
Photo source: Alana Janisse, Village of Zeballos

Northwest Vancouver Island Tsunami Risk Assessment Final Report

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EXECUTIVE SUMMARY

The northwest coast of Vancouver Island, facing towards the Pacific Ocean, is exposed to tsunami hazards from both local and distant sources. The primary local source of concern is the Cascadia Subduction Zone while the Aleutian Islands Subduction Zone in Alaska is a distant source of concern. The Strathcona Regional District, in partnership with the Ka:'yu:'k't'h'/Che:k:tles7et'h' First Nations and Nuchatlaht First Nation, engaged Northwest Hydraulic Consultants Ltd., Ocean Networks Canada Society, and Northwest Seismic Consultants Ltd. to undertake a tsunami risk assessment in the region. This is accomplished by using tsunami modelling and drawing upon community experience and indigenous knowledge. The vast study area, which is shown in Figure ES-1, expands from Yuquot northward to Cape Scott, and includes the communities of Gold River (Port), Tahsis, Zeballos, and Port Alice, as well as several Indigenous communities of the Ka:'yu:'k't'h'/Che:k:tles7et'h', Nuchatlaht, Ehattesaht Chinehkint, Mowachaht/Muchalaht, and Quatsino First Nations. By providing a sound understanding of tsunami hazard and risk, a goal of this project is to provide information that will support improvements to existing emergency and evacuation plans.

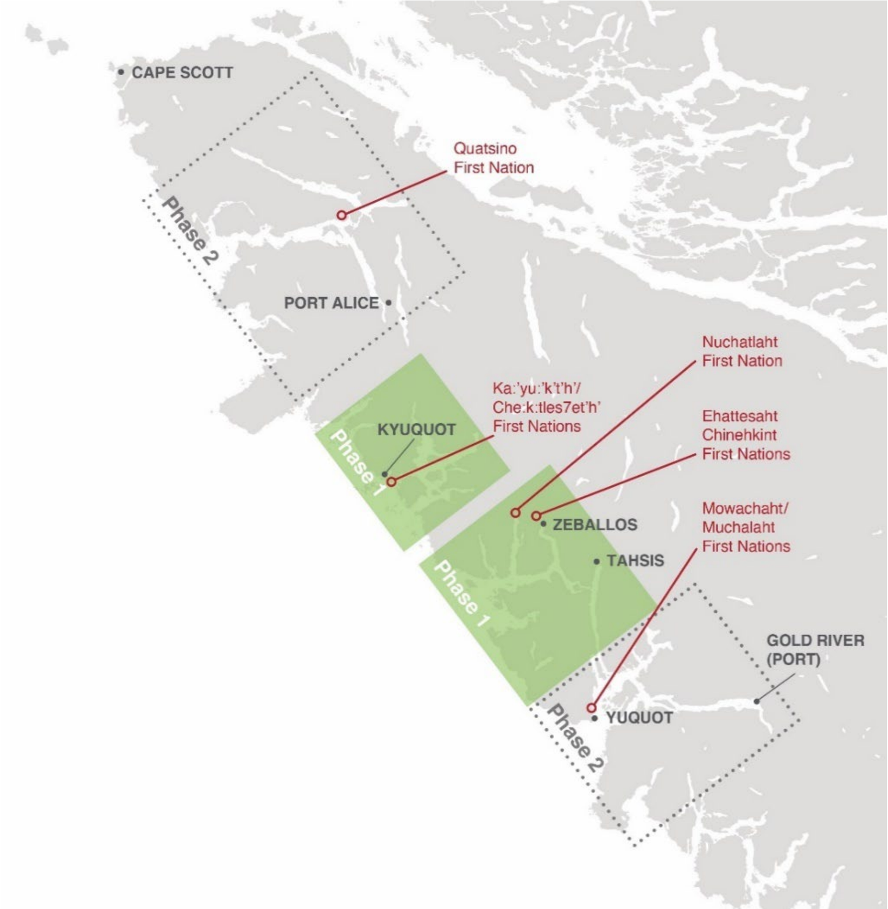

Figure ES-1. Study area and project phases.

Because the assessment covers such a large geographical area, the project has been divided into two phases. *Phase I*, which is covered in this report and focuses on the communities connected to Kyuquot Sound, Esperanza and Tahsis Inlets, began in the summer of 2020. *Phase II* began in 2022 and includes the communities in Quatsino and Nootka Sounds.

The project encompasses three main components, as summarized below:

1. **Community and Indigenous Engagement** – A project webpage, an online public community survey, and several virtual public engagement meetings were completed to learn from and share the experience, knowledge, and history of local communities. Interviews with Indigenous elders and knowledge holders were also performed. An Advisory Group was consulted throughout the project to guide the project team and promote the exchange of knowledge and ensure proper protocols were in place to safeguard indigenous knowledge ownership.
2. **Tsunami Hazard Analysis and Mapping** – Two tsunami sources were simulated, one from the nearby Cascadia Subduction Zone and another from the more distant Aleutian Islands Subduction Zone in Alaska. Local tsunami flood hazard (e.g., overland inundation) maps were developed for 25 priority areas, as shown in Figure ES-2, and overwater hazards such as maximum tsunami amplitude and maximum current speed were mapped across the study area.
3. **Risk Assessment** – Based on the tsunami hazard analysis and mapping, a community level risk assessment was completed to identify potential risk to people, roads, and buildings, as well as other assets critical to response and recovery. Assets at risk maps were developed to identify assets exposed to tsunami hazard.

Figure ES-2. Priority areas (green rectangles) considered for inundation mapping and community level risk assessment.

General inundation levels for emergency planning were defined considering both current-day and future sea levels and are presented in Table ES-1. These inundation levels include a safety factor to account for the uncertainties in the analysis and are representative of one general area. This information should only be used for high-level planning, as tsunami inundation can vary over small distances as a function of local topography. Tsunami inundation levels corresponding to current-day sea level were mapped as part of this assignment as a starting point to understand tsunami risk to life safety. Model simulations including sea level rise were undertaken by the project team and are available to support longer-term development and planning, but the sea level rise simulations have not been mapped for this assignment.

Table ES-1. General tsunami inundation level for emergency planning and arrival times at selected locations.

Area	Cascadia Tsunami			Alaska Tsunami		
	Arrival Time[1]	Inundation Level for Emergency Planning[2] (CGVD2013[3])		Arrival Time	Inundation Level for Emergency Planning (CGVD2013)	
		Current-day	Year 2100		Current-day	Year 2100
Houpsitas	0h25m	12.4 m	13.7 m	3h04m	4.7 m	6.0 m
Fair Harbour	0h45m	6.9 m	7.9 m	3h18m	5.1 m	6.4 m
Oclucje	0h38m	9.2 m	10.9 m	3h20m	3.4 m	4.8 m
Village of Zeballos	0h46m	6.8 m	8.7 m	3h31m	3.9 m	5.1 m
Chenahkint	0h35m	5.8 m	7.6 m	3h12m	2.8 m	4.0 m
Village of Tahsis	0h54m	7.5 m	8.8 m	3h41m	5.0 m	6.2 m
Tahsis River	0h54m	6.9 m	8.2 m	3h41m	4.9 m	6.1 m

Notes:

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

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

- Village of Tahsis,
- Village of Zeballos, and
- Houpsitas (Kyuquot).

These recommendations are only meant to support a review of existing evacuation plans and are by no means final or official, as more assessment and public engagement is required by local levels of government to carefully develop evacuation plans.

For a person caught in a tsunami the chance of survival is low, mainly due to the strong flow momentum and the floating debris that are often carried in the water during such event. While studies exist to evaluate human safety in flood conditions as a function of flow depth and velocity, as well as age and body characteristics, it is conservative to consider that anyone caught in tsunami flow is likely to become a casualty. For planning purposes, it is recommended to assume that people exposed to tsunami hazards will experience extreme risk of survival if unable to evacuate safely. Overland tsunami hazard varies across the study area depending on the tsunami source, whereas tsunamis pose a risk anywhere near the shoreline as well as overwater.

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

Lastly, the study results are based on a limited number of tsunami scenarios for subduction earthquakes with specific seismic parameters. Tsunami hazards and effects can vary for different earthquakes that may occur. The Cascadia earthquake and tsunami scenario analysed correspond to a severe event according to the paleoseismic record of past earthquakes and is known to be the worst scenario readily available for analysis. However, this record suggests that at least one stronger earthquake occurred in the past 10,000 years. Including a safety factor for the inundation mapping reduces the residual risk associated to a stronger event but may not eliminate it.

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1 INTRODUCTION

The northwest coast of Vancouver Island is characterized by its natural beauty and rich history. With the Pacific Ocean to the west, this region is particularly exposed to tsunami hazards from local sources, such as the Cascadia Subduction Zone and from distant sources such as the Aleutian Islands Subduction Zone in Alaska. Recent major tsunamis around the world have demonstrated the potential for widespread destruction and danger. However, previously there was relatively little information about these hazards and associated risks for this portion of the British Columbia coast, as prior to this project light detection and ranging (LiDAR) topographic data was non-existent for most of the study area.

The Strathcona Regional District, in partnership with the Ka:’yu:’k’t’h’/Che:k:tles7et’h’ First Nations and Nuchatlaht First Nation, engaged Northwest Hydraulic Consultants Ltd. (NHC), Ocean Networks Canada Society (ONC), and Northwest Seismic Consultants Ltd. (NSC) to undertake a tsunami risk assessment in the region. The goal of this project is to better understand tsunami hazard and risk on the northwest coast of Vancouver Island. This is accomplished by using tsunami modelling and drawing upon community experience and indigenous knowledge. The vast study area expands from Yuquot northward to Cape Scott (Figure 1), and includes the communities of Gold River (Port), Tahsis, Zeballos, and Port Alice, as well as several Indigenous communities of the Ka:’yu:’k’t’h’/Che:k:tles7et’h’, Nuchatlaht, Ehattesaht Chinehkint, Mowachaht/Muchalaht, and Quatsino First Nations. The study area covers many historic community locations, sacred sites, fishing and hunting areas, shellfish harvesting sites and old village sites.

With a focus on life safety, the community level risk assessment uses scenario-based tsunami hazard analysis and mapping to identify potential risks to people and assets. The risk analysis outcomes can strengthen hazard awareness and the four pillars of emergency management: mitigation, preparedness, response, and recovery. This information is expected to support development and planning decisions and improve existing emergency and evacuation plans.

Because the assessment covers such a large geographical area, the project has been divided into two phases (Figure 1). *Phase I*, which is covered in this report and focuses on the communities connected to Kyuquot Sound, Esperanza and Tahsis Inlets, began in the summer of 2020. Detailed tsunami inundation maps for areas of interest were completed and published online in the summer of 2021, and overwater hazard maps for the entire study area were published later that year (www.srd.ca/tsunami-mapping). *Phase II* began in 2022 and includes the communities in Quatsino and Nootka Sounds.

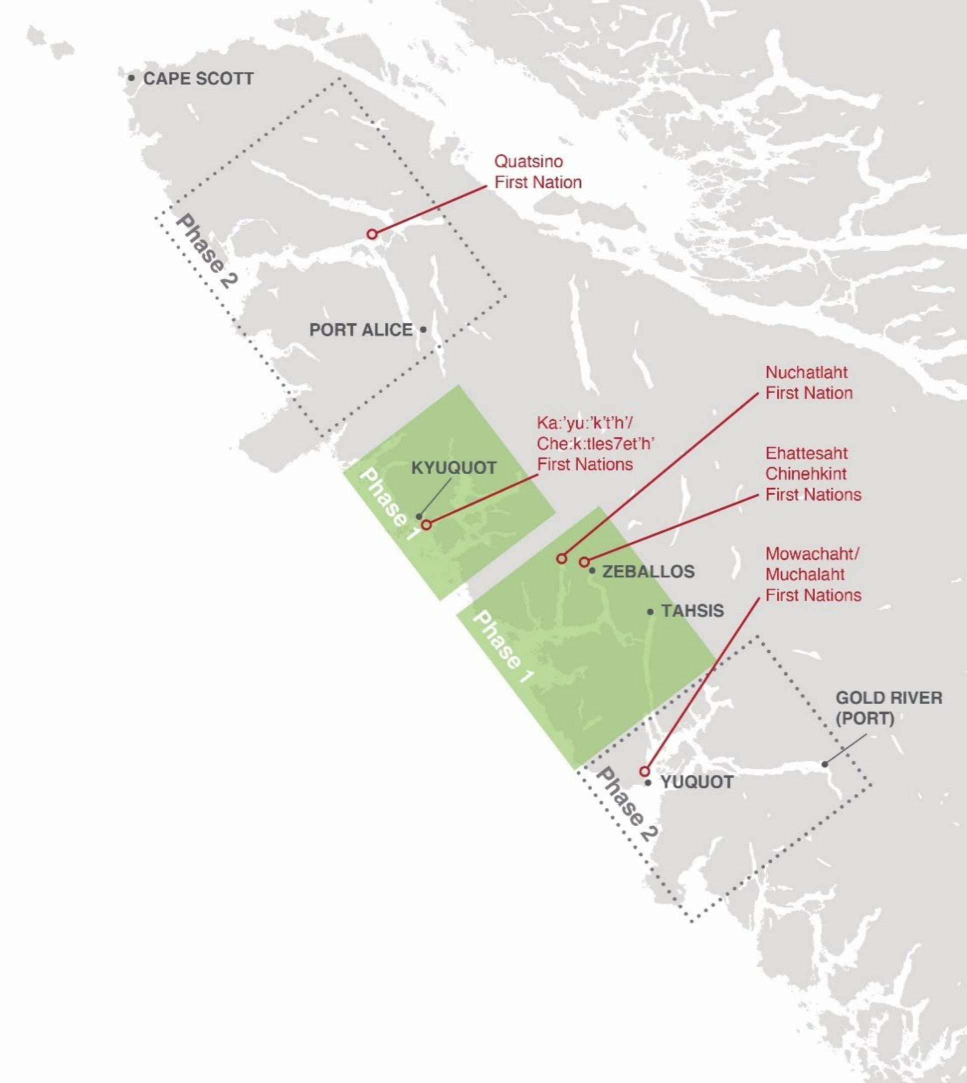

Figure 1. Study area and project phases.

1.1 Tsunami Exposure

As with many other areas along the BC coast, Vancouver Island is exposed to tsunamis originating along the Pacific Ocean's *Ring of Fire*, which consists of a nearly continuous series of tsunamigenic subduction zones surrounding the ocean (Figure 2). Several major subduction earthquakes have occurred in recent history, exemplifying the tremendous impacts tsunamis can have on communities, even ones located far away from a tsunami source. A geologically recent and well-known Canadian example is the tsunami that partially destroyed the town of Port Alberni, BC, during the night of March 27, 1964. This tsunami, which was generated by a moment magnitude (Mw) 9.2 subduction earthquake south of the Alaskan coast (United States Geological Survey, n.d.), reached Vancouver Island within approximately three to four hours after the earthquake.

Figure 2. **Subduction zones around the Pacific Ocean and locations of several major tsunamigenic earthquakes (adapted from Atwater *et al.*, 2005).**

What makes Vancouver Island susceptible to potentially large tsunami waves is its proximity to the Cascadia Subduction Zone (CSZ), which is located approximately one hundred kilometres offshore parallel to Vancouver Island. The proximity of the CSZ means there will be a short warning time between an earthquake and the arrival of a tsunami on the open coast (e.g., less than 30 minutes in some areas). Geological studies, historical records from Japan, and oral history from Indigenous communities along the west coast of North America show that a major subduction earthquake, followed by the generation of a large tsunami, occurred on January 26, 1700 (Atwater *et al.*, 2005). The earthquake associated with this tsunami is estimated to have had a moment magnitude of approximately 9.0 (Witter *et al.*, 2013).

Based on the assessment of other large historical tsunamis in the Pacific Ocean, it was determined that future CSZ events (similar to the 1700 tsunami) and a future Alaska 1964-type tsunami present the greatest risks to the coast of British Columbia and merit analysis in hazard modelling (Ferguson *et al.*, 2022).

1.2 Methodology and Approach

The project focuses on the importance of "making space at the table for everyone" in disaster risk reduction and management and actively sought input from communities in the study area. Indigenous communities living at the forefront of tsunami risk have fostered disaster resilience and knowledge over millennia. The study approach leverages Indigenous knowledge and community engagement, combined with scientific tsunami modelling and mapping. This synergetic approach seeks to strengthen outcomes and their lasting adoption by communities.

The project is divided into three components, as summarized below:

4. **Community and Indigenous Engagement** – A project webpage, an online public community survey, and several virtual public engagement meetings were completed to learn from and share the experience, knowledge, and history of local communities. Interviews with Indigenous elders and knowledge holders were also performed. An Advisory Group was consulted throughout the project to guide the project team and promote the exchange of knowledge and ensure proper protocols were in place to safeguard indigenous knowledge ownership.
5. **Tsunami Hazard Analysis and Mapping** – Two tsunami sources were simulated, one from the nearby Cascadia Subduction Zone and another from the more distant Aleutian Islands Subduction Zone in Alaska. Local tsunami flood hazard (e.g., overland inundation) maps were developed for 25 priority areas and overwater hazards such as maximum tsunami amplitude and maximum current speed were mapped across the study area.
6. **Risk Assessment** – Based on the tsunami hazard analysis and mapping, a community level risk assessment was completed to identify potential risk to people, roads, and buildings, as well as other assets included in the critical infrastructure sectors defined by the National Strategy for Critical Infrastructure (Public Safety Canada, 2009). Assets at risk maps were developed to identify assets exposed to tsunami hazard.

The outcomes of the risk analysis can strengthen hazard awareness and the four key components of emergency management: mitigation, preparedness, response, and recovery. Accordingly, this study touches on emergency management plans as well as the status of these components in terms of best practices and regulations, progress achieved during this project, and path forward. This information is expected to support development and planning decisions and improve existing emergency and evacuation plans. Lastly, this study provides recommendations for measures that can be adopted to reduce tsunami risk, in conjunction with developing and updating tsunami emergency management plans.

1.3 Report Structure

This document forms the main report for the project. It describes the main steps of the community and Indigenous engagement (Section 2) and summarizes the results of the tsunami modelling and mapping (Section 3). The focus of the report is given to the outcomes of the risk assessment which are presented in Section 4. Further on, Section 5 discusses emergency management plans and recommends various measures that can be adopted to reduce tsunami risk.

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

1.4 Project Team

This project is the result of a collaboration between many individuals of various backgrounds including, but not limited to, risk assessment and disaster management specialists, Indigenous community liaison partners, coastal engineers, tsunami scientists, and Geographic Information System (GIS) specialists. While NHC, ONC, and NSC undertook the analysis, there were valuable contributions from SRD personnel, municipal officials, and community members which were instrumental to the undertaking of this project. Below are brief background descriptions of NHC, ONC, and NSC, including their respective responsibilities on this project.

NHC

NHC is a private Canadian firm, incorporated in 1972 and wholly owned by its principals. Its engineers and scientists are focused and passionate about the assessment, measurement, and design of water-related projects. NHC is a world leader in flood hazard assessments and risk reduction projects, working extensively locally and across BC, as well as on large scale international projects. As the prime consultant on this project, NHC led the community engagement, performed engineering reviews of the modelling work by ONC, produced the maps, undertook the risk assessment, and provided recommendations for risk reduction in collaboration with NSC.

ONC

As an initiative of the University of Victoria, ONC monitors the Pacific, Atlantic, and Arctic coasts of Canada to continuously deliver real-time data for scientific research that helps communities, governments, and businesses make informed decisions for the future. ONC’s scientific credentials are grounded by a deep respect for the perspectives and values of coastal Indigenous communities. Through the collaborative engagement of local leaders and knowledge holders, ONC is experienced in building long-standing relationships that garner a broad understanding of past tsunami events and current risk considerations. On this assignment ONC engaged directly with Indigenous communities and integrated Indigenous knowledge into the study findings, developed the project’s Digital Elevation Models (DEMs), and carried out the tsunami model simulations.

NSC

NSC is a Canadian consultation company that bridges the seismic gap between technical science and engineering with evidence-based solutions that support all-of-society risk management decisions. NSC guided the public safety best practices presented in this report, authored the emergency management piece of this study, and reviewed the risk assessment and recommendations for risk reduction in collaboration with NHC.

1.5 Glossary of Terms

A glossary of terms, which are specialized to the coastal area of practice, but essential to preserve accuracy in description, are provided in Section 7 of this report.

2 COMMUNITY AND INDIGENOUS ENGAGEMENT

As a key component of risk assessment, community engagement focuses on informing and engaging the public on how to reduce their risk and better protect themselves. Such engagement also informs the assessment by identifying community priorities and values as well as understanding community preparedness, risk perception and resilience to tsunamis. Furthermore, community engagement seeks to strengthen study outcomes and their lasting adoption by the public. For this study, such engagement is enhanced by the collaborative sharing of scientific information in conjunction with traditional Indigenous knowledge on tsunami hazards, to further substantiate the study outcomes that will support future risk reduction actions and decisions by the communities.

Scientific study of tsunamis on the west coast of Vancouver Island began in earnest in the 1980s, however, the history and the impacts of tsunamis goes back much longer. This is represented in several ways including the Nuu-chah-nulth story of mountain dwarves and the foot in drum legend. Along with other references, these accounts highlight the traditional knowledge and teachings that exist with regards to earthquakes and tsunamis on the west coast of Vancouver Island. The Indigenous communities within the study area have multigenerational shared experience connecting to the land, coping with environmental change, and surviving natural disasters. Through engagement, this study seeks to work closely with these communities to leverage their ideas and guidance. As such, it needs to ensure the results are tailored to the local context.

This section of the report summarizes the engagement activities completed in this project, which include:

- Assembly of an Advisory Group to guide the project team and promote the exchange of knowledge.
- Research on Indigenous knowledge to share the experience, knowledge, and history of local Indigenous communities.
- Community touchpoints to engage with the public.

2.1 Advisory Group

An Advisory Group was assembled at the onset of the project with representation from communities within the study area. The purpose of the Advisory Group was to bring together expertise and counsel to promote the applicability of the study findings, as well as the exchange of knowledge between communities and the collaboration towards the reduction of tsunami risks. Throughout the project, the project team worked with the Advisory Group to refine engagement plans to best foster community engagement, collect background data and information, and review preliminary findings.

The Advisory Group included representation from the following communities and organizations:

Regional Districts

- Strathcona Regional District (SRD)
- Regional District of Mount Waddington (RDMW)

First Nations

- Ka:’yu:’k’t’h’/Che:k:tles7et’h’ First Nations
- Nuchatlaht First Nation
- Ehattesaht Chinehkint First Nation
- Mowachaht/Muchalaht First Nations
- Quatsino First Nation

Tribal Councils

- Nuu-Chah-Nulth Tribal Council (NTC)

Municipalities

- Village of Tahsis
- Village of Zeballos
- Village of Gold River
- Village of Port Alice

Table 1 provides an overview of the six Advisory Group (virtual) meetings that were held as part of the project. Many participants could not attend the first meeting due to widespread power outages in the region. Nevertheless, this meeting was carried out as it provided the remaining participants an opportunity to meet with the project team in an informal setting. Each Advisory Group meeting was opened by an Indigenous elder.

Table 1. Summary of Advisory Group meetings.

Meeting	Date	Aspects Discussed
0	November 18, 2020	Informal “meet and greet” meeting as many participants were not able to join due to power outage.
1	December 3, 2020	▪ Project overview ▪ Role of Advisory Group ▪ Data collection ▪ Content for project website ▪ Questions for community survey
2	January 27, 2021	▪ Indigenous knowledge research ▪ Priority areas for tsunami inundation mapping and risk assessment ▪ Community engagement
3	April 6, 2021	▪ Indigenous knowledge research (update) ▪ Community survey results ▪ Focus areas for overwater tsunami hazard mapping
4	May 25, 2021	▪ Presentation of draft mapping results ▪ Plans for public meetings
5	February 22, 2022	▪ Presentation for results of risk assessment ▪ Plans for final public meeting ▪ Introduction to Phase II of the project

The Advisory Group provided background information on each of their jurisdictions and communities and identified areas of interest within the region (Figure 3). For instance, these areas include inhabited areas, recreational areas, historic community locations, sacred sites, fishing and hunting areas, shellfish harvesting sites and old village sites. The Advisory Group was also instrumental in prioritizing areas for inundation mapping, as further discussed in Section 3.3.4.

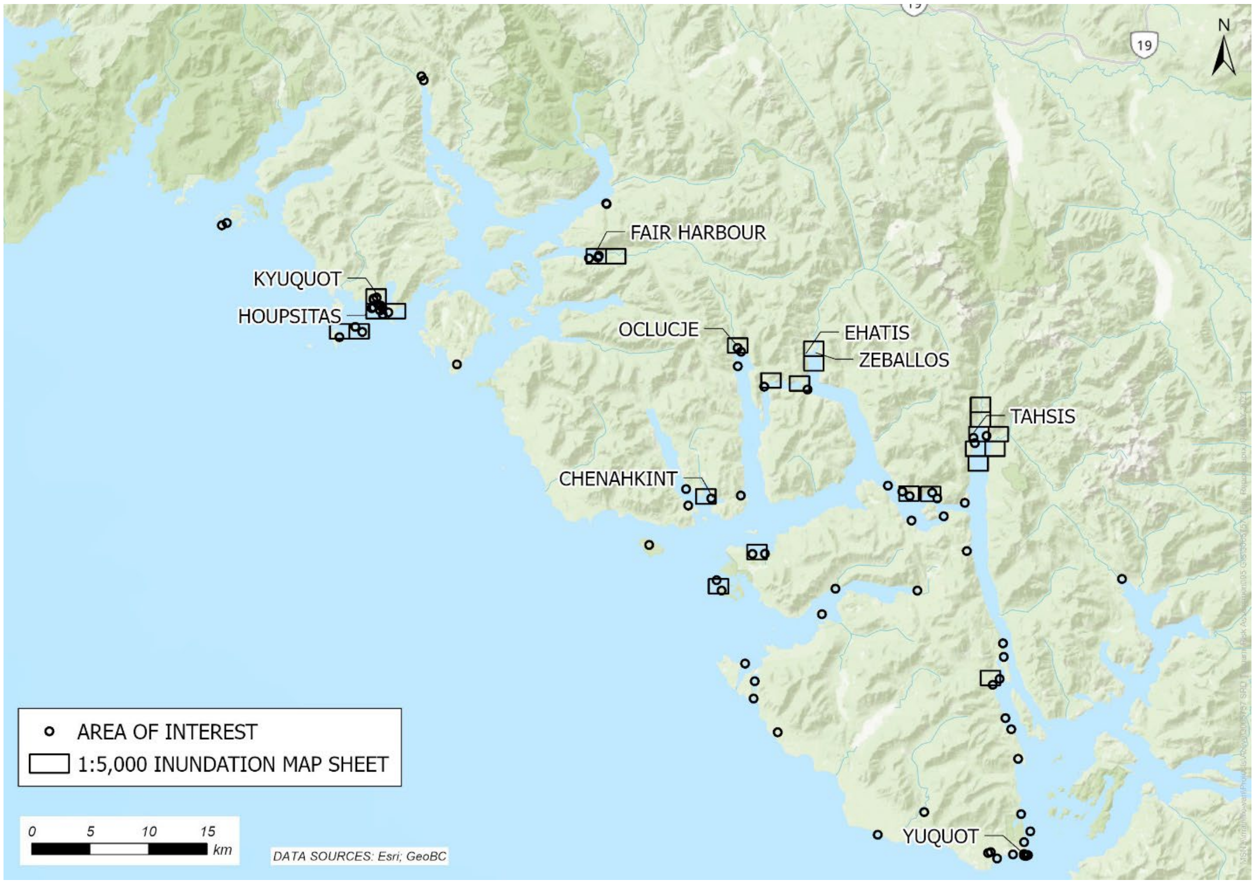

Figure 3. Areas of interest identified by the Advisory Group and areas prioritized for inundation mapping at a scale of 1:5,000.

2.2 Gathering of Background Information

Early in the project, available background information was gathered from communities and parties located within Phase I of the study area (see Figure 1), as well as publicly available sources. The following is a list of the main documents from which information was considered to advise this study, based on the community it relates to.

Ka:'yu:'k't'h'/Che:k:tles7et'h' First Nations

- Kyuquot Community Wildfire Protection Plan Evacuation Routes Maps (SuavAir, 2020a)

Nuchatlaht First Nation

- Nuchatlaht Tribe Tsunami Preparedness Strategic Plan 2018-2020 (Ducharme, 2018)
- Nuchatlaht First Nation Community Wildfire Protection Plan (SuavAir, 2020b)

Nuu-Chah-Nulth Tribal Council

- West Vancouver Island Coastal Vulnerability Study – Phase 1 – Nuchatlaht First Nation, Oclucje – Draft Report (Parsons, 2017)
- West Vancouver Island Coastal Vulnerability Study – Phase 2 – Ehattesaht First Nation, Ehatis – Draft Report (Parsons, 2018a)
- West Vancouver Island Coastal Vulnerability Study – Phase 2 – Kyuquot First Nation, Houpsitas – Draft Report (Parsons, 2018b)

Strathcona Regional District

- Strathcona Regional District Electoral Areas A 2020 Community Wildfire Protection Plan (SuavAir, 2020c)

Village of Zeballos

- Zeballos Emergency Plan (Village of Zeballos, 2020)
- Village of Zeballos Community Wildfire Protection Plan 2020 Update (SuavAir, 2020d)
- Zeballos Emergency Program – Emergency Response Plan (n.d.)
- Zeballos River Floodplain Modernization & Future Landslide Risk Assessment (BGC, 2018)
- As Built Report for Zeballos Water Tank Replacement (Stonecroft Project Engineering, 2003)

Village of Tahsis

- Tahsis Evacuation Plan (McElhanney, 2020)
- Tahsis Asset Map (O'Hara Consulting, 2019)
- Tahsis Flood Risk Assessment (McElhanney, 2019)
- Emergency Response and Contingency Plan (Village of Tahsis, 2017)
- Flood Mitigation Project – Phase 1: Record Drawings (McElhanney, 2022a)
- Flood Mitigation Project – Phase 2: Issued for Tender Drawings (McElhanney, 2022b)
- Technical Memo Re: Tahsis Dike Geotechnical Analysis (McElhanney, 2022c)

2.3 Indigenous Knowledge Research

Earthquake Foot Legend

This legend is a rendition of a Mowachaht/Muchalaht story

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

Shake Up interview with renowned artist and knowledge holder A-nii-sa-put (Tim Paul), 2020

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

Indigenous peoples on the northwest coast of Vancouver Island have been living at the forefront of tsunami risk for millennia. They have multigenerational shared experience connecting to the land, coping with environmental change, and surviving natural hazards. They hold deep understanding within their knowledge systems of disaster risk in their territories, gained through thousands of years of lived experience on their land and waters. Using a framework of "two-eyed" seeing, where different ways of knowing are used simultaneously for the benefit of all instead of one being incorporated into the other, this tsunami risk assessment utilizes Indigenous knowledge and modern risk assessment tools such as computer modelling to create a robust risk assessment. This project is a unique opportunity to showcase the resiliency of using "knowledge coexistence" for disaster management and risk assessment.

The project team worked closely with the Advisory Group members to identify elders and knowledge holders from within the study area. Through both research and interviews conducted between September 2020 and March 2021 with elders and community members, the project team collected multiple stories, teachings, and oral histories of past tsunamis including but not limited to the 1700 and 1964 tsunamis.

The knowledge shared through interviews not only illuminated the immense history of earthquakes and tsunamis on the northwest coast of Vancouver Island, but also gave insight to the hazard mapping component of this risk assessment. Elders, knowledge holders and community member's shared first-hand experiences which validate many of the results seen in the tsunami maps produced as part of this project. First-hand experiences gathered as part of these interviews are shared and correlated to modelling results in Section 3.2.3.

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

2.4 Community Touchpoints

Communities were engaged throughout the project with three main touchpoints, not only to raise awareness but also ensure that local knowledge is represented in the project. These touchpoints include a project website and a community survey prepared and communicated in collaboration with the SRD, as well as a series of online community meetings to engage with the public directly.

2.4.1 Project Webpage

Content for the project webpage was developed by the project team and hosted online by the SRD (www.srd.ca/nwvi-tsunami-risk-project/). This webpage provides an overview of the project, presents background information on tsunami hazards in the region, and informs the public of events associated with the project.

2.4.2 Community Survey

Part of this project included surveying residents of the study area to build community preparedness by:

- Sharing of experiences and knowledge between communities to help reduce tsunami risk,
- Assessing community evacuation and shelter-in-place preparedness levels, and
- Helping the communities understand where they can access emergency programs.

The survey was promoted by the SRD through a media release, neighbourhood mail outs, emails, and community-specific social media sites. Responses could be mailed in or submitted electronically. A total of 282 responses were received by the SRD, who oversaw the compilation and assessment of the responses, as well as follow-ups with the respondents that provided contact information.

Complete results of the survey are presented in the Community Survey Report provided in Appendix B. Survey questions were prepared by the project team in collaboration with the SRD and are provided in Table 2, along with responses to close-ended questions for the entire area surveyed. Responses were also assessed based on a community basis and the distribution of respondents per community is shown in Figure 4.

Table 2. Community survey questions.

General questions
Which community/location are you providing information on?
What concern do you have about a tsunami occurring in your community?
"Yes" or "no" questions on preparedness
Do you and your family have enough disaster supplies in case your community is cut off for two weeks and you have to shelter in place?
Are your supplies portable, such as in a back-pack or suitcase with wheels?
Do you know your community's tsunami meeting points?
Do you know your community's tsunami evacuation routes?
Do you know how your community will alert you if there is a tsunami threat?
Do you know how the Canadian Coast Guard's broadcasts tsunami alerts to mariners?
Do you know that the immediate signs of an approaching local tsunami are: ▪ A strong ground shaking, and ▪ A rapid and unexpected recession of water levels, and a loud roaring sound coming from the ocean?
Do you know that the immediate signs of an approaching distant tsunami are: ▪ A rapid and unexpected withdraw of water level, and ▪ A loud roaring sound coming from the ocean?
Do you know that a tsunami can also be triggered by landslides?
Are you a certified Amateur Radio Operator?
Are you interested in receiving information about how to achieve an Amateur Radio Certification to help disaster communications of your community?
Do you have a satellite communication device (Spot X, In Reach)?
Open-ended questions (responses vary)
Do you have personal experience of a tsunami event in northwest Vancouver Island? ▪ If yes, which year/specific location? ▪ Can you provide details (impacts/damage, physical observations, personal response, etc.)? ▪ Would you be willing to share your contact information to provide further details to us? If so, please enter it below. This personal information will be kept confidential by the SRD and the project team.
Do you have any recommendations or feedback you would like passed along to emergency planners?
Anything else you would like to share with us?

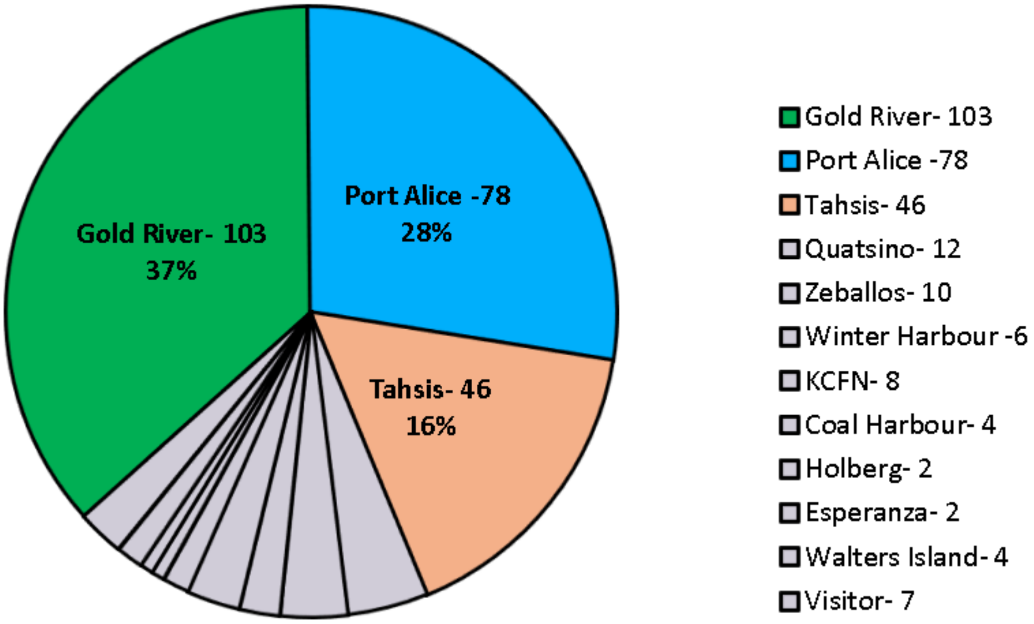

Figure 4. Total survey respondents per community

2.4.3 Public Meetings

Two rounds of public meetings took place to:

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

Due to the COVID-19 pandemic all meetings were conducted in an online format. Meetings included a presentation by the project team followed by an interactive question and answer period. The first round of meetings took place in August 2021 and the second and final round in April 2022. Each public meeting was opened by an Indigenous elder.

3 TSUNAMI HAZARD ANALYSIS AND MAPPING

According to the United Nations International Strategy for Disaster Reduction (UNISDR, 2009), a *hazard* is a potentially damaging physical event, phenomenon, or human activity that may cause the loss of life or injury, property damage, social and economic disruption, or environmental degradation. One prerequisite to any risk assessment is the definition of the hazard to which a study area may be exposed.

For this study the hazards related to tsunamis are defined by means of computer simulations (i.e., numerical modelling) which estimate the complex and nonlinear behaviour of tsunami waves as they propagate towards the coast and interact with the intricate geographical features of the coastline. For such modelling, a Digital Elevation Model (DEM) is required which represents the earth surface both above the water (*topography*) and below the water (*bathymetry*). The quality of the tsunami modelling, and ensuing mapping, is directly correlated to the quality of the DEM developed, which in turn depends on the accuracy and spatial resolution (i.e., density of data points) of the underlying elevation information used. The numerical modelling followed a *nested* approach, meaning that results from a broader and coarser model are passed as boundary conditions to successively smaller models with higher resolution that are embedded into the broader model. An approach such as this focuses the analysis to areas of interest and reduces computation time.

Further details of the DEM development, tsunami modelling, and tsunami hazard mapping are presented below.

The tsunami hazards analysed in this study include flood hazard (e.g., overland inundation) in localized areas, as well as overwater hazards, such as maximum tsunami amplitude and maximum tsunami-induced current velocity. Other overwater hazards such as shallow navigation depths and impacts with floating debris have not been assessed.

3.1 Digital Elevation Model

In simple terms, a DEM surface is generated by the interpolation of elevation information of variable spacing onto grid points of constant spacing. Several DEMs were created to support tsunami modelling and mapping for this study. DEMs of varying spatial resolutions and extents were developed following the nested modelling approach, which consists of performing broader simulations at a coarser resolution to provide boundary conditions to simulations of successively finer resolution that focus on the study area. This nesting approach is further described in Section 3.2.2, where tsunami modelling is presented. DEMs integrate both topography and bathymetry data and narrow from a coarse resolution of about 1,500 m in the Northeast Pacific Ocean to a finer resolution of 10 m in the regions of interest. A 2 m resolution topographic DEM was developed to support local scale tsunami inundation mapping in key locations and is discussed in Section 3.3.4.

Data sources and a summary of DEM development methods are described below. Further details of the development of DEMs for tsunami modelling are provided in Appendix C.

3.1.1 Elevation Data Sources and Collection

DEMs specific to the study area were developed using both pre-existing datasets and datasets collected for the purpose of this project. The latter include light detection and ranging (LiDAR) topographic data and bathymetric survey data. Data collection campaigns undertaken as part of this study are summarized below. Table 3 presents all datasets used for DEM development, listed from top to bottom in terms of priority over other datasets where they overlap.

Table 3. Elevation datasets used for DEM development.

Dataset	Date of Survey	Data Type	Spatial Resolution[1]
Commissioned LiDAR data collected by McElhanney	2020	Topographic LiDAR survey	Minimum of 1 point per square metre[2]
Commissioned multi-beam and single beam bathymetric survey performed by Terra Remote Sensing Inc. (TRSI)	2020	Multi-beam survey interpolated onto DEM surface, single beam survey tracks	1 m for DEM surface, 0.1 – 0.3 m along survey tracks ~50 m apart
DEM of the Tahsis River valley provided by McElhanney, including river bathymetry[3]	2018 – 2019	DEM surface	0.3 m
Multi-beam bathymetry data obtained from the Canadian Hydrographic Survey (CHS)	2000-2020	Bathymetric data	2 – 5 m
Bathymetric survey points obtained from the CHS	1934 – 2010	Bathymetric data	Varies
CHS non-navigational (NONNA-10) bathymetric data	2018 – 2020	Bathymetric DEM surface	10 m
Canadian Digital Elevation Model (CDEM)	1945 – 2011	Topographic DEM Surface	0.75 arc-second (~20 m)
Bathymetric DEM of British Columbia from the National Oceanographic and Atmospheric Administration (NOAA)	1930 – 2011	Bathymetric DEM surface	3 arc-seconds (~93 m)

Notes:

1. Spatial resolution of DEM surfaces relates to the constant spacing between adjacent points onto which underlying elevation information was interpolated. The resolution of a DEM may not necessarily reflect the actual resolution of the underlying elevation information from which it was derived.
2. Federal Airborne LiDAR Acquisition Guidelines (NRCan and Public Safety Canada, 2020) specify a density of 4-10 full feature points per square metre for LiDAR data to support inundation mapping in high flood risk areas (all urban areas and rural areas that are protected by diking) down to 2 full feature points per square metre for low flood risk areas (sparsely populated areas).
3. The river bathymetry data used to develop this DEM is relatively coarse as only typical river cross-sections were surveyed.[1]

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[1] McElhanney, 2021. Email communication between Philippe St-Germain (pstgermain@nhcweb.com) and Michael de Hart (mdehart@mcelhanney.com) on June 28, 2021.

3.1.1.1 LiDAR Collection

Prior to this project, LiDAR topographic data was non-existent for the majority of the Phase I study area. Therefore, McElhanney Consulting Services Ltd. was engaged as part of this project to collect such high-resolution data, which plays a crucial role in this project as it allows for detailed inundation mapping.

As part of the condition for the funding received for this project the LiDAR data was provided to the Province of BC, requiring the preparation of metadata according to GeoBC standards. Such metadata generally consists of any information that is descriptive or supportive of a geospatial dataset, including reports that details data collection, processing, and quality assurance/quality control (QA/QC), as well as other supporting information such as ground control points and shapefiles[2].

LiDAR was collected by plane in August 2020 and flight paths were planned to maximize the survey of intertidal zones at lower tides in areas of interest. Flights were performed over a total distance of 1,800 km, covering a total area of approximately 765 km^2. The coverage of the LiDAR collected is shown in Figure 5. Not all shorelines were able to be surveyed at lowest tide conditions due to the time-varying nature of the tides in relation to the duration of the flights. Flights paths were established to maximize the coverage of intertidal areas during low water conditions. A minimum survey point density of one full feature point per square metre was adopted to maximize the coverage of the survey, while a density up to approximately three full feature points per square metre was achieved in inhabited areas. Raw LiDAR data was processed to remove vegetation, buildings, and bridges to represent a bare-earth[3] surface only. This process resulted in an average density of approximately 1.5 bare-earth points per square metre in inhabited areas.

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[2] A shapefile is a vector data format for storing the location, shape, and attributes of geographic features.

[3] Bare-earth consist of a representation of the earth's surface free of vegetation, buildings, and other structures.

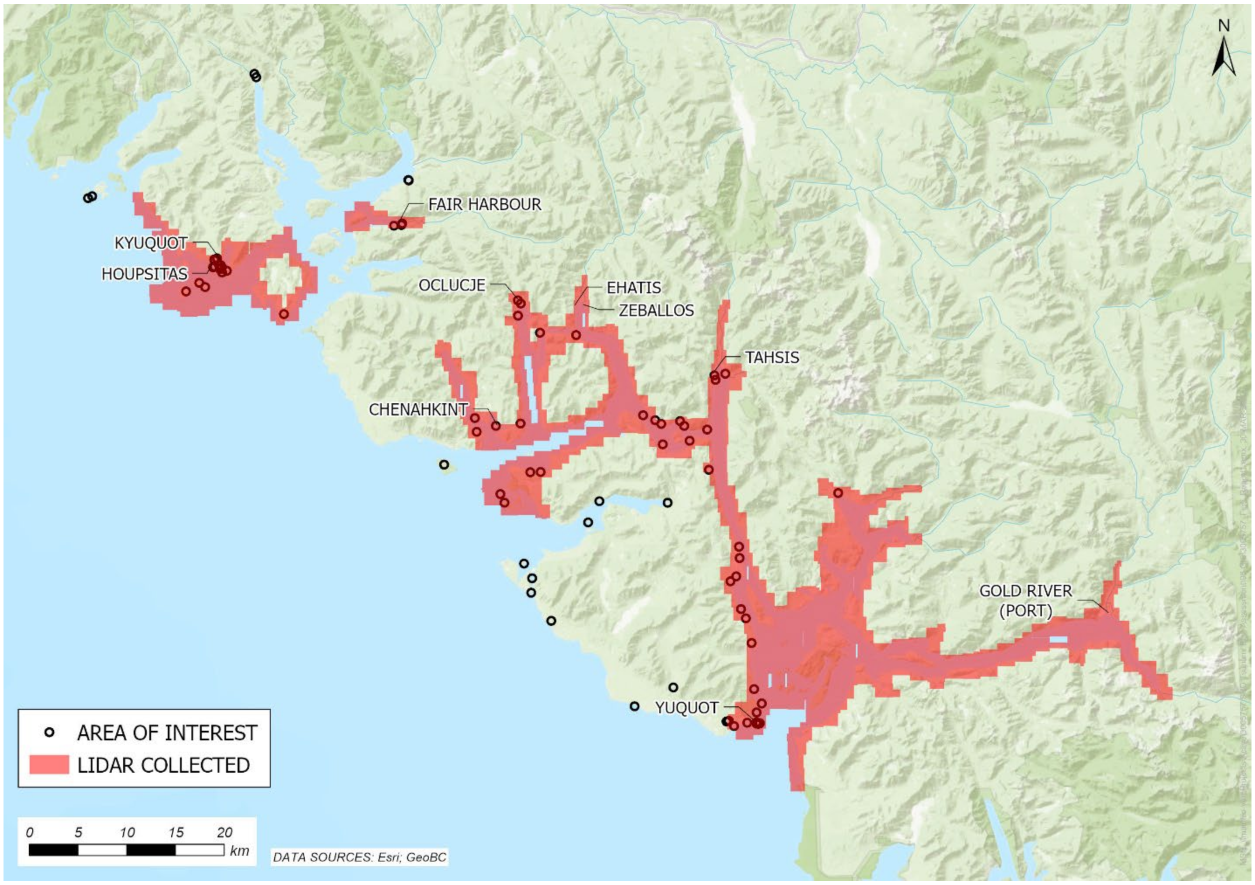

Figure 5. **Coverage of LiDAR collected as part of the project.**

3.1.1.2 Bathymetric Survey

Terra Remote Sensing Inc. (TRSI) was engaged as part of this project to conduct multi-beam and single-beam bathymetric surveys at four sites in Tahsis Inlet and Zeballos Inlet. Survey locations were prioritized to fill in gaps identified based on a review of available government data. Surveys were conducted between August 12 and August 15, 2020. A single beam echosounder was used to survey perpendicular profiles along the shoreline with a maximum distance of 50 m between each profile, and a multi-beam system was used to collect data in the remainder of the survey areas. The raw multibeam data was processed by TRSI to produce a 1 m resolution surface of the seabed, which was subsequently used for DEM development by ONC.

3.1.2 DEM Development

A total of three DEMs were developed for specific use in this study, as listed below.

- A 60 m resolution DEM to represent the northwest coast of Vancouver Island,
- A 10 m resolution DEM to represent Kyuquot Sound, and
- A 10 m resolution DEM to represent Esperanza Inlet, including Tahsis Inlet.

Broader previously developed ocean-scale DEMs were also employed but are not presented herein. The latter have resolutions of 240 m and over. The geographical extents of the project specific DEMs, which integrate both topographic and bathymetric information, are shown in (Figure 6).

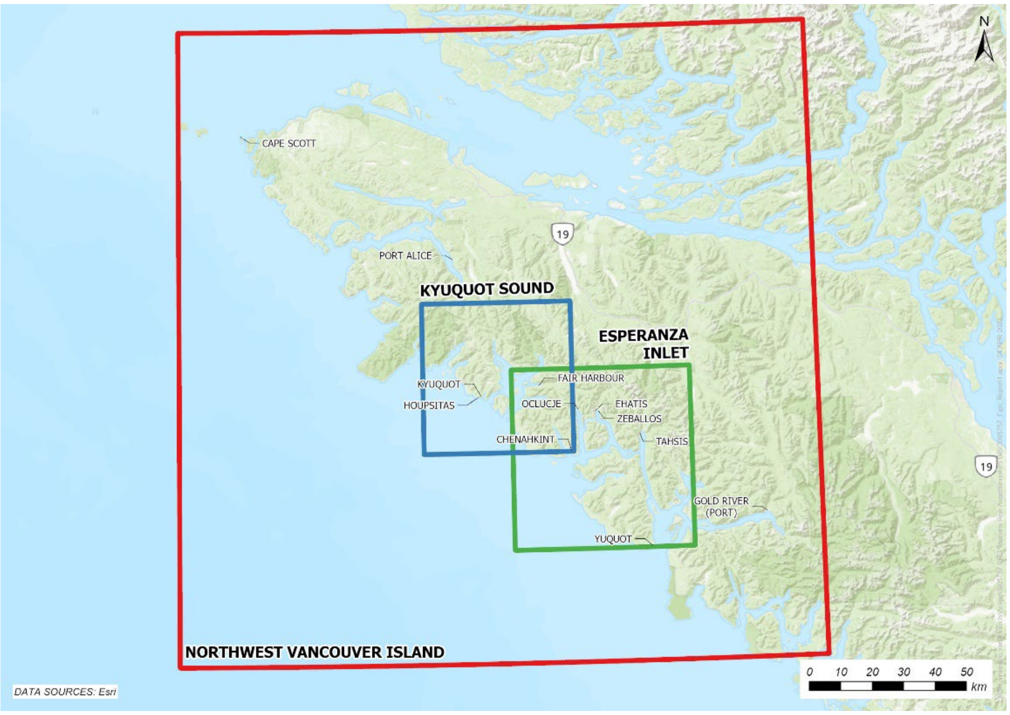

Figure 6. Geographical extents of DEMs developed to support tsunami modelling.

The DEMs were developed according to the following approach. Source datasets which are listed in Table 3 were converted to a common geographic coordinate system (latitude and longitude) with the World Geodetic System of 1984 (WGS84) as horizontal datum and the Canadian Geodetic Vertical Datum of 2013 (CGVD2013) as vertical datum. In assembling the DEMs, priority was given to finer resolution data where datasets overlapped. Interpolation methods were used to convert the elevation data to a gridded surface and smoothing of the bathymetric areas was performed. The latter is to minimize artificial features that may result from the interpolation process as well as to facilitate tsunami modelling which can be sensitive to abrupt changes in the seafloor. Information from the Canadian Hydrographic Service (CHS) was used to delineate the coastline in areas where the resolution of the source elevation data was not sufficient to define the coastline in itself (e.g., CDEM and NOAA datasets, as per Table 3).

Quality was controlled by visually comparing the shaded relief of the DEMs with satellite imagery on land and depth contours with CHS navigational charts underwater. DEMs were developed and reviewed considering the purpose of tsunami modelling only and greater attention was given to areas of interest. The DEMs produced as part of this project may not be suitable for other uses unless confirmed by review and assessment.

The vast geographical extent of the study area in conjunction with relatively sparse elevation data available leads to inherent limitations in how the DEMs reflect reality. Such limitations can also translate into limitations of the subsequent tsunami modelling and mapping, as further discussed in Section 3.4. The main limitations of the DEMs include the following:

- Spatial resolution of DEM surfaces relates to the constant spacing between adjacent points onto which underlying elevation information was interpolated. The resolution of a DEM may not necessarily reflect the actual resolution of the underlying elevation data from which it was derived. For example, to follow federal guidelines (NRCan and Public Safety Canada, 2020), detailed overland inundation mapping is not possible outside of the area covered by LiDAR (Figure 5). Where LiDAR coverage is not available the CDEM with a resolution of 20 m (see Table 3) was used. The constant 10 m resolution across the DEMs does not reflect this variation in the source elevation data.
- Several data gaps which could not be covered by the project's survey campaign exist throughout the large study area. Such areas include remote inlets and estuaries, but mostly consist of intertidal zones which are logistically more challenging to survey. For instance, intertidal zones may have been submerged at the time LiDAR was collected from the plane above. Also, shallow water depths can impede typical survey by boat unless specifically planned, explaining why depths in intertidal zones are seldom reported on CHS navigational charts. Hence, the DEM surface in intertidal zones where gaps exist results from the interpolation between topographic and bathymetric datasets, which can induce accuracies in those areas.
- Aside from Tahsis River, no bathymetric data was available for rivers located in the study area. Hence, such rivers are represented based on the interpolation of topographic data only and therefore the riverbeds generally appear to have elevations matching the adjacent riverbanks.

3.2 Tsunami Hazard Modelling

When an offshore subduction earthquake occurs, the quick uplift motion of the seafloor vertically displaces a large volume of water which induces a rapid and localized change in sea level. This results in tsunami waves propagating in opposite directions, perpendicular to the fault line. Such waves can propagate thousands of kilometres away from their generating source at considerable speeds. In deep waters, these waves will have relatively small amplitudes (often less than 1m), but their length often extends hundreds of kilometres. As these waves propagate into coastal waters, they experience an increase in amplitude, as well as a deceleration and a shortening of their wavelength due to the compressing effect of the up-sloping seafloor and the decreasing water depth. As tsunami waves approach the shoreline and intrude overland, their behaviour will be mainly influenced by local geographical features and may vary considerably from one location to another. Although most often triggered by subduction earthquakes, tsunamis can also be due to the sudden displacement of water induced by subaerial and submarine landslides, volcanic eruptions, and meteor impacts. Hazards associated with tsunamis triggered by mechanisms other than subduction earthquakes are beyond the scope of this assignment due to funding limitations. Geological and geotechnical assessment is required to determine if risks associated to landslide-generated tsunamis exist in the study area.

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

In general, inputs required for tsunami modelling include a representation of the earth surface, such as a DEM as previously described in Section 3.1.2, as well as a definition of the seafloor displacement resulting from an earthquake. The tsunami scenarios considered for this study are presented below, as well as a technical overview of the tsunami model used. A summary of the model results is also provided. Further details on the tsunami modelling work performed to support this study are provided in Appendix C.

A previous study undertaken by Parsons (2017, 2018a, and 2018b) presents the effects of a Cascadia tsunami at Oclucje, Ehatis next to the Village of Zeballos, and Houpsitas in Kyuquot. No detailed technical comparison was performed between this study with the current study, as such assessment is outside the scope of this assignment.

3.2.1 Tsunami Scenarios

Two tsunami sources were considered for this study: a *local* tsunami from the Cascadia Subduction Zone, (referred hereafter as a Cascadia tsunami) and a *distant* tsunami from the Alaska Aleutian Islands Subduction Zone (referred hereafter as an Alaska tsunami). While Vancouver Island is exposed to tsunamis originating from anywhere in the Pacific Ocean, these two sources are considered the most hazardous to the coast of British Columbia (Ferguson *et al.*, 2022). These tsunami sources are further described below.

In conjunction with the two tsunami sources considered, two sea levels were simulated, resulting in a total of four tsunami scenarios being modelled. These sea levels include a current-day sea level and a future sea level based on sea level rise (SLR) predictions published by Natural Resources Canada (NRCan, James *et al.*, 2021). Further description of the water levels simulated is also provided below.

The tsunami scenarios modelled in this study are referred to as follows:

1. Current-day Cascadia tsunami
2. Current-day Alaska tsunami
3. Cascadia tsunami with sea level rise
4. Alaska tsunami with sea level rise

General inundation levels for emergency planning were defined considering both current-day and future sea levels, as further discussed in Section 4.4. Only inundation corresponding to current-day sea level was mapped as part of this assignment as a starting point to understand tsunami risk to life safety. Model results including sea level rise are available for further mapping and assessment to support longer-term development and planning.

3.2.1.1 Tsunami Sources

Cascadia Subduction Zone

The tsunami source used for the simulations of a Cascadia tsunami corresponds to the splay-fault rupture of the CSZ developed by researchers from NRCan and the University of Victoria (Gao *et al.*, 2018). This tsunami source information was acquired from NRCan by ONC. By including the rupture of the explorer segment of the CSZ, this whole-margin megathrust scenario is appropriate for tsunami hazard assessments in the northmost portion of the Cascadia margin. Figure 7 shows the estimated *uplift* (upward motion, red shade) and *subsidence* (downward motion, blue shade) of the earth surface associated with this rupture. The rupture zone extends south from California to Brooks Peninsula to the north and corresponds to an earthquake with a moment magnitude of approximately 9.0. This earthquake scenario is generally considered similar to the historical tsunami of January 26, 1700, although believed to be stronger, as further explained below.

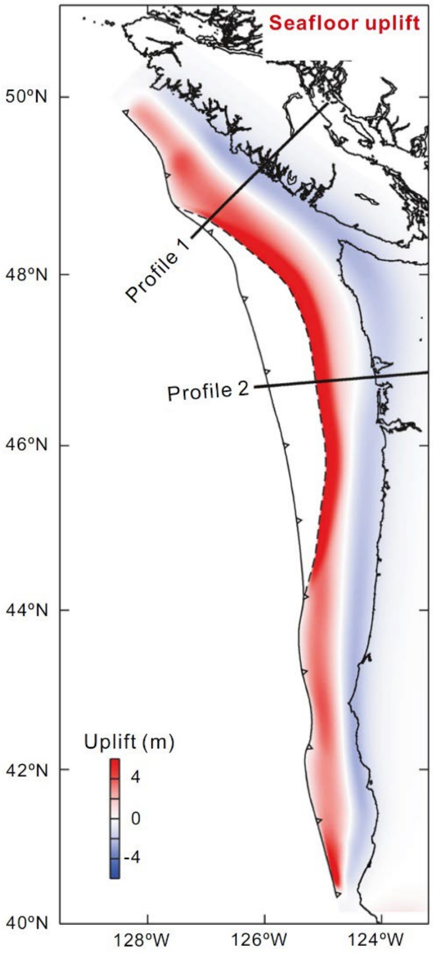

Figure 7. Vertical displacement of the earth surface associated with the Cascadia tsunami modelled (image from Gao *et al*., 2018). Uplift is represented by shades of red and subsidence by shades of blue.

The following scientific background information further qualifies the tsunami source considered at the CSZ. Writter *et al*. (2013) simulated Cascadia tsunamis to characterize the associated hazard on the Oregon Coast for which megathrust earthquake scenarios were developed based on:

- Knowledge of the structure of the Cascadia megathrust,
- Onshore and offshore paleoseismological evidence,
- Theoretical understanding of how megathrust ruptures deform the seafloor, and
- Observations after historical megathrust earthquakes.

Four earthquake size categories were established along with respective mean interevent time intervals based on the paleoseismic record of previous earthquakes going back approximately 10,000 years. These categories are defined as *small* (S), *medium* (M), *large* (L) and *extra-large* (XL) with mean inter-event time intervals of 300, 425-525, 650-800, 1050-1200 years, respectively. A fifth *extra-extra-large* hypothetical scenario was also used to simulate a maximum tsunami to guide evacuation planning (XXL) in Oregon.

From this paleoseismic record it was determined that a total of 19 Cascadia earthquakes occurred over the last 10,000 years (Table 4), with magnitudes that may have ranged from 8.7 to 9.2. According to the classification of Writter *et al*. (2013) in conjunction with rupture parameters, the 1700 Cascadia earthquake may be associated to the category M (Mw 8.9 – 9.0), and it is believed that 10 earthquakes in the same category have occurred over the record. The earthquake scenario of Gao *et al.* (2018) simulated for this study can be associated to the category L (Mw 9.0 – 9.1) for which category three earthquakes have occurred over the record. Only one earthquake of category XL (Mw 9.1 – 9.2) is believed to have occurred over the record.

Accordingly, while the Cascadia tsunami modelled in this study can be considered a severe event, it may technically not be the worst-case scenario and some residual risk remains.

Table 4. Paleoseismic record of past Cascadia earthquakes based on turbidite[4] analysis as reported by Writter *et al*. (2013).

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

Notes:

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

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

Alaska Aleutian Islands Subduction Zone

The numerical simulations of the 1964 Alaska tsunami are based on the seafloor displacement defined by Suleimani and Freymueller (2020). Such displacement, which is associated with the Mw 9.2 earthquake that generated the tsunami, is shown in Figure 8. This tsunami source information was acquired from University of Alaska Fairbanks by ONC.

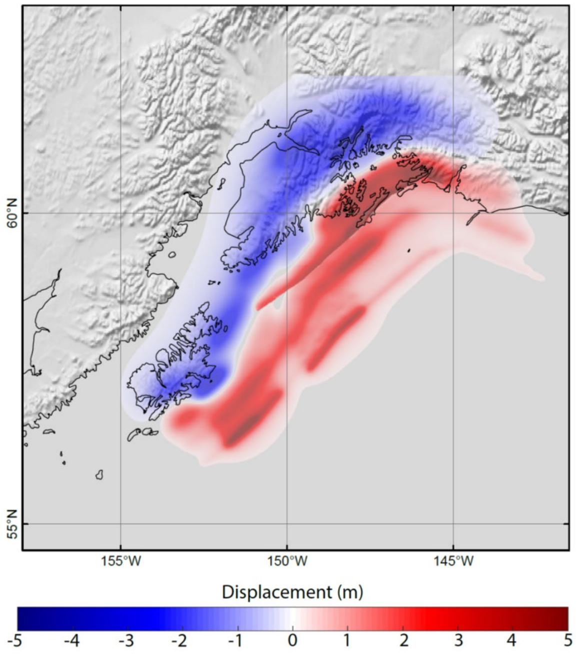

Figure 8. Vertical displacement of the earth surface associated with the Alaska tsunami modelled (image from Suleimani and Freymueller, 2020). Uplift is represented by shades of red and subsidence by shades of blue.

3.2.1.2 Water Levels

Tide Level

Tides are driven by astronomical forcing. More specifically, the gravitational forces applied on the sea water by celestial bodies such as the moon and the sun. Since the rotation of the moon as well as of the planets is a cyclic and repeated phenomenon, the variation of the water level generated by astronomical tide alone can be predicted accurately. On the other hand, storm surges are driven by atmospheric forcing which combines the effects of the wind and the barometric pressure. Because the probability of a tsunami occurring during an intense storm is low (although non-zero), no storm surge is included in the numerical simulations. (It is noted that regularly occurring storm surge is between 0.3 and 0.7 m.)

The US National Tsunami Hazard Mitigation Program (NTHMP, 2010) recommends that tsunami inundation maps be developed based on simulations performed with a tide level corresponding to, at a minimum, the Mean High Water (MHW) of a specific region. As per the NOAA's definition of tidal heights in the US, MHW corresponds to the average of all the high-water heights observed over a tidal epoch[5]. Mean Higher High Water (MHHW), which is higher than MHW, corresponds to the average of the higher high-water height of each tidal day observed over a tidal epoch. Based on the CHS definition of tidal heights in Canada, MHHW is similar to Higher High Water Mean Tide (HHWMT). In the study area HHWMT varies from 1.4 to 1.6 m with respect to CGVD2013 and an average value of 1.5 m was considered over the area covered by the model. The tide level was kept constant in the numerical simulations, which for the purpose of inundation mapping is a conservative simplification.

It should be noted that the selection of HHWMT as tide level for the simulations instead of a higher tide level such as Higher High Water Large Tide (HHWLT) implies that some residual risk remains. HHWLT corresponds to the average of the annual highest high-water heights over a tidal epoch. Such tide level generally occurs only approximately, on average, every two years at Winter Harbour, and the probability of a coinciding tsunami is low. In the study area HHWLT varies from 2.0 to 2.4 m with respect to CGVD2013 (or 0.6 to 0.8 m higher than HHWMT).

The tide levels stated above are based on information provided in the Canadian Tide and Current Tables (Fisheries and Oceans Canada, 2021) converted to CGVD2013 based on the Continuous Vertical Datum for Canadian Waters dataset developed by the CHS. This dataset constitutes a surface relating chart datum to the national geodetic reference frame with the year 2010 as baseline[6].

Sea Level Rise

Climate change is expected to result in increased global sea levels stemming from melting of ice and increased ocean volume due to rising water temperature. The *relative* sea level rise observed in one location, however, will also depend on the regional variability of global sea level rise and the localized long-term vertical movements of the earth surface (e.g., uplift or subsidence). Such vertical movement can result from a variety of geological processes such as post-glacial rebound and/or the movement of tectonic plates.

This study considers relative sea level rise projections recently published by NRCan (James *et al*., 2021). These projections are based on the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report of 2014 in conjunction with the NAD83v70VG national crustal velocity model which describes changes in ground elevation. The most adverse scenario analysed by James *et al*. (2021) is considered for this study. This scenario, which is referred to as their “enhanced” scenario, consists in the median projection of the Representative Concentration Pathway (RPC) scenario 8.5 to which was added 0.65 m of global sea level rise sourced from the West Antarctic Ice Sheet. For the year 2100, this corresponds to a relative sea level rise of approximately 1.2 m on the northwest coast of Vancouver Island, relative to a baseline of 1986 – 2005. Considering that the HHWMT tide level defined for this study is relative to a baseline of 2010 as mentioned above, slightly more sea level rise has been effectively added in the

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[5] A tidal epoch is a 19-year time period established for collecting observations on water levels and calculating tidal datum values.

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

simulations (e.g., the amount that occurred between the baseline of the NRCan projections and the baseline of the CHS surface relating chart datum to the national geodetic reference frame).

The BC Provincial Sea Dike Guidelines (BC MoE, 2011) recommend that projects consider 1.0 m of global sea level rise above year 2000 levels for year 2100 and 2.0 m of sea level rise for year 2200, with adjustments for local vertical movements of the land. As the NRCan projections are slightly higher, those have been adopted for this study.

Earthquake Land Subsidence

The land subsidence associated with a local Cascadia earthquake is accounted for by lowering the elevation of the ground in the numerical model according to the spatially-varying ground displacement estimated by Gao *et al.* (2018), which is shown by the blue shade in Figure 7. This essentially instantaneous subsidence is greater on the open coast and diminishes further inland. For instance, it corresponds to a lowering of the ground by approximately -1.0 m at Kyuquot and -0.4 m at Tahsis.

The land subsidence associated with a distant Alaska Aleutian Islands subduction zone earthquake does not affect the study area.

In consideration with the scenario of a Cascadia tsunami with sea level rise, it is assumed that the land displacement associated a Cascadia earthquake in the far-future is equivalent to the displacement associated to an Cascadia earthquake occurring in the near-future, as estimated by Gao *et al.* (2018).

3.2.2 Tsunami Model Description

This section provides a technical description of the numerical model used to simulate tsunami propagation and potential overland inundation, as per the scenario basis provided above. Simulations were performed using the fully nonlinear Boussinesq wave computer model FUNWAVE (Version 3.4) developed at and maintained by the University of Delaware (Shi *et al.*, 2016). The model, which solves governing equations for the propagation of long waves, has been benchmarked against other tsunami models as part of the US NTHMP (Horrillo *et al.*, 2014). As a Boussinesq model FUNWAVE accounts for wave frequency dispersion[7], which is important when simulating the propagation of tsunamis over long distances, such as the case of an Alaska tsunami.

The modelling followed a nested approach in which results computed on a larger computational grid are passed as boundary conditions to a smaller grid, nested inside the larger one. This nesting is performed at various levels, starting with a larger computational grid in the open ocean, going into gradually smaller nested grids towards the area of interest, in this case the northwest coast of Vancouver Island. The geographical extent of the computational grids over which tsunami results were computed for this study are shown in Figure 9. A *coarser* resolution of 60 m was used over the study area, while a *higher-resolution* of 10 m was used in regions where areas of interest were identified. These include areas in Kyuquot Sound and Esperanza Inlet, as well as Tahsis Inlet (refer to Figure 1 for the areas covered under

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[7] Wave frequency dispersion relates to the notion that waves of varying wavelengths travel at different speeds and how they interact when they pass each other.

the scope of Phase 1). Broader grids of lower-resolution were used in the Pacific Ocean but are not described in this main project report.

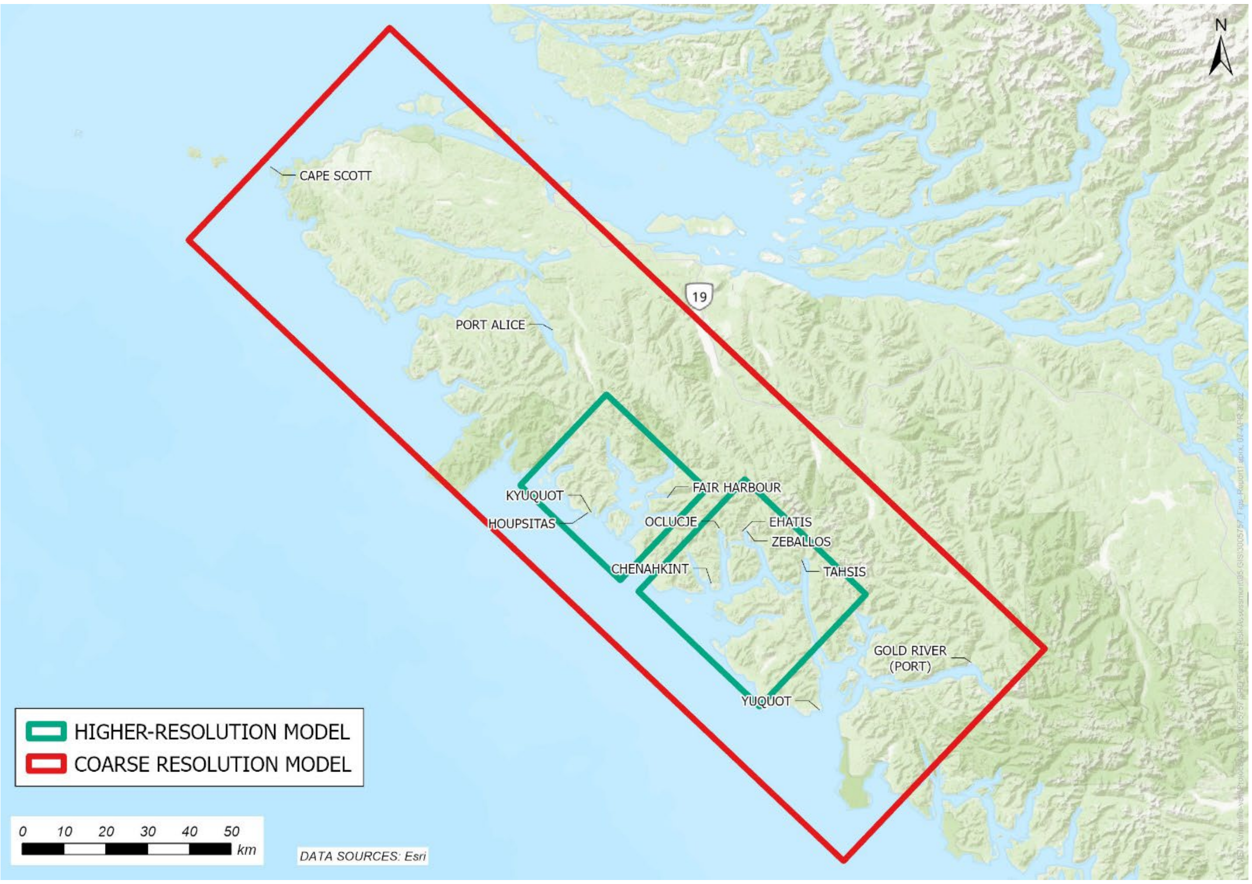

Figure 9. Geographical extents of tsunami modelling areas.

While coarser simulations allow for the identification of overwater hazards such as maximum tsunami amplitude and maximum tsunami-induced current velocity, this resolution is not sufficient to adequately simulate overland inundation. Hence, inundation mapping can only take place in areas modelled at a higher resolution, as long as high-resolution topographic information (i.e., LiDAR) is also available and integrated in the model's underlying DEM. The development of the latter and the coverage of LiDAR is discussed in Section 3.1.

The most south-eastern boundary of the higher-resolution model was originally located within Tahsis Inlet and needed to be extended into Nootka Sound to resolve technical challenges occurring at the model boundary in Tahsis Inlet (extended model coverage not shown). However, the results in the areas captured by this expansion, which are included in Phase 2 of this study (see Figure 1), are not discussed in detail in this report as they remain under development.

Additional details on the tsunami model and its results are provided in Appendix D.

3.2.3 Model Results

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

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

Below is a general overview of the results for maximum tsunami wave amplitude and maximum tsunami-induced current velocities. The results shown are limited to the extent of the overwater hazard maps produced as part of this study. These maps, whose layout is shown in Figure 18, are provided in Appendix E. Tsunami arrival times, which are also provided on the overwater hazard maps, are presented in Section 4.4 as part of the community risk assessment.

The extent of tsunami flooding, or inundation is derived by post-processing of the water surface elevation predicted by the model. Details of the methodology followed to derive inundation extent are presented in Section 3.3.4.1. The 25 areas for which inundation extent is derived and mapped are presented in Figure 20. These areas were selected based on the areas of interest identified by the Advisory Group, as shown in Figure 3. Associated inundation maps are provided in Appendix F.

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

3.2.3.1 Cascadia Tsunami

What makes Vancouver Island particularly susceptible to potentially large tsunami waves is the proximity of the CSZ, which is located approximately one hundred kilometres offshore running parallel to Vancouver Island and the west coast of the United States. This is demonstrated in Figure 10, which shows the influence of the Cascadia tsunami in the Pacific Ocean, directly affecting the west coast of Vancouver Island. Tsunamis travel outward in all directions from the generating area, with the largest waves propagating perpendicular to the fault line and in opposite directions. Waves that propagate into the open ocean radiate laterally as they propagate away from their source, which result in a reduction of their amplitude. This explains why areas such as the island of Haida Gwaii on the northern BC coast are less affected by tsunamis from the CSZ.

1700 Tsunami Oral History

As told by Chief Louie Nookmiis (1881-1964) and recorded by recorded by anthropologist Eugene Arima:
"The Pachena Bay people were lost… But (for those) who lived at maałćaas 'House Up Against Hill', the wave did not reach (them) because they were on high ground right against a cliff. Because of that they came out alive. They did not drift out to sea along with the others." Although Pachena Bay, located near Bamfield, BC, is outside of the project study area, it is geographically relevant, and an example of the devastation caused by tsunamis on the west coast of Vancouver Island.

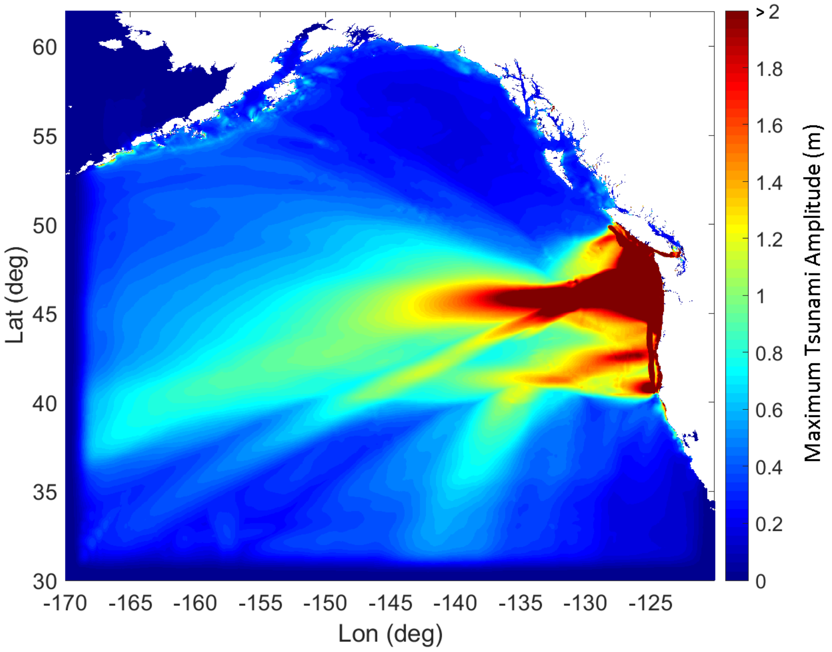

Figure 10. Maximum amplitude of Cascadia tsunami in Northeast Pacific Ocean.

Tsunami Amplitude

The maximum tsunami amplitude associated to a Cascadia tsunami affecting the northwest coast of Vancouver Island is shown in Figure 11. This region is characterized by its many narrow inlets and sounds in which tsunami waves can be amplified, increasing their potential to adversely impact communities in these areas. This amplification can be the result of several physical factors such as constricting topography, a decrease in water depth inducing wave shoaling, and/or resonance. No detailed assessment was performed to further describe the physical factors causing such amplification.

The largest amplitude generally occurs on the open coast south of Brooks Peninsula with amplitudes exceeding 6 m (up to 10 m on the west coast of Nootka Island). Results show that tsunami amplitude is smaller in areas north of Brooks Peninsula. As these areas are beyond the northern limit of the CSZ (see Figure 7), they are not affected by tsunami waves approaching directly at them.

Yuquot, which is located at the entrance of Nootka Sound on Nootka Island, has been occupied for at least the last 5,000 years although stratigraphic evidence suggests the area was abandoned following the 1700 Cascadia tsunami. Exposed to the open ocean, this location is subjected to large tsunami waves with amplitude ranging from 4 to 6 m, which is consistent with the Indigenous oral history gathered as part of this study.

1700 Tsunami Oral History

As told by Ray Williams (Mowachaht/Muchalaht First Nations):

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

Holberg Inlet, which is connected to Quatsino Sound through Quatsino Narrows and where Holberg and Coal Harbour are located, is not expected to be much affected by tsunami waves. Although this needs to be confirmed once higher-resolution modelling is performed for that area as part of Phase 2 of this project (see Figure 1). At the northern end of the island near Cape Scott, the tsunami amplitude is expected to be amplified due mainly to shoaling of the tsunami waves induced by the shallower offshore depths in the vicinity of Cook Bank. Further modelling is planned as part of the second phase of this project to confirm this.

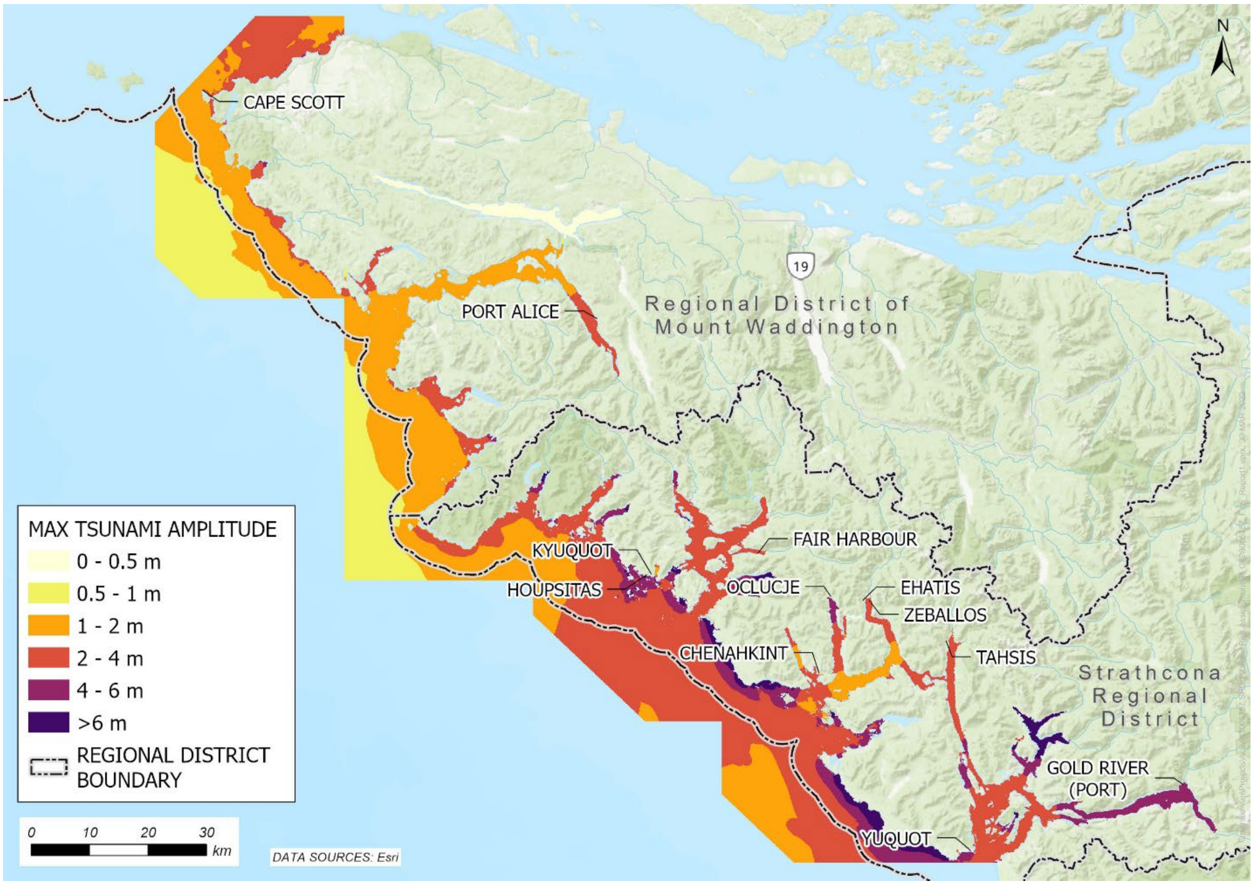

Figure 11. Maximum Cascadia tsunami wave amplitude in the broader study area.

Results of maximum tsunami amplitude in the vicinity of the areas of interest are shown in Figure 12. Located on the coast, the Kyuquot area is particularly exposed to tsunami hazard and, in comparison to typical storm waves, the nearby offshore island archipelago offers little if no protection. In comparison to Kyuquot Sound, the tsunami amplitude in Esperanza Inlet is generally smaller. Nevertheless, considerable tsunami amplitudes larger than 2 m are predicted in areas of interest inside the inlet. Tahsis, which is located at the head of a long and narrow inlet (Tahsis Inlet), is subjected to considerable tsunami amplitudes ranging from 2 to 4 m. It is suspected that the constriction induced by the delta of Tsowwin River (i.e., Tsowwin Narrows) plays an important role in attenuating waves propagating further into the inlet.

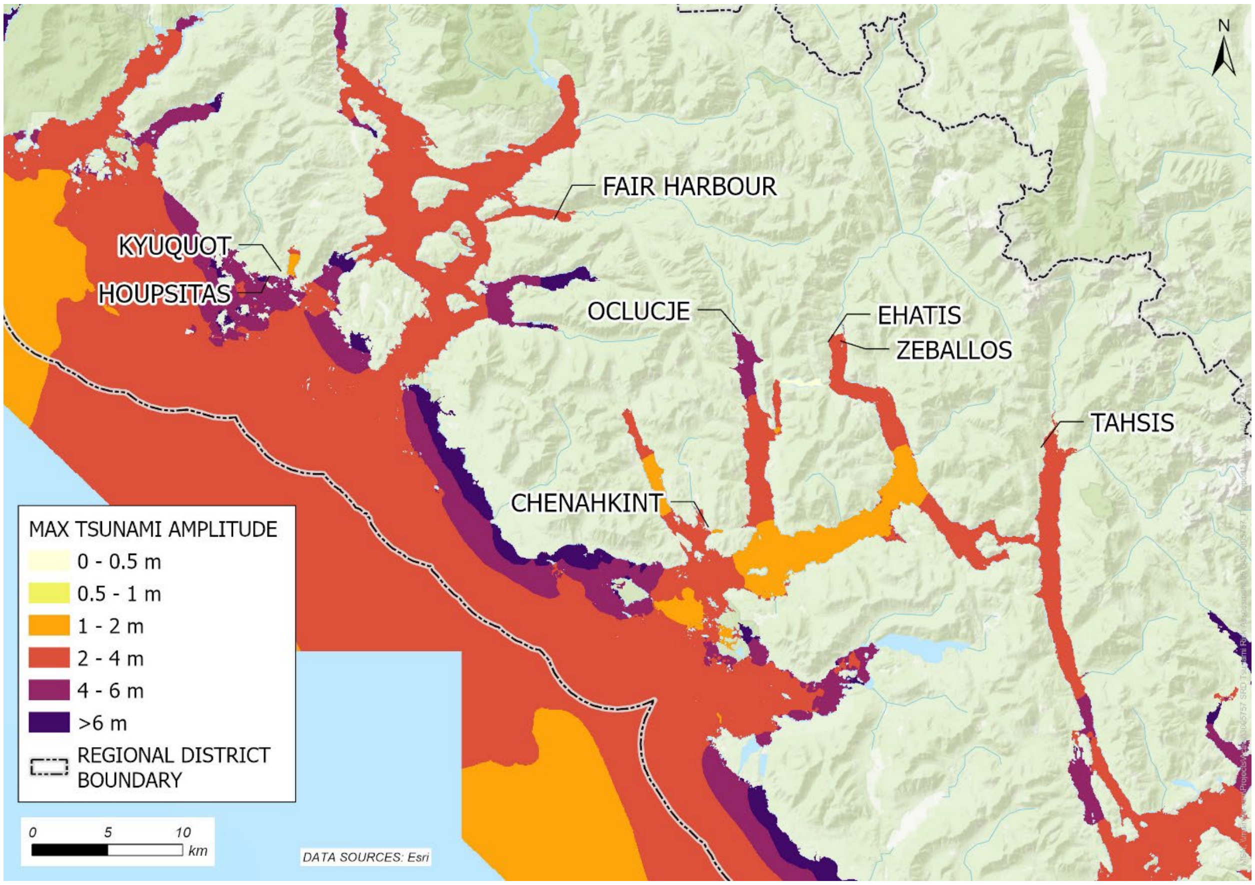

Figure 12. Maximum Cascadia tsunami wave amplitude in the vicinity of areas of interest.

Tsunami-Induced Current Velocity

Results of maximum current velocities in the vicinity of the areas of interest induced by a Cascadia tsunami are shown in Figure 13. Fast current velocities are hazardous to navigation (e.g., greater than 3 knots) and are predicted along the entire stretch of open coast shown. Particularly fast currents and hazardous currents are predicted in Gillam Channel at the entrance of Esperanza Inlet and in the Kyuquot area due to shallower depths, as well as the narrow constrictions between the many islands in the case of the latter.

Further inside Kyuquot Sound and Esperanza Inlet, tsunami-induced current velocities are slower due to greater water depths (e.g., greater than 100 m), except for constrictions and passages in which moving water converges and accelerates. As an example, the latter include Tahsis Narrow and the passage past Karouk Island leading to Fair Harbour.

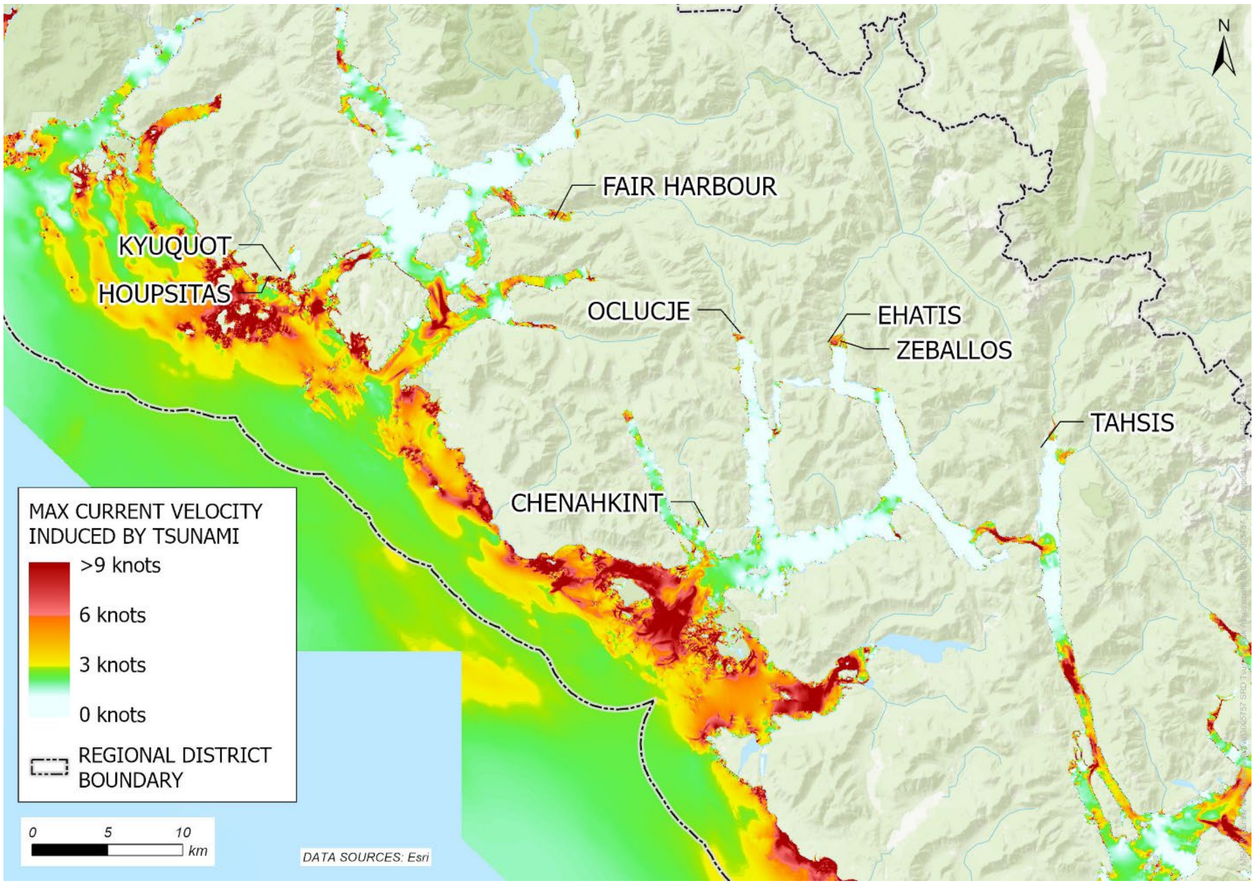

Figure 13. **Maximum current velocity in the vicinity of areas of interest induced by a Cascadia tsunami.**

3.2.3.2 Alaska Tsunami

Figure 14 shows the general influence in the Pacific Ocean of a tsunami originating from the Alaska Aleutian Islands Subduction Zone. The orientation of this fault results in the main direction of the tsunami waves aimed towards the BC coast and of the west coast of the United States. The earthquake that generated the March 27, 1964, Alaska tsunami occurred around 6:30 PM Pacific daylight saving time (3:30 AM Greenwich mean time on the 28th) and reached Vancouver Island within approximately 3 – 4 hours after the earthquake. At the time of arrival, the stage of the tide was approximately 3.0 m with respect to CD which is approximately 0.5 m lower than HHWMT in the study area.

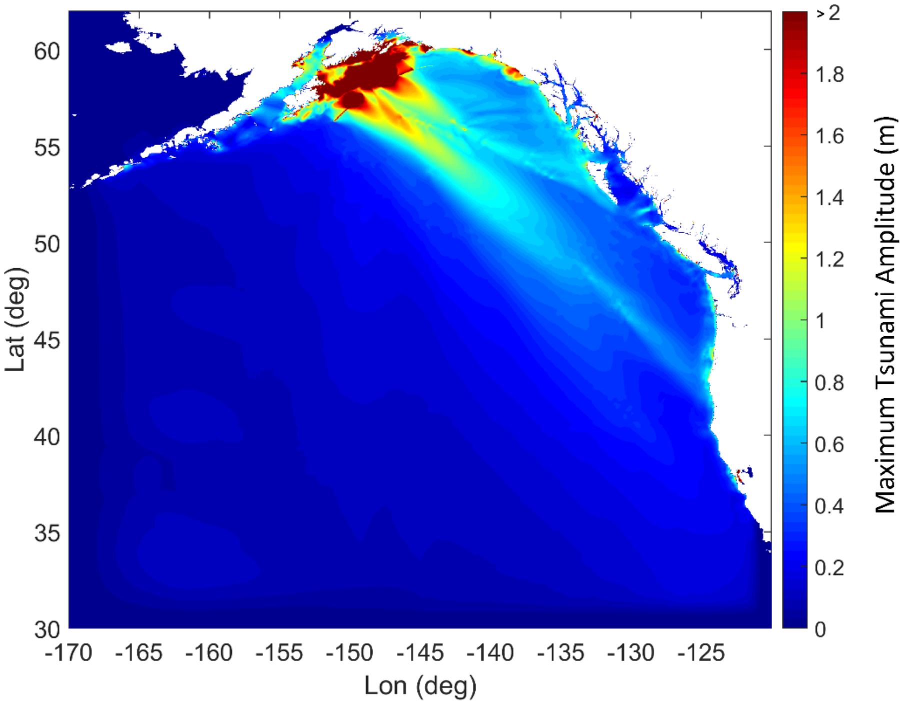

Figure 14. Maximum amplitude of Alaska tsunami in Northeast Pacific Ocean.

Tsunami Amplitude

There are no records of observed water levels (e.g., time series) within the study area at the time of the 1964 Alaska tsunami. Therefore, direct comparison of tsunami amplitude predicted by the numerical model against actual measurements is not possible. The tidal gauge at Tofino was operational at the time of the tsunami, recording a maximum wave amplitude of about 1 m (Rabinovich *et al.*, 2019). However, being outside of the study area the model results computed at that location are too coarse to perform a meaningful comparison. Therefore, model results are substantiated according to first-hand experiences of Indigenous community members, as presented below.

The maximum tsunami amplitude associated with an Alaska tsunami affecting the northwest coast of Vancouver Island is shown in Figure 15. In contrast to the Cascadia tsunami, for which the largest amplitude is generally predicted on the open coast, the largest amplitude in the case of the Alaska tsunami occurs at the head of inlets. This is particularly observed at Tahsis, Fair Harbour, and Gold River (Port). The larger amplitude at Gold River (Port), in conjunction with the stage of tide, corroborates with first-hand experiences.

First-hand Experience

From an interview with Ray Williams (Mowachaht/Muchalaht First Nations):

Ray is now 80 years old. During the 1964 Tsunami, Ray was working as a logger in Gold River and Yuquot. The waves bypassed Yuquot and shot up the inlet towards Tahsis. The bunkhouses, which were on 4-foot spruce logs, got engulfed in water in Gold River. He was 14 at the time.

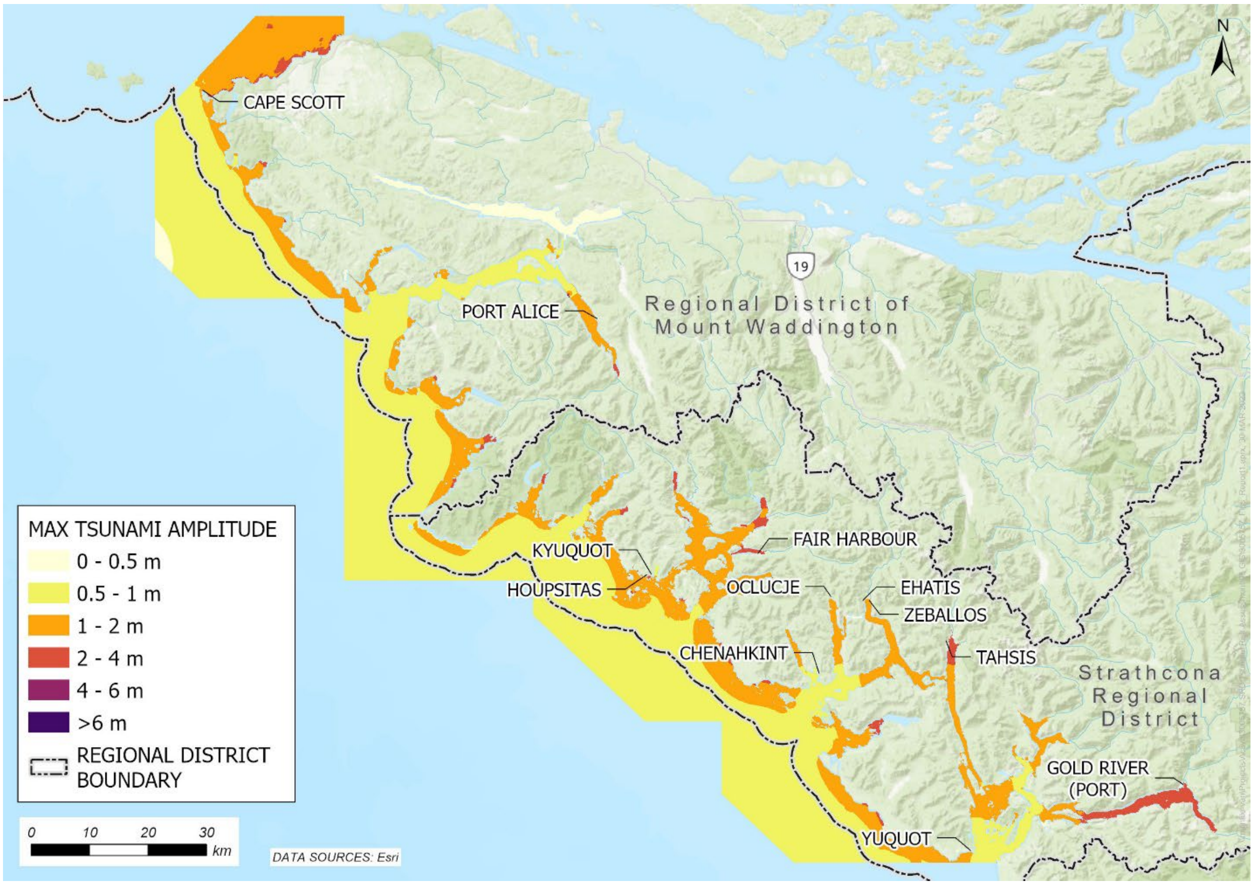

Figure 15. Maximum Alaska tsunami wave amplitude in the broader study area

In comparison to other areas in Quatsino Sound, such as Holberg Inlet and the Hamlet of Quatsino, the Village of Port Alice can be more affected by an Alaska tsunami. Waves are predicted to range from 1 to 2 m in amplitude at the village while it can exceed 2 m at the head of Neroutsos Inlet.

First-hand Experience

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

Model results of maximum tsunami amplitude in the vicinity of the areas of interest are shown in Figure 16. These results show that some areas are less affected by an Alaska tsunami where waves are not predicted to not exceed 1 m. This is the case of the Indigenous community of Chenahkint located near Queen’s Cove in Esperanza Inlet, where little inundation is predicted to occur resulting from an Alaska tsunami.

First-hand Experience

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

“The tsunami bypassed some areas… Queens Cove is right on the beach, but they were not affected in any devastating way.” Referring to Chenahkint at Queens Cove.

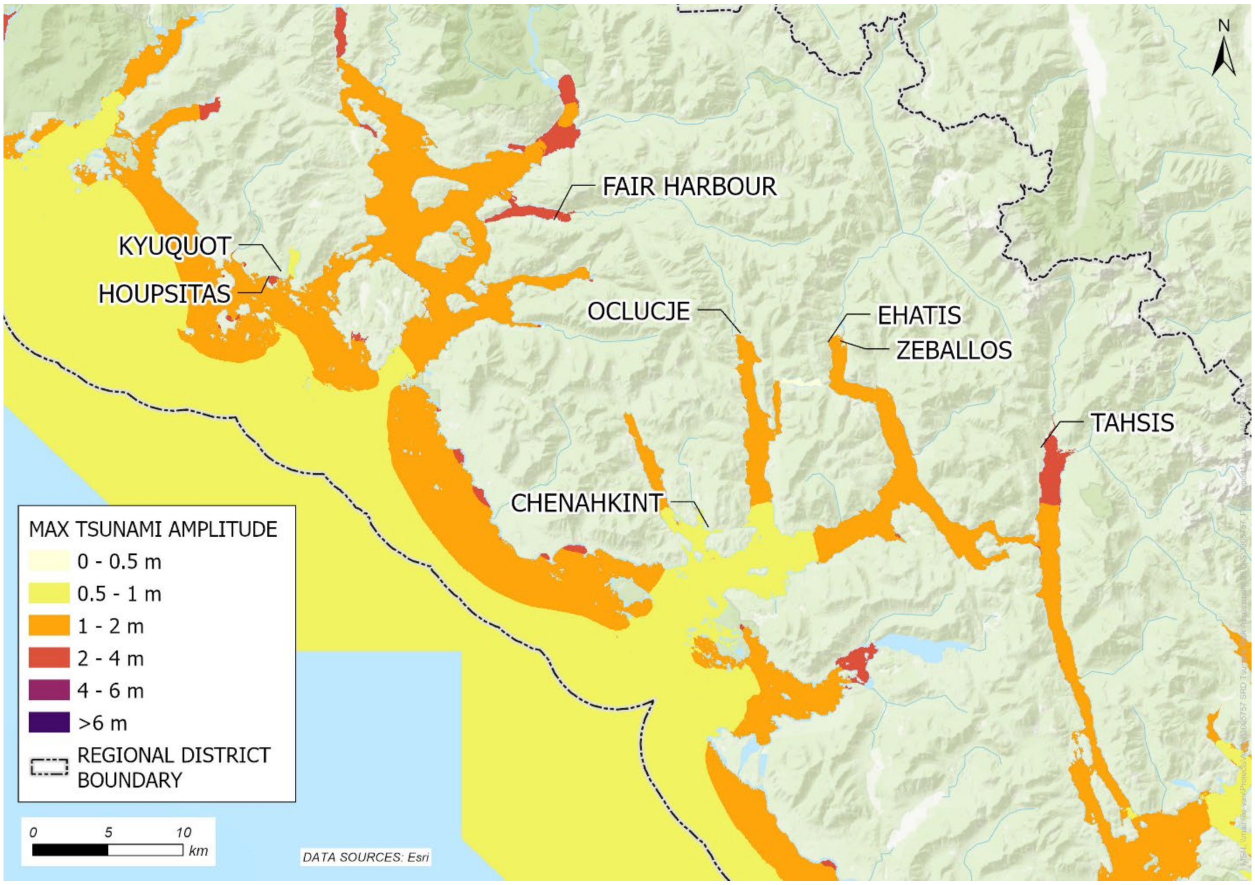

Figure 16. Maximum Alaska tsunami wave amplitude in the vicinity of areas of interest.

Tsunami-Induced Current Velocity

Results of maximum current velocities in the vicinity of the areas of interest induced by an Alaska tsunami are shown in Figure 17. While considerably slower than the velocities predicted for the Cascadia tsunami (Figure 13), fast and hazardous velocities can still occur, especially in narrow constrictions, such as Tahsis Narrow, in areas of relatively shallower depths such as Gillam Channel at the entrance of Esperanza Inlet, and in the passages between small islands as in Kyuquot.

In addition to putting mariners on the water at risks, fast current speed also puts at risk marina users as marine infrastructure can be damaged, as well as to anyone close to the water's edge and who may fall into the moving water. For instance, original bridges at Fair Harbour have been severely damaged as a result of the Alaska tsunami of 1964 which required their reconstruction (Benson *et al.*, 1997).

First-hand Experience

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

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

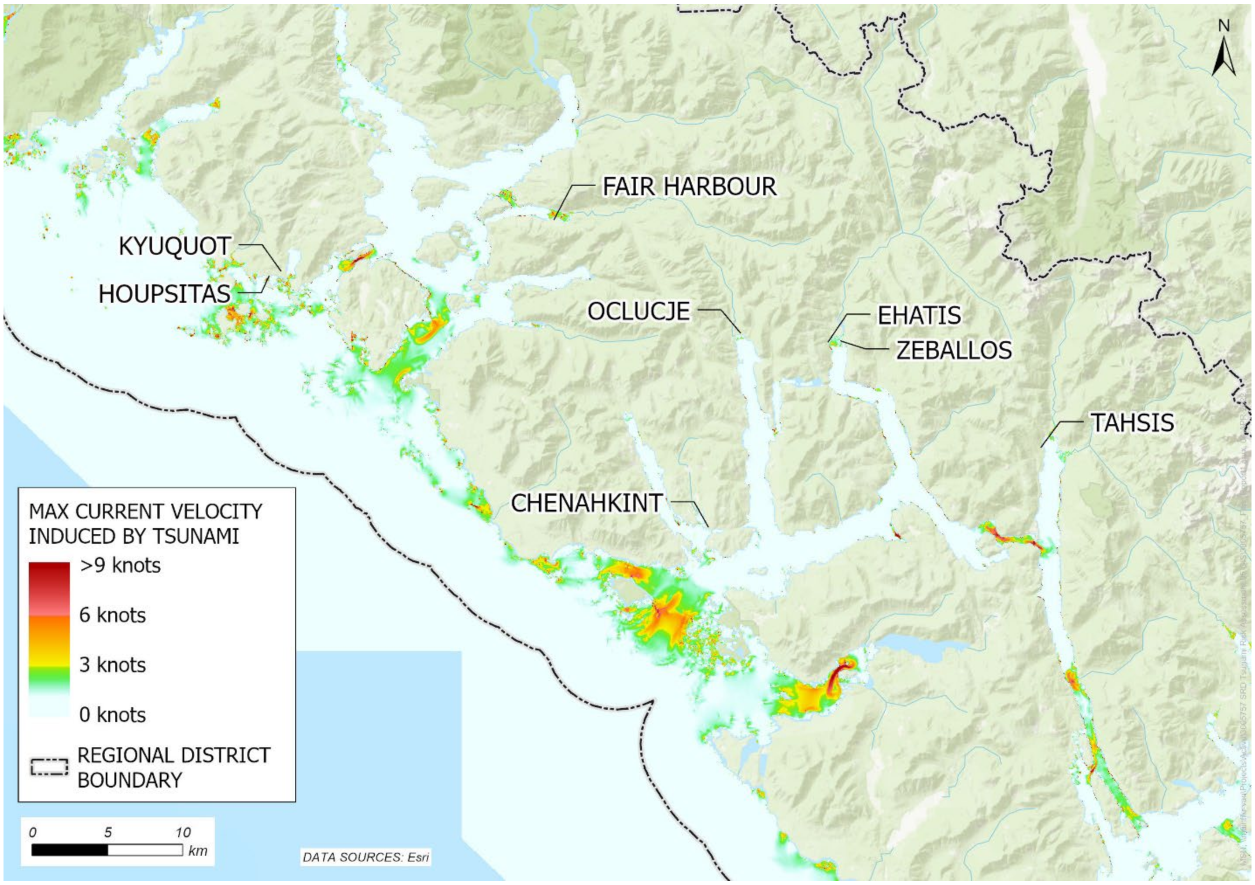

Figure 17. Maximum current velocity in the vicinity of areas of interest induced by an Alaska tsunami.

3.2.3.3 Influence of Sea Level Rise

Additional modelling results provided in Appendix D suggest that the propagation of tsunamis off land is not meaningfully influenced by sea level rise. In other words, the amplitudes of the tsunami waves in the ocean are expected to be similar in the future. However, because of the greater inundation depth associated to sea level rise, the behaviour of tsunami waves as they propagate overland will vary. Analysis of the model results at discrete locations in selected communities shows that, for the Cascadia tsunami, the increase in future inundation levels is greater than the increase in sea level, as discussed in Section 4.4. For the Alaska tsunami on the other hand, the increase in future inundation levels is approximately the same as the increase in sea level.

The overwater current velocities induced by a tsunami are not expected to be considerably affected by sea level rise, although deeper water has a tendency to reduce current velocities. The influence of sea level rise on flow velocities inland was not assessed.

3.3 Hazard Mapping

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

Several scales were considered for the mapping, from a *regional* 1:100,000 scale (approximately 26 km by 34 km on each map sheet) to show general hazard information over a larger area, down to a *local* scale of 1:5,000 (approximately 1.8 km x 3.1 km on each map sheet) to shown additional details. An intermediate *area* scale of 1:25,000 (approximately 6 km by 9 km on each map sheet) was also considered in some instances. Overwater hazards were mapped at all scales while inundation was only mapped at the 1:5,000 scale and at the locations prioritized by the Advisory Group. The mapping process and map series are described below, including the layouts for each type of map. All maps produced as part of this project were delivered in PDF format for printing on a page size of 11” x 17”.

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

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

3.3.1 Coordinate Reference System

The projection and horizontal coordinate systems of all GIS information and maps produced as part of this project consist of Universal Transverse Mercator (UTM) Zone 9. The horizontal datum is North American Datum 1983 Canadian Spatial Reference System (NAD83 CSRS). Units are metres.

The vertical datum for the project is Canadian Geodetic Vertical Datum of 2013 (CGVD2013). It should be noted however that tsunami amplitudes reported on the maps and in this report are with respect to a reference plane corresponding the water level considered for the tsunami simulations.

3.3.2 Processing of Model Results

Model output data from ONC was provided in geographic coordinates (latitude and longitude). Information included maximum water surface elevation in metres above the model's reference plane (i.e., still water level) and maximum tsunami-induced current velocity at any given moment in a simulation. This information was imported to GIS for map production and use in other GIS applications. Tsunami wave amplitude being defined as the vertical distance between the crest of a tsunami wave and a reference plane consisting of the still water level (e.g., water level without the influence of the tsunami), it is equivalent to the elevation of the water surface above this same reference plane.

Coordinates were converted to UTM, and null data points were filtered out. Points, or grid cells where the increase in the water surface elevation induced by a tsunami is less than 0.01 m were removed from the analysis. Furthermore, points where the calculated current velocity is less than 0.01 m/s were also removed. Point data was interpolated to gridded raster format. The processed results were clipped to avoid overlap between information of different resolutions, with priority given to higher-resolution data. Additional adjustments were required to ensure a smooth transition between data layers. Processed results were reviewed at the appropriate mapping scale to remove information at locations where the confidence in the model results is lower. This mainly includes remote areas where topographic and/or bathymetric information is insufficient to adequately model tsunami propagation.

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

3.3.3 Overwater Hazard Maps

Maps of maximum tsunami amplitude and maps of maximum tsunami-induced current velocity were produced based on results of simulations for current-day sea level, for both Cascadia and Alaska tsunamis.

A set of 15 map sheets at a 1:100,000 regional scale depicts the entire study area (Figure 18). Twenty-five map sheets combining a 1:25,000 area scale and a 1:5,000 local scale provide more detailed information for priority areas (Figure 19).

No safety factor nor freeboard[8] was applied to the results plotted on the overwater hazard maps. Any inundation visible on these maps, or in the underlying data, corresponds to the inundation as approximated by the numerical model without any adjustment and should not be relied upon without further site-specific assessment. The delineation of the flooding shown on the inundation maps introduced below requires careful interpretation of the model results and includes the application of a safety factor.

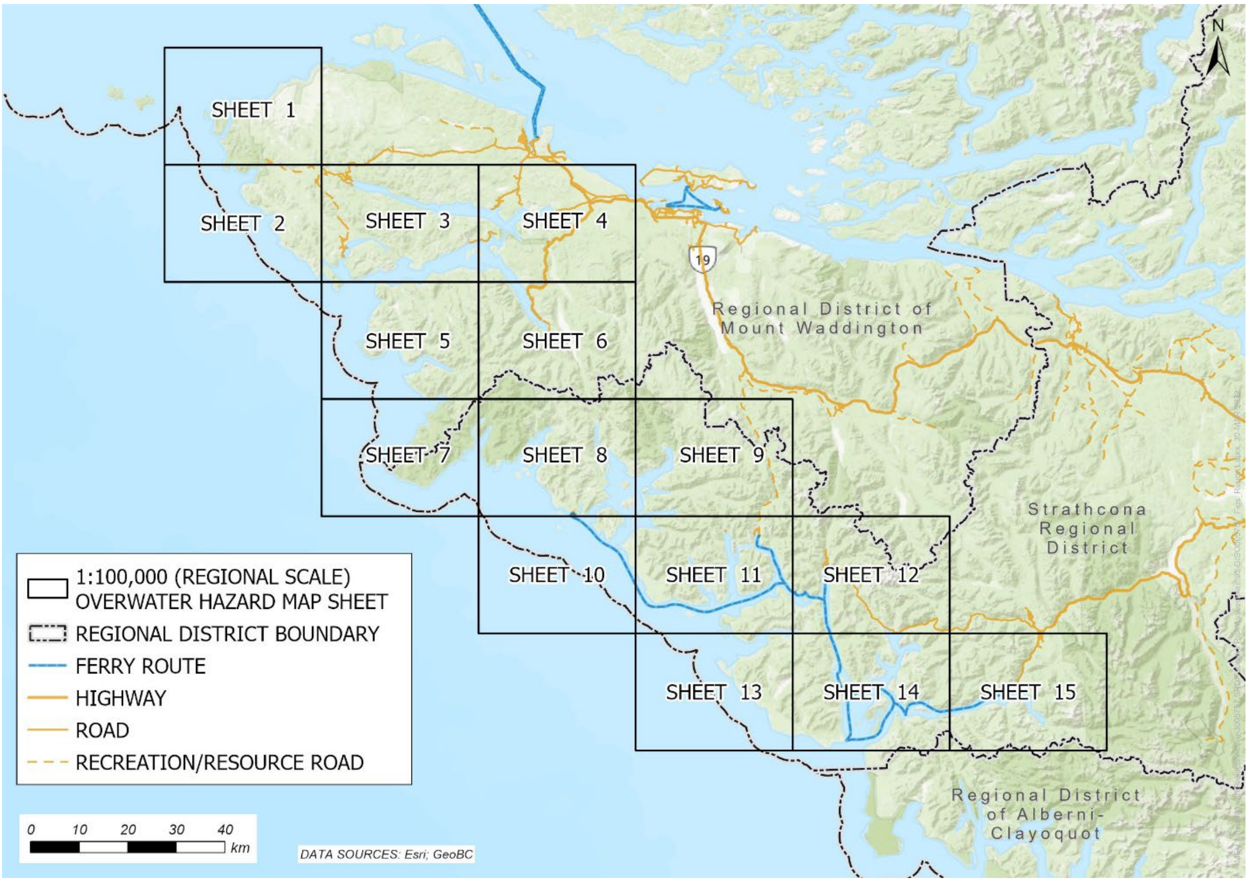

Figure 18. Regional (1:100,000) scale tsunami hazard map sheet layout.

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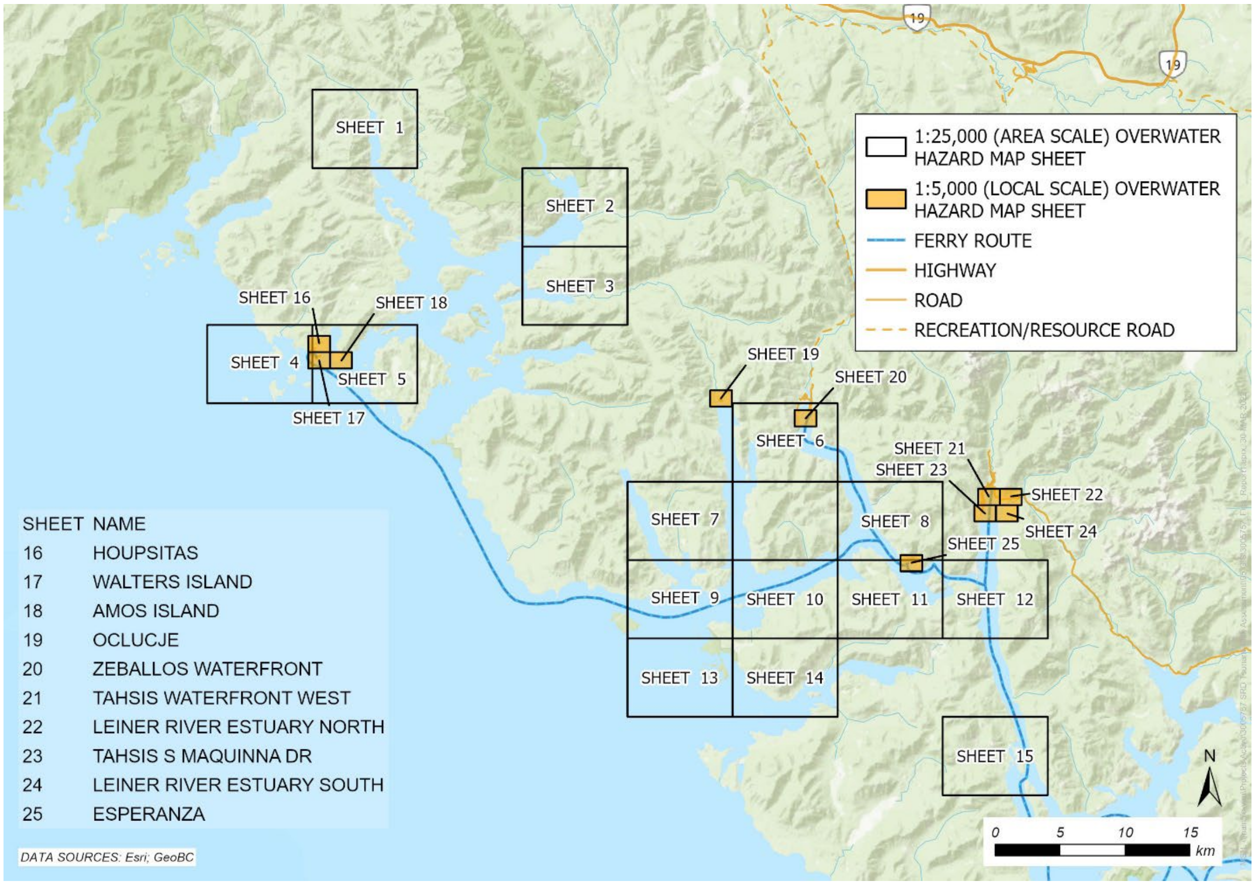
[8] A vertical distance added to the estimated inundation level to accommodate potential local wave effects and floating debris hazard. The selection of such distance also considers the risks implications associated to the hazard exceeding the refuge elevation.



SHEET	NAME
16	HOUPSITAS
17	WALTERS ISLAND
18	AMOS ISLAND
19	OCLUCJE
20	ZEBALLOS WATERFRONT
21	TAHSIS WATERFRONT WEST
22	LEINER RIVER ESTUARY NORTH
23	TAHSIS S MAQUINNA DR
24	LEINER RIVER ESTUARY SOUTH
25	ESPERANZA

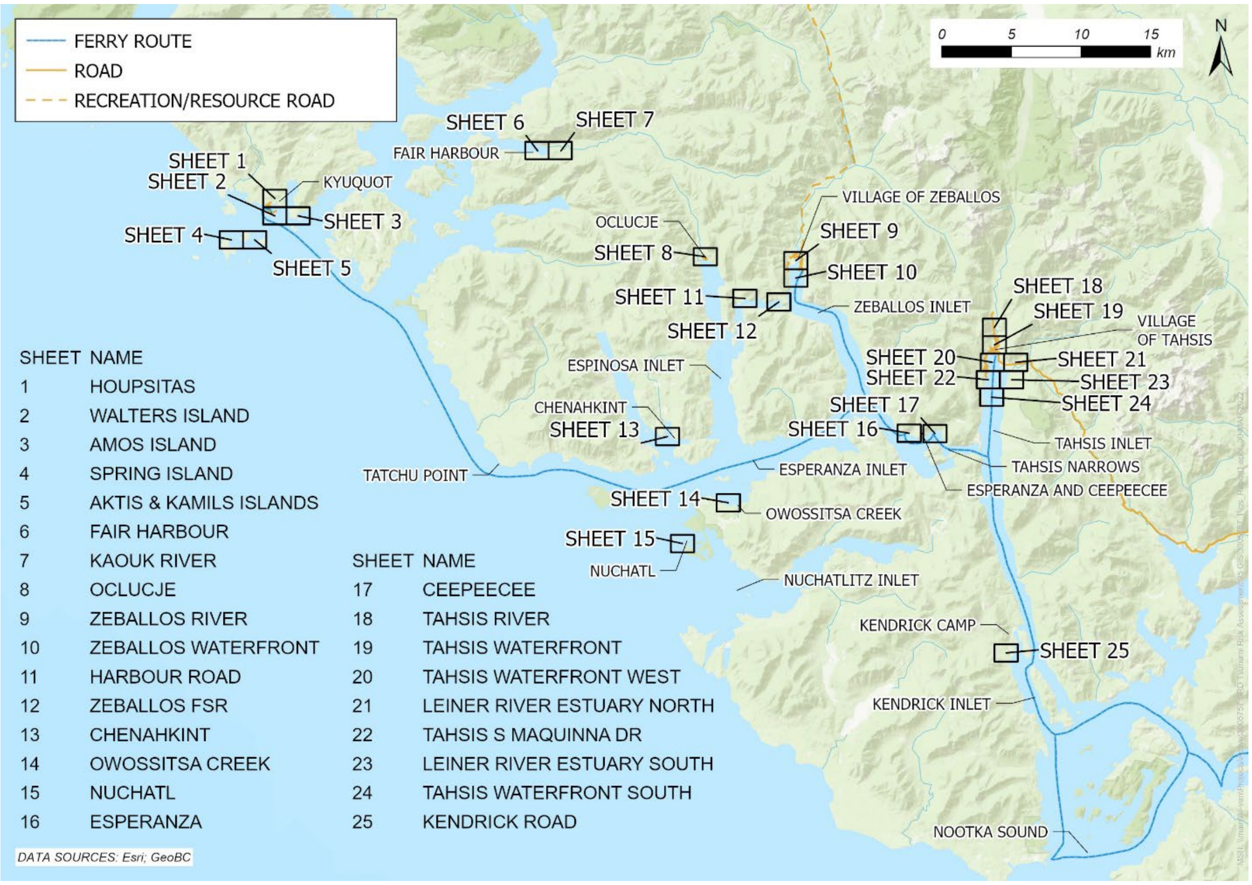
DATA SOURCES: Esri; GeoBC

Figure 19. Area (1:25,000) scale and local (1:5,000) scale tsunami hazard map sheet layout.

3.3.4 Overland Inundation Maps

Overland inundation (i.e., flood) maps were produced for both Cascadia and Alaska tsunamis to show the extent of tsunami hazard inland. The inundation mapped corresponding to simulations based on current-day sea level.

Inundation is mapped for a total of 25 priority areas selected in consultation with the Advisory Group. These areas are displayed in Figure 20 along with their identifying names. The procedure followed to define the extent of inundation is presented below, as well as the assessment performed for selecting the safety factor included in the analysis. All inundation maps were produced at a local scale of 1:5,000.



SHEET	NAME
1	HOUPSITAS
2	WALTERS ISLAND
3	AMOS ISLAND
4	SPRING ISLAND
5	AKTIS & KAMILS ISLANDS
6	FAIR HARBOUR
7	KAOUK RIVER
8	OCLUCJE
9	ZEBALLOS RIVER
10	ZEBALLOS WATERFRONT
11	HARBOUR ROAD
12	ZEBALLOS FSR
13	CHENAHKINT
14	OWOSSITSA CREEK
15	NUCHATL
16	ESPERANZA

SHEET	NAME
17	CEEPEECEE
18	TAHSIS RIVER
19	TAHSIS WATERFRONT
20	TAHSIS WATERFRONT WEST
21	LEINER RIVER ESTUARY NORTH
22	TAHSIS S MAQUINNA DR
23	LEINER RIVER ESTUARY SOUTH
24	TAHSIS WATERFRONT SOUTH
25	KENDRICK ROAD

Figure 20. Local (1:5,000) scale tsunami inundation map sheet layout.

3.3.4.1 Inundation Extents

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

Bellow is the general procedure followed to define inundation extents:

1. Spatial results of maximum water surface elevation above the model's reference plane (HHWMT) are increased by a safety factor of 50%. In simple terms, the maximum tsunami amplitude is multiplied by a factor of 1.5.
2. Factored results of maximum water surface elevation are converted to the CGVD2013 vertical datum based on the average height of HHWMT above CGVD2013 across the modelled area.
3. Zones of approximately constant water surface elevation (rounded to the nearest 0.5 m) are defined to project the water surface further inland to intersect the 2 m resolution DEM.
4. Inundation extents are interpolated in a horizontal plane to obtain a smooth delineation of the estimated flooding.
5. Inundation extents are reviewed and adjusted manually to ensure consistency with the local topography.

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

3.3.4.2 Safety Factor

A safety factor is included for the mapping of inundation extents and for defining inundation levels for emergency planning. The safety factor accounts for the uncertainties in the analysis, which include but are not limited to the following.

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

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

There are no federal nor provincial guidelines for the selection of a safety factor for tsunami inundation. Three approaches were investigated for that purpose, as listed below.

1. The American Society of Civil Engineers (ASCE) Tsunami Loads and Effects design standard (ASCE, 2016) is a design standard for the elaboration of criteria for the design of buildings exposed to tsunamis. The standard defines the *Refuge Design Inundation Elevatio*n as 130% of the maximum inundation elevation with respect to a geodetic datum, as specified by a site-specific assessment (e.g., modelling). In general terms, this safety factor corresponds to a 30% increase of the vertical distance between the maximum water surface predicted by the numerical model and the reference geodetic datum.

   It should be noted that for defining the *Minimum Refuge Elevation* for occupants of a building, the standard specifies the following freeboard. Refuge floors shall be located not less than the greater of 3.1 m (10 ft) or one-story height above the refuge design inundation elevation. No freeboard is included in the inundation extents and levels defined as part of this assignment.
2. A 50% increase of the vertical distance of the maximum water surface above a reference plane corresponding to the still water level of the numerical model (i.e., water level without any effects induced by the tsunami). The rationale for this approach is that only the vertical component above the astronomical tide level is increased, as the tide component can be predicted more accurately in comparison to the increase in water level (i.e., tsunami amplitude) estimated by the numerical model.
3. A 50% increase of the vertical distance of the maximum water surface above a reference plane corresponding to a geodetic datum. This approach is theoretically the most conservative and has been applied in previous tsunami studies.

A comparison of the approximate inundation extents calculated according to the three approaches described above is provided in Figure 21 and Figure 22 at the example locations of Tahsis and Houpsitas, respectively. Approximate extents without any safety factor are also shown for comparison. In steep areas in general, the extent of inundation is reasonably the same for all approaches, although the inundation level might vary. In flatter areas, where the extent of inundation is more susceptible to fluctuations in the water level, the third approach results in slightly greater inundation extents in comparison to the other two approaches. The first and second approaches result in relatively similar extents, but the extents related to the latter tend to be greater.

The second approach was ultimately selected for the analysis. This selection is mainly based on the rationale that a safety factor should practically be applied to the vertical components of the inundation that has uncertainties associated to it, which in this case is the predictions by the numerical model. Furthermore, this approach resulted in inundation extents similar to the first approach, which is based on a design standard developed for a related application.

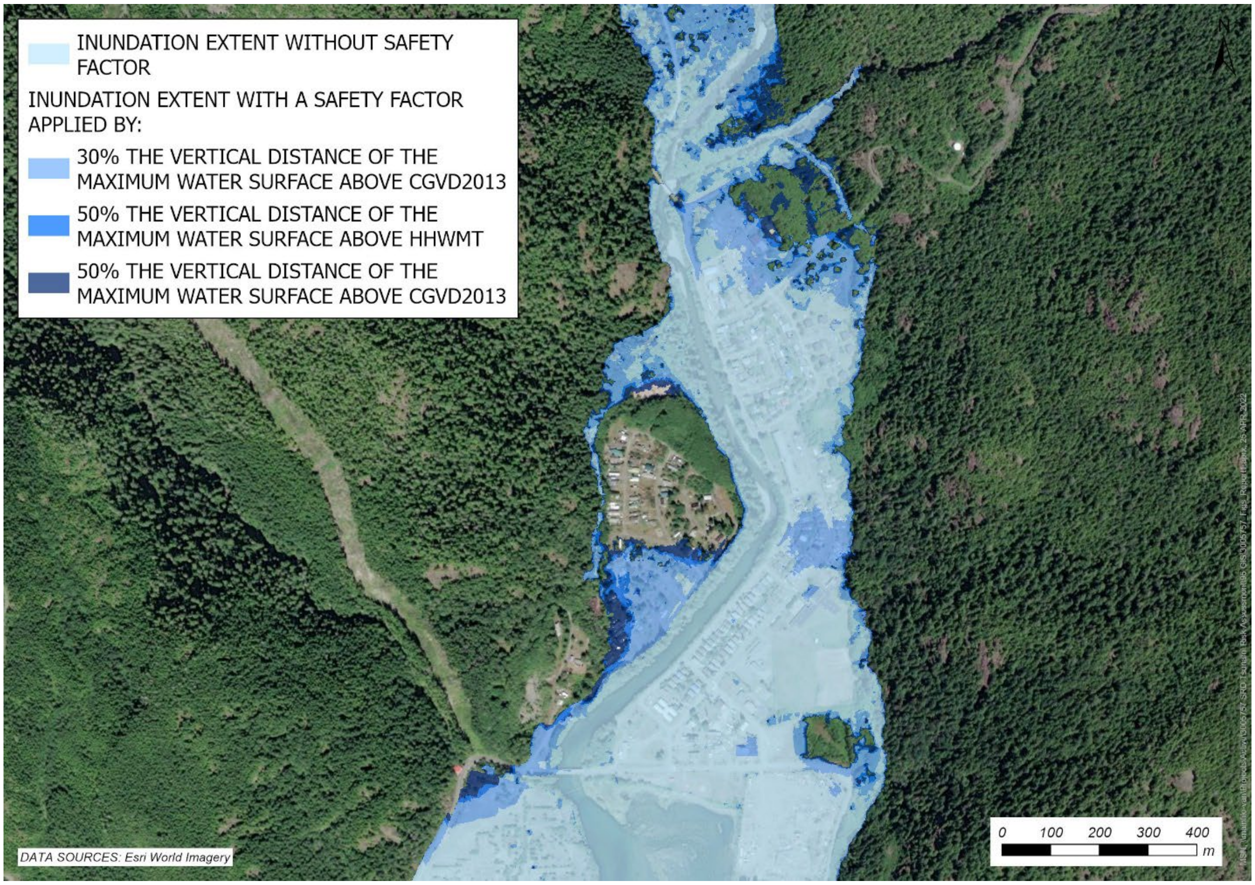
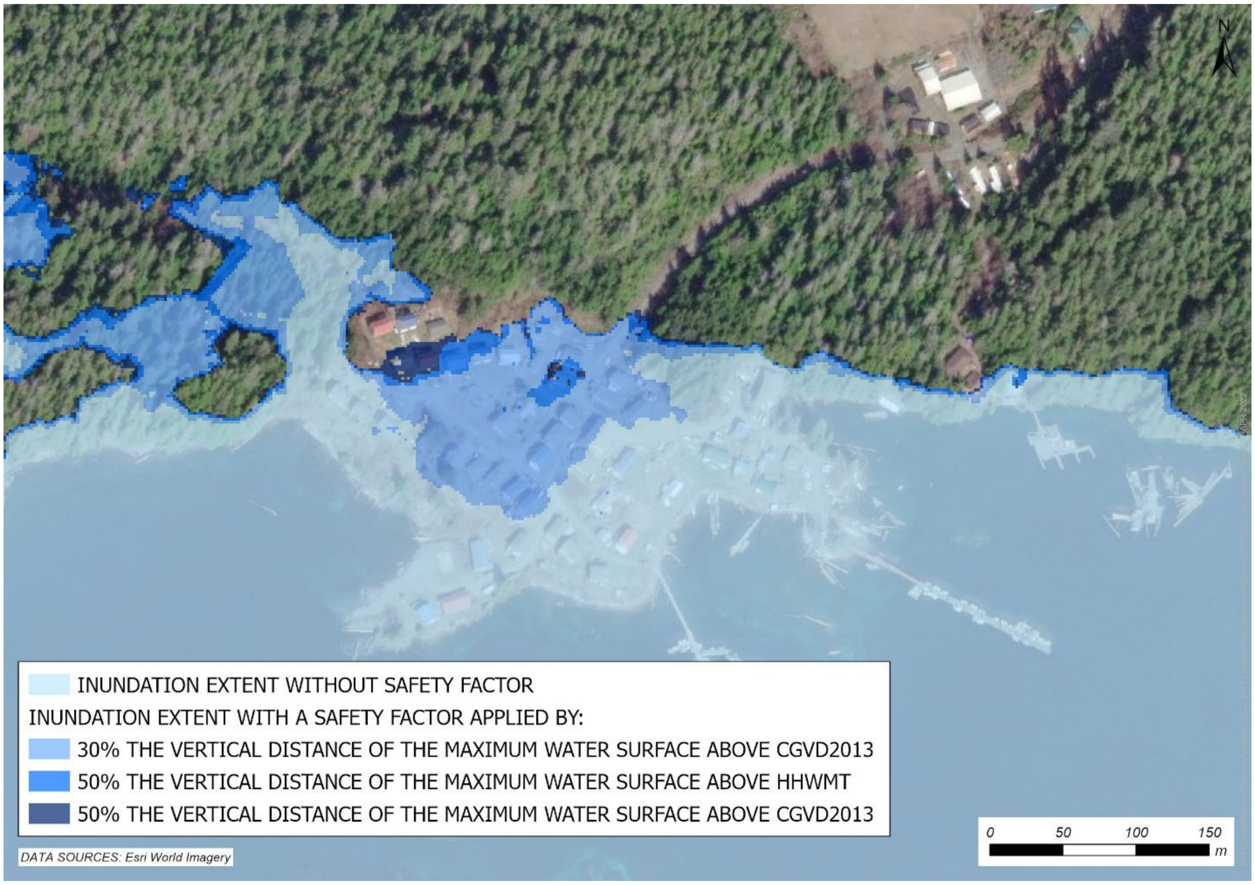


Figure 21. **Comparison of approaches considered for application of safety factor to results of inundation. Location of Tahsis as example.**



DATA SOURCES: Esri World Imagery

Figure 22. Comparison of approaches considered for application of safety factor to results of inundation. Location of Houpsitas as example.

3.4 Modelling and Mapping Limitations

It is important to take into consideration the limitations of the technical analysis when interpreting the results of the risk assessment for the purpose of updating emergency plans. These limitations may be accounted for by adopting plans and measures that tend to be conservative. The following aspects should be kept in mind when interpreting the study findings.

- The study results are based on a limited number of tsunami scenarios for subduction earthquakes with specific seismic parameters. While these scenarios are considered severe and known to be the worst scenarios readily available for analysis, the possibility of stronger earthquakes should not be ruled out unless supported by scientific research.
- Numerical simulations were undertaken at a resolution of 10 m and such simulations may not capture effects that would take place at a smaller scale (i.e., over distances shorter than 10 m). Such effects include localized runup, flow around obstacles, and overflow of solid features. The definition of any tsunami effects occurring at a scale smaller than the grid resolution of 10 m require additional assessment.

- No safety factor nor freeboard was applied to the results plotted on the overwater hazard maps of maximum tsunami amplitude and maximum tsunami-induced current velocity. Any inundation visible on these maps, or in the underlying data, corresponds to the inundation as estimated by the numerical model without any adjustment and should not be relied upon without further site-specific assessment. The delineation of the flooding shown on inundation maps requires careful interpretation of the model results in conjunction with the local topography and includes the application of a safety factor.
- For local 1:5,000 scale maps, the mapping accuracy is limited by the accuracy of the available orthoimagery[9] shown on the maps (i.e., basemap). Horizontal shifts between mapped information and the underlaying basemap vary approximately from 5 metres up to 20 metres.
- Service roads and/or resource roads shown on maps may be decommissioned and overgrown with vegetation inhibiting their use. The status of such roads should be reviewed as part of evacuation planning. Furthermore, maps may not show all roads and pathways which may be considered for evacuation planning.

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[9] Orthoimagery is aerial photography or satellite imagery geometrically corrected (i.e., orthorectified) such that the scale is uniform across the image.

4 RISK ASSESSMENT

With a focus on life safety, the community level risk assessment presented in this section leverages on tsunami hazard analysis and mapping to identify potential risks to people and assets. The information presented herein informs emergency managers, risk assessors, land use planners, as well as the public to help individuals understand their personal and community's risk.

The assessment of the risk is limited to the flood hazard reported on the local 1:5,000 scale inundation maps, which layout is shown in Figure 20. *Assets at Risk* maps that highlight roads, buildings, and critical assets exposed to tsunamis are described in Section 4.1. Risk associated to overwater tsunami hazards identified in this study is not discussed in detail. However, high-level risk to navigation and marine infrastructure is briefly discussed, where applicable.

Section 4.2 provides some general distinction between local and distant tsunamis as the development of emergency management plans may benefit of having source-designated evacuation zones, evacuation routes, and assembly areas.

To better understand the destructive nature of tsunamis and their potential for endangering human life, Section 4.3 describes the effects of tsunamis on structures and on people caught in tsunami flow.

Results of the risk assessment are presented in Section 4.4. As explained in Section 3.2.1.1 above, residual risk remains as paleo-seismological evidence suggests that the CSZ has the potential for generating stronger earthquakes than the one considered for this study. Furthermore, the risk assessment is based on the tsunami flood hazard associated to current-day sea level and the mapped flood extents correspond to an inundation level for emergency planning. Model simulations including sea level rise were performed as part of this study, although these results have not been mapped at this stage. Tsunami risks will increase in the future as sea level rises, which should be considered for longer-term development and emergency planning. Inundation levels for emergency planning considering sea level rise are reported for general guidance only.

4.1 Mapping of Assets at Risk

Assets at risk maps which form the basis of the risk assessment were produced to identify the potential risk to people, roads, and buildings, as well as assets critical for response and recovery. The latter were selected based on the critical infrastructure sectors defined by the National Strategy for Critical Infrastructure (Public Safety Canada, 2009). Critical assets considered for this assessment correspond to the sectors of Transportation, Health, Safety, Energy and Utilities, Water, and Government. The categories of assets within those sectors are presented in Figure 23, along with the symbols used to identify them on the maps.

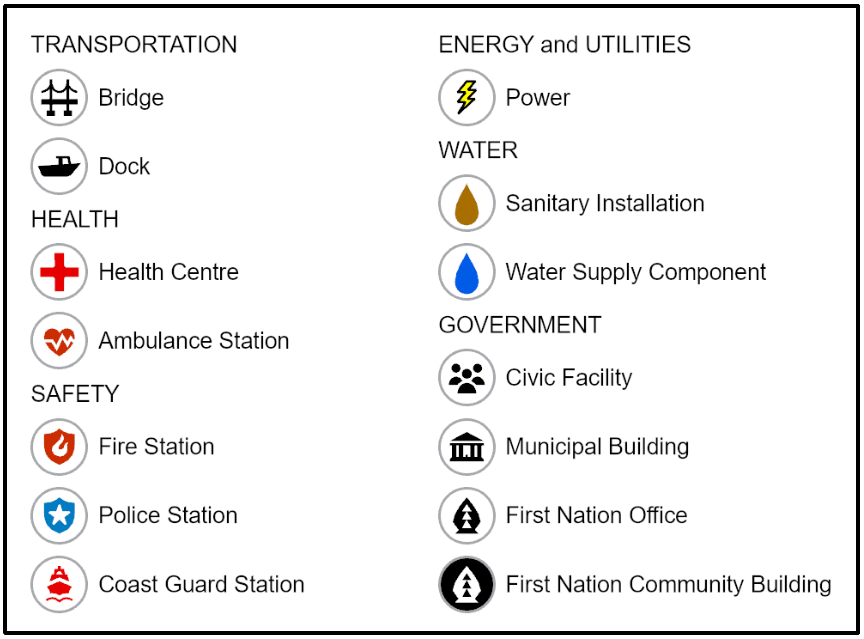

Figure 23. Categories of critical assets considered for risk assessment.

The location of roads, buildings, and assets is based on spatial datasets publicly available from the Province of British Columbia (GeoBC) and the federal government, reviewed based on the background information listed in Section 2.2. These datasets are listed below. The location of buildings was also supplemented based on the full feature LiDAR collected as part of this study.

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

Assets at risk maps are provided in Appendix G. It should be noted that these maps may not identify all buildings and assets that are exposed to tsunami hazard. Furthermore, only docks that are public or dedicated to residents are identified. Privatively owned or privately operated docks are not identified. While schools, if located sufficiently away from the flood hazard, may be important assets to provide shelter following a tsunami, they are not considered as critical infrastructure according to the National Strategy for Critical Infrastructure. Therefore, schools are not identified by a symbol on the maps but are labelled.

4.2 Local and Distant Tsunamis

According to the US Federal Emergency Management Agency (FEMA, 2019), a local tsunami is one that originates from a source that is close to the site of interest, and arrives within one hour of the triggering event. The effects of the triggering event may also be felt at the site, such as ground shaking in the case the tsunami is triggered by an earthquake. A distant tsunami is one that originates from a source that is far away from the site of interest and takes three hours or longer after the triggering event to arrive.

This assessment distinguishes between local and distant tsunamis, as the associated risk differ considerably. A local Cascadia tsunami will arrive sooner and have more adverse effects in comparison to a distant tsunami. However, the latter still poses considerable risks and are more frequent as they can originate from several subduction zones around the Pacific Ocean (see Figure 2). Furthermore, the earthquake associated with a distant tsunami will not be felt and the notification of residents and visitors will rely entirely on warning systems, which may be challenging in remote areas.

As further discussed in Section 5.2, it is generally recommended that tsunami risk reduction measures distinguish between local and distant tsunamis.

4.3 Tsunami Impacts on Life Safety and Infrastructure

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

For a person caught in tsunami flow the chance of survival is low, mainly due to the strong flow momentum and the floating debris that are often carried in the water during such event. While studies exist to evaluate human safety in flood conditions as a function of flow depth and velocity, as well as age and body characteristics (e.g., Cox *et al.*, 2010), it is conservative to consider that anyone caught in tsunami flow is likely to become a casualty.

The damage caused to buildings and infrastructure depends on tsunami flow characteristics in conjunction with structural considerations. The 2011 Tohoku Tsunami in Japan brought to light the potential such events have for causing severe damage to inland buildings and endangering human life. After this event, it was observed that multiple-storey, engineered concrete and steel buildings can also be severely damaged or destroyed (Earthquake Engineering Research Institute, 2011b) despite previous beliefs of these structures to be tsunami resistant. Figure 24 (top left) shows as example a steel frame building damaged by the 2011 Tohoku Tsunami. Furthermore, the tsunami caused the complete failure of heavy coastal protection structures specifically designed to resist tsunamis (Figure 24, bottom left). Unfortunately, these structures gave the population a false sense of safety resulting in higher casualties (Earthquake Engineering Research Institute, 2011a).

Bridges and roads, which may be damaged and/or weakened by the initial earthquake in the case of a Cascadia tsunami, are also at risk of being damaged by the subsequent tsunami. Such structure can be affected by extreme forces induced by tsunami flow as well as impacts with floating debris such boats, cars, building debris, etc. Other effects include scour of piers and abutments as well as the wash-out of asphalted surfaces. Marine infrastructure is particularly exposed to damage from tsunamis due to their proximity to the water's edge and their exposure to the full force of the tsunami.

Figure 24. Damaged infrastructure in the City of Miyako, Japan following the 2011 Tohoku tsunami (Photos: Philippe St-Germain/NHC, 2012). Top photos show damage to inland buildings, bottom left photo shows remains of tsunami protection wall, and bottom right show damage to port installations.

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

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

4.4 Community Risk Assessment

The risk assessment is divided in the following groups of communities and areas:

- Ka:'yu:'k't'h'/Che:k:tles7et'h' First Nations
- Fair Harbour
- Nuchatlaht First Nation
- Village of Zeballos
- Ehattesaht Chinehkint First Nation
- Esperanza and Ceepeecee
- Village of Tahsis and Mowachaht/Muchalaht First Nations
- Kendrick Camp

For each group the exposure to Cascadia and Alaska tsunamis was assessed and a summary of exposure for buildings and roads is tabulated. It should be noted that the total number of buildings reported corresponds to the total number of buildings on a particular map sheet and may not represent the total buildings in a community or area. Also, the impact to pedestrian walkways and trails is not discussed. Results of the risk assessment for each of the above groups are presented in the following subsections.

To support emergency planning, a summary of the general tsunami inundation levels and tsunami arrival times at main areas are provided in Table 5. The inundation levels for emergency planning reported include a safety factor to account for the uncertainties of the analysis and are representative of one general area. This general information should only be used for high-level planning, as tsunami inundation level can vary over small distances as a function of local topography. It should be noted that inundation levels reported do not include any freeboard to define safe refuge elevation.

Inundation levels for emergency planning that account for sea level rise are also reported and should be referred to as general guidance only. Results suggest that while future inundation levels for the Alaska tsunami are higher by a vertical distance approximately equal to the projected relative sea level rise of 1.2 m for the study area (see Section 3.2.1.2), the future inundation levels for the Cascadia tsunami are generally higher by a vertical distance greater than the projected relative sea level rise.

Lastly, it is very important to note that the tsunami arrival time is defined as the time of the first maximum of the tsunami waves (Intergovernmental Oceanographic Commission, 2019) and that flooding may begin before this moment is reached. Further assessment of the modelling results would be required to better understand the progression of the estimated inundation over time.

Table 5. General tsunami inundation level for emergency planning and arrival times at selected locations.

Area	Cascadia Tsunami			Alaska Tsunami		
	Arrival Time[1]	Inundation Level for Emergency Planning[2] (CGVD2013)		Arrival Time	Inundation Level for Emergency Planning (CGVD2013)	
		Current-day	Year 2100		Current-day	Year 2100
Houpsitas	0h25m	12.4 m	13.7 m	3h04m	4.7 m	6.0 m
Fair Harbour	0h45m	6.9 m	7.9 m	3h18m	5.1 m	6.4 m
Oclucje	0h38m	9.2 m	10.9 m	3h20m	3.4 m	4.8 m
Village of Zeballos	0h46m	6.8 m	8.7 m	3h31m	3.9 m	5.1 m
Chenahkint	0h35m	5.8 m	7.6 m	3h12m	2.8 m	4.0 m
Village of Tahsis	0h54m	7.5 m	8.8 m	3h41m	5.0 m	6.2 m
Tahsis River	0h54m	6.9 m	8.2 m	3h41m	4.9 m	6.1 m

Notes:

1. Arrival time is defined as the time of the first maximum of the tsunami waves (Intergovernmental Oceanographic Commission, 2019) and flooding may begin before this moment is reached.
2. The inundation level for emergency planning includes a safety factor (see Section 3.3.4.2) and accounts for the local subsidence associated to the triggering earthquake, as applicable. Freeboard is not included. The location where the inundation level was determined generally corresponds to the location of maximum runup, except for Fair Harbour, where the inundation level is higher towards the Kaouk River estuary to the east.

4.4.1 Ka:’yu:’k’t’h’/Che:k:tles7et’h’ First Nations

Background

Located on the outer coast of Kyuquot Sound, Ka:'yu:'k't'h'/Che:k:tles7et'h' First Nations are an amalgamation of two nations. Their traditional territory stretches from Porritt Creek, north of Nootka Sound, to Solander Island at the tip of Brooks Peninsula. Their current community is Houpsitas, located in Kyuquot. The 585 citizens under the Maa-nulth treaty are self-governed and are a member of the Nuu-chah-nulth Tribal Council (NTC), which consists of 14 Indigenous communities along the western portion of Vancouver Island. Kyuquot is only accessible by float plane or boat, including a water taxi service from Fair Harbour.

Risk Analysis

The mapping of assets at risk for the Ka:'yu:'k't'h'/Che:k:tles7et'h' First Nations covers the five map sheets listed in Table 6. The table provides a summary of the number of buildings and length of road estimated to be exposed to both tsunamis.

Table 6. Summary of exposed buildings and roads for Cascadia and Alaska tsunamis in Kyuquot.

Map Sheet	Total Buildings on Map Sheet	Cascadia Tsunami		Alaska Tsunami	
		Buildings Exposed	Length of Road Exposed[1] (km)	Buildings Exposed	Length of Road Exposed (km)
1. Houspitas	57	44	1.04	9	0.27
2. Walters Island	28	26	0.00	22	0.00
3. Amos Island	1	1	0.00	1	0.00
4. Spring Island	0	0	0.09	0	0.01
5. Atkis & Kamils Islands	4	4	0.00	0	0.00

Notes:

1. Any impact to pedestrian walkways or trails not included in length of road exposed.

At Houpsitas, the effects of a Cascadia tsunami would potentially affect most of the community located at the toe of the hill. This includes the health center, office, and community center. Sanitary installations would also be affected as well as the community’s generator. Taking its source from Andrews Creek to the west, the community’s drinking water supply may be affected if the tsunami reaches the intake believed not far upstream from the creek’s mouth. The water tanks, which are located uphill, are not going to be affected by a tsunami (assuming they survive the seismic event without damage). The roads within the community could suffer damage, but the inundation zone will remain accessible via Kyuquot School Rd. Parts of the community up the hill are not affected by the tsunami, which include the school. In the case of an Alaska tsunami, only buildings close to the shoreline may be exposed as well as marine infrastructure.

Several underwater utilities connecting neighbouring islands to Houpsitas, such as telecommunication and power lines, as well as a sewer effluent line which conveys sewage from Houpsitas into Nicolaye Channel south of Walters Island can potentially be damaged by strong current speeds induced by tsunamis.

The two docks used by the community are expected to be destroyed by a Cascadia tsunami, as strong current velocities are expected to occur in conjunction with large fluctuations in water level. As the community is only accessible by boat or float plane, the loss of the docks (and community vessels moored at the docks) would significantly complicate access/egress, resupply, and recovery efforts. Boat access is also possible through the logging camp at Chamiss Bay, although marine infrastructure at that location may also be damaged. In the case of an Alaska tsunami, stronger current velocities are only expected in narrow passages between islands and other constrictions, meaning that the community docks have a better chance to remain functional after the tsunami.

On Walters Island, essentially all buildings are expected to be affected by the Cascadia tsunami, and most of them by the Alaska tsunami. The island has sufficiently high ground in proximity to buildings for its inhabitants to evacuate at-risk areas on foot, but the shoreline marine infrastructure (docks and boats) would likely experience significant damages and loss.

4.4.2 Fair Harbour

Background

Fair Harbour is a small community with recreation facilities including a campground and a marina. It constitutes an important transportation access point for the Ka:'yu:'k't'h'/Che:k:tles7et'h' First Nations with a dock dedicated for residents of the Kyuquot area.

Risk Analysis

The mapping of assets at risk at Fair Harbour covers the two map sheets listed in Table 7. The table provides a summary of the number of buildings and length of road estimated to be exposed to tsunamis.

Table 7. Summary of exposed buildings and roads for Cascadia and Alaska tsunamis in Fair Harbour.

Map Sheet	Total Buildings on Map Sheet	Cascadia Tsunami		Alaska Tsunami	
		Buildings Exposed	Length of Road Exposed (km)	Buildings Exposed	Length of Road Exposed (km)
6. Fair Harbour	2	2	3.06	2	2.21
7. Kaouk River	0	0	0.63	0	0.31

Both buildings at Fair Harbour are expected to be affected by the Cascadia tsunami, as well as a large portion of the campground area. In the case of the Alaska tsunami, both buildings are also expected to be affected as well as part of the campground, which highlights the importance of warning systems as distant earthquakes will not be felt at the site.

The dock dedicated for residents of the Kyuquot area is expected to be severely damaged by a Cascadia tsunami and potentially damaged by the Alaska tsunami. The road and bridges crossing the estuary will be fully inundated by the Cascadia tsunami and partially inundation by the Alaska tsunami. Inducing strong flow velocities, both tsunamis have the potential to severely damage this route, which plays an important role for accessing Kyuquot. Part of the access road on the north shore of the Kaouk River is also expected to be affected by both tsunami scenarios.

4.4.3 Nuchatlaht First Nation

Background

Nuchatlaht means “people of the mountain” and Nuchatlaht First Nation is a member of the NTC. The Nuchatlaht First Nation has approximately 20 members living on-reserve and a total membership of 162. Historically displaced from their traditional territory, the Nuchatlaht First Nation is based in Oclucje which is within the traditional territory of the Ehattesaht Chinehkint First Nation. Located at the northern end of Espinoza Inlet, Oclucje is within a 20-minute drive from the Village of Zeballos along Harbour Rd. and the Zeballos forestry service road (FSR). The traditional territory of the Nuchatlaht First Nation includes the Nuchatl area at the entrance of Nuchatlitz Inlet.

Risk Analysis

The mapping of assets at risk in areas related to the Nuchatlaht First Nation covers the five map sheets listed in Table 8. The table provides a summary of the number of buildings and length of road estimated to be exposed to tsunamis.

Table 8. Summary of exposed buildings and roads for Cascadia and Alaska tsunamis in areas related to the Nuchatlaht First Nation.

Map Sheet	Total Buildings on Map Sheet	Cascadia Tsunami		Alaska Tsunami	
		Buildings Exposed	Length of Road Exposed (km)	Buildings Exposed	Length of Road Exposed (km)
8. Oclucje	13	3	1.45	0	0.01
11. Harbour Road	0	0	0.81	0	0.34
12. Zeballos FSR	0	0	0.04	0	0.00
14. Owossitsa Creek	8	0	0.01	0	0.00
15.Nuchatl	5	4	0.00	2	0.00

Being mostly located on elevated ground, the community of Oclucje is not exposed to distant tsunamis. In the case of a Cascadia tsunami, three buildings are affected, and the community population remains at relatively low risk. However, access/egress may be impacted as a considerable portion of the road along the water’s edge will be inundated and potentially damaged. Furthermore, water supply may be affected as the water treatment plan is on the fringe of the estimated inundation extent, although the water tanks are sufficiently elevated. The location of the water intake in Espinosa Creek, and whether it is exposed to tsunamis risk, remains uncertain. Lastly, while the dock may be subjected to some damage following an Alaska tsunami, such damage is expected to be considerably less than in the case of a Cascadia tsunami.

The bridge crossing Little Espinosa Inlet that provides access to Oclucje is at risk of being damaged during both Cascadia and Alaska tsunamis, because of strong current velocities through the constriction created by the bridge abutments and/or the potential forces of the water acting on the bridge structure. Except for some distance on either side of the bridge, the access road connecting Oclucje to the Village of Zeballos area (Harbour Rd. and Zeballos FSR) remains at low risk in either tsunami scenario.

At Owossitsa Creek, estimated impacts of tsunami are limited as no buildings are exposed. At Nuchatl, considerable flooding is anticipated in the case of a Cascadia tsunami while such flooding is limited in the case of the Alaska tsunami. Some buildings are affected for both tsunamis, as reported above, however more buildings and docks are present further east of the mapped area, which may also be affected by tsunamis.

4.4.4 Village of Zeballos

Background

The Village of Zeballos sits at the head of Zeballos Inlet and is nestled between forested mountains with access to Kyuquot Sound through Fair Harbour. The village was developed as a center for gold mining in the early 1930s and later logging was developed as a key industry in the 1950s. In addition to logging Zeballos is also home to a plant which processes a variety of fish throughout the year. More recently, Zeballos has become a destination for wilderness recreation and tourism. The community sits on a river delta and on either side of the Zeballos River, referred to as the west and east side of the village. Zeballos Inlet is the traditional territory of the Ehattesaht First Nation, which include Ehatis on the western side of the inlet, directly south of the Village of Zeballos.

Risk Analysis

The mapping of assets at risk in the Village of Zeballos and Ehatis covers the two map sheets listed in Table 9. The table provides a summary of the number of buildings and length of road estimated to be exposed to tsunamis.

Table 9. Summary of exposed buildings and roads for Cascadia and Alaska tsunamis at the Village of Zeballos.

Map Sheet	Total Buildings on Map Sheet	Cascadia Tsunami		Alaska Tsunami	
		Buildings Exposed	Length of Road Exposed (km)	Buildings Exposed	Length of Road Exposed (km)
9. Zeballos River	146	93	4.01	72	2.32
10. Zeballos Waterfront	17	17	1.97	9	1.60

The exposure of the village on either side of the Zeballos River varies, with most of the tsunami impacts concentrated on the east side. In the case of the Alaska tsunami, no buildings on the west side are exposed, although a number of buildings in Ehatis are considerably close to the inundation area. In the case of the Cascadia tsunami, 11 buildings on the west side are affected (two in Ehatis), potentially including the health center which is considerably close to the inundation area. For both tsunamis the bridge in Ehatis as well as part of the Zeballos FSR on the waterside are at risk of being impacted, potentially affecting the access/egress to the communities of Ehatis, Oclucje, and Chenahkint.

The east side of the village, where the fire station, police station, community hall, and village office are located is at high risk of being impacted by both Cascadia and Alaska tsunami scenarios, with 99 and 81 buildings affected, respectively. Furthermore, risk increases due to a number of log booms in the area which could increase the amount of floating debris, reducing chances of survival if caught in the inundation and inflicting further damage to infrastructure.

Estimated to be overtopped, the bridge on Parkway Rd. which crosses Zeballos River and connects the two sides of the village is at high risk of being affected by a Cascadia tsunami. The bridge is also at risk of being damaged during an Alaska tsunami. This bridge constitutes an important link between much of the village's affected areas and the health center, although the west side can still be accessed by detour to the north through the Zeballos FSR.

The municipal wharf is likely to be damaged in the event of a tsunami, as well as other marine infrastructure at the southern end of the village. Water supply and power infrastructure are sufficiently elevated and are not at risk. The school which is located north of Parkway Rd. is not expected to be exposed although it is located close to the estimated extent of inundation in the case of the Cascadia tsunami. It remains at-risk given the relatively flat topography of the vicinity, meaning that a relatively small increase in water level would result in a large increase in the extent of flooding. While elevated land is in close proximity, evacuation efficiencies related to effective planning, advanced warning, and public readiness efforts such as education, training and drills can decrease risk to people in the community exposed to tsunami risk.

4.4.5 Ehattesaht Chinehkint First Nation

Background

The traditional territory of the Ehattesaht Chinehkint First Nation includes areas located in Esperanza Inlet, Zeballos Inlet, and part of Espinosa Inlet. The Ehattesaht Chinehkint First Nation village of Tatchu (what is now the beach near Tatchu Point) was once a common fishing site and place where the Ehattesaht would gather to feast. Today the most populated village is Chenahkint at Queen’s Cove. They are members of the NTC. The Ehattesaht First Nation operates various companies on their territory such as an oyster farm (We’Shuk) and logging company (Aat’uu). The Ehattesaht Chinehkint First Nation is also located in Ehatis at the Village of Zeballos as discussed above.

Risk Analysis

The mapping of assets at risk in areas related to the Ehattesaht Chinehkint First Nation covers the map sheets listed in Table 9. The table provides a summary of the number of buildings and length of road estimated to be exposed to tsunamis.

Table 10. Summary of exposed buildings and roads for Cascadia and Alaska tsunamis in areas related to the Ehattesaht Chinehkint First Nation.

Map Sheet	Total Buildings on Map Sheet[1]	Cascadia Tsunami		Alaska Tsunami	
		Buildings Exposed	Length of Road Exposed (km)	Buildings Exposed	Length of Road Exposed (km)
13. Chenahkint	7	5	0.38	2	0.11

The buildings at Chenahkint are located close to the shoreline putting them at considerable risk of a Cascadia tsunami. However, the extent of the flooding is limited. In the case of an Alaska tsunami, although outside of the estimated inundated area, buildings remain at risk due to their proximity to the shoreline. The road at the shoreline at the front of the buildings on the seaward side is expected to be flooded in both tsunami scenarios.

4.4.6 Esperanza and Ceepeecee

Background

The areas of Esperanza and Ceepeecee were respectively settled as a missionary site and as the site of a cannery facility for pilchards and later for salmon. The name Ceepeecee comes from the acronym for the California Packing Corporation (CPC) (Gulf of Georgia Cannery Society, 2021) and is only inhabited seasonally[10]. The original plant was destroyed by fire in the 1950s, however, several buildings remain in the area. Esperanza, also referred to by the name Tlay Maak Tsu, is a boat-in Christian community. Nootka Mission Hospital operated from this location until 1974 (Esperanza Ministries, 2020).

Risk Analysis

The mapping of assets at risk in Esperanza and Ceepeecee covers the map sheets listed in Table 11. The table provides a summary of the number of buildings and length of road estimated to be exposed to tsunamis.

Table 11. Summary of exposed buildings and roads for Cascadia and Alaska tsunamis in Esperanza and Ceepeecee.

Map Sheet	Total Buildings on Map Sheet	Cascadia Tsunami		Alaska Tsunami	
		Buildings Exposed	Length of Road Exposed (km)	Buildings Exposed	Length of Road Exposed (km)
16.Esperanza	18	15	0.25	4	0.06
17.Ceepeecee	6	5	0.00	4	0.00

Both Esperanza and Ceepeecee would be considerably impacted by a Cascadia tsunami, with most of the buildings affected. Furthermore, docks are likely to be severely damaged, if not destroyed, making access/egress and resupply to these isolated sites more challenging. Although to a lesser extent, the Alaska tsunami scenario also poses risk to buildings and marine infrastructure.

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[10] Verbal communication between Philippe St-Germain (pstgermain@nhcweb.com) and Steinar Våge (steinarv@kcfirstnations.com)) during the project Advisory Group meeting of February 22, 2022.

4.4.7 Village of Tahsis and Mowachaht/Muchalaht First Nations

Background

The Village of Tahsis sits at the head of the Tahsis Inlet and includes settlements on either side of the Tahsis River. With many residential, commercial, and public facilities, Tahsis is home to 500 year-round residents and about 1,500 people in the summer months with many recreational opportunities (Village of Tahsis, n.d.). Tahsis is within the traditional territory of the Mowachaht/Muchalaht First Nation and was established for forestry operations which started in the late 1930s. The community was only accessible by boat until the road connection to Gold River was constructed in the early 1970s. This road passes through land administered by the Mowachaht/Muchalaht First Nations at the mouth of the Leiner River.

Mowachaht/Muchalaht First Nation traditional territory extends south to Nootka Sound and Gold River. Located in Muchalaht Inlet and the Gold River valley, the Mowachaht/Muchalaht First Nations are an amalgamation of four groups, the Mowachaht (Tahsis and Tlupana Inlet communities) and the Muchalaht (Cheeshish and Ahaminaquus) who were once whalers. Together they number 613, control 18 reserves totaling approximately 388 hectares of territory, and are a member of the NTC. One of their most famous territories is Yuqout, known for “where-the-wind-blows-from-all-directions”, is the centre of their government and of their spiritual and ceremonial world. It is the longest continuously occupied site on the west coast of Vancouver Island and one of the largest and deepest archaeological deposits in British Columbia (https://www.yuquot.ca/center-of-the-world/).

Ongoing Flood Protection Improvements

As part of the Tahsis Flood Mitigation Project, the Village of Tahsis is improving its flood protection infrastructure to further mitigate risks of storm flooding in the northeastern portion of the village (e.g., north of Quadra Rd.). This part of the village is particularly vulnerable to river flooding due to its low-lying elevation. This ongoing project includes the upgrade of the existing dike along North Maquinna Dr. and the Cook St. dike, as well as the construction of a storm storage pond at the eastern end of Boston St. These works include a diesel-powered flood pump located at the southeast corner of Alpine View Rd. and Boston Rd. The construction of the storm storage pond system and the upgrade of Cook St. Dike have been completed. Upcoming works include the upgrade of the Tahsis River dike along Maquinna Dr., from north of Quadra Rd. to south of Cook St. These dike upgrades essentially consist in rising the top elevation of the existing lock block wall by the height of one lock block and protecting the riverside slope with rip rap. As per the information contained in McElhanney (2022c), the dike upgrades do not account for applicable seismic design standards and were designed considering parallel flow only.

Based on the review of design information available, these storm flood mitigation works are not expected to be effective against tsunami inundation, even if not damaged by the initial Cascadia earthquake. As reported in Table 5, the general inundation level of 6.9 m with respect to CGVD2013 in Tahsis River for a Cascadia tsunami (4.9 m for a Alaska tsunami) exceeds the top elevation of the to be upgraded flood protection wall, which varies from approximately 4.7 m downstream to 6.6 m upstream

(CGVD2013[11]). Furthermore, as a tsunami would flow upstream in contrast to downstream as in the case of storm river flow, considerable hydrodynamic and scouring forces would be acting on the segment of the flood protection wall between Quadra Rd. and Boston Rd., as it would be on the outside bend of the river channel. Based on field observations made following the 2011 Tohoku tsunami in Japan, and unless demonstrated otherwise by structural assessment, it is not anticipated that the wall's lock block construction would resist such forces, even if not overtopped. Accordingly, for the purpose of emergency planning it is conservative to consider that the northeastern portion of the village remains at risk of being inundated in the event of both a Cascadia and Alaska tsunami scenario.

Risk Analysis

The mapping of assets at risk in the Village of Tahsis and Mowachaht/Muchalaht First Nations land at the mouth of the Leiner River covers the seven map sheets listed in Table 12. The table provides a summary of the number of buildings and length of road estimated to be exposed to tsunamis.

Table 12. Summary of exposed buildings and roads for Cascadia and Alaska tsunamis at the Village of Tahsis and Mowachaht/Muchalaht First Nations land at the mouth of the Leiner River.

Map Sheet	Total Buildings on Map Sheet	Cascadia Tsunami		Alaska Tsunami	
		Buildings Exposed	Length of Road Exposed (km)	Buildings Exposed	Length of Road Exposed (km)
18. Tahsis River	0	0	0.89	0	0.16
19. Tahsis Waterfront	230	187	6.33	135	3.77
20. Tahsis Waterfront West	112	20	2.23	15	1.25
21. Leiner River Estuary North	0	0	2.15	0	0.70
22. Tahsis S Maquinna Dr.	16	7	0.60	7	0.42
23. Leiner River Estuary South	0	0	0.00	0	0.00
24. Tahsis Waterfront South	6	0	0.00	0	0.00

For the purpose of assessing tsunami risks at the Village of Tahsis, the vicinity can be divided in four main general areas:

- **Tahsis River Eastern Shore** – Located north of Head Bay Rd. on the eastern shore of the river and included on Inundation Map Sheets No. 18 and 19.
- **Tahsis River Western Shore** – Located north of Head Bay Rd. on the western shore of the river and included on Inundation Map Sheet No. 19.

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[11] Vertical datum of the elevations reported on Issued for Tender Drawings (McElhanney, 2022b) confirmed to be CGVD1928 by email communication between Philippe St-Germain (pstgermain@nhcweb.com) and Dwayne Cybak (dcybak@mcelhanney.com) on May 2, 2022. Elevations reported herein were converted to CGVD2013.

- **Western Ocean Shore** – Located south of Head Bay Rd. on the western shore of the inlet and included on Inundation Map Sheet No. 20, 22, and 24.
- **Leiner River Estuary** – Located south Head Bay Rd. on the eastern shore of the inlet and in the Leiner Estuary and included on Inundation Map Sheet No.20, 21, and 23.

The eastern shore of Tahsis River is at risk of being flooded by both a Cascadia and an Alaska tsunami, although the impacts of the local tsunami would be much more significant. The current fire station, water treatment plant, health center, ambulance station, police station and drinking water well could be impacted by both tsunamis. For the Cascadia tsunami, an additional 46 buildings would be affected including the proposed new location for the fire station, the recreation center, and school. The electrical substation at the east end of Head Bay Rd. is also exposed to a Cascadia tsunami. In both Cascadia and Alaska tsunami cases, the bridge on Head Bay Rd. that connects the eastern shore to the western shore is expected to be subject to tsunami effects considering its location at the waterfront. The effects of the tsunamis are also expected to reach the bridge crossing Tahsis River at the north end of the village.

The western shore of Tahsis River is less exposed to tsunami risks because of its elevated topography. No buildings are estimated to be affected in the case of the Alaska tsunami, and the Cascadia tsunami is estimated to affect six buildings. Nevertheless, a considerable portion of this area including A Rd., B Rd., and C. Rd. is at risk of being flooded.

Further south on South Maquinna Dr., the commercial marina area is expected to be impacted by both Cascadia and Alaska tsunamis. While buildings located at higher elevations along Cardiac Climb Rd. are outside of the estimated inundation zone, those located closer to shore at the village core are at risk of being affected by both Cascadia and Alaska tsunamis. In either scenario, the village office and health center are not expected to be affected. On the other hand, the wastewater treatment plant and municipal dock are expected to be impacted by both tsunamis. Although the Canadian Coast Guard Station is elevated on Tootouch Pl. to avoid inundation, the dock used for the coast guard vessels is exposed.

On the other side of the inlet, no building or critical asset is estimated to be at risk aside from the road, which provides the only land access to Tahsis. Approximately 2.5 km roadway is estimated to be affected by the Cascadia Tsunami, starting at the electrical substation at the eastern end of Head Bay Rd. The Alaska tsunami is also expected to affect that road, but to a lesser extent. While located near the fringe of the estimated inundation, the bridge located at the eastern end of the Leiner River estuary may be affected by a Cascadia tsunami. Located approximately 20 km away from Tahsis on the way to Gold River, the road runs close to the shoreline along the northern end of Tlupana Inlet. Inundation hazard as not yet been assessed in that part of the study area. However, based on the results of maximum tsunami amplitude associated to a Cascadia and Alaska tsunami shown in Figure 11 and Figure 15, respectively, this stretch of the road to Tahsis is likely to be affected to some degree. Lastly, a considerable portion of the Mowachaht/Muchalaht First Nations land at the mouth of the Leiner River is expected to be inundated under both tsunami scenarios.

4.4.8 Kendrick Camp

Kendrick Camp is a logging facility located at the head of Kendrick Inlet. The mapping of assets at risk at Kendrick Camp covers the map sheets listed in Table 13. The table provides a summary of the number of buildings and length of road estimated to be exposed to tsunamis.

Table 13. Summary of exposed buildings and roads for Cascadia and Alaska tsunamis at Kendrick Camp.

Map Sheet	Total Buildings on Map Sheet	Cascadia Tsunami		Alaska Tsunami	
		Buildings Exposed	Length of Road Exposed (km)	Buildings Exposed	Length of Road Exposed (km)
25. Kendrick Road	14	0	0.81	0	0.13

The exposure to tsunamis of the buildings a Kendrick Camp is low, with no building being affected by either Cascadia or Alaska tsunami. There is a risk however that marine infrastructure would be damaged making access/egress, resupply, and recovery difficult. Both tsunamis affect the bridge just north of the camp, which would complicate the return to camp from that direction.

5 EMERGENCY MANAGEMENT AND RISK REDUCTION

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

5.1 Community Emergency Management

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

- Mitigation
- Preparedness
- Response
- Recovery

EMBC plans to repeal and replace the Emergency Program Act and introduce new legislation by Fall 2022 (EMBC, 2022). In preparation of this new legislation there are several documents that outline new standards and best practices, including the following:

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

New legislation means that while current community management plans are expected to include the phases of response and recovery, they should be revised to also include the phases of preparedness and mitigation. This section of the report summarizes the relevant best practices and regulations for each phase of emergency management, supporting updates to plans in line with the modernization of emergency management legislation in BC and other key references listed above. Existing emergency management plans are briefly discussed below to provide further context.

5.1.1 Existing Emergency Management Plans

Coastal communities in the study area understand how to work together to plan for disaster events. Rugged, remote, and rural communities follow legislated regulations and established governance structures to undertake planning before, during, and after a disaster event. Planning efforts are driven by self-determined risk management priorities and are based on the social tolerance for acceptable and unacceptable levels of risks. The drivers of risk tolerance are dynamic and often dramatic for a low probability, high consequence event such as a major tsunami.

As global tsunamis showcase the potential extent of a coastal disaster, community leadership develop plans for continuity of critical infrastructure and services such as housing, roads, bridges, water systems, utilities, first responder and health facilities, and communication systems. For this study, a number of communities provided documents, plans and procedures relevant to a tsunami risk assessment. These plans incorporate earthquake and tsunami risk as a subsection of a greater planning effort. Generally, these plans also contain public alerting and tsunami evacuation procedures in at-risk communities.

Information on existing planning efforts and community preparedness levels were gathered through the Advisory Group, Indigenous knowledge holders, oral histories, and the public survey, as introduced in Section 5. Together, these contributions clearly demonstrate strong and resilient communities, with an abundance of knowledge and experience of the risks posed by both local and distant tsunamis.

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

5.1.2 Preparedness

5.1.2.1 Best Practices and Regulations

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

Basic preparedness for tsunami hazards involves knowing and practicing how to safely respond to a tsunami alert (from a distant event) or to strong ground shaking (from a local event) and, subsequently, to know how to effectively evacuate to a safe location until the tsunami threat has ended (which can be hours and even days after the arrival of the first wave). Preparedness also includes planning for the recovery process by identifying at-risk people, assets, services, and supply chains, and developing recovery plans with key organizations, government, not for profit and private sector partners.

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

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

5.1.2.2 Progress

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

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

The vision of the plan is stated as follows:

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

Survival from a major tsunami event should be the expectation of every prepared community member and visitor on Northwest Vancouver Island. Opportunities exist in high-risk communities to improve preparedness through enhanced tsunami awareness, education, and evacuation exercises, some of which are taking place for Phase 2 of this project.

5.1.2.3 Path Forward

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

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

Preparedness efforts often lead to the identification of new risk management strategies, secure buy-in and funding for risk reduction efforts and empower community-led resilience solutions where they are most needed.

5.1.3 Response

5.1.3.1 Best Practices and Regulations

Emergency response includes action taken directly before, during or immediately after a disaster in order to save lives, reduce health impacts, ensure public safety and meet the basic subsistence needs of the people affected (United Nations Office for Disaster Risk Reduction, 2017). The focus of emergency response is the immediate and short-term needs of those affected by the disaster.

The current regulations state that a local authority is at all times responsible for the direction and control of the local authority's emergency response (Province of British Columbia, 1996). In addition, a local authority must have a local emergency plan where they establish and maintain exercises and training for emergency response staff.

In the context of a tsunami, effective, efficient, and timely response will rely on preparedness informed by tsunami risk. Communities will need to rely on their own capacities as well as emergency services and public assistance which can be provided by the public and private sector as well as broader community and volunteer participation.

It should be noted that the distinction between response and recovery is not always clear. For example, emergency utilities services are sometimes set up as part of emergency response and continue to be used into the recovery phase due to the timelines required to rebuild infrastructure.

5.1.3.2 Progress

This project did not address emergency response for tsunamis directly, however, it is able to support risk informed planning for response. For example, with the risk assessment completed for two key tsunami scenarios, the areas that are likely to be affected are now known in greater detail. This means that response training exercises could be tailored to different tsunami sources which would facilitate a more efficient and effective response.

Current emergency management plans exist at a regional district, municipal, and tribal council level. Most communities have some guidance on emergency management generally and other have tsunami specific plans. Several false alarms or near miss tsunami events where warning systems were activated but no inundation was experienced had served as an opportunity to analyze tsunami preparedness and the response to tsunami warnings.

5.1.3.3 Path Forward

Response planning is already well established across the study area it is an existing requirement with the current emergency management regulations. However, there are several ways that response specific to tsunamis can be enhanced based on the outputs of the risk assessment, and such can be in relation with:

- Early warning systems,
- Risk informed response for Cascadia and Alaska tsunami sources, and
- Whole-of-society approach for response planning.

5.1.4 Recovery

5.1.4.1 Best Practices and Regulations

As per the Sendai Framework (United Nations Office for Disaster Risk Reduction, 2017), recovery following a disaster means the restoration, or improvement of livelihoods and health, as well as economic, physical, social, cultural and environmental assets, systems and activities, of a disaster-affected community or society. This aligns the principles of sustainable development and “build back better” to avoid or reduce future disaster risk. The principle of building back better is central to effective recovery and a core principle of the Sendai Framework. Recovery could be particularly difficult for marine communities in which docks and vessels have been lost or damaged.

The BC Emergency Management Act recommends recovery planning as part of the full cycle of emergency management. Immediate recovery actions include initiating Business Continuity Plans for organizations as well as Emergency Support Services for impacted community members. For most perils, including for earthquakes, insurance is an important part of community recovery, however for tsunami events insurance coverage is not readily available. Medium and long-term recovery includes financial supports, equipment supply, and humanitarian activities from Provincial, Federal, and International agencies to achieve a ‘new normal’ in impacted communities.

5.1.4.2 Progress

This tsunami risk study did not focus on recovery but can support risk informed recovery planning. For example, knowing which areas and assets are likely to be most affected by a tsunami can help identify the highest priority areas for recovery planning. This could include work that pre-identifies recovery goals and investment options including critical infrastructure, supply chain, mutual aid planning and future needs for emergency social services and humanitarian assistance.

Recovery funding is not often identified prior to a disaster event taking place. However, pre-disaster recovery funding can be explored through government granting opportunities, private or public insurance and re-insurance expansions, disaster aid through non-governmental organizations, catastrophic bonds, and advanced private-sector recovery investments.

5.1.4.3 Path Forward

Recovery planning should be proactive and include a whole of society approach including considerations of:

- Trauma of loss and recognition of the importance of community wellness after a disaster,
- Repair and reconstruction of critical infrastructure,
- Support build back better principles,
- Support business continuity and recovery, and
- Be inclusive of all community perspectives.

5.1.5 Mitigation

5.1.5.1 Best Practices and Regulations

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

5.1.5.2 Progress

Through the Advisory Group portion of this study, it is likely that current and future community development decisions in marine and coastal areas will utilize the tsunami risk assessment results to influence community land use decisions in high-risk areas. Through Phase 2 of this project, expanded public tsunami awareness sessions will take place and signage installed in some at-risk areas.

Meanwhile, progress is being made on key tsunami risk mitigation opportunities that stem from enhanced earthquake and tsunami monitoring and updated local communications infrastructure. In the near future, technologies such as earthquake early warning and real-time tsunami observations provided at the local and individual level is likely in some areas.

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

5.1.5.3 Path Forward

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

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

Some of these risk reduction measures are further discussed in the following section, and additional ones are introduced also.

5.2 Recommendations for Risk Reduction

Reducing tsunami risk is the responsibility of all who may be affected by it. As per international best practice and priorities of the Sendai framework (UNISDR, 2015), the first step to inform action is to understand risk. Although the scope of this study does not include the detailed elaboration of risk reduction measures and plans, this section provides an overview of possible options.

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

Risk reduction plans should follow a road map that includes short-term, medium-terms, and long-term actions. The short-term plan looks at the next two years, to identify the recommended steps to early action. The medium-term plan looks at the next two to five years and includes details on opportunities for additional input. Finally, the long-term plan is where communities are going in the next 5 to 10 years and provides a vision for what this work could achieve. Such plans should also highlight measures that can achieve meaningful risk reduction while requiring relatively modest resources, as well as identify opportunities and strategies for funding. Clear objectives and evaluation criteria specific to each community should be established early on to support decision making.

The sections below briefly introduce the different categories of measures that can be developed to reduce tsunami risk in conjunction with developing tsunami emergency management plans. An example of a tsunami risk reduction plan specific to a community on Vancouver Island (District of Tofino) can be found in Northwest Hydraulic Consultants *et al*. (2020).

5.2.1 Public Awareness

Public awareness is a key component of any tsunami risk reduction plan, as involving people in reducing their own risk and educating them to know how to physically remove themselves from the hazard zone may be the most effective measure to reduce risks.

Evacuation Signage

Tsunami signage, including directional guidance indicating inundation zones, evacuation routes, high-ground areas as well as designated refuge areas, improves way-finding during a tsunami event and serves as educational/awareness tools day to day. These measures are generally targeted at visitors, who are not familiar the area’s geography or the spatial extent of the tsunami hazard, however signage also serves as a reminder for locals.

Annual Community and Neighbourhood Evacuation Drills

An annual evacuation drill can help ensure tsunami preparedness stays high on community consciousness and that people are prepared to evacuate in the event of a tsunami. Each year, a different preparedness focus can be highlighted. Based on evacuation route planning, it may be identified that different parts of the community are better evacuating to different refuge areas using different evacuation routes. Hence the potential need of evacuation drills on a neighbourhood-by-neighbourhood basis.

Visitor Education and Staff Training

A tsunami event is not the time to start preparing. Basic tsunami educational material, incorporating local risk, alerting tools and response procedures, is critical for life safety in a major tsunami. This is especially true for visitors, who are vulnerable due to their limited understanding of risk, disconnection from social networks/information sources, and lack of awareness of appropriate response procedures.

The safety of visitors and staff is a shared responsibility with, among others, local accommodation providers, tour operators and other businesses. Visitor-specific tsunami education material can capture attention, raise awareness, and be designed to empower self-reliance rather than fear.

5.2.2 Public Alerting

The SRD receives distant tsunami notification via EMBC and the National Tsunami Warning Center (NTWC). If a tsunami threat is identified, EMBC will activate the Provincial Emergency Notification System (PENS) and Alert Ready, which notifies residents and communities through email, phone call, social media, Short Messaging System (SMS), Environment Canada (EC) Alert, and Channel 16 marine radio with information on alert levels for the province's five tsunami zones (GeoBC, 2015), namely:

- Zone A – The North Coast and Haida Gwaii
- Zone B – The Central Coast and Northeast Vancouver Island Coast
- Zone C – The Outer West Coast of Vancouver Island
- Zone D – The Juan de Fuca Strait
- Zone E – The Strait of Georgia

The SRD also receives tsunami alerts directly from the NTWC via SMS and NOAA weather radio. During a distant event, the SRD will make every effort to broadcast official tsunami alerts and information by email, telephone, and text message via the Connect Rocket Community system, as well as by social media, radio and/or door-to-door contact if possible. It is recognized that in most cases, notification systems activated in a tsunami event will have some level of malfunction or failure despite rigorous pre-event testing, and several opportunities exist to improve public alerting to further reduce tsunami risks, especially for visitors.

Tsunami Sirens

The community of Oclucje as well as communities of the Ka:'yu:'k't'h'/Che:k:tles7et'h' and Ehattesaht First Nations have their own tsunami sirens. Improvements to these existing systems may include additional testing and upgrades, and/or expansion based on the assessment of sound levels and reach. Other areas where modern tsunami sirens could be deployed include, but is not limited to, the Village of Zeballos, Esperanza, Ceepeecee, as well as Fair Harbour where campsite users may not be aware of a distant tsunami approaching. It should be noted that for the case of a local tsunami the alert for evacuation should rely on the natural warnings such as strong ground shaking. In such event sirens may not be heard due to other noises associated to the earthquake and/or the siren system may be damaged during the earthquake.

Last-Mile Public Alerting

Public alerting relies on redundant tools for broad communication, including Weather Radios, sirens, traditional and social media, and cell phone alerts. Each method has advantages and limitations, and each requires on-going education, training, and practice to ensure that alerting tools meet expectations and people respond appropriately.

Last-mile public alerting for tsunami risk reduction is designed to directly improve the likelihood that information on distant tsunami is received by at-risk populations and that appropriate response actions are taken. Generally, tsunami alerting is designed specifically for distant tsunami events (>3hrs to arrival) where there is no warning from earthquake ground shaking. This is mainly because of the shorter arrival time associated to local tsunamis and the potential damage the significant ground shaking may cause to communication infrastructure.

Radio Training

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

Weather radios are robust, effective, and inexpensive. They are designed to send an alert for multiple hazards, including extreme weather and storm surge. They deliver authoritative, regionally-specific alert information, are transportable and are intrusive in nature. These attributes make them especially effective for nighttime and indoor alerting. Limitations of weather radios include that they can be a challenge to program, can have reception issues, and may deliver information more slowly, and in some conditions less reliably, than other alerting tools. However, with training and if no other communication means are available, they can serve as a crucial tool to alert people of a hazard.

5.2.3 Evacuation Planning

The survival rate of a large tsunami depends on the success of evacuation. The effective egress of people from tsunami inundation zones through evacuation routes, or pathways, and the designation and development of designated tsunami refuge areas require careful planning and assessment. The latter should be based on the characterization of the hazard and should take into consideration the time required for evacuees to leave the evacuation zone under circumstances imposed by an earthquake and tsunami (e.g., travel speed). Evacuation planning is important to distinguish a short-term tsunami *refuge* for occupants to survive tsunami flooding, in contrast to a *shelter* which would house occupants for a longer stay, as these functions will have varying requirements. The former is generally sufficient for occupants to survive the tsunami itself, which effects can last several hours to a few days, but not to survive extended periods of time without supplies, medical aid, and protection from the elements.

The assessment of the time available for evacuation should take into consideration the duration of any ground shaking associated to the triggering earthquake, the time required for people to decide to evacuate, as well as the time that may be needed to egress buildings that may be damaged by the earthquake.

The designation of tsunami refuge areas should prioritize naturally elevated ground areas. In some cases, such areas can be located as privately owned land and inaccessible land. Community agreements can be developed to respect private property rights and privacy, while supporting community members and visitors in need of a safe evacuation location. When the arrival time of the tsunami does not provide sufficient time to reach safe higher ground, the construction of a tsunami vertical evacuation (TVE) structure may be warranted, as further discussed in Section 5.2.5. Existing buildings sufficiently tall and robust can also serve as TVE structures, although their capacity to withstand tsunami loads and effects need to be assessed carefully.

Planning for the evacuation of a local tsunami in comparison to a distant tsunami will differ greatly, which will also affect means of transportation for evacuation. The latter also being influenced by local geography. Although any evacuation planning needs to be developed in close collaboration with the public, preliminary site-specific considerations are provided below for areas more impacted by tsunamis.

5.2.3.1 Tsunami Source

The designation of a single tsunami inundation zone can have some advantages for simplicity in evacuation planning, and for public awareness and understanding. However, because a single zone would have to accommodate for a larger range of tsunami scenarios, it can result in relatively frequent "over-evacuation" of a larger area than necessary for more frequent, smaller scale events (i.e., distant tsunamis). This may create inconvenience and stress for the public. As such, repeated "over-evacuation" could result in decreasing levels of community trust in, and compliance with, emergency response arrangements.

On the other hand, differentiation of inundation zones requires greater mapping resources and greater levels of coordination in planning and managing responses for each threat or event. This greater complexity can lead to some public misunderstanding about what they need to know and do in each instance. Nevertheless, two inundation zones (one for local tsunamis and one for distant tsunamis) is generally recommended where inundation extents are significantly different.

Since distant tsunamis will provide more time for evacuation and will not cause damage to road infrastructure, residents should be evacuated to shelters rather than short-term refuge areas, if possible. This could take the form of a community 'buddy system' where neighbours on elevated ground support those in low-lying areas.

5.2.3.2 Means of Transportation

Evacuation on Land

Means of transportation for evacuation on land should be assessed carefully in conjunction with the tsunami source. While many will be tempted to evacuate by car, this method of transportation is generally not recommended as it is likely to lead to road congestion and potential accidents, which can also slow down the travel of pedestrian depending on road and sidewalk configuration. This is especially the case for a Cascadia tsunami for which the arrival time is shorter and road infrastructure may be damaged by the earthquake.

Evacuation over Water

The evacuation of overwater areas as well as islands should be addressed specifically based on the results of hazard assessment. The overwater hazard maps of tsunami-induced current velocity can provide some guidance for the evacuation of boaters on the water when notified of an approaching tsunami. Furthermore, the NTHMP and US Coast Guard (2017) provides some guidance for safe minimum offshore depth for boaters in the event of a tsunami, as summarized below.

For a local Cascadia tsunami:

- If you are on land or tied up at the dock, do not attempt to take your vessel offshore. Leave your boat and go to high ground on foot as soon as possible.
- If you are in deep water or close to deep water, take your vessel further offshore beyond a depth of at least 100 m.
- If you are on the water but close to shore, use your best judgement to decide between safely beaching/docking the vessel and evacuating to elevated ground, or attempting to get beyond a depth of at least 100 m. It is noted that beaching a vessel and running to elevated ground entails numerous risks. To be successful requires a skilled vessel operator, knowledge of the upland area (forest undergrowth can be extremely difficult to climb through), and good fitness levels of all members of the party.

For a distant tsunami:

- If you are on land, it is NOT recommended that boaters try to take their vessels offshore before or during a tsunami.
- A boater on the water may consider taking their boat offshore bearing in mind the following:
    - The time available before the tsunami arrives,
    - The preparedness of the boat and experience of its captain to stay offshore for an extended period of time (12-24 hours), or to travel to safe, undamaged harbors, and
    - The weather at sea could be as dangerous as the tsunami itself.

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

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

5.2.3.3 Preliminary Considerations for Site-Specific Evacuation

Below are high-level evacuation considerations developed based on the results of the risk assessment presented above. Such considerations are only meant to support review of existing evacuation plans and are by no means final or official, as more assessment and public engagement is required to carefully develop evacuation plans.

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

The reader is referred to the asset at risks maps provided in Appendix G for a better understanding of the zones affected by either a local Cascadia tsunami or distant tsunami such one from Alaska.

5.2.3.3.1 Village of Tahsis

Existing Evacuation Plans

As per (McElhanney, 2020), the Village of Tahsis has several designated muster stations in the event of a tsunami (Figure 25). These are located at higher elevations up McKelvie Rd. on eastern shore of the Tahsis River, up School Hill Rd. on the western side of the Tahsis River, and at the southern corner of Discovery Cres. And Resolution Rd. at the village centre. All these locations are outside of the estimated tsunami inundation zone for both Cascadia and Alaska tsunami scenarios.

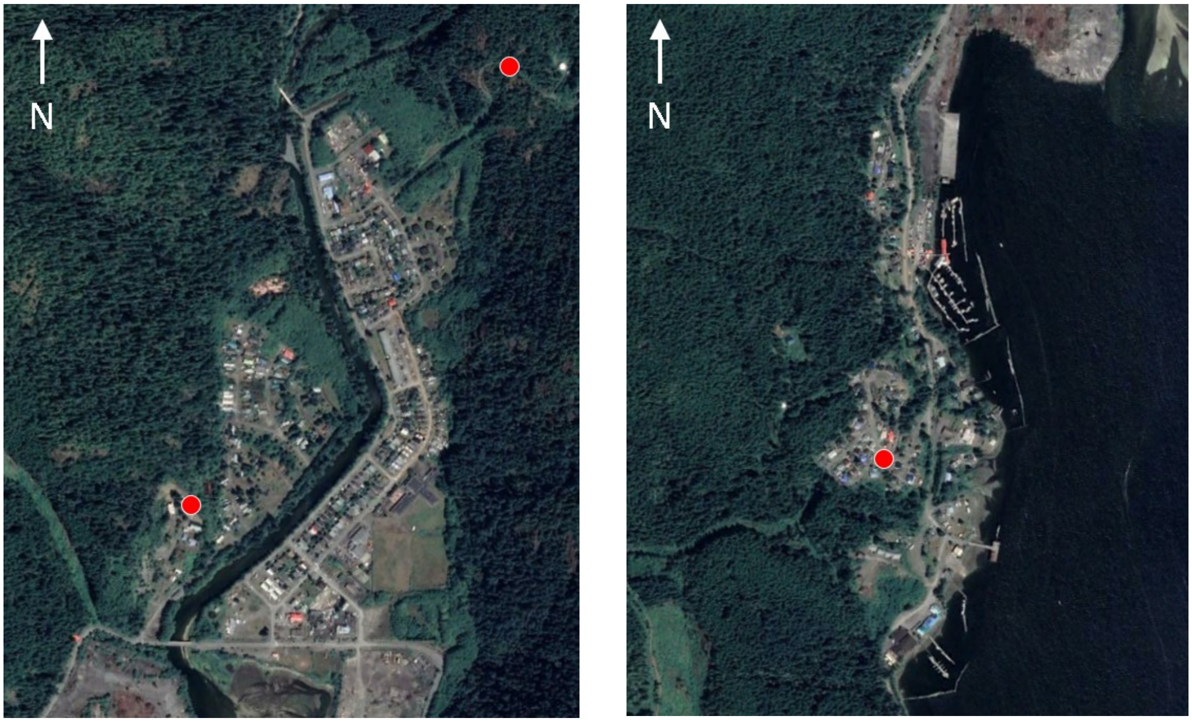

Figure 25. Approximate location of designated muster stations in the Village of Tahsis (red dots) as per McElhanney (2020). Village centre shown on the right.
Image source: Google Earth

Assessment by McElhanney (2020) suggests that evacuating to Gold River and/or Campbell River in the case of a distant tsunami could also be a viable option. While there is a good basis to plan for such evacuation considering other emergencies, this plan should be reviewed carefully considering the findings of this study as well as other tsunami-specific safety considerations. Any evacuation to Gold River puts evacuees at risk since they must get through a portion of Head Bay Rd. that can potentially be affected by a distant tsunami. While there might theoretically be enough time for such an evacuation, success would rely on the basis that all Tahsis residents and visitors have access to a vehicle, and such travel would not be impeded by congestion associated with the sudden presence of many vehicles on the road. These matters could be mitigated by organizing evacuation shuttles and traffic control by local authorities, although such activities would further complicate tsunami emergency plans. Furthermore, the road infrastructure at the north end of Tlupana Inlet, approximately 20 km east of Tahsis towards Gold River, may be affected by a distant tsunami which would put evacuees at risk if they don't make it past this point before arrival of the first tsunami wave. Lastly, such travel could be complicated by challenging winter conditions. For these reasons, it is recommended that any plans for a full-scale evacuation out of the community be reviewed before being finalized. Such review should confirm the exposure of the road to Gold River.

Evacuation to Gold River in the case of a local tsunami is strongly not recommended due to the limited time available for evacuation, and the likelihood of damaged roadways from a tsunami.

Tahsis River Eastern Shore

The area east of Tahsis River should be evacuated regardless of the tsunami source. While not all of this area is inundated by an Alaska tsunami, the area is relatively flat which makes it prone to flooding if the actual tsunami is higher than the model estimates. However, the direction where people evacuate may depend on the tsunami source and their location at the time of the event. The main factor influencing such evacuation decision-making is whether the bridge on Head Bay Rd. is functional after a Cascadia earthquake. In the case of a distant tsunami, the bridge will (likely) remain functional before the tsunami arrives, allowing evacuees to reach natural elevated ground on the western shore of the Tahsis River or on the western shore of the inlet near the village centre. It is not guaranteed however that the bridge will remain operational after the tsunami and this report does not assume the survivability of this bridge during an Alaska tsunami. In the case of a Cascadia seismic event, it is recommended to assume that the bridge will not be functional because of potential damage from the earthquake, unless confirmed by additional assessment by qualified structural and geotechnical engineers. Accordingly, people on the eastern side of the village will have to evacuate up McKelvie Rd. unless additional muster stations or tsunami refuge areas are developed for this area.

Considering the strength and duration of the local ground shaking during a Cascadia earthquake, evacuation times will depend on a number of factors including, but not limited to, the time it takes to decide to evacuate, the time needed to egress damaged buildings, and people's travel speed that may be affected by injury or other conditions (e.g., age, mobility, debris, visitors that aren't familiar with the area). It isn't clear if evacuees initially located south of Quadra Rd. will be able to make it on time up McKelvie Rd. before the arrival of the first tsunami wave, which is estimated to arrive 54 minutes after the earthquake. Accordingly, it is advisable that another tsunami refuge area be developed. This could potentially be constructed on the higher hillside directly east, the school building/rooftop if determined safe (or upgraded) by means of a tsunami specific structural assessment, and/or the construction of a TVE structure. The latter risk reduction measure is further discussed Section 5.2.5.

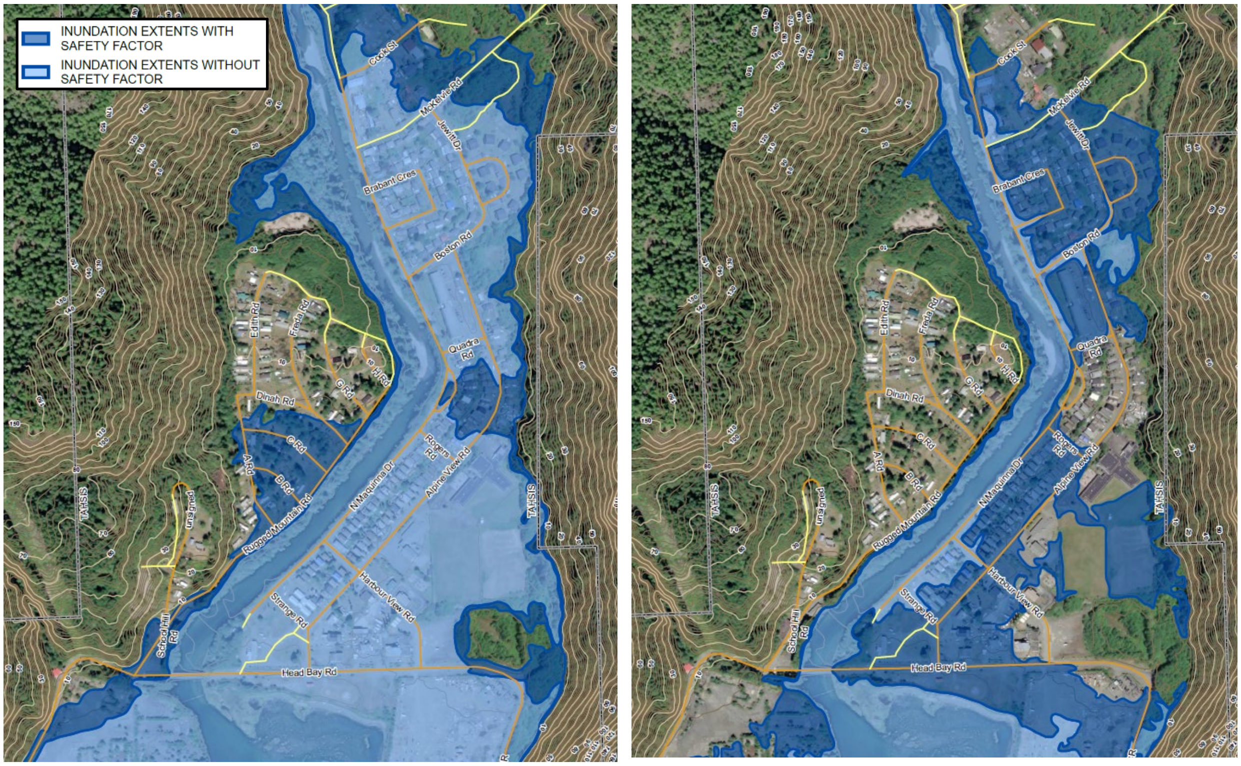

Figure 26. Estimated extent of inundation in the Village of Tahsis due to a Cascadia Tsunami (left) and Alaska Tsunami (right). Excerpts from inundation maps developed for this project.

Tahsis River Western Shore

For people in the area west of the Tahsis River the evacuation should depend on the tsunami source. In the case of a local tsunami, evacuees should travel as fast as they can to the muster station up School Hill Rd., which is located at an elevation higher that 20 m (CGVD2013). Evacuees should not use Rugged Mountain Rd. as it is expected to be inundated. This may require the development of trails connecting the lower plateau which is around an elevation of 10 m (CGVD2013) to the upper plateau where the muster station is located. Since the lower plateau is not much higher than the estimated inundation level, its evacuation is recommended. In the case of a distant tsunami, people in that area do not need to evacuate their building and they should avoid using Rugged Mountain Rd. as it located close to the estimated extent of inundation. People should not leave the area through South Maquinna Dr or Head Bay Rd. as using these pathways may expose them to tsunami flooding or bring them closer to the hazard.

Western Ocean Shore

The village centre and commercial marina area on the western ocean shore is advantaged by its steep topography. For a local tsunami, evacuees should be directed to reach higher ground as fast as possible and only then make their way to either a designated shelter or to a neighbour's residence, as many buildings are located outside of the inundation zone. This elevated part of the village is suited for storing food and other supplies, although the location of stores and restaurants was not assessed as part of this assignment.

5.2.3.3.2 Village of Zeballos

Existing Evacuation Plans

The Zeballos Emergency Program – Emergency Response Plan (n.d.) identifies the community's evacuation marshalling point as the relatively flat open area along the road approximately 1 km north of the Parkway Rd. bridge (300 m north of the "Welcome to Zeballos" sign). At that location are two storage containers (i.e., sea cans) stocked with emergency supplies. The community map included in the Zeballos Emergency Plan (Village of Zeballos, 2020) identifies a tsunami evacuation site up Khenkous Pl. in Ehatis (Figure 27). The map also shows escape, or evacuation routes including one towards the marshalling point north of the village, one off Pandora Cres. that appears to be a trail leading to the hillside to the east, and one going north on the Zeballos FSR on the west side of the village.

Figure 27. General map of the Village of Zeballos including tsunami evacuation information (north direction pointing to the right).

Distant Tsunami

In the case of a distant tsunami, the impacts on the west side of the village are considerably less than on the side east of Zeballos River, making it a safer area to evacuate to in such event. While the marshalling point north of the village on the east side of the river provides a safe location, the buildings on the west side of the village, such as the school building, may provide better shelter if an extended stay is required. There would also be services from the health center, water supply, and electricity which are some distance away from the estimated inundation zone on the west side. Although the bridge on Parkway Rd. may be damaged following the tsunami, the west side can still be accessed from the north through the Zeballos FSR, which connects with the Zeballos Main Rd. at a bridge located beyond tsunami effects. There would be approximately three and a half hours for evacuees from the east side to reach the west side before the arrival of the first wave in the case of a tsunami from Alaska. While the evacuation site in Ehatis would serve as a safe refuge to survive a distant tsunami, it may become isolated from other parts of the village due to the potential flooding of the Zeballos FSR and it is recommended that for a distant tsunami the people evacuate to a more central location on the west side of the village. Additionally, the development of trails running towards elevated forested ground and connecting to the west side could help to mitigate risk of people being stranded at Ehatis. Lastly, even though the southern end of Pandora Cres. is estimated to remain outside the inundated area during a distant tsunami, residents should evacuate to another location to avoid becoming trapped.

Local Tsunami

In the case of a local Cascadia tsunami evacuation would differ considerably to a distant tsunami, mainly because of the shorter time available to evacuate and the greater impact of the tsunami. In contrast to a distant tsunami, the ground shaking may damage the bridge separating the two sides of the village, and therefore it is conservative to plan evacuation assuming that the bridge will not remain functional. This however could be reviewed by means of structural and geotechnical assessment. For the east side of the village, evacuees should travel to the designated marshalling point north of the village on Zeballos Main Rd. However, considering the duration of the ground shaking, the time required for people to decide to evacuate, the time that may be needed to egress buildings, and people’s injuries or conditions, it is not clear if all evacuees located on the east side of the village can make it outside of the inundation zone before the arrival of the first tsunami wave which is estimated to arrive 46 minutes after the earthquake. Travel directly up the hillside to the east could provide a faster egress, although such option may require the development of trails and potentially pedestrian bridges over obstacles. However, because of rock fall hazard in that area (e.g., BGC, 2018) and potential earthquake aftershocks, some assessment would be required to determine the location of safe trails and a refuge areas along the hillside, or alternatively a trail up on the hill running parallel to the valley could be developed for evacuees to reach the marshalling point once they have reached elevated ground.

The west side of the village is more affected in the case of a local Cascadia tsunami in comparison to a distant event, with the estimated inundation coming close to the health center, First Nation office, and the school. These assets are located on a relatively flat area, meaning that a small increase in the inundation level would lead to a considerably larger flooding extent. Accordingly, it is recommended that the evacuation of the west side of the village be through Zeballos FSR to the north. This is with the exception of people in Ehatis, for which access to elevated ground up Khenkous Pl. would be faster and avoid travelling on roads in the inundation zone. Furthermore, the bridge on Zeballos FSR in Ehatis may be damaged by the earthquake and trails should be developed to allow people access to the refuge area up Khenkous Pl.

Lastly, for both local and distant tsunami scenarios, having critical assets such as the village office, police station, and fire station impacted should be accounted for in plans for alerting the population as these buildings will need to be evacuated and won’t be able to function as command centers during the local tsunami. It would be advisable to relocate such buildings as part of any long-term development planning.

5.2.3.3.3 Kyuquot Area

Mainland

With natural elevated ground located a short distance away, the evacuation of Houpsitas' central area up Kyuquot School Rd. is recommended for residents. However, being located on the open coast, the time available for evacuation is short (within 25 minutes) and the evacuation for a local tsunami will need to be completed urgently. In the case of a distant tsunami, there will be more time to alert the population and the evacuation can be limited to the areas closer to the shoreline. Dual evacuation plans should be considered.

Islands

One of the main challenges with evacuation planning in the Kyuquot area lies in the evacuation of nearby inhabited islands, as tsunamis will induce dangerous currents and eddies, as well as other overwater hazards such as breaking waves and mobilization of floating debris, making navigation extremely hazardous. As mentioned above, the general recommendations for the evacuation of islands should be reviewed with the public as well as local knowledge holders and expert mariners. In the case of inhabited islands with accessible elevations that are higher than the estimated inundation levels, it is recommended for residents to remain on the island to seek safety rather than risk travelling by boat to evacuate. Further planning is recommended for specific locations.

Based on the above, measures to reduce the risk of inhabitants of low-lying islands could include artificially increasing elevation where appropriate by means of a TVE structure, as discussed in Section 5.2.5, or assess the feasibility and effectiveness of using rapid launch safety boats with adequate installations in conjunction with safe and rapid landing areas in the main community of Houpsitas. For a local tsunami with only 25 minutes until arrival of the first wave, the feasibility of such schemes requires careful consideration.

Lastly, inhabitants of islands should make sure they have sufficient supplies because of the extended duration of the effects of a tsunami, loss of marine transportation and infrastructure, and regional damages to supply chains could result in them being stranded for some time (up to several weeks) before rescue and/or re-supply. The community may also consider maintaining a vessel capable of all-weather transits to Fair Harbour and back on a trailer under storage at a safe elevation to be available to support recovery efforts and evacuate local islands. Additionally, the community might consider storage of fuel for this vessel as Fair Harbour may not be able to supply fuel for a period of time following a large tsunami due to potential damages to their infrastructure. This may be advisable for other coastal communities as well.

5.2.4 Land Use Planning

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

- Restricting critical infrastructure and facilities in the hazard areas through zoning. Identify a hazard area where critical infrastructure and facilities are not built in. When any existing critical infrastructure or facilities in this area need renovations or upgrades, use that opportunity to relocate the infrastructure. This measure would significantly improve the recovery process as damages to key infrastructure would be limited.
- Using development permit areas in hazard areas to specify development conditions. For buildings in hazard areas, development permit requirements could be applied to new developments or major renovations requiring a permit.
- Designating hazard areas as open space areas and/or restrict density through zoning. In areas where a tsunami hazard exists, it could be incorporated into zoning plans to restrict density or development of further accommodation or facilities.

5.2.5 Structural Mitigation

Develop and Improve Evacuation Pathways

Improving evacuation pathways can significantly improve life safety during a tsunami by removing evacuation bottlenecks and improving evacuation speeds. Routes should be accessible to all including those with mobility challenges so as not to add a barrier to their evacuation. Access should be clearly marked and facilitate effective egress through wide, smooth low-angle pathways. Pathways should be also lighted to facilitate evacuation at night. Figure 28 shows as example an evacuation ramp to access higher ground in a community in Japan affected by the 2011 Tohoku tsunami. A refuge is visible further in the distance up the hill while the foundations of a destroyed building are visible in the foreground.

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

Figure 28. Evacuation pathway in the City of Miyako, Japan (Photo: Philippe St-Germain/NHC, 2012).

Tsunami Vertical Evacuation Structures

A tsunami vertical evacuation (TVE) structure provides an elevated evacuation location where high ground is either nonexistent or is located too far away for everyone to reach before the arrival of a tsunami. By creating artificial high ground through building a vertical evacuation structure, refuge can be created closer to where people live and recreate, and lives can be saved. Such structures must be designed to withstand effects associated to earthquake shaking as well as tsunami loads and effects. To reduce construction costs, they are often designed as short-term tsunami refuge for occupants to survive tsunami flooding, in contrast to a shelter which would house occupants for a longer stay. An example of a simple, single-purpose TVE is shown in Figure 29. If designed and planned appropriately, TVE structures can also consist of multi-purpose buildings such as recreational and community centers, exhibition and cultural centers, information office, schools, etc. An advantage of a multi-purpose TVE structure is the possibility for a return on investment through daily business or commercial use when the structure is not needed as a refuge. A Cascadia tsunami is an extremely rare event and a TVE structure will be rarely, if ever, used over its service life as a refuge. As such, a multi-purpose facility has the co-benefit of being able to utilize the community space and provide alternative benefits to the community. A scoping study for the development of a potential TVE in Tofino is presented in (Northwest Hydraulic Consultants, 2019).

Figure 29. Tsunami vertical evacuation tower near Kamakura, Japan (Photo: Philippe St-Germain/NHC, 2018)

Most communities and areas where the risk was assessed for this study have high ground relatively close by, allowing for the potential development of refuge areas on natural ground which reduces development costs. In the case of the Village of Tahsis and the Village of Zeballos however, more assessment is required to understand the benefits of a TVE structure since the extent of inundation and risks are relatively large. Such assessment generally falls under the process of evacuation planning. In the case of Kyuquot however, where evacuation of inhabited islands by boat is not advised because of the overwater hazards induced by a tsunami, local high ground can be further elevated by a TVE structure if needed.

6 CONCLUSION

The northwest coast of Vancouver Island is particularly exposed to tsunami hazards from local sources, such as the Cascadia Subduction Zone, and distant sources such as the Aleutian Islands Subduction Zone in Alaska. By using tsunami modelling and drawing upon community experience and indigenous knowledge, this project provides a sound understanding of the tsunami hazard in this region and of the associated risks at several communities. This information is expected to support development and planning decisions and improve existing emergency and evacuation plans.

The project focused on the importance of “making space at the table for everyone” in disaster risk reduction and management, and actively sought input from communities in the study area. With this perspective in mind, the project was divided into three components, as summarized below:

1. **Community and Indigenous Engagement** – A project webpage, an online public community survey, and several virtual public engagement meetings were completed to learn from and share the experience, knowledge, and history of local communities. Interviews with Indigenous elders and knowledge holders were also performed. An Advisory Group was consulted throughout the project to guide the project team and promote the exchange of knowledge and ensure proper protocols were in place to safeguard indigenous knowledge ownership.
2. **Tsunami Hazard Analysis and Mapping** – Two tsunami sources were simulated, one from the nearby Cascadia Subduction Zone and another from the more distant Aleutian Islands Subduction Zone in Alaska. Local tsunami flood hazard (e.g., overland inundation) maps were developed for 25 priority areas and overwater hazards such as maximum tsunami amplitude and maximum current speed were mapped across the study area.
3. **Risk Assessment** – Based on the tsunami hazard analysis and mapping, a community level risk assessment was completed to identify potential risk to people, roads, and buildings, as well as several critical assets. Assets at risk maps were developed to identify assets exposed to tsunami hazard.

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

- Village of Tahsis,
- Village of Zeballos, and
- Houpsitas (Kyuquot).

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

6.1 Recommendations for Future Assessment

The information developed as part of this assessment is anticipated to be highly useful for the reduction of existing tsunami risk, as the first step to inform mitigation actions is to understand hazards and associated risks. Nevertheless, this study also highlights some aspects that would benefit from additional assessment, as listed below.

- The communities of the project are closely connected to the ocean and marine activities are an integral part of daily life for many members. Furthermore, several at-risk islands are inhabited. Guidance (Federal and International) that is specific to overwater transportation is scarce and was generally developed for coastal areas with a coastal geography different that the one in the study area. Marine evacuation planning should be undertaken in collaboration with local mariners to develop new guidelines specific to overwater evacuation and to designate marine refuge areas. These areas could include waters considered safe for boaters and/or remote elevated land where safe emergency landing is possible.
- The risk assessment performed as part of this regional study covered aspects related to life safety and physical assets critical to response and recovery. Other elements at risk that could be analysed through community specific assessments include social, economic, environmental, cultural, and economic elements.
- While many of the communities in the study area have elevated ground nearby that can be used as refuge areas, some of these areas may be considered too far to be reached safely before the arrival of a local tsunami. Site specific evacuation assessment considering travel speed, population demographics, seasonality, and time of day would determine whether the development of TVE (tsunami vertical evacuation) structures is warranted in specific locations.
- The inundation mapping undertaken as part of this study is limited to priority areas and people may be exposed in other areas where only overwater tsunami amplitude has been defined. This information gap could be addressed by additional inundation mapping where both LiDAR and higher-resolution modelling information is available at the time of this study. Alternatively, site-specific desktop assessments based on results of tsunami amplitude in conjunction with local topography can inform the identification of safe refuge areas for these areas (such as at specific industrial or recreation sites).
- The response and recovery to both local and distant tsunamis depend on the ability of certain infrastructure to withstand the effects induced by the local earthquake and/or the tsunami. This is particularly the case for bridges which provide access to communities as well as access to key areas within those communities. Structural and geotechnical assessment would confirm if such infrastructure should be relied upon in emergency planning or if structural upgrades would be required. Unless specifically designed to withstand tsunami forces, it should be assumed by planners that marine infrastructure (wharves and docks) and bridges exposed to tsunami will be damaged and inoperable following a tsunami.
- The tsunami inundation extents and levels developed as part of this assignment are for emergency planning and do not constitute flood construction levels (FCL), as they do not include any vertical freeboard or horizontal setback. There is currently no clear guidance for

defining these parameters specific to tsunami hazard, and thus should be established in consultation with communities according to their tolerance to risk.

- Tsunami inundation levels for emergency planning including the effects of sea level rise were defined for general areas and should be referred to as high-level guidance only. The associated model results may be used to update inundation maps to further inform longer-term land use and development planning.
- Sea level rise predictions are constantly being refined by the scientistic community, as well as the understanding of the Cascadia Subduction Zone and the tsunamis it can potentially generate. Longer-term land use and development planning can benefit from the assessment of future information and associated guidelines that may be revised and updated by governmental agencies and professional associations in the relatively near term.
- This study is limited to tsunami hazards generated by earthquakes. Tsunamis generated by subaerial and submarine landslides may occur in the study area which is characterized by many hillsides, fjords, and river deltas. Geological and geotechnical assessment would determine if hazards associated to landslide-generated tsunamis exist in the study area.

7 GLOSSARY

Earthquake Moment Magnitude	Moment is a physical quantity proportional to the slip on the fault multiplied by the area of the fault surface that slips; it is related to the total energy released in the earthquake. The moment can be estimated from seismograms (and also from geodetic measurements). The moment is then converted into a number similar to other earthquake magnitudes by a standard formula. The result is called the moment magnitude. The moment magnitude provides an estimate of earthquake size that is valid over the complete range of magnitudes, a characteristic that was lacking in other magnitude scales. (United States Geological Survey, n.d.)
Exposure	The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas. (United Nations Office for Disaster Risk Reduction, 2017)
Intertidal Zone	The area of the seabed that is above water at low tide and under water at high tide.
LiDAR	Stands for Light Detection and Ranging. Remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light. Often used for measurement of land elevations.
Mitigation	The lessening or minimizing of the adverse impacts of a hazardous event. It should be noted that, in climate change policy, “mitigation” is defined differently, and is the term used for the reduction of greenhouse gas emissions that are the source of climate change. (United Nations Office for Disaster Risk Reduction, 2017)
Paleoseismicity	Refers to earthquakes recorded geologically, most of them unknown from human descriptions or seismograms. Geologic records of past earthquakes can include faulted layers of sediment and rock, injections of liquefied sand, landslides, abruptly raised or lowered shorelines, and tsunami deposits. (United States Geological Survey, n.d.)
Preparedness	The knowledge and capacities developed by governments, response and recovery organizations, communities and individuals to effectively anticipate,

	respond to and recover from the impacts of likely, imminent or current disasters. (United Nations Office for Disaster Risk Reduction, 2017)
Raster	A raster consists of a matrix of cells (or pixels) organized into rows and columns (or a grid) where each cell contains a value representing information. (ESRI, n.d.)
Still Water Level	The level of the water surface in the absence of waves.
Tsunami Inundation Depth, or Flow Depth	Depth, or height of the tsunami above the ground at a specific location. (Intergovernmental Oceanographic Commission, 2019)
Tsunami Inundation Height	Elevation reached by seawater measured relative to a stated datum at a specified inundation distance. Inundation height is the sum of the flow depth and the local topographic height. Sometimes referred to as tsunami height. (Intergovernmental Oceanographic Commission, 2019)
Tsunami Period	Amount of time that a tsunami wave takes to complete a cycle, or one wavelength. Tsunami periods typically range from 5-60 minutes. Tsunami period is often measured as the difference between the arrival time of a peak and the next one. (Intergovernmental Oceanographic Commission, 2019)
Tsunami Risk	The potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time, determined probabilistically as a function of tsunami hazard, exposure, vulnerability and capacity (United Nations Office for Disaster Risk Reduction, 2017).
Tsunami Runup	Elevation reached by water measured relative to some stated datum and measured ideally at a point that is a local maximum of the horizontal inundation (Intergovernmental Oceanographic Commission, 2019).
Tsunami Wave Amplitude	The absolute value of the difference between a particular peak of the tsunami and the undisturbed sea level (Intergovernmental Oceanographic Commission, 2019).

Tsunami Wave Height	Height measured from the wave trough to the wave crest after removing the tidal variation (Intergovernmental Oceanographic Commission, 2019).
Tsunami Wave Velocity	The speed at which the crest of tsunami waves travels across the sea and differs from the velocity of the water induced by the passage of the waves.
Recovery	The restoring or improving of livelihoods and health, as well as economic, physical, social, cultural and environmental assets, systems and activities, of a disaster-affected community or society, aligning with the principles of sustainable development and "build back better", to avoid or reduce future disaster risk (United Nations Office for Disaster Risk Reduction, 2017).
Response	Actions taken directly before, during or immediately after a disaster in order to save lives, reduce health impacts, ensure public safety and meet the basic subsistence needs of the people affected (United Nations Office for Disaster Risk Reduction, 2017).
Vulnerability	The conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards (United Nations Office for Disaster Risk Reduction, 2017).

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