District of Ucluelet Coastal Flood Mapping

Final Report

26 June 2020

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Project Number: P154

Cover Photo: Ucluelet Lighthouse Loop (Wild Pacific) Trail during typical spring conditions. Ebbwater Consulting Inc. image (2020).

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Certification

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Revision History

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The authors wish to acknowledge the support of the District of Ucluelet project manager, John Towgood (Planner 1), and Bruce Greig (Manager of Community Planning), who provided guidance and local knowledge throughout the project.

The District of Ucluelet acknowledges that it is located on the traditional territory (ḥaaḥuułi) of the Yuułuʔiłʔatḥ (Ucluelet First Nation). The Yuułuʔiłʔatḥ are neighbouring communities who share interests in the Ucluth Peninsula and surrounding area.

Ebbwater would like to acknowledge that this report was written at the Ebbwater Consulting Inc. office (and home offices), which are located on the unceded and traditional territory of the Coast Salish Peoples.

The report and accompanying materials were written and prepared by Robert Larson, M.Sc., Nikoletta Stamatatou, M.Sc., and Silja Hund, Ph.D., and Dickon Wells, M.Eng., all of Ebbwater Consulting Inc. Significant contributions to the report were made by Cascadia Coast Research Ltd. The report and accompanying materials were reviewed by Tamsin Lyle, P.Eng., principal of Ebbwater Consulting Inc. and Adrian Chantler, Ph.D., P.Eng., independent consultant.

Executive Summary

Ucluelet's stunning coastal landscape also means that it is exposed to coastal flood hazards from storms and tsunamis. These hazards are heightened by climate change and rising sea levels. The District of Ucluelet (DOU) has recognized the importance of better understanding coastal flood hazards to support policy and planning, as well as emergency management. Flood hazard maps are a foundational tool; a good understanding of where and how deep water might be in a flood event provides the basis for making sound decisions on flood management.

As a first step to support the DOU in becoming more resilient to future flooding, Ebbwater Consulting Inc. and its partner Cascadia Coast Research Ltd. assessed coastal flood hazards from coastal storms and tsunamis, considering sea level rise in accordance with BC Provincial Guidelines. Specifically, the objectives of this study were to develop a series of flood hazard maps for the area that can inform policy and planning instruments, such as flood construction levels (FCLs), Sea Level Rise Planning Areas, and general strategic planning as relevant for the Official Community Plan (OCP).

Coastal Storm Flood Hazard Mapping

Coastal storms create conditions where the total water levels in the ocean are higher than normal, flooding normally dry areas of the coastline. High coastal water levels are a function both of predictable tides, which ebb and flow on a twice-daily basis, as well as less predictable, but statistically understood storm residuals. Storm residuals include storm surge, wind set-up and wave effects. In addition to these components of total water level, the DOU, like all coastal communities, is faced with Sea Level Rise (SLR).

In this study, coastal modelling of storm-induced flood hazard was conducted using a continuous simulation approach. Tides, wind set-up, storm surge, and wave effects were hind-cast over a historical period of 40 years using measurements, or using modelling where no measurements were available. With the resulting dataset and extreme value analysis, the 6.67%, 2%, 1%, 0.5%, and 0.2% Annual Exceedance Probability (AEP; 15-, 50-, 100-, 200-, and 500-year indicative return period, respectively) floods were determined. These 5 AEP floods were considered for each of 4 Relative SLR scenarios (RSLR 0 m, 0.5 m, 1 m, and 2 m). The RSLRs are loosely associated with different time periods for this project based on climate change projections (i.e., present-day, near future, future, and far future, respectively). The combination of AEPs and RSLRs meant that a total of 20 scenarios were modelled along the coastline of the DOU. For a selection of these 20 scenarios, flood depths and extents were mapped to capture the lower and higher ends of the range of results, including more frequent and more rare flood scenarios for different RSLRs.

In addition to the science-focussed hazard maps, this project included the development of planning support maps. In the first instance, Flood Construction Level (FCL) maps that meet regulatory requirements of the Province of British Columbia were developed. These are based on the hazard maps, but also include a factor of safety, and are presented in a specific mandated format. FCL maps for near future and future (0.5 m and 1 m RSLR) scenarios were developed.

Further to the mandated FCL maps, a final series of maps, which are designed to simplify the implementation of building and zoning bylaws and policies, by grouping areas into FCL zones are provided. Each FCL zone represents an area with similar hydraulic (i.e. water levels and wave and run-up conditions) and planning (i.e. neighbourhoods and cadastral lots). As for the mandated FCL maps, these were developed for the near future and future (0.5 m and 1 m RSLR). The intent of providing two time period RSLRs is to support different planning needs (e.g. building permits for sites that may experience 0.5 m of SLR in their lifetime (near future) versus longer-term strategic planning and permitting of new neighbourhoods or critical infrastructure that might experience 1 m of RSLR over their design life).

The FCLs range widely throughout the DOU, because of the complex shorelines (Figure 1 shows a portion of the project area). For example, it is lower along the Ucluelet Inlet shoreline (i.e., 4.5 m CGVD2013 along the Small Craft Harbour and 7.5 m for portions of Hyphocus Island) and moderate along the southern tip of the peninsula (between 9.6 m and 12.2 m). On the western shores, the FCL is generally higher than within the Ucluelet Inlet (i.e., ranging from 9.2 m to 14.2 m along the northwestern shores, and between 8.0 and 11.9 m in the Big Beach area). These differences stem from both the aspect of the shoreline, where protected areas are less subject to wave effects, and from the topography of the shoreline itself; water levels are higher on steep coasts where water 'piles up' more than on gently-sloping shores.

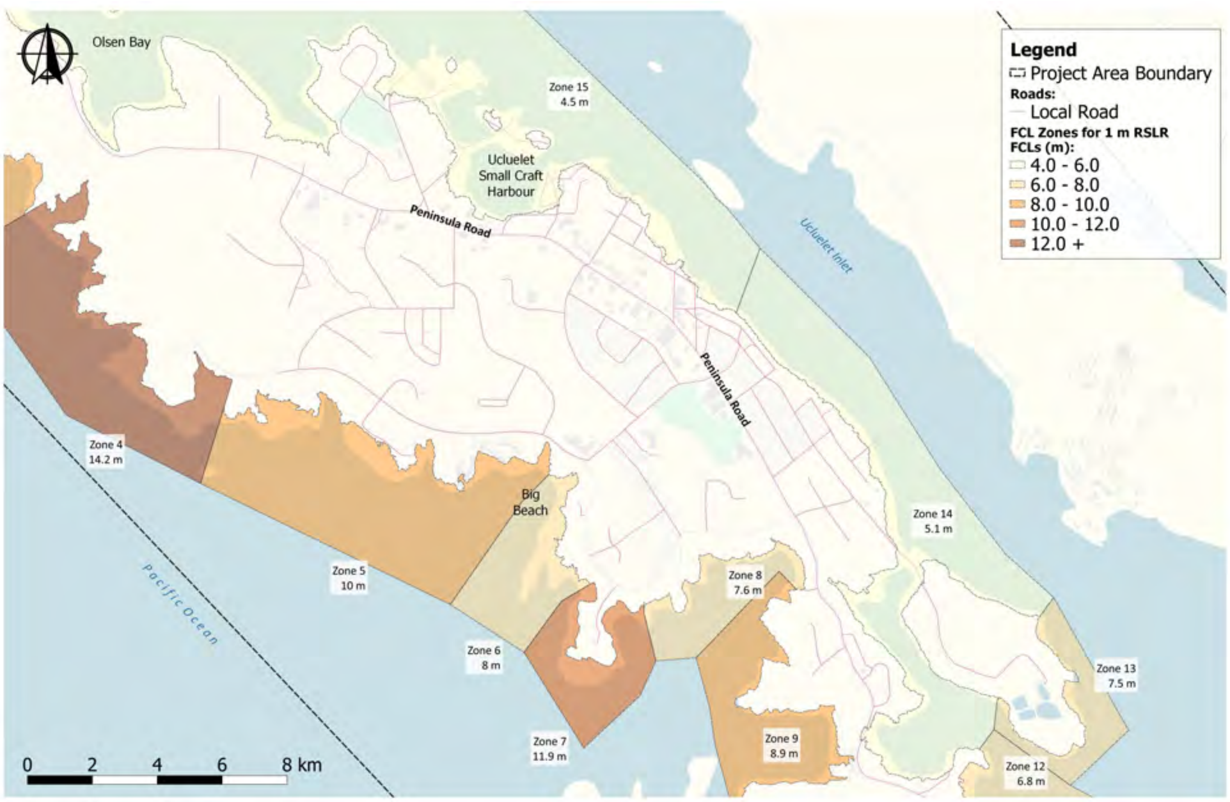

Figure 1: FCL reaches for an example area of the DOU, for the 1 m RSLR scenario.

The FCL maps focus on the DOU's boundaries; however, the results data are available for the eastern shores of Ucluelet, to be shared with neighbouring jurisdictions. The depth and extent maps, including for tsunami hazard, include this wider area as well.

Tsunami Flood Hazard Mapping

Tsunamis, which are generated when seismic activity in the ocean displaces large volumes of water, ultimately creating long and very fast waves, are a threat in the DOU.

Tsunami flood hazard modelling in this study focussed on a Cascadia Subduction Zone (CSZ) megathrust earthquake, based on 6 different rupture models (the Alaska 1964 tsunami that affected the area was also considered, though it was not modelled). This CSZ megathrust event was selected based on current understanding of the likely worst-case scenario for the DOU, and on available data to support this study. The 4 RSLRs of 0 m, 0.5 m, 1 m, and 2 m were also considered for modelling the CSZ tsunami. The rupture models and RSLR combinations meant that a total of 24 tsunami flood hazard scenarios were modelled along the coastline of the DOU. A selection of these were mapped to capture the lower and higher ends of the range of the results. These included tsunamis generated from so-called buried and splay faulting ruptures.

For all tsunami scenarios simulated, the peninsula would be cut-off due to flooding of Peninsula Road near Olsen Bay. Flood depths associated with the splay faulting rupture (considered a worst-case based on the ruptures modelled) are high, affecting nearly all shoreline areas (Figure 2). Along the Inlet shores, this includes areas in and around the Harbour in particular, where flooding may stretch across Peninsula Road. Flood water would cut-off the Helen Road causeway to Hyphocus Island. Flooding would also affect areas of, and access to, the southern peninsula. Along the western shores, flooding would occur around Big Beach, and affect Marine Drive and areas further inland.

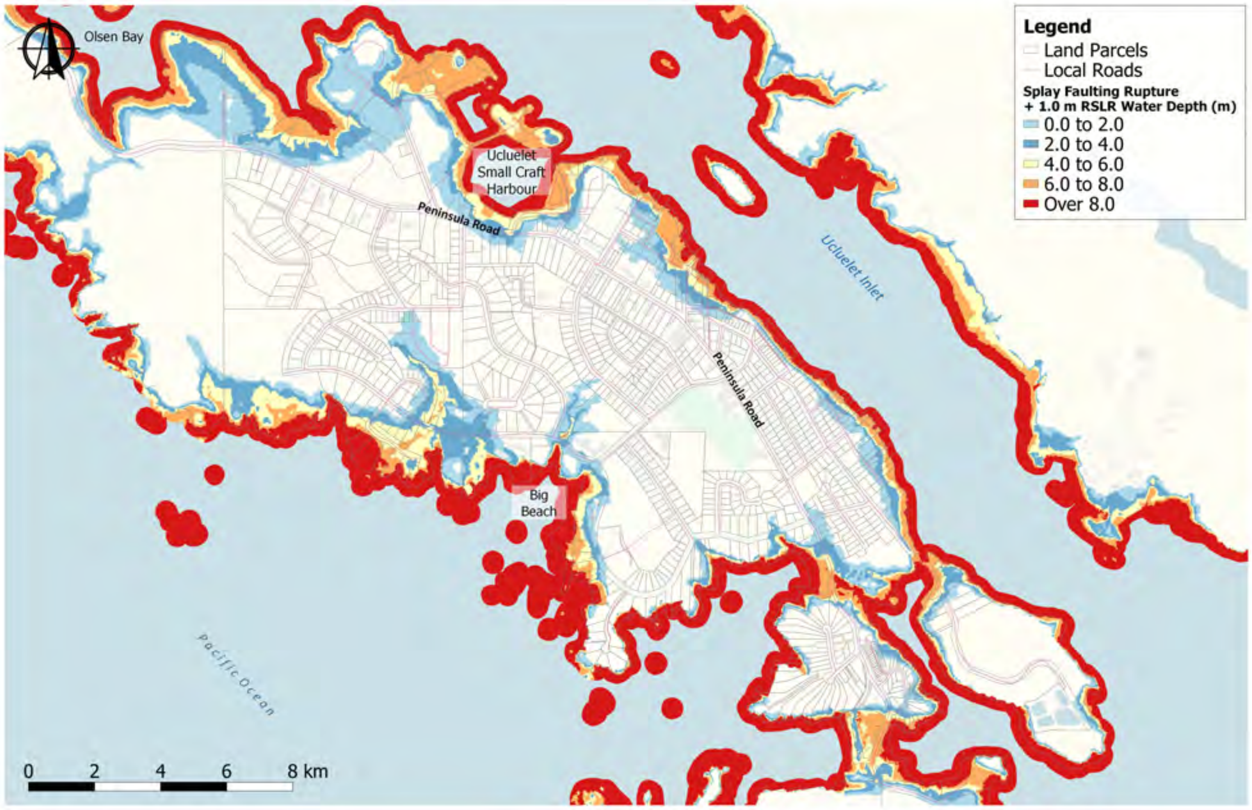

Figure 2: Tsunami flood depths for an example area of the DOU, for a tsunami generated by a splay faulting rupture, for the 1 m RSLR scenario.

The tsunami flood depth and extent maps can support emergency response planning, and other policy and planning decisions. To support these objectives, tsunami flood planning level maps were produced, both with and without a 50% safety factor. A tsunami hazard vulnerability zones map, which considers the damage potential of an event as a function of water depth and velocity, is also provided.

Summary of Technical Approaches

A summary of the technical approaches for modelling and mapping is provided in the table below. The intent is to facilitate the comparison of key details across coastal flood hazard maps in the region.

Measure	Description
Geographic References	
Mapping Outputs	Vertical Datum: CGVD2013 Coordinate System: NAD83, UTM 10N
Coastal Storm Flood Hazard Modelling	
Topographic Inputs	LiDAR 2015

Measure	Description
Bathymetric Inputs	General Bathymetric Chart of the Oceans; Electronic Navigation Charts soundings and contours (Canadian Hydrographic Services).
Coastal Storm Flood Hazard Modelling	Continuous simulation approach (hind-cast over 1979–2018). • Tides: deterministically modelled. • Wind set-up: historic wind data and 2D hydrodynamic model. • Storm surge: Tofino and Ucluelet tide gauges. • Wave conditions: 2D wave model (SWAN). • Wave effects (runup): for 48 cross-shore transects, 1D model. • 6.67%, 2%, 1%, 0.5%, and 0.2% AEP floods
Tsunami Flood Hazard Modelling	Cascadia Subduction Zone (CSZ) megathrust earthquake rupture models based on Wang *et al.* (2003) and Gao *et al.* (2018). • Rupture models: buried (2), splay faulting (2), and trench-breaching (2) • Tsunami waves: 2D hydrostatic model (RiCOM).
Climate Change Consideration	• Relative sea level rise (RSLR) scenarios for 0 m, 0.5 m, 1 m, and 2 m (qualified for this project as present-day, near future, future, and far future, respectively). • Storminess assumed to stay similar to historical records, in line with current research.
Coastal Storm Flood Hazard Mapping	
Topographic Inputs	LiDAR 2015 (0.35 m spatial resolution).
Hydraulic Methods	Inundation approach based on modelled cross-sections and 2015 LiDAR.
Planning Support (Based on Provincial guidance)	• Sea Level Rise Planning Area: 0.5% AEP flood, with 0.5 m and 1 m RSLR and 0.6 m freeboard. • Flood Construction Level: 0.5% AEP, with 0.5 m and 1 m RSLR and 0.6 m freeboard.
Flood Depth (flood depth data is provided for all AEPs and RSLRs)	• AEP floods: 6.67% and 0.5%. • RSLR: 0 m, 1 m, 2 m. • No freeboard.
Flood Extent (flood depth data is provided for all AEPs and RSLRs)	• 6.67% AEP with 0 m, 1 m, and 2 m RSLR. • No freeboard.

Measure	Description
Tsunami Flood Hazard Mapping	
Maximum Flood Depth	• Rupture models: Buried (Wang *et al.,* 2003) and splay faulting (Gao *et al.,* 2018). • RSLR: 2 m.
Maximum Flood Extent	• Rupture models: Buried (Wang *et al.,* 2003) and splay faulting (Gao *et al.,* 2018). • RSLR: 0 m, 1 m, 2 m.
Planning Support	• Tsunami flood planning level: Buried (Wang *et al.,* 2003), and splay faulting (Gao et al., 2018), for 1 m RSLR, with and without 50% safety factor. • Tsunami flood hazard vulnerability zones: Splay faulting rupture (Gao *et al.,* 2018), 1 m RSLR, without safety factor.

Recommendations

This project has established a solid foundation to help the DOU reach important flood hazard policy and planning objectives. In order to leverage this information and build resilience, the following recommendations are made:

1. **Communicate**: Maps and reporting should be shared with the public. It is best practice to acknowledge and share information related to natural hazards widely. This allows for an increased understanding of the hazard that can inform both individual and government actions to reduce risk.
2. **Monitor and Update**: The mapping provided within this report is based on the best available science. However, there is still much uncertainty associated with some elements. For example, the probability and severity of the seismic sources for tsunami, and the rate of sea level rise. Given these uncertainties, and the likelihood that the state of knowledge will improve with time, it is important to monitor new science, and to review the validity of the assumptions used to develop these maps. A 5-year review is recommended.
3. **Implement Next Steps to Reduce Risk**: In order to benefit from these maps, it is imperative that the DOU uses this information to plan for coastal flood hazards. Best practice in terms of a planning process would be to combine this hazard information with exposure, vulnerability and impacts, information in the form of a risk assessment. This can then be used as the basis of a planning framework to reduce risk and increase resilience over time.

Contents

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List of Acronyms and Key Abbreviations

AEP	Annual Exceedance Probability
AIDR	Australian Institute for Disaster Resilience
BC	British Columbia
CC	Creative Commons
CCR	Cascadia Coast Research Ltd.
CD	Chart Datum
CEPF	Community Emergency Preparedness Fund
CGVD	Canadian Geodetic Vertical Datum
CRD	Capital Regional District
CSZ	Cascadia Subduction Zone
CVS	Coastal Vulnerability Study
DEM	Digital Elevation Model
DFL	Designated Flood Level
DOU	District of Ucluelet
DPA	Development Permit Area
ECCC	Environment and Climate Change Canada
ECMWF	European Centre for Medium-Range Weather Forecasts
EGBC	Engineers and Geoscientists British Columbia (formerly APEGBC)
ENSO	El Niño Southern Oscillation
FEMA	Federal Emergency Management Agency (United States)
FCL	Flood Construction Level
FCRP	Flood Construction Reference Plane
G2018-S-A	Gao *et al.* (2018) splay faulting A rupture model
GIS	Geospatial Information Systems
HHWLT	Higher High Water Large Tide
HHWMT	Higher High Water Mean Tide
IPCC	Intergovernmental Panel on Climate Change
ISC	Indigenous Services Canada
LiDAR	Light Detection and Ranging
NCEP	National Centers for Environmental Prediction (United States)
NOAA	National Oceanic and Atmospheric Administration (United States)
OCP	Official Community Plan
PCIC	Pacific Climate Impacts Consortium
PDO	Pacific Decadal Oscillation
PTHA	Probabilistic Tsunami Hazard Assessment
RiCOM	River and Coastal Ocean Model
RSLR	Relative Sea Level Rise
SLR	Sea Level Rise
SWAN	Simulating Waves Nearshore
UNDRR	United Nations Office for Disaster Risk Reduction (formerly UNISDR)
UK	United Kingdom
UTM	Universal Transverse Mercator
W2003	Wang *et al.* (2003) buried rupture model
2D	Two-dimensional

1 Introduction

The District of Ucluelet (DOU), located on the rugged outer west coast of Vancouver Island, has a spectacular and diverse coastal landscape. The area's unique setting, on the Ucluth Peninsula between Barkley Sound and the Pacific Ocean, makes it an attractive place to live, work, and visit. The DOU is home to approximately 1,700 permanent residents, and numerous annual visitors contribute to a strong tourism economy. This coastal setting, however, also means that the area is exposed to coastal flood hazards from storms and tsunamis. These hazards are further complicated by the changing climate, particularly sea level rise (SLR).

It is well documented that preparation and planning ahead of a disaster will greatly reduce cost and suffering during and after a disaster event[1]. Flood hazard maps are an essential tool to support preparation and planning; without a good understanding of where and how deep water might be in a flood event, we have no hope of making sound decisions that will mitigate future losses. Flood maps are recognized as a necessary starting point for flood management.

The DOU has recognized the importance of understanding coastal flood hazards, especially in the context of changing sea levels and wants to better understand the nature of these hazards so that they can plan to mitigate the risk associated with them. The DOU applied for and received funds from the Province of British Columbia through the Community Emergency Preparedness Fund to develop modern flood maps to support the goal of better understanding the coastal hazards.

In November 2019, the DOU retained Ebbwater Consulting Inc. (Ebbwater) and its partner Cascadia Coast Research Ltd. (CCR) to develop a series of flood hazard maps, for both coastal storm hazards and tsunamis, that incorporate climate change. This information will be used to inform policy and planning instruments (Flood Construction Levels, Sea Level Rise Planning Areas, Hazard Development Planning Areas, etc.) with the goal of reducing community risk to coastal flooding.

1.1 Project Objectives

Flood maps are technical tools that require a significant amount of data and expertise to develop, and they are used for various purposes. To this end, the primary objectives for this project were:

1. Develop robust flood mapping for the DOU that considers storm- and tsunami-induced flood hazards for the present-day and future, with consideration of sea level rise.
2. Develop various mapping outputs to support policy and planning, and engagement including with neighbouring communities:

1 The United Nations Office for Disaster Risk Reduction (UNDRR) contains numerous resources through the lens of of better understanding risk. Weblink: https://www.undrr.org/building-risk-knowledge.

a. Establishment of a [coastal storm] flood construction level (FCL).
b. Identification of SLR Planning Areas.
c. Identification of a tsunami flood planning level.
d. Preliminary understanding of risk through flood hazard vulnerability zones.

1.2 Project Approach

This work generally followed the approach set out in the Professional Practice Guidelines for Flood Mapping in BC, henceforth referred to as the *Professional Practice Guidelines* (APEGBC, 2017). It also references the Provincial Coastal Floodplain Mapping – Guidelines and Specifications (Kerr Wood Leidal, 2011), as well as various Provincial documents developed to provide guidance on sea level rise (Ausenco Sandwell, 2011b, 2011d, 2011a), henceforth referred to as *Provincial Guidelines*. In addition, draft materials being developed as part of the Federal Floodplain Mapping Guideline Series (Natural Resources Canada, 2018) were considered in the development of this report and associated maps. Where appropriate and as detailed in the report, other standards that, in Ebbwater's professional opinion, met or exceeded the bar set by Provincial standards, were also used to inform this work.

The coastal modelling work was conducted by Ebbwater's subconsultant CCR. The modelling methods associated with CCR's work are described in detail in Appendix A and summarized in this report. The coastal modelling results were used by Ebbwater to produce flood hazard mapping for the DOU.

1.2.1 A Note on Terminology

Hazards are events or phenomena that have the potential to cause harm. Hazard mapping can be technically complex, and more detailed concepts and definitions are included in Section 2. Throughout this report, several terms have been simplified to facilitate understanding of different hazard scenarios. Two key simplifications are described below:

Future Scenarios: When describing time periods for SLR caused by climate change, we use "present-day", "near future", "future", and "far future" in a relative sense. These time periods are loosely associated with different levels of relative sea level rise (RSLR, explained further in Section 2.1.3). RSLR of 0 m is considered to represent present-day conditions, RSLR of 0.5 m represents conditions in the near future, and so on for 1 m and 2 m RSLR. It is important to understand that projections of sea level rise are highly uncertain; consequently, so are the future time-periods associated with them.

Tsunami Scenarios: When describing tsunamis, we defined one as the 'comparative-case', and another as the 'worst-case'. The comparative-case is based on a tsunami rupture model (a buried rupture defined by Wang et al., (2003)) that has been used in previous studies; it allows results to be compared with other tsunami flood hazard maps from the region. The worst-case is based on a splay faulting rupture defined by Gao *et al.*, (2018). Out of the 6 rupture models used in this study, the Gao *et al.*, (2018) rupture model (specifically the one we call G2018-S-A) resulted in the largest extents for the project area; it represents the 'worst-case' studied for this project. It is possible that other tsunami sources that were not considered within this project could result in greater flooding at Ucluelet.

A full glossary of terms is included at the end (Section 10) of the report.

1.3 Report Structure

The primary purpose of this document is to provide a summary of the background and methods used to produce the flood hazard maps for the DOU. The structure of this report is as follows:

- Section 2 contains a primer on coastal flood hazard mapping to support the understanding of this report and any decision-making based on it.
- Section 3 provides background on the study area, with description of setting and history of flooding in the DOU to give an indication of the hazard.
- Section 4 describes the coastal modelling and mapping methods used to produce the technical results and relevant flood maps.
- Sections 5 and 6 provide coastal storm and tsunami flood hazard mapping results and discussion, respectively (with additional maps provided in Appendix C).
- Section 7 provides a summary of study limitations.
- Section 8 includes the recommendations from this study.
- Section 9 contains the study conclusions.

The main report is supported by the following appendices:

- Appendix A details the coastal storm and tsunami hydrodynamic modelling analyses (completed by CCR).
- Appendix B provides a preliminary data evaluation on coastal erosion.
- Appendix C is the Coastal Flood Hazard Map Atlas.
- Appendix D provides additional information on the methods and differences in approaches for the mapped coastal storm flood depths and flood construction levels.
- Appendix E provides the Association of Professional Engineers and Geoscientists of BC (APEGBC now EGBC) Flood Mapping Assurance Statement.

Other deliverables for this project include materials for display in an open exhibit for the public to learn about the project findings, as well as on a project website. Ebbwater also provided a data package that includes all the files necessary to reproduce, and build on, the project outputs.

2 Coastal Flood Hazard Map Primer and Definitions

This section provides an introduction to coastal flood hazards and flood mapping, and how these relate to flood management and planning. It provides background materials to support the understanding and interpretation of the main body of the report.

2.1 What is a Coastal Flood Hazard?

The British Columbia (BC) coastline is exposed to a number of coastal flood hazards; a hazard is a process or phenomenon that may cause damage. Coastal flood hazards are generally grouped into two main categories: coastal storm floods and tsunamis. Erosion, induced by flood hazards, can also cause damage along the coast.

Not all coastal flood hazards are created equal—flood hazard characteristics can differ in terms of water depth and velocity, frequency, onset, and duration. These characteristics affect how the shore and the assets on it are impacted by flood. Therefore, it is important to understand as many aspects of the hazard as possible. In addition, these characteristics are changing due to climate change; the frequency of weather-driven events is likely to increase and sea levels are rising (IPCC, 2014).

2.1.1 Coastal Storm Flood Hazard

Weather-driven hazards arise when water levels are higher than normal in the Pacific Ocean because of storm activities. Water levels in the ocean off the coast are a function of many components. Some of these components are predictable (deterministic), such as tides. Other components are less predictable (probabilistic); these are factors that increase water elevations as a result of storm events and include storm surge, wind and wave set-up, and waves (see Figure 1). These processes have varying likelihoods of occurrence and require detailed analyses of specific events to quantify the resultant combined effect on total water levels.

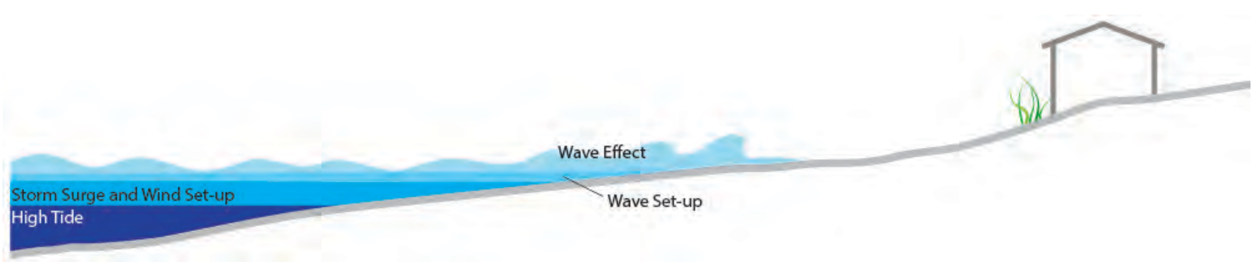

Figure 1: Components of total water level (total water level is composed of tide, storm surge, wind set-up, wave set-up and wave runup).

Tides (Deterministic)

Tides are the periodic rise and fall of the ocean surface. Tide levels vary throughout the day, but are also subject to longer-term cycles, caused primarily by the relative positions of the sun, moon, and Earth. The maximum tidal elevation occurs once every 18.6 years in BC, but the level comes close to this for a few tides each year. These yearly large tides are often referred to as king tides.

Storm Surge (Probabilistic)

A storm surge is a localized increase in water levels due to low-pressure systems in the atmosphere (storms). As these systems move from the Pacific into coastal water, the reduced localized atmospheric pressure on the ocean causes the water levels to rise.

Wave Effects (Probabilistic)

Large waves that break on the beach cause both a static increase in water level (wave set-up) and a dynamic, oscillating variation in water level (wave runup).

Wind Set-Up (Probabilistic)

Wind set-up is associated with strong local onshore winds blowing over shallow water. This wind blows the water onto the shore resulting in a localized increase in the water level as the water is “piled up” against the shore.

Inter-Annual Climate Variation

Inter-annual climate variation refers to cyclical shifts in climate conditions due to global atmosphere-ocean circulations, for example the Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO). Variations of sea level with these oscillations are mostly due to changes in water temperatures and the resulting expansion or contraction of sea water.

In addition to affecting total still water levels, many components of coastal storms have significant associated forces that can damage the shoreline and assets on it. Wave effects can be particularly damaging. Coastal erosion can be induced by storms and creates a significant secondary hazard (see Section 2.1.4).

2.1.2 Tsunami Flood Hazard

Tsunami flood hazards are series of waves of potentially large magnitude created by displacement of mass in the ocean. The causes vary from sub-sea landslides to earthquakes, which release tremendous amounts of energy. This energy spreads outwards from the source as tsunami waves. The generating source may be proximal (near to) or distal (far away) relative to the area of interest.

Initially, the waves are small, but have long wave periods and wavelengths, and can travel at great speeds (up to 700 km/hr). As tsunami waves approach land, the waves slow and grow in height (this is called shoaling), ultimately landing on shore with great energy and causing significant destruction (Australian Government. Bureau of Meteorology, 2018). A tsunami wave that reaches land is characterized by its maximum inundation elevation and distance (Figure 2).

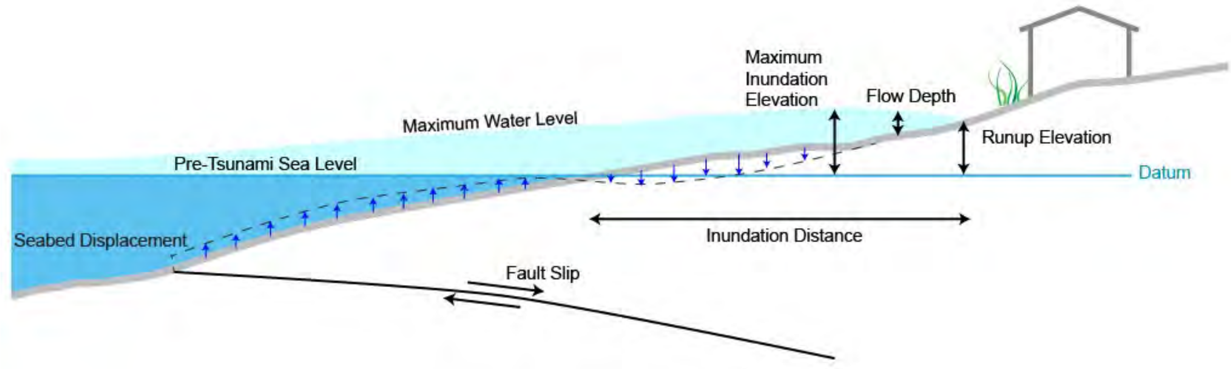

Figure 2: Features of a tsunami caused by an earthquake. The fault slip causes seabed displacement that generates the tsunami. Maximum water levels increase towards the shore due to shoaling (figure adapted from UNISDR, 2017).

2.1.3 Climate Change and Sea Level Rise

Around the world, sea levels are rising due to the melting of ice caps and glaciers with climate change, and the expansion of ocean water caused by warming (Union of Concerned Scientists, 2015). Variations in local sea level rise (SLR) occur due to differences in topography, gravitational forces, and ocean currents; the west coast of North America generally experiences lower than average global SLR rates.

Relative sea level rise (RSLR) is a function of the rise in sea level compared to vertical changes resulting from geological processes (land subsidence or uplift over time) (Figure 3).

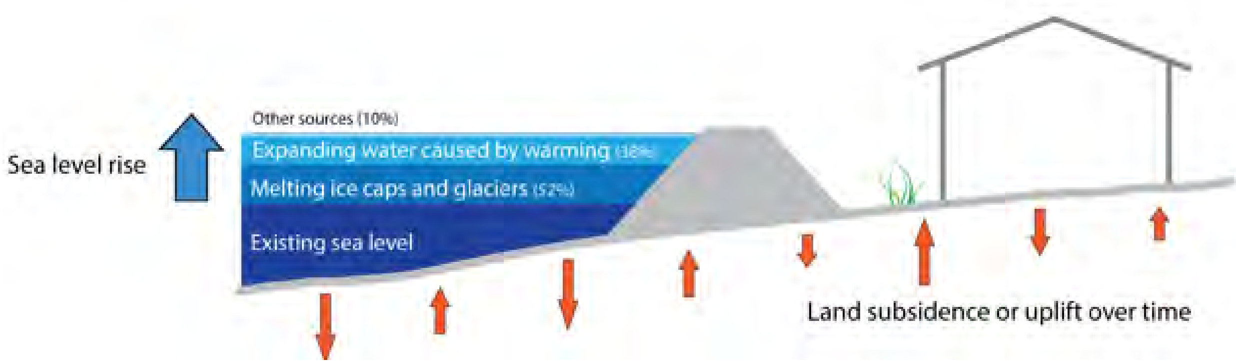

Figure 3: Drivers of RSLR including components of SLR and land subsidence or uplift—estimates of factors contributing to SLR are based on Union of Concerned Scientists (2015).

SLR is a quasi-deterministic process (i.e., the upward trend is known, but the rate of change is unknown) and the uncertainty in projections is large. For example, while the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report projected global SLR of less than 1 m by 2100 (IPCC, 2014), more recent studies project SLR of several metres on a time scale of 50 to 150 years (Hansen *et al.,* 2016). The more recent study considered the possibility that the Greenland and Antarctic ice sheets would melt; this has begun and is assumed to be a non-linear process.

The *Professional Practice Guidelines* and the *Provincial Guidelines* both propose 1 m of SLR by 2100 (see Figure 4). This guideline was developed in 2011 and is arguably out of date given recent emissions projections and new understanding of SLR science (West Coast Environmental Law, 2017). However, new guidance is not expected for another 3 to 4 years (Ebbwater Consulting and Compass Resource Management, 2018) as it is reliant on updates to global emissions and SLR estimates from the Sixth Assessment Report from the IPCC (expected in 2022). In the meantime, it is prudent to assume that 1 m of SLR will occur at some point, and it is the timing (in the next 50 years to 100 years) that is uncertain.

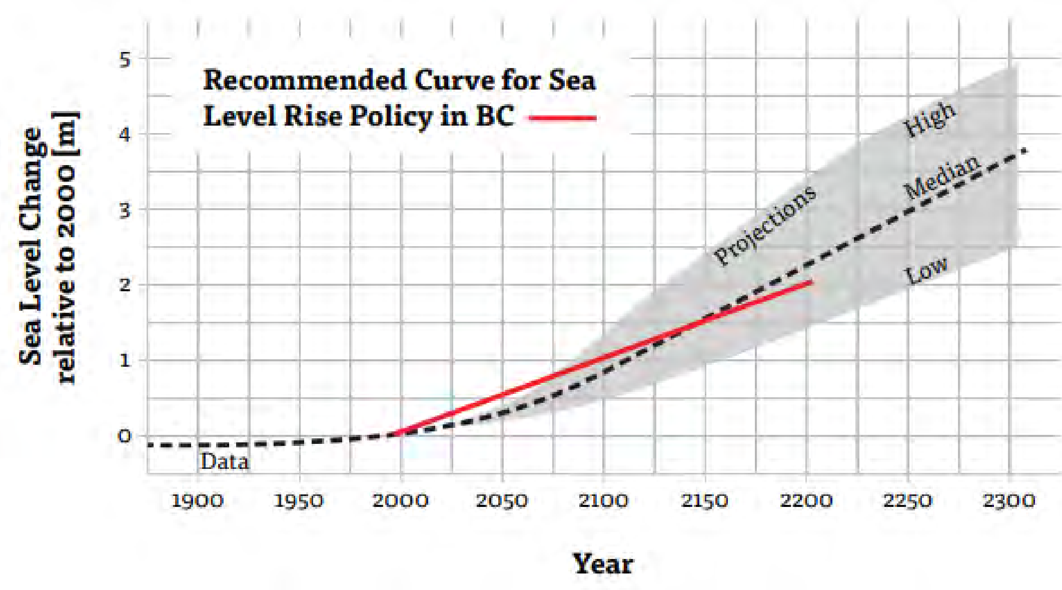

Figure 4: Projections of global SLR (Figure from (APEGBC, 2017)**.**

Climate change and SLR must be considered to determine total water levels resulting from storm hazards. It should be noted that there is limited information to inform changes to the storm hazard intensity (sometimes called storminess) and frequency off the west coast of Canada as a result of climate change. At present, the guidance is to continue to use historic records to inform flood hazard assessments and mapping (see Section 4.3 for discussion of this in the DOU area in particular).

2.1.4 Erosion Hazards

Coastal erosion describes the loss of land due to the net removal of sediment or bedrock (UNISDR, 2017). It can occur as a result of the forces associated with waves and currents, and therefore significant coastal erosion is generally associated with extreme weather events and other coastal hazards (e.g., tsunamis). During extreme weather, waves are generally more intense, but also reach further inland to landforms that are otherwise not exposed. Waves are often also accompanied by intense precipitation, which can saturate and weaken the coastal landforms. Coastal erosion can also occur as a result of geomorphic mass wasting processes, and subsidence. However, these are not directly related to flood hazards. Climate change is expected to accelerate erosion on Canada's coasts (Vadeboncoeur, 2016).

2.2 Hazard Components

A natural hazard such as coastal flooding is generally defined by considering a hazard profile, which is made up of the flood hazard magnitude and associated characteristics (onset, depth, velocity, etc.) and the likelihood (probability) of the hazard occurring. Storm events have a range of likelihoods and associated magnitudes. Risk management professionals generally consider the risk associated with an event to be the product of the probability of it occurring and the consequences.

An understanding of the hazard profile is important when considering planning and response. A full flood hazard assessment requires an understanding of what will flood, and how likely this is. The work conducted as part of this project considered a variety of hazard scenarios to support the concept of a hazard profile, and future risk profiles.

2.2.1 Flood Hazard Magnitude

The magnitude of flooding of an area as a result of a flood hazard is best estimated through the development of detailed coastal hydraulic analyses. Coastal modelling provides information on present-day and future (with climate change) estimates of the depth of water that might be expected, as well as flood extents.

2.2.2 A Note on Hazard Likelihood

In addition to an understanding of where water will go in a flood, it is important to consider the likelihood of an event occurring. This is generally represented as an Annual Exceedance Probability (AEP), where the AEP refers to the probability of a flood event occurring or being exceeded, in any given year, and where the probability is expressed as a percentage. For example, an extreme flood that has a calculated probability of 0.2% of occurring (or being exceeded) in this year (or any given year) is described as the 0.2% AEP flood. In the past, flood hazard likelihood was commonly represented as an X-year return period. However, this tends to cause confusion as to the frequency of an event with lay people (e.g., it is commonly thought that if a 100-year flood has just occurred, it will not recur for another 99 years, which is not the case), and therefore best practice dictates the use of an AEP to describe flood likelihood.

Another way to think about flood likelihood is through the use of encounter probabilities, where it is possible to calculate the likelihood of encountering an event of a given size over a defined time period—for example, the length of an average mortgage (25 years) or the lifespan of a human (75 years). For instance for a 1% AEP event, there is a 22% chance that an event of this size or greater will occur over a 25-year period (Table 1). Understanding the likelihood of an event, as well as the encounter probability of an event, can support decisions related to flood management.

Table 1: Encounter probabilities for various flood likelihoods.

Annual Exceedance Probability (AEP)	Indicative Return Period	Encounter Probability of Occurrence in 25 years	Encounter Probability of Occurrence in 50 years	Encounter Probability of Occurrence in 75 years	Encounter Probability of Occurrence in 100 years
6.67%	Once every 15 years	82%	97%	99%	100%
2%	Once every 50 years	40%	64%	78%	87%
1%	Once every 100 years	22%	39%	53%	63%

Annual Exceedance Probability (AEP)	Indicative Return Period	Encounter Probability of Occurrence in 25 years	Encounter Probability of Occurrence in 50 years	Encounter Probability of Occurrence in 75 years	Encounter Probability of Occurrence in 100 years
0.5%	Once every 200 years	12%	22%	31%	39%
0.2%	Once every 500 years	5%	10%	14%	18%

2.3 Flood Maps

Flood hazard maps are an essential tool to reduce flood risk as they provide a visualization of a flood hazard and an understanding of where and how deep water might be in a flood event. This can be used for understanding the current flood risk of an area and for planning to help ensure that flood risk is not increased. Flood maps are recognized as a necessary starting point for flood management.

Flood maps are produced by taking information from hydraulic models and calculations and applying these to base maps to show the extent of flooding. The *Professional Practice Guidelines* suggest that flood maps can show a variety of flood effects, and depending on the purpose and budget of a project, these include:

- **Flood Inundation Maps:** These maps show the extent of the flood hazard area.
- **Flood Hazard Maps:** Hazard maps go beyond extent maps by providing information on the hazards associated with defined flood events, such as water depth, velocity, or duration of flooding.
- **Flood Risk Maps:** Risk maps reflect the potential damages that could occur as a result of a range of flood probabilities by identifying populations, buildings, infrastructure, residences, and environmental, cultural, and other assets that could be damaged or destroyed.

Flood maps can also include the following map types (Herbert, Picketts and Lyle, 2014):

- **Flood Event Maps**: Event maps document a specific flood event based on imagery and surveying at time of flooding. They can be used for future flood planning and to evaluate modelling results.
- **Flood Emergency Maps**: Emergency maps show basic information about the flood hazard area, as well as disaster response routes and evacuation zones.
- **Probabilistic Flood Hazard Map Series**: These depict a series of flood hazard maps showing hazard under various events. This includes mapping for coastal storms and tsunamis.

The intent of this project is to develop a series of flood hazard maps for coastal storm flood hazards. With additional processing, the hazard maps can be used to create maps to better inform policy and planning decisions. These include Flood Construction Level (FCL), tsunami flood level planning, and tsunami vulnerability mapping, which are part of the project deliverables. While all the produced maps provide an initial understanding of risk, risk mapping requires additional information regarding exposed elements in the flood hazard area; risk mapping is not within the scope of this project.

2.4 Guidance for Flood Mapping

In 2011, the Government of BC commissioned a number of reports that provide guidance for land use planning and mapping in consideration of coastal flood hazards and SLR (Ausenco Sandwell 2011a, 2011b, 2011c; Kerr Wood Leidal 2011). Collectively, these documents are referred to as the *Provincial Guidelines*. The guidance in these documents was further refined in the Association of Engineers and Geoscientists British Columbia (APEGBC) Professional Practice Guidelines for Flood Mapping in BC, released in 2017 and referred to in this report as the *Professional Practice Guidelines* (APEGBC, 2017). The CEPF grant program requires consideration of these provincial guidelines.

2.4.1 Water Levels and Terms used in Flood Mapping and Flood Planning

The *Provincial Guidelines* define a number of key water levels to be used in flood planning and mapping.

Designated Flood Level (DFL). The DFL is the still water level resulting from a chosen flood hazard event or designated storm.

DFL =

Future SLR Allowance

+ High Tide (HHWLT)

+ Total Storm Surge (deep water storm surge + estimated wind set-up + inter-annual climate variation)

Flood Construction Reference Plane (FCRP). The FCRP is the maximum level that flood water is predicted to reach, based on analysis.

FCRP =

Designated Flood Level (DFL)

+ Estimated Wave Effect

Flood Construction Level (FCL). The FCL is an elevation relative to the Canadian Geodetic Vertical Datum (CGVD), and it is used in planning to establish the elevation of the underside of a wooden floor system (or top of concrete slab) for habitable buildings (Figure 5). It includes a freeboard (for safety) to account for uncertainties in the analysis (see Section 2.4.3 on freeboard).

FCL =

Flood Construction Reference Plane (FCRP)

+ Freeboard

The FCL is extended from the shoreline horizontally landward, until the land surface elevation reaches the FCL. All land with an elevation below the FCL landward of the shoreline is considered within the FCL extent. It is important to note that the FCL always refers to an elevation above a geodetic datum; for this project, the Canadian Geodetic Vertical Datum (CGVD) 2013[2] was used (see also Section 4.2).

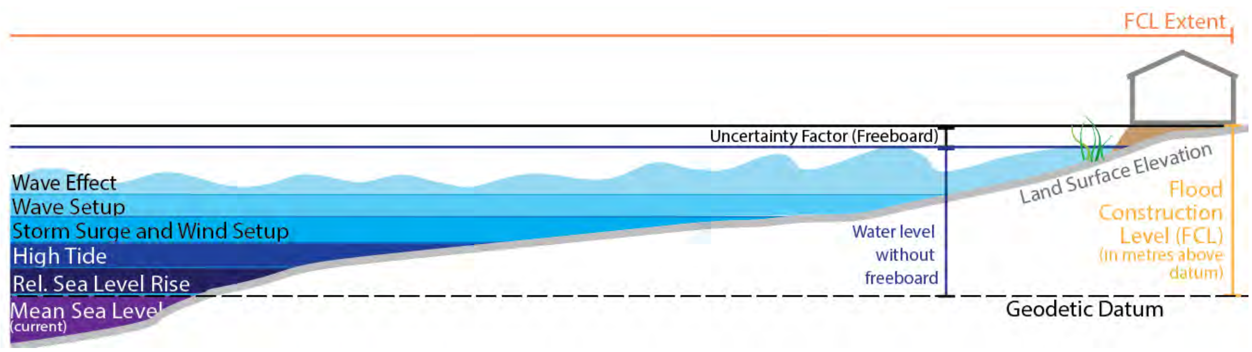

Figure 5: Conceptual drawing of the Flood Construction Level (FCL).

2.4.2 Selection of the Designated Storm

The *Provincial Guidelines* suggest that the minimum designated storm to be used in the calculation of FCL and SLR Planning Areas is 0.5% AEP, but that this can be reassessed to 0.2% AEP for heavily populated areas. In coastal areas, the designated storm consists of several elements including storm surge, wind, and wave effects.

2.4.3 Freeboard

Freeboard is a vertical distance that is added to water levels as a safety margin to account for uncertainties in the calculation of water levels and to account for localized increases in water levels. The *Provincial Guidelines* state that a freeboard of 0.6 m should be applied to the flood construction reference plane (FCRP) to calculate the FCL for coastal flood mapping. While a freeboard assumption is helpful in ensuring that possible problems are not missed, it is not an exact science. The freeboard used should also depend on the uncertainties in the flood extent mapping and the risk tolerance of the regulating jurisdiction. The *Professional Practice Guidelines* state that there is no provincial standard for freeboard and suggest a range of 0.3 to 1.0 m, noting that it is ultimately the decision of the local government as to how to apply freeboard.

[2] The Canadian Geodetic Vertical Datum (CGVD) of 2013 is defined by a reference surface that represents the coastal mean sea level for North America, and it replaces the former CGVD28 from 1928. Vertical elevation is reported relative to this datum.

2.4.4 SLR Planning Areas

As time goes on, the FCL and the flooded extent it defines will change due to RSLR (Figure 6).

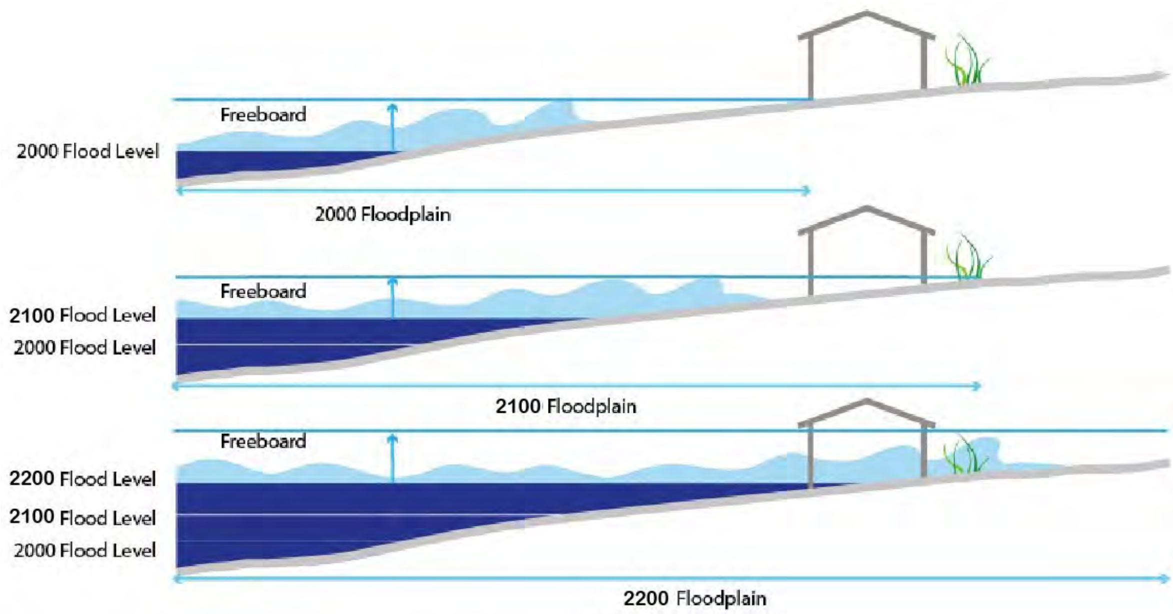

Figure 6: Increase in flood construction level (FCL) with sea level rise (SLR).

SLR Planning Areas reach from the natural boundary[3] of the sea landward to the contour elevation of the future FCL. The natural boundary of the sea will change over time and move further inland, as sea levels rise. SLR Planning Areas are used to show the change in flood extent over time and may be designated by local governments, by bylaw, as flood hazard areas. SLR Planning Areas show likely future flood extents considering RSLR (Figure 7). Due to changes associated with SLR, both the natural boundary and SLR Planning Area are subject to change, and will require revision and updates over time. The latest update to the *Provincial Guidelines* suggests that as a minimum, the FCL for the year 2100 should be established for areas not subject to significant tsunami hazard.

[3] The natural boundary is defined in the *Provincial Guidelines* as "The visible high watermark of any lake, river, stream or other body of water where the presence and action of the water are so common and usual and so long continued in all ordinary years as to mark upon the soil of the bed of the lake, river, stream or other body of water a character distinct from that of the banks, thereof, in respect to vegetation, as well as in respect to the nature of the soil itself. For coastal areas, the natural boundary shall include the natural limit of permanent terrestrial vegetation. In addition, the natural boundary includes the best estimate of the edge of dormant or old side channels and marsh areas."

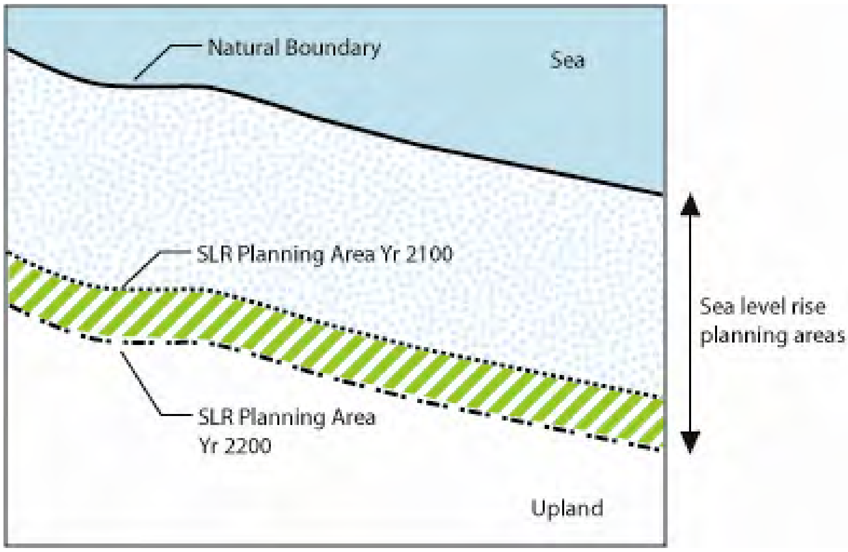

Figure 7: Sea Level Rise Planning Area example (Figure from Ausenco Sandwell 2011a, 2011b, 2011c).

2.5 Legislative Framework

In BC, the *Local Government Act* and *Land Title Act* were amended in 2003 and 2004 to remove the role of the Minister of Environment from floodplain designation and approving administration, shifting the authority to local governments. Due to this change, local governments have an increasingly important role to play in the management of flood hazards and gain this authority from the Provincial legislation—the *Community Charter* and the *Local Government Act*.

Community Charter [2003]

The *Community Charter* provides the statutory framework for local governments within the province of BC; it sets out areas of authority and procedures. Of relevance to flood management are the provisions with Division 8 of the *Charter* that set out the authority of local government to have a Chief Building Inspector permit buildings and occupancy of structures, and to require certification of a *qualified professional*[4] that "land may be safely used" in areas subject to flood (and other hazards).

The use of the *Community Charter* generally requires base information from flood mapping (either extents or extents and flood depths or FCLs) to support the Chief Building Inspector and qualified professionals to determine if a site and/or building is safe for intended use. In the absence of an approved flood map, this statute still provides a local government's Chief Building Inspector with the ability to require a geotechnical report to be prepared by a qualified professional for new buildings and for structural alteration or addition to an existing building or structure. The qualified professional may also determine an FCL for new construction on parcels that are or may be subject to sea level rise (i.e., likely to be subject to flooding) [Section 56].

[4] In the case of the *Community Charter*, a *qualified professional*, is defined as "(a) a professional engineer, or (b) a professional geoscientist with experience or training in geotechnical study and geohazard assessments".

Local Government Act [2004]

Where flood mapping is available, this statute provides both policy and regulatory provisions that can be implemented as stand-alone provisions or collectively to form a framework to effectively manage flood hazard areas. Specific tools available under the *Local Government Act* relevant to coastal flood management are:

1. **Regional Growth Strategy (RGS) Bylaw:** Is a strategic plan that defines a regional vision for sustainable growth. Policies can be incorporated into an RGS to prepare for climate change by supporting adaptation strategies and by allowing for sea level rise to the year 2200 and beyond.

2. **Official Community Plan (OCP) Bylaw:** Is a guiding policy document used to inform land use decision. OCPs can include policies in support of climate adaptation and strategies to mitigate sea level rise. Where coastal flood mapping studies have been completed, these findings and results should be reflected in an OCP.

3. **Development Permit Areas (DPAs):** Are designated areas requiring special treatment. An Official Community Plan may designate DPAs for specified purposes, including the protection of development from hazardous conditions like coastal flooding [Section 488]. Hazard DPAs are generally triggered by alterations to the land associated with development activities. DPAs must include conditions or objectives that justify the designation and must also provide guidelines for developers and homeowners to meet the requirements of the DPA.

4. **Flood Bylaw**: If a local government considers that flooding may occur on land, the local government may adopt a bylaw to designate a floodplain area and specify flood levels for it, establish setbacks and construction elevations for habitable space for new buildings and structures, and for landfill within the flood hazard area [Section 524]. Most often, applications for building permits trigger flood bylaw requirements.

5. **Zoning Bylaw:** Land use zoning bylaws are used to regulate the use of individual parcels of land, including parcel configuration, the density of the land use, and siting and standards of buildings and structures [Section 479]. These bylaws have been used historically for flood hazard areas to ensure public safety is maintained by limiting the types of uses associated with those lands.

6. **Subdivision Bylaw:** Standards for subdivision design that take into consideration sea level rise can be established by local governments (within the *Provincial Guidelines)*. In the case of Regional Districts, the Approving Authority for subdivision is the Ministry of Transportation and Infrastructure, which is required to consider the *Provincial Guidelines* to determine the conditions for subdivision approval.

7. **Local Building Bylaw:** There is also provision under the *Local Government Act* [Section 694] for a local building bylaw or permit process to require floodproofing. Generally, these are no longer used as the updated BC Building Code has some provisions for floodproofing and any additional

conditions can also be integrated into a flood bylaw. It should also be noted that the National Research Council of Canada and partners are working to incorporate new floodproofing standards into future iterations of the Canadian Building Code.

2.5 Provincial Direction on Disaster Risk Reduction

As stated, the *Local Government Act* provides provisions that enable local governments to manage development in relation to lands prone to flooding. In doing so, the local government must give consideration to the Provincial Flood Hazard Area Land Use Management Guidelines (the *Provincial Guidelines*). The guidelines are intended to minimize injury and property damage resulting from flooding and are linked to the Provincial Compensation and Disaster Financial Assistance Regulation. Together, the Provincial Regulation and Guidelines are used to determine if property has been adequately protected and whether a local government is eligible for financial assistance following a flood event.

A more recent development in BC, mostly stemming from the criticisms and recommendations in the 2018 report on the findings of the 2017 BC Flood and Wildfire season (Abbott and Chapman, 2018), is the commitment to adopt the Sendai Framework for Disaster Risk Reduction[5]. The Government of Canada endorsed Sendai in 2015, and in late 2018, the Government of British Columbia announced that it would also adopt Sendai, stating, "Canada is already a signatory to the framework and the Province will now also adopt the framework to align and improve our approach to all phases of emergency." (Emergency Management BC, 2018). Emergency Management BC is currently modernizing the *Emergency Program Act* [1996] to further align with Sendai[6].

The Sendai Framework is the global blueprint for building disaster resiliency; it is supported by the United Nations. The goal of the framework is to prevent new and reduce existing disaster risk. This is promoted through four priorities for action:

1. Understanding disaster risk.
2. Strengthening disaster risk governance.
3. Investing in disaster risk reduction for resilience.
4. Enhancing disaster preparedness.

Sendai provides a framework to support all levels of government, including local governments, to increase their resilience to both chronic and acute shocks.

This direction is relevant to the DOU as it works to develop plans and policies to mitigate flood impacts. In the short-term, it is important to note that the new direction from senior government is a shift

[5] United Nations Office for Disaster Risk Reduction (UNDRR): Sendai Framework for Disaster Risk Reduction 2015-2030; https://www.undrr.org/.

[6] Modernizing BC's Emergency Management Legislation. Weblink: https://engage.gov.bc.ca/app/uploads/sites/121/2019/10/modernizing_bcs_emergencymanagement_legislation.pdf. Accessed October 28, 2019.

towards risk-based planning and policy, as opposed to the prescriptive hazard-focussed policy outlined above (i.e., regulatory tools that require designation of a specific hazard area). A risk-based approach requires consideration of the impacts and consequences of flood so that different treatments can be applied for different types and severities of impact. Further, a true risk-based approach considers a variety of hazard scenarios (and not a single hazard event—0.5% AEP—as is the current practice). This project has developed an atlas of hazard scenarios to support that are the foundational piece of information to support risk assessment (e.g. Sendai priority #1).

3 Project Background

The following provides background information on the project site, as well as a summary of related and relevant studies.

3.1 Physical Setting

The DOU is a small community on the west coast of Vancouver Island. It covers the narrow Ucluth Peninsula, which is located between the Pacific Ocean and Barkley Sound (and approximately resembles the extents of the DOU). The western and southern sides of the area are exposed to the ocean, while the shores on the eastern side of Ucluelet Inlet are more sheltered. The shoreline is shallow to moderately sloped and is characterized by rocky bays interspersed with beaches and salt marshes. The area is low-lying and undulating, and the average and maximum elevations are 12 m and 89 m (CGVD2013), respectively. The area's northern extent is within 2 km of Pacific Rim National Park (Figure 8).

Figure 8: Project area overview map.

3.2 Climate Setting

The climate of Ucluelet is influenced by the Pacific Ocean. The average total annual precipitation from 1981 to 2010 was 3,189 mm[7], making it one of the wettest places in North America. Winter is an active weather season with a series of low-pressure westerly storms moving into the area, bringing strong winds and high-intensity rainfall (Lerner, 2011). These storms often result in coastal flooding (see Section 2.1.1). The maximum 24-hour precipitation in Ucluelet from 1981 to 2010 was 185 mm[8].

While there is no marked dry season, the summer months have lower precipitation, due to the prevalence of high-pressure systems and fewer storms during the summer season (Lerner, 2011). Over the next century, climate change is expected to increase annual temperatures and precipitation in this region. The Pacific Climate Impact Consortium (PCIC) estimates that by the 2080s, annual temperatures will increase by around 2.3°C and annual precipitation will increase by around 10%, when compared to a 1961–1990 baseline. However, summer months are expected to be drier with around 10% less rain falling over this period (PCIC, 2013).

3.3 Societal Setting

The region has been home to the Nuu-chah-nulth people for thousands of years. In the Nuu-chah-nulth language, Ucluelet means "people with a safe place to land". Europeans arrived in the late 1700s and ultimately settled in the current Ucluelet townsite in the late 1800s. Ucluelet was incorporated in 1952, and this status changed to District in 1997. The DOU is located on the traditional territory of the Yuułuʔiłʔatḥ (Ucluelet First Nation). Local First Nation communities include Hitacu (Yuułuʔiłʔatḥ) and Macoah ('tukʷaaʔath (Toquaht First Nation)), which are located across Ucluelet Inlet.

After the construction of the logging road through the mountains between Port Alberni and the coast in 1959, the population in Ucluelet grew substantially, and was supported by logging and fishing industries. Today the DOU has just over 1,700 permanent residents (Statistics Canada, 2016), and in the last decade the town's economy has shifted to focus on tourism and hospitality.

In the summer months, thousands of tourists visit the area's natural amenities and attractions. Pacific Rim National Park was created in 1970. On average, the Clayoquot Sound area receives up to 1 million tourists annually[9]. Popular recreational activities in the area include nature-walking and sight-seeing (e.g., whale watching and salmon migration), kayaking and stand-up paddle boarding. A popular hike is the Lighthouse Loop (or Wild Pacific) trail (Figure 9).

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[7] Amphitrite Point (Climate ID 1030426), Canadian Climate Normals station data, Government of Canada; Weblink: https://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?searchType=stnProx&txtRadius=25&optProxType=station&coordsStn=48.945283%7C-125.527236%7CUCLUELET+KENNEDY+CAMP&txtCentralLatMin=0&txtCentralLatSec=0&txtCentralLongMin=0&txtCentralLongSec=0&stnID=227&dispBack=0. Accessed 23 May 2020.

[8] Ibid.

[9] A Brief Tofino History. Weblink: http://www.tofino-bc.com/about/tofino-history.php. Accessed 29 May 2020.

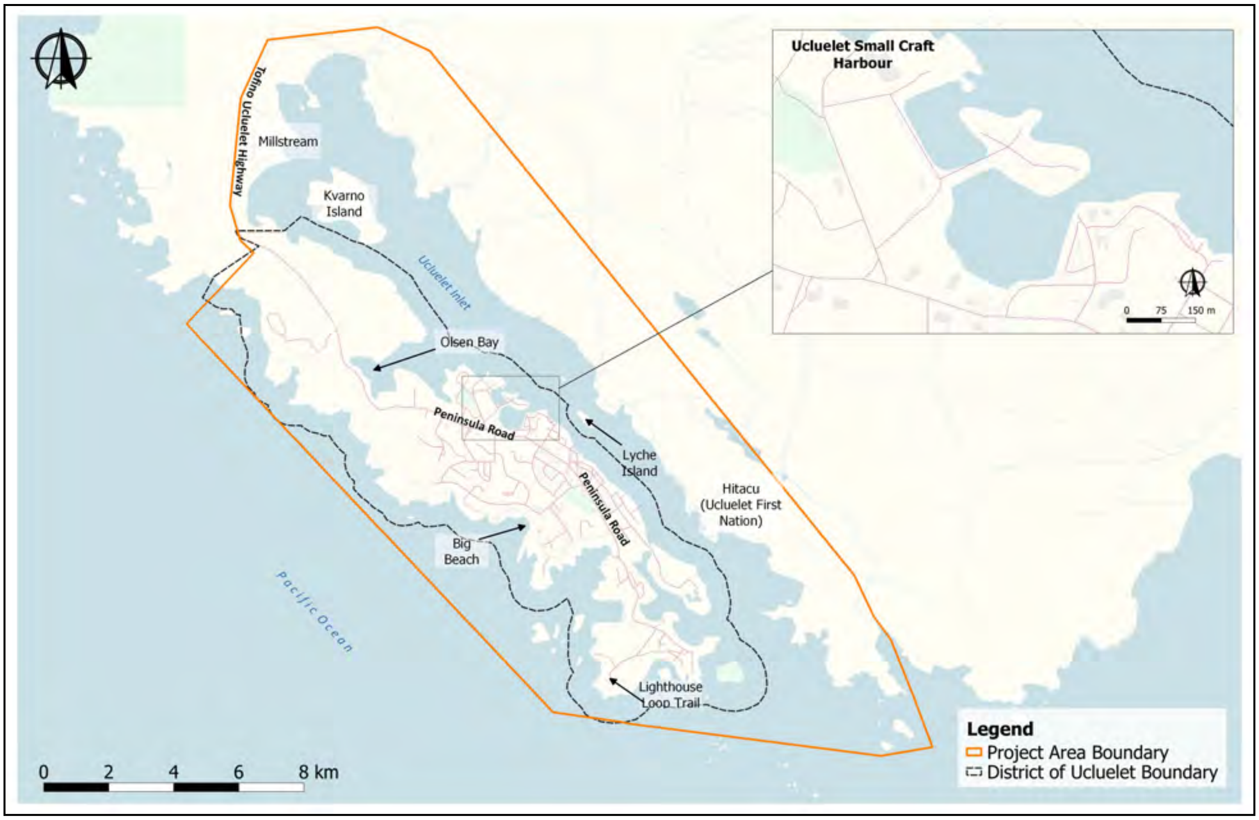

Figure 9: Project area map (zoomed-in to community setting).

3.4 Field Visits

Field visits were conducted by the project team in December 2019 (by CCR) and March 2020 (by Ebbwater). The first field visit is discussed in Section 4.4.7, and in more detail in Appendix A. The second field visit is discussed below.

On March 3 and 4, 2020, the Ebbwater technical team toured portions of the project area with the DOU Project Manager. The objective was to provide the team with an opportunity to observe and document the diversity of shoreline areas impacted by coastal flooding. The information was used to ground truth the coastal flood mapping results, and the preliminary data reviewed for coastal erosion (Appendix B). The visited areas included the Whiskey dock, Ucluelet Small Craft Harbour (Figure 10), the Pat Leslie boat launch, the marshlands behind the hostel, Big Beach (Figure 11), Little Beach, Amphitrite Point (Figure 12), points along the Wild Pacific Trail (Lighthouse Loop), and the Hyphocus Island causeway.

Figure 10: Ucluelet Small Craft Harbour with view of homes, boats, and seaplane. Photo taken 3 March 2020.

Figure 11: Big Beach with view of rocky shore and resort infrastructure. Photo Taken 3 March 2020.

Figure 12: Amphitrite Point with view of Pacific Ocean and shallow, rocky slope. Photo taken 4 March 2020.

3.5 Coastal Flood Hazards in Ucluelet

The DOU is flanked by the ocean on three sides, and as such, the area is exposed to coastal flood hazards that include flooding during coastal storm events and potential tsunamis. These flood hazards will grow in future with SLR, which is slowly increasing the still water elevation. The SLR value must be locally adjusted to account for land uplift or subsidence of the local area (RSLR). SLR is discussed in more detail in Sections 2.1.3 and 4.3.

3.5.1 Coastal Storm Flood

A number of physical processes combine to produce a coastal storm. These include short-term processes, such as tides, waves, storm surge, and wind, and longer-term processes, such as SLR, land subsidence/uplift, and inter-annual climate variability, such as El Niño. General information on these are presented in Section 2, and are discussed briefly in the context of the DOU in this section. These form the basis of the coastal modelling discussed further in Section 4.4.

Tides

The tides in the DOU have a range of about 4.1 m (between the highest and lowest tides) and a maximum water elevation of 2.1 m CGVD28[10]. They are generally larger in the winter and smaller in the summer. The maximum tidal elevation occurs once every 18.6 years, but the level comes close to this for a few tides each year (commonly referred to as king tides).

Storm surge

Levels associated with storm surge typically peak at less than 0.5 m in the DOU but can also be greater than 1 m on top of ambient water levels and can last from a few hours to a few days.

Waves

The DOU is directly exposed to the Pacific Ocean on the southwest shore. Large waves breaking on the beach causes both a static increase in water level (wave set-up) and a dynamic, oscillating variation in water level (wave runup). Wave runup is generally the first- or second-largest contributor to high water level events on the west shore of the DOU.

Wind Set-Up

Wind set-up impacts all shores of the DOU, but to a greater degree the east shore with the expansive adjacent mudflats. The impact of wind set-up is usually the smallest factor in the creation of coastal storm water level.

Inter-Annual Climate Variation

The DOU is impacted by two different inter-annual climate variations, the Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO). These effects have been reported to influence water levels by as much as 0.4 m (Bornhold and Thomson, 2013). In practical applications, the effect of these longer-term variations is often combined with storm surge.

3.5.2 Tsunami Flood

The DOU is exposed to multiple tsunami sources, as it is positioned on the edge of the Pacific Ocean within the "Ring of Fire", named for the abundant earthquakes and volcanic eruptions in the region. In this region, earthquakes commonly occur from four sources (Figure 13; Province of British Columbia 2018):

[10] The Canadian Hydrographic Service database is currently maintained in the now outdated Canadian Geodetic Vertical Datum of 1928 (CGVD28). Please see Section 7.3 for a discussion of datums.

1. Earthquakes along the Cascadia Subduction Zone (CSZ) occur when the Juan de Fuca Plate moves under the North American Plate. This type of earthquake has the highest magnitudes (megathrust) and will trigger a tsunami.
2. Deep earthquakes occur well below the earth's surface, within the subducting Juan de Fuca Plate. This will typically result in weaker shaking.
3. Crustal earthquakes occur within the North American Plate, close to the earth's surface and, depending on their magnitude, can cause significant damage.
4. Earthquakes along the Queen Charlotte Fault, offshore of Haida Gwaii, occur when the Pacific Plate slides past the North American Plate horizontally.

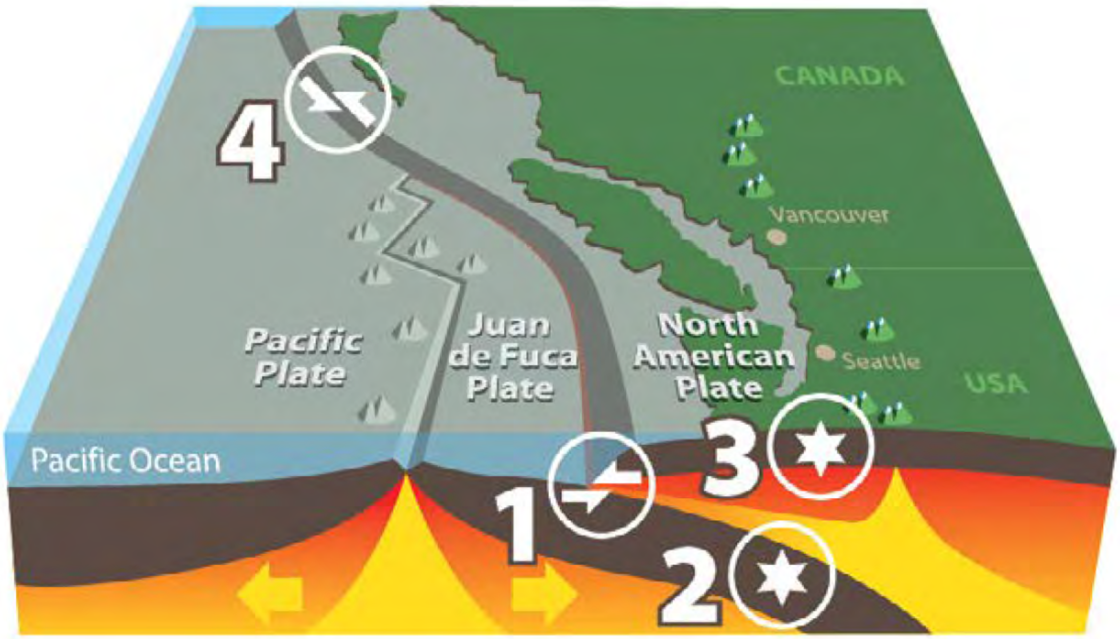

Figure 13: British Columbia earthquake hazard sources. See above text for description of the 4 earthquake sources (figure from Province of British Columbia, 2018).

It is believed that a megathrust fault of the CSZ (source 1 in Figure 13) poses the largest hazard to the DOU. Relative to the DOU, the CSZ is an example of a proximal (near to) earthquake. Distal (far away) earthquakes may also cause tsunami waves that could reach the Ucluelet coastline. An example of a recent distal earthquake that impacted the region was the one that caused the 1964 Alaska tsunami. This earthquake source is the Aleutian Subduction Zone (not shown in Figure 13).

3.5.3 Erosion Hazards

A detailed analysis of erosion hazards was out of scope for this project; therefore, erosion setbacks are not explicitly considered within this report. However, Appendix B contains a preliminary review of coastal erosion data and recent research for the Ucluelet area.

A review of data availability found that surficial geology data, which is critical to erosion assessments, is coarse and limited for the project area. However, a shoreline sensitivity to sea level rise model developed by BC Parks (Biffard and Stevens, 2014) provides a good initial understanding of the factors affecting coastal erosion in Ucluelet. The objective of the model outputs is to help managers and planners develop an appropriate set of adaptation and mitigation responses to sea level rise. Since sea level rise is connected to erosion issues, the model outputs were used to make inferences about coastal erosion.

Based on existing datasets that characterized backshore and foreshore reaches, the BC Parks model categorizes shoreline sensitivity to erosion and ecosystem impacts based on a five-point sensitivity rating scale: red indicates very high shoreline sensitivity, orange indicates high sensitivity, yellow indicates moderate sensitivity, light green indicates low sensitivity and dark green indicates very low sensitivity. These are shown in Figure 14 for the mapped shorelines of the project area. The annotations in Figure 14 explain why areas were rated as very high (red) or high (orange). Shoreline type, exposure, and slope are key factors.

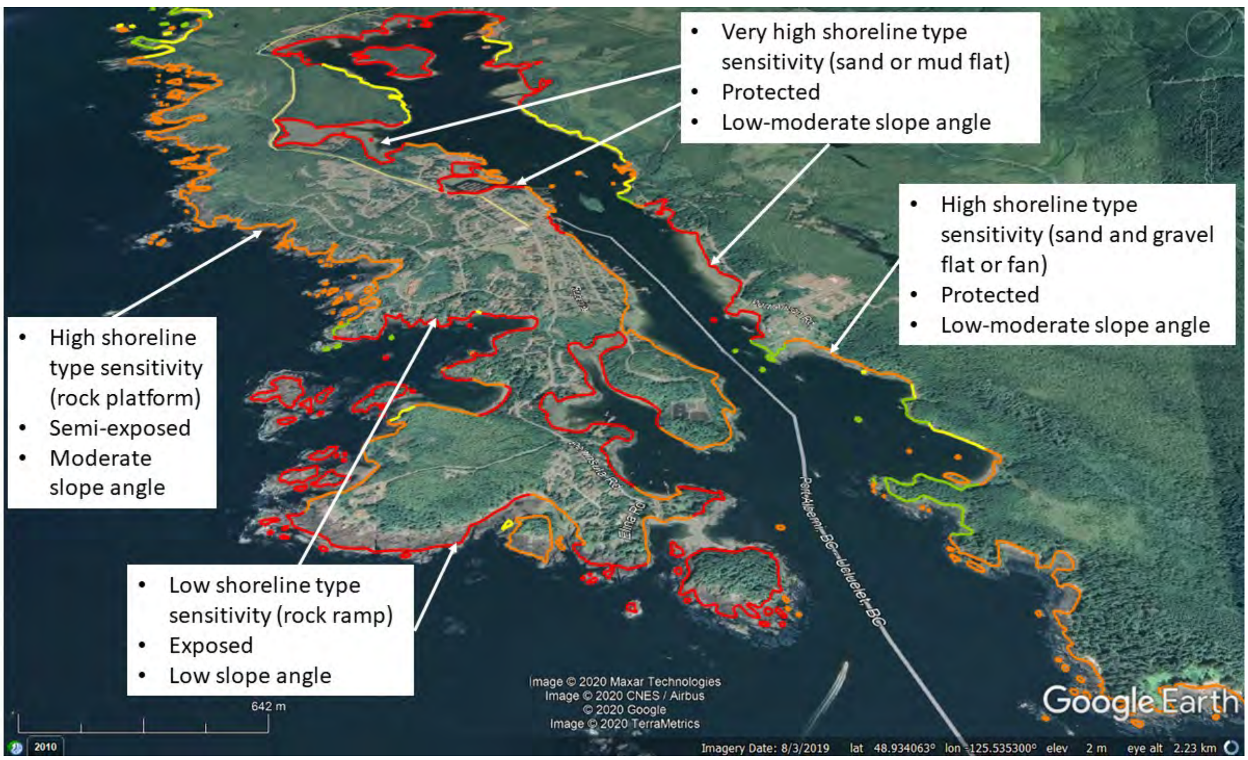

Figure 14: Shoreline sensitivity to sea level rise (Biffard and Stevens, 2014)**. Red indicates very high shoreline erosion sensitivity, orange indicates high sensitivity, yellow is moderate sensitivity, light green is low sensitivity and dark green is very low sensitivity. Annotations by Ebbwater.**

Based on output from the BC Parks Model, susceptibility to erosion in the project area varies geographically, as follows:

- **Areas on the ocean side of the peninsula.** These are more exposed to waves, increasing the erosion potential. However, these areas generally consist of rocky shorelines that are less likely to erode. Even where slopes are steep, erosion is less likely to occur due to the dominance of rock (in contrast to sediment and sand).

- **Areas in the inlet.** These areas are protected from wave exposure. However, flat sandy areas are susceptible to changes in sea level rise and erosion of sediment along the foreshore zone.

While limited erosion data is currently available for the DOU, the preliminary data review nevertheless complements the flood hazard assessment presented in this report and can be used to inform a future detailed and localized erosion hazard assessment. A more detailed discussion of limitations of the data, and next steps towards a coastal erosion assessment, is provided in Appendix B.

3.6 Historical Coastal Flood Hazard Events

Although there are relatively few recorded occurrences of coastal flooding in the DOU, it has a long history of big storms and large waves.

3.6.1 Coastal Storm Flood

In January 2018, an extreme wave hazard advisory was issued for the area, predicting waves of up to 9 m in height and high tides that could result in shoreline and beach flooding (District of Ucluelet, District of Tofino and Pacific Rim National Park, 2018)[11]. A 9.5-m wave was recorded by the La Perouse Bank Buoy and the storm caused power outages and ferries to be cancelled across Vancouver Island (BC Hydro, 2018; ECCC Weather British Columbia, 2018).

Cascadia Coast Research Ltd. completed a high-level review of storm measurements and modelling of waves running up on the shores of Ucluelet for this January 2018 storm (using a similar method as described later in this report for storm hazard modelling). They found that the storm did not have a particularly high still water level; it was about 1.8 m, which is less than the higher high water large tide (HHWLT). However, the waves were some of the largest over the historical record (see Section 4.4.7 for images). Therefore, the AEP was much larger at locations where wave runup dominated the total water levels. For instance, for most sections along the west coast, the January event was the largest event throughout the 40-year historical period. The median estimate of the AEP at these locations was typically less than 1% (100-year indicative return period), but in some cases was less than 0.2% (500-year indicative return period). However, there is large uncertainty associated with these AEP flood values. For other sheltered locations within the Ucluelet Inlet, where wave runup did not dominate, the AEP was closer to 100% (i.e. these levels are exceeded every year).

3.6.2 Tsunami Flood

In addition to large storms, multiple small tsunamis hit the DOU coast harmlessly every year. In January 2018, a tsunami warning was issued, and communities were evacuated following a magnitude 7.9 earthquake in the Gulf of Alaska. While the resulting wave was not large enough, when it arrived at the DOU, to cause damage, the event was a reminder of the threat from tsunamis.

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[11] District of Ucluelet, District of Tofino, and Pacific Rim National Park. 2018. Extreme Wave Hazard Advisory." Weblink: http://tofino.ca/blog/view/extreme-wave-hazard-advisory. Accessed December 2018.

Records show that the last CSZ megathrust event occurred in 1700. This magnitude 9 earthquake caused a large tsunami that impacted North America and Japan (Fine *et al.,* 2018). It is believed that this could have resulted in a wave of over 9 m along the west shore of Vancouver Island. This is demonstrated by numerical models, but is also supported by information passed down through the oral tradition of First Nations (Clague, 1997; Province of British Columbia, 2018). Recent research has indicated that the probability of a CSZ event in the next 50 years is roughly 1 in 3 (Goldfinger *et al.,* 2012).

The most damaging tsunami on the Canadian west coast in recent history was the 1964 earthquake that originated on the coast of Alaska. Waves generated from the magnitude 9.2 earthquake quickly reached the outer coast of Vancouver Island, causing around $10 million worth of damage across the coastline (Clague, Munro and Murty, 2003). The highest wave from this event was at Port Alberni (with an amplitude of over 4 m). The tsunami wave amplitude measured at the gauge in the Ucluelet area was more moderate at 1 m and it was estimated at 2.2 m in Barkley Sound (Seaconsult Marine Research, 1988). Oral accounts obtained from the Ucluelet Historical Society refer to a three to four-foot wave, which corroborates the gauge readings. Refer to Section 4.5 for details.

Prior to the Alaska event, the area was also hit by a smaller tsunami in 1960, which resulted from a magnitude 9.5 earthquake off the coast of Chile. The maximum wave height was recorded by the gauge in the Ucluelet area as 1.2 m, but runup was much higher in many places (Clague, Munro and Murty, 2003).

3.7 Previous and Ongoing Coastal Flood Hazard Assessments

Coastal flood hazard modelling studies have been completed with varying focuses and levels of detail on the west coast of Vancouver Island in recent years. Factors related to overlapping scales and jurisdictions has led to project processes that have been disjointed. To increase collaboration and consistency of information, Ebbwater has convened a knowledge sharing group on storm and tsunami flood issues for coastal regions of BC since 2018. Meetings have been held quarterly and include local governments such as the District of Ucluelet, District of Tofino, Capital Regional District, as well as Indigenous Services Canada, Parks Canada, Natural Resources Canada, National Research Council; academic institutions such as the University of Ottawa and University College London (UK); and numerous consultants.

While the knowledge-sharing group process has increased understanding of the various projects that are being conducted on Vancouver Island, it has by no means solved all collaboration challenges. The following sections describe some key storm and tsunami flood studies relevant to the project area in more detail.

3.7.1 Coastal Storm Flood

Simplified coastal flood maps were completed for the entire coastline of the Province of British Columbia in 2012 (Kerr Wood Leidal, 2012). These maps show areas of potential flood hazard in 2100, including SLR. The purpose of these maps was to identify coastal flood hazards at a large scale to help in land use planning and SLR adaptation strategies. While these maps do cover the DOU, they do not provide detailed information on the depth or location of flooding. They were also produced using several generic assumptions (for example, on wave runup) and low-resolution elevation data.

Since 2017, Indigenous Services Canada (ISC) has been completing Coastal Vulnerability Studies (CVS) for First Nation communities across Vancouver Island (and the BC Coast). In the Ucluelet region, storm flood hazard modelling was completed for the communities of Hesquiaht, Tla-O-Qui-Aht, Yuułuʔiłʔatḥ, and Toquaht First Nations. However, the reports for the latter two First Nation areas, which are located closest to the District of Ucluelet, could not be obtained for this project.

3.7.2 Tsunami Flood

There has been a growing body of research on the potential impacts of tsunamis on the BC Coast in recent years, with a focus on the Cascadia Subduction Zone (CSZ) 1700 megathrust event. Details on key research papers used as the basis for the tsunami modelling for this flood mapping report are discussed in Section 4.5 and Appendix A. A summary of the research results relevant for Ucluelet is described below.

Several projects have estimated the tsunami wave amplitude[12] at Ucluelet. Most recently, results from Takatabake *et al.* (2020) show a tsunami wave amplitude in Ucluelet Inlet that appears to be about 3.5 m south of Lyche Island and less than 1 m north of Lyche Island. In 2019, Ebbwater Consulting Inc. and Cascadia Coast Research Ltd., (2019) simulated a tsunami amplitude exceeding 6 m offshore at Ucluelet (as part of the District of Tofino tsunami flood hazard assessment). A previous study of the CSZ 1700 event by Cherniawsky *et al.* (2007) simulated that a tsunami amplitude of up to 7 m occurred on the exposed outer shores of the DOU, and about 4 m within Ucluelet Inlet. The range of results simulated for the Ucluelet area highlights the importance of sharing information[13].

In 2013, the Capital Regional District (CRD) completed a tsunami hazard and risk study with a hypothetical modern faulting of the CSZ (AECOM, 2013b). Simulation results from that work indicated a tsunami amplitude of greater than 5 m offshore of Ucluelet. Building on that and subsequent work in 2015, the CRD and local government partners are currently working with consultants to produce storm and tsunami flood modelling and mapping for the entire capital region. A number of communities within the region have also undertaken detailed modelling. For tsunami flooding, three CSZ events are being modelled based on various rupture types. A total of eight proximal and distal rupture sources are included, and each has associated probabilities. The modelling resolution is 30 m or less[14].

Previous work completed by the District of Ucluelet identified 20 m as an elevation that would be safe from a tsunami wave. This and other information is contained in the DOU's Tsunami and Earthquake

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[12] Tsunami wave amplitude is defined as the maximum elevation of the wave crest with respect to the surrounding or prevailing water levels.

[13] The recent CVS studies for local First Nation communities, mentioned in the previous section for storm flood hazards, also included tsunami flood modelling results. However, results could not beobtained for study locations near Ucluelet.

[14] Personal communication, Nikki Elliott, CRD Climate Action Program Coordinator, 19 May 2020.

Information brochure[15]. Kurowski (2011) used the District as a case study to assess how tsunami hazard assessment information can be used to design evacuation maps for public education. That work built on Johnstone and Lence (2009), who assessed non-structural mitigation alternatives, including evacuation and sheltering in place.

It is well known that tsunami hazard exists in the Ucluelet region. Researchers have made progress in growing understanding of the hazard, as it relates to earthquakes and different rupture types. The advances of computer modelling has facilitated the process of simulating multiple scenarios.

[15] Weblink: https://ucluelet.ca/images/Ucluelet_Tsunami-Earthquake_Info.pdf, accessed 19 May 2020.

4 Flood Hazard Analysis Methodology

The following provides an overview of the methods used to develop flood elevations for the various coastal hazards. This work was conducted by Cascadia Coast Research Ltd. and is detailed in Appendix A; a summary of key components is provided here and is augmented with text from Ebbwater.

Coastal modelling was used in this study to assess the storm flooding hazard (considering effects of tides, storm surge, wind set-up, wave set-up, and wave runup) and the tsunami flooding hazard for various time horizons (i.e., incorporating RSLR due to climate change and tide effects). This work generally followed the *Provincial Guidelines* for coastal flood hazard assessment as described in Section 2.4. First, a digital elevation model (DEM) was developed to aid as base input for models, then coastal modelling was conducted to assess storm and tsunami hazards, and lastly, flood hazards were mapped.

4.1 Flood Hazard Scenarios

Coastal storm-driven and tsunami floods were modelled and are presented in this report. A summary of the scenarios considered is presented in this section.

Often, coastal storms are presented as single scenarios (i.e., one hazard magnitude and likelihood), which then become the designated event (this is generally the 0.5% AEP scenario). However, impacts of flooding can also occur at lower magnitudes, and, although rare, larger-magnitude events do occur. Thus, best practice for flood management is to consider multiple events (from smaller, more frequent events through larger, rarer events). Therefore, for the purposes of this project, 5 AEPs were considered—from the 6.67% AEP, which is meant to represent an event that would have occurred in the recent memory of the community members—through to the 0.2% AEP, a very large but very rare event. The selection of AEP scenarios was driven by the scope and effort of the modelling team, but also by thinking ahead to future risk mapping and modelling, which is greatly improved by considering a range of events. It should be noted that the general form of extreme-value statistics for coastal events is a curve that rises steeply before becoming quite shallow (i.e., the difference in flood elevation between the higher likelihood events is great but becomes quite minimal—a matter of centimetres—when considering the difference between the lower likelihood 0.2% and 0.1% AEP).

As discussed earlier in the report, the DOU is subject to changing hazard profiles as a result of RSLR, and therefore the hazard modelling also considered scenarios with incremental rises in base sea level elevation. The various RSLR scenarios are roughly associated with years as follows: 0.0 m (year 2000), 0.5 m (year 2050), 1 m (year 2100), and 2 m (year 2200). However, due to the high uncertainty in future projections, and the possibility of sea levels occurring more rapidly than anticipated (Section 2.1.3), qualifiers are used throughout this project's deliverables (as shown in Table 2)) instead of numbers to indicate time periods. Summaries of the flood hazard scenarios that we assessed are presented in

Table 2 and Table 3 for coastal storm and tsunami, respectively. For Table 3, additional information on rupture types and their research sources is provided in Section 4.5.1, as well as in Appendix A.

Table 2: List of coastal storm flood hazard scenarios simulated for this project.

RSLR (m)	Scenario No.	AEP (%)	Indicative Return Period (years)
0.0 (Present-Day)	1	6.67	15
	2	2.0	50
	3	1.0	100
	4	0.5	200
	5	0.2	500
0.5 (Near Future)	6	6.67	15
	7	2.0	50
	8	1.0	100
	9	0.5	200
	10	0.2	500
1.0 (Future)	11	6.67	15
	12	2.0	50
	13	1.0	100
	14	0.5	200
	15	0.2	500
2.0 (Far Future)	16	6.67	15
	17	2.0	50
	18	1.0	100
	19	0.5	200
	20	0.2	500

Table 3: List of tsunami flood hazards simulated for this project.

RSLR (m)	Scenario No.	Rupture Type	Research Source
0.0 (Present-Day)	1	Buried	Wang *et al.* (2003)
	2	Buried	Gao *et al.* (2018)
	3	Splay faulting A	Gao *et al.* (2018)
	4	Splay faulting B	Gao *et al.* (2018)
	5	Trench-breaching 50% peak slip	Gao *et al.* (2018)
	6	Trench-breaching 100% peak slip	Gao *et al.* (2018)
0.5 (Near Future)	7	Buried	Wang *et al.* (2003)
	8	Buried	Gao *et al.* (2018)
	9	Splay faulting A	Gao *et al.* (2018)
	10	Splay faulting B	Gao *et al.* (2018)
	11	Trench-breaching 50% peak slip	Gao *et al.* (2018)
	12	Trench-breaching 100% peak slip	Gao *et al.* (2018)

RSLR (m)	Scenario No.	Rupture Type	Research Source
1.0 (Future)	13	Buried	Wang *et al.* (2003)
	14	Buried	Gao *et al.* (2018)
	15	Splay faulting A	Gao *et al.* (2018)
	16	Splay faulting B	Gao *et al.* (2018)
	17	Trench-breaching 50% peak slip	Gao *et al.* (2018)
	18	Trench-breaching 100% peak slip	Gao *et al.* (2018)
2.0 (Far Future)	19	Buried	Wang *et al.* (2003)
	20	Buried	Gao *et al.* (2018)
	21	Splay faulting A	Gao *et al.* (2018)
	22	Splay faulting B	Gao *et al.* (2018)
	23	Trench-breaching 50% peak slip	Gao *et al.* (2018)
	24	Trench-breaching 100% peak slip	Gao *et al.* (2018)

4.2 Spatial Input Data – Digital Elevation Model

As a first step for the coastal modelling, a single coastal DEM was developed to support nearshore modelling. The DEM was assembled from multiple sources, which are summarized in Table 4. The processing of datasets into a single coastal DEM is described in detail in Appendix B. In general, preference was given to higher-resolution data, where available.

Table 4: Data sources for the DEM.

Data Description	Coverage	Source
Bathymetry/Topography DEM	Global	General Bathymetric Chart of the Oceans [16]
Electronic Navigation Charts Soundings and Contours	Mid-Island Coastal Waters	Canadian Hydrographic Service[17]
High Water Contour	BC Coastal Waters	Canadian Hydrographic Service
Bathymetry Survey data	DOU and surrounding waters	Canadian Hydrographic Service
0.3 m Topographic Contours	District of Ucluelet	LiDAR, District of Ucluelet[18]
20 m Topographic Contours	Canada	CanVec Database[19]

The aerial LiDAR (Light Detection and Ranging data) of the DOU was collected on 4 September 2015, by Eagle Mapping Ltd. (Eagle Mapping Ltd., 2016) for the area of interest of approximately 25 km^2. The LiDAR data had an average density of 8–10 points per square metre, and was delivered in the UTM10

[16] General Bathymetric Chart of the Oceans. Weblink: https://www.gebco.net/.
[17] Canadian Hydrographic Services, Fisheries and Oceans Canada. Weblink: http://www.charts.gc.ca/data-gestion/index-eng.asp.
[18] LiDAR, District of Ucluelet from September 4, 2015. (Eagle Mapping Ltd., 2016).
[19] Topographic data of Canada – CanVec Series. Weblink: https://open.canada.ca/data/en/dataset/8ba2aa2a-7bb9-4448-b4d7-f164409fe056.

NAD83 coordinate system, with units expressed in metres. The vertical datum is the Canadian Geodetic Vertical Datum of 2013 (CGVD2013), which uses the CGVD2013 geoid to obtain vertical heights. The LiDAR data is accurate to <15 cm vertically and <30 cm horizontally and its internal accuracy was calculated at ± 3 cm. This is the highest resolution data available, and forms the primary source of information for the DEM.

Considering the recent transition from the Canadian Geodetic Vertical Datum of 1928 (CGVD28) to the CGVD2013 for this study, some datasets had been obtained in CGVD28 (e.g., bathymetry data) and others in CGVD2013 (e.g., LiDAR data from the DOU). The conversion between CGVD28 and CGVD2013 can be done by applying an approximate localized offset β (Natural Resources Canada[20]);

$$H_{CGVD2013} = H_{CGVD28} + \beta$$

where $H_{CGVD2013}$ is the elevation in metres according to CGVD2013, H_{CGVD28} is the elevation in metres according to CGVD28, and β is the offset in metres[21].

However, the offset β varies throughout the study area, and vertical datum conversion is not straightforward and may introduce further error. In contrast to other regions in Canada, the vertical differences between CGVD28 and CGVD2013 are considered relatively small on Vancouver Island, with an approximate local β value between 0.15 and 0.17 m[22]. Therefore, for the purposes of this study, the differences were assumed to be minor and within the general tolerance of error of modelling and mapping. Addition of freeboard to total water evaluation, when determining FCLs, can also mitigate for some of the resulting uncertainties.

Elevations in chart datum may be converted to CGVD28 by using an offset α:

$$H_{CGVD28} = H_{CD} + \alpha$$

where H_{CGVD28} is the elevation in metres according to CGVD28, H_{CD} is the elevation in metres according to chart datum, and α is the offset in metres. Based on surveys at the Ucluelet station[23], the local value of α is -2.05 m.

For flood hazard mapping, a DEM of the shore and inland topography at a spatial resolution of 1 m, using the aforementioned LiDAR data, was obtained from the DOU.

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[20] Natural Resources Canada: Weblink: https://www.nrcan.gc.ca/earth-sciences/geomatics/geodetic-reference-systems/9054#_Toc372901507.

[21] Natural Resources Canada: Weblink: https://www.nrcan.gc.ca/earth-sciences/geomatics/geodetic-reference-systems/9054#_Toc372901507.

[22] Natural Resources Canada, Canadian Active Control System (CACS), https://webapp.geod.nrcan.gc.ca/geod/data-donnees/cacs-scca.php?locale=en

[23] Fisheries and Oceans Canada, Station Benchmark for Ucluelet, B.C. (#8615); http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/twl-mne/benchmarks-reperes/station-eng.asp?T1=8615&region=PAC&ref=maps-cartes

4.3 Relative Sea Level Rise Consideration

Consideration of SLR due to climate change is an essential component of coastal flood hazard assessments. According to the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report from 2013 (IPCC, 2013), sea levels have been globally rising by approximately 3.2 mm/year since 1993 and by 1 mm/year over the last 100 years. Both the *Professional Practice Guidelines* and the *Provincial Guidelines* suggest planning for 1 m of SLR by 2100. Estimates of SLR in the literature vary considerably, with studies since 2013 tending towards larger values (Garner *et al.,* 2018). See also section 2.1.3 for information on SLR rates.

On the coast of British Columbia, however, RLSR has been less than the global mean (Mazzotti, Jones and Thomson, 2008). RSLR combines the effects of vertical land movements and SLR. Tectonic uplift is occurring on the west coast of Vancouver Island due to rebounding of the land after the last ice age ("isostatic effects") and tectonic activity. This uplift partially offsets SLR, and the RSLR rate over the last 60+ years was estimated at 0.9 mm/year (in contrast to 1 mm/year globally) (Mazzotti, Jones and Thomson, 2008).

This study considered RSLR scenarios of 0 m (present-day), 0.5 m, 1 m, and 2 m, independent of any specified year of occurrence (refer also to section 1.2.1 for a discussion of how this is presented as relative time ranges). This range of scenarios will allow short- to long-term planning.

4.4 Coastal Storm Flood Hazard Assessment

To assess the total water levels from storm-induced coastal flooding, RSLR, tides, storm surge, wave effects, and wind effects on water levels were included. The *Provincial Guidelines* and the *Professional Practice Guidelines* suggest that storm flooding be based on an annual exceedance probability (AEP) of 0.5% or 0.2%. To provide a wider range of potential scenarios, this study assessed 6.67%, 2%, 1%, 0.5%, and 0.2% AEPs. The AEP is the chance of an event occurring, or being exceeded, in any given year (see also Section 2.2.2).

In Canada, the historical record of monitored coastal water levels is rarely long enough to contain a large storm with a statistically low probability of occurrence. In this case, the anticipated water levels of the design storm are extrapolated from available data. While there are many methods to do this, most rely in some way on extreme value analysis. A key assumption in extreme value analysis is stationarity of climate, that is, the assumption that the statistics of climate are not changing over time. Assessments of historical wave records in the Pacific Ocean (Erikson *et al.,* 2015) led to the conclusion that climate stationarity is an acceptable assumption for 1979 to 2009 for the DOU, and future climate change studies do not indicate a large change in wave climate in the region of the DOU (Hemer *et al.,* 2013; Wang, Feng and Swail, 2014). While acknowledging that climate change may change storm activity in the future (non-stationarity of climate) and thus potentially increase design waves towards the end of the 21st century, for purpose of this study, estimates of future storm statistics were assumed based on the record of past storm activity.

An event-based approach (or designated-storm approach) to flood hazard assessment is often applied in BC. In this approach, one or more designated storms are specified based on the analyst's knowledge of local coastal weather patterns and storm responses. The design storm is then combined with a high tide and RSLR to enable calculation of the FCL. This approach can be efficient, and it works reasonably well where the studied shoreline is similarly exposed to storm conditions, where one flooding component (i.e., wind or wave runup, etc.) tends to dominate the others. The drawback of this approach is that usually multiple flooding components are important to different degrees at different locations. To address this, a larger set of design storms may be specified, but assigning a probability to these storms with confidence remains a challenge (FEMA, 2003a).

For this project, we used a response-based (continuous-simulation) approach. In this approach, historical total water levels are modelled over a long past period (called hind-casting). For this, all factors contributing to total water elevations (such as tides, storm surge, wave and wind effects) are based either on historical measurements or are modelled if no continuous records are available. This hind-cast historic water level record is then used to empirically determine the relationship between frequency of a storm event and the corresponding magnitude of total water elevation. The resulting data points of storm frequency and the responding total water elevations are then used to develop a curve (frequency-response curve). The curve is extrapolated beyond the length of the historic record to allow estimation of larger (and less frequent) storms, which have not occurred within the measured historical record, but may occur in the future. This curve can then be used to estimate the magnitude of flooding associated with any given AEP. A benefit of this approach is that there is no need to assign a probability to each of the individual water level components; the joint probability of the individual water level components is already inherently contained within the hind-cast. While this approach is computationally more expensive, it is less reliant on the judgment of the analyst to determine extreme flooding levels. The response-based approach is also advocated by FEMA for coastal flood hazard analysis on the Pacific Coast (FEMA, 2003b).

In this study, a hind-cast was produced for DOU for the past 40 years (1979–2018) for the total runup elevation (i.e., the maximum water level reached for each historic storm), which included effects of tides, storm surge (including multi-year climate variation), local wind set-up, and wave set-up and runup (see Sections 2.1.1 for definitions). Ideally, each of these components is available from measurements, but in practice, computational modelling is usually required.

Tides were modelled deterministically based on sun, moon, and Earth gravitational forces; storm surge was inferred from gauge measurements; wind set-up was modelled based on local historical wind conditions; and wave effects were modelled based on tide, storm surge, and offshore wave data (Figure 15). The total runup elevation was then modelled based on the individual components (Figure 15).

The hind-cast was then used to calculate frequency-response curves a 48 points along the coast (see Section 4.4.5 for more information). This process was repeated for RSLR of 0.5 m, 1 m, and 2 m.

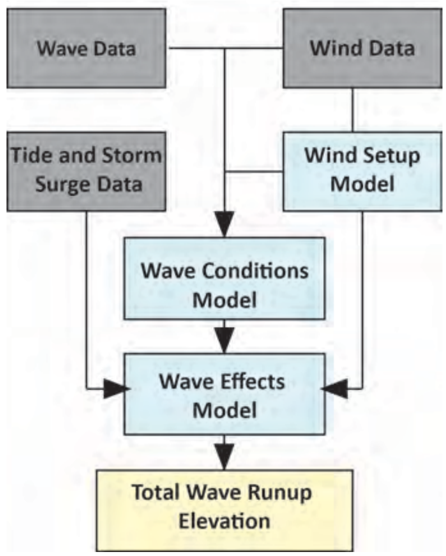

Figure 15: A schematic showing the relationship between data (grey), models (blue), and results (yellow) in the coastal hind-cast (simplified from Cascadia Coast Research Ltd., see Appendix A).

4.4.1 Wind Set-Up

Wind set-up (i.e., the fluctuation in water level resulting from shear stress of wind over the water surface) was modelled with a two-dimensional (2D) hydrodynamic model, forced by local historic wind data.

Wind data from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 global reanalysis model was used to drive waves and local wind-surge within this coastal hind-cast. Wind data from this reanalysis model is available from 1950 to 2019 at 0.25° spatial resolution. The advantage of this dataset over measurements or other coarser models, is that the record is complete over the hind-cast period, and full spatial coverage is available for the Ucluelet domain. The largest wind speed in the hind-cast wind dataset (1979–2018) was 23 m/s from a southeastern direction.

Wind set-up was modelled using the 2D RiCOM software (Walters, 2016). The model was forced by local winds as described above and run with a still water level corresponding to high tide. The largest wind surge estimates occurred adjacent to the head of Ucluelet Inlet and total just a few centimetres.

4.4.2 Tides

As tides result from the gravitational interaction of the sun, the moon, and the earth, they can be described deterministically. Tidal water levels were calculated based on data available from the Canadian Hydrographic Service and the T_TIDE tidal analysis and prediction software (Pawlowicz, Beardsley and Lentz, 2002). At the Ucluelet tide gauge, higher high water large tide (HHWLT) is 2.0 m CGVD28[24].

4.4.3 Storm Surge

Storm surge accounts for local atmospheric effects on water elevation, as well as water level variations that propagate off the Pacific Ocean (including multi-annual variations such as the PDO and ENSO).

The hind-cast time series of storm surge was calculated as the difference between the measured water level and the elevation predicted by the tidal constituents, a quantity also known as the tidal residual. In the coastal hind-cast, storm surge was represented as spatially uniform. The hind-cast time-series was calculated based on the tidal residual at the Ucluelet and Tofino tide gauges (see Figure 16). The largest storm surge event found in the hind-cast period (1979–2018) was 1.06 m.

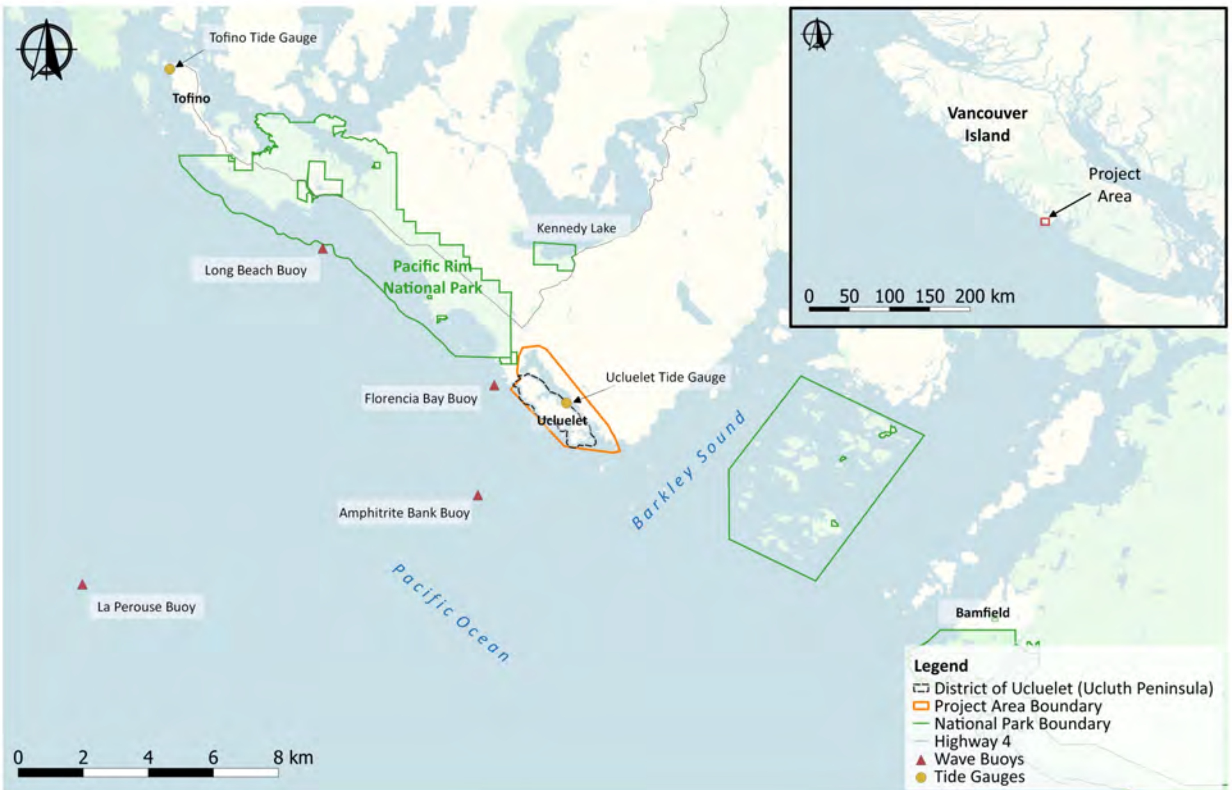

Figure 16: Map of project area showing key sites referenced for coastal storm flood model development.

4.4.4 Wave Conditions (Ocean Wave Modelling)

Large waves impacting the DOU primarily originate offshore in the Pacific Ocean and propagate into coastal waters. The exception is the upper reaches of the Ucluelet Inlet where waves are be primarily locally generated.

To estimate ocean waves approaching each shoreline reach over the entire historical record, a 2D computational wave model was developed using the SWAN wave modelling software (Booij, Ris and Holthuijsen, 1999). The computational grid for this model was based on the bathymetric and topographic data described in Section 4.2 and extends from Bamfield to Tofino and offshore as far as La Perouse Bank (see Figure 16). Grid resolution varied from approximately 1,000 m at the ocean boundary to 30 m at the western shoreline.

The model was forced with the local wind dataset (Section 4.4.1) and with wave data from the NCEP Wavewatch III hind-casts[25]. Water levels were specified based on measurements at the Ucluelet and Tofino tide stations (Sections 4.4.2 and 4.4.3). The NCEP wave model data was calibrated to wave measurements from the La Perouse weather buoy and scaled accordingly.

The wave model was evaluated by comparing model results to short-term wave measurements. These were obtained from buoys that were deployed at Amphitrite Bank, Long Beach and Florencia Bay (see Figure 16). The model was found to reproduce wave conditions satisfactorily (see Appendix A).

The wave model was run on a 3-hourly time step for the 40-year hind-cast period (1979–2018). The largest waves occurred around the exposed west shore of the Ucluelet Peninsula. The largest significant wave heights in the hind-cast are about 12 m, whereas in the sheltered areas it rarely exceeds 0.5 m.

4.4.5 Wave Effects (Wave Set-Up and Runup on Shoreline)

In practical applications, wave runup and wave set-up are often lumped together and assessed as a single quantity referred to simply as wave runup. In this assessment, the largest of all individual waves were used to describe the wave runup.

The shoreline DEM was split into 48 different sections ("reaches") of approximately 500-m width, with each reach having a similar slope and direction of exposure (Figure 17). For each reach, a transect across the shore from ocean towards inland was constructed that was considered representative of the reach.

[25] NCEP Wavewatch III; National Centers for Environmental Prediction (NCEP), National Oceanic and Atmospheric Administration (NOAA), U.S.; http://polar.ncep.noaa.gov/waves/wavewatch/

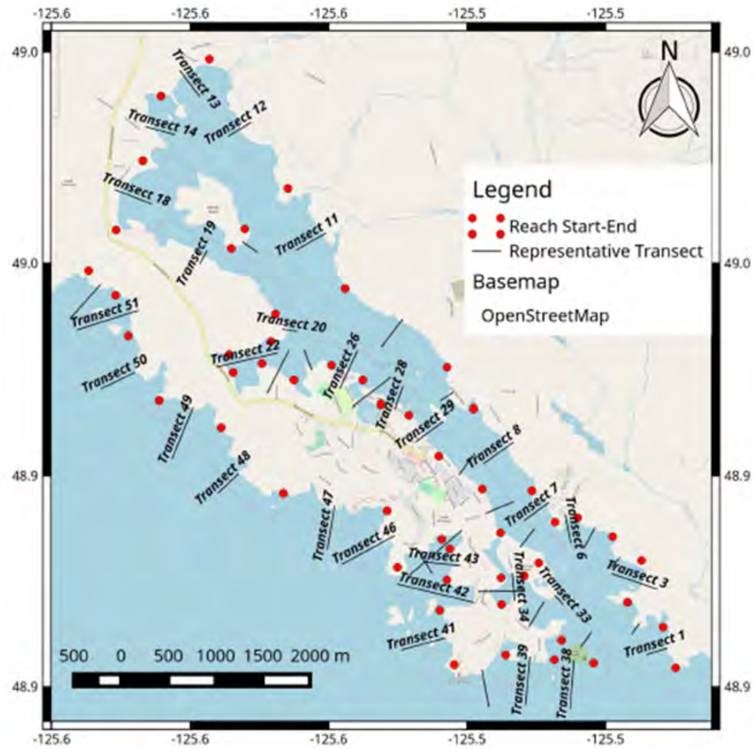

Figure 17: Example of location of shore reaches and representative cross-shore transects. All transects are shown in Appendix A (figure from Cascadia Coast Research Ltd., see also Appendix A).

Wave runup was estimated at each transect at each time step throughout the hind-cast. The runup estimated at each transect was considered representative of the runup along the entire reach. It should be noted however that variability in shore slope conditions within the reach will result in variability in wave runup that would not be captured. This is particularly true on Ucluelet's exposed western shore, where the rocky shoreline is extremely irregular.

Two approaches were used for calculating wave runup; one for shallower-sloped shores (Northwest Hydraulic Consultants, 2005) and one for steeper slopes (following Van der Meer *et al.* 2016) (see Appendix A for details). Inputs to the wave runup calculations are wave parameters (see section 4.4.4) and the average beach slope at each transect. The largest wave runup occurred where large waves broke on a steep slope, where runup alone can exceed 10 m.

4.4.6 Total Wave Runup Elevation

The total wave runup elevation combines the influence of tides, storm surge, and waves to estimate the total vertical extent of wave runup relative to geodetic datum. This is the maximum flooding impact of the storm on the coast.

The total wave runup elevation was calculated at 15-minute time steps throughout the hind-cast period. The storm surge (at 1-hour time steps) and the wave conditions (at 3-hour time steps) were interpolated to achieve this temporal resolution. The hind-cast was also run with RSLR = 0.5 m, 1 m, and 2 m to estimate total wave runup elevation with increasing levels of RSLR.

4.4.7 Hind-Cast Model Evaluation

The hind-cast modelling was evaluated by comparing modelled storm elevation to the elevation of visual indicators of recent storm activity along the shoreline (e.g., ocean debris and coastal erosion). One of the largest storms in the hind-cast occurred on January 18, 2018. However, a site visit in December 2019 showed few signs of the 2018 storm remaining. Fortunately, DOU staff were able to provide photos of the storm event (Figure 18 to Figure 19**Error! Reference source not found.**), along with location and flood water elevation estimates. In general, the model agrees reasonably well with the observations. This is illustrated by the annotations of observed and model estimated water levels on Figure 18 and Figure 19**Error! Reference source not found.**. More detailed information on the model evaluation is found in Appendix A.

Observed: 9.3 m
Model Estimated: 10.3 m

Figure 18: Amphitrite Point. Photo Credit: District of Ucluelet.

Observed: 4.5 m
Model Estimated: 5.5 m

Figure 19: Terrace Beach. Photo Credit: District of Ucluelet.

Orthophotography and LiDAR data were used to establish the elevation of storm evidence and therefore the likely total wave runup elevation of historic storms. Based on this evaluation, the storm evidence corresponded well with the modelled hind-cast total wave runup elevation (see Appendix A for details).

4.4.8 Total Wave Runup

The total wave runup elevation of each of the hind-cast runs (i.e., for the 4 different RSLR scenarios) at each cross-shore transect was used to estimate frequency-response curves for each transect.

From the generated total wave runup elevation data, only values over the 99.95th percentile of occurrences were used (i.e., only the largest events). For most transects, this resulted in about 1-2 events identified in each year. Next, a continuous frequency-response curve was fit to each storm set and extended beyond the historical record to provide an estimate for even greater events. This frequency-response curve was then used to estimate the total wave runup elevation associated with the 6.67%, 2%, 1%, 0.5%, and 0.2% AEPs. Note that the hind-cast period is relatively short, and consequently, the 0.5% and 0.2% AEP estimates in particular have high uncertainty.

4.4.9 Coastal Storm Flood Hazard Mapping

Out of the five coastal storms modelled, the storms of frequent (6.67% AEP) and rare (0.5% AEP) likelihood were mapped to show depths and extents. The qualifiers for these two storms appear as bolded text in Table 5, which summarizes the links between AEP, likelihood, storm size, and indicative return period for each of the coastal storms modelled[26]. Various maps were completed to reflect the RSLR scenarios. More details are in Section 5.

Table 5: Coastal Storm Flood Qualifiers.

AEP	Likelihood	Storm Size	Return Period (indicative)
6.67%	**Frequent**	**Small**	**15 year**
2%	Moderately frequent	Small-moderate	50 year
1%	Moderately infrequent	Moderate-large	100 year
0.5%	**Rare**	**Large**	**200 year**
0.2%	Very rare	Very Large	500 year

To develop the coastal storm depth and extent maps, storm hazard modelling results of total wave runup elevation were tabulated at each cross-shore transect. To develop a continuous water elevation map from this dataset, the water elevations from the cross-shore transects (most of which are at a 500 m to 1,000-m distance), were spatially interpolated at 10-m resolution using the inverse distance weighting interpolation method. It should be noted that there is inherent uncertainty in the interpolated areas. However, the alternate approach, which would be to assign water levels to the reach either side of the transect, results in discontinuities at the reach breaks. This then makes the development of

[26] In the planning support maps (explained further in Section 5.3), the rare (0.5% AEP) coastal storm was used, following guidelines and to be consistent with previous work for other jurisdictions in the region.

planning maps and implementation of the results challenging. And therefore, in this case, we have used an interpolation approach.

Next, the LiDAR-based DEM (spatial resolution of 1 m CGVD2013, see Section 4.2) was used to calculate water depth as the difference between water elevation and ground elevation. Careful cleaning was conducted to ensure that no water artefacts remained in the final depth layer. For this, disconnected water artefacts with a size smaller than 200 m^2 and larger disconnected artefacts with a distance of more than 10 m from the main flood extent were removed. Colours for map visualization were chosen so that different depths of flooding are easily distinguishable.

4.5 Tsunami Flood Hazard Assessment

In addition to storm-induced flooding, flooding due to tsunami was also evaluated in this study. This section provides an overview of the tsunami flood hazard modelling.

As stated in the current *Professional Practice Guidelines*, there are no tsunami criteria for flood mapping set out in guidelines from the Province. There are numerous ways to define the water surface elevation associated with tsunami. Wave height is defined as the vertical distance between successive crests and troughs of a wave (Figure 2). This is not a useful measure for tsunami because the waves are very asymmetric. Alternatively, wave crest elevation is defined as the maximum value for water level with respect to a fixed reference, such as mean sea level or a land reference. However, this quantity includes tides and other sea level variations, so must be corrected for comparisons between different sites. Tsunami wave amplitude is defined as the maximum elevation of the wave crest with respect to the surrounding or prevailing water levels. Thus, tsunami observations are corrected for tide and other variations to derive this quantity. For the most part, amplitude is the quantity of interest in this report and can be combined with tides, storm surges, or other water level variations to give the total water elevation.

As discussed previously in this report, the British Columbia coastline is exposed to tsunami hazard from multiple sources that may be proximal (near to) or distal (far from) sources. The BC Flood Hazard Area Land Use Guidelines requires assessment of, at minimum, the hazard due to the 1964 Alaska megathrust event and a possible CSZ event (MWLAP, 2004).

For this project, it was assumed that a fault of the CSZ poses the greatest hazard to the DOU (Myhre *et al.,* 2013). However, information on the 1964 Alaska megathrust was attempted to be obtained by contacting the Canadian Hydrographic Service, the Department of Fisheries and Oceans, and the Ucluelet Historical Society in an effort to gather evidence of the impact at Ucluelet. While insufficient information was available for mapping, useful qualitative information on the event was provided. These oral accounts, which were kindly shared by the Ucluelet Historical Society, are provided in Appendix A (one is provided below) and provide a visual and local account of tsunami impacts in Ucluelet. Further details from this event, as they are available, are also provided in Appendix A.

My grandparents lived on Imperial Land, and I remember my Grandpa saying the water in the harbour raised three feet. When I asked my Dad about it, he said that he was standing with my mother on the dock at Imperial Oil and they listened to the roaring of the water in the darkness and the water in the harbour raised four feet. The Imperial Oil dock doesn't exist anymore, but it was larger than the Main Street Dock (Whiskey Dock). All the trollers were out in the middle of the harbour waiting for the tsunami to arrive. The rapidly rising and falling tide caused by the tsunami caused the log booms and bundles to move at the head of the bay. The booms and bundles became battering rams, which knocked out pilings and dolphins and the logs scattered.

-Barb Gudbranson, member of Ucluelet Historical Society

For the CSZ event, Tsunami Flood Construction Reference Planes (FCRPs) were modelled (see Section 2.4.1 for details on the FCRP). The tsunami hazard was investigated using a sophisticated hydrodynamic model. A full probabilistic tsunami hazard assessment[27] was not within the scope of this work.

4.5.1 CSZ Earthquake Rupture Models

The impacts of the CSZ 1700 earthquake and tsunami have been studied extensively through fieldwork, the oral history of BC First Nations, and written history from Japan (which was impacted by the tsunami) (Atwater *et al.,* 2015). However, it can be difficult to assess the hazard from this event at specific locations based on these studies. Hence, simulation using a computational model is typically used to study tsunami hazard in more detail.

Research progress from the last two decades has enabled simulation of a range of possible megathrust earthquake rupture models. Rupture models define the initial conditions of the tsunami waves that are generated. These conditions can then be input to a tsunami simulation model. Wang *et al.* (2003) characterized a CSZ earthquake resulting from a buried rupture. The rupture model was used in recent local tsunami modelling studies (e.g., for the District of Tofino (Ebbwater Consulting Inc. and Cascadia Coast Research Ltd., 2019); and in Cherniawsky *et al.,* 2007).

Gao *et al.* (2018) updated the buried rupture model from Wang *et al.* (2003) and expanded the research by characterizing other potential CSZ earthquake rupture models. Figure 20 shows the rupture types and the resulting seabed deformation, which represents the initial condition for the generated tsunami.

[27] A probabilistic tsunami hazard assessment (PTHA) considers multiple tsunami events following rupture scenarios having assigned likelihoods..

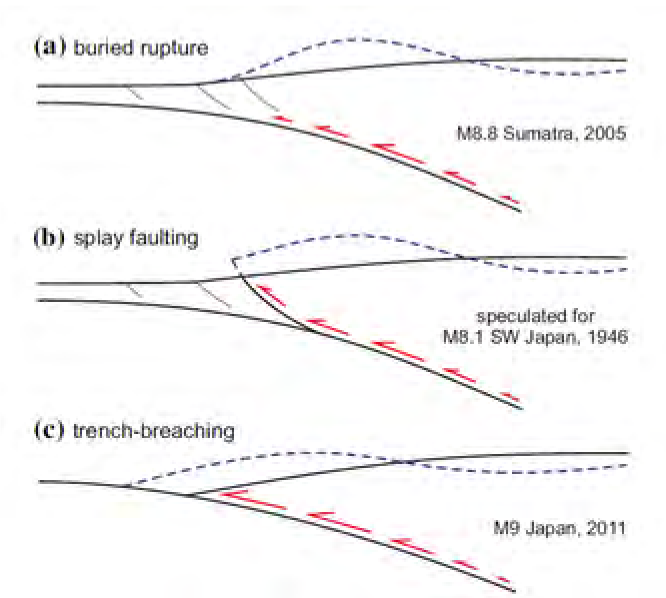

Figure 20: Megathrust earthquake rupture types and seabed deformation (dashed purple line) (Adapted from Wang and Tréhu, 2016**).**

For this project, tsunami waves were modelled based on 2 variations of each of the 3 rupture models (Table 6).

Table 6: CSZ rupture types considered for tsunami modelling in this study.

Rupture Model	Research Source	Model Abbreviation
Buried	Wang *et al.* (2003)	W2003
Buried	Gao *et al.* (2018)	G2018-B
Splay faulting A	Gao *et al.* (2018)	G2018-S-A
Splay faulting B	Gao *et al.* (2018)	G2018-S-B
Trench-breaching 50% peak slip	Gao *et al.* (2018)	G2018-T-50
Trench-breaching 100% peak slip	Gao *et al.* (2018)	G2018-T-100

4.5.2 Tsunami Simulation

Modelling tsunami wave dynamics requires a series of steps. First, a grid of land and seabed topography is generated. Then, the initial sea level conditions are specified, and finally the wave propagation and runup are calculated using a numerical model. Vertical displacement due to land subsidence of 2 m at Ucluelet was assumed, based on a conservatively high assumption, as a result of the fault deformation.

The numerical model RiCOM was used to model the tsunami. For the simulations in this study, a 2D (horizontal) hydrostatic version was used (Walters and Casulli, 1998). This approximation is suitable for long-wave (tsunami) propagation. Bathymetric and topographic data were sourced from the DEM (see Section 4.2). Grid resolution varied from 5,000 m at the ocean boundary to 5 m over the DOU and contained 710,744 nodes. More background on the earthquake rupture types, tsunami simulation, and resonance analysis are provided in Appendix A.

4.5.3 Resonance Analysis

The 1964 Alaska earthquake generated a tsunami which impacted much of British Columbia. The tsunami excited a resonance in the Alberni Inlet which amplified the wave to over 4 m in amplitude. Historical accounts of the tsunami from the Ucluelet community estimate the tsunami amplitude at 1.0 to 1.5 m. This is a similar amplitude to that measured at Tofino (Dunbar et al, 1992), and suggests that the Ucluelet Inlet did not experience significant resonance during the 1964 tsunami.

The potential for the resonance phenomenon to occur in Ucluelet Inlet was investigated as part of this work. For the simulated CSZ scenarios, the wave amplitude at the head of the inlet was similar to that at the mouth of the inlet, suggesting little resonance for these events. A more detailed spectral analysis estimated the Inlet's main resonant mode is for wave periods between 66 and 75 minutes. The CSZ scenarios produce a wave period of about 30 to 40 minutes. The 1964 Alaska tsunami had a period of about 112 minutes in Barkley Sound. However, it is possible that a different tsunami could have a wave period within the resonant mode of the Ucluelet Inlet, so the possibility of resonance cannot be excluded.

4.5.4 Tsunami Flood Hazard Mapping

Tsunami flood hazard mapping was limited to a subset of the modelled potential megathrust simulations. Out of the 6 rupture models simulated in the tsunami model, two were mapped based on the following rationale[28]:

- **Buried rupture (W2003).** This rupture model result from Wang *et al.* (2003) provides a basis for comparison with previous tsunami modelling studies in the region. For this reason, it is referred to as the *Comparative Case* scenario. The deformation model is similar to the one updated by Gao *et al.* (2018). As well, based on the results for all ruptures simulated for this project, results for the W2003 simulation correspond to the lower end of the tsunami amplitudes (i.e., leading to the least impact on shore).
- **Splay faulting rupture (G2018-S-A).** The tsunami amplitude resulting from this rupture model from Gao *et al.* (2018) is generally the largest out of all the project simulations. The results of the simulation, especially with 2 m of RSLR, are considered the *Worst-case* scenario.

Section 6 details the tsunami flood hazard maps, and includes a comparison of the extents of the above two rupture model simulations. Tsunami depths and extents were mapped for the comparative and worst-case scenarios. Tsunami planning support maps (described in more detail in Section 6.5) focussed also on these two scenarios. Various maps were completed to reflect the various RSLRs. A different colour range was chosen compared to that used for the coastal storm hazard maps to highlight the different type of flooding caused by a tsunami.

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[28] Note that spatial data is provided for all rupture models.

Tsunami characteristics that were mapped included the depth, extent, wave amplitude, and current speed. The tsunami amplitude describes the maximum water elevation of the wave crest reached during the 3-hour simulation of the event with respect to the ambient water levels (which included the HHWLT and RSLR).

The maximum total water depth during a tsunami was also mapped. Total water depth included the (maximum) tsunami amplitude, high tide (HHWLT, 2.0 m CGVD28), subsidence resulting from the CSZ earthquake (2.0 m), and the relevant RSLR value. Subsidence was treated as an apparent increase to the maximum tsunami elevation and is relatively uniform throughout the DOU. These results were clipped to a buffered shoreline boundary data provided by DOU (which is consistent with their parcel data and planning maps) and combined with base maps for the area.

4.6 Uncertainties and Freeboard

The above analysis represents the best available understanding of coastal storm flood and tsunami hazard at Ucluelet. However, there is inherent uncertainty in the science used to develop the flood maps. Consequently, safety factors (termed freeboard for coastal storm floods) are used. The following provides a brief overview of the proposed safety factors for both flood hazard types. There is a noted difference in approaches, as there are standards and guidelines for coastal storm floods, and not for tsunami.

4.6.1 Coastal Storm Flood

As discussed in Section 2.4.3, the freeboard allowance is intended to account for uncertainties in the hazard analysis and local differences in water level. This is required to produce FCL and SLR Planning Areas.

For coastal storms, the *Provincial Guidelines* recommend that a freeboard of 0.6 m be used to define the FCL and SLR Planning Areas, unless the analysis uses HHWLT, in which case a freeboard of 0.3 m can be used. As tidal levels used in this study are absorbed by the continuous simulation approach, we have used a freeboard of 0.6 m for FCL and SLR Planning Area maps to provide a conservative estimate. Note that this method is consistent with that followed in the District of Tofino Flood Mapping Report (Ebbwater Consulting Inc. and Cascadia Coast Research Ltd., 2019).

In using the FCL and SLR Planning Areas to drive flood planning and policy, the application of freeboard requires careful thought and analysis. As recommended in the *Professional Practice Guidelines,* freeboard can vary depending on the level of uncertainty and the risk tolerance of the regulating jurisdiction (the DOU). Adequately defining the risk tolerance requires an assessment of what is at risk from flooding. This is outside of the scope of this current study. The following are a number of observations from this study that should be considered regarding the use of freeboard:

- The continuous simulation approach used in this study is considered best practice (FEMA, 2005). This gives a relatively high level of certainty in defining the likely impacts of a storm, when compared to more limited assessments using the designated storm approach.

- The generated frequency-response curves were extrapolated from a 40-year historical record. This gives increased uncertainty for larger events (e.g., the 0.2% AEP), and also includes the assumption of climate stationarity, whereas potentially, storm intensity may increase in the future.
- This study does not consider what is at risk from flooding. Different freeboard may need to be applied in different areas. This is the approach recently recommended to the Province (BGC Engineering Inc. and Ebbwater Consulting, 2017).
- There is inherent uncertainty in SLR scenarios events of the future.
- To produce FCLs and SLR Planning Areas, a conservative freeboard of 0.6 m has been applied.
- There is a high level of wave runup along the exposed coast of the DOU, and a more specific analysis of these areas may be useful before defining freeboard.

For further discussion of uncertainties and limitations of this study, also refer to Section 7.

4.6.2 Tsunami Flood

The destructive nature of tsunamis as well at their relative infrequency means that they do not naturally fit within the definition of FCL provided in the *Provincial Guidelines.* This study analyzed a set of tsunami scenarios based on a potential megathrust event. While all of these rupture events are plausible based on the evidence, we do not have relative probabilities for the different scenarios. It is possible that a present day CSZ event would result in smaller deformation than the ones modelled (as only a shorter time period has passed since 1700 than before that event), but that is not certain. Even for an event with smaller or similar deformation, the characteristics of the deformation may result in a larger response in the DOU. This is illustrated with the significant differences in the flood extents of the tsunamis generated by the buried and splay faulting rupture models (i.e., as defined by Wang *et al.* (2003) and Gao *et al.* (2018), explained in Section 4.5.1).

Uncertainties exist in the tsunami flood estimates due to the rupture model simulated, bathymetry data, and assumptions about the tide level. Emergency Management British Columbia (EMBC) recommends a 50% safety factor to determine tsunami flood planning level; albeit this focuses on screening-level large-scale tsunami assessments (Coastal Floodplain Mapping Guidelines; Kerr Wood Leidal 2011). The implication of setting a relatively high safety factor of 50% are further discussed in Section 0.

5 Coastal Storm Flood Hazard Maps

For this project, 20 simulations were run to produce coastal storm flood hazard data. These included the 6.67%, 2%, 1%, 0.5%, and 0.2% AEP floods across four different RSLR scenarios (0 m, 0.5 m, 1 m, and 2 m) (see Table 2 in Section 4.1). An output from this project is raw data files of flood extent polygons and flood depth grids to allow integration into DOU Geographical Information Systems (GIS) to support the planning and development of bylaws.

For mapping, the frequent (6.67% AEP) and rare (0.5% AEP) floods were selected as they represent the lowest and highest flood impacts, respectively. For RSLR, 3 out of the 4 scenarios were used (i.e., results for 0.5 m RSLR were not mapped as the differences between 0 m, 0.5 m, and 1 m RSLR are small). Since projections for sea level rise are changing rapidly (Section 2.1.3), time periods are not associated with each RSLR. Rather, 0 m of RSLR is referred to as "present-day", 1 m is referred to as "future", and 2 m is referred to as "far future" (see also note on terminology in Section 1.2.1).

To provide a full understanding of the level of hazard, we have produced flood depth and flood extent maps for a selection of the simulated scenarios; these are the more science-focussed maps. Flood maps were also produced to show FCL and SLR Planning Areas, as defined by the *Provincial Guidelines* (Table 7); these maps are intended to directly support planning and decision-making. This section provides example maps for discussion purposes. The Coastal Flood Hazard Map Atlas (Map Atlas) accompanies this report and contains all the storm flood maps listed in Table 7. Examples of the different map types follow this section.

Table 7: Coastal storm flood hazard map series provided in the accompanying Coastal Flood Hazard Map Atlas. A freeboard (0.6 m) was added for the FCL and SLR Planning Areas maps, but not to the other map series (see Section 4.6 for discussion of freeboard).

Map Type	Map No.	Map Title	Scenario Description
Coastal Storm Flood Hazard (Map Series 1)	1	Flood Depth – Frequent Event (Present-Day)	6.67% AEP, 0 m RSLR, no freeboard
	2	Flood Depth – Frequent Event (Future)	6.67% AEP, 1 m RSLR, no freeboard
	3	Flood Depth – Frequent Event (Far Future)	6.67% AEP, 2 m RSLR, no freeboard
	4	Flood Depth – Rare Event (Present-Day)	0.5% AEP, 0 m RSLR, no freeboard
	5	Flood Depth – Rare Event (Future)	0.5% AEP, 1 m RSLR, no freeboard
	6	Flood Depth – Rare Event (Far Future)	0.5% AEP, 2 m RSLR, no freeboard
	7	Flood Extent – Frequent Event (Present-Day, Future, Far Future)	6.67% AEP, for 0 m, 1 m, and 2 m RSLR, no freeboard

Map Type	Map No.	Map Title	Scenario Description
	8	Flood Extent – Rare Event (Present-Day, Future, Far Future)	0.5% AEP, for 0 m, 1 m, and 2 m RSLR, no freeboard
Coastal Storm Flood Planning Support (Map Series 2)	1	Sea Level Rise Planning Areas – Rare Event (Near Future and Future)	0.5% AEP, 0.5 m and 1 m RSLR, with 0.6 m freeboard
	2	Flood Construction Level – Zones for Rare Event (Near Future)	0.5% AEP, 0.5 m RSLR, with 0.6 m freeboard
	3	Flood Construction Level – Zones for Rare Event (Future)	0.5% AEP, 1 m RSLR, with 0.6 m freeboard
	4	Flood Construction Level – Contours for Rare Event (Near Future)	0.5% AEP, 0.5 m RSLR, with 0.6 m freeboard
	5	Flood Construction Level – Contours for Rare Event (Future)	0.5% AEP, 1 m RSLR, with 0.6 m freeboard

5.1 Coastal Storm Flood Depth Maps

Flood depth maps provide a detailed assessment of flooding, as they provide the extent of flooding, but also the depth of water on the land. The depth of water during flooding has significant consequences for flood impacts. For instance, 10 cm of flooding can cover streets and cause nuisance effects, such as temporary interruption of traffic. On the other hand, deeper water depth can lead to houses being flooded, with much more significant consequences (e.g. permanent damage, evacuations, etc.). As an example, potential consequences of flooding at different depths are described in Table 8 for a residential building.

Table 8: Description of potential damage and disruption consequences of flooding at different depths for a single- or multi-family residential building (Ebbwater Consulting and Compass Resource Management, 2018)

	Minor Flooding (0–10 cm)	Moderate Flooding (20–40 cm)	Severe Flooding (80–100 cm)
Condition	Water laps up at doorstep, may enter the house through crawlspace/basement windows, flood garages.	Water in house on main level, crawlspaces/basements likely flooded.	Extensive flooding in house and extensive flooding in crawlspaces/basements.

	Minor Flooding (0–10 cm)	Moderate Flooding (20–40 cm)	Severe Flooding (80–100 cm)
Damage	No significant damage to residential structures, though damage to contents may occur in garages and crawlspaces. Damage likely less than 200 $/m^2$.	Moderate damage to structures, higher damage to contents in basements and main level, including furnaces and water heaters, major appliances. Damage likely 200–300 $/m^2$.	Considerable damage to structure, extensive damage to content, most major appliances, electronics, furniture on main level and in basements. Damage likely 580–610 $/m^2$.
Disruption	Residents not likely required to leave their homes, but will need to clean up yards and possibly basements. Disruption likely over a week. Limited emergency response required.	Residents likely displaced from homes for several days and weeks emergency response likely needed for elderly and people with disabilities, etc.	Residents likely displaced for 1– 2 weeks and disrupted for a month. Emergency response needed including possibly addressing utilities interruptions outside flooded area.

Presented below are flood depth maps for the 6.67% AEP (Figure 21) and the 0.5% AEP (Figure 22) for the future (RSLR of 1 m). Further flood depth maps are provided in Appendix C. The complex geography of the DOU means that a single storm event may play out differently in different areas. For instance, the January 18, 2018 storm event had an estimated AEP that ranged from less than 1% to 100%, depending on the exposure of the area to wind (see Section 3.6.1).

Figure 21: Coastal storm flood depth map for the frequent (6.67% AEP) flood and future scenario (1 m RSLR) scenario.

Figure 22: Coastal storm flood depth map for the rare (0.5% AEP) flood and future scenario (1 m RSLR) scenario.

The water depth maps show that, while extents between different flood events do not change significantly with changing AEP (see also Section 5.2), water depths increase for the rarer (0.5% AEP) flood in comparison to the frequent (6.67% AEP) flood. The difference in depth between these two scenarios for 1 m RSLR is shown in Figure 23.

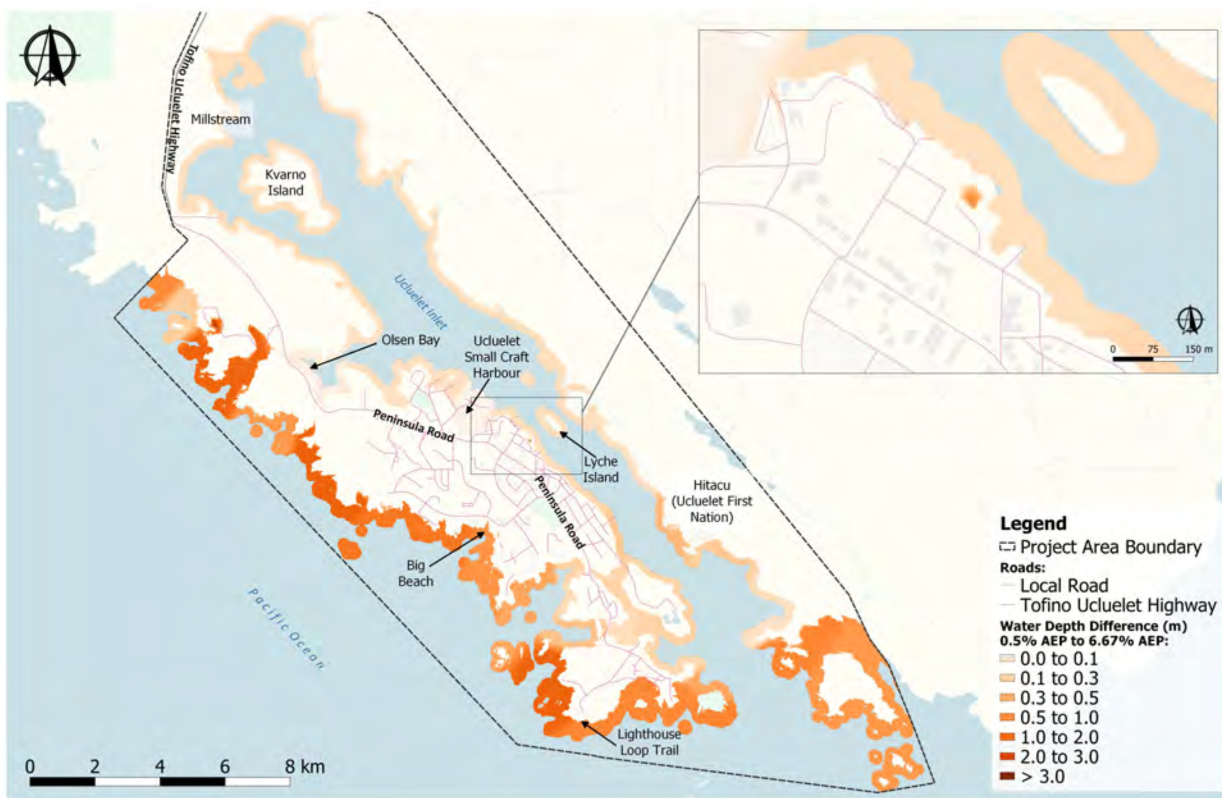

Figure 23: Coastal storm flood depth difference map between the rare (0.5% AEP) and frequent (6.67% AEP) floods for the future (1 m RSLR) scenario.

In Figure 23, the differences for the shores of Ucluelet Inlet are small to negligible. The largest differences between the rare and frequent events occur in the areas that are exposed to coastal storms, on the western and southern exposures of the project area boundary. This is expected as these areas are where the rare events are likely to produce larger wave runups due to wind, surge, and wave effects stemming from the Pacific Ocean.

5.2 Coastal Storm Flood Extent Maps

Flood extent maps show the overall area where flooding may occur. We compared flood extents for different AEP floods for the present-day RSLR scenario (Figure 24), and the 0.5% AEP flood for multiple RSLR scenarios (Figure 25).

Figure 24: Comparison of the different AEP flood extents with 0 m RSLR at Ucluelet. Base layer: CARTO's Positron, created using derivatives of OpenStreetMap data - openstreetmap.org (© OpenStreetMap contributors; cartography license CC BY-SA).

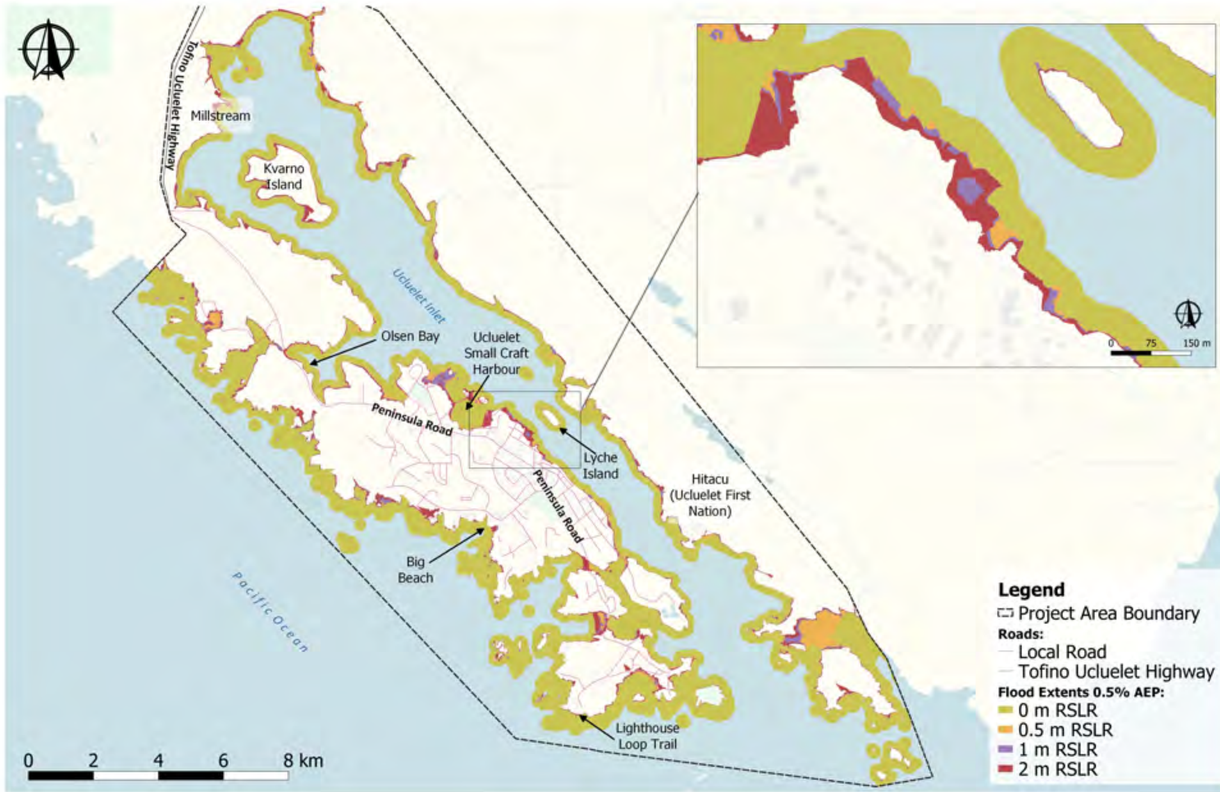

Figure 25: Comparison of the different RSLRs flood extents for the very rare (0.5% AEP) flood, zoomed to Ucluelet. Base layer: CARTO's Positron, created using derivatives of OpenStreetMap data - openstreetmap.org (© OpenStreetMap contributors; cartography license CC BY-SA).

Differences between flood extents for different storm intensities are relatively minimal for different AEP floods. This is mostly due to the shape of the frequency-magnitude curve for storm events, which rises steeply before becoming quite shallow (i.e., the difference in flood elevation decreases substantially for the rarer events). In contrast, different RSLRs show a clear increase in flood extents with rising sea levels (Figure 25). As described in Table 7, Map 7 of Series 1 of Appendix C contains a map similar to that shown in Figure 25, for the frequent (6.67% AEP) flood.

5.3 Coastal Storm Flood Planning Support Maps

The depth maps were used as the basis to prepare the coastal storm planning support maps. Due to the complexity and diversity of the DOU coastline (especially on the western shores), changes were required to translate the depth maps into usable form for planning purposes. A balance was required to provide a conservative estimate, which addresses modelling uncertainties, while not creating unreasonable spatial constraints for land use planning.

Therefore, there are differences between the coastal storm flood depth and extent maps, and the planning support maps. The differences in the planning support maps are explained in more detail in Appendix D, with the main differences summarized as follows:

- The transects used to model wave runup (and depth) were grouped into zones, thus simplifying the model output from 48 transects to 15 zones within the DOU boundary (and an additional 3 zones including the wider project area).
- Within each zone, the maximum water elevation within each zone was assigned to the entire zone.
- A freeboard of 0.6 m was added to calculate the FCL for the zone.
- Specific adjustments were made to four transects to account for the extreme variability of the western shores of the DOU.
- Professional judgement was required to assess the relative accuracy of transects located on opposite sides of the peninsula, and how these should influence the landward area between the transects in the narrow land corridor at Terrace Beach.

The map series and maps, as ordered in the Map Atlas, are described here.

5.3.1 Sea Level Rise Planning Area Map

The *Provincial Guidelines* state that as first step in land use planning for SLR is to establish future SLR Planning Areas and map the associated FCL. The SLR Planning Areas represent the areas between flood extents of the designated storm at the present-day and a future time with a rising sea level. They therefore show the land that is currently not exposed to flooding from the designated storm but will likely be so in the future with sea level rise, and therefore, planning should account for this.

The *Provincial Guidelines* suggest that the minimum design storm to be used in the calculation of FCL and SLR Planning Areas is 0.5% AEP (i.e., a rare event), but that this can be reassessed for a 0.2% AEP (i.e., a very rare event) for heavily populated areas. Due to the relatively low population density in the DOU, a design storm of 0.5% AEP plus freeboard was used for this project. The extents of the SLR planning areas are based on the extents of the FCL zones, as discussed in the section below.

To prepare for future climate change and associated sea level rise, SLR Planning Areas are presented for a rare (0.5% AEP) flood, for the near future and future (0.5 m and 1 m RSLR, respectively) (Figure 26).

Figure 26: Sea Level Rise Planning Area map for a rare (0.5% AEP) flood and for the near future and future (0.5 m and 1 m RSLR). The areas are defined by the seaward side of the relevant RSLR extent. This figure is intended to provide a snapshot of the full-scale map found in the Map Atlas.

In general, there are small differences in the SLR Planning areas for the 0.5 m and 1 m RSLRs. However, differences are noticeable in a few specific areas including the south side of Ucluelet Harbour and the Ucluelet Village Centre, and areas within Olsen Bay and on the northwest shores of the DOU.

5.3.2 FCL Maps

The Coastal Floodplain Mapping Guidelines (Kerr Wood Leidal, 2011) recommend specifications for what flood maps should contain and how they should be presented. This is reported in the *Professional Practice Guidelines* as broadly similar to the draft federal guidelines for flood mapping. The topographic mapping specification is summarized in Table 9, and was applied for FCL maps. In addition to showing FCL maps with these exact mapping requirements, we also provide FCL maps (with the same FCL zones) without the elevation contour lines and at a slightly smaller scale, with the goal to provide better readability in the maps.

Table 9: Coastal Floodplain Mapping Guidelines criteria for topographic mapping used for flood hazard areas (Kerr Wood Leidal, 2011)**.**

Map Property	Criterion (Kerr Wood Leidal, 2011)	Criterion Used
Scale	1:10,000 minimum (1:5,000 preferred)	1:10,000
Contour Interval	0.5 m minimum (0.3 m preferred)	0.5 m
DEM Point Spacing	10 m minimum (1.5 m preferred)	1.0 m
Accuracy	Sufficient to define the flood hazard area boundary and consistent with the standard accuracy implied by 0.5 m contours	
Horizontal Datum	North American Datum 1983 (NAD83)	NAD83
Vertical Datum	Canadian Geodetic Vertical Datum 1928	CGVD2013
Horizontal Accuracy (95% confidence interval)	1:10,000 scale: 6.1 m 1:5,000 scale: 3.05 m 1:2000 scale: 1.25 m	1.0 m
Vertical Accuracy (95% confidence interval	50% of contour interval	< 15 cm

As for the SLR Planning Areas, FCLs were calculated for a rare (0.5% AEP) flood for the near future and future climate (0 m and 1 m RSLR, respectively). The FCL is the sum of the flood construction reference plane (FCRP), which equals the total wave runup elevation and includes storm surge, tides, wind and wave effects, as well as an assigned freeboard of 0.6 m. The FCL map for 1 m RSLR is presented in Figure 27.

As mentioned at the beginning of Section 5.3, FCL zones were defined to allow easier integration into land use planning. We recommend that these FCL zones be incorporated into a flood bylaw. The DOU may wish to add the possibility of variances through sign off on a different (i.e. lower) FCL by a *qualified professional.*

The approach used to define the FCL zones is conservative. Using the highest transect water level in each FCL zone to define the FCL meant that in some areas, the FCL extent was larger than the modelled extent shown in the depth maps. In addition, creation of the zones resulted in the creation of differences in the FCL from one zone to another (e.g., for neighbouring parcels). While these zones have been roughly mapped to the changes in flood extent and topography, there is additional uncertainty in these transitions between FCL zones. Appendix D explains how this process has a notable effect on some specific areas. This conservative approach to defining FCL zones needs to be recognized by the DOU as related policies (such as the OCP) are developed.

Figure 27: FCL map for a rare (0.5% AEP) flood for the future (1 m RSLR), including 0.6 m freeboard. FCLs are relative to CGVD2013. This figure is intended to provide a snapshot of the full-scale maps found in the Map Atlas.

Figure 27 shows that FCLs range widely throughout the DOU's complex shorelines. FCLs are lower on the Inlet shores (i.e., 4.2 m CGVD2013 along the Ucluelet Small Craft Harbour and 7.5 m on Hyphocus Island) and are moderate along the southern areas (between 9.6 m and 11.9 m at the southern tip of the peninsula). The FCLs on the western shores range from 7.7 m to 14.2 m along the Ancient Cedars Loop Trail, and 10.0 m at Brown's Beach. Cliff zones on the western shores have the highest FCLs, as wave runup is generally high along these steep slopes that are exposed to the Pacific Ocean. As discussed in Sections 2.5 and 4.6, while these maps provide an indication of present and future flooded area, care should be taken when translating these maps into planning policy.

5.4 Coastal Storm Flood Hazard Summary

A variety of maps have been produced to visualize the coastal storm flood hazard in the DOU. The flood extent and depth maps provide a scientific basis for insights on the range of AEP floods and RSLR scenarios. They can be used within the context of a risk assessment. The planning support maps are produced based on guidelines, are more conservative, and can facilitate policy and planning.

6 Tsunami Flood Hazard Maps

For this project, 24 scenarios were run to model tsunami flood hazard caused by a CSZ megathrust earthquake. Six rupture type variations (Section 4.5.1) and 4 RSLR scenarios (RSLR of 0 m, 0.5 m, 1 m, and 2 m) were simulated. As mentioned under Section 5 for coastal storm flood hazard map outputs, the raw data files associated with all the tsunami flood simulations have been provided to the DOU.

For mapping, two earthquake rupture type variations were selected (i.e., the W2003 and G 2018-S-A models) as explained in Section 4.5.1. These rupture types were mapped for 0 m, 1 m, and 2 m RSLR.

Tsunami flood hazard maps include maximum tsunami flood depths and extents, as well as maps that can support the DOU with policy and planning objectives. This section provides some example maps, while more maps are provided in the Map Atlas (Appendix A), which accompanies this report and contains all the tsunami flood hazard maps listed in Table 10.

Table 10: Tsunami flood hazard map series for the Cascadia Subduction Zone event, provided in the accompanying Coastal Flood Hazard Map Atlas. Maximum tsunami flood depth is the sum of land subsidence due to the fault rupture, maximum tsunami amplitude, 2 m HHWLT, and RSLR. Freeboard was not included, as no guidelines are available regarding tsunami freeboard.

Map Type	Map No.	Map Title	Scenario Description
Tsunami Flood Hazard (Map Series 3)	1	Flood Depth – Splay Faulting Rupture (Present-Day)	G2018-S-A model, 0 m RSLR
	2	Flood Depth – Splay Faulting Rupture (Future)	G2018-S-A model, 1 m RSLR
	3	Flood Depth – Splay Faulting Rupture (Far Future)	G2018-S-A model, 2 m RSLR
	4	Flood Depth – Buried Rupture (Future)	W2003 model, 1 m RSLR
	5	Flood Extent – Splay Faulting Rupture (Present-Day, Future, Far Future)	G2018-S-A model, for 0 m, 1 m, and 2 m RSLR
	6	Flood Extent – Splay Faulting and Buried Ruptures (Present-Day)	G2018-S-A and W2003 models, 0 m RSLR
	7	Flood Extent – Splay Faulting and Buried Ruptures (Future)	G2018-S-A and W2003 models, 1 m RSLR
	8	Flood Extent – Splay Faulting and Buried Ruptures (Far Future)	G2018-S-A and W2003 models, 2 m RSLR
Tsunami Flood Planning Support (Map Series 4)	1	Tsunami Flood Planning Level – Buried Rupture (No safety factor)	W2003 model, 1 m RSLR
	2	Tsunami Flood Planning Level – Splay Faulting Rupture (No Safety Factor)	G2018-S-A model, 1 m RSLR

Map Type	Map No.	Map Title	Scenario Description
	3	Tsunami Flood Planning Level – Buried Rupture (Safety Factor)	W2003 model, 50% safety factor, 1 m RSLR
	4	Tsunami Flood Planning Level – Splay Faulting Rupture (Safety Factor)	G2018-S-A model, 50% safety factor, 1 m RSLR.
	5	Tsunami Flood Planning Level – Scenario Comparisons	W2003 and G2018-S-A with and without safety factor, 1 m RSLR
	6	Tsunami Flood Hazard Vulnerability Zones – Splay Faulting Rupture (Future)	G2018-S-A model, 1 m RSLR

6.1 Tsunami Amplitude Maps

The tsunami amplitude describes the maximum elevation of the wave crest with respect to the surrounding (ambient) water levels (here, relative to 2 m of tide and 2 m of RSLR). The tsunami amplitude can then be combined with storm surges or other water level variations to find the total water elevation (or water depth).

As described in Section 4.5.1, 6 tsunami rupture variations were simulated. Results for the maximum tsunami wave amplitude for the splay faulting rupture A present-day (0 m RSLR) scenario are presented below for the Northwest Pacific region from the Cascadia Subduction Zone towards the west shore of Vancouver Island (Figure 28), and with focus on the DOU (Figure 29). The maximum tsunami wave amplitude describes the highest wave amplitude reached across the 3-hour simulation of the tsunami event.

The DOU lies approximately 75 km northeast of the CSZ fault (Figure 28). Most of the tsunami energy is directed westward in the offshore direction towards Japan and Russia, and eastward toward the Pacific coast of North America. The initial water displacement at the location of the Cascadia fault is about 4 m to 12 m depending on the fault. As the eastward wave propagates towards the BC shoreline, the amplitude decreases to about 2 m or about half the initial amplitude. However, as the waves pass into more shallow water (i.e., less than 50 m of ocean depth), the amplitude increases again to nearly its initial amplitude, due to the effect of the shallower water (shoaling) (Figure 29).

In addition to the tsunami, the CSZ fault rupture will cause the shoreline at the DOU to drop (subside) by about 2 m relative to pre-rupture levels. The model shows the water receding for about 5 minutes into the subsidence trough that was created slightly offshore. Following this, the model shows water flooding over a period of about 25 minutes and reaching a depth relative to the new land surface level, equal to the sum of the subsidence plus the ambient water level plus the tsunami amplitude.

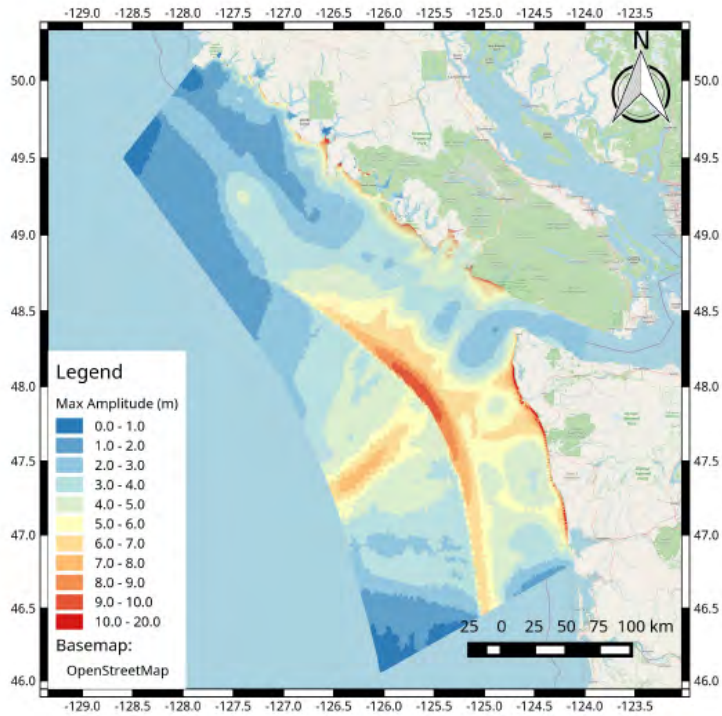

Figure 28: Maximum tsunami amplitude for splay faulting rupture (Gao2018-S-A) in metres relative to ambient water level. Ambient water level = 2 m tide (HHTWL) + 0 m RSLR (figure from Cascadia Coast Research Ltd., see also Appendix A).

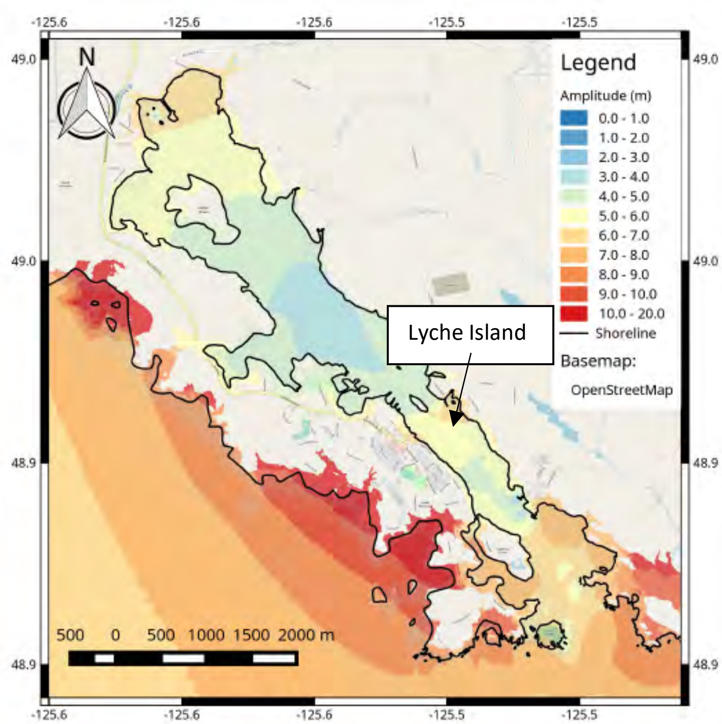

Figure 29: Maximum tsunami amplitude for splay faulting rupture (Gao2018-S-A) in metres relative to ambient water level. Ambient water level = 2 m tide (HHTWL) + 0 m RSLR (figure from Cascadia Coast Research Ltd., see also Appendix A).

The tsunami wave peaks arrive in the DOU approximately 30 minutes after the rupture. The amplitude at shore depends somewhat on the RSLR scenario considered. The splay faulting rupture A produces the largest tsunami wave of the considered rupture scenarios (e.g., it is almost twice as large as the buried rupture scenario). In the present-day (RSLR 0 m) scenario, the tsunami amplitude reaches 6 m in Ucluelet south of Lyche Island and at the entrance of the inlet. The maximum tsunami amplitude reaches 8 to 12 metres on the DOU's western shore. The wave overtops the Ucluelet Peninsula in several places: transect 49, transect 44 (Little Beach), and transect 42 (Terrace Beach). The lowest tsunami amplitudes in the Inlet occur at Lyche Island and Kvarno Island and are around 4 m. At the head of the Inlet, the tsunami amplitude again increases to about 6 m (Figure 29).

6.2 Tsunami Current Speed Maps

Tsunami current speed maps represent the maximum current speed that was reached during the event simulation of three hours. This helps with understanding potential damages, as speeds translates into force.

The tsunami wave is delayed somewhat as it enters Ucluelet Inlet. The flow associated with the tsunami is constricted to Lyche Island, accelerating the flow to up to 6 m/s, and heavily damping basin-scale oscillations.

For the splay faulting rupture A present-day scenario (0 m RSLR), the oscillations caused by the tsunami result in the peninsula being over-topped several times with current speeds of up to about 6 m/s. The tsunami wave is delayed somewhat as it enters Ucluelet Inlet (Figure 30).

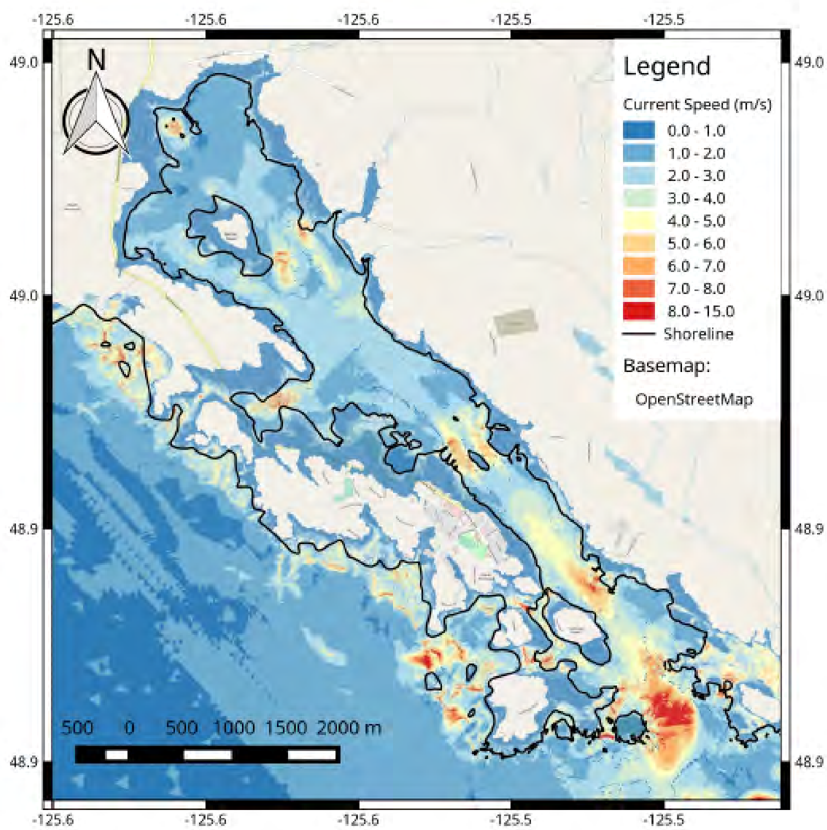

Figure 30: Maximum tsunami current speeds for splay faulting rupture (Gao2018-S-A) in metres per second. Ambient water level = 2 m tide (HHTWL) + 0 m RSLR (figure from Cascadia Coast Research Ltd., see also Appendix A).

6.3 Tsunami Flood Depth Maps

Tsunami flood depth maps show the maximum total water depth above the land surface during a tsunami, in contrast to tsunami wave amplitude maps that show only the height from pre-tsunami water levels to the top of the tsunami wave crest.

Due to the earthquake that causes the tsunami, a subsidence of the land surface may be experienced. The modelled CSZ events would lead to an approximate 2 m of subsidence in the region of the DOU. To calculate the total tsunami depth, the subsidence is added to the tsunami wave amplitude, and to be conservative, a high tide (HHWLT) is assumed. For the future scenarios, RSLR is also added.

Figure 31 shows that flood depths due to the worst-case tsunami are high (i.e., 6-8 m on shores and 4-6 m for some inland areas). Along the inlet shores, this includes areas in and around the Harbour in particular. Flood water would cut-off access and egress to much of the Peninsula due to flooding of Peninsula Road in several areas, including the Helen Road causeway to Hyphocus Island and the southern peninsula. Along the western shores, flooding would occur along beaches such as at Big and Brown's Beach areas. Flooding would also occur on portions of Marine Drive, and areas further inland. Tsunami water depth also increases with rising sea levels (Figure 32).

Figure 31: Maximum total water depth for splay faulting rupture (Gao2018-S-A) with RSLR 2 m (worst-case tsunami). Total water depth includes maximum tsunami wave amplitude, earthquake subsidence, and high tide (HHWLT). Depths are relative to CGVD2013. This figure is intended to provide a snapshot of the full-scale maps found in the Map Atlas.

Figure 32: Maximum total water extents for the splay faulting rupture (Gao2018-S-A) with RSLR 0 m, 1 m, and 2 m. Total water depth includes maximum tsunami wave amplitude, earthquake subsidence, and high tide (HHWLT). This figure is intended to provide a snapshot of the full-scale maps found in the Map Atlas.

6.4 Tsunami Flood Extents

Figure 33 compares the flood extents of the tsunami generated by the buried (Wang2003) and splay faulting (Gao2018-S-A) rupture models under multiple RSLRs. The tsunami amplitudes for the Wang2003 rupture model were considered to be on the lower end of the range of tsunamis simulated. In contrast, those for the Gao2018-S-A were considered to be on the larger end.

Figure 33: Maximum total water extents for the two rupture models with RSLR 0 m. Total water depth includes maximum tsunami wave amplitude, subsidence due to the earthquake, high tide (HHWLT), and RSLR. This figure is intended to provide a snapshot of the full-scale maps found in the Map Atlas.

As shown in Figure 33, in some areas the differences between the simulations are small, and in others they are large. This observation highlights that tsunami flood extents are dependent on the rupture model simulated. It is therefore prudent to consider multiple rupture models to define a worst-case scenario (i.e., conduct a fully probabilistic assessment). For the simulation runs for this project, the tsunami extents for the Gao2018-S-A rupture were clearly the largest for the majority of the areas for the respective RSLR scenario. This rupture thus represents the worst-case (see Section 4.5.1). The maps shown in the following section thus focus on results for the Gao2018-S-A rupture model simulations.

6.5 Tsunami Planning Support Maps

In addition to the detailed hazard maps presented above, maps that are intended to support planning have been provided. These intentionally simplify the hazard information, consider the planning context, and include a factor of safety. These are analogous to the Flood Construction Level maps provided for the coastal storms.

6.5.1 Tsunami Flood Planning Level Map

A tsunami flood planning level is an elevation below which areas are considered exposed to tsunami hazard, and above which areas are considered unlikely to be touched by tsunami hazard. It can provide guidance on various planning objectives. The level is very approximate, as tsunami wave heights and runup vary greatly depending on the tsunami source (e.g., earthquake source, rupture model) and local physical characteristics (e.g., shape of coastline, effects of offshore bathymetry).

6.5.1.1 <u>Maximum Tsunami Runup Elevation</u>

For this project, for each tsunami rupture model, wave propagation of the tsunami was modelled for a 3-hour simulation. From this 3-hour simulation, the maximum tsunami wave amplitude for each grid cell was selected to calculate the maximum inundation depth. The inundation depths and their respective runup elevation varied across the many grid cells of the DOU (see Section 6.3). Runup elevations were typically higher along the west coast of the peninsula than on the east coast. As for the FCL zone approach described in Section 5.3.2) a simplification was made to obtain one consistent runup elevation across the DOU. In this conservative approach the maximum runup elevation of all grid cells (discounting a couple of outlier grid cells) was applied across the project area. As an example, for the splay faulting rupture model (Gao2018-S-A) simulation, the maximum tsunami runup elevation was 18 m, including 1 m of RSLR. This 18 m elevation contour line was then delineated using LiDAR data to obtain extents. Figure 34 provides the resulting tsunami flood planning level map for the worst-case tsunami, without safety factor.

Figure 34: Tsunami flood planning level map for the worst-case, without safety factor. The elevations are relative to CGVD2013. This figure is intended to provide a snapshot of the full-scale maps found in the Map Atlas.

6.5.1.2 Safety Factor

There are no guidelines that prescribe which safety factor to use when detailed tsunami hazard modelling is available for a location. Typically, the intent of a safety factor is to manage known and unknown uncertainties of the tsunami hazard modelling. Thus, if a detailed tsunami hazard modelling study has been completed, a smaller safety factor may be applied than for a high-level study. For this project, maps were produced based on no runup safety factor, and a safety factor of 50%. The 50% safety factor is in line with recent detailed tsunami hazard mapping from BC's west coast (e.g., for the District of Tofino (Ebbwater Consulting Inc., 2019), for the City of Prince Rupert (NHC, 2019), the Capital Regional District (AECOM, 2013a), and Seal Cove in Prince Rupert (Fine *et al.*, 2018). The range of resulting planning levels can be considered by the DOU, in conjunction with an understanding of the community's risk tolerance.

6.5.1.3 Risk Tolerance

The establishment of risk tolerance, where a community works to understand what risk is acceptable and/or tolerable (given the tradeoffs), and what is unacceptable, is a good means of making locally-relevant, informed and transparent decisions for disaster risk reduction.

To obtain an understanding of risk tolerance, a comprehensive coastal flood risk assessment is required. While the hazard information produced from this project provides an excellent basis for a risk assessment, such an assessment was out of the scope of this study (we do recommend, in Section 8, that this be a next step). However, given the importance of the tsunami flood planning level, we provide high-level insights on risk tolerance here for the DOU to consider in its application of the maps. The insights provided are based on the coastal flood risk assessment that was completed for the District of Tofino (Ebbwater Consulting Inc., 2019).

For this project, 4 tsunami flood planning level maps were produced to provide an understanding of the spectrum of risk tolerance for the DOU. These are based on the two mapped rupture models described in Section 4.5.4 (i.e., the *comparative-case* based on the Wang2003 buried rupture, and the *worst-case* based on the Gao2018-S-A splay faulting rupture), and the application of a safety factor. As stated in Section 4.5.4, the *comparative-case* tsunami has been used to simulate tsunamis elsewhere in the region, including for the District of Tofino. Basing a tsunami flood planning level on the *comparative-case* would thus provide consistency for the DOU compared to other jurisdictions. However, the DOU should understand that the smaller flood extents associated with the *comparative-case* means that a higher risk tolerance would be implicitly adopted. The way in which the *comparative-* and *worst-case* rupture models influence risk tolerance is described in Table 11.

Table 11: Matrix of rupture models and safety factors to determine relative risk tolerance.

Risk Tolerance Spectrum	Safety Factor	Rupture Model Tsunami	Flood Planning Level (m)	Map Atlas Series 4 Map No.
Higher	None	*Buried rupture (Wang2003)*	15.0	1
⇕		*Splay faulting (Gao2018-S-A)*	18.0	2
	50%	*Buried rupture (Wang2003)*	22.5	3
Lower		*Splay faulting (Gao2018-S-A)*	27.0	4

Figure 35 shows the difference between the highest and lowest relative risk tolerance tsunami flood planning level maps (i.e., maps 1 through 4 in Table 11), for the Village Centre and Big Beach areas of the DOU.

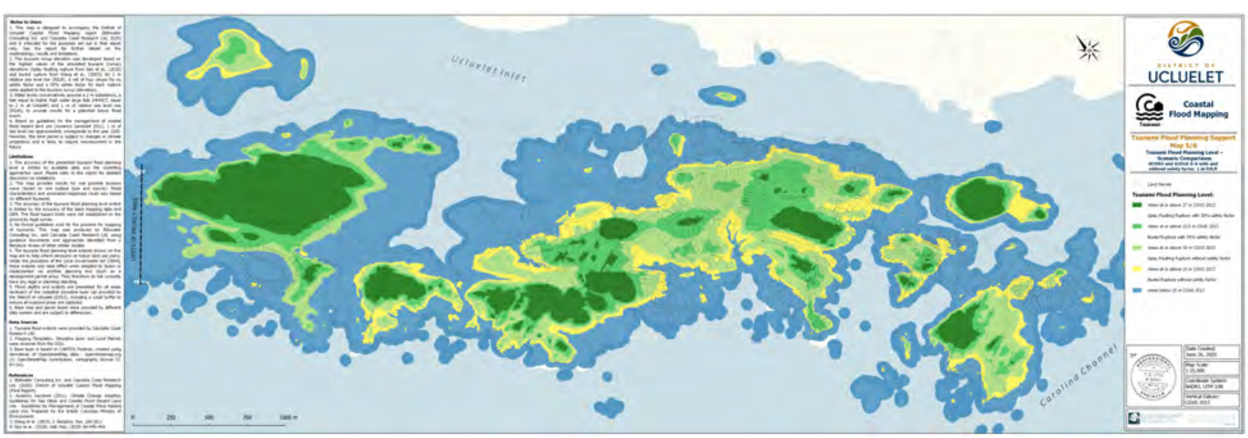

Figure 35: Difference in tsunami planning levels as an indication of risk tolerance.

It is not considered feasible to design all buildings to be tsunami-resilient, nor to site all buildings above the tsunami flood planning level. However, for emergency management and critical infrastructure siting in particular, the tsunami flood planning level should be taken into consideration. This involves weighing trade-offs between public safety and land use planning objectives. Building on the higher and lower risk tolerance framework provided in Table 11, example high-level risk tolerance trade-offs are described in Table 12.

Table 12: Trade-offs associated with higher and lower risk tolerance (based on maps used in Table 11).

	Higher Risk Tolerance	Lower Risk Tolerance
Advantages	• Greater flexibility in site development, facilitating planning efforts. • Potentially lower design, construction, and operating costs. • More potential to fit with municipal objectives and budgets.	• There is more certainty in safety. • Assurance that critical infrastructure services will continue to function (assuming dependent services such as water and electricity are not affected). • Community functions as 'business-as-usual'.
Disadvantages	• There is uncertainty in safety. • Potential for infrastructure to be damaged in the event of a tsunami. • Higher potential for consequences related to direct loss of service due to infrastructure damage. • Potential for widespread cascading consequences (e.g., psychosocial, environmental, productivity).	• Greater constraints in site selection, requiring additional planning and design effort. • Relocation costs for existing infrastructure. • For new infrastructure, potentially greater site development, design, construction, and operating costs. • May not be feasible to achieve desired service levels given DOU budgets.
Potential Applications	• Siting of non-critical infrastructure. • Establish "minimum safety zones" for emergency management; these may be areas to travel to if "maximum safety zones" cannot be reached within the estimated time required.	• Siting of critical infrastructure, emergency operations centre, and refuge shelters with supplies. • Establish "maximum safety zones" for emergency management.

Based on DOUs decisions related to trade-offs such as those described in Table 12, the DOU can select one of the 4 tsunami flood planning level maps.

6.5.2 Tsunami Flood Hazard Vulnerability Zone Map

The further step after modelling and mapping flood hazards, is to see the potential of the flood water to cause damage to the community and its assets (as a component of a risk assessment). This can be indexed by using vulnerability curves in conjuction with hazard thresholds. These thresholds are related to vulnerability of people as they walk or drive through flood waters, or as they remain inside a structure during a flood event. Flood hazard vulnerability zones for a community are defined based on the combination of flood depth and velocity as shown in Figure 36Figure 36. The flood hazard vulnerability mapping is based on international best practice for disaster resilience (AIDR, 2017). Figure 37 shows the vulnerability zones for the DOU and provides a high-level understanding of risk for the project area.

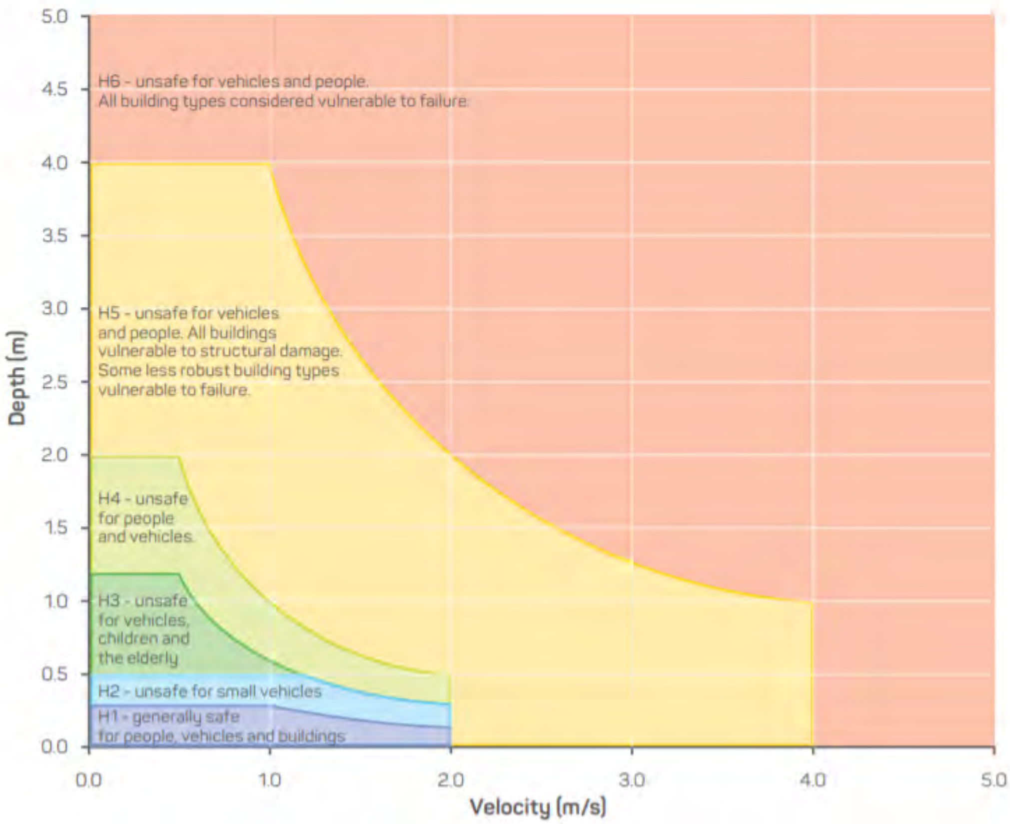

Figure 36: Combined flood depth and velocity curves (flood hazard curves) (AIDR, 2017).

Figure 37: Tsunami flood hazard vulnerability zones for the DOU, based on the worst-case tsunami with 1 m RSLR.

This mapping (Figure 37) shows that there is little variation in the vulnerability across the DOU, and that unfortunately, the predominant hazard index rating is H6 (unsafe for vehicles and people, all building types vulnerable to failure). There are portions of land to the north of the downtown core on the inlet side, where a lower rating is found (i.e. H5 and H4).

6.6 Tsunami Flood Hazard Summary

The results of the modelling and mapping study showed that in the DOU, the estimated tsunami flood hazard tended to be larger than the coastal storm flood hazard[29]. A series of tsunami flood map types were produced and explained in the above section to provide a better understanding of the tsunami hazard. While multiple rupture models where simulated, two of them were selected to provide an understanding of the range of results. The rupture models of focus was the splay faulting A (Gao2018-S-A), as it represents a worst-case scenario, as well as a buried rupture (Wang2030), as it is comparative to other tsunami studies in the region.

[29] The only areas where the coastal storm flood level is similar or slightly higher than the tsunami flood level occurs for RSLR = 0 m, and this occurs in areas with very steep beach slopes exposed to high energy waves. These areas are dominated by wave runup, which can raise water levels onshore substantially. For RSLR > 0 m, the tsunami hazard is larger than the storm hazard at all transects.

7 Limitations

As with any study of this type, many uncertainties exist, and modelling and mapping can only provide a simplified representation of a complex reality. This section summarizes some of the limitations and uncertainties from this study that should be kept in mind when using the provided flood hazard maps.

7.1 Coastal Storm Modelling

The accuracy of the coastal storm flood estimates relies on the accuracy of the hind-cast. The water level estimates (tide + surge) were based on measurements but were assumed to be spatially constant throughout the DOU, introducing a small amount of uncertainty. Wave conditions were modelled, and while modelled results were compared to offshore and nearshore measurements, uncertainties due to model simplifications still persist. While the shoreline was divided into reaches, variations in shoreline type, slope, and orientation still exist, and therefore, the wave runup portion of the coastal hind-cast will have a larger uncertainty compared to the tide and storm surge contributions. This is particularly true on the exposed west coast of the DOU, where runup can exceed 10 m and the shore is extremely irregular.

The use of the hind-cast to estimate probability of future coastal storm flooding assumed that the future climate at the DOU will be similar to the historic climate (assumption of climate stationarity). This means that it was assumed that the DOU will experience a similar number of storms each year with similar intensities to those that have been experienced historically. However, climate change will cause the future climate to deviate from the existing one and these changes will be different from region to region. While available literature to date suggests that only minor changes to ocean storm activity will affect the DOU over the next century, this might change with future research or observed changes.

Another limitation of the study was that the frequency-response curves were generated from a relatively short historical record, as is common where longer records do not exist. However, this means that extrapolation from the 40-year hind-cast introduced uncertainties, especially for the very large events, such as the 0.2% AEP (500-year return period), as these require the greatest degree of extrapolation.

There is also inherent uncertainty in RSLR values. Although the RSLR levels presented in this report are based on established guidance (*Professional Practice Guidelines, Provincial Guidelines,* and BC Ministry of Forests, Lands and Natural Resource Operations 2017), there is a large degree of variation in currently predicted levels. These guidelines are also liable to change in the future, as predictions are adjusted, and the effects of climate change are increasing.

7.2 Tsunami Modelling

The accuracy of the tsunami flood estimates relies on the accuracy of the tsunami modelling, including the deformation model of the fault rupture, bathymetry data, and assumptions about the tidal level at the time of the fault rupture.

One of the principal limitations of this work is that only a small set of deterministic events were modelled based on a CSZ event with 500 years of accumulated stress. The fault rupture models are an estimate based on the available evidence at the time of development(Wang *et al.,* 2003; Gao *et al.,* 2018). While all of these fault ruptures are plausible based on the evidence, the rupture study authors have not provided relative probabilities (Wang *et al.,* 2003; Gao *et al.,* 2018). It is likely that a present day CSZ event would result in smaller deformation than the one modelled, due to the shorter time period for build-up of stress (i.e., only about 320 years, instead of 500 years), but this is not certain. Even for an event with a smaller deformation, the characteristics of the deformation may result in a larger tsunami response in the DOU. This is illustrated with the significant differences in the magnitude of the tsunami generated by the G2018-S-A and G2018-B events.

Finally, a tidal level of HHWLT (2.0 m) was assumed to coincide with the tsunami event. This likely represents a worst-case tidal condition, but it could potentially be even worse with, for instance, additional storm surge, or mitigated by a lower tide level.

7.3 Flood Mapping

When producing the flood hazard maps, there are uncertainties introduced by the creation of the DEM. Although the vertical accuracy of the LiDAR was generally high, estimated better than 15 cm vertically, and with a horizontal resolution of 1 m, there may be small inaccuracies introduced.

The data used for mapping and modelling is only accurate for the day it was surveyed. Bathymetric and topographic data for example is likely to change over time, which may affect flood map results for future flood conditions. The LiDAR data was collected in 2015, and small changes to observed elevations may have occurred since then (for instance, due to erosion, sediment accumulation, construction, etc.).

In addition to the general uncertainty from the coastal modelling and hind-casting, there is a limitation caused by the interpolation of results between representative transects across the shoreline. Although the shoreline is sub-divided into 48 characteristic reaches, variation in shoreline type, slope, and orientation still exists within each reach.

There is a difference in the datum used to produce the water elevations at transects (CGVD28) and that used to map flood elevations (CGVD2013). This is due to not being able to source hind-cast data in the newer datum reference. Unfortunately, vertical datum conversion is not straightforward and may introduce further error. The differences between the two datums differs across the study area, in the range of 15 and 17 cm. This figure, however, is relatively small when compared to uncertainties due to modelling and is felt to be within the tolerance for error.

In order to produce flood hazard maps, flood depths have had to be categorized into depth bandings, typically of 1 m. A greater resolution has been used for smaller depths to better show the variation in initial flooding levels, but some of the detailed variation in levels is not shown in the maps.

A freeboard of 0.6 m is included in the assessment of FCL and SLR Planning Areas, as required by the *Provincial Guidelines*. It has not, however, been included in the other maps. This is to avoid distorting the flood extents shown by the modelling and to allow the DOU to use its discretion on which values to use, for example, based on what is at risk.

8 Recommendations

Considerable effort has been expended to create the flood maps for the DOU. They will however have no value unless they are used by the DOU, neighboring communities and the public to both understand and act on the information. The following recommendations are made to ensure that this occurs:

1. **Making flood hazard information public.** We recommend using the provided flood hazard maps and accompanying digital datafiles to make this information accessible to the general public. Short, simplified, and interactive reporting materials accompany this report that are targeted for communication to the general public. It is, in our opinion, essential that the general public has access to information on where it may flood in the future. Further, providing digital GIS files online will allow further studies to use this information, and by doing so, increase the general knowledge of coastal flood impacts for Ucluelet and in the region.

2. **Sharing information with neighbouring communities.** Much of the information prepared for this project may be useful for neighbouring communities. In particular, the mapping extends to the east side of the inlet and is directly valid for these areas. Other communities may benefit from the general findings and the approach applied to balance science with policy-oriented mapping.

3. **Using coastal flood hazard maps as the base for policy-making.** While flood hazard maps provide essential information on where water may go in a flood, and importantly, on how deep the water may be, flood maps are only the first step in making a community more resilient to flooding. It is essential that flood hazard maps and FCLs are used as the base for policy-making, and are incorporated into Official Community Plans (OCPs) and into development of a flood bylaw or development permit area regulations. We understand that the OCP update in the DOU is aiming towards this goal. Flood risk assessments play another important role in setting flood hazard maps into perspective by indicating where people, infrastructure and other cultural and environmental assets are most exposed to a flood hazard (see next recommendation).

4. **Complete a coastal flood risk assessment.** The results of this project provide an excellent groundwork for a risk assessment to be completed for the DOU. Exposure and vulnerability are additional components of risk that require attention. Exposure analysis considers elements related to people, economy, infrastructure, culture, environment, transportation and utility networks, etc. that are located in the hazard areas. Vulnerability analysis identifies the sensitivity of these elements to the hazard. A better understanding of these components can help the DOU reduce risk better and better prepare for disasters through emergency management planning. This type of project can also extend to understand and report on risk tolerances, which can help with adaptation planning, and with emergency response planning (see also next recommendation). Existing grant programs (CEPF for example) support this type of project.

5. **Use tsunami maps to inform emergency response planning.** A series of tsunami planning maps have been developed for this project. These can be used to help with evacuation planning, as well as for siting of emergency supplies and critical infrastructure.

In addition, we provide the following recommendations related to future updates and potential refinements to the work provided here:

6. **Review flood hazard maps in 5 years.** This recommendation follows guidelines by FEMA in the United States (FEMA, 2003a); it is more frequent than the BC guideline recommendation, which was based partially on past practice and available funding at the time of guideline development. While a review does not necessarily need to involve new hazard mapping (if conditions have not changed significantly since the last update), it is essential to assess potential changes in conditions and newly available data and information. This study was based on current best practice and followed the guidelines for coastal flood hazard modelling and mapping, but there are, as is typical with these kinds of studies, limitations and uncertainties to this work (discussed in detail in Section 7). As new methodologies and data emerge in the future, these can be incorporated to improve the current flood hazard mapping.

7. **Incorporate updated climate change information (e.g., changes to storminess) where possible.** For this project we assumed, based on currently available research, that storm intensity over the Pacific Ocean affecting Ucluelet will not change in the future. This assumption, as well as assumptions on RSLR, should be reassessed in the future, as new information on climate change emerges. Global and local climate modelling research is underway in many research institutes around the world and may provide updated estimates for future changes in the study region. Further, time itself may also make potential climate change impacts on storm intensities and sea level rise evident.

8. **Reassess sea level rise scenario projections and associated timelines.** New information on sea level rise can be incorporated once it becomes available. As we did not associate RSLR scenarios with a specific point in time, our provided RSLR scenarios may still be useful, but may need to be re-dated to occur earlier than anticipated if sea levels rise faster than assumed.

9. **Conduct coastal erosion study. Sea level rise will exacerbate coastal erosion.** A detailed study of coastal erosion in the DOU is recommended to identify areas of concern, and to integrate the knowledge into policy and planning. The preliminary data review provided in Appendix B may be used as a starting point for this objective.

10. **Conduct studies to enhance studies of tsunami hazard.** Given the substantial tsunami exposure of the DOU, we also recommend that more work be completed to improve the understanding of the tsunami hazard prior to major investments (e.g. infrastructure, new building/planning zones) that are currently on the edge of the tsunami hazard extent. This work could include the collection of bathymetric data, and the completion of a full probabilistic tsunami hazard assessment.

9 Conclusions

As the District of Ucluelet works towards becoming more resilient to flooding, an essential first step is the development of flood hazard maps and a flood construction level. These can then be integrated into flood policy-making and be used for flood risk assessments. In this project, our objectives were to assess storm and tsunami flooding hazards and provide hazard mapping to help the DOU with future land use policy and planning objectives. Both storm- and tsunami-induced flood hazard were modelled, including multiple sea level rise scenarios for the near and far future (RSLR of 0 m, 0.5 m, 1 m, and 2 m). For coastal storm hazard, storm events for five different AEPs (6.67%, 2%, 1%, 0.5%, and 0.2% AEP) for each of the four RSLR scenarios (20 scenarios in total) were modelled. For the tsunami hazard, 6 potential fault ruptures of a megathrust earthquake resembling the CSZ fault rupture were modelled (24 scenarios in total). Based on this modelling work, a selection of flood hazard maps was produced, including flood depth maps. We have also provided FCLs, SLR Planning Areas, and other planning-type maps for the DOU that can be used to develop flood policy. We hope this work can be a base for the continuing efforts of the DOU in making the community more resilient to floods and preparing for the impacts of a changing climate.

10 Glossary

Term	Definition	Source
Annual Exceedance Probability (AEP)	The probability of an event occurring, or being exceeded, in any given year.	
Cascadia Subduction Zone (CSZ)	A subduction zone is where two tectonic plates are moving towards each other and one is pushed below the other. The Cascadia Subduction Zone is the area where the *Juan de Fuca Plate* is moving under the *North American Plate*.	
Comparative-Case Tsunami	For this project, the comparative-case tsunami was based on the CSZ earthquake from a buried rupture model (W2003). When the extents of the modelled tsunami flood wave associated with this rupture model were mapped, they were generally on the lower end of the range of those modelled. This rupture model's results were named as such because they may be compared with other studies in the region that have used the same W2003 rupture, or a similar buried rupture model.	Wang *et al.,* (2003)
Designated Storm	A storm, which may occur in any given year, of such a magnitude as to equal a storm having the designated *AEP*. (In this report, we used 0.5% AEP). The designated storm has several phenomena associated with it that will define components of the *designated flood level*, including *storm surge*, *wind set-up*, *wave runup,* and *wave set-up.*	*Provincial Guidelines*
Designated Storm Approach	In this approach, one or more *designated storms* are specified based on the analyst's knowledge of local coastal weather patterns and storm responses. These storms are used to assess likely flood impacts and generate an *FCL*.	
Coastal Erosion	The loss of coastal lands due to the net removal of sediments or bedrock from the shoreline.	
Designated Flood Level (DFL)	The observed or calculated elevation for the designated storm. It is used in the calculation of the flood construction level. The DFL is a still water level. In coastal areas, it includes the appropriate allowance for future SLR, tide, and the total storm surge expected during the designated storm but does not include wave effects.	*Provincial Guidelines*

Term	Definition	Source
Digital Elevation Model (DEM)	A grid that describes the elevation (or height) of a series of points across a geographical area.	
Exposure	A measure of the amount of a structure, life, or other asset-at-risk that could be affected by a potential hazard. Example: parts or all of houses, schools, and livestock in a flood hazard area that are exposed to a potential flood.	
Extreme Value Analysis	Extreme value analysis is a branch of statistics that deals with either very large of very small values in a probability distribution and uses tools like distribution curves to predict values outside of the recorded range.	
Flood Construction Level (FCL)	The FCL is the *FCRP* plus the allowance for freeboard. This is used to establish the elevation of the underside of a wooden floor system or top of concrete slab for habitable buildings.	(MWLAP, 2004)
Flood Construction Reference Plane (FCRP)	The FCRP is used in the calculation of the *FCL*. In coastal areas, it includes the appropriate allowance for future SLR, tide, and the *storm surge* and wave effects expected during the *designated storm*. It does not include a *freeboard* allowance.	
FCL Reach	A reach is defined here as a section along the shoreline, that is characterized by similar FCLs of the individual cross-shore transects and similar natural geography.	
Flooding	Overflowing of water onto land that is normally dry. It may be caused by overtopping or breach of banks or defences, inadequate or slow drainage of rainfall, underlying groundwater levels, or blocked drains and sewers. It presents a risk only when people and human assets are present in the area where it floods.	(RIBA, 2009)
Freeboard	A vertical distance added to the actual calculated flood level to accommodate uncertainties (hydraulic and hydrologic variables).	*Professional Practice Guidelines*
Frequency	The number of occurrences of an event in a defined period of time.	(Public Safety Canada 2018)

Term	Definition	Source
Frequency-Response Curves	A frequency-response curve presents the relationship between the *frequency* of a flood event and the magnitude of the response (or water level). This curve can be used to estimate the magnitude of flooding associated with any given *AEP*.	
Hazard	A potentially damaging physical event, phenomenon, or human activity that may cause the loss of life, injury, property damage, social and economic disruption, or environmental degradation. Hazards can include latent conditions that may represent future threats, and can have different origins: natural (geological, hydrometeorological, and biological) or be induced by human processes. Hazards can be single, sequential, or combined in their origin and effects. Each hazard is characterized by its location, intensity, frequency, and probability.	(UNISDR, 2015)
Hazard Assessment	Acquiring knowledge of the nature, extent, intensity, frequency, and probability of a hazard occurring.	MODIFIED (Public Safety Canada 2018)
Higher High Water Large Tide (HHWLT) & Higher High Water Mean Tide (HHWMT)	The HHWLT is the average of the highest annual tides taken over a 19-year tidal cycle. HHWMT is the average of the highest daily tide heights over the 19-year tidal cycle.	(NOAA, 2018)
LiDAR	LiDAR stands for Light Detection and Ranging. It is a remote sensing method that uses light in the form of a pulsed laser to measure variable distances to the Earth. This is used to evaluate relative height of the surface and create a DEM.	(NOAA, 2018)
Likelihood	A general concept relating to the chance of an event occurring. Likelihood is generally expressed as a *probability* or a *frequency* of a *hazard* of a given magnitude or severity occurring or being exceeded in any given year. It is based on the average frequency estimated, measured, or extrapolated from records over a large number of years, and is usually expressed as the chance of a particular hazard magnitude being exceeded in any one year.	(RIBA, 2009)

Term	Definition	Source
Probability	In statistics, a measure of the change of an event or an incident happening. This is directly related to *likelihood.*	(Public Safety Canada 2008)
Professional Practice Guidelines	The guidance in the *Provincial Guidelines* documents was further refined in the recently released Association of Engineers and Geoscientists British Columbia (EGBC) Professional Practice Guidelines for Flood Mapping in BC, referred to in this report as the *Professional Practice Guidelines* (APEGBC, 2017).	
Provincial Guidelines	In 2011, the Government of BC commissioned a number of reports that provide guidance for land use planning and mapping in consideration of coastal flood hazards and SLR (Ausenco Sandwell 2011a, 2011b, 2011c; Kerr Wood Leidal 2011). Collectively, these documents are referred to as the *Provincial Guidelines*.	
Relative Sea Level Rise (RSLR)	The rate of SLR relative to a specific location. This is driven by uplift (ground levels rising) or subsidence (ground levels sinking).	
Response-Based Approach	In this approach, historical total water levels are modelled over a long past period (called hind-casting). This hind-cast is used to generate a *frequency-response curve* for the effect of storms on the local area. This curve can be extrapolated to estimate the magnitude of flooding associated with any given AEP.	
Risk	The combination of the probability of an event and its negative consequences.	(UNISDR, 2015)

Term	Definition	Source
Risk Assessment	A methodology to determine the nature and extent of risk by analyzing potential hazards and evaluating existing conditions of vulnerability that together could potentially harm exposed people, property, services, livelihoods, and the environment on which they depend. Risk assessments (and associated risk mapping) include: a review of the technical characteristics of hazards, such as their location, intensity, frequency, and probability; the analysis of exposure and vulnerability, including the physical, social, health, economic, and environmental dimensions; and the evaluation of the effectiveness of prevailing and alternative coping capacities, with respect to likely risk scenarios. This series of activities is sometimes known as a risk analysis process.	(UNISDR, 2015)
Sea Level Rise (SLR)	The increase in sea level over time, associated with the impacts of climate change. The two major causes of global SLR are thermal expansion caused by warming of the ocean (since water expands as it warms) and increased melting of land-based ice, such as glaciers and ice sheets.	(NOAA, 2013)
Sea Level Rise (SLR) Planning Area	An area of land that may be subject to future flooding due to *SLR*. This area defines a future coastal flood hazard area. The SLR Planning Area extends from the existing Natural Boundary landward to the highest predicted point of potential flooding related to SLR plus flooding expected from the combination of high tide, total storm surge, and expected wave runup during the designated storm. Predictions of *SLR* for the SLR Planning Area definition shall use best predictions for minimum periods of 90–100 years and 200 years forward.	*Provincial Guidelines*
Storm Surge	A change in water level caused by the action of wind and atmospheric pressure variation on the sea surface. The magnitude of a storm surge on the BC coast will be dependent on the severity and duration of the storm event in the North Pacific, its track relative to the BC coast, and the seabed bathymetry at the site.	*Provincial Guidelines*
Total Wave Runup	The total wave runup is the total the vertical distance that waves runup the seaward slope of a structure or a shoreline when combined with other storm effects, such as *storm surge*, *wave set-up*, *wind set-*	

Term	Definition	Source
	up, tides, and *SLR*. This also represents the *FCRP*.	
Transect	A transect is a single line for each reach (stretch of shoreline). The transects run perpendicular to the shore and are chosen to be representative of each reach. These transects are used to simulate the effect of an event for that reach. Following the modelling, the response at each transect is interpolated to demonstrate the response for the whole coast.	
Wave Runup	The vertical distance that waves runup the seaward slope of a structure or a shoreline.	*Provincial Guidelines*
Wave Set-Up	An increase in mean water surface close to the shoreline caused by wave action; important during storm events as it results in a further increase in water level above the tide and surge levels, landward of the location where waves start to break.	*Provincial Guidelines*
Wind Set-Up	A rise of the water surface above the water level on the open coast due to the local action of wind stress on the water surface.	*Provincial Guidelines*
Worst-Case	For this project, the worst-case tsunami was based on the CSZ earthquake from a splay faulting rupture model (G2018-S-A). When the extents of the modelled tsunami flood wave associated with this rupture model were mapped, they were generally the greatest compared to those associated with the other five rupture models. In this sense, "worst-case" is relative to the cases modelled for this project only.	Gao *et al.*, (2018)

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Appendix A Coastal Flood Hazard Analysis (Cascadia Coast Research)

Provided as a separate document

Appendix B Coastal Erosion Preliminary Data Evaluation

Provided as a separate document

Appendix C Coastal Flood Hazard Map Atlas

Provided as a separate document

Appendix D Coastal Storm Flood Depths and FCL Differences

Provided as a separate document

Appendix E Flood Mapping Assurance Statement

Provided as a separate document