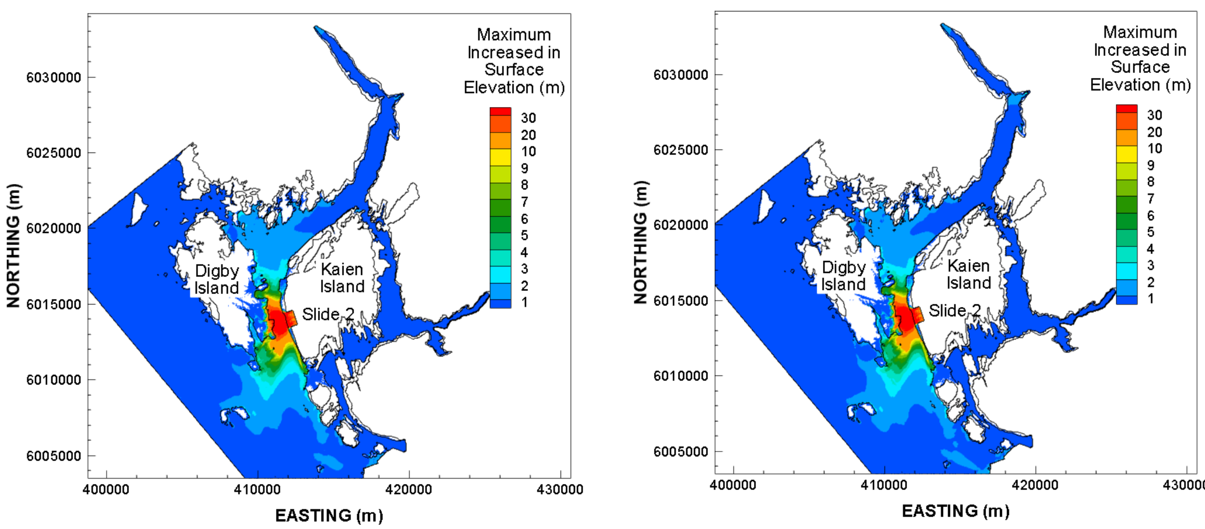
Figure 5-7 shows the distribution of maximum increases in water level over the course of 30 minutes after the Slide 1 event under the present day condition (left panel) and with 1 m of sea level rise (right panel). **Figure 5-8** shows the distribution of the maximum increase in water level over the course of 30 minutes after the Slide 2 event under the present day condition (left panel) and with 1 m of sea level rise (right panel). As in the case of the seismic-generated tsunami, the increase of 1 m of sea level does not significantly impact the overall tsunami wave characteristic in the Prince Rupert region.

Maximum increase in water level and maximum velocity at selected locations for Slide 1 and Slide 2 events are summarized in **Table 5-2** and **Table 5-3**, respectively.



Present day **Future climate change**

Figure 5-7 Maximum increase in water level (m) over a period of 30 minutes after Slide 1 for present day (left panel) and with 1 m of sea level rise (right panel)



Present day **Future climate change**

Figure 5-8 Maximum increase in water level (m) over a period of 30 minutes after Slide 2 for present day (left panel) and with 1 m of sea level rise (right panel)

Table 5-2 Slide 1 - Maximum increase in surface water level and velocity

Location	Increase in water level (m)		Maximum velocity (m/s)	
	Present	Future Climate Change	Present	Future Climate Change
Metlakatla Marina	0.1	0.1	0.2	0.2
Digby Island Ferry	0.4	0.4	0.5	0.5
Airport Ferry	1.0	0.8	0.7	0.6
Cow Bay Marina	1.3	1.4	0.7	0.6
Hays Cove	3.0	2.9	7.3	5.7
Lax Kw'Alaams Ferry	0.7	0.7	0.4	0.4

Table 5-3 Slide 2 - Maximum increase in surface water level and velocity

Location	Increase in water level (m)		Maximum velocity (m/s)	
	Present	Future Climate Change	Present	Future Climate Change
Metlakatla Marina	0.4	0.3	0.3	0.3
Digby Island Ferry	1.3	1.2	1.8	1.7
Airport Ferry	2.6	2.6	1.4	1.4
Cow Bay Marina	0.9	0.8	0.5	0.5
Hays Cove	0.9	0.8	0.4	0.4
Lax Kw'Alaams Ferry	0.6	0.7	0.5	0.5

6 FLOOD MAPPING

Model results from the seismic-generated tsunami events (**Section 4**) and the landslide-generated tsunami events (**Section 5**) were used to generate a series of maps. The seismic tsunami flood maps are presented in Appendix E and were used to inform the vulnerability and risk assessment (**Section 7** and **Appendix F**). The landslide-generated tsunami flood maps are presented in **Appendix G**.

For the given water level scenario, the results of the two landslide simulations have been merged on the depth maps to show the extents of the flood hazard area. On velocity maps, results are shown separately for the two landslide simulations.

For the given water level scenario, the results of the seismic tsunami simulations have been merged on the depth maps to show the extents of the flood hazard area. On velocity maps, results are shown separately for the two seismic tsunami simulations.

The maps show the maximum water depth and the maximum current velocity that occur during the tsunami simulations. The maximum values do not occur simultaneously within the project area.

7 RISK ASSESSMENT

A qualitative risk assessment was conducted using inundation depth and velocity results from the seismic-generated tsunami simulations to evaluate the risk to people and physical assets in Prince Rupert associated with seismic-generated tsunami events. The Primary Assessment Area for the analysis focused on the City of Prince Rupert and its assets, and Prince Rupert Airport on Digby Island. The Secondary Assessment Area includes communities outside of the City of Prince Rupert and port and marine assets not owned by the City. A discussion of results is presented in this section and the complete results are included in **Appendix F**.

The risk assessment was based on a tsunami occurring in the Alaska-Aleutian subduction zone. While a tsunami occurring in the Cascadia subduction zone is also possible, the inundation depth and velocity of an Alaska based tsunami are greater than for a Cascadia based tsunami. This applies to all geographical locations in both the Primary and Secondary Assessment areas. Warning times for both tsunamis would be similar although the arrival time of the first wave of an Alaska based tsunami would have somewhat shorter (3 hours and 40 minutes compared to 4 hours for a Cascadia based tsunami). Consequently, the assessment results have been documented for an Alaska based tsunami but not for a Cascadia based tsunami. Although the results are similar, detailed documentation has focussed on an Alaska based tsunami as that scenario would have more negative potential consequences (i.e., greater inundation depth, greater velocity and shorter warning time).

Note that landslide generated tsunamis have not been evaluated in this risk assessment. The reason for this is that there is no evidence at this time of a history or risk of slope failure for the steep slopes in the vicinity of Prince Rupert, and it is believed that the probability of slope failures generating large mass landslides is small enough to not warrant consideration in the risk assessment for the City. Due to the potential consequence of a large slope failure as indicated by the modeling in this study, detailed geotechnical studies of these slopes are recommended to improve the understanding of the probability of slope failures.

7.1 Likelihood Assessment

The probability of a tsunami can be estimated based on previous occurrences. The last major Cascadia based tsunami occurred on January 27, 1700. Although there are no written records in North America, the estimated date is inferred from records in Japan, archaeological and oral histories in the Pacific Northwest and tree ring analysis in Washington and Oregon. The last major Alaska based tsunami that affected B.C. occurred on March 27, 1964 which resulted in significant property damage in Port Alberni. These two tsunamis with origins in different fault zones indicate return periods of 419 and 55 years respectively. While the probability of each seismic induced tsunami is low, it is not negligible.

Modelling of a landslide generated tsunami was also undertaken. Two hypothetical scenarios were prepared depicting the 'worst-case' landslide that could produce a damaging tsunami within the study area. Slide 1 represented a potential rockslide on a steep slope approximately 4 km northeast of Seal

Cove in the Prince Rupert Harbour. Slide 2 is located on the west side of Kaien Island approximately 3 km south from the Prince Rupert Ferry Terminal to Digby Island. While the consequences would be catastrophic, particularly for the Slide 2 scenario, there is no evidence to postulate that either slope will fail based on aerial photographs and bathymetric data. Because no geomorphic evidence was found for such failures, either on rock slopes or on the seafloor below, it is assumed that none has happened within the past 12,000 years. This represents the approximate time period since the study area was deglaciated at the end of the last 'Ice Age'. The possibility that such a landslide might happen within the next several hundred years cannot be totally ruled out but is extremely unlikely.

Smaller landslides within a 20-km radius of Prince Rupert are much more likely, but they would produce correspondingly smaller tsunamis. It is likely that landslides with average annual probabilities of 1 in 200 years (0.005) would have little or no effect on Prince Rupert or Port Edward. Therefore, a risk assessment under these scenarios was not included at this time.

The probability of a tsunami can be compared to other potential hazards. Two commonly used standards are the protection of habitable buildings from flood hazards under Provincial Flood Hazard Area Land Use Management Guidelines and the protection of building construction from seismic risk under the BC Building Code. The flood hazard standard for B.C. has historically been 1 in 200 years (i.e. annual probability of 0.005). Some Lower Mainland municipalities have recently adopted a more stringent standard of 1 in 500 years (i.e. annual probability of 0.002). Most other Canadian provinces and the USA have adopted a less stringent standard of 1 in 100 years (i.e. annual probability of 0.01). The BC Building Code (2018) requires seismic slope stability assessment under both static and seismic conditions to be addressed as part of the foundation design. The seismic hazard probability cannot exceed a return period of 1 in 2,475 years (or a 2% probability of exceedance in 50 years).

For both flood and seismic hazards, the likelihood of a very low probability event can be calculated, but that does not pose an obligation to protect buildings to eliminate all possible risk nor is it possible to do so. The following table indicates a risk management approach for a tsunami that is more conservative then the Building Code requirement for seismic protect and much more stringent than occurs for flood protection.

Table 7-1 Probability, consequence and risk thresholds

Probability (Likelihood)	X	Consequences	=	Risk
> 1:2,500 years	X	Variable	=	Risk below mitigation threshold
< 1:2,500 years	X	Variable	=	Mitigate risk

7.2 Hazard Consequences and Interpretation

As the following analysis in 7.3 indicates, both scenarios indicate virtually all inundation would be confined to intertidal areas with a depth of 2.0 metres or less. Neither scenario indicates a tsunami would result in overland flows beyond minimal areas. Two additional variables could increase the impact of the inundation. One is if a tsunami coincides with the Maximum Higher High Water (MHHW) level. The other is a future scenario that results in one metre of sea level rise. This sea level rise represents Provincial guidance based on a 2011 study by Ausenco (see Figure 3-3). This increase in sea level is not specific to Prince Rupert and has a projected estimate of occurring around year 2100. There are many factors that affect the rate of sea level rise. As a result, it is appropriate to consider one metre of sea level rise as representing a margin of safety but not with specific application to Prince Rupert in the year 2100.

The velocity maps indicate highly variable conditions depending on the local topography. In most of the study area, including a large majority of the Prince Rupert Harbour, the tsunami velocity would be under 0.5 metres per second. In more constrained channels, velocities would be much higher and could exceed 2 metres per second. These areas consist of Venn Passage east to Crippen Cove on Digby Island, Fern Passage, Butze Rapids, Galloway Rapids, the south entrance to Prince Rupert Harbour (south of Fairview Harbour) and the narrow passage between Kaien and Watson Islands. Maximum wave velocities of up 3.0 metres per second for an Alaska tsunami are projected in the two channels around Digby Island and up to 4.0 metres per second close to Seal Cove. The velocities for a Cascadia based tsunami would be less than half that of an Alaska tsunami. Higher velocities do not necessary correspond to higher inundation levels.

Given an anticipated warning of over three hours for a tsunami (Alaska or Cascadia based), it is unlikely that consequences will include persons killed or injured. No residential development in Prince Rupert is located in areas at risk. As a result, no residential areas need to be evacuated. The protection of the public will be maximized by an effective warning system and the evacuation of waterfront areas to higher ground. Given no need for evacuation of residential areas, the warning time of over three hours should enable the securing of mooring lines and the orderly evacuation of marinas, ferry terminals and waterfront work sites. The risk appears minimal for industrial terminals but loading facilities should be shut down and waterfront work locations evacuated as a precautionary measure.

The consequences are primarily focussed on waterfront businesses and industry. Aspects of the hazard event which contribute to the overall damaging effects of a tsunami include: flood water depths (large depths cause more damage and require more significant repair); flood water velocity (higher velocities cause greater damages); wave action (the energy from waves causes more damage than still water); and the duration of the flood including the time-to-peak of a flood (long duration and short warning floods cause higher damages). Aspects of the area and infrastructure which affect flood damages include: contamination; sediment and debris; and construction type and age of structures. It is assumed that if infrastructure or a community asset is inundated, regardless of depth, it will not be available for use.

There may be no damage, but the asset will be taken out of service as a precautionary measure[6]. Flood-specific time disruptions are assumed to last at least two days for coastal flooding.

7.3 Assessment Results

Risk is the product of the likelihood (or probability) of a hazard and the corresponding consequences. Risk evaluation using a risk matrix was used to determine the estimated risk, if any, and then, the appropriate mitigation to reduce risk.

7.3.1 Primary Assessment Area

Emergency Services and Operations

All emergency services including the Prince Rupert Royal Canadian Mounted Police (RCMP), Ambulance Station and the Prince Rupert City Fire Rescue Department are located away from and above any potential impacts from a tsunami. The Prince Rupert City Hall, which will serve as the Emergency Operations Centre during and following a tsunami, is also not at risk from a tsunami.

The Canadian Coast Guard (CCG) Seal Cove base includes vessels homeported for search and rescue and maintenance of aids to navigation throughout the north coast. CCG Seal Cove is a base for helicopters servicing remote locations with aids to navigation, and also operates a Marine Communications Centre. The Seal Cove base is at the entrance to Fern Passage where velocities of 3.0 m/s are projected with a local maximum up to 4.0 m/s during a tsunami. This poses a risk to marine based facilities which could be compounded if nearby log booms detach from their moorings and are broken up. However, inundation is not projected to affect any buildings in Seal Cove.

Community Infrastructure

The Prince Rupert Regional Hospital is located away from and above any potential direct impacts from a tsunami and does not need to be evacuated. Likewise, all schools, community centres and daycare centres will not be impacted and do not need to be evacuated. The Prince Rupert Civic Centre (Jim Ciccone Civic Centre) serves as the is the City's evacuation area, with the Charles Hays Secondary School as a secondary evacuation area. Inundation is not projected to affect the Civic Centre or the Secondary School.

Water, Sewer and Energy Infrastructure

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[6] This is a conservative standard, but is appropriate for a high-level overview. For reference, the following depth thresholds were developed by FEMA for critical facilities that may be closed in a particular flood scenario: hospitals – 0 m, community services and schools 0.15 m, police stations 0.30 m and fire halls 0.60 m.

Prince Rupert currently draws water from Shawatlans Lake for its municipal needs while work is taking place on a dam at Woodworth Lake which normally supplies the City's water. The multi-million dollar dam replacement project involves decommissioning of the old dam and a rebuilding a new dam and water supply lines. Both lakes are located northeast of Kaien Island on the mainland and are outside projected tsunami inundation extents. While Woodworth Lake is outside of the tsunami inundation zone, the boat docks for site access are within the hazard zone.

The City of Prince Rupert water supply comes from Shawatlan Lake on the mainland east of Kaien Island. Strong currents of 2 m/s are predicted in Fern passage from a large tsunami. These velocities are additive to any tidal currents for the purpose of risk assessment for infrastructure. A 600mm underwater line crosses under Fern Passage from the mainland west to Duncan Road on Kaien Island. A separate 500mm crossing is located approximately 200 metres to the north. The water supply intake and chlorination station are above any tsunami impact area. The water supply crossings under Fern Passage provide redundancy and are armoured or encased in concrete. The risk of water supply disruption is low.

Currently, the City discharges its sewage and storm water through combined pipes directly into the ocean. Depending on the duration of high water levels, backwater effects in the combined sewer system could cause potential upstream surcharging and flooding. An appropriate outfall level should be considered for any future design upgrades. Planning is underway for a sewerage treatment plant.

Electrical power is provided to the City by the Oldfield Substation, located at the intersection of Highway 16 and 11th Avenue East. The substation is above any projected tsunami inundation. Three other substations provide service to industrial areas on Ridley Island and Watson Island. None of these substations are located within a tsunami inundation area. All major 69 kV transmission circuits to these substations are above inundation levels.

Transportation Infrastructure

The City is located on Kaien island and the western terminus of Highway 16 (the Yellowhead Highway) and is connected to the mainland via a short bridge over Galloway Rapids. BC Ferries provides passenger ferry service from the City to Haida Gwaii and Port Hardy on Vancouver Island. The Yellowhead Highway is a major interprovincial highway that passes through Prince George, Edmonton, Saskatoon to its eastern terminus in Winnipeg. Alaska Marine Highway provides ferries to Ketchikan, Juneau, Sitka and other ports along Alaska's Inside Passage. Prince Rupert Airport (YPR) is located on nearby Digby Island and connected to the City by a ferry to Kaien Island.

The runway and terminal buildings at Prince Rupert Airport are at an elevation of 35 m above sea level (ASL) and more than 200 m from the shoreline which is outside of projected tsunami impacts. The tsunami modeling did not indicate any threat to airport infrastructure, including approach lights at the south end of the runway. However, the Prince Rupert Island Ferry Terminal on the northeast coast of Digby Island is vulnerable to water velocities of over 2.0 m/s from a tsunami.

Passenger ferry services via BC Ferries are provided to Skidegate on Haida Gwaii and to Bella Bella and Klemtu on the Central Coast and Port Hardy on Vancouver Island. Passenger ferry services are provided on the Alaska Marine Highway system to Ketchikan, Juneau and Sitka and other ports along Alaska's Inside Passage. The two adjacent ferry terminals are subject to low velocities of under 0.5 m/s and no inundation beyond the intertidal area. The anticipated warning of over three hours should allow ample time for a safe and orderly evacuation of passengers, vehicles and crew that are docked.

Two other ferries connect Prince Rupert from the Cow Bay Marina to the Metlakatla Marina and from Prince Rupert at Seal Cove (Port Simpson Ferry) to the Tuck Inlet (Lax-Kw'Alaams Ferry). The dock at the north end of Tuck Inlet faces a high wave amplitude of 1.5 metres but a low wave induced current of under 0.1 m/s. The Port Simpson Ferry in Seal Cove is subject to a maximum wave amplitude of about 1 metre as is the Cow Bay Marina. The highest velocities of up to 4.0 m/s are projected in Fern Passage by Seal Cove. The Metlakatla Marina is largely protected from the high projected velocities flowing through nearby Venn Passage. Although the risks at the different facilities vary, all ferries and docks should be evacuated.

Arterial Roads including Highway 16 and the Major Roads designated under the Official Community Plan (OCP) are located away from and above projected tsunami impacts. The Galloway Rapids Bridge would experience water velocities of over 2.0 m/s in the Galloway Rapids, but water depths are too low to inundate the bridge. It is understood that the bridge piers are anchored in rock and not at risk of damage from scour. Evacuation of the island is not recommended in the event of a tsunami. Given no residential areas or any critical infrastructure in Prince Rupert is at risk, the mass evacuation of Kaien Island is not recommended. Such evacuation would not improve public safety, would likely create a traffic jam and would potentially interfere with emergency measures.

Prince Rupert Airport (YPR) is located on Digby Island, serviced by a ferry connection to Kaien Island operated by the City of Prince Rupert. YPR provides scheduled air service, primarily to Vancouver through Air Canada. Chartered flights to regional destinations are also provided.

VIA Rail service to the City is by way of the CN railway lines. The rail line is above the inundation height of the simulated tsunamis and no disruption to passenger rail service to the city is expected in the event of a seismic tsunami.

Commercial Areas

The City's commercial areas are mostly in the downtown core and within the City's marinas, including Cow Bay and Seal Cove. The downtown sits at least 150 m from the shoreline and behind the terminus of the CN Rail Line and Rotary Waterfront Park and is not at risk from a potential tsunami. The section of the downtown core along 1st Avenue W, between Bill Murray Drive and McBride Street, is located closer to the shoreline but at an elevation well above any tsunami scenario. Rotary Waterfront Rotary Park and the CN Rail Terminus are connected to the downtown via by a walking trail that runs along the shoreline and crosses Manson Way via an elevated footbridge before reaching the cruise ship terminal. As a result of this major elevation change, the downtown is not exposed to a tsunami hazard.

Inundation is projected to be up to 2.0 metres above the high water tide level along the waterfront at Cow Bay Marina and along Cow Bay Road. Existing buildings extending on piers past the shoreline include commercial rental units and the Atlin Terminal, which houses the Prince Rupert Port Authority administrative complex. Commercial buildings along George Hills Way would be above the inundation level; however, building extending on piers into the harbour are at risk and should be evacuated to a higher elevation as should the Cow Bay Marina. Strong currents associated with the tsunami could dislodge moored vessels and lead to debris hazards, but modeling suggests strong currents are not expected at Cow Bay.

Seal Cove includes the Prince Rupert Coast Guard facilities, the Lax-Kw'alaams Ferry Terminal, Seal Cove Float-plane Base and helijet landing, Seal Cove Fish Plant and the Prince Rupert Curling Club are located at Seal Cove. Inundation is not projected to affect any buildings at this location. Access roads to these facilities extend away from and above projected inundation. Inundation and strong currents may affect marine facilities, and there is a potential for debris to impact marine facilities from log booms which could be dislodged in this area.

7.3.2 Secondary Assessment Area

The Secondary Assessment Area includes communities outside of the City and port and marine assets not owned by the City.

Communities

The Lax Kw'a Laams Indian Reserve 1 is located on both sides of Venn Passage. Current settlement of Metlakatla Village is concentrated around Mission Point on the Tsimpsean mainland, where water velocities are projected to exceed 2.0 m/s. The physical vulnerability of Metlakatla is mitigated by the high elevation along the waterfront; dwellings are located above the maximum water depth, which does not exceed 1.0 m. Several homes are at a low elevation in the community and these (**Figure 7-1**) should evacuate to high ground toward Prospect Hill to the north as a precautionary measure. Similarly, while the water taxi and marina docks are in a more protected area, any vessels should be secured and the marina area evacuated as a precaution.

Figure 7-1 Metlakatla Village aerial photo and tsunami hazard zone (yellow shaded area)

Rural residents on Digby Island are vulnerable, as dwellings are located on the waterfront on the east coast of the island where projected water velocities could exceed 2.0 m/s. The residential communities on Digby Island should evacuate from the shoreline areas. The access road rises away from the waterfront and connects to the airport. The Digby Island residential community is small and the YPR airport building is a potential place of refuge. Dodge Cove is a relatively protected area as residential community, the public dock and other marine facilities are located in a well protected cove surrounded by land on three sides. Vessels there should be secured. Residential areas by Crippen Cove and Charles Point are much less protected as they are adjacent to wave velocities of over 2.0 m/s.

Prince Rupert Port Authority Facilities

The Prince Rupert Port Authority is a local port authority constituted under the Canada Marine Act and Letters Patent issued under the Act. Port facilities are located in the Prince Rupert Harbour and on the west side of Ridley Island. The Port's vulnerability is generally low but several facilities have some vulnerability under the modelled tsunami scenarios:

- Fairview Container Terminal (24 ha in size) is a dedicated intermodal (ship to rail) container terminal located south of the Fairview Harbour and Yellowhead Highway terminus. No inundation of the Terminal deck is anticipated, but a tsunami can generate strong current velocities adjacent to the terminal which could affect vessels berthed at the terminal.

- Westview Wood Pellet Terminal is a purpose-built wood pellet export facility. The facility south of Rotary Waterfront Plant has an annual capability of shipping 1.25 million tonnes of wood pellets to world markets. Inundation of most infrastructure is not anticipated as the CN Rail line elevation is approximately 6.0 m, more than 4.0 m above the maximum projected inundation. However, the car dumper extends below the four pellet storage facilities. Risk of flooding to below grade infrastructure at this site is outside of the scope of this assessment but should be evaluated further.
- Northland Cruise Terminal is located south of Cow Bay Marina and can accommodate vessels of up to 300 m (960 ft.) in length and 15 m (50 ft.) in draft. A 400 m^2 (4,000 $ft.^2$) terminal building provides customs and immigration services. The shoreline along the Northland Cruise Terminal is subject to possible tsunami inundation of up to 2.0 m above existing water levels at the start of the tsunami, but the existing marine infrastructure is above the tsunami hazard level.
- Prince Rupert's BC Ferries is located at the end of the Yellowhead Highway on Kaien Island. The terminal serves routes extending from Port Hardy to Haida Gwaii. Tsunami wave heights of up to 1.0 m are possible at the terminal along with higher velocity currents. It is recommended that BC Ferries suspend vessel loading / unloading during tsunami warnings until more detailed vessel berthing and mooring line load analysis is complete.
- The Alaska Ferry Terminal is operated by the State of Alaska's Marine Highway System. Tsunami wave heights of up to 1.0 m are possible at the terminal along with higher velocity currents, and similar recommendations to those for BC Ferries are given.
- The Atlin Terminal is home to the Prince Rupert Port Interpretive Centre as well as the offices of the Prince Rupert Port Authority. The commercial buildings of this facility would be above the inundation level but extend on piles into the harbour. Evacuation of the Cow Bay Marina area to a higher elevation is advised as a precautionary measure.
- The elevation of the CN Rail line next to the Grain Terminal on Ridley Island is 7.0 m, and the elevation of the adjacent Ridley Coal loop rail elevation to the south is 10.4 m. Riprap and coastal protection measures protect the rail line and other structures behind the rail line on Ridley and Watson Islands, which are more than 4.0 m above the maximum projected inundation level. The offloading structures for the Ridley Coal Terminal and the Prince Rupert Grain Terminal on Ridley Island are not protected by the CN Rail line, but projected velocities west of Ridley Island are less than 0.5 m/s.

The impact of the wave depth and velocity on all docked ships should be considered. Mooring lines should be secured and all loading operations shut down in the event of a tsunami warning for the Prince Rupert area. Any shoreline or marine infrastructure below terminal decks, such as electric motors, are at greater risk. It is recommended that terminal work forces be evacuated from marine (shoreline: berths, vessel loading) facilities to muster stations as a precautionary measure during a tsunami warning.

Port Edward Harbour Authority Facilities

Port Edward Harbour Authority is responsible for the operations and management of four small craft harbours in the Prince Rupert and Port Edward area. The sites show some vulnerabilities under the tsunami scenarios.

- Fairview Harbour is a public marina located south of the Yellowhead Highway terminus with tie-up floats and open moorage to accommodate about 250 vessels. Fairview Harbour could experience tsunami wave heights of up to 2.0 m but the wave velocity is under 0.5 m/s.
- Cow Bay is located between the Yacht Club and City of Prince Rupert Cow Bay Marina. Cow Bay floats are wood floats with a capacity for about fifteen smaller vessels. Water surface elevation increases may be up to 2.0 m along the waterfront at Cow Bay but the wave velocity would be less than 1.0 m/s.
- The Rushbrook Harbour at 299 George Hills Way has a capacity of 400 vessels. There is a loading and offloading float, two gang ramps entering the harbour from a single-lane timber-decked approach wharf. The site is subject to a maximum inundation of up to 2.0 m but the wave velocity is under 0.5 m/s.
- Porpoise Harbour Marine Complex in the Village of Port Edward has a capacity for approximately 250 vessels up to about 60 m in length. The floats are mainly wood-decked and attached to concrete drive-down ramps on both the north and south sides of the harbour. Water velocities are expected to be less than 1.0 m/s at the Porpoise Bay Marine Complex.

The tsunami modelling indicates the initial wave would take over three hours to arrive in Prince Rupert. This would allow mooring lines for vessels to be secured and evacuation of the two port authority facilities. While the risk would be low for marine facilities located where velocities would less than 0.5m/s and inundation levels limited to intertidal areas, evacuation of marine facilities is recommended as a precautionary measure.

Marine Traffic

The lowest velocities and inundation levels are in the Prince Rupert Harbour or west of Digby Island. These locations away from land will avoid the strong velocities moving through Venn Passage, Fern Passage or south of the Fairview Harbour. These may be the safest locations for marine vessels. However, that may pose a conflict with the Pacific Pilotage Authority for docked vessels, depending on the qualified human resources available in Prince Rupert as the time of a tsunami warning. Further discussion with Port Authorities and the Pacific Pilotage Authority is recommended.

Vessels on anchor should be alerted and ready to respond should they drag anchors. Vessels at berth and in the middle of loading/unloading operations are potentially at the highest risk should vessels in the berth exceed the load capacity of the berth structures or mooring lines. Sudden movements of vessels could be hazardous to crew and ship personnel. For vessels loading raw logs from the water, the tsunami wave could disturb their operations and precautions are advised.

7.3.3 Cumulative or Cascading Impacts

People and buildings (including their contents) are a primary concern during a tsunami event; however, a tsunami can act as a catalyst and may instigate a chain of cascading events which impact environmental, cultural, economic, social and community values. For example, an export terminal could be undamaged but goods destined for shipment (e.g. aquaculture or logs) could become damaged, delayed or unavailable. Similarly, although residential areas in Prince Rupert would not be directly affected, indirect impacts could include layoffs of waterfront employees for the time a port facility is shut down or out of service. Other indirect effects include reduced revenues to businesses where supply chains are broken or temporarily suspended. This would not only have a negative impact on the Prince Rupert economy, it could result in social impacts as families struggle with reduced incomes. These cumulative impacts are beyond the scope of this report.

7.4 Community Resilience

Community resilience refers to the community's ability to resist, respond and recover from the effects of a hazard. Due to the relatively low impacts forecasted in this report, a simple risk evaluation of key City assets has been undertaken (see **Appendix F**, Asset List). The intent was to identify the assets deemed at risk under the tsunami scenarios to assist the City in determining emergency management priorities. Because many of the tsunami impacts are to critical marine infrastructure that is essential for the connectivity and economic activity of the community, risk avoidance is not necessarily an appropriate response for the community. Instead, a level of risk acceptance, which is an informed decision to accept the potential consequences of a determined risk, and risk reduction, which refers to applying strategies or procedures to reduce the likelihood of risk, are a better approach for the City of Prince Rupert. Some risk transfer, which involves shifting the burden of risk to another party by mechanisms such as insurance, might also be considered.

The objective of this section is to identify the City of Prince Rupert's capacity for tsunami risk reduction by identifying and reviewing its relevant policies for hazard mitigation, hazard response and system restoration. These policies include its Official Community Plan and other land-use planning policies to mitigate risk, its Emergency Management Plan to direct emergency procedures during and following a tsunami and system restoration processes to reinstate the normal functioning of City services following an emergency.

7.4.1 Hazard Mitigation

Community resilience can be enhanced by aligning policies to reduce hazard exposure and therefore mitigate the overall risk from identified hazards. With regard to a tsunami, the proximity and/or elevation above an area exposed to hazard is an important factor in determining the resiliency of a community. Hazard mitigation can include future land-use planning that ensures new development occurs outside of areas exposed to the hazard or incorporates flood hazard standards in areas exposed to risk.

Official Community Plan

The City of Prince Rupert's Quality of Life Community Plan (QLCP) is the community's Official Community Plan. It emphasizes the integration of social, environmental and economic values in land-use planning. The QLCP was adopted in 2008 to drive identified opportunities for the community in port expansion and tourism growth following a period of economic downturn. The QLCP focuses on providing quality employment, sustainable social services and a supportive community network to enhance the resilience of the Prince Rupert community.

The QLCP provides a Climate Action Commitment that includes greenhouse gas emission reduction and environmental protections, but it does not extend to climate change risks and resilience building. Community resilience to natural disasters or physical hazards is not included as a core objective in the QLCP, nor is it an obvious driver behind land-use planning decisions. Major streams and adjacent riparian areas are protected as Development Permit Areas, which does provide some protection from flood hazards.

The QLCPs broad focus on addressing poverty, promoting housing affordability and providing social services is nonetheless an important factor in building overall community resilience. Social vulnerabilities tend to be exacerbated during disaster events, so having a strong community network is essential to increasing overall resilience. Likewise, the QLCPs objective of providing quality city services such as cleanliness and maintenance can provide a strong framework for necessary clean-and-recovery works following a disaster.

The City might consider adding Hazard Avoidance/Risk Mitigation to the list of Quality of Life Planning Principles in order to build a safe and resilient community. The QLCP should address restrictions on the use of land that are subject to hazardous conditions as per Section 473 (1) (d) of the *Local Government Act*. Prince Rupert's low vulnerability to a tsunami risk is a feature to be celebrated. Nevertheless, the QLCP could add policies to avoid residential waterfront development, particularly in low lying areas adjacent to water passages subject to high wave velocities from a tsunami. Although not currently an issue, houseboats should be avoided in areas subject to high wave velocities such as Fern Passage.

Waterfront Development Vision

The City's waterfront is largely controlled by private owners and serves important port and transportation functions. A new Waterfront Development Vision that aims to better connect the downtown core to the waterfront with nodal open space/view points and public spaces was unveiled in 2017. It forms an important direction for the City to gradually transform the waterfront into a sustainable mix of commercial, light industry and other uses that support public access. While this direction will provide important physical connections throughout the community and enhance the appeal of the City to tourists and residents alike, any future development should be assessed in context of tsunami hazard exposure and vulnerability.

Interim Land Use Policy Framework

The Interim Land Use Policy Framework was developed in 2016 in response to the increased demands placed on City Council and Staff as a result of speculation surrounding the construction of a major industrial project in the Prince Rupert area. It provides interim policies and strategies to manage growth in the community. The policy framework identifies appropriate areas for future development and created policies that address funding for non-market housing, maintain the character of local neighbourhoods, and address many of the unique challenges that accompany large-scale industrial development. They include an urban containment boundary where all new residential and commercial development proposals and/or subdivision applications must be directed. The designated greenfield development sites and most infill development would be located away from any impacts of a tsunami. Future waterfront uses should be assessed in the context of tsunami hazard exposure and vulnerability.

Zoning Bylaw

While residential development is not located in waterfront locations, the future potential of accommodating such development should be reviewed. For example, the Zoning Bylaw permits Multiple Family development in the Marine Commercial zone (C5). There also appear to be significant unzoned water areas within the City limits.

7.4.2 Emergency Response

Emergency response refers to the procedures and actions taken during a hazardous event. Communications for seismic tsunami events will initially come from Emergency Management BC (EMBC) in response to a coastal earthquake. This will be the trigger for the City to activate its local Emergency Response Plan.

In the case of the tsunamis modelled under the earthquake scenarios of the Alaska or Cascadia subduction zone, impacts from the tsunami would not occur for over three hours. This means that there is adequate time for the Emergency Operations Centre and the Emergency Management Plan to be activated and for the appropriate response to be coordinated. (Note: for a landslide triggered tsunami, there would be only minutes of warning from the time of the landslide to the arrival of waves and, for practical purposes, no time would be available to activate response plans in advance of the tsunami wave reaching City property.)

Emergency Management Plan

The City of Prince Rupert has an Emergency Management Plan which establishes an emergency management organization and local emergency plan under the *Emergency Program Act* (RSBC 1996 - Chapter 111). This 154 page plan, dated February 2016, guides the operations, organisation, responsibilities, and coordination necessary to provide an effective response and recovery from major emergencies or disasters in the City. The scope of the Plan addresses incidents that may cause damage of sufficient severity and magnitude to warrant execution of all or part of the Emergency Plan, not emergencies that are normally handled at the scene by the appropriate first responding agencies.

Key elements of the Plan:

- Provide an overview of the City's emergency management and reporting structure.
- Outline the roles and responsibilities of City staff and departments and other agencies involved in the response effort.
- Provide an overall strategy for the City's emergency mitigation preparedness, response and recovery measures.
- Identify key priorities and actions to be undertaken in preparing for and responding to a major emergency or disaster.
- Outline the procedures for Declaring a State of Local Emergency and delegating the required powers.
- Encompasses Prince Rupert's jurisdictional boundaries for response operations and the type of emergencies that are beyond routine events.

The Plan is comprehensive in covering the reporting structure, procedures, responsibilities of key positions, and the actions to be taken by each position for the different phases of an emergency. The first part of the Plan makes a clear distinction for each key position between the different phases of an emergency consisting of the activation, operational and demobilization phases. The remainder of the Plan consists of contacts, resources and forms.

Section 5 covers 13 specific hazards including a tsunami. The tsunami section (section 5.1.2) is brief and consists of 2+ pages. The specific hazard sections are generic, merging the activation, operational and demobilization phases. For example, tsunami activities include tracking its progress, deploying damage assessment field observers and anticipating the long-term feeding and accommodation of recovery workers.

The Tsunami hazard section 5.12 needs updating including the addition of information from this report that includes the following:

- A breakdown of activities by phase. A typical breakdown would consist of planning activities in advance of a tsunami, operational activities during a tsunami, and recovery activities after a tsunami.
- Information on anticipated warning times resulting from a Cascadia or Alaska based tsunami.
- Locations which should be evacuated in the event of a tsunami warning.
- Updating the Emergency Plan on a regular basis is important. At the front is a section stating, "This Emergency Management Plan is a living document and should be reviewed and updated on a regular basis." The remainder of the page provides space for documenting updates. February 2016 is the last indicated update. An update in procedures, responsibilities, and the organizational structure would not necessarily be required in the three years since the plan was adopted. However, a more regular update to accommodate emergency personnel changes, new

telephone numbers and the current members of Council is needed. The value of an emergency plan depends on accurate and current information. Clarification as to the type of update is needed with an update of key emergency personnel information done at least annually.

- Key information such as the addresses of the Emergency Operations Centre, hospital, health services, and emergency services should be included. None are currently provided. While this is common knowledge to Prince Rupert emergency personnel, incoming emergency personnel responding to a disaster may not know where these facilities are located. A section listing all terms and acronyms used in the Plan would be helpful.
- Prince Rupert has designated emergency evacuation locations but they are not are identified in the Plan. Such locations would apply not only to a tsunami, but to many other types of disasters. A map showing the location of the primary and secondary evacuation centres plus safe access routes is needed.

Communications Plan

The City has a communications plan to provide information and updates to the community through the Alert Notification System. Updates occur to landlines, cell phones and email addresses. The City's website and social media platforms, as well as local media outlets will provide consistent information and updates.

Community education should occur prior to a potential hazard event. This includes knowledge and awareness raising with key stakeholders and the broader community about the procedures to follow during a tsunami event. This is critical to counteract the effects of misinformation during the event. The City's Tsunami Preparedness Brochure provides some good information in the event of a tsunami. Updating aspects of the brochure is recommended based on the findings of this study, including the extent of the Tsunami Advisory Zone.

Evacuation Signage

Tsunami signage should be provided in areas exposed to a hazard. Emergency evacuation locations should be well known and marked for residents and visitors alike. Muster stations where visitors and employees of marine facilities can assemble following a tsunami warning should be identified.

Port terminals and commercial operators will have their own health and safety planning, and should already have emergency preparedness plans. It is recommended that the Port of Prince Rupert work with their tenants to share information on tsunami risk to allow them to initiate appropriate signage on their worksites.

Tsunami Notification Process Plan

EMBC's Comprehensive Emergency Management Plan refers to The BC Tsunami Notification Process Plan, last revised on November 18, 2013. This document states that the Cascadia Subduction Zone "presents the highest tsunami threat to British Columbia". An update with reference to the Alaska-Aleutian subduction zone and its greater threat to Zone A, which include Prince Rupert and Haida Gwaii, is recommended. The warning time of as little as 5 minutes does not distinguish between the Northern Coast of BC and Southern Vancouver Island.

7.5 Summary

The analysis of the inundation and velocity maps from the seismic-generated events show that no residential areas are exposed to the tsunami hazards. Similarly, emergency services such as the Emergency Operations Centre, RCMP Station, Ambulance and Fire Hall, and critical community infrastructure such as the Prince Rupert Regional Hospital, Prince Rupert City Hall, Jim Ciccone Civic Centre and all schools are all located away from the impacts of these tsunami scenarios. All road transportation corridors, BC Hydro corridors and substations, and the municipal water supply are not within any tsunami impact area. The most exposed areas under both scenarios consist of marinas and other marine infrastructure in Fern Passage, Venn Passage and the east coast of Digby Island.

8 CONCLUSIONS AND RECOMMENDATIONS

This study shows that:

- The City is vulnerable to seismic-generated tsunamis associated with Cascadia and Alaska-Aleutian subduction zones. Maximum increases in water levels from the Alaska-Aleutian subduction zone seismic event are greater than those from the Cascadia subduction zone seismic event.
- The vulnerability assessment based on seismic-generated tsunami scenarios shows that no residential areas were exposed to the tsunami hazards under any of these scenarios.
  - Emergency services, critical community infrastructure and all schools are all located away from the impacts of these tsunami scenarios.
  - All road transportation corridors, BC Hydro corridors and substations, and the municipal water supply are not within any tsunami impact area.
  - The most exposed areas under both scenarios include marine infrastructure and port facilities.
- The probability of landslide-generated tsunami within the study area is very low, but the risk posed by these events is moderate given their potential damage. The resulting inundation depths and velocities are greater than those from seismic-generated tsunamis.
- The analysis based on LiDAR and satellite images, the aerial photographs, and LiDAR data shows that there is no evidence of recent or ongoing slope instability near Prince Rupert that might indicate that the city is at a high risk of being impacted by a landslide-generated tsunami. Given the potential hazard due to landslide-generated tsunami wave, it is recommended that a detailed geotechnical study be conducted to examine steep and high slopes in the region.
- The addition of 1 m of sea level does not significantly alter the overall tsunami wave characteristic in the Prince Rupert region.

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