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# Nature based alternatives regarding coastal and environmental climate change hazards;

## a case study of the Tsleil-Waututh Nation foreshore

**GROUP MP307**

KERR WOOD LEIDAL
consulting engineers

TU Delft

# Multidisciplinairy project

## Nature based alternatives regarding coastal and environmental climate change hazards, a case study of the Tsleil-Waututh Nation foreshore

by


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# Preface

This report is written as the result of the multidisciplinary project conducted by us, five TU Delft students, from February 1st until April 24th. The research is carried out on behalf of Kerr Wood Leidal and the TU Delft. Kerr Wood Leidal (KWL) has supported us throughout the whole project. Aside from facilitating a work space in the office together with many helpful colleagues, they supported us through multiple meetings and site visits.

We respectfully acknowledge that we live, work, and study on the unceded traditional territories of the Coast Salish peoples of the ʷmaθkʷəy̓əm (Musqueam), Skwxwú7mesh (Squamish), Stó:lō, and Səl̓ílwətaɬ.

We would like to acknowledge and express our gratitude to our two supervisors at KWL, Amir Taleghani and Max Scruton, for helping us a lot during our project. Not only by providing data and connections, but also by helping us getting around in a new city and country. In addition we would like to thank Robin Hawker (KWL) for all her support concerning First Nation history and culture and Bryce Whitehouse (KWL) for providing the bathymetry data of the Burrard Inlet.

A special thanks to the people from Tsleil-Waututh Nation for welcoming us at their reserve and sharing their personal stories with us. This has been of great added value to our project and our perception of the project location.

Thanks to our supervisors from TU Delft, Maurits van Ertsen, Stuart Pearson and Stefan Aarninkhof for the guidance you gave us in completing this report.

A special thanks to all the people that helped us come home and helped us finish what we started during difficult times.


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*Delft, June 19, 2020*


*"This report has been prepared by Delft University students for Kerr Wood Leidal Consultants. It does not necessarily reflect the views of Tsleil-Waututh Nation community, Council or staff."*

# Glossary

**Aboriginal People** Defined in the *Constitution Act 1982* to include all *Indigenous People* of Canada, *Status Indians*, *Non-Status Indians*, *Métis* and *Inuit people*.

**Aboriginal Rights** "Aboriginal title refers to the inherent Aboriginal right to land or a territory. The Canadian legal system recognizes Aboriginal title as a *sui generis*, or unique collective right to the use of and jurisdiction over a group's ancestral territories. This right is not granted from an external source but is a result of Aboriginal peoples' own occupation of and relationship with their home territories as well as their ongoing social structures and political and legal systems. As such, Aboriginal title and rights are separate from rights afforded to non-Aboriginal Canadian citizens under Canadian common law" (Hanson, 2009a) .

**Active coastal zone** The active coastal zone is the beach zone over which sand is exchanged in cross-shore direction by natural processes. The seaward limit corresponds to the closure depth and the landward limit to a hard boundary (seawall, cliff, ..). In the case of a cliff, dune or bank coast the active zone comprises part of the front cliff, dune or bank that can be eroded by storm waves. .

**Band** The *Indian Act* defines "Band", in part, as a body of *Aboriginal People* for whose use and benefit in common, lands have been set apart. Each Band has its own governing Band Council, usually consisting of a chief and several councillors. The members of the Band usually share common values, traditions and practices rooted in their language and ancestral heritage. Today, many Bands prefer to be known as First Nations.

**Band Council** The Band's governing body. Community members choose the Chief and councillors by election under section 74 of the *Indian Act*, or through traditional custom. The Band Coucnil's powers vary with each band.

**Burrard Inlet IR#3** The main *reserve* of the Tsleil-Waututh Nation.

**ceded** A term used to describe land that used to belong to the *traditional territory* of *Aboriginal People* and was yielded by *treaty* to colonists. See also *unceded* and *Crown land*.

**clam garden** Cultivated areas along the shores where *Aboriginal People* would enhance growing conditions for clams to grow.

**Closure depth** The most landward depth waterward of which there is no significant change in bottom elevation and no significant net sediment exchange between the nearshore and the offshore. .

**Constitution Act 1867** British North America Act, also called Constitution Act, 1867, the act of Parliament of the United Kingdom by which in 1867 three British colonies in North America—Nova Scotia, New Brunswick, and Canada—were united as "one Dominion under the name of Canada" and by which provision was made that the other colonies and territories of British North America might be admitted. It also divided the province of Canada into the provinces of Quebec and Ontario and provided them with constitutions. The act served as Canada's "constitution" until 1982, when it was renamed the Constitution Act, 1867, and became the basis of Canada's *Constitution Act 1982*, by which the British Parliament's authority was transferred to the independent Canadian Parliament (Encyclopaedia Britannica, 2014).

**Constitution Act 1982** Canada Act, also called Constitution Act of 1982, Canada's constitution approved by the British Parliament on March 25, 1982, and proclaimed by Queen Elizabeth II on April 17, 1982, making Canada wholly independent. The document contains the original statute that established the *Constitution Act 1867* Canadian Confederation in 1867 (the British North

America Act), the amendments made to it by the British Parliament over the years, and new material resulting from negotiations between the federal and provincial governments between 1980 and 1982 (Encyclopaedia Britannica, 2019).

**Crown** The Crown is an abstract concept or symbol that represents the state and its government. The Queen of the constitutional monarchy of Canada is the living embodiment of the Crown, a role independent of that as Queen of the United Kingdom and the other Commonwealth realms (Canada, 2018).

**Crown land** A term used to describe land claimed by federal and provincial governments. See also *ceded* and *unceded*.

**Elders** A person whose wisdom about spirituality, culture and life is recognized and affirmed by the community. Not all Elders are ”old”: sometimes the spirit of the Creator chooses to imbue a young Aboriginal person. The Aboriginal community and individuals will normally seek the advice and assistance of Elders in a wide range of traditional and contemporary issues.

**Equilibrium profile** The natural form that the beach would take for a given volume of sediment under the prevailing wave climate. The equilibrium profile is affected by the presence of natural features such as headlands and structures. The equilibrium profile is a dynamic concept as the wave field and water level change constantly. .

**First Nation** A term that came into common usage in the 1970s to replace the term ”Indian band, which many found offensive. The term ”First Nation” has been adopted to replace the word ”Band” in the name of many communities and can refer to a single *Band*, many *Bands*, an Aboriginal governing body, organized and established by an Aboriginal community or an Aboriginal community as a whole.

**Fisheries Act** The Fisheries Act is the main federal law governing fisheries in Canada. It has been in charge of administering fish and fish habitat and regulated seacoast and inland fisheries since 1868 .

**Greater Vancouver Region** Formal name of *Metro Vancouver* .

**hereditary leadership system** A system in which the power is passed down from one generation to the next along blood lines or other cultural protocols.

**Indian** The origin of the term ”Indian” dates back to Christopher Columbus, who mistakenly thought he had reached the East Indies, so referred to the people in the lands he visited as ”Indios” which is Spanish for Indian. The term ”Indian” may have different meanings, depending on context. Under the *Indian Act*, Indian means ”a person who pursuant to this Act is registered as an Indian or is entitled to be registered as an Indian”.

Nowadays the term ”Indian” has been replaced with *Indigenous People*.

**Indian Act** The *Indian Act* is federal legislation that regulates *Aboriginal Peoples* and reserves and sets out certain federal government powers and responsibilities toward *First Nations* and their *reserve* lands. The first Indian Act was passed in 1876, although there were a number of pre-Confederation and post-Confederation enactments with respect to Indians and reserves prior to 1876. Since then, it has undergone numerous amendments, revisions and re-enactments. The federal department of Aboriginal Affairs and Northern Development Canada administers the *Indian Act*.

**Indigenous People** ”Peoples in independent countries who are regarded as indigenous on account of their descent from the populations which inhabited the country, or a geographical region to which the country belongs, at the time of conquest or colonization or the establishment of present state boundaries and who, irrespective of their legal status, retain some or all of their own social, economic, cultural and political institutions”.

**Inuit** Aboriginal people in northern Canada, living mainly in Nunavut, Northwest Territories, northern Quebec and Labrador. Ontario has a very small Inuit population. The Inuit are not covered by the *Indian Act*. The federal government has entered into several major land claim settlements with the Inuit.

**Métis** People of mixed Aboriginal and European ancestry. The Métis history and culture draws on diverse ancestral origins such as Scottish, Irish, French, Ojibway and Cree.

**Metro Vancouver** Metro Vancouver is a political body and corporate entity operating under provincial legislation as a 'regional district' and 'greater boards' that deliver regional services, policy and political leadership on behalf of 23 members (21 municipalities, one Electoral Area and one Treaty First Nation) (Metro Vancouver, 2019). The formal name of the region is *Greater Vancouver Region* .

**midden** "A place where *Aboriginal People* placed their clam shells after consumption. Archaeologists use these midden sites to count the layers of clam shells, similar to counting rings on a tree, to see how long and how many people lived in an area" (Johannessen et al., 2020).

**Navigation Protection Act** The Navigation Protection Act (formerly the Navigable Waters Protection Act) is one of the oldest regulatory statutes enacted by the Parliament of Canada. It requires approval for any works that may affect navigation on navigable waters in Canada .

**Plain wars** A number of conflicts from 1850 to 1870 between native inhabitants and settlers over the governing of the Great Plains between the Mississippi River and the Rocky Mountains leading to costs up to 20 million for the colonists $ (Wooster, 2011; Hall, 2017) .

**reserve** Defined by the *Indian Act* as "... tract of land, the legal title to which is vested in Her Majesty, that has been set apart by Her Majesty for the use and benefit of a band." A result of the definition of reserve land in the *Indian Act* is that reserve land cannot be privately owned by the *Band* or Band members.

**since time immemorial** A time in the past that was so long ago that people have no knowledge or memory of it. See also *since time out of mind*.

**since time out of mind** A time in the past that was so long ago that people have no knowledge or memory of it. See also *since time immemorial*.

**Sleil-Waututh** (SW) This is the anglicised name of the reserve land (Burrard Inlet IR#3) currently occupied by Tsleil-Waututh.

**traditional territory** "The (traditional) geographic area defined by a *First Nation* to be the area of land which they and/or their ancestors traditionally occupied or used" (Johannessen et al., 2020).

**treaty** An agreement between government and a *First Nation* that defines the rights of *Aboriginal Peoples* with respect to lands and resources over a specified area, and may also define the self-government authority of a *First Nation*.

**Tsleil-Waututh** (TWN) - or "səlilwətaɬ" in the Coast Salish hən̓q̓əmin̓əm̓ language means "the people of the inlet". Tsleil-Waututh People have occupied, governed and served as stewards of the waters and langs surrounding Burrard Inlet since since time immemorial.

**unceded** A term used to describe land belonging to the *traditional territory* of *Aboriginal People* that was never officially given up to colonists. See also *ceded* and *Crown land*.

# Abstract

The Tsleil-Waututh Nation (TWN) reserve (Sleil-Waututh), located at the north shore of the Burrard Inlet, is strongly influenced by climate change. Sea level rise, coastal flooding and shoreline erosion are contributing to erosion of land, damages to infrastructure, ecosystems changes and exposure of historic sites with cultural value. Kerr Wood Leidal (KWL) was retained by TWN to develop a climate change hazard and vulnerability assessment and a ten year climate change adaptation action plan. Informed by the findings of this work, the aim of our student project is to explore various natural based alternative solutions to protect the shoreline in front of the Sleil-Waututh reserve lands. This exploration includes using the hydrodynamic features of Xbeach to assess the effects of the different alternatives and scenarios, using predictions and pre-feasibility analysis to assess potential technical (physical), environmental and economic conditions, and evaluating each alternative against a set of adaptation action screening criteria developed in consultation with TWN.

An extensive area analysis is done, including a study of the community context of the TWN. Because of the sacred obligation to be caretakers of the lands and how these lands are impacted by climate change, the TWN has taken initiative to reduce these impacts and preserve the land for future generations (Taleghani et al., 2019). The existing conditions are investigated from a technical, environmental and sociological point of view. The shores and waters of the Burrard Inlet are subject to intensive development, including shipping, industry and residential buildings. The shorelines of the Sleil-Waututh Nation reserve are characterized by sandy and muddy flat beaches. The hydrodynamic conditions at the shoreline of the project site depend on the effects of tide, storm surge, sea level rise and (wind-induced) waves. The tides are semi-diurnal and with data from the CHS Vancouver station (7735) in the Burrard Inlet, a tidal range of 3.24 meters is determined. The dominant wind direction is East, which leads to a wind-wave climate also dominated by Easterly waves. A wave buoy from Marine Labs has been measuring wind and wave data in front of the project area. Many vessels pass the Burrard Inlet IR#3 everyday and can therefore in combination with high water levels also cause erosion at critical locations, on a daily basis.

Climate change causes change in different events, such as the sea level rise, acidification, temperature changes in air and water and more. KWL has assessed thirteen different hazards for the TWN site. Not all hazards are relative for the scope of this study. In consultation with KWL the following hazards are assessed: Coastal flooding, coastal erosion, intertidal area change, ocean acidification, harmful algae blooms and other ocean conditions.

Stakeholders that the TWN might have to work with or keep informed when implying the project, are placed side by side with the legislative and jurisdictional framework they have to deal with to execute the project. By focusing on understanding the characteristics of social networks and considering a range of perspectives, the likelihood of collective action and successful project management is increased.

Four different alternatives will be discussed that are a conclusion from a mind-map made in a brainstorm session. Each alternative is designed for two representative 1D cross sections of the TWN-reserve. One steeper cross section(Big John Creek) and one cross section with a tidal flat (Canoe shed). The two sorts of alternatives are: A more marine rip rap revetment and based on ecosystem improvement potential, a salt marsh and clam garden, which gives home to vegetation and create habitats for birds, fish and invertebrates, and a nourishment, which stabilizes the coastline at locations were a loss or lack of sediment is causing erosion problems. Each solution will be evaluated based on a couple feasibility studies. In the technical feasibility analysis, the alternatives will be designed and their effectiveness against erosion will be determined. The environmental study will most importantly asses the impact of the solution on the ecosystem services in the Burrard Inlet. Within the building with nature concept a good balance has to be found between 'building nature', which sometimes damages nature and 'redeveloping nature', which aims to keep the existing nature as intact as possible when enhancing the ecological area. A rough cost estimate is made in the economical feasibility study, where as provincial or federal acts that regulate the construction activities are checked in the legislative analysis. Involvement and consultation of the local community and environmental associations will be key in order to design a social/environmental valued solution and will therefore be assessed in the social

aspect feasibility.
All alternatives help the TWN in their own way and although further research has to be done, this report provides an insight in four possible alternatives that could support the process of developing a satisfactory solution for the coastal hazards that cause problems for the TWN people and their reserve.

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# Part 1 - Existing conditions

# 1

# Problem analysis

## 1.1. Introduction

The Tsleil-Waututh (TWN), is an Indigenous community and government, that currently occupies the Sleil-Waututh reserve lands located along the north shore of the Burrard Inlet. This location (see Figure 1.1, towards the northern part of Greater Vancouver, a coastal urban area in the Canadian province of British Columbia (BC). Sleil-Waututh reserve lands (also referred to as Burrard Inlet IR#3), is already experiencing the influences of climate change. Sea level rise, coastal flooding and shoreline erosion are contributing to erosion of land, damages to infrastructure, ecosystems changes and exposure of historic sites with cultural value (Muir and Menezes, 2014; Taleghani et al., 2019, 2020). Kerr Wood Leidal (KWL) was retained by TWN to develop a climate change hazard and vulnerability assessment and a ten year climate change adaptation action plan. Informed by the findings of this work, the aim of our student project is to explore various natural based alternative solutions to protect the shoreline in front of the Sleil-Waututh reserve lands. This exploration includes using the hydrodynamic features of Xbeach to assess the effects of the different alternatives and scenarios, using predictions and pre-feasibility analysis to assess potential technical (physical), environmental and economic conditions, and evaluating each alternative against a set of adaptation action screening criteria developed in consultation with TWN.


Figure 1.1: Project area in context. Sleil-Waututh boundaries are indicated in white (Made with Natural Earth (Kelso and Patterson, 2009). GIS data provided by Kerr Wood Leidal (2020). Maps created with QGIS software (QGIS Development Team and others, 2020)

## 1.2. Problem definition

Climate change and shoreline erosion influence Burrard Inlet IR#3. This leads to six hazards; coastal flooding, coastal erosion, intertidal area change, ocean acidification, harmful algae blooms and other changing ocean conditions. These hazards are studied and several alternatives are thought of. The possible application and the feasibility of these alternatives are to be investigated. Therefore the research question is:

**How can the shoreline of the Tsleil-Waututh Nation be protected against the climate change induced social, ecological and coastal hazards?**

## 1.3. Problem objectives

The objective of this study is to analyse the possible climate change induced hazards and elaborate on several alternatives to protect the Tsleil-Waututh against these hazards. This includes feasibility studies and substantiated predictions of expected results. To get to this final objective, several specific objectives are listed below.

- Provide an analysis of the existing conditions at the study area
- Provide an analysis of the community context of the TWN
- Assess the hazards of the study area
- Give an outline of the stakeholders involved and the legislative framework to cope with
- Identify several alternatives to manage the climate change and coastal erosion hazards
- Develop conceptual designs for dealing with all hazards
- Provide feasibility studies for each design concerning technical, social, environmental, economical and legislative feasibility
- Give an insight in how well the alternatives work regarding the erosion
- For each conceptual design provide an overview of the advantages, disadvantages and the hazards it tackles
- Give insight in the required or desired additional research

## 1.4. Approach

In order to achieve the project objectives, several steps are taken. To get a complete sense of the project area, an extensive area analysis is done including site visits, community research and coastal data analysis. The existing conditions are investigated from a technical, environmental and sociological point of view. The different hazards are defined and the coastal and climate change hazards are investigated to select the hazards that are of importance for the scope of this project. First a do nothing concept is defined as the base case. Second, four alternatives are subjected to a series of feasibility studies. The technical feasibility is assessed by the use of hydraulic and morphological models. Next to that, social, environmental, economical and legislative feasibility studies are performed. All alternatives will be evaluated against the adaptation screening criteria developed in consultation with Tsleil-Waututh Nation.

# 2
# Community context

The Tsleil-Waututh (TWN) are the “People of the Inlet”, a First Nation that has lived in harmony on the lands and waters of the Burrard Inlet since since time out of mind. Together with the Musqueam and Squamish, two other First Nations around the Greater Vancouver Region area in British Columbia (BC), they are part of a group called the Coast Salish people. The Coast Salish have strong spiritual, cultural and economic ties with the lands in and around the city of Vancouver. They are one of three recognized groups of Aboriginal People in Canada: First Nations. Other Aboriginal groups in Canada are Inuit and Métis. First Nations is the name of a group of Aboriginal Peoples in Canada that do not identify as either Inuit or Métis (Wilson and Henderson, 2014).

## 2.1. History of First Nations in Canada

Many different cultures and languages among First Nations exist as the First Nation peoples have lived all over Canada for many thousands of years, since time immemorial. Since first contact with Europeans and the institution of the Government of Canada, Aboriginal Peoples had to undergo many changes: they lost the rights of their lands and the rights to practice their culture.

In 1763, the Royal Proclamation, instituted by the British Crown, recognized the Aboriginal People as owners of the land that was used and occupied by Europeans, implying that colonisers should deal with Aboriginal inhabitants on a Nation-to-Nation basis.

From 1764 to 1854, the Pre-Confederation Treaties were signed: a series of agreements between different First Nation groups and the Crown were composed, in which a shift in the power balance gradually took place, in favor of the Crown. The attitude towards Aboriginal Peoples shifted towards them being British subjects, and not independent nations acting on equal foot with the Crown (Joseph and Joseph, 2007).

Between 1871 and 1921, eleven treaties between First Nation peoples and the Crown (Canada) were signed, the Numbered Treaties. With these treaties, the Canadian government aimed to extend its authority further north- and westward. Taking the Plain wars as an example, the government decided to aim for a relatively peaceful and cheaper approach instead, thus expanding its borders westward by signing Treaties with the Aboriginal Peoples (Wooster, 2011; Hall, 2017). By signing these Treaties, the government appropriated the rights to access and exploit natural resources on the lands while the Indigenous Peoples retained the rights to live and sustain themselves on lands that were marked as ceded territories. During Treaty negotiations, First Nations also bargained to receive further compensation for the exploitation of their resources. Promised amendments by the government were however never completely fulfilled. An annual compensation of $5 (CAD) that many treaty peoples received and still receive, does not have a significant impact. For some, it is even considered an example of the persistence and suppression by the government toward Aboriginal Peoples (Hall, 2017; Equay and Bird, 2018).

As opposed to the main part of Canada, most of the First Nations living in what today is called BC did not sign any of the Numbered Treaties between the First Nation peoples and the Crown (Hall, 2017; Equay and Bird, 2018). This means that a big part of British Columbia, including the city of Vancouver is considered to be in unceded Coast Salish traditional territory (Suleman, 2011).

Starting in 1857, the creation of different acts culminated into the Indian Act in 1876, allowing the government to gain more control over Aboriginal Peoples and restricting the power of Band Council (Hanson, 2009b). Earlier on, the Government of Canada had already abolished the First Nation peoples' own system of government and forced the institution of a Band, a community of Aboriginal Peoples recognised by the government, and bBand Council, introducing a system where the council and chief would be elected instead of a traditional hereditary leadership system (Wilson and Henderson, 2014). Until the Indian Act, the Aboriginal People had the rights to live and sustain themselves on the lands of their traditional territories. With the Indian Act, Aboriginal People were assigned a small portion of their traditional territory. These designated parcels of land became known as Reserve Lands (Joseph and Joseph, 2007). Another way in whichFirst Nations were prevented from practicing their lifestyle is through the Potlatch Law, constituted in 1884 under the Indian Act. With this law, the potlatch, an important tradition held on special occasions and a key part of First Nation culture and governance, was banned by the government (Hanson, 2009b; Joseph and Joseph, 2007).

Through imposed education, the Canadian government tried to prevent Aboriginal knowledge to be passed on from one generation to another. From 1870 to 1997, for over one hundred years, Aboriginal children were sent off to Indian Residential Schools. Here, the children were re-educated to Euro-Canadian culture, forbidden to practice cultural traditions and languages, and prohibited to have contact with their parents, family and the other sex, including siblings. Since Aboriginal culture is passed on from generation to generation graphically, orally and experimentally, many traditions and practices have been lost due to the younger generation not being able learn from their Elders. Aside from this, many children grew up with psychological damage, with widespread reports of physical and emotional abuse and neglect in residential schools across Canada (Wilson and Henderson, 2014; Truth and Reconciliation Commission of Canada, 2015, 2016). Nowadays, First Nations are focusing on raising awareness of the injustices they faced in residential schools and other areas of insitutionalized racism. Nations are focusing on strengthening local languages, traditional practices, and community health and wellbeing to build resilience and self-sufficiency (Wilson and Henderson, 2014; Tsleil-Waututh Nation, 2020a).

### 2.1.1. Recognition and reconciliation

The first steps towards recognition of the Aboriginal peoples and reconciliation have been taken by the government starting with the 1951 Amendments after the Second World War (Hanson, 2009b). Another step forward was achieved with the Constitution Act 1982. With this act Canada obtained full sovereignty. In the act, the existing rights of the Aboriginal Peoples of Canada were acknowledged, however these rights were left undefined (Azzi, 2016). On June 11th 2008, the Prime Minister of Canada made a Statement of Apology, on behalf of the Government of Canada, to former students of the Indian residential schools (Government of Canada, 2010). Already in the year before, the Truth and Reconciliation Commission (TRC) had begun to be implemented. From 2007 to 2015, the TRC travelled throughout Canada to hear from witnesses and created awareness by hosting several national events. The TRC completed their work in a Final Report including a list of nearly 100 recommendations for further reconciliation steps between the Indigenous People and Canadian peoples (NCTR, 2015; Government of Canada, 2019).

### 2.1.2. Modern day situation

In 1974, the Office of Native Claims (ONC) was founded. Two types of land claims were established: specific and comprehensive land claims. Specific land claims comprise requests for (often financial) compensation due to injustice, suffered by the non-fulfillment of treaties by the government (Hall, 2017; Albers, 2015). Comprehensive land claims can be considered as modern-day treaties between the federal government and Indigenous Peoples living on unceded lands. The contents of these treaties cover multiple categories varying from self-government, to money, to management of natural resources (Crowe, 2019). Comprehensive land claim negotiations in BC are complicated by the fact that not only the First Nation in consideration and the federal government need to come to an agreement, but the provincial government is involved as well. Claims are negotiated within the BC Treaty Commission established in 1993. In 2000, the Nisga Nation, located near the north-western coast of BC, were the first Nation to sign a treaty in BC and restore their right to self-government (Powell and Jensen, 2016). Closer to Vancouver, the Tsawassen First Nation signed the first urban treaty, reconciling their Aboriginal Rights and restoring the self-governance over a small part of their traditional territory located south of Vancouver (Tsawassen First Nation, 2020; Crowe, 2019). In 2011, the Maa-nulth First Nations signed a Final Agreement. The Maa-nulth First Nations represent five First Nations and are part of the Nuu-chach-nulth people living on what today is called Vancouver Island (Toquaht, 2009; Crowe, 2019). As of today, 58 First Nations are in the process of negotiating treaties in the BC Treaty Commission (BC Treaty Commission, 2020b). Negotiations go through six stages, where the sixth state is signing the Final Agreement (BC Treaty Commission, 2020a). Negotiations with the TWN are currently in stage 4, where all elements of the agreement are identified and defined (BC Treaty Commission, 2020b,a; Commission, 2020).

## 2.2. The Tsleil-Waututh Nation

According to oral history and archaeological evidence, the TWN has lived in harmony on the lands and waters of the Burrard Inlet since since time out of mind. Oral transmission of traditional knowledge and historical events function as a shared memory for the Nation. Narratives recounting presence of civilization or events of natural disasters dating back several thousands of years have been confirmed by several studies that used archaeological evidence to confirm these records (Lindo et al., 2016; McRanor, 1997; Mortillaro, 2016; Hanson, 2020). As can be seen from Figure A.1, the TWN traditional territory extends from the Burrard Inlet down to the Fraser river and up north to the Mamquam Lake with an area of about 5000 square kilometers (Wilson and Henderson, 2014; Tsleil-Waututh Nation, 2020a,d).

The lands used to provide abundant resources and food to sustain the TWN. In return, members of the Nation consider it an obligation as well as their birthright to take care of the lands and waters of the traditional territory and to secure it for future generations to come (Tsleil-Waututh Nation, 2020a,d). Because of the sacred obligation to be caretakers of the lands and how these lands are impacted by climate change, the TWN has taken initiative to reduce these impacts and preserve the land for future generations.

Today, the majority of TWN members live on the Sleil-Waututh Reserve on the shores of the Burrard Inlet. The reserve is governed by an elected Chief, Band Council and Traditional Council. The last one is a family-based council, consisting of representatives all of the nine family groups that are part of the TWN (Wilson and Henderson, 2014). The Nation has never ceded lands outside of the reserve or abandoned its role as steward, but resources on the traditional territory have been exploited and diminished by industries and growth of urban areas (Tsleil-Waututh Nation, 2020a,d).

An additional motivation for land restoration and preservation is cultural and historical education. For the TWN, the shores of the Burrard Inlet are of high cultural value: in older times, during low tide, the community would gather on the beach and harvest shellfish. The Nation describes this as follows: *"When the tide went out, the table was set"* (Wilson and Henderson, 2014; Tsleil-Waututh Nation, 2020a). Traces of TWN civilization can be found on beaches in the form of middens (Pierson, 2011). Remains of utensils and shells in these middens teach about old practices and traditions. Being able to preserve their culture and pass it on to the next generation, is an important additional reason for the TWN to protect their natural resources (Taleghani et al., 2019).

# 3

# Physical background

## 3.1. Project area

The Sleil-Waututh reserve (IR #3) is located along the northern shores of the Burrard Inlet in a shallow coastal fjord (see Figure 1.1) (Taleghani et al., 2019). Burrard Inlet supports a major port, and the shores and waters of the inlet are subject to intensive development, including shipping, industry and residential buildings (Muir and Menezes, 2014). The Sleil-Waututh reserve has a size of about 1.11 square kilometers that includes 2 km of shoreline. The type of shores found along the coast of the reserve vary from mudflats in the west to steep rocky shores in the east. Three creeks run through the reserve and empty into Burrard Inlet. The waters in the fjord are subject to a semi-diurnal tidal regime combined with boat and wind induced waves (Taleghani et al., 2020).

### 3.1.1. Bathymetry and sediment

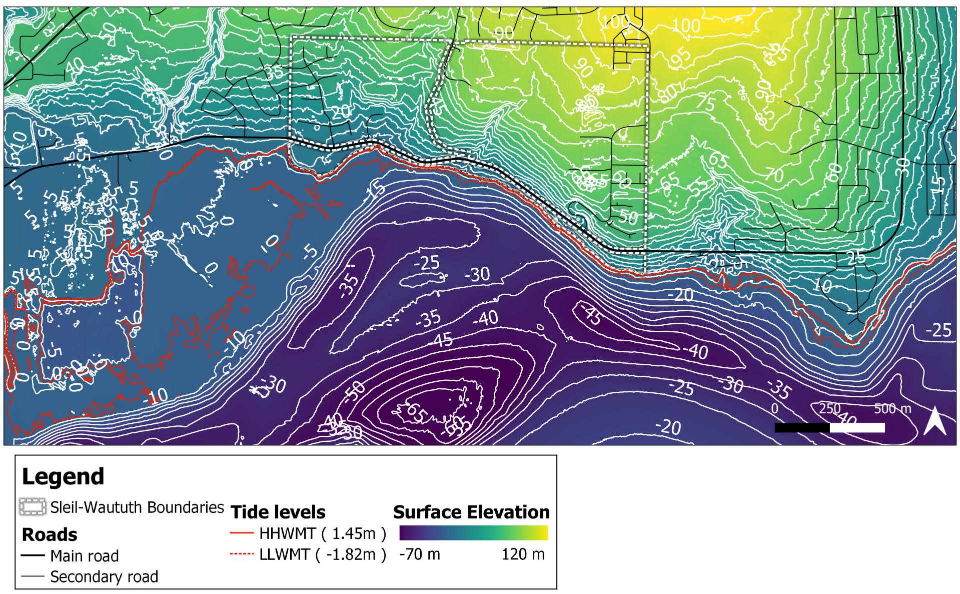



Figure 3.1: Surface elevation (CGVD28) of the project area and bathymetry of the shores in front of the project area (GIS data provided by Kerr Wood Leidal (2020). Maps created with QGIS software (QGIS Development Team and others, 2020))

As is common for fjords, the shores of the Burrard Inlet IR#3 are distinguished by steep slopes and large differences in heights (National Geographic, 2012). In Figure 3.1, large changes in bed elevations can be observed. The depth of the bed ranges from -25m to -65m CGVD28. The Canadian Geodetic Vertical Datum of 1928 (CGVD28) is the current height reference system in British Columbia, comparable to the Amsterdam Ordnance Datum (NAP) in the Netherlands and will be used as point of reference in this report unless otherwise specified (Government of Canada, 1948-2018). The bathymetry of the shores of the project area can be distinguished in two characteristic areas: the western part of the area is dominated by a flat shelf that reaches about 500 to 600 meters into the inlet after which it drops from -5m CGVD28 to -25m CGVD28 when it reaches the end of the shelf; in the eastern part of the area the length of the shelf is much shorter before elevations drop in the deeper channel.

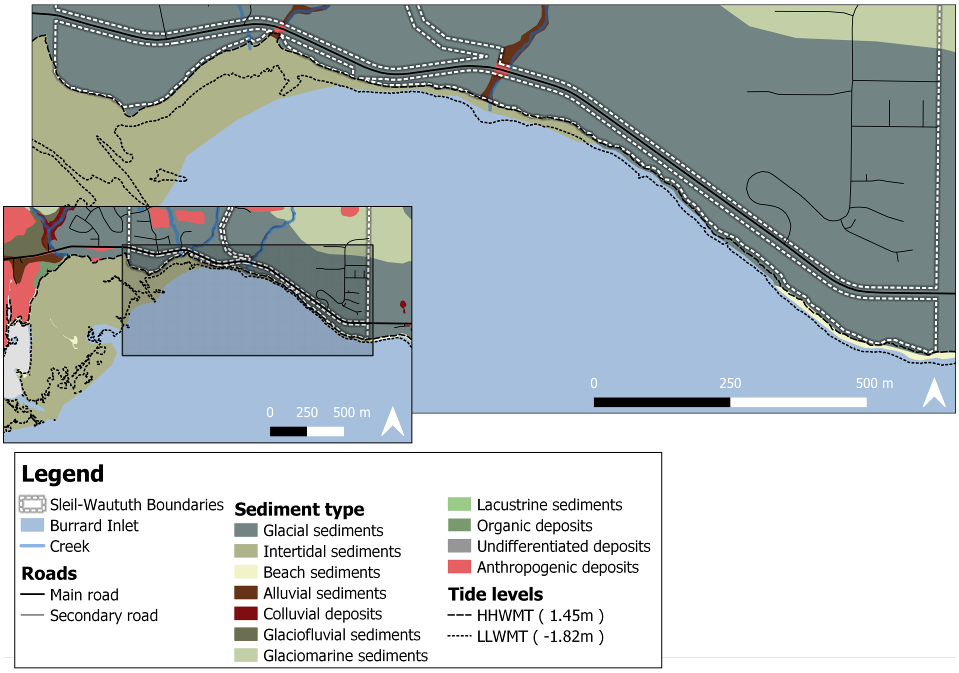



Figure 3.2: Surface geology of the project area (GIS data provided by Kerr Wood Leidal (2020). Maps created with QGIS software (QGIS Development Team and others, 2020)

In Figure 3.2 the surface soil types are displayed: the main part of the Sleil-Waututh reserve and its shorelines are located on glacial sediments. The mudflat consists of marine and beach sediments. The eastern shores of the project area occasionally exists of marine and beach sediments.

## 3.2. Infrastructure and land use

The grounds of the Sleil-Waututh reserve are used for various purposes (see Figure 3.3). In the west, community housing can be found, along with a community centre and administrative building. A driving range can be found in the central northern part of the reserve. Further to the east, several apartments have been build with the purpose of leasehold housing. Three creeks run through the reserve. The remaining part of the reserve is covered by deciduous and mixed forests (Taleghani et al., 2019). Dollarton Highway crosses the reserve from east to west, parallel to the coast but is not part of the reserve grounds.

In older times, during low tide, the TWN community would gather at the beach and clams could be harvested. Archaeological evidence has been found that date signs of civilization on the lands and shores of the inlet back to thousands of years (Wilson and Henderson, 2014). Additionally, a cemetery is located near the southwestern part of the shore (Taleghani et al., 2020). A little to the east, a canoe shed used by the community is found. Preserving such areas of cultural importance has a high priority for the TWN (Taleghani et al., 2020).

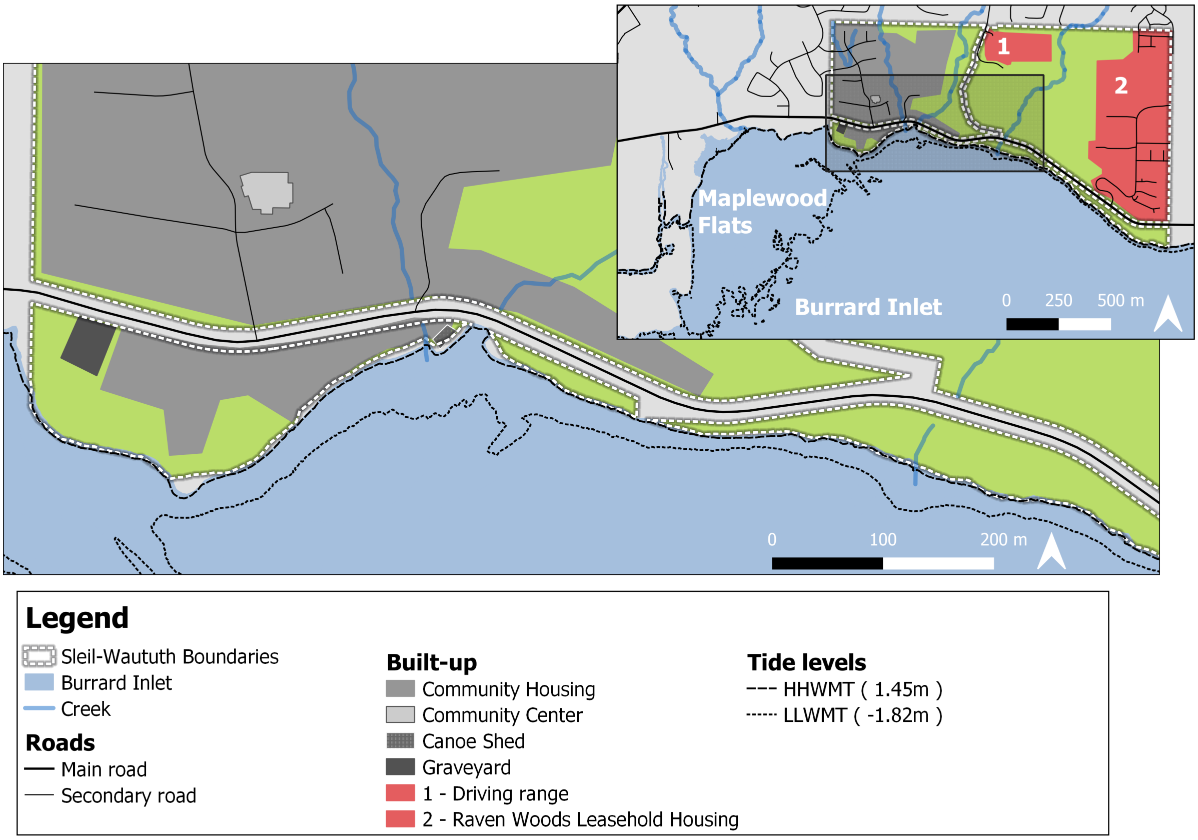
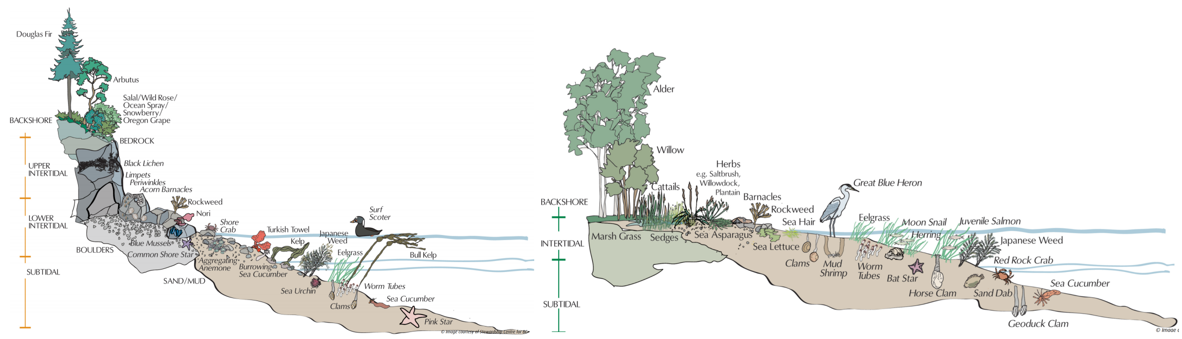



Figure 3.3: Spatial use of project area (GIS data provided by Kerr Wood Leidal (2020). Maps created with QGIS software (QGIS Development Team and others, 2020))

## 3.3. Ecology

Evidence found along the shores of the Burrard Inlet IR#3, show that the waters and intertidal zone of the inlet have provided the TWN with a traditional food staple, consisting for a large part of salmon, forage fish, and shellfish, since time out of mind (Toniello et al., 2019; Goodman, 2020; Kerr Wood Leidal, 2020; Taleghani et al., 2019; Pierson, 2011). The shorelines of the Sleil-Waututh reserve are characterized in the west by sandy and muddy flat beaches. Moving to the east, the shores change into steeper and more rocky shores (See Figure 3.4).




(a) A sketch of the intertidal zone with a gravel/rocky scarp, and a steeper slope

(b) A sketch of the intertidal zone with a sandy beach/mudflat, and a mild slope

Figure 3.4: A comparison between two different tidal areas. Different shapes of the tidal zone due to different grain sizes and different bathymetry cause different ecology's (Stewardship Centre for BC, 2013)

### 3.3.1. Marine riparian zone

The riparian zone lies at the interface of land and water. In this project, the zone is defined as the edge between the water level during high tide in the Burrard Inlet (upper part of intertidal zone) and land. Despite the riparian zone having a different layout across the shores, at most shores acrross the reserve a change in slope or drop in elevation is observed (See also Figure 3.1).

Along the mudflat in the west, the riparian zone is marked by shrubs, trees and driftwood, that has been deposited by high tides.

Down the western shores of the reserve, the riparian zone changes into landscaped yards with undercut banks in which the roots of trees growing on the banks are exposed. The undercut banks can be interpreted as a sign of bank erosion. Clues of attempts to mitigate the erosion are visible here as well, in the shape of asphalt slabs, rip rap, cobbles and small boulders. The soils observed in the undercut banks are expected to be glacial sediments (See Figure 3.2).

Further to the east, signs of erosion gradually disappear and the riparian zone is characterized by an abrupt transition between boulders and cobbles, and a steep vegetated bank with overhanging vegetation (Muir and Menezes, 2014; Kerr Wood Leidal, 2020).

### 3.3.2. Intertidal ecosystem

The intertidal zone is the area of the shores over where the tide changes: during high tide the area is submerged and during low tide it is becomes visible. The intertidal zone plays an important role in TWN's culture. Clams, oysters and mussels were harvested here, contributing to the Nation's wealth (Tsleil-Waututh Nation, 2020a; Toniello et al., 2019; Pierson, 2011; Haggarty, 1997). On the shores of the reserve used to be two big clam beds where members of the Nation could take what they needed. By just taking what they needed and not over-harvesting the clam beds, the clam beds were able to sustain themselves (UBC Coastal Adaptation Lab, 2020; Morin, 2015). Loss of the width of the intertidal zone up to 9 meters has been observed by members of the community (George and Hyland, 2018; Muir and Menezes, 2014).

The current state of the intertidal zone is displayed in Figure 3.5: west of the reserve, the Maplewood Flats are located with wetlands and mudflats close to the coast, gradually changing into a coarser bed with native aquatic vegetation such as eelgrass and sea lettuce (Taleghani et al., 2019). In front of the western shores of the reserve lie outskirts of the mudflat, but the width of the intertidal zone has strongly decreased already. Moving further to the eastern shores of the reserve, the intertidal zone becomes even more narrow and consists of a strip of coarse gravel and boulder beaches, followed by a strip of fine sediments overgrown with native aquatic vegetation such as fucus and sea lettuce (Kerr Wood Leidal, 2020).

Hence, the intertidal ecosystems observed on the shores of the reserve vary from mudflats and sandy beaches in the west, gradually transforming into steeper gravel and rocky beaches in the east. Along with this, a change in the width of the intertidal zone can be seen: the maximum width of the intertidal zone develops from approximately 400-600 meters in the west to 30 meters in the east.

**Native species**

Native shellfish species found on rocky or harder substrates in the intertidal zone of the Burrard Inlet IR#3 are the *Olympia oyster* and *Blue mussel* (Dethier et al., 2006; Couch and Hassler, 1989; Northwest Climate Adaptation Science Center, 2019; Lassuy, 1989; Bayne and Bayne, 1976). Clams are found in intertidal areas with softer substrate, such as sand, mud and small gravel, in which they bury themselves. Native species found in the Inlet are the *Geoduck Clam*, *Washington Butterclam*, *Pacific Gaper Clam*, *Fat Gaper Clam*, *Pacific Littleneck Clam* and the *Atlantic Jack-Knife* (Dethier et al., 2006; Fisheries and Oceans Canada, 2019; Traditional Animalfoods, 2019; Goodwin and Pease, 1989).

The shellfish mentioned above are filter feeders that mainly feed on plankton. An advantage of filter feeders is that they clean waters from nutrients and contaminants, having a positive effect on the water quality (Dethier et al., 2006).

When fully grown, these shellfish are resilient to a range of water temperatures and salinity levels, but prefer water temperatures ranging from 6 to 22 °C and salinity levels over 25 PSU (Couch and Hassler, 1989; Dethier et al., 2006; Goodwin and Pease, 1989). Additionally, the waters in which the shellfish live should not be too acidic, as this limits their ability to from their shells. Ideally, pH should be over 8 for ideal shell formation circumstances (Doyle, 2017; Marliave et al., 2011).

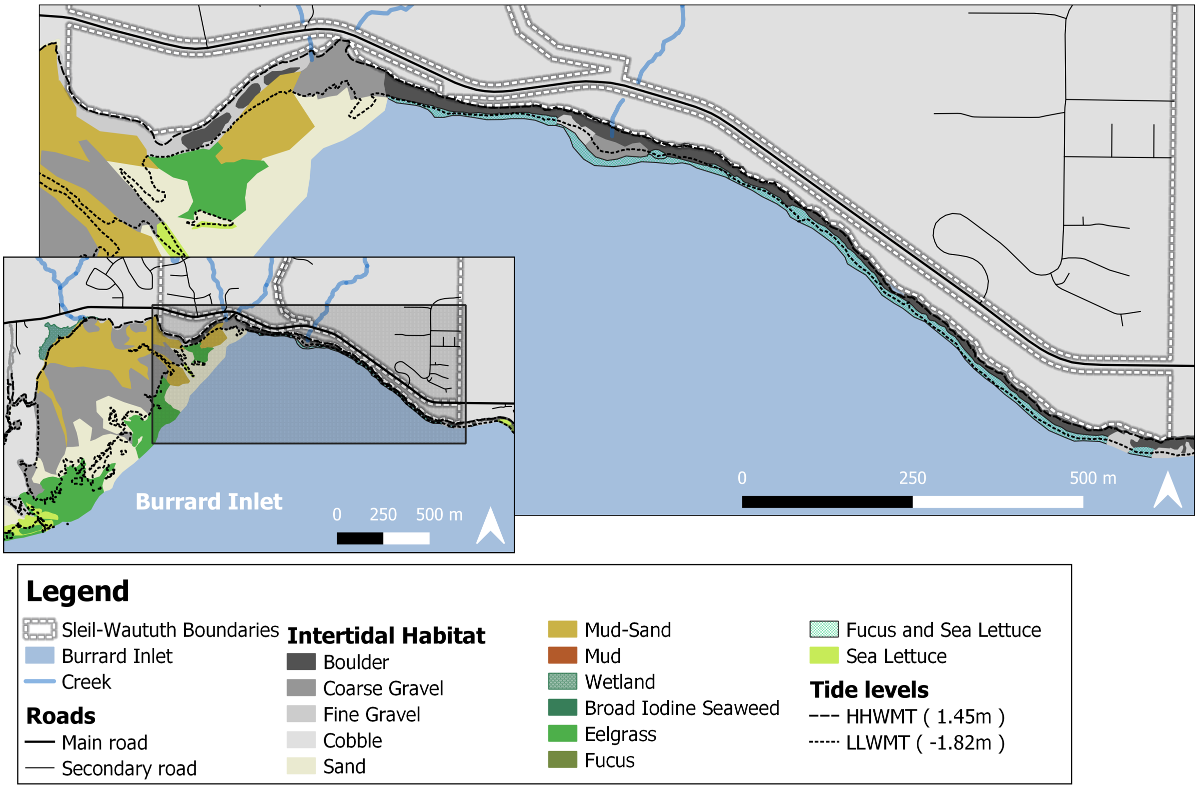



Figure 3.5: Intertidal habitat at the shores of the project area (GIS data provided by Kerr Wood Leidal (2020). Maps created with QGIS software (QGIS Development Team and others, 2020)

**Clam harvesting**

Before contact, the intertidal shores of the Burrard Inlet IR#3 used to be covered in clam beds (George and Hyland, 2018; Goodman, 2020, 2016). Especially the shellfish beds on the shores of the SW reserve and Maplewood Flats were intensively used by the Nation (Morin, 2015). Clams were not only an important staple of TWN diet (Goodman, 2020), but were of high cultural and economic importance for the Nation (Bergquist et al., 2019; Goodman, 2020; Morin, 2015).

### 3.3.3. Aquatic ecosystem

The fjord inlet is a saline water body that receives fresh water from various sources, the Fraser river being the main one. This river system, one of the main in British Columbia (BC), mouths into the Salish Sea below the Burrard Inlet. During high river flow, the river can be responsible for inflow of lower saline water (PSU>= 9). Two water layers can be identified in the Burrard Inlet: a relatively warm top layer with lower salinity (PSU > 20) and a depth of 5 meters can be distinguished above a colder and more saline water body. Both salinity and temperature vary spatially and temporarily, being affected by seasonality, creek and river runoff, tidal flows and winds. During summer, water surface temperatures can reach up to 20 °C in shallow surface waters and up to 15 °C in deeper waters. Surface temperatures during winter range between 6 and 8 °C. Temperatures have declined by 5 to 10 °C at the bottom of the surface layer. Salinity of the lower layer is relatively stable, around 29 to 30 PSU all year long (Pierson, 2011; Johannessen et al., 2020; Haggarty, 1997)

**Changes in water quality**

Across the shores opposite of the project area, a number of industries are located. West of the Iron Workers Memorial Bridge, the port of Vancouver is located (see figure 3.6). Discharges from industrial activities, along with urban discharges and disposal from ships among others, affect the level of nutrients and other pollutants in the waters of the Burrard Inlet. Harvesting of shellfish is forbidden because of high fecal coliform levels due to overflow storm discharges (Pierson, 2011; Haggarty, 1997).
In the last decade, several algae blooms or Red Tides have occurred in the Burrard Inlet. Even though the cause is considered to be natural, caused by ideal circumstances of present nutrients and higher

water temperatures, the phenomenon used to be considered rare in the waters of BC (NOAA, 2020). Nevertheless, a Red Tide has occurred every year since 2017 (Tiffany Crawford, 2019; Cory Correia, 2018; Matt Robinson, 2018; Strange Sounds, 2014).
Waters in the inlet are characterized by a relatively high acidity. In the past 60 years, pH has decreased from stable levels between 7.8 and 8.1 in the period from 1954 to 1974, to a pH ranging between 7.3 to 7.9 in 2010. This decrease in pH can be related to industrial pollution. Current water quality standards require a pH between 6.5 and 8.5, so water quality is deemed acceptable. However, as pH levels drop below 7.9, shellfish begin to show signs of decreased ability of shell formation. If the pH drops further down to 7.5, increased juvenile shellfish mortality rates emerge due to their shells dissolving by the acid waters while adult shellfish show reduced activity (Doyle, 2017; Marliave et al., 2011).

**Native species**
Besides the native shellfish and aquatic vegetation mentioned in the previous section (3.3.2), several native fish species reside in the waters of the inlet as well. For the TWN, important native fish species are the *Pink*, *Chum* and *Coho salmon*, *Herring* and *Surf Smelt* (Haggarty, 1997; Pietsch and Orr, 2015). Most of these species only spend part of their lifetime in the inlet during certain seasons of the year. Salmon, for example, lay their eggs in freshwater streams in the inlet and descent down to the fjord as juveniles where they try to survive in shallow waters with temperatures ranging from 6 to 15 °C and a mixed substrate of consisting of bedrock, boulders, rip rap, cobbles, sand and mud overgrown with submerged aquatic vegetation such as eelgrass beds (Haggarty, 1997; Raleigh and Nelson, 1985; Pauley et al., 1988; Bonar et al., 1989; Laufle et al., 1986; Hale et al., 1985; McMahon, 1983; Emmett, 1991; Penttila, 2007). Herring prefers to reside in turbid waters with temperatures ranging between 0 and 10 °C and eelgrass beds (Pierson, 2011; Barnhart, 1988; Emmett, 1991), while Surf Smelt prefers a mixed sand and gravel substrate and eelgrass beds (Pierson, 2011; Penttila, 2007; Emmett, 1991).

## 3.4. Coastal system characteristics

The following section describes the hydrodynamic conditions of the coastal zone at the study area. It is important to make a considered overview of all different aspects that influence the hydrodynamic conditions in the bay.


Figure 3.6: Overview of the Sleil-Waututh in the Burrard Inlet

### 3.4.1. Water levels

The project location Sleil-Waututh (Burrard Inlet IR#3) is located several kilometres within the Burrard inlet. Vancouver Island is located in front of the Burrard inlet as can be seen in Figure 3.6, therefore large wind and (swell) waves due to large storms at the North-Pacific ocean will be blocked by the Island and thus considered not be significant at the Burrard inlet. However the temporary rise in water level due to these storms can be serious, and needs to be taken into account. The same principle holds for high wind-induced waves from the Strait of Georgia, see Figure 3.6. These waves are considered not able to reach the project site, since Stanley Park is right in front of the project location, an overview of wave penetration in the Burrard can be seen in Figure B.1 in Appendix B. This assumption is made based on a wave climate model of Burrard Inlet developed by the University of Miami, see Appendix B.1 for further elaboration and an overview of the wind-generated wave field within the Burrard Inlet. The water level at the shoreline will therefore depend on the effects of tide, storm surge, sea level rise and (wind-induced) waves. The goal of this study is to determine the design water level and design wave to analyse the bank and shore processes at the location.

The water elevations in this section will be given in geodetic datum (GD). Most of data is presented Chart Datum, which is -3.011 m lower than CGVD28. The Canadian Geodetic Vertical Datum of 1928 (CGVD28) is the current height reference system in British Columbia, comparable to the Amsterdam Ordnance Datum(NAP) in the Netherlands. In order to convert the water level data to a geodetic water level, this 3.011 meters is subtracted from the observed water level dataset. (Government of Canada, 1948-2018)

**Tides**
The tidal range has been calculated with data from the CHS Vancouver station (#7735), see figure 3.6. The tides are semi-diurnal, which means approximately 2 high tides and 2 low tides a day. With the water level data from the station, the Higher High Water Large Tide (HHWLT) is calculated: the highest high water level from each year out of 19 years of data, which represents one metonic cycle, is taken and an average is taken over those 19 water levels. The same is done for the Lower Low Water Large Tide (LLLWT), but with the lowest low water level from each year out of 19 years of data. The Lower Low Water Mean Tide (LLWMT) can be determined, by averaging the lower low water on a daily basis over 19 years of data. Same can be done for the Higher High Water Mean Tide (HHWMT). The results in table 3.1 concludes a tidal range of 5.26 meters.

Table 3.1: Tidal elevation at Vancouver Harbour station 7735, period: 1998-2018

| Characteristic Tide | Elevation at CGVD28 (m) |
|---|---|
| Higher High Water Large Tide (HHWLT) | +2.27 |
| Higher High Water Mean Tide (HHWMT) | +1.49 |
| Mean Sea Level (MSL) | +0.1 |
| Lower Low Water Mean Tide (LLWMT) | -1.74 |
| Lower low Water Large Tide (LLWLT) | -2.99 |

**Mean sea level (MSL)**
The MSL has been determined from the #7735 CHS station in Vancouver harbour, which consist of hourly-data. (Government of Canada (1948-2018)) First an average is taken over each period of ten years. As can be seen in Table 3.2, the mean sea level changes considerably over the years. This clearly indicates the effects of sea level rise, which will be elaborated in Chapter 4.1.1. The MSL used in calculations will be determined from 19 years of data (1998-2018), which represents one metonic cycle. This leads to an Mean Sea Level in the current situation of +0.1 m Geodetic Datum.

Table 3.2: MSL 10 year period at Vancouver Harbour #7735 CHS station

| Year | MSL at CGVD28 (m) |
|---|---|
| 1948-1958 | 0.036 |
| 1958-1968 | 0.047 |
| 1968-1978 | 0.057 |
| 1978-1988 | 0.062 |
| 1988-1998 | 0.072 |
| 1998-2008 | 0.081 |
| 2008-2018 | 0.108 |

**Sea level Rise(SLR)**
The relative sea level rise consists of the global rise in sea level and the ground subsidence in the area in that period. There red line in Figure 4.1 in Chapter 4.1.1 illustrates the recommended curve for sea level rise policy in BC which is 1 meter global sea level rise in 2100 and 2 meters for 2200 (Sandwell, 2011). Further elaboration of the expected sea level rise at the site, compared to global sea level rise can be found in Chapter 4.1.1. The results are shown in table :

Table 3.3: Absolute and relative sea level rise year 2100 and 2200(Sandwell, 2011)

| Design year | Absolute SRL (m) | Relative SRL (m) |
|---|---|---|
| 2100 | 1 | 1.1 |
| 2200 | 2 | 2.2 |

**Design water level**
To calculate the design water level, a frequency analyses is done based on observed water level data at the #7753 CHS station.(Government of Canada, 1948-2018) Since the dataset contains observed water levels, residual water level effects, storm surge and climatic changes, are included. It is also possible to subtract the observed water level from the predicted water level and calculate the residual water level effects. For this preliminary design phase no further calculation is done and the extrapolated water level will include these residual water level effects. This means that only the effects of (wind-induced) waves and sea level rise will need to be added in order the get a final design water level. The determination of the design water level is done on the basis of an Extreme Value Analyses. A Weibull distribution resulted in the smallest Root Mean Square Error, see Appendix B.2 for further elaboration. The confidence intervals are set at 90%, 95% and 99%, typical design standards in engineering. (Rock Manual, 2007) The Annual Exceedance Probability (AEP) can be found in Tabel3.4 and is calculated according to $Q = 1/(R \cdot N_s)$, where $N_s$ is the number of 'storm water levels' per year taken in account in the Peak over Treshold method, see Appendix B.2. The determination of the final water design level including sea level rise, will be elaborated in Chapter 4.2.1. The results are presented in Table 3.4 and Figure 3.7. Further elaboration of the calculation can be found in Appendix B, section B.2.2.

Table 3.4: Results confidence intervals: water level prediction normally distributed (Goda, 1985)

| Confidence level | AEP (Q) | Return period(Yr) | Water level(m) | Upper bound | Lower bound |
|---|---|---|---|---|---|
| 90% | 0.001 | 100 | 2.63 | 2.68 | 2.58 |
| 90% | 0.0005 | 200 | 2.68 | 2.73 | 2.62 |
| 95% | 0.001 | 100 | 2.63 | 2.69 | 2.57 |
| 95% | 0.0005 | 200 | 2.68 | 2.74 | 2.61 |
| 99% | 0.001 | 100 | 2.63 | 2.71 | 2.55 |
| 99% | 0.0005 | 200 | 2.68 | 2.76 | 2.59 |

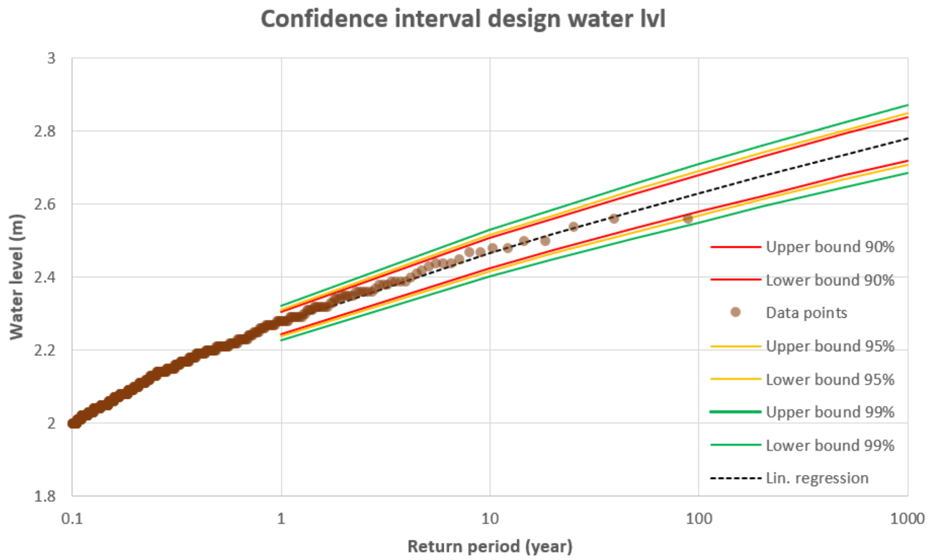



Figure 3.7: Confidence interval 90% water level design according to GODA method (Goda, 1985)

### 3.4.2. Tsunamis

British Columbia is located at the boundary zone of the North-American tectonic plate, touching the Juan de Fuca and the Pacific plate at the western side. The Cascadia subduction zone that is related to these plates, extends from northern Vancouver Island to northern California. The Cascadia subduction zone undergoes deformation over a period of 500-600 years, on average. Such a deformation causes strain releases that cause great earthquakes (magnitude $\tilde{9}$ (Atwater, 1987; Thomson et al., 2008)). Rapid changes in water level over small periods of time (minutes to hours) that are associated with these events, can cause tsunamis with maximum heights of $\tilde{1}0$ m at locations on the west coast of Vancouver Island. In more protected waters such as the Strait of Georgia, this results in a tsunami of $\tilde{1}$m height (Cherniawsky et al., 2007; Thomson et al., 2008). As the Burrard Inlet IR#3 is located in an even more protected area inland, the effect of tsunamis is assumed to be negligible for within the scope of this project.

### 3.4.3. Wave and Wind climate

lTo determine wave effects on the shore, two different waves will be distinguished: the local wind-generated waves and the ship induced waves.

**Wind waves**

The local wind-generated waves will be fetch limited and the dominant direction can be determined with a wind frequency analyses. A step by step elaboration of the process of determining the dominant wave direction and the design wind speeds, can be found in Appendix B. Based on hourly records from the Point Atkinson station (Government of Canada, 1996-2019), a wind rose is made to display the dominant wave direction. As can be seen in Figure 3.8, the dominant wind direction is east. The wind rose shows a frequency distribution, which is categorized according to the legend included. An important note has to be made, since Point Atkinson is not located at the Burrard Inlet #3, as can be seen in Figure 3.6 in the previous section. Point Atkinson is located at the entrance of the Burrard Inlet, a light house right next to the Straight of Georgia. Compared to Point Atkinson, the Burrard Inlet IR#3 location is far less exposed to large storms, since it is sheltered by several mountains and vegetation. Fetches are smaller and the wave heights will be considerably smaller, compared to a far more open location, Point Atkinson. However, the dominant wind direction is east, see Figure 3.8, which causes a more or less comparable fetch length between the two locations. Wind speeds will probably slightly smaller at the Burrard Inlet IR#3, due to its geographical location. However for this preliminary design phase it is assumed that for the design storms coming from the East, Point Atkinson gives a reasonable dataset, which will lead to a conservative design load. The confidence intervals are set at 90%, 95% and 99%, typical design standards in engineering. (Rock Manual, 2007) The uncertainty in the predication

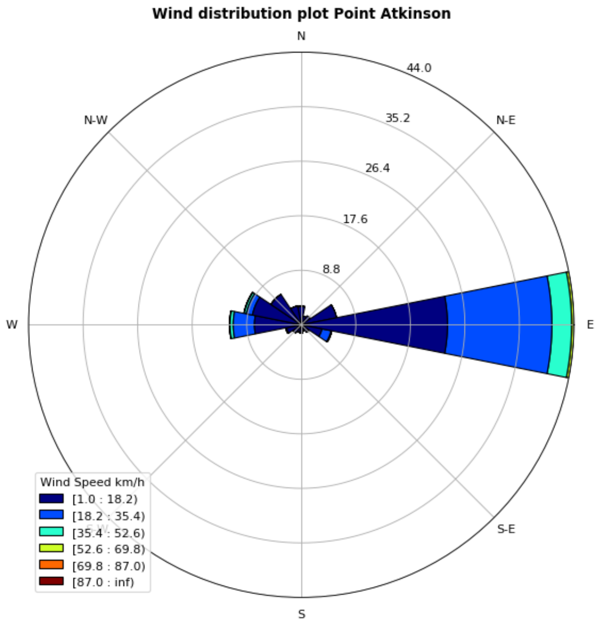



Figure 3.8: Wind rose Point Atkinson. Wind speed in m/s

is determined according to the Goda method.(Goda, 1985) The full calculation and results can be found in Appendix B.2.2. The conclusions are shown in Table 3.5 and Figure 3.9.

Table 3.5: Results confidence intervals: wind speed prediction normally distributed (Goda, 1985)

| Confidence level | AED (Q) | Return period (Yr) | Wind speed (m/s) | Lower bound | Upper bound |
|---|---|---|---|---|---|
| 90% | 0.001 | 100 | 23.3 | 22.2 | 24.5 |
| 90% | 0.0005 | 200 | 23.9 | 22.7 | 25.1 |
| 95% | 0.001 | 100 | 23.3 | 21.9 | 24.7 |
| 95% | 0.0005 | 200 | 23.9 | 22.5 | 25.3 |
| 99% | 0.001 | 100 | 23.3 | 21.5 | 25.11 |
| 99% | 0.0005 | 200 | 23.9 | 22.0 | 25.8 |

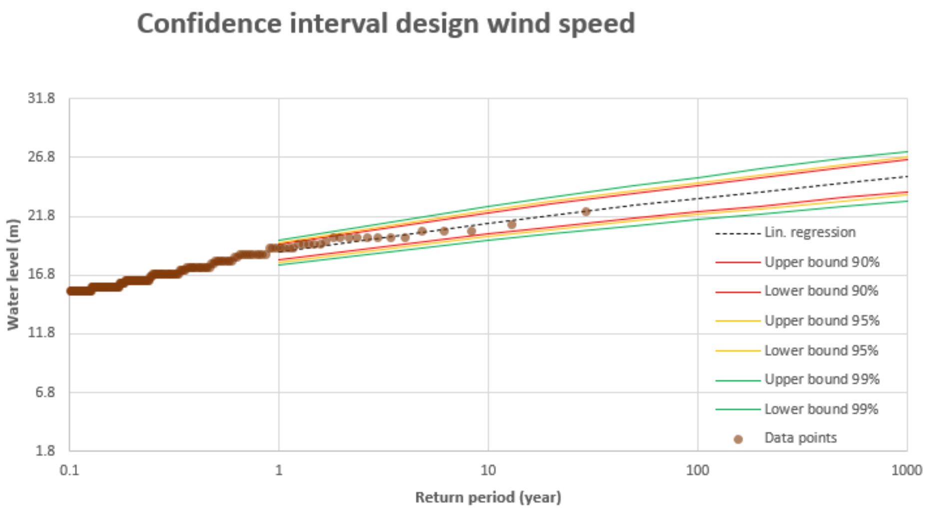



Figure 3.9: Confidence interval 90% wind speed design according to GODA method (Goda, 1985)

The wave height of these wind induced waves are dependent on the maximum fetch length and bathymetry. Figure 3.10 shows the maximum fetch lengths for the location, which is calculated in Appendix B.2.2.

The significant wave height ($H_s$), without considering the bathymetry of the location, is estimated using the simplified Sverdrup-Munk-Brettschneider (1951) formula:

$$\frac{g \cdot H_s}{u^2} = 0.283 \cdot \tanh\left(0.0125\left(\frac{g \cdot F}{u^2}\right)^{0.42}\right) \tag{3.1}$$

$$\frac{g \cdot T_s}{u} = 2.4 \cdot \pi \cdot \tanh\left(0.077\left(\frac{g \cdot F}{u^2}\right)^{0.25}\right) \tag{3.2}$$

With input parameters: Fetch (F) = 3800 m, Wind speed (U) = 23.9 m/s, as described in Chapter 3.4.3. This fetch length, originally 3900 meters, corresponds with a ESE wind direction reaching Reach 2 as can be seen in Figure 3.10. By taking a fetch of 3800 m, the significant deepwater wave height can be calculated at approximately the start of the cross sections used in the concept designs in Chapter 8-12. Elaboration on the selected cross sections can be found in Chapter 6. East-South-East with a fetch length of 3800 meters is assumed to be the dominant wind/wave direction for the chosen cross sections. This is more or less inline with the dominant wind direction from the wind distribution at Point Atkinson coming from the East, see Figure 3.8. In the frequency analyses all wind directions between 80-100 degrees are taken into account, so the assumed dominant direction East-South-East in this situation is within these limits. This leads to the following deepwater design waves $H_s$, according to different return periods in Table 3.6. For the overall picture, the corresponding water levels as elaborated in section 3.4.1 are included.

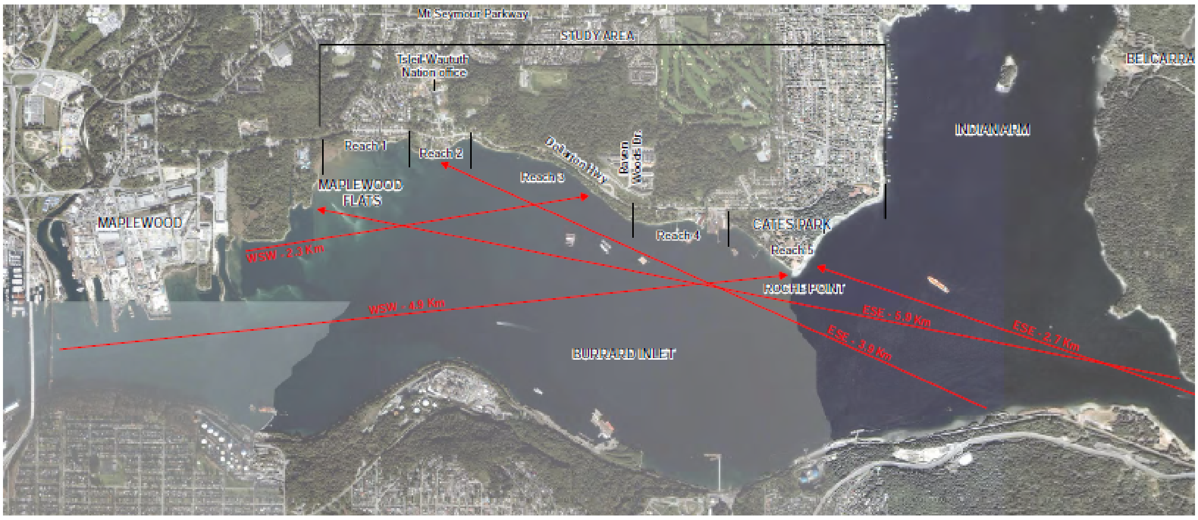



Figure 3.10: Wind fetch determination (Muir and Menezes, 2014)

Table 3.6: Final return periods Wind-induced significant wave height and water level

| Return period [Yr] | Windspeed [m/s] | $H_s$ [m] | Water level [m] |
|---|---|---|---|
| 1 | 18.74 | 0.90 | 2.27 |
| 10 | 21.20 | 1.03 | 2.47 |
| 20 | 21.86 | 1.07 | 2.52 |
| 50 | 22.70 | 1.12 | 2.58 |
| 100 | 20.31 | 1.15 | 2.63 |
| 200 | 23.91 | 1.19 | 2.68 |
| 500 | 24.67 | 1.23 | 2.74 |
| 1000 | 25.23 | 1.27 | 2.78 |

### 3.4.4. Ship waves

Sleil-Waututh (Burrard Inlet IR#3) is located close to the Port of Vancouver, which is the largest port on the West Coast of North-America, with a total cargo of 147 million metric tons.(Port of Vancouver, 2018) Wave loads due to ships can be subdivided into three different types: the primary waves, which are related to the length of the ship, the secondary waves, related to the shape of the bow of the ship, and the propeller wash, related to the propelling force of the ship. (Schierick, 2nd Edition 2012)

*Primary waves*
The primary wave has a wavelength about the same length of the ship that is sailing along the channel. It starts with the front wave, which is followed with a depression at the side of a ship, which induces a return current, ending with the stern wave. It must be taken into account when the waterway is relatively small compared to the cross-section of the ships. Since the channel is quite deep (2020 Navionics S.r.l. or its subsidiaries, 2020), these primary waves will be neglected in this preliminary design, assuming the ships will navigate not too close to the banks. (Schierick, 2nd Edition 2012)

*Secondary waves*
Due to the discontinuities in the shape of the ship, secondary waves are formed. The can be distinguished in transverse waves, which travel in the same direction and with the same speed as the ship, and diverging waves which travel slower and at an angle of about 35°with the sailing line. Unfortunately, wave heights are quite hard to determine and they are most dependent on the shape of the bow. Therefore, the wave height is mostly determined with experiments. These secondary waves can cause high waves in the Burrard Inlet IR#3 area, especially tug boats are known to cause high waves in channels. Lots of empirical relations can be found, but most of them depend on many parameters. The more parameters are known, the better the data will fit to the empirical formulas.

*Propellor wash*
The propeller wash is important when ships maneuver at low speeds, close to the river banks or in shallow water. Since this is not the case, the effect due to the flow induced by the propeller will not be considered in this stage of the preliminary design.

**Ship waves formulas**
In this design phase different design formulas are used to estimate the secondary ship induced waves, or ship wakes. These results can found in Table 3.7. The different methods depend on different parameters and can be used in different scenarios, which are briefly described in Appendix C.

Table 3.7: Comparison different methods

| **Method** | Waveheight at x=30 [m] |
|---|---|
| Bhowmik (1975) | 2.26 |
| Gates and Herbich (1977) | 0.99 |
| Bhowmik, Demissie, Guo (1982) | 0.52 |
| Blaauw et al. (1984) | 0.69 |
| PIANC (1987) | 0.42 |
| Bhowmik et al. (1991) | 0.88 |
| Kriebel, Seelig (2005) | 0.61 |

Although the conditions and parameters are kept the same as much as possible, the results of the ship wakes vary a lot. This is due to the fact that some methods take more parameters into account. Also many methods are based on empirical formulas, with a data set collected by the author, making the method thus limited to the vessel type and operational conditions. Most of the formulas also lack general information for example: ship dimensions, vessel speed, number of experiments, location of interest and so on. This makes a well substantiated estimate of the correct significant wave height from vessels sailing in the Burrard Inlet IR#3 hard. The values from Table 3.7 will be compared with the dataset from the wave buoy located right in front of the Burrard Inlet IR#3.

*Ship waves data buoy Burrard Inlet IR#3*
The goal of this analyses is to exclude the ship induced waves from the wind-induced waves from the data set. This will be interesting, since many vessels pass the Burrard Inlet IR#3 location everyday. Large ship-induced waves in combination with high water levels can also cause erosion at critical locations, on a daily basis. It might be more useful to look at ship waves and see if these ship waves are considerable. Maybe these ship waves cause more erosion on a daily basis than for example the 200 year storm event. Using the website www.MarineTraffic.com, which shows live sailing tracks and speeds, it can be verified that especially tugboats sail past the project location with quite decent sailing speeds (10-14 knots). A wave buoy is located at a more or less fixed location in front of the Burrard Inlet IR#3 shoreline, see Figure 3.6.
The wave buoy from Marine Labs has been measuring wind and wave data since September 2019. This dataset consists therefore out of almost 7 months of daily records. In Figure 3.11 the wave directions are displayed in a wave rose. There is no distinction between wind- and ship-induced waves in this obtained dataset.

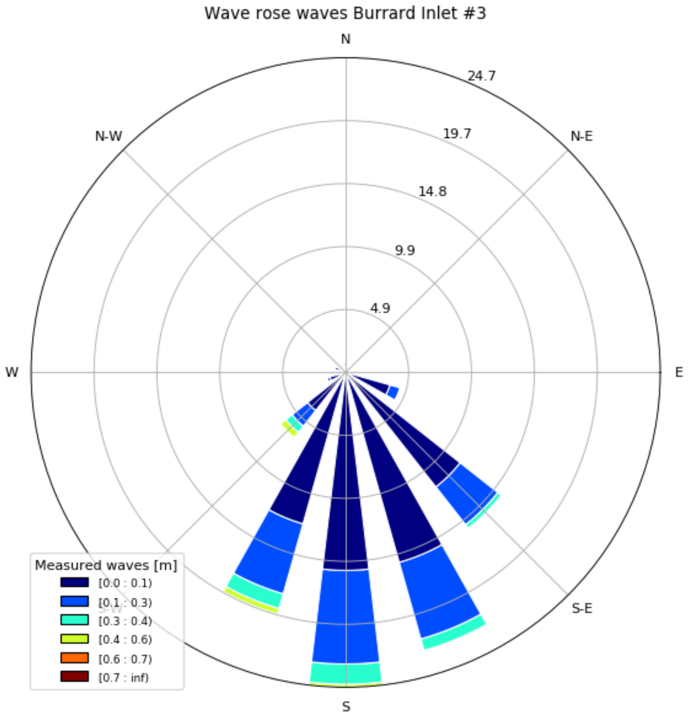



Figure 3.11: Wave rose based on dataset Marine Labs Burrard Inlet 01

To filter out the ship waves, one has to look at conditions where the wind speed is relatively low, but the measured wave height is significant. To come up with a set of ship-induced waves some assumptions need to be done. First the wind speed limit was set to 2 m/s, which is approximately 4 knots. With the earlier used formulas according to the Sverdrup-Munk-Brettschneider method, it can be verified that these wind speeds are is not able to induce significant waves. This wind speed limit is also set to filter out a possible combination of high ship waves and high wind-induced waves, the goal of this analyses is to filter out ship waves only. The first results showed that most of the higher measured waves, where during low wind speed conditions, which might indicate ship waves. To confirm expectation, the directional difference, the difference between the wind direction and wave direction, is taken into account. The results are displayed in a scatter-plot in Figure 3.12.

As can be seen in Figure 3.12, most of the higher waves are measured during low wind speed, which indicates ship-induced waves. In Table 3.8 the 20 highest waves are given to indicate the ship waves. Again, the table shows that most of the higher measured waves occur during low wind speeds, indicating ship waves.

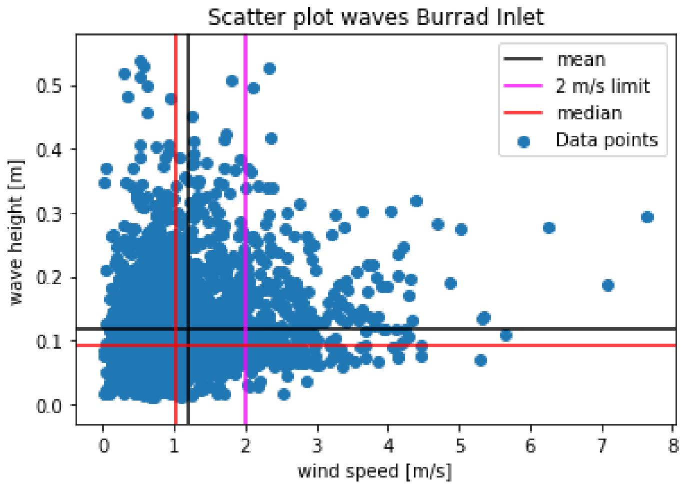



Figure 3.12: Scatter plot with measured maximum wave heights in meters

**Hydro- and morphodynamic analyses**

The next step will be a frequency analyses to be able to determine a design wave induced by vessels sailing in the Burrard Inlet. This is a different scenario than before, since in Chapter 3.4.3 the determined design wave height is based on a 200 year storm event. Comparing this design wave($H_s$) of 1.19 meter, with the ship-induced waves from Table 3.8, the ship induced waves are way lower. However, ship waves happen on a daily basis and can therefore cause much more erosion than a wave with a return period of for example 200 year. For the determination of the design ship wave, one has to look closer at what type of vessels sail in the Burrard inlet, to check if these measured waves are representative for the vessels. Furthermore, with ships increasing in size, the ship-induced waves can be larger, a well considered assumption is needed for the design wave. Also, the time of occurrence needs to be taken into account, together with a stochastic analyses. One can take for example the maximum wave height that occurred in this period of measurements or choose a wave height that occurs regularly on a daily basis, with a small safety factor. Moreover joint probability needs to be considered, a closer look has to be taken for situations where ships sail in high wind wave conditions or high water levels.
For a well considered quantitative erosion pattern, many parameters need to be known. As stated before, due to lack of time and data available, no morphodynamic analyses will be done. It would be interesting to put the ship waves in a model and compare the erosion due to ship wakes over certain time frame and compare that to a couple design storm scenarios. However, to correctly model ship waves, one cannot use a Johnswap spectra, since ship waves are periodic and stationary, therefore not having a wave spectrum.

Table 3.8: Ship waves Burrard Inlet IR#3

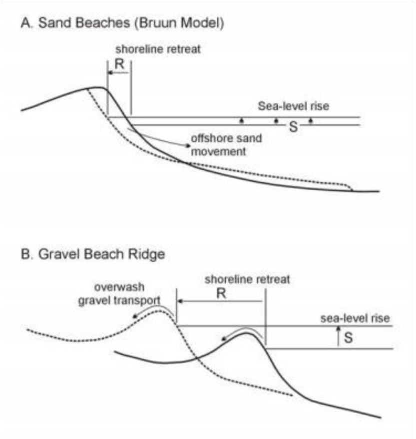
| Time | Wind speed [m/s] | Wave height [m] | Diff. angle ° |
|---|---|---|---|
| **Max wave height** | | | |
| 2020-01-05 22:00:00 | 8.54 | 0.693 | 47.3 |
| **Datapoints** | | | |
| 2019-12-29 17:00:00 | 0.514256 | 0.537744 | -148.262568 |
| 2020-02-03 10:00:00 | 0.563402 | 0.531006 | 159.248032 |
| 2019-12-08 21:00:00 | 0.293897 | 0.518748 | 172.503082 |
| 2019-09-16 19:00:00 | 0.519983 | 0.514127 | 107.226177 |
| 2020-01-21 01:00:00 | 1.791763 | 0.508634 | 145.292610 |
| 2020-01-09 19:00:00 | 0.612438 | 0.498622 | -124.957447 |
| 2019-09-20 19:00:00 | 0.016085 | 0.494820 | 46.934380 |
| 2019-11-19 11:00:00 | 0.341832 | 0.483282 | 88.477081 |
| 2020-01-29 01:00:00 | 0.519880 | 0.479413 | -39.181715 |
| 2019-12-23 15:00:00 | 0.935385 | 0.479019 | -104.332248 |
| 2020-01-09 18:00:00 | 1.510877 | 0.474764 | 24.550665 |
| 2020-01-29 05:00:00 | 0.621414 | 0.456082 | -134.211125 |
| 2019-11-12 20:00:00 | 1.252725 | 0.450835 | 118.683531 |
| 2019-12-13 19:00:00 | 1.737925 | 0.423900 | 95.736342 |
| 2019-08-25 02:00:00 | 1.694914 | 0.413591 | -183.515795 |
| 2019-12-01 04:00:00 | 1.276367 | 0.411093 | -143.834307 |
| 2019-11-08 03:00:00 | 0.925260 | 0.407139 | -114.776348 |
| 2019-09-06 07:00:00 | 0.517260 | 0.406135 | 202.695114 |
| 2019-09-02 07:00:00 | 0.744056 | 0.402485 | 125.107601 |
| 2020-02-03 12:00:00 | 0.920438 | 0.394363 | 112.359928 |

## 3.5. Sediment behaviour

The coast line of the TWN site is different over the whole area. Different grainsizes and D50's are distributed over the coast of the TWN. The general consensus is that the coastline has a mixed sand-gravel grainsize distribution (Taleghani et al., 2020). In Figure 3.13b the grainsize distributions of specific areas in and around the TWN coastline are determined by KWL. The behaviour of mixed sand-gravel beach is difficult to determine as sand and gravel both have different equilibrium conditions under a storm.

A sandy beach does not behave the same as a gravel beach. The Bruun effect states that the profile shape of a sandy beach remains the same (the length of the vertical and horizontal lines respectively is constant), but the profile moves up and landwards as a result of SLR. The volume of sediment eroded from the upper profile is equal to the deposited volume in deeper water. (Bosboom and Stive (2015))

Gravel beaches will mitigate land inward due to the SLR. The gravel will be carried land inward due to overwash/rollover events. For the TWN site the grain distribution is however not only sand or only gravel, but a mixture of sand and gravel as shown in Figure 3.13b. According to Mason and Coates (2001) mixed sand-gravel beaches should contain at least 5 to 10 percent sand to behave somewhat similar to a sand beach.




(a) Bruun effect for sandy beaches (top) and for gravel beaches (bottom)

**Table 1: Shoreline Surface and Sub-surface Material Median of Grain Size Distribution**

| Site | Median Grain Size, $D_{50}$ | | |
|---|---|---|---|
| | Surface | Sub-surface / % sand[1] | Sub-surface Fine Grained Sediment Portion[2] |
| Whey-ah-wichen (Cates Park) Headland - East | 4 mm | 4.4 mm (40% sand) | 0.7 mm |
| Whey-ah-wichen (Cates Park) Headland - West | 20 mm | 3.3 mm (32% sand) | 0.8 mm |
| BC Archaeology site DhRr-15 | 25 mm | 9.1 mm (28% sand) | 0.7 mm |
| Cemetery Headland | 27 mm | 3.2 mm (45% sand) | 0.4 mm |
| Maplewood Flats - East | 0.1 mm (98% sand) | | |

Notes:
1. % of sub-surface sample finer than 2 mm by weight.
2. Truncated to exclude grain size distribution above 2 mm (sand).

(b) Grain size distribution for the TWN shoreline

Figure 3.13

## 3.6. Currents

Unfortunately no data is available of the currents at the specific site, therefore a dataset from a data station close to the site is used: Second Narrows, see Figure in Appendix B.5 3.4. Since this station measures in one of the smallest cross sections of the Burrard inlet, currents will be considerably higher compared to the currents at the tidal area at the site (Burrard Inlet IR#3). Therefore currents are assumed to be considerably smaller than the values in Table 3.9 and are not taken into account in further analyses.

Table 3.9: measured tidal currents 2018,2019,2020

| | max current (m/s) | avg current (m/s)) |
|---|---|---|
| Flood | +2.67 | +2.32 |
| Ebb | -3.45 | -3.01 |

## 3.7. Sediment budget of a coastal system

To determine estimates for the sediment budget for the coastal system the different sediment pathways, sediment sources and sinks, and proccesses influencing them should be determined. It is important to have a basic understanding of the hydrodynamics and aeolian processes mainly driving the sediment budget and dynamics of the coastal system. In this way quantitative estimates of sources and sinks and their timescales can be estimated for the sediment budget. In Figure 3.14 an example of an hypothetical coastal system is given with the associated processes. Additionally, relative sea level rise contributes as a sediment sink in the coastal system due to the gradual increase in water level and/or land subsidence which is elaborated more extensive in chapter 4.1. Climate change aspects may also change sediment pathways by increase in rainfall patterns or changes in hydrodynamics (Deltares, 2018).

### 3.7.1. Sediment budget

A sediment budget is the sum of all the sediment gains and losses or sources and sinks in a control volume (sediment cell) over a specific time. The difference between the sediment sources and sinks in the cell must equal the rate of change in sediment volume in the cell, this is expressed in variables in the sediment budget Equation 3.3. Where $Q_{source}$ and $Q_{sink}$ are the sources and sinks in the control volume, $\Delta V$ is the net change in volume within the cell, P and R are the amounts of material placed and removed from the cell (for example a nourishment as a placement of sediments and dredging activities

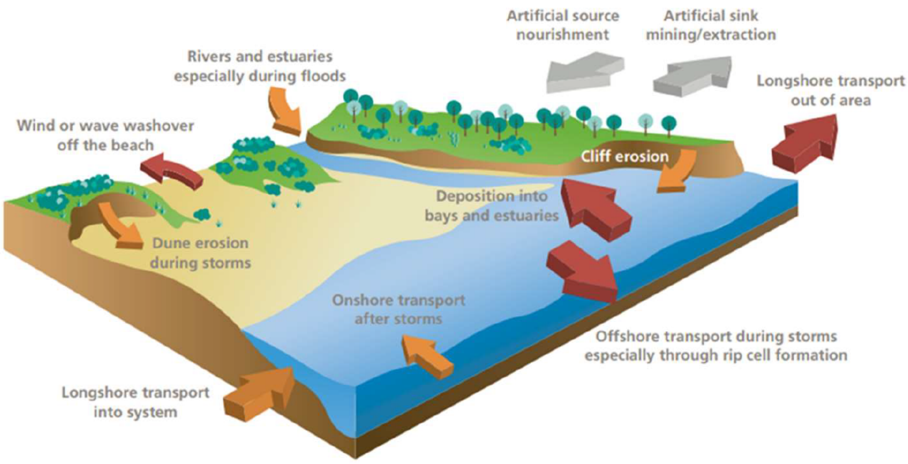



Figure 3.14: Conceptual understanding of a coastal system (Deltares, 2018)

as a removal of sediment), and residuals is the degree of balance of the cell where for a balanced the residuals are zero (Rosati, 2005).

$$\sum Q_{source} - \sum Q_{sink} - \Delta V + P - R = Residual \tag{3.3}$$

A sediment budget allows to make estimates for the volume or volume rates of sediment entering or leaving a specific coastal system or cell. In this way coastal accretion, if there is a surplus in sediment in the system, or coastal erosion, if there is a deficit in the system, can be determined. A good understanding of all the sediment pathways and the state of the coastal system is of major importance for planning and designing of coastal projects. An overview of the sediment budget parameters as explained from Equation 3.3 is given on the right in Figure 3.15. On the left in figure 3.15 pathways of sediment fluxes are illustrated and the red arrow indicates shoreline retreat by the effect of relative sea level rise or a lack in sediment supply. Sources of the sediment budget include longshore sediment transport into the cell (Longshore transport is indicated with LST in Figure 3.15), erosion of bluffs/dunes/banks, transport of sediment to the coast by rivers, erosion of the beach, beach fill and dredged material placement and relative sea level fall. Sinks of sediment include longshore sediment transport out of the cell, accretion of the beach, dredging and mining of the beach or nearshore, relative sea level rise, and losses to a submarine canyon. Possible sources and sinks are visualized for a coastal system in Figure 3.14.

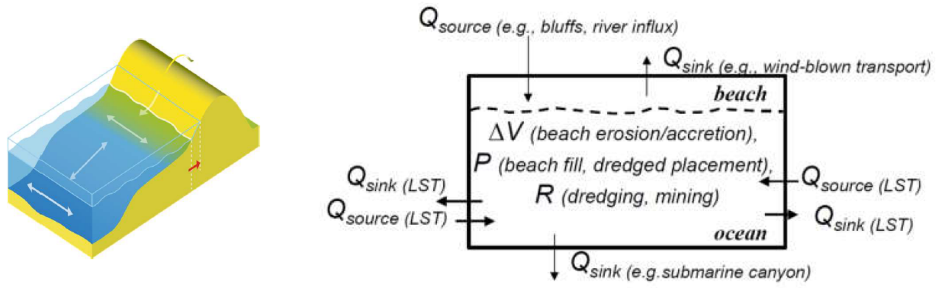



Figure 3.15: Quantification of a sediment budget in a coastal system. Sediment fluxes pathways (left) and sediment budget parameters (right) (Rosati, 2005) (Deltares, 2018)

To make a quantitative sediment budget for the TWN site more research should be done to understand the sediment transport processes such as longshore transport rates, sediment sources from the rivers and other processes illustrated in Figure 3.14 that influence the project area. As this information is not known yet sediment transport rates are not further used in this project to determine erosion rates.

This project however can help form a starting point for further research on sediment pathways in the Burrad inlet.

# 4 Climate induced coastal hazards

In this chapter the climate induced coastal hazards determined for the Tsleil-Waututh Nation are elaborated. First the four major climate change forces are explained on global, regional level and local level. Afterwards the hazards caused for Tsleil-Waututh Nation by the previous explained climate change forces are explained and where possible quantified. Finally important elements of the Tsleil-Waututh Nation community are assessed on how vulnerable they are to the different climate induced coastal hazards.

## 4.1. Climate change context

Globally, the climate of the earth has been changing since the beginning of time. Glacial and interglacial periods have been occurring with colder and warmer climates over the past thousands of years. On a more regional scale at the pacific coast of BC, El Niño-Southern Osccillation (ENSO) and Pacific Decadal Oscillation (PDO) largely influence climate and marine conditions (Vadeboncoeur, 2016). Besides these natural climate change fluctuations, an anthropogenic element is added to the climate system. Human activities release so called greenhouse gasses into the atmosphere which is expected to cause the rise of the global temperature on earth. Increasing temperatures will affect the global climate and is also referred to as global warming (Bosboom and Stive, 2015). Next to this regional affects play an important role in climate change

For the TWN community the four major climate change forces have been identified by KWL: sea level rise, precipitation changes, air temperature changes, and ocean condition changes (Taleghani et al., 2020). For the scope of the project the climate change forces sea level rise and ocean conditions changes are elaborated in this chapter based on international, provincial and regional studies on global climate change trends and how these trends affect the Metro Vancouver area. Precipitation changes and air temperature changes are shortly elaborated in Appendix D.

### 4.1.1. Sea level rise

The global sea level has been rising over the past century and is expected to rise in the future increasing risks of coastal flooding, and erosion. The rising sea level is measured by determining the variability in relative sea level, which is the sea level measured relative to the land. The relative sea level consists out of the global sea level together with regional sea level variability's. The primary mechanisms determining the relative sea level are (Thomson et al., 2008):

- Changes in global ocean volume due to melting of ice caps, continental ice sheets and mountain glaciers.
- Global and regional changes in ocean volume due to thermal and salinity effects on water density.
- Regional variability due to changes in ocean and atmospheric circulation including variations in currents, wind and atmospheric pressure.
- Local changes due to vertical land motions caused by subsidence, post-glacial rebound and tectonic processes.

**Projected global mean sea level change**
The global mean sea level has been rising over the past century mainly due to the combination of thermal expansion of the oceans as it warms and the melting of continental glaciers and ice caps. The ocean responds slowly to climate change which will result in an ongoing rise of global sea water level for the coming centuries as thermal expansion of the oceans and melting of ice masses will continue (White et al., 2016). Based on worldwide tide gauges, corrected for the vertical land movement, the global sea level rose 1.7 millimeters per year on average over the 20th century (Thomson et al., 2008). This average has increased to 3.2 millimeters per year over the last two decades (although the estimates differ in scientific literature) and was determined by combining satellite and tide gauge measurements (Thomson et al., 2008).

In Figure 4.1 the projections of global sea level rise for the coming centuries is illustrated. The projections were made for the BC ministry of Environment as guidelines for sea dikes and Coastal flood hazards. The predicted sea level rise is moderate in the coming years until 2025. Afterwards the rate is predicted to increase more quickly until 2100 form whereon it will increase steadily. In the projections the wide range of uncertainty can be clearly seen including the low, mean and high projections. The red line in Figure 4.1 illustrates the recommended curve for sea level rise policy in BC which is 1 meter global sea level rise in 2100 and 2 meters for 2200 (Sandwell, 2011). The recommended global sea level rise curve is based on international studies on global sea level rise including the IPCC Assessment Report 4 from 2007 and US Army Corps of Engineers Planning and Design Curves from 2009. The recommended curve for Sea level rise policy is also compared with the IPCC special report on the Ocean and Cryosphere in a Changing Climate which was published in 2019 and predicts a rise in global mean sea level of 0.43 m under low greenhouse gas emissions scenarios and 0.84 m under high greenhouse gas scenarios in 2100 (IPCC, 2019). There can be concluded that the guidelines from the BC ministry of environment for the predicted amount of global sea level rise are slightly higher but approximately in line with the high greenhouse gas emissions scenario from the IPCC special report on the Ocean and Cryosphere in a Changing Climate .

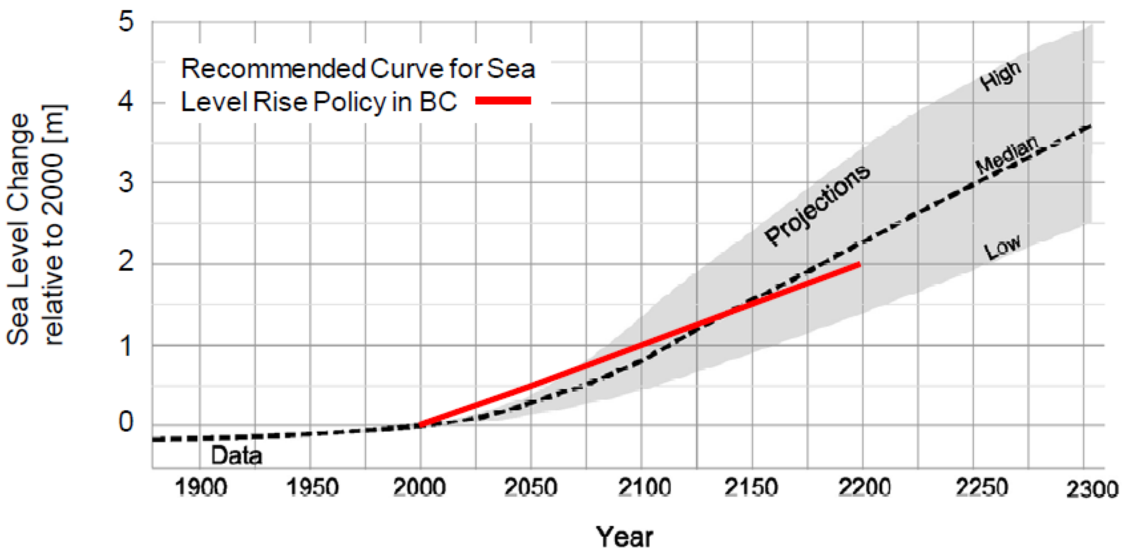



Figure 4.1: Recommended Global Sea level Rise Curve for Planning and Design in British Columbia (Sandwell, 2011)

**Projections regional sea level change metro Vancouver**
Regional sea level observations differ considerably from global sea levels due to regional processes including ocean volume changes due to water density differences, changes in ocean and atmospheric circulation and vertical land motions (uplift/subsidence). Therefore, the global sea level rise expectations must be adjusted for the regional factors. At the coast of British Columbia the crustal movements are in particular of importance for the regional sea level change due to post-glacial rebound and shifting

of tectonic plates in the BC region.

Along most parts of the British Colombia coast the relative sea level has risen over the last century. The future projections for regional sea level rise due to climate change in the BC region are discussed in the BC Sea level report (Thomson et al., 2008), which determines the regional sea level rise estimates on land subsidence/uplift in the Vancouver area in combination with a global sea level rise scenario of 0.3 m and an extreme scenario of 1 m global sea level rise for 2100. Current land subsidence/uplift measurements for the Metro Vancouver area differ for different measurements instruments with a subsidence of 0.3 mm/year measured with GPS and 1.2 mm/year uplift measured with a tidal gauge (Sandwell, 2011). More specific sources suggest neutral /uplift in most of the District of North Vancouver with local land subsidence areas along the north side of the Burrard inlet as illustrated in Appendix D.1.1. No specific data is available for the TWN project area, therefore, subsidence rates of 1 mm/year are assumed from the closest unfavorable subsidence shoreline location near the TWN project area. This would result in a relative sea level rise of 1.1 m in 2100. Additionally, sea level changes have been described more locally in the Burrard Inlet by Iggy George, elder of the TWN nation, at the Tsleil-Waututh Nation Climate Summit in 2018. In the past 60 years Nation members have observed high tides increasing from 13 feet in 1959 to 16.7 feet in the most recent years, which is equivalent to an increase of 1.13 m in sea level (George and Hyland, 2018).

### 4.1.2. Ocean condition changes

The changing climate is effecting the world's oceans, which absorb solar heat and carbon dioxide and receive freshwater inflows from the land. This results in changes in the ocean including ocean acidification, salinity changes, increasing water temperatures and shifting ocean circulation patterns

**Ocean acidification:**

Ocean acidification is the long-term change in ocean chemistry as carbon dioxide is absorbed from the atmosphere. Human activities have increased carbon dioxide emissions into the atmosphere over the past century resulting in the oceans absorbing more carbon dioxide than in the past. When carbon dioxide dissolves in the sea surface water it forms the weak acid called carbonic acid ($H_2CO_3$), which is unstable and breaks further down into bicarbonate ($HCO_3^-$), carbonate ions ($CO_3^{2-}$) and hydrogen ions ($H^+$), (Fisheries and , DFO).

$$CO_2(atmos) \leftrightarrow CO_2(aq) + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + H^+ \tag{4.1}$$

Resulting from this chemical reaction is an increase in hydrogen ions, which decreases the ocean pH level making it more acidic, and a decrease in availability of carbonate ions. The reduced availability of carbonate ions will especially cause harm to species that use calcium carbonate ($CaCO_3$) as a building block for their skeletons and shells. These species include clams, mussels, crabs, phytoplankton and corals that are at the base of the marine food chain causing limits for the food supply of larger organisms. Therefore, Ocean acidification can have major affect on marine life and coastal communities that depend on them (Denman and Macdonald, 2017).

Since the beginning of the industrial revolution the ocean uptake of carbon dioxide has resulted in a decrease of ocean surface water pH of 0.1, which is equivalent with a 26% increase in acidity measured as hydrogen ion concentration (IPCC, 2014). Further uptake of carbon dioxide emissions could result in a further decrease in global ocean surface water pH of 0.3 by 2081-2100, relative to 2006-2015 levels, according to high greenhouse gas emission scenarios (IPCC, 2019). Next to the global uptake of carbon dioxide by the ocean, causing global ocean acidification, regional factors play a role resulting in variability in acidification along the west coast of British Columbia. Examples include inputs from oceanographic physical processes such as coastal upwelling, river discharge containing organic carbon and nutrients, local $CO_2$ emissions and (industrial) wastewater. These factors can increase acidification locally compared to the global ocean surface water pH levels due to carbon dioxide uptake alone.

In the Burrard inlet there is evidence that the pH levels may have declined between the years 1950 and 2010. During this period the pH level range shifted from 7.8-8.1 in the period of 1954-1974 to 7.3-

7.9 in the period of 1974-2010 (Marliave et al., 2011). This is inline with the observations from the TWN community who have been observing pH declines over the past decades. Next to decreasing pH levels by global uptake of carbon dioxide, the increase in permitted industrial discharges in the Burrard Inlet potentially contributes to the observed decrease in pH levels (Hyland, 2018). The permitted industrial discharges into the Burrard Inlet have gone up 25 times in volume since 1975 (Alliance, 2003). Additionally, the Burrard Inlet pH is affected by inflow from the Indian Arm which has a natural lower pH level due to the depth of the Indian Arm (Figure 4.2) leading to longer residency times for the deepest water layer of approximately 3 years. This causes the deep water to become anoxic and more acidic (Allen, 2018). As pH levels are falling below 8.0 in the Burrard Inlet shell formation can be disrupted causing shell dissolution, low growth rates and juveniles to die (Allen, 2018) (Barton et al., 2012). Arguably the most culturally important species at risk for the TWN nation are the marine calcifying bivalves; clams, cockles, oysters, mussels, and scallops. Shellfish were, and remain, an important portion of TWNs and Coast Salish peoples diets, ceremonies, social interactions and economy (Hyland, 2018).

**Effect on salinity**

Climate change effects on ocean salinity will vary globally depending on geographical location as ocean salinity is largely influenced by fresh water inputs and air and ocean surface temperatures (Whitney et al., 2007). Globally, areas with lower ocean and air surface temperatures and large freshwater inputs will have lower ocean salinity while areas with higher ocean and air temperatures, where evaporation dominates, and less freshwater input will have higher ocean salinity (IPCC, 2014). For the Burrard Inlet reduced salinity levels are predicted as freshwater inputs, from the Fraser River, Capilano River and Seymour River, and net-annual precipitation patters are expected to increase (Metro Vancouver, 2016).

Salinity in the Burrard inlet is strongly affected by runoff and precipitation with runoff the dominant factor (Davidson, 1973). At the outer basin of the Burrard Inlet freshwater runoff from the Fraser River creates a complex surface salinity distribution which is varies greatly with tide, wind and runoff conditions. For depths below 10 m salinity becomes quite uniform throughout the year at 29-30 ppt. During summer periods the lowest salinity levels occur with 10 ppt or less at the surface in the southwest of the outer basin where a tongue of low-salinity water from the Fraser River can be observed. Moving more northwards salinity's increase to 20 ppt at the surface of the north shore. During winter periods salinity drops to 25 ppt at the surface of the outer basin. Moving further into the Burrard inlet there is a gradual decrease in surface salinity from East of First Narrows to the head of Indian Arm regardless of the season. The salinity's also become more consistent due to mixing of the water column at the sills of First and Second Narrows with salinity ranges between 18-20 ppt during summer and 20-26 during winter. At the Indian Arm salinity's decrease further to 15 ppt at the southern entrance of Indian Arm to 10 ppt midway along the channel. Distributions in mid-channel section through Burrard Inlet can be found in Appendix D for summer and winter periods (Thomson, 1981).

**Ocean temperature changes**

Increased greenhouse gasses into the atmosphere is causing the rise of atmospheric temperatures. Oceans are storing an estimated 90% of the increase in heat energy of the climate system as a result of the greenhouse gasses causing the ocean temperature to rise. Globally the sea surface has increased at a rate of 1.1 degrees per century measured over 1971 – 2010 according to the IPCC which is similar to the warming trend along the west coast of Vancouver Island. Along the coast of BC monitoring stations have been measuring the sea surface temperatures over 1935 - 2014 showing different trends in increasing sea surface temperatures annually and seasonally. Seasonal temperature warming trends differ from a low of 0.7 degrees per century winter trend to a high of 2.2 degrees per century summer trend measured over 1935 – 2014. Annually averaged sea surface temperature trends differ from a low of 0.6 degrees per century to a high of 1.4 degrees per century. Sea surface temperature is expected to continue to rise in the coming century with an average global sea surface temperature increase of 0.6 degrees to 2 degrees in the top 100m of the ocean by the end of the 21st century. Local sea surface temperature warming trends may differ from each other and the global sea surface temperature increase due to local effects such as tidal mixing, local evaporation and precipitation rates and freshwater runoff from rivers (White et al., 2016).

**Effect on ocean circulation**

The Strait of Georgia and the Burrard Inlet are both estuarine systems with fresh surface water flowing out of the inlet overlying more saline water flowing in from the Strait of Georgia. Between first narrows and second narrows turbulent mixing occurs due to the shallow constrictions (Figure 4.2). Water flowing from the Indian arm mixes with more saline water from the Strait of Georgia resulting in colder and more saline surface waters between first narrows and second narrows while deeper waters become warmer and more fresh than they would be in a simpler estuarine environments. Additionally, the surface water flowing out of first narrows into the Strait of Georgia will encounter an area with fresh water inflows from the Fraser river and corresponding lower densities (Davidson (1973);Allen (2018)).

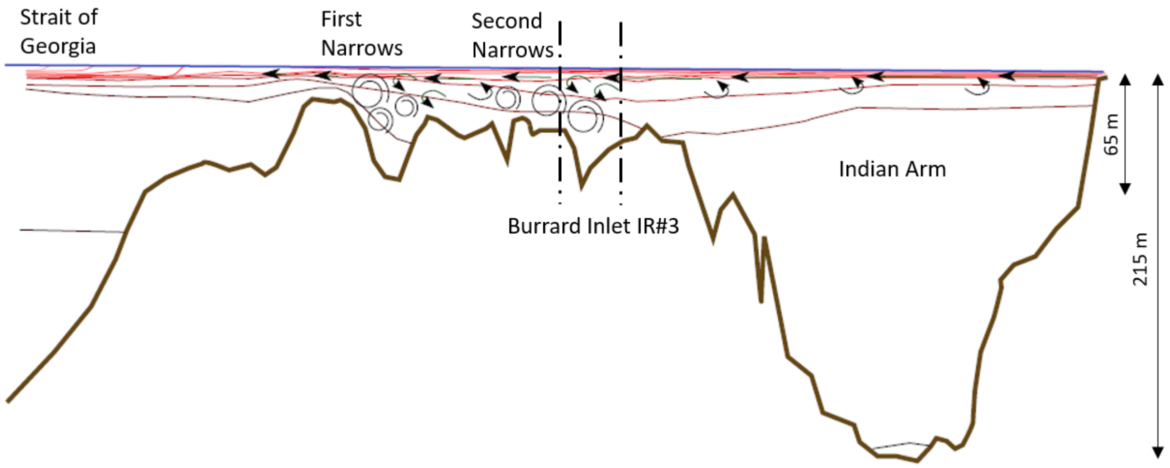



Figure 4.2: Circulation Burrard inlet (Allen, 2018)

Projections for the circulation pattern changes due to climate change in the Burrard inlet are hard to predict as circulations patterns are quite complex (Taleghani et al., 2020). Nonetheless, with the information provided in the previous sections about climate induced changes for the TWN nation well considered assumptions can be made. Current circulations in the Strait of Georgia may weaken due to increasing ocean surface temperature and freshwater input (from increasing precipitation and melting glaciers) which results in surface water become lighter and less dense than the colder more saline water deeper in the water column (IPCC (2019); White et al. (2016). The same prediction can be made for the Burrard inlet as freshwater inputs from the Fraser River, Capilano River and Seymour River are expected to increase (Section 4.1.2). As a result the water column becomes more stratified making it harder for mixing to occur between the warmer less dense surface water and cooler denser deeper water. Reduced mixing can lead to decreases in oxygen levels throughout the water column and further increases in surface temperatures which could have major consequences for marine life in the Straight of Georgia and Burrard Inlet (White et al., 2016).

Ocean pH levels, circulation patterns, temperature and salinity are import factors for marine ecosystem health and productivity. Long term changes in these factors could have major impacts on marine species and ecosystems which certain industries and human communities depend on. For example, higher sea surface temperatures are linked to changes Salmon distribution and migrating patterns, reduce food availability and effect the stability of the water column which effects ocean productivity through nutrient supply (White et al., 2016).

## 4.2. Hazard assessment

Climate change causes change in different events, such as the sea level rise, acidification, temperature changes in air and water and more. Some of those events could cause harm to the Tsleil-Waututh (TWN) reserve. Kerr Wood Leidal (KWL) has assessed thirteen different hazards for the TWN site. These hazards range from Wildfire to Coastal erosion. In Appendix D the steps that were taken to come up with hazards are explained. Most of these hazards fall outside the scope of this project. Therefore the decision was made, in consultation with KWL, to look into six out of the thirteen hazards that fall within the scope of this project. These are:

- Coastal flooding
- Coastal erosion
- Intertidal area change
- Ocean Acidification
- Harmful algae blooms
- Other ocean conditions (such as changing salinity and water temperature changes)

The first three hazards are assessed through analytical approaches such as erosion modelling. The other three hazards are assessed through literature review, global trends or online interviews. The focus of the hazard assessment was to identify and investigate the exposures within the scope of the project and to support the assessment of the vulnerabilities.

The amount of impact of the thirteen hazards on the TWN, taking the opinion of the TWN in account, is based on a vulnerability score. This assessment is called the vulnerability assessment. It describes how climate change-related hazards impact TWN and which of those elements is more concerning. This thorough assessment is done by KWL. In Chapter 4.3.1 the vulnerability assessment is done for six hazards of this project.

### 4.2.1. Coastal Flooding

The flooding of a low-laying land by seawater is possible via three different ways. These failure mechanisms are:
*Direct flooding*, where the sea height exceeds the elevation of the land, often where waves have not built up a natural barrier such as a dune system.
*Overtopping of a barrier*, where the barrier can be natural or human engineered and overtopping occurs due to swell conditions during storm or high tides often on open stretches of the coast. The wave height exceeds the heights of the barrier and water will flow over the barrier, flooding low-laying lands behind it.
*Breaching of a barrier*, where the barrier can again be natural or human made. Due the extensive hydraulic conditions, the barrier is broken down or destroyed allowing the water to flow land inwards.

The four main causes of coastal flooding are: *Tsunami's*, *Storm surge*, *Land subsidence* and *Sea level rise*. An explanation of most of these causes can be found in chapter 3.4. A quick recap follows.

- *Tsunami's*, often caused by seismic activities, can have a wave height up to 14m or higher and a length of hundreds of kilometers, causing them to travel with a shallow water wave speed of several hundred meters per second.
- *Storm surge*. Large offshore storms cause a wide range of waves, which will travel in groups to the shore. Such a storm also causes a low air pressure area which causes a shift in water level gradient, creating a *storm surge*.
- *Sea level rise* causes the base water level to be significantly higher. This creates a the new base water level where wind waves can even cause a flooding.
- *Land subsidence* cause the coastline to drop, creating a flood wave to have more impact on the shore. As explained in chapter 4.1.1, the determination of this land subsidence is not that easy. For the TWN site a governing land subsidence of 1 mm is assumed. The total subsidence is therefore 10cm in 100 years and 20cm in 200 years.

The water level arising from the combination of tide and storm surge is referred to as the predicted still water level. This water level is calculated in Appendix B and is the upper bound of the 90 percent confidence interval of the water level in 100 years and 200 years. This does not include wind and wave effects. Wind and waves impact can intensify the flooding but are limited in their effect on flooding of

areas setback from the shoreline (Taleghani et al., 2020).
As the TWN site is a sheltered area, tsunami is not a governing concern as explained in chapter 3.4.2. For the total flood still water level a safety factor in the form of the freeboard is introduced. Freeboard is a vertical distance added to water surface elevations to account for scientific uncertainty. A typical value of 0.6 m is used in British Columbia for flood risk management planning (e.g., for flood construction levels for new buildings). (Taleghani et al., 2020)
The total flood still water level is a combination of the predicted water level, sea level rise (SLR), local subsidence, and freeboard is the governing cause of a potential flooding:

$$\begin{matrix}\text{total flood}\\ \text{still water level}\end{matrix} = \text{predicted water level} + \text{local subsidence} + \text{sea level rise} + \text{freeboard} \tag{4.2}$$

These parameters are specified in the following table:

Table 4.1: Summation of events to get the Coastal flood still water level

| Scenario | Predicted water level [m] | Sea level rise (SLR) [m] | Local subsidence [m] | Freeboard [m] | Total flood still water level [m] |
|---|---|---|---|---|---|
| 1 m SLR | 2.630 | 1 | 0.1 | 0.6 | 4.330 |
| 2 m SLR | 2.667 | 2 | 0.2 | 0.6 | 5.467 |

These two governing flood-still-water levels of 4.330 m and 5.457 m are assessed with the help of the QGIS program. The assessment is visualised with flood maps in Figure 4.3.

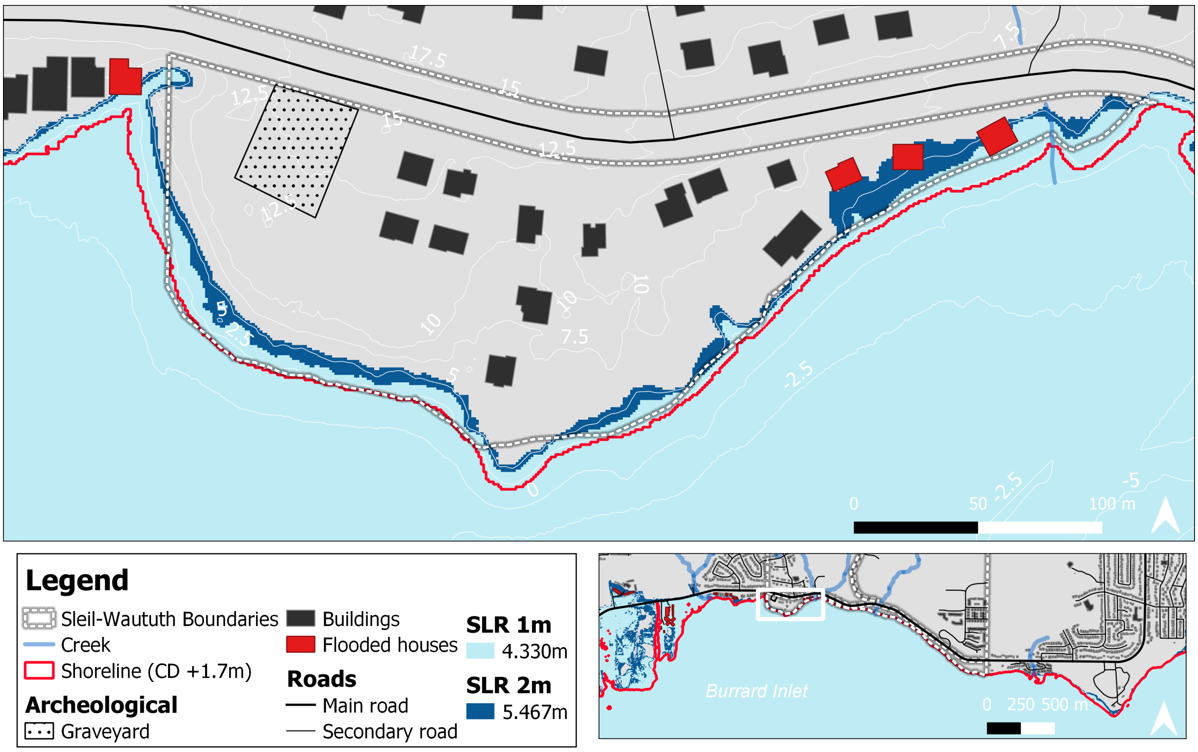



Figure 4.3: Flood levels for 1m SLR and 2m SLR, made with QGIS

The flood maps show that for a 1m SLR 1 structure within the reserve is considered vulnerable as it is located within the danger zone. For a 2m SLR scenario, a couple of structures within the TWN reserve are in the danger zone. Based on these results, the coastal still water flood hazard is considered low in relation to the other hazards. The cause of the low amount of danger lays in the steep topography of the shoreline, which is extended for a big part of the reserve.

With implementing climate change adaptation measures, TWN is limited by the boundaries of the reserve lands. This means for example that options to install flood defences that take up a lot of space on land are limited. Another flood defence option is retreat and relocating buildings on the reserve. This option is not only restricted due to reserve boundaries, but also difficult due to the fact that culturally significant areas such as middens and graveyards are hard to relocate. This is a unique challenge that many First Nations in BC face with regard to flood management (Hawker, 2020).

### 4.2.2. Coastal erosion

Erosion is the geological process in which earthen materials are worn away and transported by natural forces such as wind or water (Jeannie Evers, Emdash Editing (2012)). Erosion of the shore is mainly caused by hydraulic action, such as wind waves, ship waves, tide, etc. These hydraulic impacts cause earthen material to be transported from the shoreline into the surfzone. Human activities usually accelerate this process (Julien (2010)). For instance, the cutting of vegetation from the shoreline decreases the strength of the shore, which exposes the shoreline to erosion.
Another cause of erosion is land subsidence, which occurs due to the slow movement of tectonic plates or when large amounts of groundwater have been withdrawn from certain types of rocks, such as fine sediments (Loren Metzger, USGS, 2020).
Other human activities such as dredging, implementation of hard solutions and pipelines and deforestation are all enhancing the erosion risk of the shoreline.
Finally sea level rise amplifies the coastal erosion hazard by increasing the base sea level above which the wave effects occur (Taleghani et al. (2020)).

The concept of erosion described above is based on knowledge retrieved from scientific papers, books and scholars. A source whose concept of and experiences with erosion is not yet discussed, is the Tsleil-Waututh (see also 2.2). In an interview from the Tsleil-Waututh Nation Climate Summit 2018 with elder Iggy George and Hillary Hyland, Iggy states that in 1958 the maximum tide was 13 feet (3.96 meters) in January. In the past few years a maximum January tide of 16.7 feet (5.09 meters) was observed, which implicates an increase of 1.13m has occurred in the last 60 years.
Iggy also made comments about the amount of erosion, unfortunately not with specific time indications. He lost about 25-30 feet (7.62m-9.14m) of his western shore and 25 feet (7.62m) of his eastern shore to erosion. The end of the reserve even lost up to 100 feet (30.48m) to erosion. He ends this topic with the following sentence: "I heard about [...] rip rap against the beach, which stops certain growth and it stops things that fish need, but from our perspective, what we lost of our shore now, I would say is in the acres, and that is not going to be replaced" (George and Hyland (2018)).

Although no exact data is available for erosion rates the coastal erosion hazard for different locations at the project site is rated by KWL by the exposure to wind-generated waves and scarp slope. To better understand the project site and take a look at the erosion of the shoreline of the Tsleil-Waututh Nation a site visit was done. This site visit is described in Appendix K with the help of pictures to give an impression of the erosion of the shoreline at the project site. The scarp is clearly visible resulting from storm conditions and high water levels in combination with waves and shipwaves. This gives a good impression of the current erosion processes although research must be done to determine exact erosion rates.

### 4.2.3. Intertidal area change

The intertidal zone (sometimes referred to as the littoral zone) is the area that is exposed to the air at low tide and is underwater at high tide (the area between upper- and lower tide lines in Figure 3.4)(Beachpedia (2015)). As explained in chapter 3.3, the intertidal beach is important for the ecology in the area. The amount of tidal elevation and the shape of the beach due to grain sizes and bathymetry determine the ecology that is present in the intertidal zone, as is shown as well in Figure 3.4.

Sea level rise will raise the high tides and the low tides. The amount of runup of the tide on the shore depends on the slope of the shoreline, which increases the more you get land inward. The high tide will therefore increase less than the low tide. This is called the *'Tidal Squeeze'*. When the intertidal area decreases, the ecology that lives in this area looses a part of the intertidal habitat. The tidal squeeze can be caused by SLR, an increase of the storm frequency and it can be a consequence of the built of a hard structure. For the determination of the tidal squeeze two maximum tides (HHWLT/LLWLT) and the average tides (HHWMT/LLWMT) are used for a comparison. The explanation of these tides is done in 3.4.1. The interdial zone is determined by subtracting the high and the low tides from each other. This gives us two main scenarios:

1. Max tide: The difference between the maximum tides (HHWLT-LLWLT) is 5.22m.
2. Mean tide: The difference between the mean high/low tides (HHWMT-LLWMT) is 3.27m.

These two main scenarios are investigated in the program QGIS with a sea level rise of 1m and 2m. This results in the total water levels compared to the 0m CGVD28 (Canadian Chart-datum), which are shown in table 4.2.

Table 4.2: The parameters used for MSL, Scenario 1 and for Scenario 2

| Scenario's | Tide | Without SLR | With 1m SLR | With 2m SLR |
|---|---|---|---|---|
| | MSL | 0.1 | 1.1 | 2.1 |
| 1) Max | LLWLT | -2.99 | -1.99 | -0.99 |
| | HHWLT | 2.27 | 3.27 | 4.27 |
| 2) Mean | LLWMT | -1.74 | -0.74 | 0.14 |
| | HHWMT | 1.49 | 2.49 | 3.49 |

The DEM data set, containing LIDAR data points per meter, shows the bathymetry. This is in meters compared to the 0m CGVD28, and is shown in Figure 3.1. From the DEM-data file the contour lines of the specific water levels could be subtracted, creating an area which represents the intertidal area. The total intertidal area for 0, 1 and 2 m sea level rise for the mean tide (HHWMT-LLWMT) is shown in each of the two figures. Figure 4.4 represents scenario 1 and Figure 4.5 represents scenario 2. Every scenario is divided in two sections, the mudflat and the rest of coastline of the of the TWN reserve, simply called 'reserve'. These sections are split up for the calculation of the tidal areas. If they were not divided, the tidal area would not give a representative value as the change of the intertidal area of the mudflat is a lot bigger than the change of the intertidal area of the rest of the reserve. This is due to the differences in slope

**Scenario 1**

The change of the intertidal area's is visible in Figure 4.4. The lightest blue color represents the tidal area 0m SLR. The slightly darker blue color represents the intertidal area with 1 m SLR. The dark blue color represents the intertidal area with 2 m SLR. In this picture it can be seen that with a 2 m SLR the intertidal area shrinks to almost half of the 0m SLR tidal range.

The area's of the tidal ranges, round to the nearest 100 $m^2$ are shown in table 4.3. In this table the area of the intertidal zones is shown. This is calculated with a python script. It can be concluded that the higher the SLR, the smaller the tidal area, the bigger the tidal squeeze. The fact that for a 2m SLR the mudflat is still quit large compared to scenario 2, is because the area increases due to flooding.

Table 4.3: Scenario 1. Intertidal area's for the mudflat, the reserve and there change due to SLR. Rounded to 100 $m^2$.

| SLR [m] | Mudflat [m$^2$] | Reserve [m$^2$] |
|---|---|---|
| 0 | 794900 | 119500 |
| 1 | 605000 | 86200 |
| 2 | 446500 | 78900 |

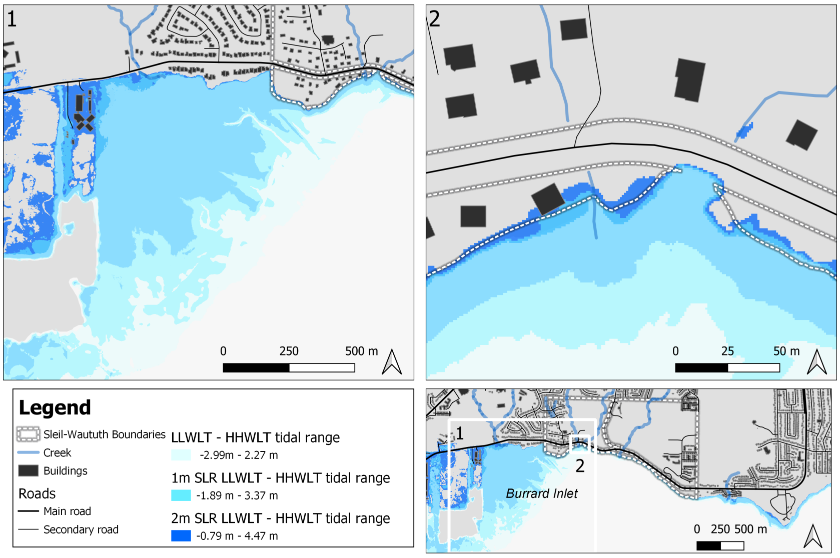



Figure 4.4: Scenario 1 Max: Maximum tidal range for 0m, 1m and 2m SLR. A tidal squeeze is visible

**Scenario 2**

Scenario 2 has the same layout as scenario 1, only now the HHWMT and LLWMT are shown. In this scenario the shrinkage of the intertidal zones is visible. The difference with scenario 1 is that scenario 2 is less extreme, this is as expected, as the high tides are higher and the low tides are lower.

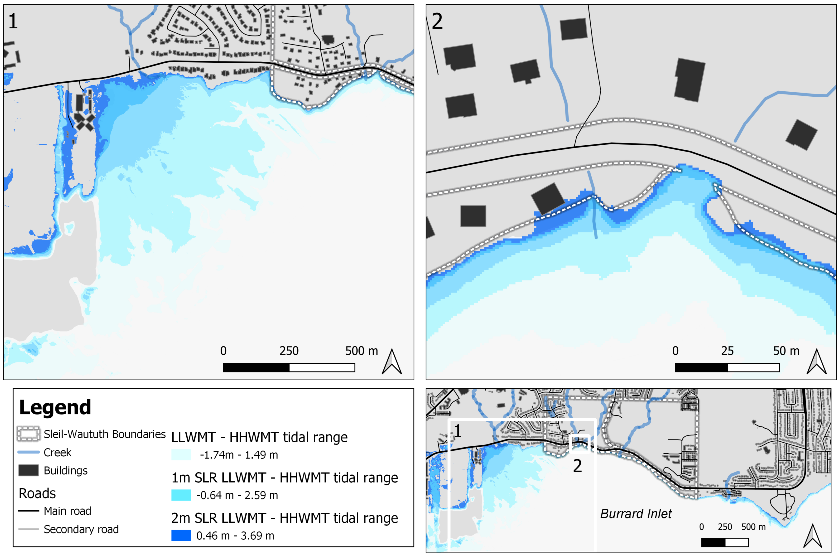



Figure 4.5: Scenario 2 Mean: Mean of the maximum tidal elements (HHWMT/LLWMT). Tidal range for 0m, 1m and 2m SLR. A tidal squeeze is visible

The area's of the tidal ranges, round to the nearest 100 $m^2$ are shown in table 4.4. The area's are decreasing as the sea level is rising, indicating a tidal squeeze.

Table 4.4: Scenario 2. Intertidal area's for the mudflat, the reserve and there change due to SLR. Rounded to 100 $m^2$.

| SLR [m] | Mudflat [$m^2$] | Reserve [$m^2$] |
|---|---|---|
| 0 | 513200 | 67900 |
| 1 | 343600 | 60200 |
| 2 | 149200 | 45300 |

### 4.2.4. Ocean Acidification

As elaborated in chapter 4.1.2, ocean acidification is the long term change in ocean chemistry as carbon dioxide is absorbed from the atmosphere resulting in decreasing pH levels. This process is enhanced due to increased carbon dioxide emissions into the atmosphere by human activities. Acidification in the Burrard Inlet can be enhanced due to local factors such as organic carbon from sewage and industrial waste water which volumes have gone up 25 times since 1975 (Alliance, 2003).

Water in the Burrard inlet is naturally quit acid due to mixing with waters from the Indian Arm. Additionally, Burrard Inlets waters are influenced by global ocean acidification and local factors enhancing this process resulting in substantial threats to the Burrard inlet ecosystem and diversity. Shell formation gets disrupted due to pH levels falling under 8.0 causing shell shell dissolution, low growth rates and juveniles to die. The Maplewood Mudlats, the beaches in front of IR #3, northeast of Roche Point, Bedwell Bay, and the south shore of Indian Arm used to have productive clam beds harvested by the TWN, but since the bivalve populations have declined by 80% since the 1970s these sites are now unused or unhabited. Contrary to the past when marine sources made up approximately 96% of TWN's protein uptake including clams and herring which used to be in abundance but now are considered a rarity (Hyland, 2018).

### 4.2.5. Harmful algae blooms

Algae blooms are a natural phenomenon that occur when there is a rapid increase in the population of algae in freshwater or marine environments due to the rise in water temperature as explained in section 3.3.3.

A fine line exists between an algae bloom and a harmful algae bloom (Taylor and Harrison (2002)): during an algae bloom, higher concentrations of nutrients are present in the water which means more food for fish, shellfish and aquatic vegetation. This does not pose an immediate threat on the ecosystem, but can indirectly harm humans: nutrients and biotoxins accumulate in bivalves. When the shellfish are consumed, these contaminants can cause paralytic or amnesic shellfish poisoning (Taylor and Harrison, 2002; NOAA, 2020; Government of Canada, 2020).

Algae blooms become harmful when the concentrations of algae reach a level where they cause fish to die, either by producing harmful toxins or by blocking the fish's gills, eventually suffocating the specimen (DH Vancouver staff, 2017). In the final phase of the algae bloom, the decay of the algae mass can deplete the waters of oxygen, to such an extent that the flora and fauna will decay as well, due to hypoxic water conditions - devastating the whole local ecosystem (NOAA (2020)).

As the temperature of the water in the Burrard inlet is increasing, as well as the salinity is expected to decrease (see next section 4.2.6), conditions for the formation of algae blooms are becoming more favorable. Change in nutrient levels caused by industrial and urban discharge into the outlet may also favor the conditions for algae blooms, but projected changes in discharge levels is not considered here. No harmful algae blooms have been recorded in the Burrard Inlet, and the event is considered rare. However, in the past decade, the frequency of algae bloom events has increased, implying a change in water conditions favoring the algae blooms is already happening (NOAA, 2020; Tiffany Crawford, 2019; Cory Correia, 2018; Matt Robinson, 2018; Strange Sounds, 2014).

### 4.2.6. Other ocean conditions

The ocean system is an interconnected aquatic system in which many factors influence each other. Both the salinity and the temperature of the waters in the inlet are projected to change. These two factors can for example influence the occurrence of algae blooms (see the previous section 4.2.5). The projected changes and implied hazards are discussed below.

#### Salinity

As explained in Section 4.1.2, climate changes imply reduced salinity levels at the Burrard Inlet due to increased freshwater input and increased precipitation patterns. A decrease of the salinity induces changes to the ecosystem conditions. As mentioned in Section 3.3, shellfish prefer salinity levels over 25 PSU. Also for other species lower salinity levels might induce problems. Section 3.3.3 gives the current salinity values which are around 29 to 30 PSU year round. Therefore it is concluded that salinity levels are not a hazard at the moment, but salinity levels need to be monitored as it might become a hazard in the future.

**Temperature changes**
Climate change is projected to increase the air temperature. The sea temperature is expected to follow this trend and increase in temperature of 0.6 to 2 degrees Celsius in the top 100m of the ocean by the end of the 21st century, as is explained in chapter 4.1.2. This water level rise is harmful in the way that it by itself could harm creatures that only live in a certain water temperature but it also causes a chain reaction of other harmful events such as: it can alter stream metabolism, rates of nutrient cycling, and reduction of dissolved oxygen concentrations, along with increased toxicity of certain environmental contaminants such as harmful algae blooms (GHa Nuel Lee, Kwan Leung & Hyemin Lee, 2020).

## 4.3. Vulnerability assessment

Not every hazard mentioned in Section 4.2 is as important to the Tsleil-Waututh. In this chapter the amount of impact that climate-related hazards have on the TWN is assessed in order to visualize the concern of those impacts.

### 4.3.1. Methodology

The vulnerability assessment is done by Kerr Wood Leidal and is designed by using a values-based approach. It focuses on a set of sectors and elements that the community is most concerned about. These are for example: shellfish, TWN community housing, beaches and shorelines, Social, Cultural and spiritual well being. Each element is assessed per hazard in a qualitative and quantitative way. This means that every element is rated for each of the thirteen hazards, resulting in a larger matrix of scores, shown in D.4. The sum of all the scores gives a final score per element. This number gives an indication of the vulnerability of an element due to the hazards that work on them. A ranking of the top ten scores is shown in Table D.1. From this table it can be concluded that the elements: 'Social, Cultural & Spiritual Well-being' together with 'Archaeological Sites' and 'Other cultural & Traditional use sites' are most vulnerable to the given hazards. This can be declared by the fact that almost all the hazards have an effect on these elements. The next three element in the top 10 are three types of marine animals: Shellfish, Salmon, Forage Fish. It shows that these animals are very vulnerable to climate change.

The results from the vulnerability assessment are based on a combination of expert judgement, community input, and spatial analysis to predict potential impacts on elements of the community. There is a high degree of uncertainty in these results. This is not a major concern as the results are considered as a starting point for more detailed planning and technical analysis. The assessment is a starting point to build on through future work as community priorities change and more information about climate change is discovered.

### 4.3.2. Scoping of the hazards and vulnerabilities

As mentioned in Section 4.2, only six hazards are considered within the scope of this project. However, when limiting to six out of the thirteen hazards there is a thread of excluding too many hazards. An example of this is that in this process the hazard 'Creek erosion' is neglected. Despite the fact that the Creek erosion is in close contact with 'the change of the intertidal area', which is a hazard that is included in the assessment. This is because the sediment that erodes from the river could end up within the intertidal zone, causing changes to that particular area.
The decision of excluding certain hazards is made based on the causes and consequences of hazards that are in the scope of this project.

### 4.3.3. Conclusion and remarks

A vulnerability assessment for the six hazards elaborated in Section 4.2, has been done with the relevant elements. An overview of the results of this vulnerability assessment is shown in Table 4.5

Table 4.5: Top 5 most vulnerable elements based on vulnerability score to the six out of the thirteen hazards

| Element | Vulnerability Score | Hazards associated with the element |
|---|---|---|
| Shellfish | 20 | Coastal erosion, Intertidal area change, Ocean Acidification, Harmful algae blooms, Other ocean conditions |
| Social, cultural, and spiritual well-being | 20 | Coastal flooding, Coastal erosion, Intertidal area change, Ocean Acidification, Harmful algae blooms, Other ocean conditions |
| Archaeological sites | 17 | Coastal flooding, Coastal erosion, Intertidal area change, Ocean Acidification |
| Forage fish | 16 | Coastal erosion, Intertidal area change, Ocean Acidification, Harmful algae blooms, Other ocean conditions |
| Salmon | 15 | Coastal erosion, Intertidal area change, Ocean Acidification, Harmful algae blooms, Other ocean conditions |

# 5

# Stakeholders and legislative framework

In this chapter the stakeholders that the Tsleil-Waututh Nation might have to work with or keep informed when implementing the project, are elaborated together with the legislative and jurisdictional framework they have to deal with to execute the project.

Executing changes to an area has an impact on different parties. All parties that may in any way have an interest (a stake) in a project are stakeholders. By focusing on understanding the characteristics of social networks and considering a range of perspectives, the likelihood of collective action and successful project management is increased (Richards et al., 2004).

To be able to assess all stakeholders, first the role of the client, TWN, is described. After that, the legislative framework of Canada and British Columbia, is to be known, together with all the jurisdictional parties involved in the TWN project. This is of great importance to determine the laws and guidelines that may in any way limit the project (Prell et al., 2009; Crona and Bodin, 2006). At last all stakeholders are assessed together with their interests.

## 5.1. Tsleil-Waututh Nation

Tsleil-Waututh Nation is an Indigenous community and government that currently occupies and governs the Burrard Inlet IR#3 reserve lands. The TWN government has six departments and an elected Chief and Council to serve and support its community (Tsleil-Waututh Nation, 2020a). The TWN Public Works Department addresses the housing and infrastructure needs of the Nation, while the TWN Treaty Lands and Resources Department addresses climate change action, habitat enhancement and restoration, archaeological and cultural sites protection and more. Community buildings, infrastructure and servicing, cultural sites, vulnerable populations, coastal lands, intertidal and foreshore habitat areas all have the potential to be impacted by climate change.

## 5.2. Legislative and jurisdictional framework

Canada's government consists of three levels; federal, provincial and local governments. The different levels of governments have different legislative rights and jurisdictions in Canada. The legislative framework and how their jurisdictions apply to the coastal shore line in British Columbia, in particular the TWN shore line, will be discussed in this section. An overview of the governmental levels and jurisdictional parties involved in the project is shown in Figure 5.1.

### 5.2.1. Government levels in Canada

Canada is governed on a national level by the federal Government who deals with areas of law listed in the Constitution Act 1867, which generally affect the whole country. The Tsleil-Waututh Nation fall under the federal government level according to the Indian Act. Scoping further down, Canada is subdivided into 10 provinces and three territories. The provinces have a provincial government which receive their power and authority form the Constitution Act 1867, whereas the territories have a territorial government who have powers delegated to them by the federal Government. They are in charge of regional matters such as education, health care and road regulations (Government of Canada, 2017). Lastly the third level of government are the local governments. Local governments run cities, towns or districts and are responsible for areas such as libraries, parks, community water systems, local police, roadways and parking. Local governments receive authority from the provincial or territorial governments (Parliament of Canada, 2020). In addition the province of British Colombia has regional districts which are federations composed out of municipalities, electoral areas and in some cases First Nations. The Metro Vancouver area is a good example of a regional district, which main goal is to collaborate together on region scale services such as drinking water, waste water treatment and solid waste management (British Columbia, 2020).

TWN works together and has agreements with the government of British Columbia (BC), Metro Vancouver Regional District (MVRD) and the District of North Vancouver (DNV) on matters such as park co-management agreements (all parties); water, sewer and garbage collection services (DNV).

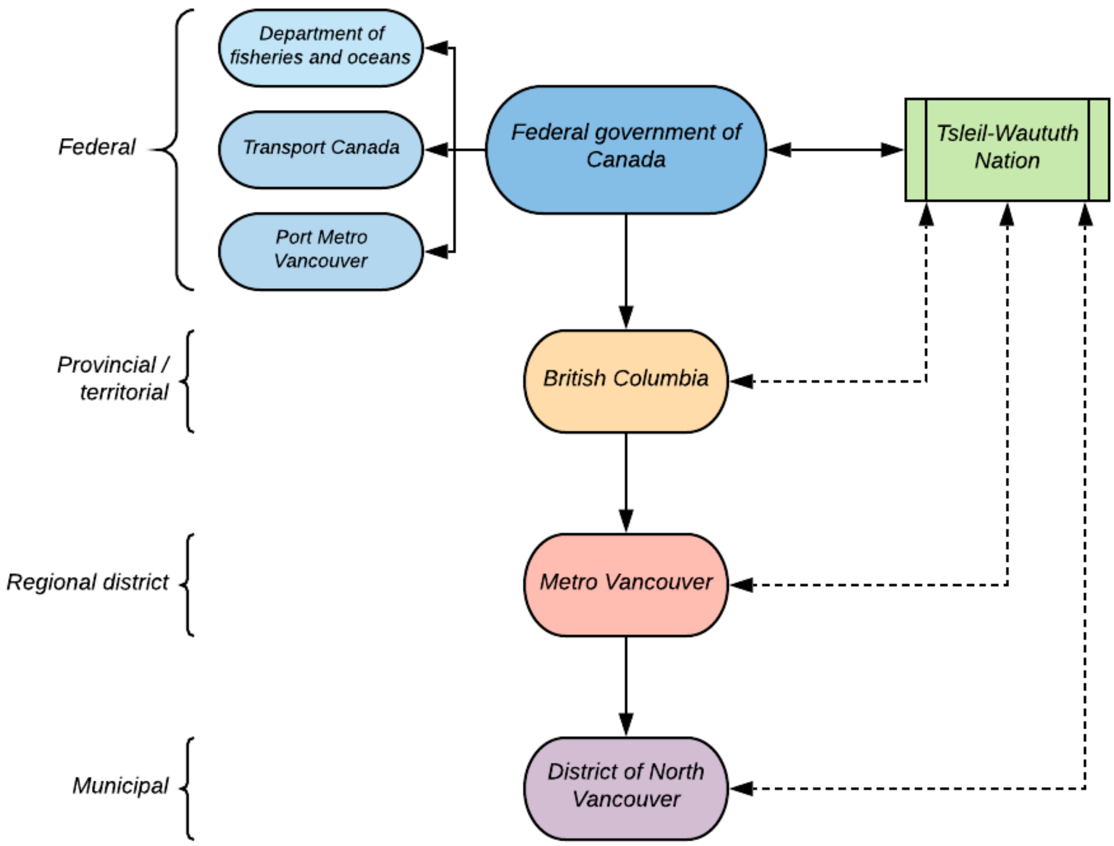



Figure 5.1: Overview of jurisdictional parties involved in the TWN project

### 5.2.2. Coastal shore jurisdiction BC

Managing the shoreline and marine environment in BC falls under many different legal authorities and regulations involving all the levels of government in Canada; federal, Indigenous (First Nations), provincial and municipal (local government). The complicated regulatory environment is illustrated in the infographic in Figure 5.2 (Carlson, 2018).

*The federal government* has jurisdiction over offshore waters from the low water mark out to 12 nautical miles along the outer coast. Under federal legislation, the federal department of Fisheries and Oceans is responsible for managing and protecting fish populations and fish habitat under the Fisheries Act, this also includes shoreline riparian habitats and maintaining maritime safety through the Coast Guard (Shores, 2009). The TWN must apply for a Fisheries Act Authorization for their proposed project. Transport Canada is responsible for preserving the public right of navigation under the Navigation Protection Act. The TWN has to receive an approval under the Navigation Protection Act. Port Authorities such as the Port of Vancouver are also under federal legislation to manage harbours and facilities that are federal Crown lands (Shores, 2009). The Burrard inlet waters at the TWN project site are under federal jurisdiction by the Port of Vancouver, as illustrated in Appendix E.1 and therefore the TWN must consult with the Port of Vancouver for the proposed project.

*The provincial government* of BC owns most of the foreshores in Canada with a few exceptions on privately owned foreshores granted historically by the Crown and some foreshores owned by the federal government, for example major harbours like the Port of Vancouver. The provincial government of BC also owns the beds of inland seas such as the Strait of Georgia, Juan de Fuca strait and Johnstone strait (Shores, 2009).

*Local government* such as municipalities and regional districts hold the authority to plan and regulate land use within their respective boundaries which may extend over foreshore and nearshore areas (Shores, 2009).

*First Nations*, such as the TWN, have authorities similar to provincial and local governments over upland and aquatic land within their reserve. Constitution Act 1982 section 35 provides constitutional protection to indigenous and treaty rights of indigenous people in Canada. Section 35 protects remaining aboriginal title to certain lands in Canada, aboriginal right to use lands for certain traditional purposes and rights conferred on indigenous peoples under historical and modern treaties. Provincial and federal Government have a constitutional duty to consult with the First Nations on any projected land use plans or projects which might affect their reserve and rights according to Section 35 of the Constitution Act 1982 (Shores, 2009). Besides the national indigenous laws the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) describes the rights of Indigenous peoples around the world. UNDRIP offers guidance on co-operative relationships with Indigenous peoples based on the principles of equality, partnership, good faith, and mutual respect. The Federal government of Canada fully supports UNDRIP together with some provinces in Canada. The federal government is taking measures to ensure that the laws of Canada are consistent with UNDRIP and implement a national action plan to achieve the objectives of UNDRIP (Fasken, 2020).

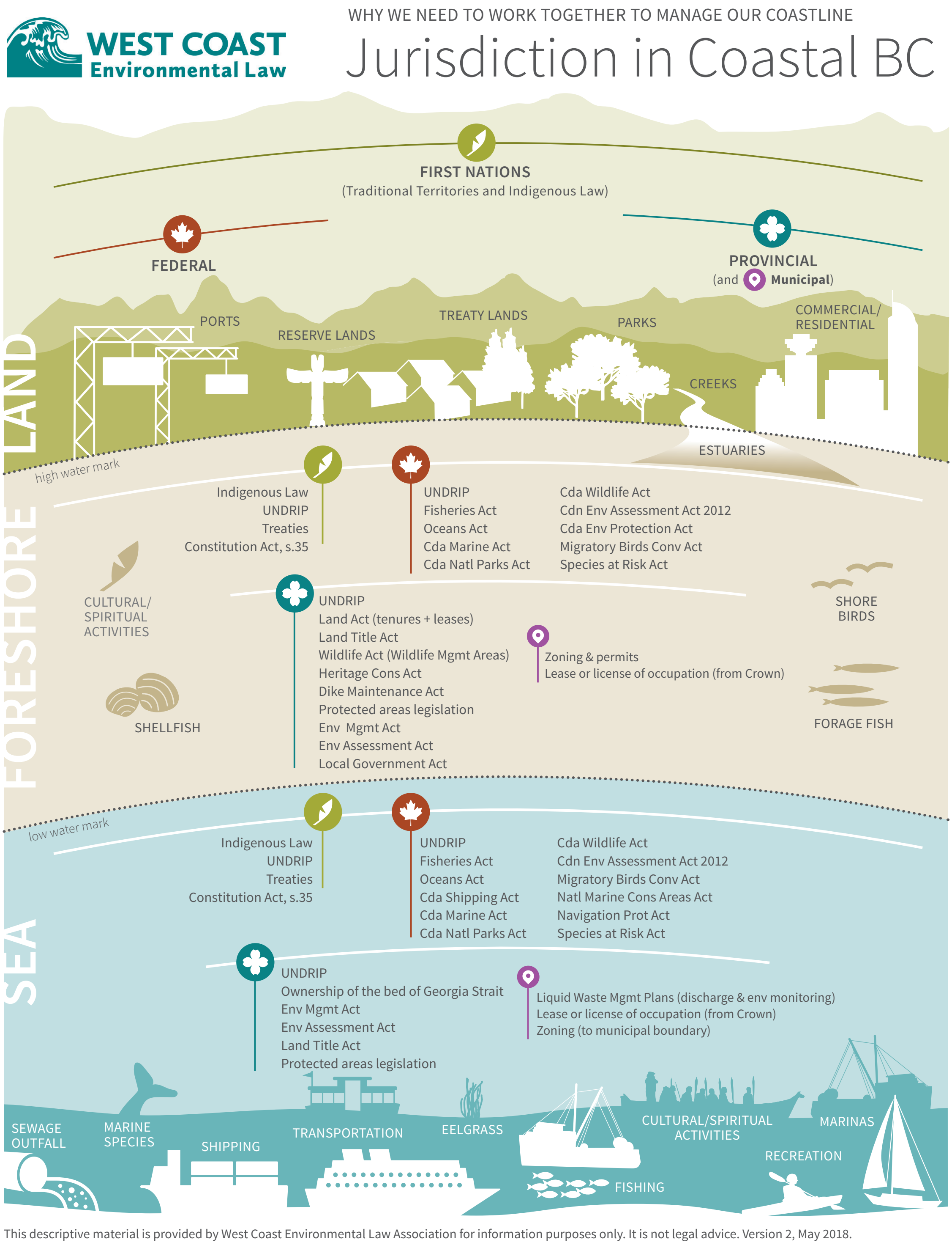



Figure 5.2: Jurisdiction Coastal Britisch Columbia (Carlson, 2018)

## 5.3. Stakeholders

All stakeholders involved in this project are listed in Table 5.1, together with their power and interest in the project. To provide a clear analysis of all the stakeholders, they are grouped based on their main interests. The groups that are distinguished are landowners, governments, transport services, employers, NGOs and society. It should be noted that some stakeholders contribute to multiple groups and are therefore mentioned multiple times. An overview of how each stakeholder is part of one or more groups is given in Table 5.1.

Table 5.1: Visualisation of how each stakeholder involved in the TWN project is part of one or more groups

| Stakeholders / Groups | Landowners | Governments | Transport services | Employers | NGOs | Society |
|---|---|---|---|---|---|---|
| **Federal Government** | x | x | | | | |
| **Metro Vancouver** | | x | | | | |
| **City of Burnaby** | | x | | | | |
| **Vancouver Port Authority** | | x | x | | | |
| **TransLink** | | | x | | | |
| **North Shore Emergency Services** | | | x | | | |
| **NGOs (from TWN)** | | | | | x | |
| **Union of BC Indian Chiefs** | | | | | x | |
| **District of North Vancouver** | x | x | x | | | |
| **Government of BC** | x | x | | | | |
| **Private or corporate owners** | x | | | | | x |
| **Tourism** | | | | | | x |
| **Fishing Industries** | | | | | | x |
| **Individual businesses developed by TWN people** | | | | x | | |

- **Landowners**
  In Canada most of the land (about 90 percent) is claimed by the Queen of Canada. This land is referred to as Crown land (Eidelman, 2016). The Sleil-Waututh reserve is managed by the First Nation itself. The surrounded area however, is not. As the surrounded area might indirectly be influenced by the implementation of measures against climate change hazards, these landowners are treated as stakeholders as well. From Figure E.2 it can be seen that the surrounded area consists out of Crown land, private, and corporate land (District of North Vancouver, 2020). The surrounding area consists predominantly of Crown land, which is subdivided in Crown land owned by the federal Government and Crown land owned by the Province. Metro Vancouver Regional District and the District of North Vancouver also own regional park, watersheds and other lands. The land on the other side of the Burrard Inlet is part of the City of Burnaby and is amongst others owned by private owners, corporate owners, Shell and the Crown (City of Burnaby, 2020). Although it is acknowledged that these parties might be influenced by a project executed at the shoreline of Burrard Inlet IR#3, they will not be taken into account in the scope of this project. The main interest of all landowners for this project is to preserve the land and preserve or even increase its value.

  – District of North-Vancouver
    *Manages most of the adjacent land (Taleghani et al., 2020; District of North Vancouver, 2020)*
  – Federal Government
    *Owner of the Maplewood Conservation Area (District of North Vancouver, 2020)*
  – Private or corporate owners
    *Multiple parcels adjacent to the TWN area are private or corporate ownership (District of North Vancouver, 2020)*
  – Government of BC (BC Ministry of Transportation)
    *Owner of the Dollarton Highway (Taleghani et al., 2020)*

- **Governments**
  This group accounts for all stakeholders whose permission is needed for the execution of a project within or around the Sleil-Waututh area. The function of each governmental stakeholders listed below, is explained in Section 5.2. The main priorities of the federal, provincial and local government agencies are that the final measure for this project causes minimum disturbances and does not negatively influence livability, safety or attractiveness of the area. The governments role is elaborated in Chapter 5.2.
  - TWN government
  - Federal Government (Department of Fisheries and Ocean)
  - The Vancouver Fraser Port Authority
  - Government of BC
  - Metro Vancouver
  - District of North-Vancouver
- **Transport services**
  All stakeholders in the group of transport services take care of the infrastructure within the reserve. Some of the roads, including Dollarton Highway, are located close to the shoreline and thus might be affected by coastal erosion hazards. Therefore some of the transport serving stakeholders have an interest in the project. All of the transport servicing stakeholders might have a power in facilitating construction traffic.
  - Government of BC (BC Ministry of Transport)
    *Owns the Dollarton Highway.*
  - District of North-Vancouver
    *Providing support for road maintenance including snow clearance (Taleghani et al., 2020)*
  - North Shore Emergency Services
    *Together with the District of North-Vancouver they are responsible for the emergency services including fire fighting and ambulance (Taleghani et al., 2020).*
  - Vancouver Port Authority
    *The Vancouver Port Authority provides navigation and transport within the Burrard Inlet and therefore has a stake in changes made in the water area*
  - TransLink
    *Provides the bus transportation along Dollarton Highway*
    *Vancouver's regional transit authority established by the provincial legislation, but overseen by a council of mayors across the region, operates a revolving land account that the agency uses to raise operating revenues via asset sales or development partnerships (Eidelman, 2016; Translink, 2020).*
- **Employers**
  For all employers that are active within the Sleil-Waututh reserve, the TWN organization is distinguished from the individual business developed by TWN. The organization and the individual business cooperate however, to acquire new lands for the community and share profits to support TWN's programs and services for its members (Tsleil-Waututh Nation, 2020b). The individual businesses will be shortly elaborated and after will be referred to as one group. All employers present in the reserve in general have interest in solutions that attract more people to the area. Even though their power as employers to influence the project is little, they should be managed within the project.
  - Inlailawatash
    *Provides cultural and renewable resource services to Aboriginal and crown governments, communities, private-sector and non-profit organizations. Services include vegetation management, ecosystem restoration, archaeology, mapping and information management, renewable resource management*
  - MST Development Corporation
    *Historic partnership between Musqueam, Squamish and Tsleil-Waututh Nation (Section 2 to regain ownership of traditional lands (Tsleil-Waututh Nation, 2020b)*

  - Takaya Developments
    *Real estate development company (Tsleil-Waututh Nation, 2020b)*
  - Salish Seas *Partnership with Musqueam and Tla'amin Nations; leases commercial fisheries licenses and harvest fisheries products (Tsleil-Waututh Nation, 2020b)*
  - Tackaya Golf Center
    *North Vancouver's largest range (Tsleil-Waututh Nation, 2020b)*
  - SPAL Constructors
    *Project management company to establish joint ventures with companies offering construction services (Tsleil-Waututh Nation, 2020b)*
  - Takaya Holdings
    *A distributor agreement for beachcomber branded hot tubs and related products (together with EMC Business solutions)*
  - Takaya Tours
    *The only First Nations kayak and canoe tour business in the Lower Mainland, leading cultural tours in traditional style canoes for people from around the world (Tsleil-Waututh Nation, 2020b)*
  - TWN Community Centre Rentals
    *Offers attractive rental space for banquets, meetings, gatherings, rehearsals, and storage*

- **NGOs**
  Non-governmental organizations are all voluntary citizens' groups with a common interest trying to achieve social or political aims (Willetts, 2002). Which NGOs are of importance for the project and the amount of power and interest they have are significantly dependent of the eventual project.

  - TWN
    *TWN has several groups that can be seen as NGOs; the TWN community garden (engages TWN youth in healthy food and lifestyle), Child and Family Development Centre (promotes healthy development in children, families and the community) and several others. (Tsleil-Waututh Nation, 2020c)*
  - Union of BC Indian Chiefs (UBCIC)
    *An NGO that aims to work towards the implementation, exercise and recognition or the inherent Title, Rights and Treaty Rights of Aboriginal People in BC and protect the Lands and Waters through the exercise and implementation of their own laws and jurisdiction (Union of British Columbia Indian Chiefs, 2020). Therefore this NGO is not involved in this project particularly, but has interest in projects that influence the Lands and Waters of Aboriginal People in general.*

- **Society**
  The society in this project can be seen as all individuals that share the same geographical or social territory. These are all inhabitants, but also visitors of the area. They are affected by changes in land use causing changes in space, resources and the possibility to practice activities.

  - Private or corporate owners
    *Inhabitants of the area have interest in an increased value of the area*
  - Tourism
    *An increased value of the area, will attract more tourists. However, their power to influence this project is none as is their interest since they are not bounded to the reserve*
  - Fishing industry
    *The amount of fish present in the Burrard Inlet depends on the water conditions. These conditions might be influenced by the project and thus the fishing industries have an interest in the project.*

# II

# Part 2 - Outline of alternatives

# Executive summary of part I

The reserve of the Tsleil-Waututh Nation (TWN), Burrard Inlet IR#3, located at the north shore of the Burrard Inlet, is strongly influenced by climate change. This leads to shoreline erosion inducing loss of land and infrastructure, ecosystem changes and exposure of historic sites with cultural value. TWN retained Kerr Wood Leidal (KWL) to determine coastal erosion and climate change hazards.

An extensive area analysis is done, including a study of the community context of the TWN. The TWN is a First Nation that has lived in harmony on the lands and waters of the Burrard Inlet since time out of mind. They are, amongst other First Nations, part of an Indigenous tribe called the Coast Salish People. The Coast Salish have strong spiritual, cultural and economic ties with the lands in and around the city of Vancouver.

Because of the sacred obligation to be caretakers of the lands and how these lands are impacted by climate change, the TWN has taken initiative to reduce these impacts and preserve the land for future generations (Taleghani et al., 2019). The existing conditions are investigated from a technical, environmental and sociological point of view.

The shores and waters of the Burrard Inlet are subject to intensive development, including shipping, industry and residential buildings. The shorelines of the Sleil-Waututh Nation reserve are characterized by sandy and muddy flat beaches. The hydrodynamic conditions at the shoreline of the project site depend on the combined effects of tide, storm surge, sea level rise and (wind-induced) waves. The tides are semi-diurnal and with data from the CHS Vancouver station (7735) in the Burrard Inlet, a tidal range of 5.3 meters is determined. The dominant wind direction is East, which leads to a wind-wave climate also dominated by easterly waves. A wave buoy from Marine Labs has been measuring wind and wave data in front of the project area. Many vessels pass the Burrard Inlet IR#3 everyday and can therefore in combination with high water levels also cause erosion at critical locations, on a daily basis.

Climate change causes change in different events, such as the sea level rise, acidification and temperature changes in air and water. KWL has assessed thirteen different hazards for the TWN project site. Not all hazards are relevant for the scope of this study. In consultation with KWL the following hazards are assessed: coastal flooding, coastal erosion, intertidal area change, ocean acidification, harmful algae blooms and other ocean conditions.

Tsleil-Waututh Nation is an Indigenous community and government that currently occupies and governs the Burrard Inlet IR#3 reserve lands. The TWN government has six departments and an elected Chief and Council to serve and support its community. Community buildings, infrastructure and servicing, cultural sites, vulnerable populations, coastal lands, intertidal and foreshore habitat areas all have the potential to be impacted by climate change. Managing the shoreline and marine environment in British Columbia falls under many different legal authorities and regulations involving all the levels of government in Canada; federal, Indigenous (First Nations), provincial and municipal (local government).

# 6

# Alternatives overview

The problem outline and the existing conditions are explained extensively in Part I. In Part II different alternatives for these problems are posed and explained. The advantages and disadvantages of each solution will be discussed as well as the technical, environmental, economical, legislative and social feasibility. The four alternatives that will be discussed are:

- Alternative 1: Rip rap revetment
- Alternative 2: Salt marsh
- Alternative 3: Clam garden
- Alternative 4: Nourishment

## 6.1. Scoping alternatives

These four alternatives are a conclusion from a mind map made in a brainstorm session. This process began by drawing thought spins about solutions on a drawing board. After some time, similar ideas were grouped and regarding the determined hazards in Chapter 4.2, resulted in four different alternatives: a nourishment, a revetment, tidal ecosystem rehabilitation and an offshore alternative. These were then worked out further and eventually four alternatives were investigated.

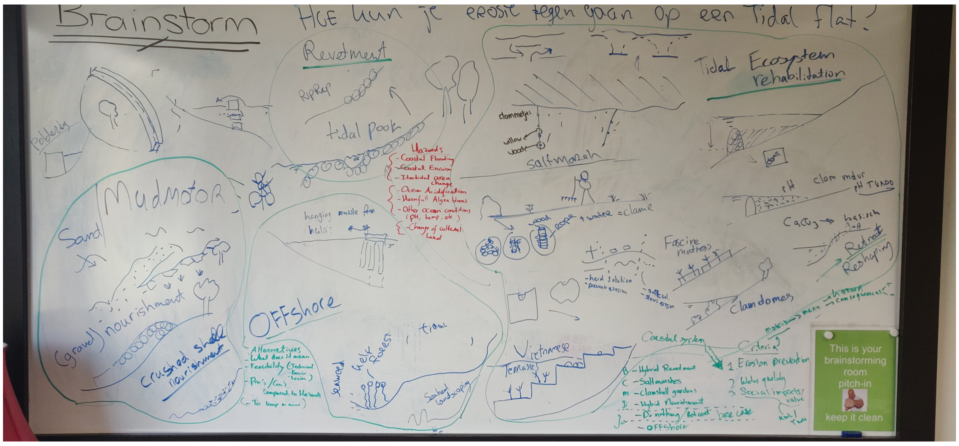



Figure 6.1: Mind map made in the brainstorm session. Different alternatives were grouped with a green circle resulting in four alternatives

Within the building with nature concept a good balance has to be found between 'building nature', which sometimes damages nature and 'redeveloping nature', which aims to keep the existing nature as intact as possible when enhancing the ecological area. The nourishment is an alternative that aims to build with nature (sand), and therefore provides a habitat in the long term but does significant harm to the existing nature. The clam garden and the salt marsh do try to keep the existing nature as intact as possible and try to enhance the ecosystem services. The revetment contains the least amount of aspects of building with nature, but is expected to be a cheap and effective solution.

## 6.2. Governing cross sections

For the design and the evaluation of the alternatives, two governing cross sections are chosen. These are: 'the Canoe shed' and 'Big John Creek'. These cross sections were chosen based on the shape of the cross section and the vulnerability to erosion.

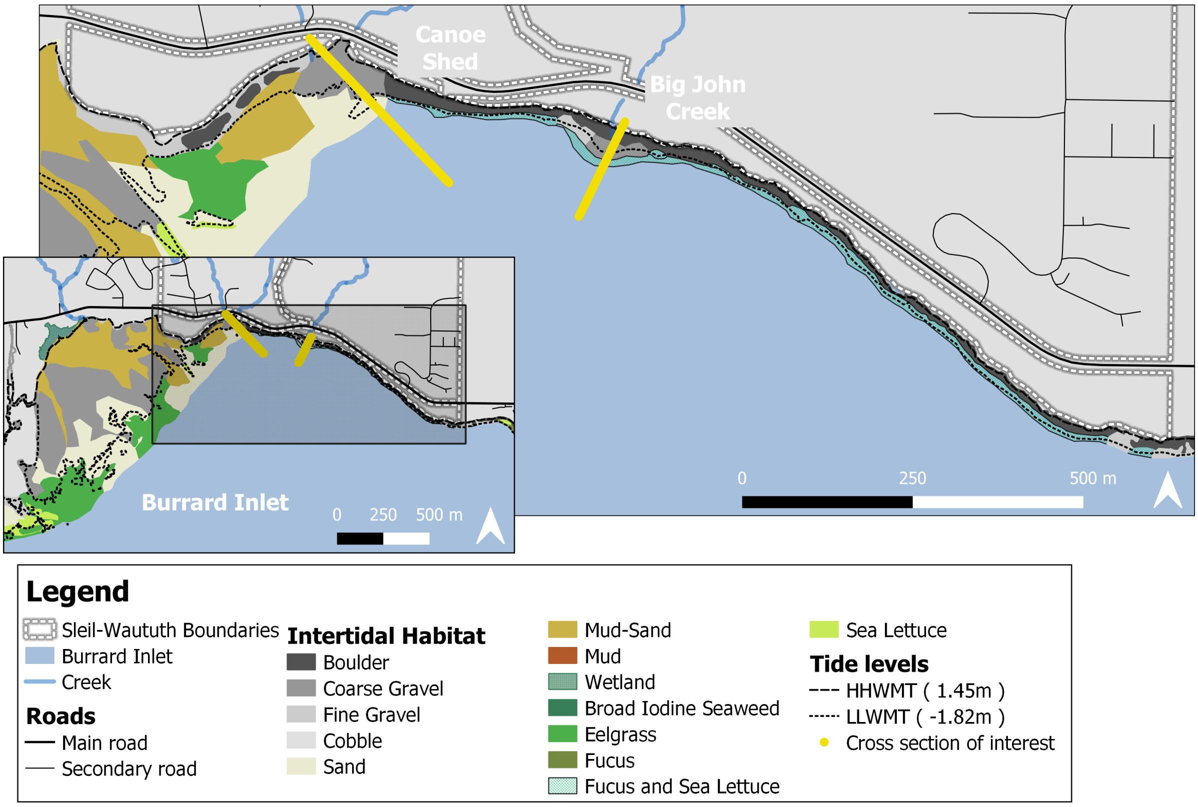



Figure 6.2: Overview of the two governing cross sections. West the Canoe Shed cross section and right the Big John Creek cross section

The shape of the coastline of the project location has two different profiles. One steeper profile with a steep scarp and one flatter profile containing a large tidal flat and a steeper scarp at the end of the cross section. These scarps are caused by erosion as explained in Chapter 4.2.2.

The Canoe shed (CS) contains a medium slope of 1:5 from 0m to 40 m, a flat slope of 1:20 from 40 m until 160 m and a tidal flat of circa 100 m between low tide (LLWMT) and mean sea level (MSL). After that a steep slope/cliff of 1:2.5 just in front of the canoe shed, shown in figure 6.3. This represents a longer flatter cross section and is situated next to the mudflat, adjacent to the TWN reserve as shown in figure 6.2.

Big John Creek (BJC) contains a medium slope of 1:5 from 0 m to 80 m, then there is 20 m of flat surface which is most likely a measurement error, followed by a flatter slope of 1:10 which finally increases to a steep scarp with a slope of 1:2.5. The difference with the CS cross section is that Big john Creek does not have a 100 m tidal flat and is therefore a lot shorter as is shown in figure 6.4. Also the cross section is considered to be a steep representation and it is situated about halfway the TWN-reserve.

For each of the following alternatives the design is made in one or both of these cross sections, depending on the design criteria of the alternative. Then a model is made with the program XBeach, to evaluate the effectiveness of the alternatives.

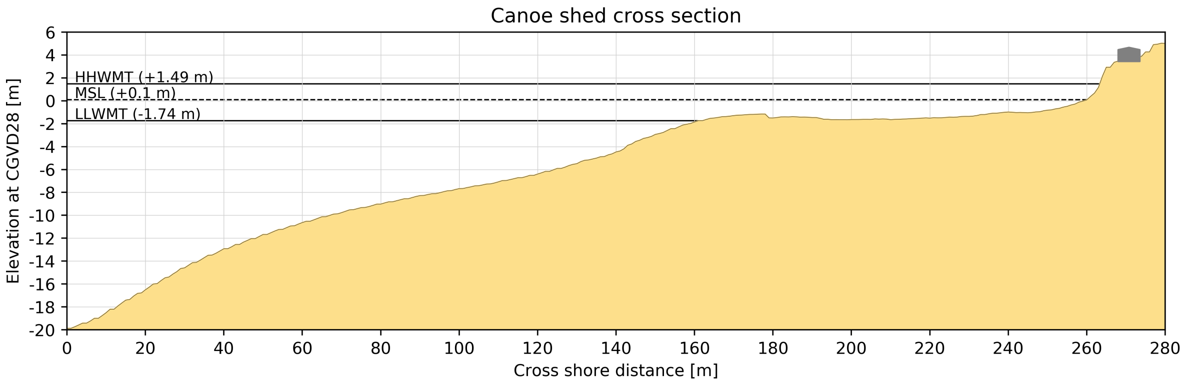



Figure 6.3: Canoe shed cross section. In the top right of the image the grey canoe shed is drawn to scale. A tidal flat of 100 m between low tide (LLWMT) en mean sea level (MSL) is visible

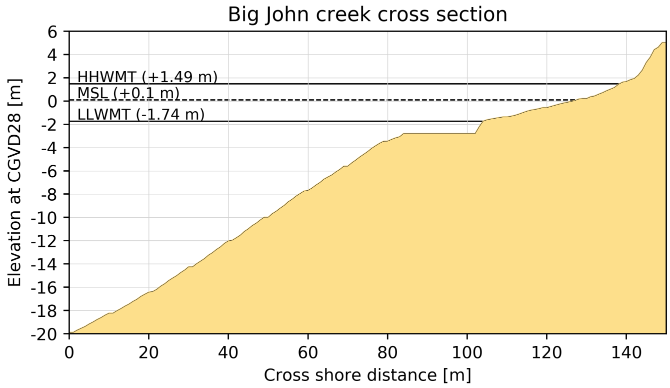



Figure 6.4: Big John Creek cross section. A small measurement error is visible at -2.8m in the form of a flat surface

## 6.3. Boundary conditions

Apart from the governing cross sections, two scenarios were made to test each alternative. One scenario is based on a storm event that is likely to happen at this moment in time and is chosen specifically to test the alternatives on the existing conditions. The second scenario is chosen to see what would happen with the alternatives if they are exposed to an extreme event in the future, including a SLR of 1 m. It is chosen to not take land subsidence into account as the determination of land subsidence at TWN is very uncertain, see Chapter 4.1.1).

### 6.3.1. Scenario 1

Scenario 1 is an event that is likely to occur at this moment in time. It is defined by a wave height with a return period once every 10 years. That design wave that statistically occurs at the TWN coast once every 10 years, has a deep water wave height of 1.03 m. This is calculated in Chapter 3.4. For the tide the Higher High Water Mean Tide is taken. As this event is for this moment in time, the SLR is set at 0m, and the mean sea level is 0.1 m. So this results in the following input parameters:

Table 6.1: Parameters used in scenario 1

| Input parameter | Value |
|---|---|
| Mean sea level (MSL) | 0.1 m |
| Higher High Water Mean Tide (HHWMT) | 1.49 m |
| Sea level Rise (SLR) | 0 m |
| Significant wave height (Hs) | 1.03 m |
| Peak wave period (Tp) | 3.92 s |

### 6.3.2. scenario 2

Scenario 2 is a future design scenario with an event statistically happening once every 200 years. A combination of an extreme storm event (less likely to happen) and a SLR of 1 m is taken into account. This contains a design wave height of 1.19 m. The 200 year wave is chosen because of the design criteria of the revetment, which will be further elaborated in Chapter 7.

Table 6.2: Parameters used in scenario 2

| Input parameter | Value |
|---|---|
| Mean sea level (MSL) | 0.1 m |
| Higher High Water Mean Tide (HHWMT) | 1.49 m |
| Sea level Rise (SLR) | 1 m |
| Significant wave height (Hs) | 1.19 m |
| Peak wave period (Tp) | 4.17 sec |

To conclude, four alternatives will be designed for the TWN reserve to cope with the existing hazards. The design is done for two representative cross sections. Using the hydrodynamic features of Xbeach, the effects of the different alternatives and scenarios will be calculated and evaluated.

## 6.4. Base case: XBeach

XBeach Deltares (2012) is a two-dimensional model for wave propagation, long waves and mean flow, sediment transport and morphological changes of the nearshore area, beaches, dunes and backbarrier during storms (Consortium of UNESCO-IHE, Deltares, Delft University of Technology and the University of Miami (2020)). Erosion at the TWN site is morphological process that can be modelled with XBeach, but the program has a maximum grain size input of 0.8 mm. Deltares (2015). This means that morphodynamic results of the existing sand/gravel beaches at the TWN reserve can not be modelled correctly. Therefore, wave energy is chosen as an indicator for the amount of erosion at the shoreline. This is possible since the relation between wave energy and erosion is considered to be linear (Nicoletta Leonardi and Fagherazzi (2016),Carolyn A. Currin and Malhotra (2016)). Because of the amount of models that had to made and the complications that come with 2D models, only 1D models will be executed.

The input files for the program are made by using the coding program Matlab. First, the bathymetry is loaded into the program and plotted to validate the correctness, shown in figure 6.5.

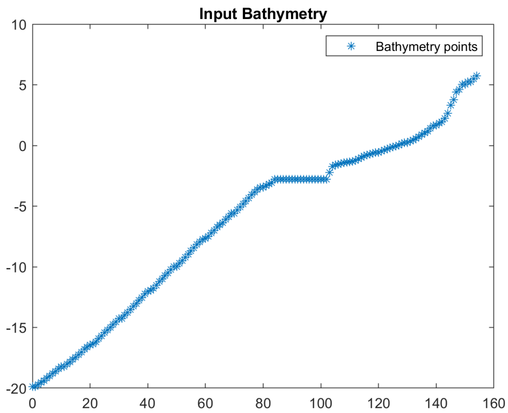



Figure 6.5: Example of the bathymetry of the Big John Creek cross section that has been put into the XBeach program

The grid applied is a staggered grid, where the bed levels, water levels, water depths and concentrations are defined in cell centers, and velocities and sediment transports are defined at the cell interfaces. In the wave energy balance, the energy, roller energy and radiation stress are defined at the cell centers, whereas the radiation stress gradients are defined at u- and v-points. Consortium of UNESCO-IHE, Deltares, Delft University of Technology and the University of Miami (2020). To reduce the computation time of the program the amount of calculations is reduced by reducing the amount of grid points in offshore conditions and slightly increasing the amount of grid point around the shoreline. The bathymetry result is shown in Figure 6.6.

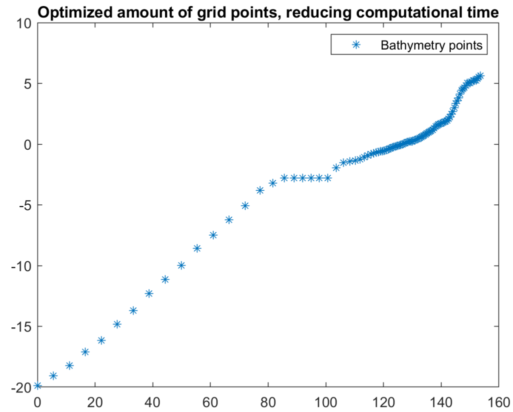



Figure 6.6: Example of the bathymetry with reduced offshore grid points and slightly increased grid points around the shore line to reduce the computation time

Next the general input parameters are defined. These input parameters will not change during different runs of XBeach. These parameters are shown in figure 6.7 and concern the model time, time interval, the boundaries of the model, density of seawater, wave spectrum parameters,etc. It is important to note that the tide is assumed as a static water level instead of a varying water level. Due to this input parameter, the timespan of the event is set to 9000 seconds. If the duration of the storm event would have been larger, a varying water level should have been imposed. The general input parameters are shown in Figure 6.7.

```
%% 5) General Model settings
% Directly save model settings in XBeach structure
params_struc = xb_generate_settings('zs0',zs0,...
    'front','abs_1d','left','wall','right','wall',...
    'sedtrans',0,'morphology',0,...
    'rho',1025,'random',0,...
    'D50', 0.0008,...
    'thetanaut',1,'thetamin',180,'thetamax',360,'dtheta',20,...
    'tstart',0,'tstop',9000,'tintg',1,...
    'outputformat','netcdf',...
    'nglobalvar',{'H','zs','u','zb','E'},...
    'nmeanvar',{'H','zs','E'});
```

Figure 6.7: General input parameters for XBeach, defined with Matlab

Then the scenario input parameters nee to be determined, as is explained in Chapter 6.3. These contain mean sea level, tide (imposed as water level), sea level rise, spectral wave height and peak wave period.

Finally, possible vegetation could be implemented by determining four parameters per vegetation sort:

- ah = vegetation height (m)
- bv = stem diameter/blade width (m)
- Nv = density (units/m2)
- Cd = drag coefficient (-)

This results in the final bathymetry setup:

These files are saved in the correct form and XBeacx is ready to run the simulation. After this, the output file is opened in Matlab and graphs are made to see the results of the wave energy dissipation,

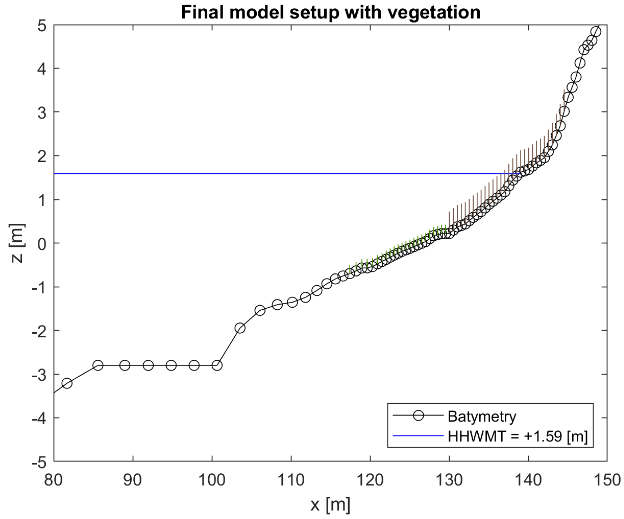
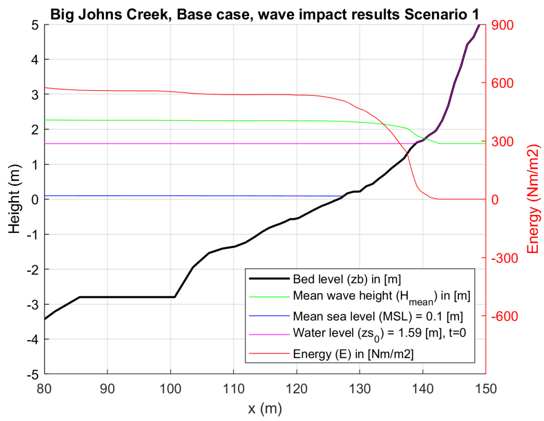



Figure 6.8: Example of a final model setup, showing what the reduced bathymetry with vegetation and the implemented water height looks like

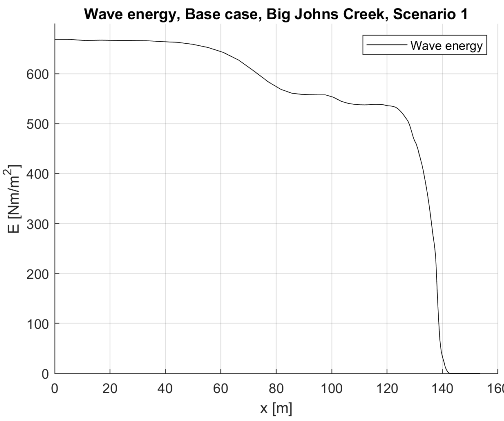
the wave height and the water level development in time and space as the waves travel towards the shore.

### 6.4.1. Base case

The existing conditions as determined in scenario 1 are implemented in XBeach and the results will be referred to as the base case. This is a representation for the existing wave energy along the two cross sections. The wave energy for the two cross sections are shown in Figure 6.9b and Figure 6.10b.

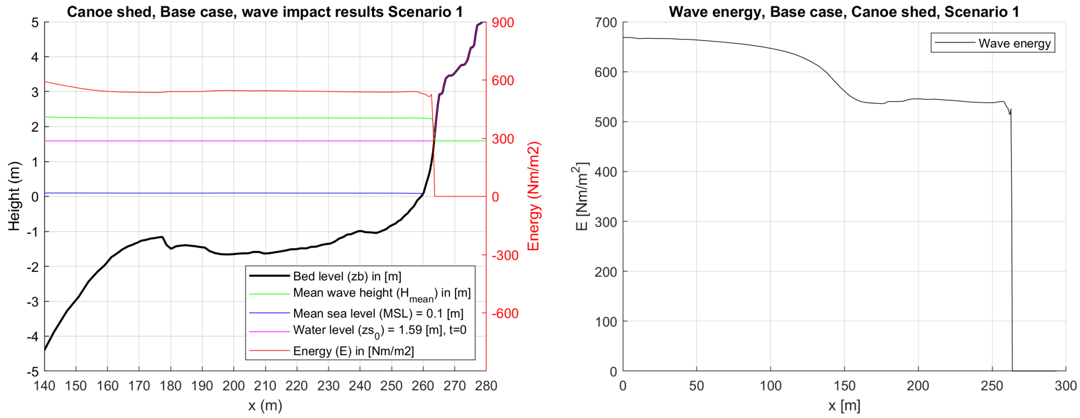



(a) Zoomed view of the XBeach results showing in black the bed level, in red the wave energy, in green the mean wave height, in purple the water level on t=0 and in blue the MSL




(b) XBeach result showing the cross section and the decreasing wave energy as the waves approach the shore. Given the same results as the stated expectations

Figure 6.9: Base case Xbeach results for the Big John Creek cross section




(a) Zoomed view of the XBeach results showing in black the bed level, in red the wave energy, in green the mean wave height, in purple the waterlevel on t=0 and in blue the MSL

(b) XBeach result showing the cross section and the decreasing wave energy as the waves approach the shore. Given the same results as the stated expectations

Figure 6.10: Base case Xbeach results for the Canoe Shed cross section

# 6.5. Evaluation of alternatives

Each alternative will be evaluated on several topics. The wave energy of each alternative will be compared to the wave energy of the base case. From this a conclusion can be drawn to see if the alternatives reduce the wave energy significantly, and therefore work.

Also, the results of each alternative are rated against the principles that are formulated by the TWN in collaboration with Kerr Wood Leidal. This rating is done with the awareness that no one other than the TWN itself can fill-in these principles in the name of TWN, as the TWN might have a different perspective and sense on the principles and its realisation than others. Due to a lack of opportunities to discuss these alternatives and principles together with TWN, an assessment to rate these principles with the knowledge currently present is done. This is done with the best intentions. This rating should only be seen as a rough indication of the contribution of each alternative to the principles, instead of a TWN's perspective. The principles of TWN are shown in the Appendix in Figure F.1.

# 7

# Alternative 1 - Rip rap revetment

A revetment is traditional marine sloping structure, often constructed out of various layers of armour stone, to minimize future bank erosion. The structure absorbs the energy from the incoming wave- or ship-induced waves and therefore prevents damage at the river bank. Many literature studies are done on rock revetments and therefore many guidelines for the design of a traditional rip rap are available. In this chapter a traditional rock revetment will be designed at the riverbank of the Burrard Inlet #3, on the basis of guidelines according to the Rock Manual and Bed Bank and Shore Protections. (Schierick, 2nd Edition 2012)
By covering up the existing shoreline with an armouring layer, the cultural heritage and archaeological sites, which are of high social value, can be protected. However there are also downsides considering intertidal habitat/vegetation, both up- and downsides of a rip rap revetment will be elaborated in this section.

At various points at the shoreline some rip rap is already placed, often placed illegally and thus not in an proper designed manner. A site visit showed severe erosion behind the armour stones, which is caused by a combination of overly sized rocks and the lack of a well designed filter layer, see Figure 7.1. The large armour stones fail to trap the sediment behind the revetment, since the spacing between the rocks is too large. Waves that reach the revetment can therefore transport the sediment behind the rock revetment. By designing a new revetment in combination with various filter layers or geotextile, sediment can be trapped and further erosion can thus be prevented.

Figure 7.1: A site visit at SWN showed erosion behind the currently placed rip rap

## 7.1. Technical feasibility

A traditional rip rap revetment is relatively easy to construct and when the accuracy demands are not very specific, equipment is rather cheap. The revetment along the riverbank does not necessarily have to be homogeneous, as the most vulnerable riverbanks of the Burrard Inlet #3 might need a stronger armour layer. For this preliminary design a revetment will be designed, as an example, located at the Big John Creek which is assumed to be an important and representative cross section, since the field experiment showed severe erosion at this location. See Chapter 6, for further elaboration.

Key elements and design formulas are briefly discussed in this section, for further elaboration is referred to Appendix G.

**Cross section revetment**

The steepness of the slope is one of the most important parameters for the design of a rock revetment. A optimum can be found between the slope angle and stone size. A gentler slope, increases the stability and reduces the stone size. However, with a gentler slope more stones are needed. Therefore the slope of the rock revetment is chosen to be relatively steep and follow more or less the shape of the existing river bank. When this results in to large required stone sizes, the slope angle can be reduced by creating an artificial slope with sand. The slope of the rip rap revetment is set at 1V:2H, which follows the natural slope of the river bank and is a common slope for rock revetments at a river bank. (Schierick, 2nd Edition 2012)
Since the profile of the the river bank is not consistent in longshore direction, the river bank needs to be equalized by placing sand on the bank, to ensure this 1:2 slope. In this way digging in the soil can be prevented, as the purpose of the revetment is to protect cultural heritage and archaeological sites. In order to prevent sediment from eroding underneath, a geotextile is placed which acts like a sand-tight filter. Between the top or armour layer, an extra layer is designed to prevent damage to the geotextile by individual armour stones and to prevent flapping of the geotextile.
Also a toe protection is needed to support the entire protection and prevent erosion at the toe itself. Multiple variations are possible, but since this is only preliminary design, a standard toe protection is designed. The rip rap revetment will be design for a design lifetime of 50 years, which is a common value for bank protections in civil engineering. (Schierick, 2nd Edition 2012) Therefore a Sea Level Rise of 50 years is considered in the design water level determination. The design scenario is the 200 year high water level with the 200 year design storm, both are determined in Chapter 3.4. This leads to the following boundary conditions for the revetment design:

Table 7.1: Boundary conditions rip rap design

| Input parameter | [m] |
|---|---|
| 200 yr water level | 2.63 |
| Sea level rise | 0.5 |
| 200 yr wave height $H_s$ | 1.19 |

The determined water level will be used as input parameters in Swanone and Xbeach, see Figure 7.2 for the design water level at Big John Creek.

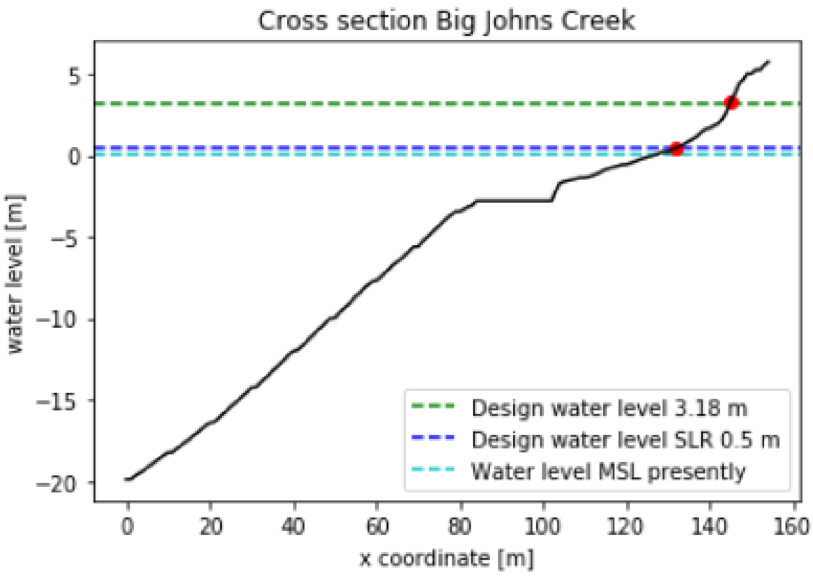



Figure 7.2: Cross section of Big John Creek

**Determination design wave**
The deep water wave conditions are elaborated in Chapter 3.4, this means a wave height and wave period is determined, and a spectrum shape is assumed: the Jonswap spectrum. The results are given in Table 7.2:

Table 7.2: Wind-induced significant wave height

| **Peak Period ($T_p$)** | **Windspeed ($U_{10}$)** | **Wave height ($H_s$)** |
|---|---|---|
| 4.17 s | 23.9 m/s | 1.19 m |

The next step is to calculate the shallow water wave conditions, which can be done using a spectral model. With this model the local wave height ($H_{m0}$) and wave period ($T_m$)can be calculated. In Appendix G.1 the output plots are figured. The design wave height ($H_{m0}$) for the calculation of the size of the armour stones needed using the Van Der meer formulas, is defined as the wave height at the toe of the structure. The length of the structure is yet to be determined, so first an assumption is made to be able to assume a reasonable wave height. This assumption is checked after the full dimensions of the revetment are calculated and adjusted if needed. This led to a toe of the structure at x = 2 meters from the still water level. The corresponding wave height $H_{m0}$ can be determined from the SwanOne plots and is indicated with a red dot in Figure 7.3. The local design wave height will be $H_{m0}$ = 1.05 m.

## 7.1.1. Required armour stone size

The Van Der Meer formulas give a relation between the stability of the armour rock with respect to the local significant wave height $H_{m0}$. The higher the stability number, the higher the stability of the construction: a higher stability number means that the same rock is still stable under higher waves. A significant wave height represents a characteristic height of random waves, it is thus a well-defined average. In engineering practice, it is common to use the 2% exceedance value $H_{2\%}$ which indicates that 98% of the waves are lower than the local significant wave height ($H_{m0}$). In deep water, waves follow a Rayleigh distribution (J.P. van den bos, Edition 2018), which means that the ratio $H_{2\%}$ / $H_s$ has a fixed value. The Rock Manual (2007) recommends to use the deep water equations of Van Der meer only if the local water depth at the toe of the structure is more then 3 times the local significant wave height. (J.P. van den bos, Edition 2018) This is not the case, since the SwanOne plots in Appendix G.1 show a water depth of only 1-2 meters at the toe. This means that the shallow water formulas will be used as described in The Rock Manual (2007), which are based on the Van der Meer equations (1988) but additional model test data is added for shallow water conditions (Van Gent et al 2004):

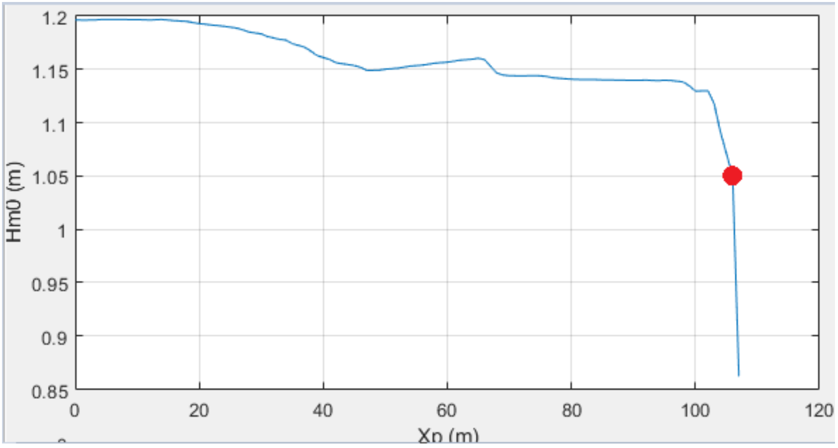



Figure 7.3: Design wave height at toe of structure, red dot

$$\frac{H_s}{\Delta \cdot d_{n50}} = 8.4 \cdot P^{0.18} \cdot (\frac{S}{\sqrt{N}})^{0.2} \cdot (\frac{H_s}{H_{2\%}}) \cdot \xi_{m-1,0}^{-0.5} \tag{7.1}$$

Where:
$\frac{H_{sc}}{\Delta \cdot d_{n,50}}$ = Stability parameter [-]
$H_{2\%}$ = can be determined from SwanOne model or using Battjes-Groenendijk (2000) equations (J.P. van den bos, Edition 2018)
$\Delta$ = relative mass density $(\rho_s - \rho_m)/\rho_m$, $\rho_s$ is mass density of stone and $\rho_w$ is mass density of water [-]
$d_{n,50}$ = nominal median block diameter [m]
P = notional permeability coefficient
S = damage level
N = number of waves
$\xi_{m-1,0}$ = surf similarity parameter (Iribarren parameter)

The calculations are done using a python script which, with extra elaboration of the various parameters, can be found in Appendix G.1. The armour stone needs to have a nominal median block diameter ($d_{n50}$) of 0.43 m, as can be seen in Figure 7.4:

The required stone size must be large enough to remain stable under the wave forces in the design scenario. It is common practice to round up the calculated stone size, as determined in Figure 7.4, to standard class gradings. The required stones of the revetment are designed according to European Standard Grading EN13383. (Schierick, 2nd Edition 2012)
The European Standard Grading EN13383 Table can be found in Appendix G.7, the final results are shown in Table 7.3

Table 7.3: Final result armour layer $d_{n50}$

| Local wave height ($H_{m0}$) | Class | $d_{n50}$ | Range | Layer thickness |
|---|---|---|---|---|
| 1.05 m | $HM_A$ 300-1000 | 0.59 m | 300-100 kg | 0.88 m |

As can be seen in Table 7.3 the stone class when rounding up to standard class gradings, is considerably larger than the $D_{n50}$ value needed that was calculated. Since the design scenario is an extreme scenario as explained in Chapter 3.4. Also, one can do optimisations by varying the slope of the revetment, for example a flatter slope leads to smaller required rock sizes. Also one has to take into account the availability of rock armour in the area, since the armour stone need to be obtained from quarries, the further away these quarries or the harder to produce a typical armour stone, the higher the costs of the revetment. Since this is only preliminary design, these conditions will be considered in a later design phase. In combination with data used located at Point Atkinson 7.5, which is not entirely representative for this Burrard Inlet #3 location, it is chosen to choose a stone class grading close to the $D_{n50}$ value

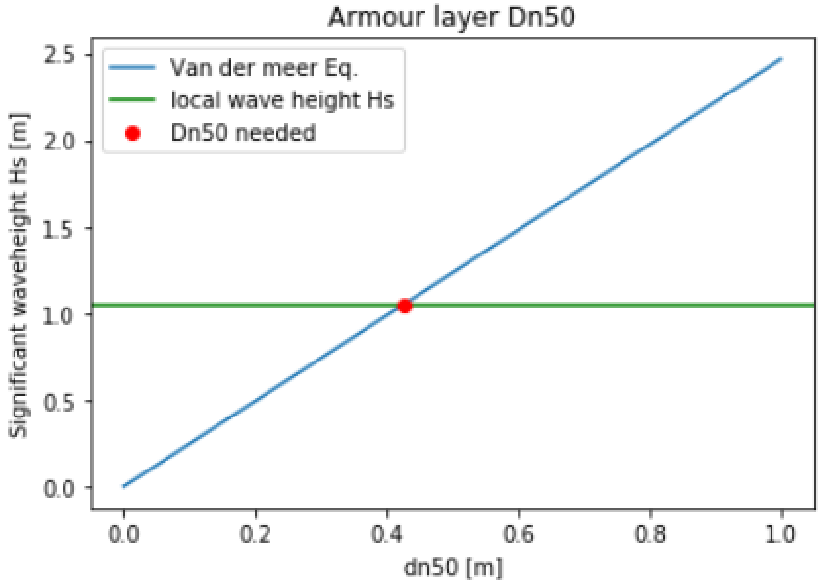



Figure 7.4: Needed armour layer shallow water conditions Van Der Meer (1990)

that was calculated with Python and is shown in Figure 7.4 This resulted in a stone grading class $LM_a$ 60-300 kg, with a $D_{n50}$ of 0.38 m.

### 7.1.2. Required filter layer and Geotextile

The top armour layer is designed in the previous section, but a filter layer is needed for a couple of reasons. One important reason is prevention for erosion of the covered subsoil and on the other hand a drainage layer is needed to prevent a build-up of pressures beneath the top layer. Since the armour stones in the top layer can be quite heavy and sharp, another benefit of a filter layer with smaller gravel is to prevent damage to the geotextile. The geotextile will prevent the sand below the bed protection from moving around/flowing away. The permeability of the geotextile should be at least 10 times greater than that of the subsoil (Schierick, 2nd Edition 2012), so no significant pressures underneath the geotextile and no clogging of the pores will occur. On the other hand, the geotextile openings should not be too large, to prevent severe erosion trough. In preliminary design phase in engineering practice it is common to use a rule of thumb of a factor of 10 per layer. (Schierick, 2nd Edition 2012) This results in a gravel layer with a $D_{n50}$ of 0.043 m.

### 7.1.3. Wave run-up

The definition of wave run-up is the maximum water level on a slope relative to the still water level, during a wave period. The vertical distance between the still water level and the highest point reached by the wave tongue is called the run-up $R_u$. In the Netherlands the $R_{u2\%}$ is used, which is the run-up level that is exceeded by 2% of the incoming waves. (Schierick, 2nd Edition 2012). Research in physical models and prototypes has resulted in an empirically developed formula 7.2, where A, B and C are determined by curve fitting.

$$\frac{R_{u2\%}}{H_{m0}} = \gamma_f \cdot \gamma_\beta \cdot (B - \frac{C}{\sqrt{\xi_{-1,0}}}) \tag{7.2}$$

Where:
$H_{m0}$ = 1.05 m, = local significant waveheight, see Chapter 7.1
$\gamma_f$ = 0.7 [-], roughness factor rubble slope rip rap (Schierick, 2nd Edition 2012)
$\gamma_\beta$ = 1 [-], angle of attack factor (Schierick, 2nd Edition 2012)
$\xi_{-1,0}$ = 2.26 [-], the Iribarren number based on $T_{m-1,0}$ , see Appendix G.2
A = 1.65 (Schierick, 2nd Edition 2012)
B = 4.0 (Schierick, 2nd Edition 2012)

C = 1.5 (Schierick, 2nd Edition 2012)

Filling in the parameters in Equation 7.2, results in a $R_u 2\%$ of 2.2 m.

### 7.1.4. Dimensions revetment

For the final design the crest height of the revetment needs to be determined. Therefore the area of wave attack on the slope needs to be known and the water elevations need to be calculated. A practical measure in engineering is to take the length of the revetment approximately equal to the region of wave attack, which is approximately 1.5-2 times the local significant wave height $H_{m0}$. (Schierick, 2nd Edition 2012) Therefore the crest height of the revetment will have a total height of:

Design water level + wave run-up = MSL + SLR + water level 200 year + wave run-up = 0.5 + 2.68 + 2.2 = MSL + 5.38 m. Where the upper limit is well in the 2 times the local significant wave height $H_{m0}$ margin.

For the toe of the revetment one has to consider the large large tidal elevations and the critical eroding parts of the cross section, that need to be protected. It is therefore not necessary to construct the revetment over the total tidal elevation. It would also have enormous ecological consequences, let alone the additional costs of extra material. It is therefore assumed that the area that needs protection is around + 1.8 m MSL, which based on the field experiment. Therefore the cross section of the revetment at the Big John Creek section will be constructed from +1.8 m MSL to MSL +5.38 m , reaching the calculated crest height needed, as determined in this section. It's again important to keep in mind that these are assumptions based on a field experiment, which was not site specific. Above the crest of the newly designed revetment lots of vegetation was seen during the site visit. It is assumed that if overtopping would occur, this vegetation is sufficient to keep the sediment on it's place and no severe erosion will appear. For further detailed design, more site visits are needed to determine the area that are most vulnerable and design a site specific revetment.

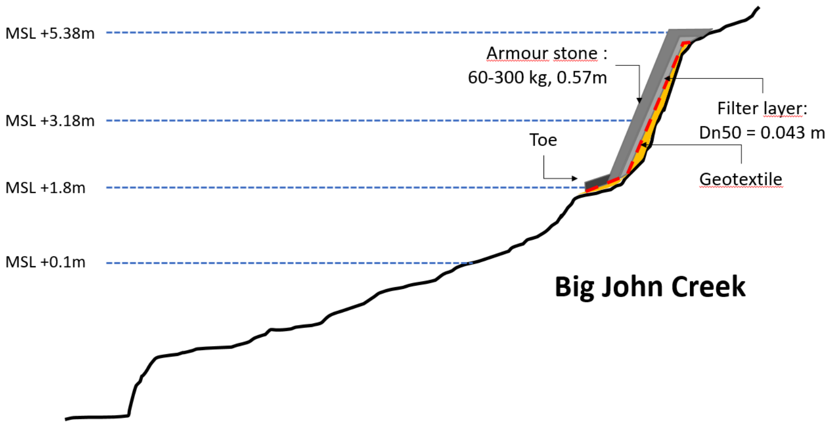



Figure 7.5: Revetment design Big John Creek, reference level CGVD28 m

### 7.1.5. Construction

The constructability of the revetment will be challenging since the river bank is not accessible by roads. Therefore the material and the equipment to construct the revetment cannot be transported to the river bank. One option is to construct a temporarily access road, but one has to keep in mind the extra costs and more important, the possible harm to the surroundings with respect to archaeological and ancestral spiritual value. The other option is to supply and construct the revetment via the water. However, large tidal elevations and possible weather conditions will limit the workability, which also comes with extra costs. Optimising by means of a cost-benefit analysis , including environmental, economical and social aspects will lead to the best option.

## 7.2. Environmental feasibility

River banks are part of a larger ecosystem, since they form the transition between water and land. Construction of a new revetment will have a significant influence on the the existing ecosystem. The consequences must be assessed and if possible quantified, if needed remedial measures can be designed. Extensive research will lead to recommendations concerning the ecosystem as well aquatic life (section 3.3.2) as terrestrial life. Research must be done to find the best possible construction period to minimize harm to living organisms and habitat in the ecosystem. The existing vegetation will also be removed in order to be able to construct the revetment. The consequences of this loss of vegetation must all be within limits of regulations. An overview of the regulations and jurisdictional demands will be discussed in section 7.4

## 7.3. Economical feasibility

In Table 7.4 a cost estimation is made based on a example calculation from Bed Bank and Shore protections (Schierick, 2nd Edition 2012) and Home Advisor (2020). It is important to note that this is only a indication, since this is preliminary design. Therefore, more research is needed to determine how many hours should go into the construction of the rip rap revetment. The revetment might not have the same constructive design along the entire shoreline of the project, as stated earlier. Therefore the cost analysis in Table 7.4 is given per meter revetment.

Table 7.4: Overview of the estimated costs for the construction of the revetment, per meter. Bulk price estimations of rocks from Home Advisor (2020); materials and equipment estimates (Schierick, 2nd Edition 2012) ;average salary in Canada per hour from Neuvoo (2020);

| Construction | Units | Cost per unit (CAD) | Quantity | Total (CAD) |
|---|---|---|---|---|
| Armour layer stone | $m^3$ | 85 | 8 | 680 |
| Filter layer stone | $m^3$ | 40 | 2 | 80 |
| Sand | $m^3$ | 20 | 3 | 60 |
| Geotextile | $m^2$ | 15 | 10 | 150 |
| Worker salary | hour | 18 | 15 | 270 |
| Equipment | hour | 140 | 8 | 1120 |
| Site preparation | | | | 100 |
| Unforeseen | 3% | | | 75 |
| **Total project costs (CAD)** | | | | 2535 |

The rough cost estimation made in Table 7.4 does not include maintenance costs. However, monitoring is necessary to ensure the safety of the revetment structure. Depending on the contract with the contractor, agreements can be made regarding monitoring on a regular basis.

## 7.4. Legislative feasibility

Various provincial and federal Acts regulate the construction of river bank protections. (of British Columbia, 2000) The following Acts are important considering a rip rap revetment:

- **Water Act**
  The Water Act is regulated by the Regional Water Management Office of MELP. (Ministry of Environment, Lands and Parks) It contains regulations about periods where construction may be undertaken. It can therefore restrict the construction activities. The federal Department of Fisheries and Oceans (DFO) and provincial Fish and Wildlife may review and comment on construction proposals.

- **Dike Maintenance Act**
  In British Columbia the Dike Maintenance Act is the most important legislation considering flood protection works. It states that written approvals are needed for every construction or maintenance work of a revetment by the Deputy Inspector of Dikes.

- **Canada Fisheries Act**
  The federal Department of Fisheries and Oceans conducts the Canada Fisheries Act, which ex-

press that all work in rivers and oceans inhabited by fish requires approval. Under this Act the management of many fish species is done by the provincial Fish and Wildlife.

- **Land Act**
  This act contains the regulations around removal of sediment. Crown Land or private land, permission is necessary of the land owner.
- **Canada Navigable Waters Protection Act**
  Transport Canada is responsible for the management of the Canada Navigable Waters Protection Act, through the Navigation Protection Program (NPP). It contains regulations that apply to every bank protection around navigable waters.

However this is far more complicated, since the shoreline is within the Tseilwatuh Nation reserve, who manages the land of the reserve. They are striving to achieve Nation-to-Nation based contact with the Federal Government, which holds to restore their independence. This is further elaborated in Chapter 5.

## 7.5. Evaluation of Tsleil-Waututh Nation’s principles

The new designed revetment will change the existing landscape and its habitat significantly. In order to construct the revetment for example access roads will be needed, which can harm the current ecosystem. Involvement and consultation of the local community and environmental associations will be key in order to design a social/environmental valued, yet durable revetment. All stakeholders as discussed in Chapter 5 will need to be involved from the beginning of the project. Involvement and consultation of the local community and environmental associations will be key in order to design a social/environmental valued, yet durable revetment.

- **Leadership**
  The TWN assumes is taking a leading role to build resilience for the land of their people. They can therefore make an example of themselves with respect to other First Nations, encourage cooperation between each other for the common good of cultural heritage.
- **Self-reliant**
  The rip rap revetment it self is a self reliant structure, once constructed minimum maintenance is needed when properly designed.
- **Science-based**
  Revetments have been constructed in many places all over the world, which means that there are lots of reference projects. This makes it possible to construct a conservative design with a well considered safety region and lifetime period of the structure.
- **Values-based**
  By construction an revetment at the shoreline of the Burrard Inlet IR#3 , the cultural heritage and archaeological sites, which are of high social value, can be protected. However, the change considering intertidal habitat/vegetation, must be weighed against each other and additional ecosystem services improvements need to be considered.
- **Strength-based**
  Once constructed, the revetment instantly full fills its function of protecting the river bank against erosion. Again, with countless reference projects a well considered reliability estimate can be done.
- **Collaborative**
  The construction of a rip rap revetment should be combined with more nature-based solutions. A compromise must be found between a structure/solution that guarantees a certain safety and a solution which takes environmental aspects into account. By working together with biologists, ecologists and engineers, lots of possibilities and scenarios can be proposed from different perspectives.

- **Cost-effective**
  A rip rap revetment is a relatively cheap and conservative solution for the erosion problem, since materials can be used from local quarries. Also no advanced machines or models are needed to be able to construct a revetment in a safe manner.

- **Multi-solving**
  The revetment it self should be combined with other alternatives and ideas, to take the ecosystem services into account, since its not solving multiple hazards on it's own.

- **Adaptive**
  A rock revetment is a solid and abstract structure and has a relatively high guaranteed safety by itself, but can therefore not simply be adapted once constructed.

## 7.6. Possible improvements

There are many possibilities for the design of a rip rap revetment. In this design a traditional rip rap design method is taken as example. As a possible alternative, the current wrong placed armour stones can be moved further downslope into the tidal zone. They will act as small submerged breakwaters which will reduce wave energy and provoke wave-breaking so that wave heights reaching the revetment on the bank will decrease considerably. With less wave energy and smaller wave heights, smaller armour stones are needed, leading to a more economical design. It's important to note that in this phase of the preliminary design the consequences of two/three dimensional flow/morphodynamic disturbances around the submerged breakwaters are not taken into account. As an indication Figure 7.6 shows the decrease in wave energy clearly. However, no ecological or morphodynamic analyses is done, but Figure 7.6 shows promising results. In Figure 7.6 two point in the cross section have been raised by 1 meter, indicating a pile of old loose armour stones that were wrongly placed at the river bank, acting as a submerged breakwater. This is a rough estimate only, purely to show the possibility of re-using the old revetment stones as energy dissipators. Various sizes of submerged breakwaters and numerous locations can be evaluated with a hydrodynamic model. More extensive research can be done to check both the technical and ecological feasibility, site specific.

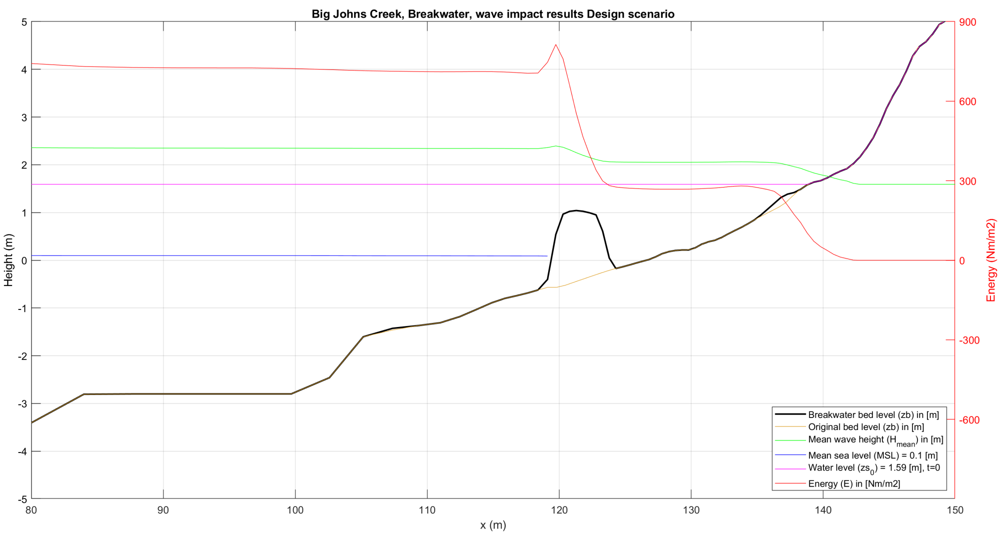



Figure 7.6: Xbeach result example submerged breakwater

# 7.7. Conclusion

## 7.7.1. Advantages and disadvantages

Table 7.5: Advantages and Disadvantages rip rap revetment

| Advantages | Disadvantages |
|---|---|
| Absorb wave energy | Hard to construct/repaired at location |
| Highly durable | Negative effect surrounding area w.r.t erosion |
| History of use | designed for specific conditions e.g. sea level rise |
| Material availability | |
| Material relatively cheap | |
| Minor deformations will not lead to failure of structure | |

## 7.7.2. To keep in mind

- One has to keep in mind that there is a large uncertainty in the design load, e.g. the design wave height $H_s$. The occurrence of these design wind speeds leading to a design wave field, is a stochastic process based on observed storm data. The design storms and therewith design wave heights $H_s$ during the lifetime of the revetment are uncertainties on their own.
- There are large uncertainties in the design parameters caused by variable correlations between for example wave height and water or wave height and wave direction. (J.P. van den bos, Edition 2018) A study needs to be done a the joint probability of for instance extreme wave heights and water levels at the Burrard Inlet #3.
- In this preliminary design phase the revetment is strongly simplified designed with a deterministic approach, which doesn't include probabilistic and randomness in the calculations. This is greatly recommended since it is mandatory to design structures with an acceptable risk of failure, which means that the probability that the load exceeds the strength should remain below a certain value.
- The revetment is only an example for a cross section at some point along the riverbank. More research and site visits are needed to determine the most vulnerable locations or possible locations where nothing needs to be done
- More extensive research is needed to determine the effects of the submerged breakwaters as regards to hydro- and morphodynamic changes.Also a structural design needs to be done for the submerged breakwaters made out of the existing .
- Availability of the armour stones is assumed to be sufficient. However if this is not the case, other options might be considered for example block mattresses or concrete elements.
- For the design on waves are considered based on a chosen design scenario. However, it is very important to include sediment transport due to currents as explained in Chapter 3.4. A sediment at the toe structure exposed to large tidal currents can erode, making the entire structure unstable. Extensive research is therefore needed and recommended.
- There are more eco-friendly alternatives available than a traditional rip rap revetment, which may have large benefits and opportunities for the ecosystem.
- A lifetime period of 50 years is assumed in the beginning of the design process. Monitoring needs to be done on a regular basis to make sure that the revetment is working properly. Maybe a longer design lifetime of say for example 20 years is relatively cheap and not necessarily more work. A cost-benefit analysis can be done to look for an optimum solution.
- The revetment is designed for a certain design scenario. With sea level rise on the run, the crest height of the structure will not be sufficient anymore. When that happens one should evaluate if increasing the crest height is an option, or the revetment should be re-designed.
- There are promising 'nature based' or so called 'green-gray' solutions based on rip rap design, that enhance the ecological functions on/around a revetment.

### 7.7.3. Comparison to hazards

This section compares the determined coastal hazards found in Chapter 4.2.

Table 7.6: Hazard evaluation rip rap revetment

| Hazard | Comparison |
|---|---|
| Coastal flooding | +/- |
| Coastal erosion | ++ |
| Intertidel area change | +/- |
| Ocean Acidification | - |
| Harmful algae blooms | - |
| Other ocean conditions | - |

- **Coastal flooding**
  By construction a rip rap revetment along the shoreline of the project site, the coastal flooding hazard will not change considerably compared to the current situation. It will not change the hydrodynamic conditions of the design cross section, but instead absorbs the energy from the incoming waves and therefore prevents damage at the river bank. However, one should keep in mind that for example overtopping of the revetment, can still lead to failure mechanisms of the soil at the river bank or er even the structure itself.
- **Coastal erosion**
  A rip rap revetment will not necessarily be a measure against coastal flooding, it is a structure instead that will minimize the consequences due to coastal flooding. It is an effective way to stop the erosion of a river bank by placing a ’unerodable’ cover layer of heavy stones.
- **Intertidal area change**
  For the rock revetment the current vegetation needs to be removed, changing the existing ecosystem. This will have consequences for the aquatic- and terrestrial life. Extensive Research must be done to minimize harm to living organisms and habitat in the ecosystem. Various alternatives need to be considered to improve the ecosystem services at the project site.
- **Ocean Acidification**
  The designed rip rap revetment has no direct influence on ocean acidification.
- **Harmful algae blooms**
  The designed rip rap revetment has no direct influence on harmful algae blooms.
- **Other ocean conditions**
  The designed rip rap revetment has no direct influence on the other ocean conditions determined in Chapter 4.2.

# 8

# Alternative 2 - Salt marsh

In this chapter the option of implementing a salt marsh at the TWN project site to mitigate the climate change hazards is evaluated. First an introduction is given for the general approach of a salt marsh and the climate restrictions and ecological aspects that are incorporated. After that, the technical feasibility is considered in which a salt marsh is designed for the two considered locations at the TWN project site; Big John Creek and Canoe Shed (Chapter 6) and construction and maintenance guidelines are taken into account. Thereafter, in the environmental feasibility section, the environmental developments that come along with the construction of a salt marsh are discussed. Next, the economical and legislative feasibility are considered to evaluate the costs and the restrictions that have to be considered when implying this alternative. This is followed by an evaluation using the TWN climate change adaptation action screening criteria. In the last section a conclusion is given as an evaluation of the alternative. The advantages and disadvantages of the alternative are considered as well as a remark on which things have to be kept in mind when implying this solution. Lastly the results are rated against the hazards described in Chapter 4.2.

Salt marshes are areas formed in the intertidal zone of low-energy shorelines. They consist of silty soils and are covered with salt resistant vegetation. Salt marshes are naturally present in coastal systems, but are recently threatened by human actions and climate change effects. They are mostly found on mid- to high-latitude coasts where moderate climates are present (Bosboom and Stive, 2015; Giuliani and Bellucci, 2019; Barbier et al., 2011; Mcowen et al., 2017). Salt marshes provide ecosystem services by giving home to (edible) vegetation, creating habitats for birds, fish and invertebrates, improving the water quality and enhancing carbon sequestration (Zedler et al., 2008; Gedan et al., 2009; Mcleod et al., 2011).

Aside from the ecosystem services, salt marshes are known for their erosion protection capabilities for shorelines because of wave energy dissipation (Barbier et al., 2011; Vuik et al., 2016). Examples from anthropogenic salt marshes and salt marsh restorations that are used to mitigate erosion however, are rare within the Vancouver area. Though there are multiple examples at the East Coast of Canada (Canadian Press, 2018; Szabo-Jones, 2014; Bowron et al., 2012) and at many places around Europe (Barbier et al., 2011; Giuliani and Bellucci, 2019; Allen, 2000).

## 8.1. Technical feasibility

As salt marshes can cover wide ranges of the intertidal zone, different species are present as well. All species growing on salt marshes are salt resistant, but each one of them has their own ideal depth, duration and frequency of inundation (de Blasio and Silver, 2018). As shown in Figure 8.1, distinction is made between different zones. The low marsh, the high marsh, the edible rhizome (Turner et al., 2013). The low marsh are flooded two times a day and the high marsh is flooded only two times per month (de Blasio and Silver, 2018).
There are different ways how salt marshes can be made. It can be done with or without the use of a rockwork (stone) wall (Figure 8.1), depending on the available area, the initial bathymetry and the

design purpose. By the use of a wall, the lower marsh can be elevated in order to enlarge the area in which the preferred vegetation can grow. The wall can be build up partly with rocks available at the beach or it can be a more sophisticated design or anything in between. In addition, the wall offers an additional protection against erosion. If sufficient sediment supply is available from river discharges and long shore sediment transport, the salt marsh can fill itself. If insufficient sediment supply is available or an instant salt marsh is desired, sediment can be moved towards the desired location and an artificial slope can be made. The area between MSL and HHWMT is then filled with fine sediment (silty sand) to create an ideal salt marsh slope of 1:30 to 1:20 for vegetation to grown on. Vegetation is to be planted shortly after construction or it can evolve naturally. Maintenance work is needed to clean the beach and to prevent one species to run out the others. The people of the nation can be involved in the maintenance work. With taking advantages of the opportunities, the salt marsh area holds for both cultural aspects and food contribution.(Adnitt et al., 2007; de Blasio and Silver, 2018; Turner et al., 2013).

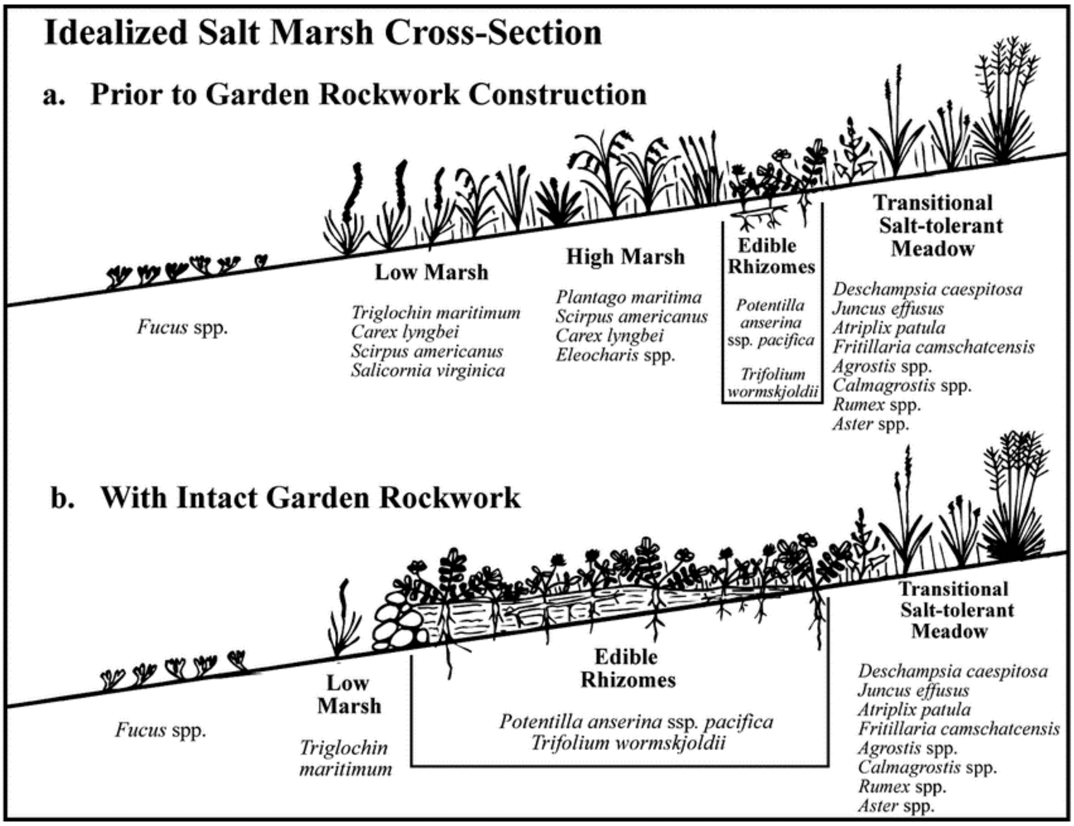



Figure 8.1: Illustration of how the area around a certain tidal elevation can be enlarged by the use of a wall (Turner et al., 2013)

In this case, as the main purpose of the design is to cope with coastal erosion hazards, it is chosen to fully construct the salt marsh including a wall, sediment filling and planted vegetation. Both the wall and the vegetation contribute to wave dissipation. For lower wave energy, vegetation opportunities and establishment increase and vegetation is more likely to grow. More dense and tall vegetation has a higher effectiveness in dissipating wave energy which contributes to a positive feedback system of the salt marsh development (Vuik et al., 2016; Anderson and Smith, 2014).

### 8.1.1. Cross sections

The total area between MSL and HHWMT, is the potential area for a salt marsh. The construction of a wall below MSL, leads to a larger potential salt marsh area. By filling the area behind the wall with sediment, the slope and elevation can be adjusted and optimized (Adnitt et al., 2007; UBC Coastal Adaptation Lab, 2020). Taking this into account, the total area between one meter below MSL and HHWMT is seen as potential salt marsh area. The resulting potential salt marsh area for Burrard Inlet

IR#3 is highlighted in the top view shown in Figure 8.2. As described in Chapter 6, two cross sections are evaluated, Big John Creek and Canoe Shed which are also highlighted in Figure 8.2.

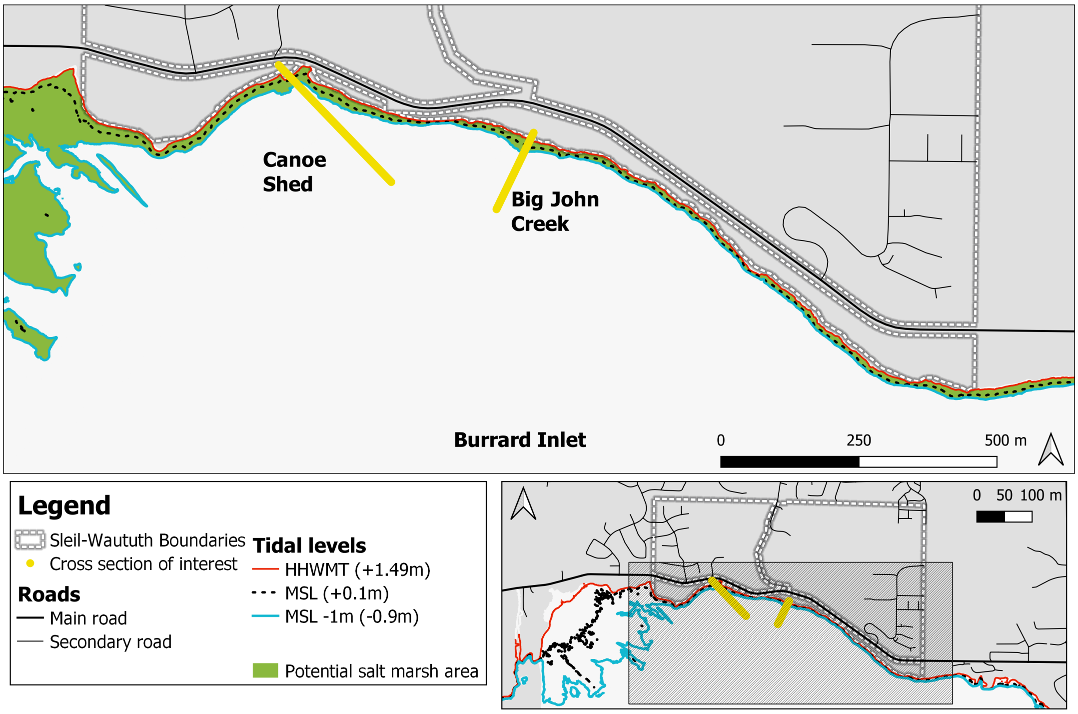



Figure 8.2: Top view of the potential salt marsh area around Burrard Inlet IR#3

### Canoe Shed cross section

The design of the bathymetry of the Canoe Shed cross section with salt marsh is based on current water levels and tidal elevations as is shown in Figure 8.3. In the current situation the area between MSL and HHWMT is only 4 meter and has a slope of 1:2 which make rough conditions for vegetation to grow.
At one meter below MSL a stone wall with a height of 1.5 meter is built. The area behind the wall is filled with fine sediment until a slope of 1:30 is reached. The wall is designed higher than the elevation of the sediment behind the wall to create space for sedimentation and adjustment to sea level rise or other causes of water level changes. Additionally, the wall height can be increased to account for water level changes. The area is planted with various types of vegetation. This design results in an increase of the salt marsh area from 4 to 84 meter with a decrease of the slope from 1:2 to 1:30.

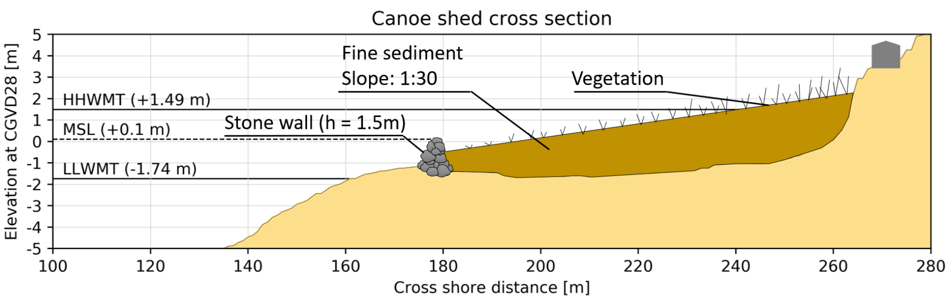



Figure 8.3: Adjusted cross section at Canoe Shed for the creation of a salt marsh

**Big John Creek cross section**

The design of the bathymetry of the Big John Creek cross section with salt marsh is based on current water levels and tidal elevations as is shown in Figure 8.4. In the current situation the area between MSL and HHWMT is 10 meter and has a slope of 3:20.
At one meter below MSL a stone wall with a height of 1.5 meter is built. The area behind the wall is filled with fine sediment until a slope of 1:20 is reached. The wall is designed higher than the elevation of the sediment behind the wall to create space for sediment and adjustment to sea level rise or other causes of water level changes. In addition, the wall can be heightened to account for water level changes. The area is planted with various vegetation. This design results in an increase of the salt marsh area from 10 to 19 meter with a decrease of the slope from 3:20 to 1:20.

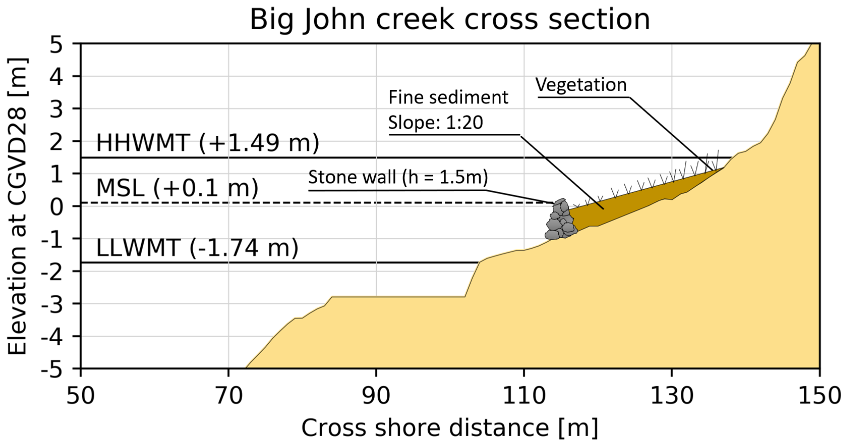



Figure 8.4: Adjusted cross section at Big John Creek for the creation of a salt marsh

### 8.1.2. Model results

As explained in Chapter 6, XBeach is used to predict the influence of each alternative on the wave energy. These are compared to the wave energy that is present in the current situation, the base case, which is shown in Chapter 6 as well. This is done for two scenarios, of which only Scenario 1 will be further elaborated in this Section. The overview of the model setup and results for water levels given scenario 2 can be found in Appendix H. This model used a simplified approach to predict the influence of vegetation on the wave energy. This is done with the use of representative values based on information obtained from and can be found in Table 8.1 (Consortium of UNESCO-IHE, Deltares, Delft University of Technology and the University of Miami, 2020). The representative values of seagrass have been chosen as the vegetation is expected to have a similar texture all over the length of the salt marsh and only one type of vegetation could be represented in the XBeach model.

Table 8.1: X-beach parameters to simulate the roughness of the surface of a salt marsh

| Symbol | Value | Description |
|---|---|---|
| *ah* | 0.2 | Vegetation height [m] |
| *bh* | 0.02 | Stem diameter [m] |
| *Nv* | 1200 | Density (units / $m^2$) |
| *Cd* | 1.0 | Drag coefficient $[-]$ |

**Canoe Shed cross section**

In Figure 8.5 the wave energy present at Canoe Shed cross section after the construction of a salt marsh is shown, given the water level and wave conditions of Scenario 1. The model set up that is used and the wave impact results are shown in Appendix H. Figure 8.5 shows the wave energy for a construction with and a construction without vegetation. When comparing Figure 8.5 to the base case in Figure 6.10b it can be noted that for both the construction with and without vegetation the wave energy reduces significantly. Compared to the base case the breaking point of the waves is shifted offshore about 80 meters. Also it can be concluded that the vegetation has a significant contribution to the wave dissipation. A lower wave energy on the shore leads to less erosion (Chapter 6).

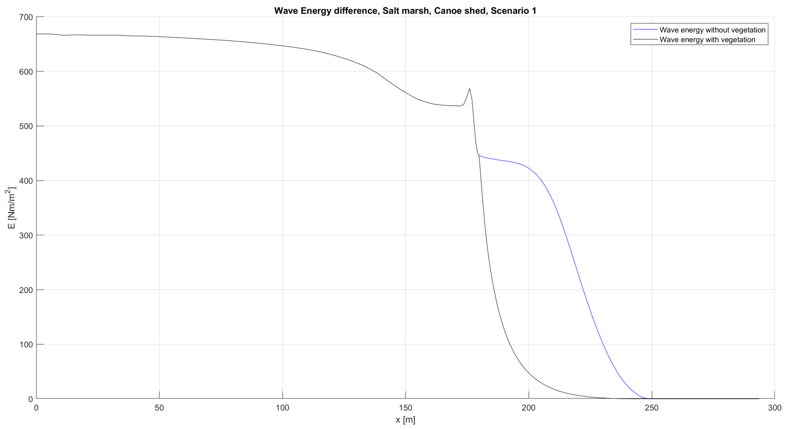



Figure 8.5: Wave energy at Canoe Shed after construction of salt marsh with and without vegetation

**Big John Creek cross section**

In Figure 8.6 the wave energy present at Big John Creek section after the construction of a salt marsh is shown, given the water level and wave conditions of Scenario 1. The model set up that is used and the wave impact results are shown in Appendix H. Figure 8.6 shows the wave energy for a construction with and a construction without vegetation. When comparing Figure 8.6 to the base case in Figure 6.9b it can be seen that for both the construction with and without vegetation the wave energy reduces significantly. Compared to the base case the breaking point of the waves is shifted offshore about ten meters. Also it can be concluded that the vegetation leads to significant wave dissipation. A lower wave energy on the shore leads to less erosion (Chapter 6).

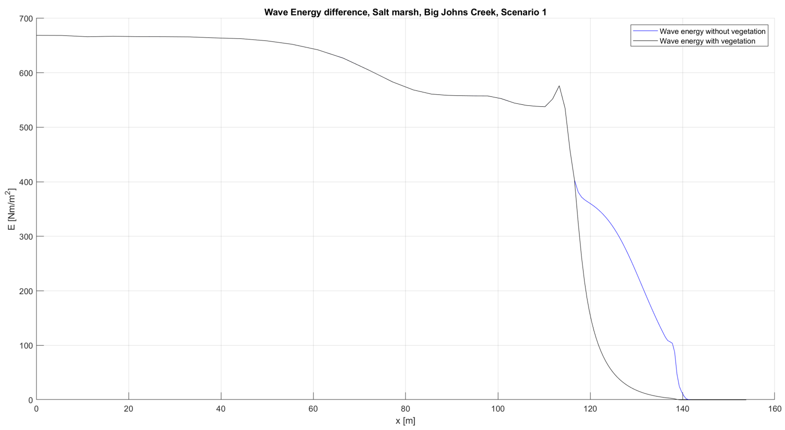



Figure 8.6: Wave energy at Big John Creek after construction of salt marsh with and without vegetation

## 8.2. Environmental feasibility

Given the moderate climate present in Vancouver (Section 3.4), the creation of salt marshes is in theory applicable at the project location. Several examples of (salt) marsh restoration and creation projects are present within the Vancouver area, as part of the Habitat Enhancement Program. The Habitat Enhancement Program is a Vancouver Fraser Port Authority initiative focused on creating, restoring, and enhancing fish and wildlife habitat (Port of Vancouver, 2018; Tranmer, 2018). The examples that are located closest to the Burrard Inlet IR#3 are the salt marsh at New Brighton Park, created in 2017 (Tranmer, 2018), and the salt marsh at the Maplewood Flats (Vancouver Fraser Port, 2018). These locations are shown in Figure 3.6. From these examples it can be concluded that the conditions are such, that salt marshes are applicable and can be livable in this area.

From oral history as described by Morin (2015), it can be concluded that lots of vegetation used to be present around the reserve and areas where managed for food harvesting; ”Plant foods were a notable competent of the pre-contact Tsleil-Waututh subsistence economy.”, ”All of the intertidal and foreshore environments were regularly and intensively used for harvesting activities”, and ”... plant harvesting activities must be understood as a practice that made Tsleil-Waututh culture what it was.” Enlarging the edible rhizome area (Figure 8.1, creates a larger habitat for edible vegetation and might therefore be of added value for the Tsleil-Waututh culture.
Besides it is found that a (restored) salt marsh provides productive habitat for birds, juvenile fish and invertebrates. In the current situation juvenile fish from the Indian and Seymour rivers experience high mortality as they migrate through the Burrard Inlet due to a lack of habitat area. Creating more habitat spaces for these species contributes to the ecosystem services and adds value to the shoreline area of Burrard Inlet IR#3 (Tranmer, 2018; Zedler et al., 2008; Morin, 2015; Barbier et al., 2011). In addition, salt marshes are able to create buffers to prevent harmful algae blooms to grow and are able to accumulate great amounts of organic matter, enhancing carbon sequestration (Hackney et al., 2002; Moosdorf et al., 2014; Hartmann et al., 2007; Gedan et al., 2009; Mcleod et al., 2011).

## 8.3. Economical feasibility

To have an indication of the construction and maintenance costs of a salt marsh, a global Class 4 cost calculation is made for the Big John Creek cross section. An overview of these costs is given in Table 8.2. The calculations are based on rough estimates and are shown in Appendix H. Construction costs might be reduced by using rocks available on the beach to build the wall or submerged breakwater. Maintenance costs can be reduced by doing the maintenance work on voluntary basis.

Table 8.2: Overview of the estimated costs for the construction and maintenance of the proposed salt marsh designs. Prices are obtained from Home Advisor (2020); Sharecost (2020); Neuvoo (2020); Lewis (2005); Scruton (2020)

| Construction | Units | Cost per unit (CAD) | Quantity | Total (CAD) |
|---|---|---|---|---|
| Sand/gravel | $m^3$ | 20 | 20 | 400 |
| Rocks (wall) | $m^3$ | 65 | 4 | 260 |
| Vegetation | $m^2$ | 1 | 19 | 19 |
| Transport of sediment | t (tonne) | 7 | 32 | 224 |
| Worker salary | hour | 18 | 10 | 180 |
| Equipment | hour | 140 | 4 | 560 |
| Site preparation | per meter | 100 | 1 | 100 |
| Monitoring | year | 50 | 5 | 250 |
| Maintenance | year | 60 | 5 | 300 |
| Unforeseen | 3% | | | 69 |
| **Total project costs (CAD)** | per meter | | | 2362 |

## 8.4. Legislative feasibility

The legislative framework that applies to this project is discussed in Section 5.2. In this section, the legislative framework that applies to this alternative is discussed.

- **Water Act**
  The Water Act is regulated by the Regional Water Management Office of MELP (Ministry of Environment, Lands and Parks). It contains regulations about periods where construction may be undertaken. It can therefore restrict the construction activities. The federal Department of Fisheries and Oceans (DFO) and provincial Fish and Wildlife may review and comment on construction proposals.

- **Canada Fisheries Act**
  The federal Department of Fisheries and Oceans conducts the Canada Fisheries Act, which express that all work in rivers and oceans inhabited by fish requires approval. Under this Act the management of many fish species is done by the provincial Fish and Wildlife.

## 8.5. Evaluation of Tsleil-Waututh Nation's principles

- **Leadership**
  The principle of TWN is to stand as a leader in climate action. Implying an alternative that both fights the hazards, and contributes to the redevelopment of the natural habitat that was historically present at the project site, creates an opportunity to combine historical knowledge with innovative solutions. Developing and sharing their findings can be an inspiration for other First Nations.

- **Self-reliant**
  Good maintenance contributes to a better operating salt marsh and higher vegetable yields. This might help members to see their role and motivate them to participate in the project. A larger intertidal area provides a larger natural space which gives more opportunities to keep youth connected to climate action.

- **Science-based**
  Oral history describes the successes of TWN with plant harvesting at the intertidal and foreshore environments, meaning knowledge is present about the opportunities of the intertidal zone. The results from 8.1 show the potential of a salt marsh to reduce coastal erosion at the project site.

- **Values-based**
  The intertidal and foreshore environments of Burrard Inlet IR#3 used to be vegetated (Morin, 2015). Although a constructed salt marsh differs from the historical present vegetation, it may contribute to strengthen the role of intertidal vegetation in the TWN culture.

- **Strengths-based**
  The construction of a salt marsh helps to access the climate change hazards and comes along with additional both long- and short-term advantages.

- **Collaborative**
  Aside from the area the salt marsh is built on, the adjacent area and ecosystems around the salt marsh will experience positive impact. This gives an extra opportunity for collaboration with neighbouring communities and neighbouring projects as the salt marsh at the Maplewood flats and New Brightons Park (Tranmer, 2018; Vancouver Fraser Port, 2018).

- **Cost-effective**
  The final costs for a salt marsh strongly depend on the material available on site and the way the maintenance work is assigned (voluntary or not voluntary).

- **Multi-solving**
  Salt marshes are convenient as erosion protection for shorelines, but also provide ecosystem services by giving home to (edible) vegetation, creating habitats for birds, fish and invertebrates, improving the water quality and enhancing carbon sequestration. Therefore, they create an opportunity and enlarge the area to practice traditional and communal activity.

- **Adaptive**
  Salt marshes can be adapted to changing water levels by either changing the wall height or relocating the wall.

## 8.6. Conclusion

In general salt marshes are convenient as erosion protection for shorelines, but also provide ecosystem services by giving home to (edible) vegetation, creating habitats for birds, fish and invertebrates, improving the water quality and enhancing carbon sequestration. Therefore, they create an opportunity and an area to practice traditional and communal activity. Based on the salt marshes located at Maplewood flats and New Brightons Park and the former presence of intertidal vegetation at the project site, it is concluded that the environmental conditions at the shores of Burrard Inlet IR#3 are viable for a salt marsh.
From the XBeach models it is concluded that the construction of a salt marsh causes wave dissipation for both the Canoe Shed and the Big John Creek cross section and is therefore a suitable approach for erosion control.

### 8.6.1. Advantages and disadvantages

The advantages and disadvantages that are present for the implementation of a salt marsh at the project site are listed in Table 8.3.

Table 8.3: Advantages and Disadvantages of a salt marsh

| Advantages | Disadvantages |
|---|---|
| Wave energy dissipation | Hard to predict exact decrease of erosion |
| Adjustable to changing water levels | Hard to predict exact influence of vegetation |
| Creating habitats for birds, fish and invertebrates | Maintenance needed |
| Creating habitat for (edible) vegetation | |
| Multi-solving | |
| Nature friendly solution | |

### 8.6.2. To keep in mind

Before a construction of a salt marsh can be realized, there are several things that should be kept in mind.

- The exact location and dimensions of the wall are of great influence in the wave energy decrease. The higher the wall, the more the wave energy is reduced, but also the more important the strength becomes. It should be taken into account that this is a preliminary design that gives an indication only of how a salt marsh can influence the wave energy. More extensive calculations are needed.
- There are several options to build the wall. This can be done by using rocks, but also with the use of wooden poles, ropes, or a combination. Other possibilities can be thought of to create more advantages, lower costs, or more opportunities for different species.
- The kind of vegetation growing on the marsh influences the wave dissipation. Further research has to be done to find which species are desired by the TWN and which were present in the area historically. The elevation and location of the salt marsh might be adjusted to create an idealized area for these species to grow on.
- The vegetation is included in the models, but is strongly based on assumptions. In addition, the initial strength of the vegetation is less due to incomplete vegetation establishment. This should be taken into account.

### 8.6.3. Comparison to hazards

In this section the results of the salt marsh are rated against the hazards as discussed in Section 4.2.

Table 8.4: Hazard evaluation of the salt marsh

| Hazard | Comparison |
|---|---|
| Coastal flooding | +/- |
| Coastal erosion | + |
| Intertidel area change | + |
| Ocean Acidification | +/- |
| Harmful algae blooms | +/- |
| Other ocean conditions | +/- |

- **Coastal flooding**
  A salt marsh does not influence coastal flooding.
- **Coastal erosion**
  A salt marsh reduces coastal erosion by increasing wave dissipation. Vegetation increases the wave dissipation significantly.
- **Intertidal area change**
  The original intertidal area is extended by elevating parts of the original bed to the desired elevation and adjusting the slope to an idealized value. This induces an enlarged habitat area for (edible) vegetation, birds, fish and invertebrates.
- **Ocean acidification**
  Further study is needed as contradictory results are found for the influence of salt marshes on the pH level.
- **Harmful algae blooms**
  Studies show that salt marshes are able to create a buffer, to reduce the growth of harmful algae blooms.
- **Other ocean conditions**
  Studies show that salt marshes enhance carbon sequestration.

# 9

# Alternative 3 - Clam gardens

On the coastlines from Alaska to Washington, including the shores of the Sleil-Waututh, evidence of shellfish harvesting are found in the form of anthropogenic beach modifications: in middens the remains of discarded shells indicate shellfish harvesting and enhancement of the beach substrate to improve shellfish growth (Isabella, 2011; Caldwell et al., 2012; Augustine and Dearden, 2014; Thomson, 2015).

Clams were not only an important staple of TWN diet (Goodman, 2020), but were of high cultural and economic importance for many First Nation groups living along the coasts of the Pacific Northwest (The Clam Garden Network, 2015; UBC Coastal Adaptation Lab, 2020; Trost, 2005; Lepofsky and Caldwell, 2013; Groesbeck et al., 2014; Lepofsky et al., 2015; Smith et al., 2019; Morin, 2015).

Before contact, the intertidal shores of the Burrard Inlet used to be covered in clam beds (George and Hyland, 2018; Morin, 2015; Goodman, 2020, 2016). Especially, the shellfish beds on the shores of the SW reserve and Maplewood Flats were intensively used by the TWN. The beds in front of the reserve still exist but are neither in harvested nor maintained (Morin, 2015).

Besides middens, structures have been found on beaches that are visible during low tide, recognizable by flat beach slopes and some form of a stone wall at the lower end of the beach (Goodman, 2020, 2016; The Clam Garden Network, 2015; UBC Coastal Adaptation Lab, 2020; Shore, 2016; Augustine and Dearden, 2014; Caldwell et al., 2012; Salter, 2018). The formations are often indicated as “clam gardens”, as they would enhance clam shell growth and thus be a reliable source of nutrition for the First Nations. However, according to some sources, the term “clam garden” is unjust as the clam gardens would provide the people with much more sources of food than just clams, such as sea cucumbers, sea weed, crustaceans and migrating fish (The Clam Garden Network, 2015; Thomson, 2015; Lepofsky and Caldwell, 2013; Groesbeck et al., 2014; Deur et al., 2015). With this in mind, the term “clam garden” will be used to address the sea terraces described here.

By analysing middens, the species abundance and moment of harvest can be determined, as well as the allowed size of the clam harvest. Investigation of other artefacts found in middens can deepen knowledge about how clam gardens were maintained and better the understanding of traditional beliefs and knowledge that form the base of the strong connection of the Indigenous People with the waters and lands they live in harmony with (Lepofsky et al., 2015; Goodman, 2016; UBC Coastal Adaptation Lab, 2020; Toniello et al., 2019). Next to orally transmitted knowledge, both clam garden and middens are an important connection to past generations and traditions for the TWN (Taleghani et al., 2019).

Another added value that is thought to be obtained by a the construction of a clam garden, is that the extension and change in slope of the beach will affect incoming waves that have caused problems in the project area. During higher tides, the walled structure and extended beach would function as a submerged breakwater which is expected to dissipate wave energy and mitigate bank erosion.

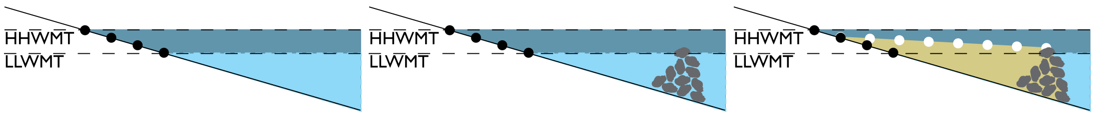
Adaptation capacity is another strength of the clam garden: on several beaches multiple terrace levels have been observed which are thought to be coping measures of past fluctuations in sea levels. The height of the rock wall can be adjusted or a new wall can be built at a higher or lower location on the beach, dependent on the change of sea level and tidal ranges (Neudorf et al., 2017).

Ramsdell et al. (2011) also found that shells can shield substrates such as sand from erosion (Ramsdell et al., 2011).

Therefore, revival of existing clam beds through the creation of clam gardens and reintroducing the practice of clam harvesting has not only the potential to be of high cultural value for the TWN, but also to mitigate coastal problems caused by climate change that are already manifesting in the project area.

## 9.1. Technical feasibility

The practice of constructing and maintaining clam gardens is a tradition of which the knowledge has been partially lost when several generations of First Nation children were forced to attend residential schools, see also Section 2 (Wilderness Comittee, 2020; Goodman, 2016). In the past decades, efforts have been made in restoring knowledge by interviewing Elders and performing fieldwork (The Clam Garden Network, 2015).




(a) Phase 0: Initial beach conditions - The initial intertidal zone is indicated with black dots

(b) Phase 1: Building of a stone wall to trap the sediments

(c) Phase 2: Established clam garden - The enhanced intertidal zone is indicated with white dots

Figure 9.1: The three phases of establishing a clam garden

### 9.1.1. Construction

A clam garden was created by placing a pile of stones at the lower end of the intertidal zone to construct a rock wall. Behind the rock wall sediments would be trapped, changing the slope of the beach, creating a sandy or muddy flat that is the ideal growing ground for clams (see Figure 9.1). The gardens were managed by individuals of the community, but accessible by anyone of the community who would ask for permission for access. While harvesting clams, only clams over a certain size were harvested, leaving room for growth for younger clams. By harvesting with a digging stick, oxygen could access the sediments, further favoring growing conditions for developing clams. Emptied clam shells were deposited on the beach. This shell hash further improved chemical conditions in the water and soil and guaranteed maintaining a coarse substrate. The broken shells would also release chemicals in the water: a signal to stimulate young clams to settle themselves nearby (The Clam Garden Network, 2015; UBC Coastal Adaptation Lab, 2020; Thomson, 2015; Holmes, 2016; Salter, 2018; Groesbeck et al., 2014; Neudorf et al., 2017; Smith et al., 2019). Maintaining the clam garden also meant keeping the area clear of rocks, debris and vegetation to prevent suffocation of the clams in the substrate below (The Clam Garden Network, 2015; UBC Coastal Adaptation Lab, 2020; Thomson, 2015; Holmes, 2016; Salter, 2018; Groesbeck et al., 2014; Neudorf et al., 2017; Smith et al., 2019).

### 9.1.2. Design guidelines

Most clam gardens are found in semi-protected inlets with strong tidal currents (Groesbeck et al., 2014; Neudorf et al., 2017). They were created by clearing beaches of rocks and debris: rocks found on the beaches, ranging in sizes from baseballs to basketballs (The Clam Garden Network, 2015; Holmes, 2016), were placed at the lower end of the intertidal zone, around the LLWMT level at the time of construction (UBC Coastal Adaptation Lab, 2020; The Clam Garden Network, 2015; Caldwell et al., 2012; Lepofsky and Caldwell, 2013; Groesbeck et al., 2014; Neudorf et al., 2017; Mathews and Turner, 2017). Sediments would be trapped behind the wall and change the slope of the beach to range between 5 to 20 % (UBC Coastal Adaptation Lab, 2020; Groesbeck et al., 2014). This slope change would increase the length of the beach and enlarge the surface that was at ideal clam habitat level, which is assumed to be in the upper part of the lower half of the local tidal range (Groesbeck et al., 2014; Goodman, 2016; The Clam Garden Network, 2015; UBC Coastal Adaptation Lab, 2020). The height of the wall would gradually be increased and the wall would be maintained during usage to prevent collapse or correct sinking (Tomkins, 2020). Evidence has been found that clam gardens were created in single engineering events as well (The Clam Garden Network, 2015; Groesbeck et al., 2014). The ideal height of the wall would depend on the local height range of the clam habitat range and the local tidal levels (Goodman, 2016; The Clam Garden Network, 2015; UBC Coastal Adaptation Lab, 2020). Clam gardens have been found to be built on both bedrock and mudflat foundations, so walls were designed and maintained to work on both substrates (Tomkins, 2020).

At beaches around the Salish Sea where clam gardens were found, the ideal clam habitat was estimated to have been between 0.6 and 1.8 m above current LLWMT with wall heights between 0.63 and 2.52 above current LLWMT (Groesbeck et al., 2014; Neudorf et al., 2017; Smith et al., 2019).

### 9.1.3. Maintenance guidelines

Maintaining a clam garden requires community participation for regular harvesting of clams and clearing the area of rocks, debris and vegetation to keep clams from suffocating. By maintaining traditional harvesting practices, where only shells above a certain size would be harvested and the digging in the soil introduces oxygen into the lower lying sediments, younger clams would get enough space and oxygen to grow. Research has shown that this can result in up to four times higher densities of clams per square meter and up to two times higher growing rates of the clams in clam gardens(The Clam Garden Network, 2015; Augustine and Dearden, 2014; Salter, 2018; Goodman, 2016; UBC Coastal Adaptation Lab, 2020; Deur et al., 2015).

Another way in which the clam gardens were maintained, was by adapting the garden to changes in water levels: evidence has been found that the the stone walls would be moved or rebuilt as a response to changing tidal ranges (Neudorf et al., 2017). This strategy can also be applied by the TWN taking the projected changes in water level into account, as described in Section 4.1.1.

### 9.1.4. Clam garden design

The guidelines discussed above have led to a design for the two normative cross-sections. Design choices for each alternative is motivated below. Besides the construction of the wall and placing the sediments, the installation of the clam garden also includes the placement of a shell hash layer of several centimeters over the length of the garden. The substrate, including this shell hash layer, will be overturned as mature clams are placed into the substrate ($1kg/m^2$) after construction to stimulate young shells to settle in the clam garden.

**Canoe Shed cross section**

This dimensions of the clam garden designed for the Canoe Shed cross section are based on current water levels and depicted in Figure 9.2,. The toe of the clam wall is located at the LLWMT level of $-1.7$ m, at a cross shore distance of approximately $160$ m. The wall is located just left of the small elevation in bed level at the left end of the shelf.

The MSL lies at a height of $0.1$ m CGVD28 at a cross shore distance of $260$ m, and the clam garden is designed to end at this level.

Over 100 metres, a height difference exists of $1.84$ m. This results in a potential beach slope of around $2\%$ between the two points.

Since both the height difference between the begin and end point of the garden is small, and the is wall designed to be located near a local high point, the design height of the wall is, at $0.6$ m, chosen in such a way that it is slightly higher than the local high point and at the lower end of observed clam garden wall heights. To adapt to changes in water levels, the height or location of the wall can be adjusted.

**Big John Creek cross section**

The design for the Big John Creek cross section is depicted in Figure 9.3. The dimensions are based on location specific features, such as the aquatic vegetation, and current tidal elevations. The wall is located on the LLWLT line at a depth of $-2.8$ m, just right of the present aquatic vegetation (see Figure 3.5), at a cross shore distance of $92$ m. The garden is designed to end at the MSL water level of $0.1$ m, at a distance of $128$ m.

This means that a height difference of $2.9$ m is covered in $37$ m. To obtain a beach slope of $5\%$, the wall should have a height of $1.1$ m, which lies within the range of found clam gardens. With this wall height, the top of the wall reaches an elevation of $-1.7$ m, which corresponds to the LLWMT level. With this design, the area that lies between LLWMT and MSL water level, which is at ideal clam habitat level,

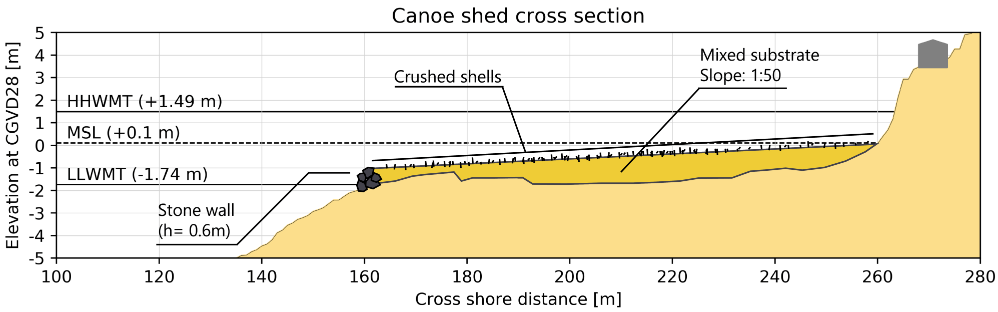



Figure 9.2: Design of clam garden at the Canoe Shed cross section. A small wall has been built around X = 160m and traps sediments from a level of $-1.1m$ up to $+0.1m$. The sediments that lie on top of the original bed are indicated in a darker shade yellow. On top of this layer, shell hash is placed to maintain a rough substrate. All the way to the right, in grey, the location of the canoe shed is displayed.

is extended with about 20 metres. With changing water conditions, the height and location of the wall can be adjusted.

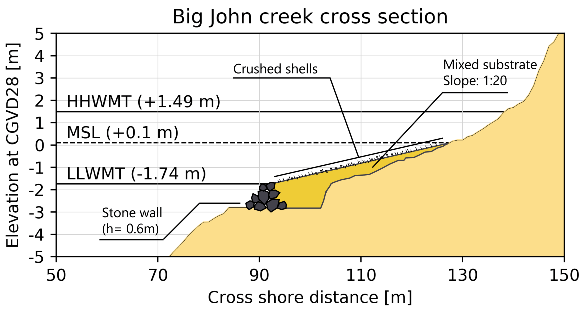



Figure 9.3: Design of clam garden at the Big John Creek cross section. A small has been built around X = 90m. Behind the wall, sediments have been placed which are enriched with shell hash at the top

**Map overview**

In Figure 9.4 the location of the clam garden in fron of the Sleil-Waututh reserve are displayed. On the left hand side of the reserve, the extents of the clam garden lie between elevations of $-1.7$ and $0.1$ m. Halfway the Canoe Shed and Big John Creek cross sections, the elevations extents increase to $-2.8$ and $0.1$ m. Despite the enlarged range, the clam garden on the right side of the reserve remains smaller than those on the left side.

### 9.1.5. Model set-up

To test the effect of the clam garden on incoming waves, an X-Beach model has been set up. In this model, not only the effect of the changes in cross section elevations are simulated, the roughness of the clam garden surface is taken into account as well. The roughness has been simulated with the properties as described in Table 9.1.

The values for the shell height (*ah*) and width (*bh*) are based on the assumption that emptied broken shell pieces were placed back into the substrate to maintain a coarse substrate. Since the average sizes of adult clams can vary from 5 to 12 cm, broken shells are assumed to be a fraction of that (Traditional Animalfoods, 2019; Dethier et al., 2006).

Due to accumulation of shell hash over time, it is assumed that the broken shells will not cover the whole surface but occur regularly. To simulate this, a density of 500 units per square meter has been chosen as a value for *Nv*.

Since the shells are placed in the sand anthropologically, it is assumed that the shells will stand right up initially, but will be covered by sediments and assume a flatter position due to tidal water

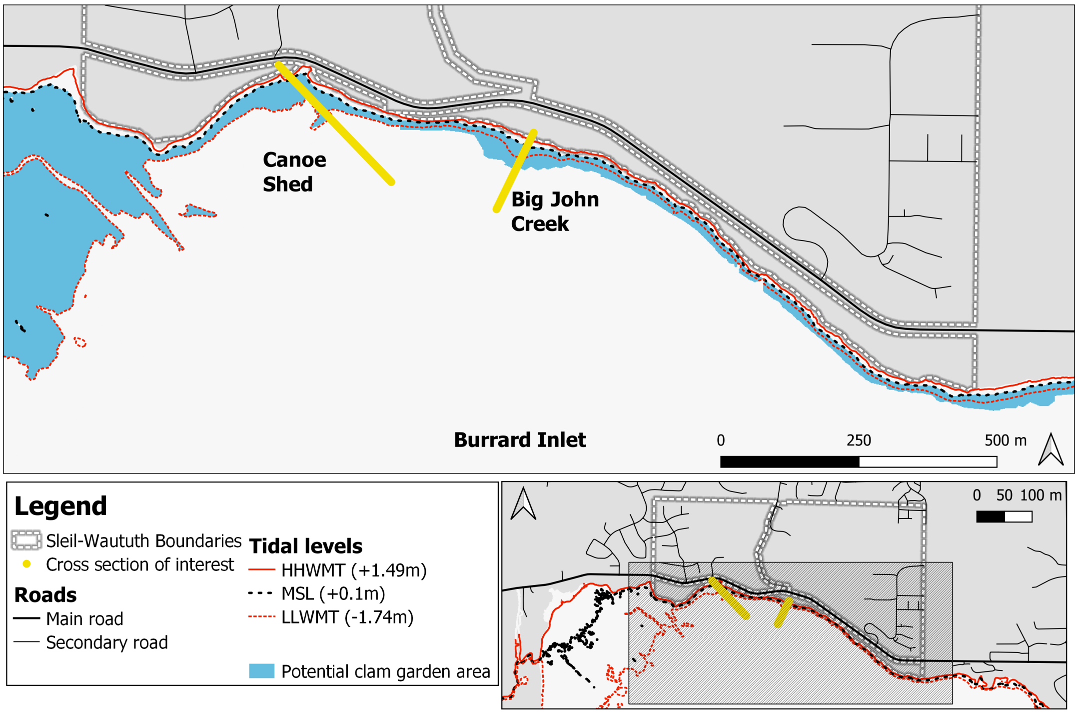



Figure 9.4: Map overview of the clam garden extents in front of the Sleil-Waututh reserve. The potential clam garden area is indicated in blue. At the left side of the reserve, a shelf exists between MSL and HHWMT level, which is an ideal location for a clam garden. More to the right, this shelf becomes shorter. Here, the wall is placed below HHWMT level. The height of the wall increases, just as the length of the indertidal zone

movements. Since the drag coefficient (*Cd*) partially depends on the shape of the object, the choice has been made to choose a value that lies between the *Cd* of a streamlined half-body (0.09) and an angled cube (0.80) (Ramsdell et al., 2011). Between these two values, a *Cd* of 0.5 has been chosen to simulate the roughness of the clam garden surface.

The models will be tested to the scenarios as described in Section 6.

Table 9.1: X-beach parameters to simulate the roughness of the surface of a clam garden

| Symbol | Value | Description |
|---|---|---|
| *ah* | 0.03 | Shell height [m] |
| *bh* | 0.02 | Shell width [m] |
| *Nv* | 500 | Density (units / $m^2$) |
| *Cd* | 0.5 | Drag coefficient |

### 9.1.6. Model results

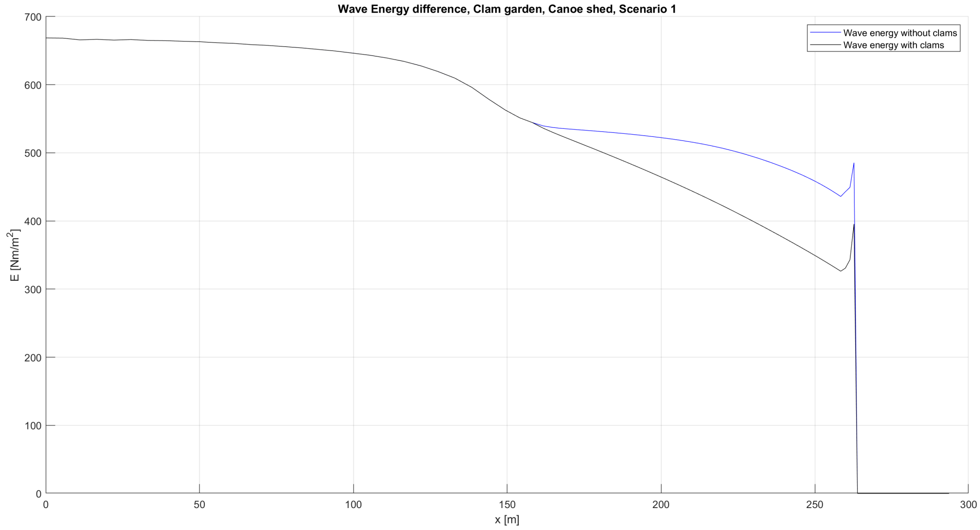
The results of the X-beach model are presented per cross section. Each cross section design is subjected to two scenarios as described in Section 6. The Wave Energy difference output can be found below and will be compared with the Base case in Section 6.4. The model setup of both cross sections and scenarios along with the Wave Impact can be found in Appendix I.

#### Canoe Shed

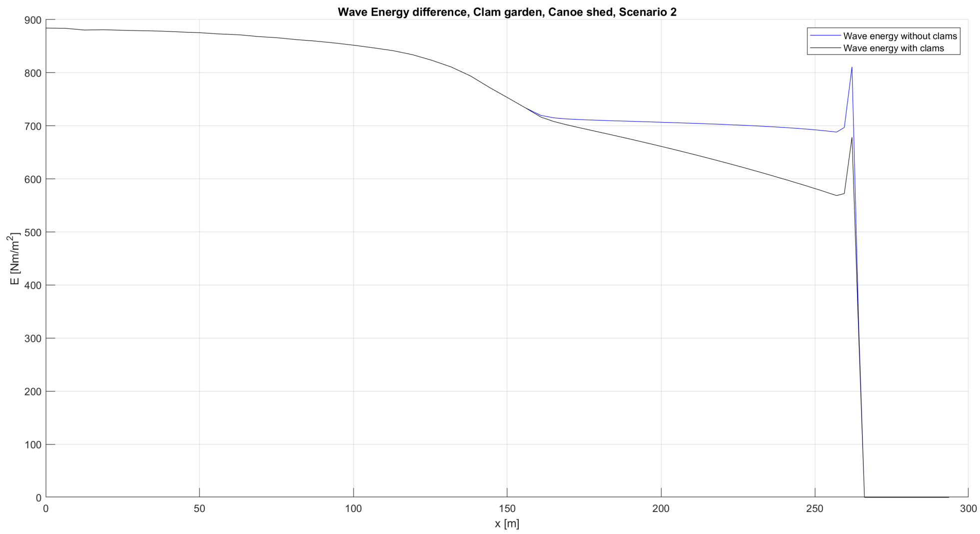
Figure 9.5a depicts the wave energy for scenario 1. It compares the energy that is dissipated over a clam garden without clams and a clam garden with shell hash, which has a rougher bed surface. Due to the addition of clams, the wave energy dissipates faster but not earlier down the beach.

Figure 9.5b depicts the wave energy for scenario 2 and compares the energy dissipated over a clam garden with and without shell hash.

When comparing both figures to the base case of the Canoe shed cross section, in Figure 6.10b, a strong decrease in wave energy is observed for both cross sections with and without clams. The location of the breaking point does not significantly change.




(a) Comparison of wave energy in the Canoe shed cross section in Scenario 1 for a clam garden without a rough substrate (covered in clams) and with a rough substrate, respectively in blue and black




(b) Comparison of wave energy in the Canoe shed cross section in Scenario 2 for a clam garden without a rough substrate (covered in clams) and with a rough substrate, respectively in blue and black

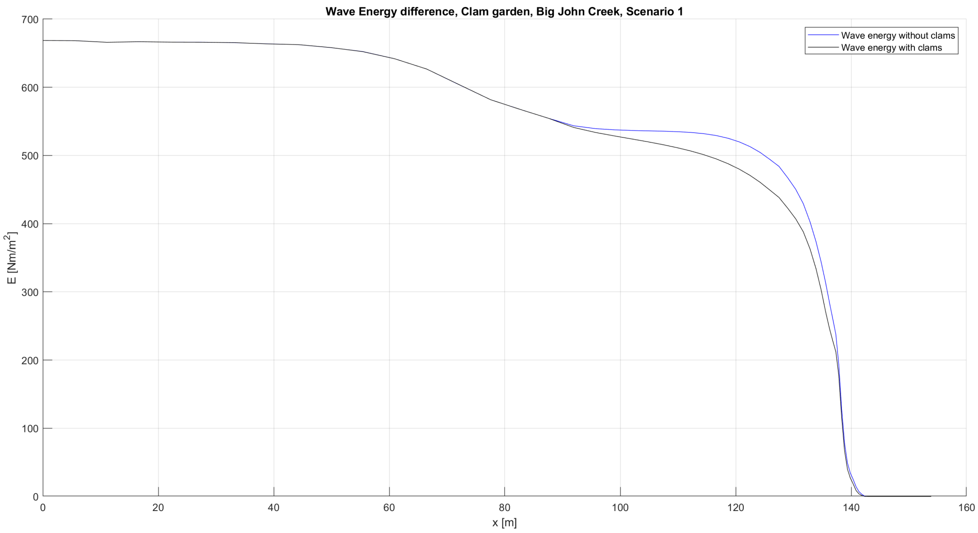
Figure 9.5: X-beach wave energy modelling results of the Canoe shed cross section for scenario 1 & 2

**Big John Creek**

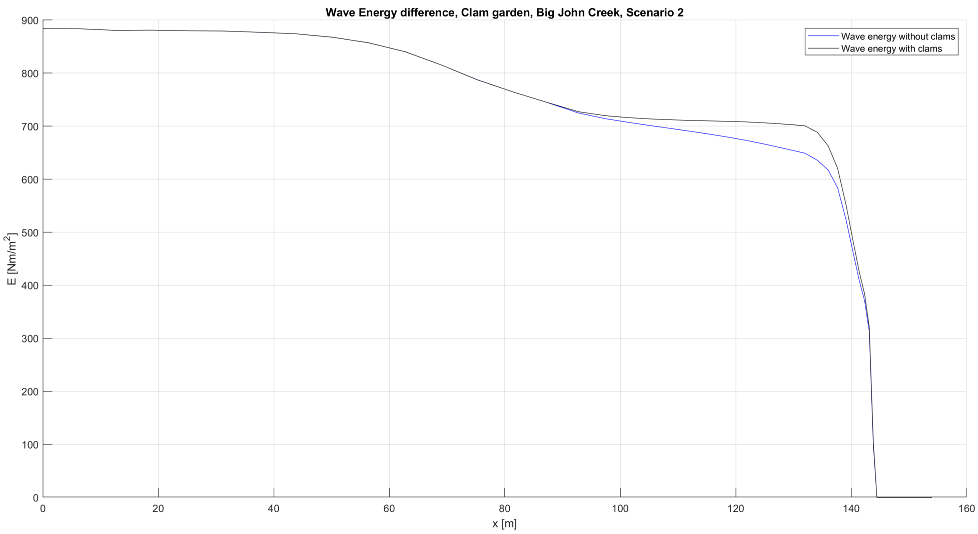
Figure 9.6a compares the wave energy of scenario 1 in the Big John creek cross section of a clam garden with and without shell hash. Shell hash decreases the total wave energy that hits the cross section.

Figure 9.6b shows the difference of wave energy in scenario 2 in the Big John creek cross section. The energy difference between a clam garden with and without shell hash is compared and a decrease can be observed, but no change in breaking point.

Comparing both figures to the base case (Figure 6.9b), a subtle decrease is observed.




(a) Comparison of wave energy in the Big John creek cross section in Scenario 1 for a clam garden without a rough substrate (covered in clams) and with a rough substrate, respectively in blue and black




(b) Comparison of wave energy in the Big John creek cross section in Scenario 2 for a clam garden without a rough substrate (covered in clams) and with a rough substrate, respectively in blue and black

Figure 9.6: X-beach wave energy modelling results of the Big John creek cross section for scenario 1 & 2

## 9.2. Environmental feasibility

In the past, an abundance of clams throughout the Burrard Inlet has been recorded, implying that the living conditions in the nearshore waters were sufficient for clams to survive and even thrive. Since the clams already grew on clam beaches, there was no need to construct clam gardens (Morin, 2015; Hawker, 2020; Tomkins, 2020).

A modern-day clam garden is located in the Burrard Inlet near the shores of Belcarra (see Figure 3.6). It seems that the waters in the area are still suitable to inhabit the growth and survival of clams (Hawker, 2020).

### 9.2.1. Climate restrictions

As mentioned in Section 3.3.2, clams prefer water temperatures ranging from 6 to 22 °C and salinity levels over 25 PSU. Additionally, they prefer waters with a pH over 8 for ideal shell formation. Below this pH level, shellfish mortality rates increase as shells are dissolved by the acidity of the water, as is described in Section 3.3.3. In the inlet, other concerns exist regarding water quality and contaminated sediments caused by industrial and anthropological discharges. Following traditional harvesting practices, the clams are dug out by turning over the substrate. If the substrate contains earlier precipitated contaminants, these can be reintroduced to the waters by being turned over, aggravating the water quality (Hawker, 2020). This is especially bad as the water quality in the inlet is at the moment already of such a level that clam harvesting is forbidden as the consumption is deemed dangerous for human health (Pierson, 2011; Haggarty, 1997). Based on the fact that the clam garden at Belcarra is viable, it is assumed that the water quality and acidity levels are still within a suitable range for the clams to survive.

Opposite, clams can impact water quality as they are filter feeders. Clams are able to filter contaminants and nutrients out of the water, thus improving the water quality (Dethier et al., 2006). The size of the effect on the water quality and filter rates remain uncertain (Dethier et al., 2006).

Another potential impact the presence of clams can have on water quality, is through the discarding of shells in the clam garden. As mentioned earlier in this chapter, shell hash was often added to the substrate in the clam garden to maintain a coarse substrate. Some studies suggest that these shells could function as a pH buffer as well, locally mitigating acidification of the surrounding waters caused by climate change or anthropogenic discharges (Kelly et al., 2011; Waldbusser et al., 2013; Ekstrom et al., 2015; Mathews and Turner, 2017), though Doyle (2017) did not find a significant impact of shell hash on pore-water conditions (Doyle, 2017). This suggests that more research is needed concerning the pH buffering capacity of shell hash.

### 9.2.2. Ecological aspects

Following harvesting and maintenance practices, the clam gardens are kept clear of vegetation, rocks and other debris that could suffocate clams in the underlying substrate. This means that biodiversity would decrease. On the other hand, the walls at the lower end of the garden become a place rich in vegetation, such as sea cucumbers and seaweed, crustaceans and resident and migrating fish fish (Goodman, 2020, 2016; The Clam Garden Network, 2015; Thomson, 2015; Isabella, 2011; Lepofsky and Caldwell, 2013; Groesbeck et al., 2014; Deur et al., 2015; Doyle, 2017).

Concluding from the available data (Figure 3.5), no vegetation occurs in the Canoe Shed cross section, so the construction of a clam garden is expected to increase the diversity of aquatic vegetation. The clam garden design of the Big John Creek cross section is built adjacent to the existing vegetation, so this vegetation will be kept intact and potentially be positively affected.

## 9.3. Economical feasibility

In Table 9.2 a cost estimation for the construction of the Big John creek cross section is presented. The aim is to construct the clam garden in a traditional manner within a single engineering event: this means that initially, the rocks and debris that are found on the shore are used to construct the clam garden wall. With this activity, the area should also be cleared of aquatic vegetation. Before construction, an inventory of the area should be taken to estimate that sufficient material is available to build a wall of the desired size. If this is not the case, additional materials to build the wall should be acquired. In the cost estimate, these costs are included.

After construction of the wall, the area will be filled with a mixture of fine and coarse material. Finally, clams and shell hash is added into the substrate.

Further research is needed to determine how many hours should go into the maintenance and harvesting practices should be to maintain the structure and favour the clam growth. Costs for these activities can be reduced if they are conducted on a voluntary basis.

## 9.4. Legislative feasibility

Based on the analysis of the stakeholders and legislative framework in Section 5, the following Acts are important for the project's implementation:

- **Water Act**
  The Water Act is regulated by the Regional Water Management Office of MELP. (Ministry of Environment, Lands and Parks) It contains regulations about periods where construction may be un-

Table 9.2: Overview of the estimated costs for the construction and maintenance of the proposed clam garden design in Big John Creek. Bulk price estimations of rocks from Home Advisor (2020); substrate price estimations from Sharecost (2020); shell hash price estimation from Myco Supply (2020); clams price estimation from Lobsterman (2020); average salary in Canada per hour from Neuvoo (2020)

| Construction | Units | Cost per unit (CAD) | Quantity | Total (CAD) |
|---|---|---|---|---|
| Sand/gravel | $m^3$ | 20 | 20 | 400 |
| Rocks (wall) | $m^3$ | 65 | 1.2 | 78 |
| Shell hash | $m^3$ | 100 | 37 | 3700 |
| Clams | kg | 10 | 37 | 370 |
| Transport of sediment | t (tonne) | 7 | 35 | 245 |
| Worker salary | hour | 18 | 16 | 288 |
| Equipment | hour | 140 | 4 | 560 |
| Site preparation | per meter | 100 | 1 | 100 |
| Monitoring | year | 100 | 5 | 500 |
| Maintenance | year | 100 | 5 | 500 |
| Unforeseen | 3% | | | 205 |
| **Total project costs (CAD)** | per meter | | | 7046 |

dertaken. It can therefore restrict the construction activities. The federal Department of Fisheries and Oceans (DFO) and provincial Fish and Wildlife may review and comment on construction proposals.

- **Canada Fisheries Act**
  The federal Department of Fisheries and Oceans conducts the Canada Fisheries Act, which express that all work in rivers and oceans inhabited by fish requires approval. Under this Act the management of many fish species is done by the provincial Fish and Wildlife.

- **Land Act**
  This act contains the regulations around removal of sediment. Crown Land or private land, permission is necessary of the land owner.

- **Canada Navigable Waters Protection Act**
  Transport Canada is responsible for the management of the Canada Navigable Waters Protection Act, through the Navigation Protection Program (NPP). It contains regulations that apply to every bank protection around navigable waters.

The legislative situation is actually more complicated since it is unclear whether the shoreline falls within the Sleil-Waututh boundaries. The Acts above are meant to give a first indication of involved parties and the enumeration above will probably be expanded. An overview of more Acts can be found in Figure 5.2.

## 9.5. Evaluation of Tsleil-Waututh Nation's principles

The following climate change adaptation screening criteria were developed by Kerr Wood Leidal in consultation with TWN, and will provide a useful framework for evaluating the different nature based alternatives.

- **Leadership**
  By undertaking the action to set up a project to tackle climate change induced hazards, the TWN assumes an active role to build resilience for the land of their people. By looking at innovative solutions, combining traditional knowledge and practices with modern day technology to solve future problems, they can set an example for other First Nations facing similar problems

- **Self-reliant**
  The construction and maintenance of a clam garden is traditionally performed by manual labour. With a clam garden, the TWN can take matters into their own hand: the Nation can take the responsibility in maintaining a clam garden and adapting the structure to changing conditions. In

the past it has proven to be a practice that could be sustained by a small group of people, based on traditional knowledge

- **Science-based**
  Oral history recounts the productivity of clam gardens, which has been confirmed by archaeological studies. The X-beach models show that a clam garden has the potential to decrease erosion, even under the extreme circumstances of scenario 1 and 2

- **Values-based**
  Clam gardens have no place in TWN traditions, as the Burrard Inlet already had naturally occurring rich clam beds. Clams have been of mayor importance for the Nation, and by reintroducing clam harvesting through clam gardens, the role of clams in TWN culture can be revived

- **Strengths-based**
  With the construction of a clam garden, the TWN can manage their local climate change induced hazards. Clam harvesting was of mayor importance for the Nation and traditional knowledge to maintain productive clam beds can be applied in the garden

- **Collaborative**
  Implementation of the clam garden can serve as a best-practice combination of traditional knowledge and nature-based solution

- **Cost-effective**
  If the clam garden can be built in a traditional way, with resources coming directly of the beach (boulders for the rock wall, clams from nearby beds, volunteers who perform maintenance), the construction and maintenance can be low-cost

- **Multi-solving**
  The clam garden has the potential to not only reduce coastal erosion, it can also improve water quality and potentially mitigate ocean acidification. Additionally, it is an opportunity to regain knowledge about the traditional clam garden practice and an opportunity for a communal activity, bringing together different groups of people

- **Adaptive** Evidence has been found that clam gardens were adapted to changing water level conditions by either adapting the wall height or relocating the wall higher or lower on the beach. Since this can be done manually, the TWN have the opportunity to undertake adaptive measures on their terms.

## 9.6. Conclusion

Based on the clam garden at Belcarra in the Burrard Inlet and a past record of abundance of clams in the inlet, the waters and shores of the project area are deemed to be viable living grounds for clams. The water quality in the inlet allows for clam growth, but still affects the clams in such a way that they cannot be consumed by humans. This is because of the filter feeding mechanism of clams, where clams take up nutrients and contaminants out of the water, which can improve the water quality. There is also a potential of a pH buffering capacity of clam hash in the substrate, but more research is needed regarding the effect.

Based on the X-Beach models, it is concluded that the clam garden cannot prevent coastal erosion in neither of the two scenarios, but is does help to reduce the erosion.

Maintaining a clam garden requires regular action by keeping the beaches clear of boulders, debris and vegetation and by harvesting clams. Also, the stability of the stone wall should regularly be checked and maintained. If required, the height of the stone wall can be readjusted as well and a new wall can be built to adapt to changing water levels. All of this labour can be done by members of the Nation. Community participation is required for a successful result.

The initial costs of construction are initially high compared to the other solutions. Costs can be reduced by taking building materials from the beach and slowly build up the clam garden in phases. If the construction and maintenance can be conducted as a community effort, on voluntary basis, this could even make the solution more economical feasible.

### 9.6.1. Advantages and disadvantages

Table 9.3: Advantages and disadvantages of a clam garden

| Advantages | Disadvantages |
|---|---|
| Use of traditional knowledge and practices | Regular maintenance required |
| Nature based | Erosion is reduced, not prevented |
| Self-reliant and low-entry | Clams not edible due to water quality concerns |

### 9.6.2. To keep in mind

- Clam gardens have just recently been re-discovered by modern science and little attempts have yet been made to restore them. Traditional knowledge about the construction and maintenance has partially been lost. Because of this, the clam garden should regularly be checked to see if the wall structure remains intact and to monitor the living conditions of the clams
- At the moment, clam harvesting is prohibited in the Burrard Inlet as the consumption is deemed dangerous for human health. Given that part of the value of a clam garden lies in being a source of nutrition, attempts should be made in monitoring and improving the water quality in the inlet
- The clam garden has the potential to improve water quality and mitigate acdification levels in the inlet, but further research is required to to assess the size of the impact

### 9.6.3. Comparison to hazards

Table 9.4: Hazard evaluation of the clam garden

| Hazard | Comparison |
|---|---|
| Coastal flooding | - |
| Coastal erosion | +/- |
| Intertidal area change | + |
| Ocean acidification | +/- |
| Harmful algae blooms | +/- |
| Other ocean conditions | +/- |

- **Coastal flooding**
  The clam garden cannot prevent coastal flooding
- **Coastal erosion**
  The clam garden does not stop coastal erosion from happening but reduces the amount of erosion
- **Intertidal area change**
  The original intertidal area is extended by elevating parts of the original bed bed to the intertidal range and changing the slope of the area
- **Ocean acidification**
  Clam hash has a potential to function as a local pH buffer
- **Harmful algae blooms**
  Clams can filter nutrients out of the water which can prevent algae blooms from happening
- **Other ocean conditions**
  Clams do not affect salinity levels in the waters. Since the clam garden can retain water, local water temperatures can be affected

# 10

# Alternative 4 - Nourishment

## 10.1. Introduction

This chapter discusses how coastal erosion problems can be mitigated by making use of sediment nourishments at the project site. Sediment nourishment adaptation measures are carried out by placing sediment at or near the shoreline to stabilize the coastline at locations were a loss or lack of sediment is causing erosion problems (Bosboom and Stive, 2015). Nourishments artificially replace a deficit in the sediment budget but do not stop the erosion process. Therefore, the sediment is gradually sacrificed as erosion continues and nourishments have to be replenished from time to time to maintain enough sediment in the system. Nourishments are generally only applicable for larger sections of coastline as otherwise the loss of sediment to neighbouring sections will be too large. Nourishing coastlines leaves the project area in a more natural state by using natural materials, as opposed to structures, having little adverse impact on the surroundings. Erosion rates have to be monitored to determine how much sediment should be placed and when a re-nourishment has to be carried out. A re-nourishment must be carried out when the available sediment drops below a critical level making nourishments a long-term maintenance project and not one time only project. Sediment nourishments can use sediment dredged from the ocean by dredging vessels or sediment from land-based sources moved to the project site by barges or trucks. Although, to make sediment nourishments feasible the sediment source must be close to the problem area (Bosboom and Stive, 2015; Van Rijn, 2014).

Sediment nourishments are placed for different reasons listed below (Bosboom and Stive, 2015):

- To compensate for losses as a result of structural erosion (long-term erosion)
- To enhance the safety of the hinterland against flooding and to protect the beach and bank area and properties built close to the edge of the bank to storm erosion (temporal erosion)
- To broaden a beach, create new beaches (for recreation) or reclaim large areas of new land such as artificial islands

For the TWN the first two reasons listed above are the main objectives. By reducing wave energy and creating a sacrificial beach the encountered shoreline transgression at the TWN may be reduced or even completely stopped. The shorelines of the TWN have been eroding over the past decades with in particular erosion of the banks as explained in section 4.2.2. By applying sediment nourishments shoreline transgression due to erosion and sea level rise could by stopped by adding sediment to the system, which is than gradually sacrificed. Additionally goal number three can also be satisfied when the nourishment results in a broader beach which could be used for recreational and cultural purposes.

For a beach nourishment the physical processes at the project site must be well understood to come up with a design for the nourishment. Erosion rates must be measured and sediment transport paths should be analysed to make a sediment budget for the project site, as discussed in Section 3.7, to quantify the amount of beach fill material needed per year. Morphological models are often used to model erosion rates, cross-shore and longshore sediment transport, evaluate storm impacts and predict

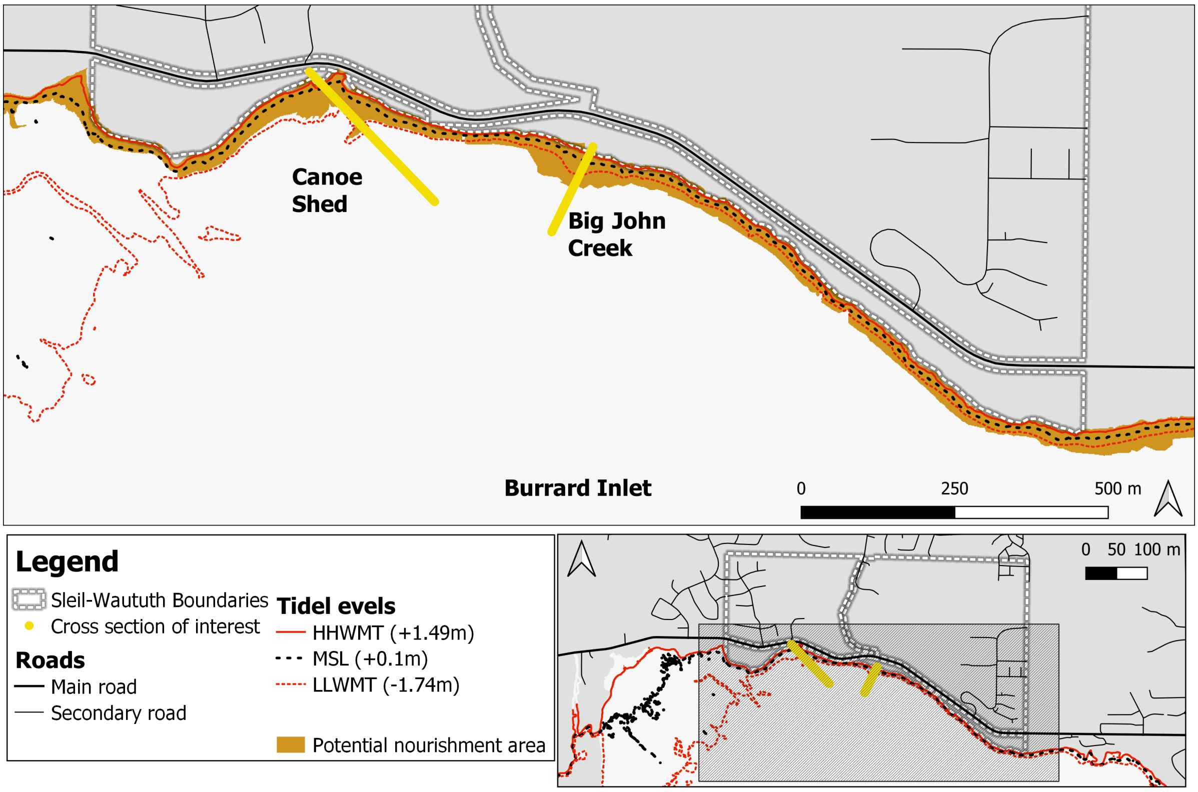



Figure 10.1: Overview potential location area of a profile nourishment for the TWN including locations of the cross-sections used in the design

the profile evolution of the beach nourishment (Dean and Dalrymple, 2002). For this project erosion rates and sediment transport rates were not measured. Therefore, guidelines for nourishment designs were used with the guidelines of the Puget Sound area in the state of Washington (Johannessen and Shipman, 2014) as main guideline as the Puget Sound area has some similar conditions as project site area. Nevertheless, morphological studies for the project site must be done to to come up with more accurate designs for nourishments based on the local conditions.

In this chapter a nourishment is designed for the two considered locations as discussed in Chapter 6; Big John Creek and Canoe Shed. first the technical feasibility is discussed where the design is made and evaluated for the proposed nourishment. Secondly the environmental impacts and consequences are discussed in the environmental feasibility. Afterwards the legislative feasibility and social feasibility of the nourishment are elaborated. Lastly the advantages and disadvantages, limitations and a comparison to the hazards from Chapter 4.2 is made. An overview illustration of the coastal cross sectional profile and corresponding terms used in this chapter can be found in Appendix J.

## 10.2. Technical feasibility

### 10.2.1. Wave climate

The wave climate can be classified based on the significant wave height $H_s$ based on yearly averaged basis. Although no yearly averaged data is available the assumption was made that the project site has a low energy wave climate, which corresponds to yearly averaged waves $H_s$ smaller than 0.6 m. This is based on wave data measured over seven months from the wave buoy of Marine labs which data is visualised in a wave rose in Figure 3.11. Besides this source, the assumption was made based on a wave model for a storm event in the Burrard Inlet in from the University of Miami which can be found in Appendix B. For low-energy coasts 10 to 50 $m^3/m/yr$ fill volume is recommended (Van Rijn, 2014) as first estimate for the design section.

### 10.2.2. Placement location of the nourishment in the cross-shore profile

A sediment nourishment can be placed at the backshore/bank, beach, foreshore or as an entire profile nourishment. The difference in placement locations in the cross-shore profile are visualised in Figure 10.2. For the design of the nourishment two different locations are further studied; the backshore nourishment and the profile nourishment. These two nourishments locations cover the eroding bank of the project site for which they can act as an eroding buffer of sediment. The backshore nourishment is placed above the intertidal zone in the backshore dry beach area. In this way the nourishment is out of reach of non-storm waves and only erodes during high water levels and storm conditions. The profile nourishment is a combination of the four locations as it is a nourishment over the entire profile from the backshore to the Closure depth. In this way less redistribution of sediment occurs in the cross-shore profile and the nourishment has a longer lifetime. The other four different nourishment locations are further elaborated in Appendix J.

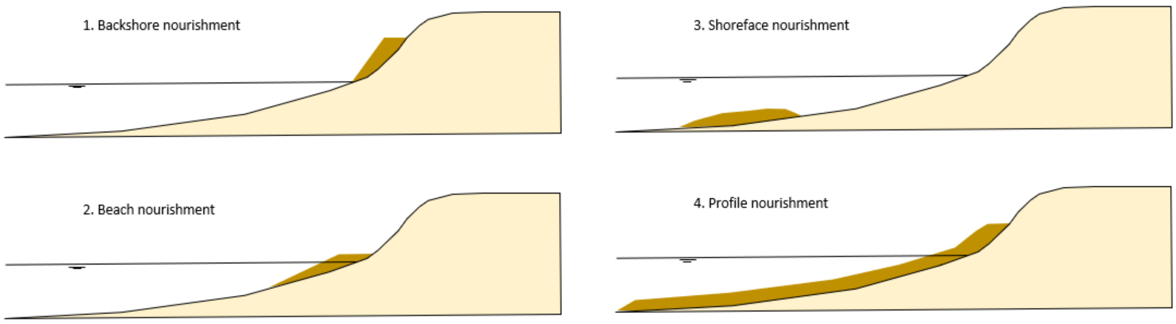



Figure 10.2: Placement locations nourishment: 1. Backshore nourishment, 2. Beach nourishment, 3.Shoreface nourishment, 4. Profile Nourishment

### 10.2.3. Sediment characteristics

Newly supplied sediment will follow the existing physical laws that dominate the morphology in the same way as existing sediment. Major changes is slopes and coastal features such as longshore sediment transport are expected if the size of the supplied sediment differs from the native material. Usually these changes are not acceptable. Therefore, the fill material should be similar in grain size and grading to the native material. Slightly coarser fill material is advisable as this will increase the lifespan of the nourishment as coarser material reduces erosion losses over time. Coarser material can also be placed on a slightly steeper slope which will remain until the fill material is removed by wave action (Bosboom and Stive, 2015; Van Rijn, 2014).

The sediment at the project site has a broad sediment distribution ranging from coarse gravel to fine sediments with large differences between surface and sub-surface sediment distributions as illustrated in Table 3.13. For the two locations where the alternatives will be placed discussed in Chapter 6 only for Big John Creek (BC Archaeology site DhRr-15) a sediment analysis is executed by KWL. Therefore, the sediment distribution and size for the Canoe Shed is for this preliminary design assumed to be similar to that of Big John Creek so that similar grain size and grading for the fill material can be used. An overview of the results is given in Table J.1.

An slight increase in sediment diameter of $25\%$ is used to increase longevity of the nourishment. This percentage is applied on the entire sieve curve of the Big John Creek sediment analyses as the sediment distribution should stay the same for the nourishment to behave similar to the native material. The resulting sediment grain sizes are given in Table 10.1. The sediment sizes for the sub-surface are used as normative sediment sizes for the nourishment. A slightly steeper Equilibrium profile will result from the coarser material used for the fill material of the sediment nourishment compared to the slope of the native material.

Table 10.1: Increased sediment analysis with 25% for the sub-surface of Big John Creek

| | $D_{16}$ [mm] | $D_{50}$ [mm] | $D_{84}$ [mm] |
|---|---|---|---|
| Sub-surface Big John Creek | 0.9 | 9.1 | 22.1 |
| fill material | 1.1 | 11.4 | 27.6 |

For Big John Creek 28% of the sub-surface material is sand and the rest of material consists out of gravel and cobble. The finer sand is mostly found in the subtidal area while coarser sediment as gravel and cobble remain high on the intertidal and supratidal beach profile. Gravel is used as the dominant sediment for the nourishment as most of the native sediment consists out of gravel. Gravel beach nourishments absorb large amounts of incident wave energy and can help form a high berm for storm protection (Johannessen and Shipman, 2014). The storm berm dissipates storm wave energy by reducing wave runup through increased friction. Gravel is more resistant to erosion and longshore transport than sand and dissipates wave energy and reduces wave runup through increased friction. The gravel used for the nourishment must be rounded in order to resemble natural beach gravel and to allow for good drainage, as well as for habitat reasons (Johannessen and Shipman, 2014).

### 10.2.4. Borrow area

Natural sand and gravel is usually dug or dredged from a pit, bank, river, lake or seabed (Lehigh Hanson Heidelberg Cement Group, 2020). The place where the sand or gravel originates from is referred to as borrow area. The Fraser river bed could be a source of fill material for the nourishment as maintenance dredging is executed in the Fraser river to ensure navigation depth (FRPD, 2017). This sediment should then be analysed whether it matches with the previously prescribed sediment characteristics. Therefore, the gravel and sand quarry company Lehigh Hanson Heidelberg cement group is chosen as supplier of the sediment. Their quarry's are in the neighborhood of Squamish and Sechelt from which they can transport the sediment to their gravel and sand aggregates depot in North Vancouver right next to the project area. From here the sediment can be transported by truck or ship to the project site depending on the volumes that have to be transported (Lehigh Hanson Heidelberg Cement Group, 2020). An overview of the quarry locations, depot and the project site location (IR#3) is given in Figure J.4. The distance between the quarry in Britannia Beach and the project site is 57 kilometers. Whether the sediment is brought from the quarry directly to the project site by dump trucks depends on the volumes needed for the nourishment. When these volumes are large it might be more economically feasible to first use barges to bring the sediment from the quarry to the depot and secondly use dump trucks to transport the sediment from the depot to the project site.

### 10.2.5. Nourishment profile shape

Equilibrium slopes for gravel are considerably steeper than equilibrium slopes for sand. Gravel tends to form a relatively steep beach profile with slopes of 1:5 to 1:10, in the vertical and in the horizontal respectively (Johannessen and Shipman, 2014). For the nourishment location in the coastal profile a backshore nourishment option and profile nourishment option are considered 10.2.2. The current coastal profile of Big John Creek and Canoe shed are assumed to be in equilibrium with corresponding slopes. This is referred to as the Equilibrium profile and is elaborated in Appendix J.

**Big Johns Creek nourishment profile slopes**

For Big John Creek, after the flat slope between x-coordinate 85-100, the slope is approximately 1:10, which is in the range of previously described beach profile slopes for gravel, after which the slope steepens rapidly to a scarp with a slope of 1:2.5. Therefore, the slope for the backshore nourishment is made 1:5 between x-coordinate 120-130 after which the slope becomes 1:10. These slopes are in the range of the gravel slopes described before. For the profile nourishment the entire nourishment slope is 1:10 which resembles the original slope. Therefore, the profile nourishment is expected to have less redistribution of the sediment in the cross-shore.

**Canoe Shed nourishment profile slopes**

The Canoe Shed has a tidal flat of circa 100 m between low tide (LLWMT) and mean sea level (MSL). After that the slope increases rapidly to a steep slope/cliff of 1:2.5. For the Canoe Shed only a profile nourishment is considered as the dry beach/backshore area is limited. The profile nourishment is placed with the same slope 1:10 as the profile nourishment for Big John Creek. This is done because the sediment used for the Canoe shed is based on the sediment characteristics of Big John Creek. Therefore, for the same wave climate and sediment characteristics a similar Equilibrium profile slope can be expected and is assumed for the design in this preliminary stage without predictions made with morphological models.

### 10.2.6. Design

The design for the nourishment for Big John Creek and Canoe shed are visualised in Figure 10.3. The design is based on the parameters described and determined in the previous sections of this chapter. The design profile is already made in resemblance of the (assumed) equilibrated profile to model the effects on wave dissipation in Xbeach as if the waves have already redistributed the sediment. The predicted behaviour of the nourishment is further explained in Section 10.2.9 and illustrated on the right in Figure 10.8. This is done so that Xbeach models wave dissipation on the predicted Equilibrium profile and not on the construction profile of the nourishment. The construction profile is made for the contractor to make placement more easy and cheaper but it does not resemble the shape the profile will eventually take.

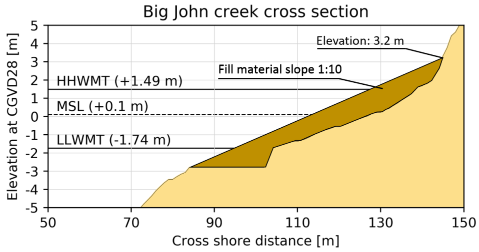
To determine until where the nourishment must reach to protect the upper beach and backshore against erosion and act as a buffer against wave attack scenario 1 is used , which is described in Chapter 6. For this scenario the wave runup is calculated in Appendix J.6 by using Hunt's formula for the $Ru_{2\%}$, which is the runup associated with the heighest 2% of the waves. This is 0.75 meter for the nourishment design with slopes of 1:10. As the nourishment main project goal is to prevent erosion from the backshore during storm waves and setup 3 feet (0.91 m) (Johannessen and Shipman, 2014) is added to the highest elevation point of the nourishment. This results in a maximum height of the nourishment at the backshore of 3.2 m, Equation 10.1.

$$Height_{nourishment,backshore} = HHWMT(1.49m) + Ru_{2\%}(0.75m) + 0.91m = 3.15 \approx 3.2m \tag{10.1}$$

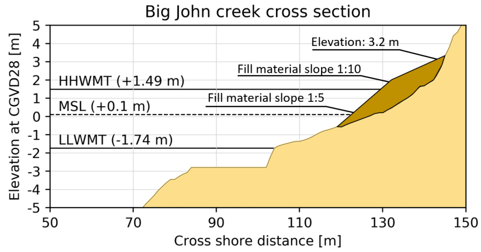
The corresponding fill volumes per meter length of the nourishment are calculated using a python script (Appendix H.2 which calculates the area between the original bathymetry and the new bathymetry including the nourishment. The results are given in Table 10.2. These volumes should be multiplied with the desired length of the nourishment for the project site. Whether the project volumes are large enough to sustain the beach nourishment for a desired amount of years can be determined the yearly erosion rates and sediment transport rates are known. But a rough estimate for low wave energy coasts is that they require 10-50 $m^3/m/yr$ (Van Rijn, 2014).

Table 10.2: Calculated volume needed for the nourishments for Big John Creek and Canoe Shed in $m^3/m$

| | volume of fill material per m [$m^3/m$] |
|---|---|
| Profile nourishment Big John Creek | 70 |
| Backshore nourishment Big John Creek | 25 |
| Profile nourishment Canoe Shed | 73 |




(a) Profile nourishment design Big John Creek




(b) Backshore nourishment design Big John Creek

Figure 10.3: The two designs for the Big John creek nourishment: Profile nourishment (left a) and backshore nourishment (right b)

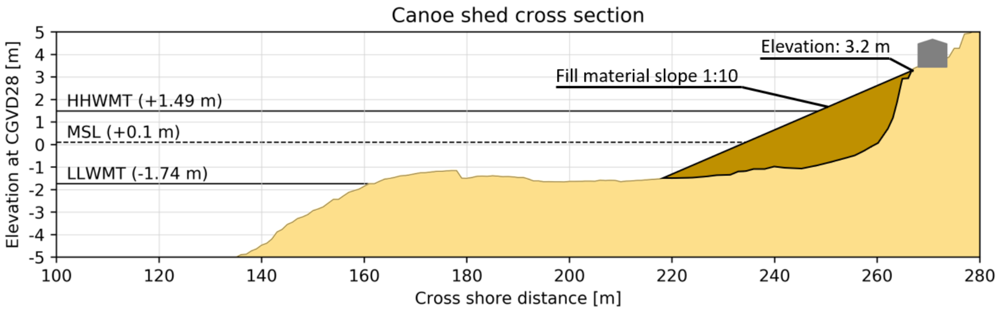



Figure 10.4: Profile nourishment design Canoe Shed

### 10.2.7. effectiveness of the nourished beach

The effectiveness of the beach nourishment is measured in the dissipation of wave energy for the different scenario's ( 1 & 2), beach nourishment placement locations (Profile nourishment and backshore nourishment) and cross-sections at the project site (Big John Creek and canoe Shed). The wave energy dissipation is compared to the original situation without the nourishment to comment on the effectiveness of the nourishment on wave energy. This is done using the Xbeach model setup as discussed in Chapter 6. In Figures 10.5, 10.6 and 10.7 the wave energy is plotted against the corresponding x-coordinate in the cross-shore direction for both Big John Creek (profile nourishment and backshore nourishment) and Canoe Shed.

**Big John Creek**

For Big John creek, in the original situation without nourishment, the wave energy dissipates gradually at the beginning from x=120 to rapid dissipation of the wave energy close to x=140. Both the profile nourishment and the backshore nourishment shift the wave energy dissipation to the left (lower x-coordinate). The location where all the wave energy is dissipated shifts from approximately x=140 to x=130. For the profile nourishment, the wave energy dissipation has an slightly less steep but very similar slope as the original wave energy line making the wave dissipation follow a more gradual decrease over the entire profile nourishment( Figure 10.5). For the backshore nourishment the wave dissipation decreases more rapidly having a steeper slope than the original wave energy line. Therefore, the energy dissipates very rapidly at once as the waves hit the backshore nourishment (Figure 10.6). Both the profile nourishment and backshore nourishment results in less wave energy reaching the bank of the project site, but for the profile nourishment the wave dissipation happens more gradually over the entire profile. Besides this, the wave energy curve is shifted more to the left for the profile nourishment than for the backshore nourishment compared to the original situation resulting in a bigger shift in wave energy.

**Canoe Shed**

For the Canoe shed, in the original situation without nourishment, the wave energy dissipates very rapidly at once with a steep line around x=260. This is the location where the slope of the bank increases very rapidly as seen in Figure 10.4. Placing the profile nourishment results in a shift of wave energy to the left and a more gradual decrease in wave energy over the cross-shore profile (Figure 10.7. Therefore, less wave energy will reach the backshore as waves will brake and lose their energy on the nourishment.

The overview of the model setup and results for waterlevels en scenario 2 can be found in Appendix J.7. From scenario 2 can be concluded that the nourishments start dissipating wave energy earlier than for the original profiles but the wave energy reaches further into the backshore than for scenario 1. This is due to the increase in water level due to sea level rise and the slightly higher wave height. To adapt to this scenario the nourishment must fill in the space created by the sea level rise as seen in Figure 10.10 which is explained in Section 10.2.11.

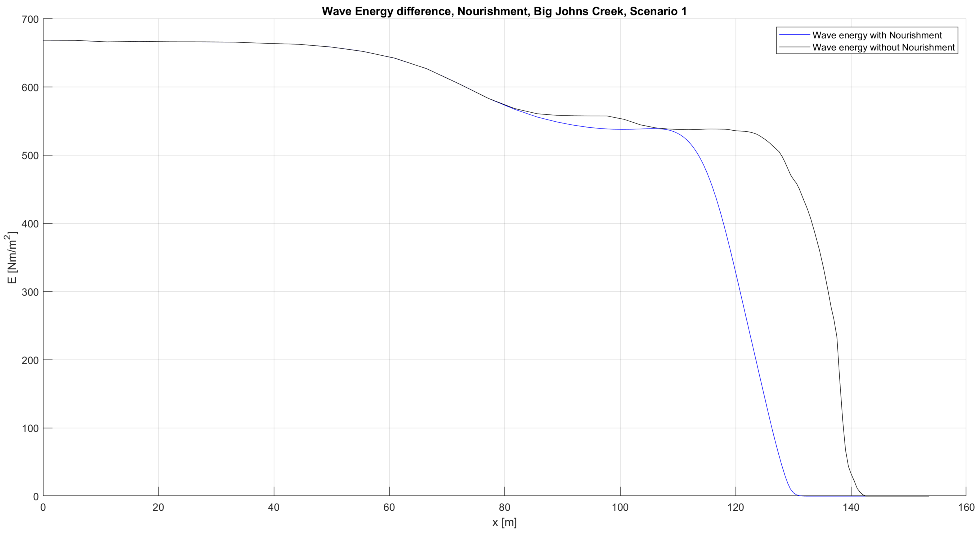



Figure 10.5: Wave energy plotted against x-coordinate for the profile nourishment design at Big John Creek

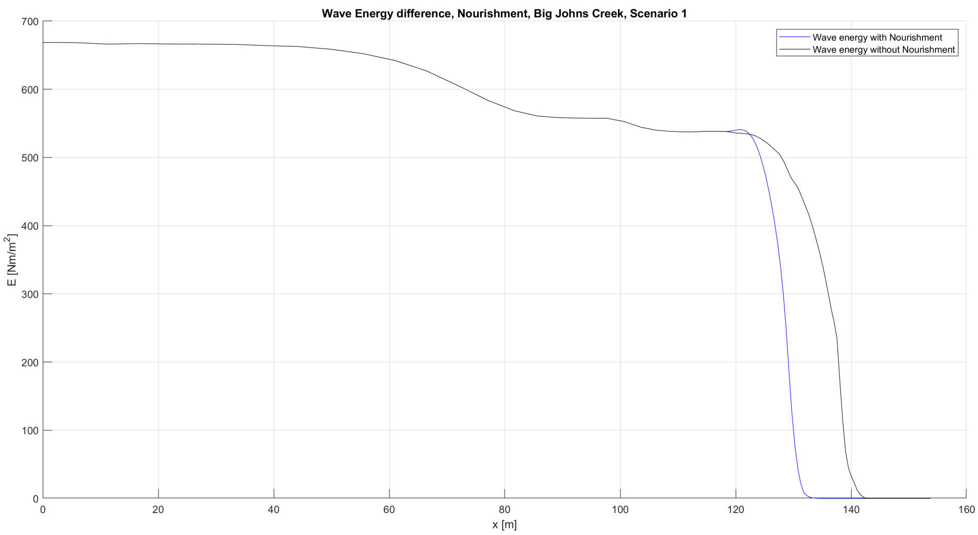



Figure 10.6: Wave energy plotted against x-coordinate for the Backshore nourishment design at Big John Creek

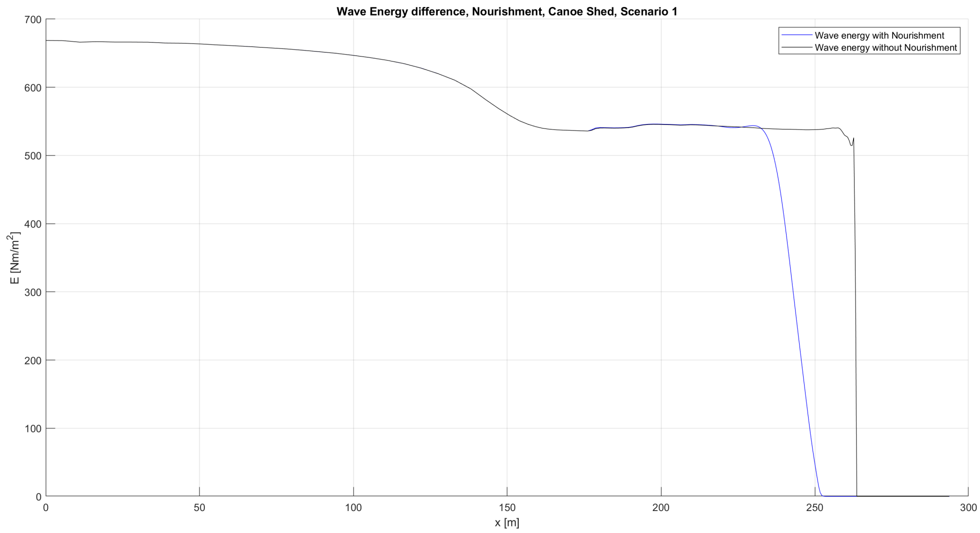



Figure 10.7: Wave energy plotted against x-coordinate for the Profile nourishment design at the Canoe Shed

### 10.2.8. Placement methods nourishment

Placement of the nourishment can be done with waterborne vessels or landborne equipment. For the waterborne vessels trailing suction hopper dredgers can be considered as they could rainbow the sediment through a high arc to the desired location within 50-150 meters from the ship and they can dispose the sediment through a pipeline to the desired location at the beach. However, they become feasible from sediment volumes of 300.000 $m^3$(H.P. Laboyrie, M. Van Koningsveld, 2018). An other option would be to use a Backhoe dredger which is a hydraulic excavator installed on a pontoon which can operate in shallow waters and can be used for sediment volumes until 900.000 $m^3$. Barges have to be used with a Backhoe dredger from which the excavator takes the sediment and places it on the beach (H.P. Laboyrie, M. Van Koningsveld, 2018). An other option for waterborne equipment could be split hopper barges. These barges split open on the bottom to dispose the sediment. However, due to their draught of minimal 3 meters when loaded they could not operate in the shallow waters of the project site (Nielsen, 2020). When using waterborne vessels landborne equipment such as bulldozers might still be needed to distribute the sediment on places which are out of reach of the waterborne vessels. Landborne placement of the sediment is done by trucks and bulldozers. The trucks bring in the sediment from the quarry or sediment depot to the project site from where bulldozers can spread and redistribute the sediment to the prescribed construction profile. Whether the backhoe dredger with barges is used or the trucks to move the sediment to the project site depends on the required sediment volumes for the nourishment.

### 10.2.9. Behaviour of the nourishment after placement

After placement of the nourishment the shoreline is usually out of equilibrium in both the cross-shore direction and in longshore direction. The fill sediment mixes with the native sediment and is distributed in longshore and cross-shore direction by waves and currents. The distribution of sediment can be categorised in three sediment transport processes illustrated in Figure 10.8; Cross-shore equilibration from the construction profile to the equilibrium profile, spread out losses due to a transfer of sediment out of the nourished area and ongoing background (structoral) erosion.

Following the Equilibrium profile reasoning, as discussed more extensively in Appendix J.2, sediment placed on the coastal profile with the same grain size as the native sediment will be distributed by waves back to the original profile. Coarser sediment however, will form a steeper slope than the original slope and finer sediment a less steep slope (Johannessen and Shipman, 2014). Therefore, the slope for Big John Creek will become slightly steeper than the measured 1:10 slope where the nourishment design shape is based on as the sediment characteristics of the used fill material are 25 % coarser than the native material, 10.2.3. How much steeper this slope will exactly become must be monitored and measured after the nourishment is placed. The spread out losses in alongshore directions depend on the length of the project. Shorter nourishment projects will tend to have relatively greater spread out losses in longshore direction than longer projects (Johannessen and Shipman, 2014). However, it is difficult to predict the morphological behaviour of a beach nourishment especially when fill material is used which differs from the native sediments. Modelling the morphological behaviour for sand and gravel mixtures could not be done for this project as Xbeach does is only intended for sand mixtures. Therefore, there is need to develop better modelling and design methods to cope with these problems and uncertainties (Bodegom, 2014).

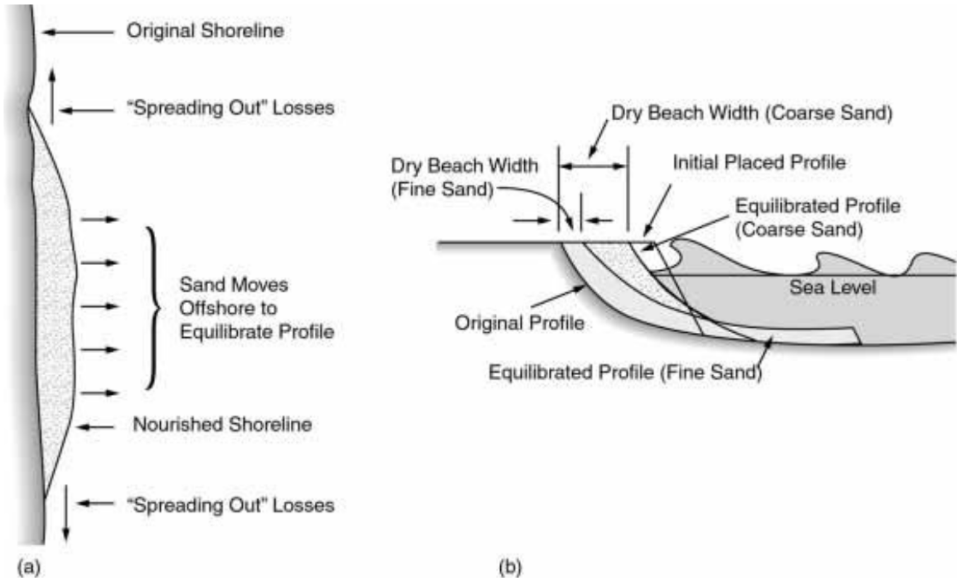



Figure 10.8: Beach nourishment behaviour after placement in plan view and cross-shore profile. (a) Plan view of spreading out and equilibration of the profile (b) Cross-shore profile view of initial placed profile and resulting equilibrium profiles for coarser and finer sediment than the native material (Dean and Dalrymple, 2002).

### 10.2.10. Monitoring and maintenance

Monitoring a nourishment is an important element for the project and determines the success of of the nourishment from an erosion control and ecological standpoint. Monitoring also determines if and when maintenance is required. Monitoring is often done on an annual basis. Additionally, taking measurements after a major winter storm can give time-sensitive information about changes in the profile due to the storm activities. Monitoring measurements include beach profile measurements and if a higher standard is desired full beach topography. By comparison of different topographic surfaces over time erosion and and accretion areas can be determined. Other monitoring measurements include characterising beach sediment along profiles, waterward vegetation line, elevation of storm and active berm crest levels and other parameters that are useful for the success of a nourishment.

As described in the previous section sediment is gradually transported away from the placement area of the nourishment. Eventually the fill material is eroded away and the cross-shore profile is back at it's original position before the nourishment was placed. This can be explained due to the fact that a beach nourishment provides new sediment to be eroded but does not stop the erosion. Therefore, after some time a replenishment of the nourishment is necessary (Dean and Dalrymple, 2002). A plan for periodic nourishment must be made for the desired lifetime. In Figure 10.9 a periodic maintenance scheme is illustrated. In this example there is a defined minimum volume that must be guaranteed. When this minimum is reached (at time t1 in Figure 10.9) a re-nourishment project has to be carried out. In this example the difference can be seen between fill material used which has the same grain size as the native material (red line). A clear difference can be seen between material used that has a smaller grain size (blue line), which corresponds to more longshore sediment transport and therefore a shorter lifetime, and material used with a larger grain size (black line), corresponding with less longshore sediment transport and therefore a longer lifetime of the nourishment. Generally a lifetime of 5-10 years is aimed at as initial costs of mobilising equipment for a nourishment project are quite high (Bosboom and Stive, 2015).

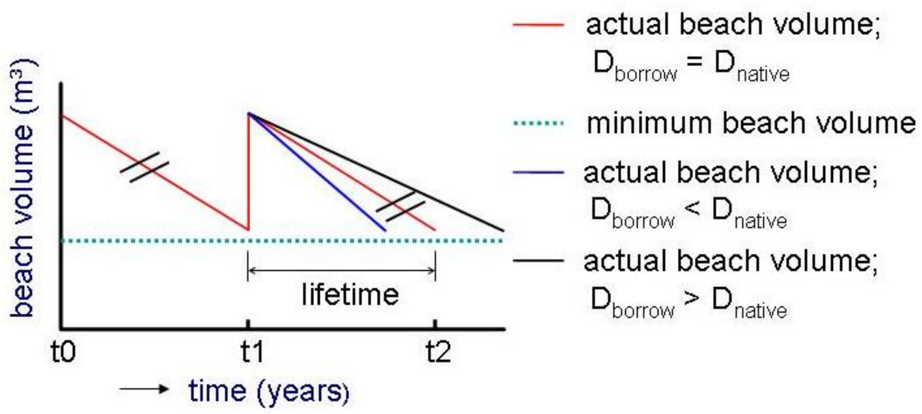



Figure 10.9: Periodic maintenance scheme for a nourishment (van de Graaff and Kroon, 2019)

### 10.2.11. Sea level rise adaptation

A nourishment can also be used to counteract structural coastal retreat due to sea-level rise. This is illustrated in Figure 10.10 where the nourishment should fill the space created by sea-level rise which is the area between the original profile and the new profile. In this way there is a balance between the sediment supply of the nourishment and sea-level rise. A rough estimation for the volume of the nourishment needed is given by multiplying the SLR with the fill distance L (Bosboom and Stive, 2015). A sea-level rise of 1 meter from scenario 2 and an apprximated fill length of 60 meter for Big John Creek and 100 meter for Canoe Shed would correspond to a volume of 60 $m^3/m$ and 100 $m^3/m$ over a time span of 100 years. This would mean 0.6 $m^3/m$ and 1 $m^3/m$ should be added per year.

The Bruun rule is often used to asses possible effects of sea-level rise. It gives a qualitative insight into the profiles response to sea level changes but is in general an over simplification as for instance the time that is required for the new equilibirum to be established is often not considered (Bosboom and Stive, 2015). Therefore, these results shoudl only guide as an indication.

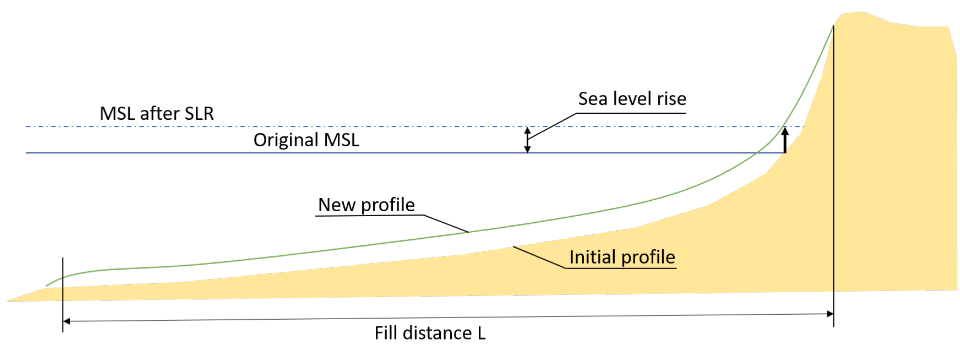



Figure 10.10: Nourishment profile adaption to sea-level rise adapted from (Bosboom and Stive, 2015)

## 10.3. Environmental feasibility

Nourishment projects mostly have to goal to control erosion by adding sediment to the shoreline. Although some nourishment projects have been developed to enhance habitats. Through the use of fine gravel various nourishment projects have created spawning habitat for surf smelt. Therefore, a combination can be made in the design for erosion control and enrichment of natural habitat. However, most design do not consider habitat enhancement and consist only out of placing a layer of sediment over the existing shoreline affecting the ecology in the riparian, intertidal and aquatic zones.

**Short-term effects**

On the short-term, covering up and burial of the marine life with the fill material results in the loss of shellfish, aquatic vegetation and animals depending on these organisms. It also disrupts species that use beach habitats or adjacent areas for nesting nursing and breeding (NRC, 1995). Construction activities also effects the habitats of marine life by the use of equipment such as dredging vessels, bulldozers and trucks to place the sediment. For instance by increased turbidity during placement of the sediment in the intertidal zone, especially during rainbowing or when using pipelines to place the sediment on the beach. An increased amount of fines that settle in the surrounding areas also have negative effects on the likes of shellfish and aquatic vegetation near the project site (NRC, 1995).

**Long-term effects**

On the long-term a nourishment leaves the project area in a more natural state by using natural materials, as opposed to structures, having little adverse impact on it surroundings. This gives opportunities for species to use the nourishment as a habitat in the long run. Using wooden debris for instance at the backshore helps grow plants which not only strengthen the nourishment but also creates habitats for other species.

Nevertheless, there has been little standardization in the design of environmental monitoring studies for nourishments and most studies that have been done have a limited duration or scope. This results in many environmental concerns remaining unresolved for nourishments (NRC, 1995).

## 10.4. Economical feasibility

For the nourishment a cost class 4 estimate is made in this section which are common for feasibility studies or preliminary design of a project. In Figure 10.3 a rough estimate is made for construction costs and maintenance costs for the nourishment based on reference projects from the Puget Sound, internet sources and expertise from KWL. Primary elements of a nourishment project include costs for design, permitting, contractor mobilization, site preparation/debris removal, sediment purchase, sediment delivery, and grading. Besides these elements, costs should be included for regular monitoring and resulting advice on maintenance if needed. The nourishment will not have the same dimensions everywhere at the project site due to site specific conditions in for instance topography and vulnerability to the hazards. Therefore, the costs are given per meter width of the nourishment in the longshore direction. Whether it is cost efficient to use waterborne or landborne equipment as discussed in Section 10.2.8 depends in the project length. The project length of the nourishment is an important factor for scaling affects of the cost analyses. For this cost analysis landborne transport and placement of the sediment by trucks and bulldozers is assumed. Besides this a lifetime of 5 years is taken for the monitoring and maintenance . For the volume of the nourishment in $m^3/m$ of the cross-sections Big John Creek is taken which equals 70 $m^3/m$. However, more additional studies should be done to determine the construction and maintenance planning with corresponding hours and costs for the nourishment.

Similar nourishments projects executed in the Puget Sound region range from 2658 CAD/meter to 5960 CAD/meter for larger nourishments with lengths ranging between 92 to 366 meters with cross-sectional placement volumes ranging from 18.8 to 31.8 $m^3/m$. The cost estimate for the nourishment falls well in this range of reference costs from the Puget Sound region.

Table 10.3: Cost analysis nourishment per meter width

| Construction | Units | Cost per unit (CAD) | Quantity | Total (CAD) |
|---|---|---|---|---|
| Sand/gravel | $m^3$ | 20 | 70 | 1400 |
| Transport of sediment | t (tonne) | 7 | 112 | 784 |
| Worker salary | hour | 18 | 8 | 144 |
| Equipment | hour | 140 | 4 | 560 |
| Site preparation | per meter | 100 | 1 | 100 |
| Monitoring | year | 10 | 5 | 50 |
| Maintenance | year | 20 | 5 | 100 |
| Unforeseen | 3% | | | 94 |
| **Total project costs (CAD)** | per meter | | | 3232 |

## 10.5. Legislative feasibility

The legislative framework in Canada is elaborated in Chapter 5 together with the complicated regulatory environment of coastal shore jurisdiction in British Columbia illustrated in the infographic of Figure 5.2. The nourishment reaches over the whole cross-shore coastal profile from below the low water mark until above high water mark. Therefore, all three jurisdictional areas (land, foreshore and seas) and jurisdictional demands of Federal, provincial and municipal should be met. From the infographic applicable acts for the design and construction of the nourishment are listed below:

- **Water Act**
  The Water Act is regulated by the Regional Water Management Office of MELP. (Ministry of Environment, Lands and Parks) It contains regulations about periods where construction may be undertaken. It can therefore restrict the construction activities. The federal Department of Fisheries and Oceans (DFO) and provincial Fish and Wildlife may review and comment on construction proposals.
- **Canada Fisheries Act**
  The federal Department of Fisheries and Oceans conducts the Canada Fisheries Act, which express that all work in rivers and oceans inhabited by fish requires approval. Under this Act the management of many fish species is done by the provincial Fish and Wildlife.
- **Navigation Protection Act**
  Transport Canada is responsible for the management of the Canada Navigable Waters Protection Act, through the Navigation Protection Program (NPP). It contains regulations that apply to every bank protection around navigable waters.

Besides these acts the TWN must consult very well with the Port of Vancouver. The Burrard Inlet waters are under federal jurisdiction by the Port of Vancouver as the waters are part of their harbour. Therefore, agreements must be made on for instance the use of waterborne vessels if necessary. The legislative feasibility is very complex as different jurisdictions and corresponding acts are applicable to the nourishment. Corresponding permits for the realization of the project should be looked into in the next step of the nourishment design.

## 10.6. Evaluation of Tsleil-Waututh Nation's principles

- **Leadership**
  The use of nourishments to protect the shoreline against coastal hazards is still relatively uncommon in Britisch Columbia. Most adaptations against hazards and especially erosion are still made from classical rip-rap or other structures. By controlling erosion by means of sediment nourishment shows that TWN is looking into the future to more adaptable and natural solutions for their coastal hazards. Besides this there is much to be learned from sand/gravel mixture beaches and how nourishments made out of sand/gravel will behave morphologically over time.

- **Self-reliant**
  The nourishment can not be made without resources and expertise from designers and contractors. Nevertheless, with the right education the TWN can monitor their beaches which would give more insight in erosion and climate change hazards affecting the nation.

- **Science-based**
  Nourishments are based on measuring, monitoring and modelling of the hydrodynamics and morphology at the project area. Every project area is different and therefore the used guidelines should be adjusted for the situation of the specific site. Traditional knowledge of shoreline transgression and visual observations of erosion from elders can significantly help designing the nourishment as there is a lack of erosion data.

- **Values-based**
  Placement of a nourishment is very adaptable. Therefore, almost along the whole shoreline of the TWN nourishments could be constructed protecting the most important areas for the TWN. Besides this the nourishment could contribute to cultural practices and values by providing broader beaches and protecting valuable areas.

- **Strengths-based**
  To make a good design for the nourishment more studies must be done on sediment transport pathways and erosion quantities at the shoreline of TWN. These studies could be started today by TWN members as much data over longer periods of time are required to ensure a reasonable level of effectiveness of a design.

- **Collaborative**
  Everywhere around the world and more locally in Vancouver organisations are developing solutions like nourishments to cope with these hazards. By working together and sharing knowledge from projects with similar conditions as at the TWN site much can be learned. The main issue at this moment is for instance how sand/gravel mixtures can be modelled morphologically as most models are only made for sandy beaches.

- **Cost-effective**
  To build a nourishment cost effectively several borrow areas must be considered. Studies could be done to determine whether the dredged sand from the fraser river could be used for the nourishment which would result in much lower costs than sediment from a quarry. Funding options must also be looked as more experience on nourishments in the Vancouver area could be beneficial for future nourishments in British Columbia and the Vancouver area.

- **Multi-solving**
  A nourishment is build with natural material which behaves according to the site conditions having having less negative effects on the surroundings compared to a structural solution. Besides this it can protect cultural areas and can broaden the beaches.

- **Adaptive**
  Monitoring and adaptability are key features of a nourishment. With changing conditions and erosion rates the nourishment can be adapted making it suitable as a long term solution.

## 10.7. Conclusion

A nourishment is primarily designed to control erosion of the shoreline by feeding sediment into the coastal system. As the erosion itself is not changed nourishments must be replenished over time when the fill material is eroded away. Therefore, sediment nourishments are not a stand alone solution but must be maintained and monitored. A nourishment executed by placing sediment at certain locations in the coastal profile resulting in a shift of the coastal profile in offshore direction. In this way not the bank of the shoreline is eroded but the fill sediment of the nourishment. Waves break earlier on the fill sediment of the nourishment directing the wave energy from the bank onto the placed nourishment. From the hydrodynamic modelling done with Xbeach the clear shift of wave energy can be seen from the bank to the beginning of the nourishment. At the TWN project site the erosion rates are not known nor are the sediment transport pathways. Therefore, the design is based on guidelines but this is no guarantee for effectiveness of the project. Besides this, the shoreline of the TWN consists out of a sandy/gravel mixture for which the morphological function of models calibrated on sandy beaches are not applicable. Therefore, more research must be done on the behaviour of these sediment mixtures to give a more qualitative design based on local data and research from the project site. Nevertheless, a sediment nourishment is a promising alternative which can provide an adaptive long-term and cost-efficient solution to coastline retreat in coastal regions.

### 10.7.1. Advantages and disadvantages

In table 10.4 the advantages and disadvantages are shown.

Table 10.4: Advantages and disadvantages of a nourishment

| Advantages | Disadvantages |
|---|---|
| Temporarily stops erosion at the shoreline | Erosion process not reduced or solved |
| Provides storm buffer | Lack of knowledge to ensure effective |
| Use of natural materials | Covers existing marine life with sediment |
| Adaptive solution | |
| Can be used to counteract sea-level rise | |

### 10.7.2. To keep in mind

- Majority of the nourishment literature is based on open coast sandy beaches with mild slopes exposed to long-period waves. Therefore, design guidelines for these coastal regions might not be fully applicable as the Burrard Inlet consists out of sandy/gravel mixture beaches and is dominated by fetch-limited waves and shipwaves.
- As erosion rates and sediment transport pathways are unknown the volume of fill sediment is based on guidelines and must be adjusted when erosion data is known.
- Ideally an erosion rate should be determined over a period of 30 or more years (Johannessen and Shipman, 2014)
- Post-project erosion rates will be greater than background erosion rates since the beach profile is moved in offshore direction (Johannessen and Shipman, 2014).
- The nourishment profile is based on the current profile and the closure depth is estimated from the bathymetry. These parameters should be determined based on data or models to be more reliable.
- To determine the performance and effectiveness of the nourishment the behaviour of the nourishment after placement under the site specific conditions should be modelled.

### 10.7.3. Comparison to hazards

Table 10.5: Hazard evaluation of the nourishment

| Hazard | Comparison |
|---|---|
| Coastal flooding | + |
| Coastal erosion | + |
| Intertidal area change | + |
| Ocean acidification | - |
| Harmful algae blooms | - |
| Other ocean conditions | - |

- **Coastal flooding:**
  By designing the nourishment to reach high up into the backshore area a storm buffer is created against storm waves and water levels. This protects and strengthens the backshore and

the bank of the shoreline. Nevertheless, this is only temporary and must be monitored extensively as longer periods of flooding could endanger the nourishment effectiveness by washing away/eroding of the sediment. The nourishment is adaptable so that subsidence and sea-level rise can be compensated for by supplying more sediment in the coastal system.

- **Coastal erosion:**
  The nourishment does not solve to coastal erosion problem itself. The nourishment acts as a sediment buffer which is eroded instead of the shoreline of the TWN. Therefore, this is a temporary solution which must be replenished over time. It is a very adaptable solution though as nourishment volumes can be changed if the erosion rates change or to adapt to the uncertain rise in sea-level.
- **Intertidal area change:**
  Intertidal area change can be reduced by placing nourishments to compensate for the rise in sea-level. Nourishments could also widen beaches for which the intertidal area will increase, altough this is not the main purpose for the nourishment elaborated in this chapter.
- **Ocean Acidification:**
  The nourishment itself has no direct influence on ocean acidification but could provide habitat living space for plants or marine life which do reduce ocean acidification.
- **Harmful algae blooms:**
  The nourishment has no direct effect on Harmful algae blooms
- **Other ocean conditions:**
  The nourishment has no direct effect on salinity and temperature changes.

# 11

# Conclusion

The Tsleil-Waututh Nation's coastline is threatened by the force of nature. Climate change causes social, ecological and coastal hazards that have a high potential of influencing the current lifestyle of the nations community. This project has mainly focused on the coastal and environmental part of the hazards which are determined mostly by 10-year wind waves of around 1.03 m and 200-year wind waves of 1.19m. Although this wave height is not large, the coastline of the TWN-reserve still has experienced erosion up to 30 m. Ship waves might play a role in this but mainly a sea level rise of 1.13 m in the last 60 years (according to TWN elder Iggy George) is the cause of the erosion. This sea level rise is the consequence of the global warming which causes other coastal hazards such as: algae blooms caused by higher water temperatures, flooding caused by sea level rise a.o., ocean acidification caused by carbon dioxide emissions and an intertidal change caused by sea level rise a.o..

To cope with these hazards four possible alternatives that could solve these hazards are investigated. These are: a rip rap revetment, a clam garden, a salt marsh and a nourishment. Each alternative is designed for two representative 1D cross sections of the TWN-reserve. One steeper cross section (Big John Creek) and one cross section with a tidal flat (Canoe shed).
A rip rap revetment provides several layers of protection, where the outer armour layer has a $D_{n50}$ 0f 0.38 m. It is concluded that the implementation of a rip rap revetment is a very effective, durable and relatively cheap way of countering erosion, however it has a negative effect on the surrounding area which has a significant impact on the community.
The implementation of a salt marsh is done by constructing a small wall in the lower intertidal area, implement sediment filling and plant vegetation. This is a building with nature solution which can not only reduce erosion due to wave dissipation by the drag coefficient of the plants, but it also enhances the upper intertidal habitats which improve the coastal and ocean conditions.
The clam shell garden is an implementation of a small wall below the lower tidal zone, some sand filling, and the plantation of clams. This building with nature solution is with the right maintenance a self-sustaining building with nature solution. It cannot prevent coastal erosion but it does reduce the amount of erosion. The filter mechanism of the clams improve the water quality by taking up nutrients and contaminants out of the water. Clams also play a big role in the history of the TWN culture so by restoring/reintegrating clam gardens the traditional and cultural benefits are significant.
The installation of a nourishment provides an long-term and cost-effective solution to the coastline retreat. Placing a nourishment will reduce the amount of erosion on the TWN coastline significantly but as a nourishment includes placing sediment on the excising bed, it damages the intertidal habitats on the short term.

Although further research has to be done, this report provides an insight in four possible alternatives that could support the process of developing a satisfactory solution for the coastal hazards that cause problems for the Tsleil-Waututh people and their reserve.

## 11.1. Alternatives overview

As stated in section 6.5 the evaluation of each alternative is done by looking at the difference in wave energy dissipation, resembling the amount of erosion that occurs. Also each alternative is weighted against a couple of feasibility studies, an overview of these findings is given in table 11.1

And finally the effectiveness of the alternatives is evaluated against the posed six hazards. An overview of these findings is given in the table 11.3.

Table 11.1: Overview feasibility studies per alternative

| | Technical feasibility | Environmental feasibility | Economical feasibility | Legislative feasibility | Evaluation of Twn's principles |
|---|---|---|---|---|---|
| **Rip rap revetment** | - No erosion riverbank.<br>- Relatively easy to construct, highly durable.<br>- History of use, many reference projects . | - Ecosystem damaged, remedial measures needed.<br>- Research needed to minimize harm to living organisms. and habitat in the ecosystem. | - Relatively cheap, good resources.<br>- Maintenance is minimum. | - Provincial and federal Acts regulate the construction of river bank protections. | - Ecosystem damaged, remedial measures needed.<br>- Research needed to minimize harm to living organisms and habitat in the ecosystem. |
| **Salt marsh** | - Erosion is not prevented but reduced.<br>- Easy adaptation to changing water levels.<br>- Significant wave dissipation due to vegetation. | - Reference projects imply viability in the given area.<br>- Enlarging edible rhizome area.<br>- Provide productive habitat for birds, juvenile fish and invertebrates | - Costs can be reduced by using material available on site and put maintenance work on voluntary basis. | - Jurisdictional demands must be fulfilled. | - multi-solving solution to assess both erosion problems as providing ecosystem services.<br>- opportunity to combine historical knowledge with innovative solutions.<br>- opportunity to motivate members of the nation to participate. |
| **Clam gardens** | - Erosion is not prevented but reduced<br>- Easy adaptation to changing water levels<br>- Regular maintenance required | - Reference case and past records indicate clam habitat suitability<br>- Clams are not edible due to water pollution levels<br>- Potential pH buffer | - Costs can by reduced by using by building and maintaining the structure in traditional manner | - Collaboration with multiple parties key to success | - Set an example by combining traditional knowledge to solve modern problem<br>- Take manner to build resilience in own hand |
| **Nourishment** | - Feeds sediment to the system to control erosion.<br>- Adaptable to increasing erosion rates and sea-level rise.<br>- Lack of knowledge to ensure erosion control and predict profile behavior.<br>- Monitoring and maintenance required. | - Damages ecosystems by covering them with sediment.<br>- Could be designed as spawning place. | - Most be repeated every 5-10 years.<br>- Large volumes of sediment needed. | - Must comply with federal and provincial regulations.<br>- Consult with Port of Vancouver . | - Provides accommodating space for cultural activities .<br>- Adaptive and uses natural materials.<br>- Innovative non-traditional solution to erosion. |

Table 11.3: Overview hazard assessment per alternative

| | **Coastal Flooding** | **Coastal erosion** | **Intertidal area change** | **Ocean Acidifaction** | **Harmful algae blooms** | **Other ocean conditions** |
|---|---|---|---|---|---|---|
| **Rip rap revetment** | - Hydrodynamic conditions do not change w.r.t current situation.<br>- Failure mechanisms of structure should be considered | - No erosion. | - Ecosystem of existing aquatic- and terrestrial life changes.<br>- Research needed<br>- Alternatives to improve ecosystem services needed. | - No direct influence. | - No direct influence. | - No direct influence. |
| **Salt marsh** | - Cannot prevent flooding | - Reduced wave energy implying reduced coastal erosion. | - Enlarging habitat area for (edible) vegetation, birds, fish and invertebrates. | - Further study needed as contradictory results are found. | - Create buffers to reduce growth.<br>-Further research needed. | -Enhancing carbon sequestration.<br>-Further research needed. |
| **Clam gardens** | - Cannot prevent flooding. | - Reduced erosion. | - Change in bed slope.<br>- Area is extended. | - Shell hash has potential to funcion as pH buffer. | - Clams can take up nutrients from water, reducing risk of HAB. | - Might affect water temperature due to water retention in structure |
| **Nourishment** | -Effective if placed at the backshore as storm buffer. | -Does not solve erosion problem itself.<br>-Fill sediment eroded instead of the shoreline. | - Counteracts sea-level rise<br>-Can broaden beaches to reduce tidal squeeze. | - No direct influence. | - No direct influence. | - No direct influence. |

# 12 Discussion

In this report measures are assessed and designed to reduce the effects and overcome the hazards associated with the coastal erosion and climate change for the Tsleil-Waututh. Literature studies, but especially talking to the local community, made a well considered overview possible of the current climate change induced social, ecological and coastal hazards. After identifying the measures to manage the climate change and coastal erosion hazards, alternatives could be designed dealing with all the hazards. These alternatives were analyzed and evaluated based on a number of feasibility studies. Some required a certain moderate level of expertise, were others were a little bit more complicated, for example the economical feasibility. Therefore, more research is recommended and an overview of the key elements per feasibility study is listed below:

- Technical feasibility is only assessed for a conceptual design, which means a preliminary design and a simplified representation. In this preliminary design phase the concept and load conditions are simplified with a deterministic approach, which does not include probabilistic or randomness in the calculations. Also joint probability on the uncertainties in the design loads needs to be included for a more realistic design proposal.
- Environmental feasibility is estimated based on information provided by KWL and an ecological study based on information that was available on internet websites and conversations with the local community. Further research and more consults of experts will give new insight of the possibilities within the different alternatives. A team of biologists, ecologists, engineers and community representatives should all be involved and work together in the discussion of developing the ecosystem in the project area.
- For the economical feasibility very rough estimations are done in order to give a first impression of the total costs of the different alternatives. However, it is important to state that most of the values are based on various internet websites and no database of a contractor or the like is consulted. Therefore, in further detailed design these numbers can change radical.
- Legislative and Social feasibility has to be checked by an expert in order to continue with the conceptual designs. Most of the acts and permits concerning the project area are briefly described per alternative. However, it is possible that not all the rules and regulations are described. Therewith as many stakeholders need to be involved as early as possible, since this will keep the possibility of parties protesting or disagreeing to a minimum. Involvement and consultation of the local community and environmental associations will be key in order to design a social/environmental valued alternative, positively influencing the current ecosystem.

Lots of aspects of the entire study project had their own difficulties and perspectives. The concept specific aspects can be found in each design Chapter. An overview of the most important notes of the full project study is listed below:

- All the alternatives are designed based on two chosen design scenarios, one with sea level rise and an extreme storm event, the other with a more common scenario in the present situation without sea level rise. However, these design scenarios are determined based on logical reasoning, but no expert validated the final scenarios. In addition, more scenarios will need to be added since the cost involved of these different scenarios will also have an important role in the decision for the final design scenario. If for example by increasing the height of the revetment the costs will only increase a bit, but the increase of the durability and safety of the structure improves considerably, this might be a better option.
- No limits for the constructability of each alternative were assumed during this preliminary design phase, which means that each design can be constructed without major construction issues. However, this is not the case, since material and equipment has to be moved towards the location, possibly damaging the project site and its locations. Also the availability of materials used and equipment/labour needed is assumed to be sufficient. By means of a cost-benefit analysis , including environmental, economical and social aspects, a best option can be chosen minimizing unforeseen expenses.
- The was no site specific sediment transport data at the project location, therefore (longshore) sediment transport processes were not included in the designs of the different alternatives. This is also the reason that no quantitatively estimate is made for the erosion problems in the Burrard Inlet IR#3. However, it is extremely important to include these cross- and longshore effects in the area study. To make a well considered estimate for the sediment budget in the coastal system, different sediment pathways, sediment sources and sinks, and processes influencing them should be determined. A broader perspective is needed for the long term solution looking at the entire Burrard Inlet. Where are the sediment sources/sinks in the Burrard Inlet? Why is there erosion at the project site? Is there a sediment sink close by? What are the possibilities?
- More analyses are possible with the data set used for the determination of ship waves at the project site from Marine Labs. Maybe these ship wakes cause more erosion on a daily basis than the design scenarios assumed as representative. Also the results are not verified by means of a field experiment. Predictions for the height of the design ship waves should be made based on a frequency analyses. Then, a model is required that can compare the erosion due to ship waves over a certain time frame with different design scenarios. However, to correctly model ship waves, one cannot use a Johnswap spectra, since ship waves are periodic and stationary, therefore not having a wave spectrum. This was unfortunately not possible in the time available for this study project.
- Two governing cross sections were chosen for the design and evaluation of the four alternatives, the Canoe shed and Big John Creek. However, the most important reason to go for these cross sections was the data availability. A well detailed cross section could be made for both profiles, but for most of the sections along the coastline of the project location this was rather difficult. Therefore, an analyses should be done for the most vulnerable locations at the shoreline and based on these results, the representative locations, and thus cross-sections, should be determined for the design of the alternatives.
- The datasets used in this study were taken as close to the project location as possible. when there was no data available, well considered assumptions are done and elaborated in each section. The used wind data set is not located at the Burrard Inlet IR#3, but at Point Atkinson, which is located at the entrance of the Burrard Inlet. The Burrard Inlet IR#3 location is far less exposed to large storms, since it is sheltered by several mountains and vegetation. However, the dominant wind direction as determined is east, which causes a more or less comparable fetch length between the two locations. Wind speeds will probably be slightly smaller at the Burrard Inlet IR#3 due to its geographical location. However, for this preliminary design phase it is assumed that for the design storms coming from the East Point Atkinson gives a reasonable dataset. The same holds for the

dataset used for the water level analysis, a CHS station located at the Vancouver Harbour. The project site is located a couple of kilometers further into the Burrard Inlet and therefore not entirely representative. Bathymetry changes, rivers, storm surge or even local wind gusts can change the hydrodynamic conditions considerably. It would be recommendable to model the hydrodynamic changes along the Burrard Inlet and validate the input parameters used in this study.

- A more advanced sediment study needs to be done about the different grain sizes that are distributed over the coast of TWN. The coastline mainly consists out of a mixed sand-gravel grain size distribution. These sediment distributions can vary locally along the shoreline, meaning different sediment sizes at different locations. In addition, the behaviour of mixed sand-gravel beach is difficult to determine as sand and gravel both have different equilibrium conditions. Especially with the nourishment, salt marsh and clam garden, the grain size characteristics should be similar to the native material in size and grading. If this is not the case, major changes in slopes and coastal features are expected.

- It is hard to validate the effectiveness over time for the nourishment, salt marsh and clam garden design, since there are not many reference projects with similar conditions and these 'nature based' concepts are relatively new. This might also mean that for the most vulnerable parts along the shoreline, a rip rap revetment or something similar might still be needed. However, this will depend on the local conditions, type of solution and the vulnerability of the location itself.

- An explorative study regarding native clam habitat requirements has been performed. Invasive clams have not been taken into account in this study. Also, as multiple sources have mentioned, clams are not the only species that benefit from the habitat a clam garden offers. The effect of a clam garden on other aquatic species such as fish or crustaceans, or on aquatic vegetation has yet to be explored.

- The study for viability of the clam garden and salt marsh are limited by the lack of data regarding water quality, salinity and temperature in the inlet. Current assumptions are based on older data that are in need of updating

- The restoration of clam gardens has only recently begun. Though results of archaeological research and interviews with Elders have brought promising information, the practice of clam gardens has not yet proven itself in terms of mitigating erosion

- Xbeach is not made for gravel beaches, so the modeling of gravel beach had to be done very carefully. This resulted in the fact that the morphodynamics could not be taken into account. Also the amount of models was on the high side. this caused problems when a scenario had to be changed or a base case cross section had to be adjusted. Finally, XBeach is not an easy program and it has no interface. This was a challenge but a fun one. It has to be said that because the erosion is not modelled with XBeach, but only the wave energy, other (easier) models could have been used too.

# 13 Recommendations

In the previous section compromises and choices were discussed, that were made to make a simplification of reality possible. Therewith, the study project showed a lot of potency for further development. The most important recommendations are:

- **Data**
  More site specific data collection in general, to verify and come up with more detailed results and designs.
- **Cross sections**
  A detailed analysis must be done to determine the most vulnerable parts of the shoreline at TWN. They must be selected among other things based on for example fetch lengths, wave exposure, erosion patterns, sediment transport data and cultural heritage.
- **Sediment transport**
  Sediment sources/sinks must be analyzed in the entire Burrard Inlet, in combination with the full bathymetry, morphodynamic models can be be made
- **Sediment grain size distribution**
  Sediment characteristics, site specific, must be gathered. Properties as size, weight, distribution, sieve curves, should be collected in order to make a detailed, long term overview.
- **Joint probability**
  The joint probability of events occurring at the same time need to be taken into account for a more realistic design proposal.
- **Ship waves**
  A frequency analysis in combination with a design wave have height over a certain period of time should be done. The results might show erosion patterns due to ship wakes from vessels sailing across the Burrard Inlet on a daily basis.
- **XBeach**
  A more thorough investigation of the possibilities of using XBeachG, Delft3D or another program for modelling of gravel beaches has to be done.
- **Ecology**
  Little data was available regarding the water quality, salinity and temperature in the inlet. This let to uncertainties in environmental studies regarding habitat suitability for aquatic flora and fauna.

  Studies regarding current flora and fauna in the inlet have been limited to native shellfish and aquatic vegetation. Taking into account crustaceans, migrating fish and invasive species, a complete overview of the ecology in the Burrard Inlet can be drawn.

- **Hydrodynamic conditions**
  There was no data available about currents in the Burrard inlet at the location of the project. These need to be known in order to make a detailed quantitative analyses about erosion and sediment transport.

- **Stakeholders**
  the Tsleil-Waututh has to keep all stakeholders involved, since executing changes to an area has an impact on all different parties. Input and feedback from stakeholders is needed in each design phase in order to successfully execute the project.

- **Final constructive**
  A study must be done to look at the possibilities of combining the positive aspects of each of the 4 different solutions, to optimize the area development on a large scale.

# A

# Community context

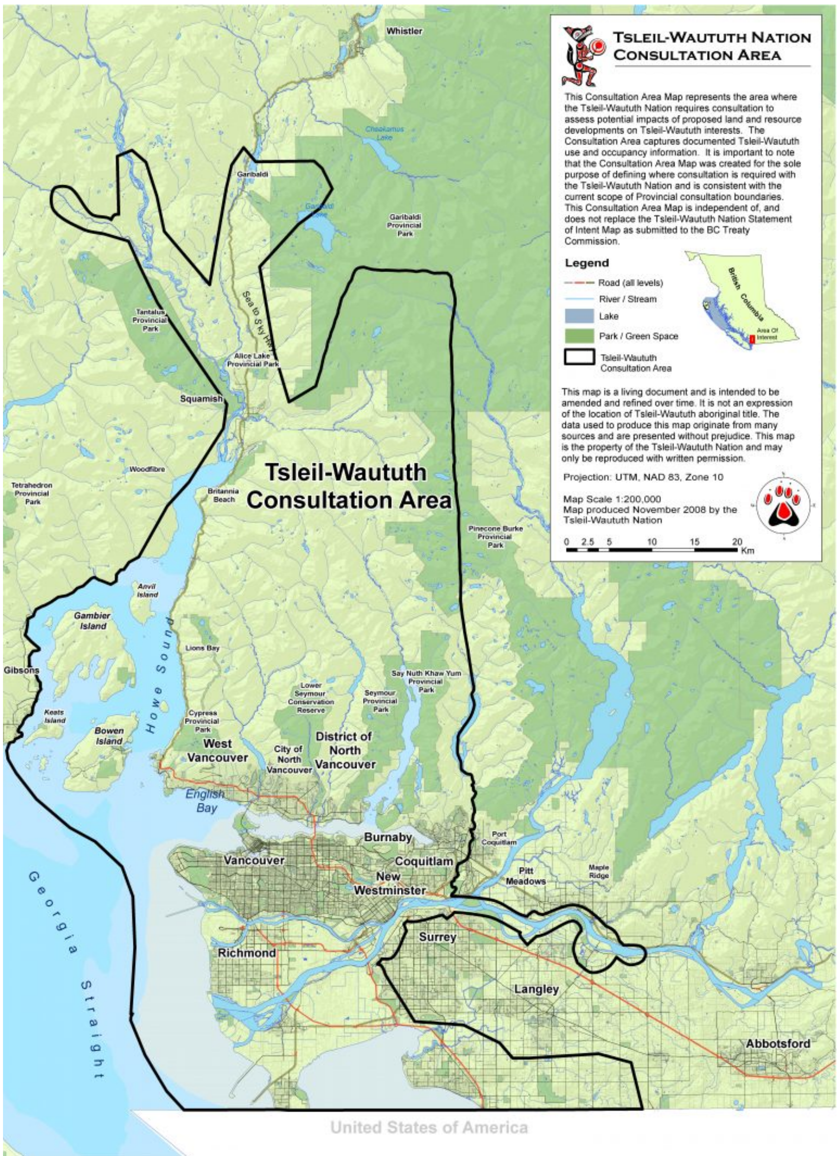



Figure A.1: The traditional territory of the Tsleil-Waututh Nation (Tsleil-Waututh Nation, 2020a)

# B

# Coastal system Characteristics

## B.1. Wave propagation in Burrard Inlet

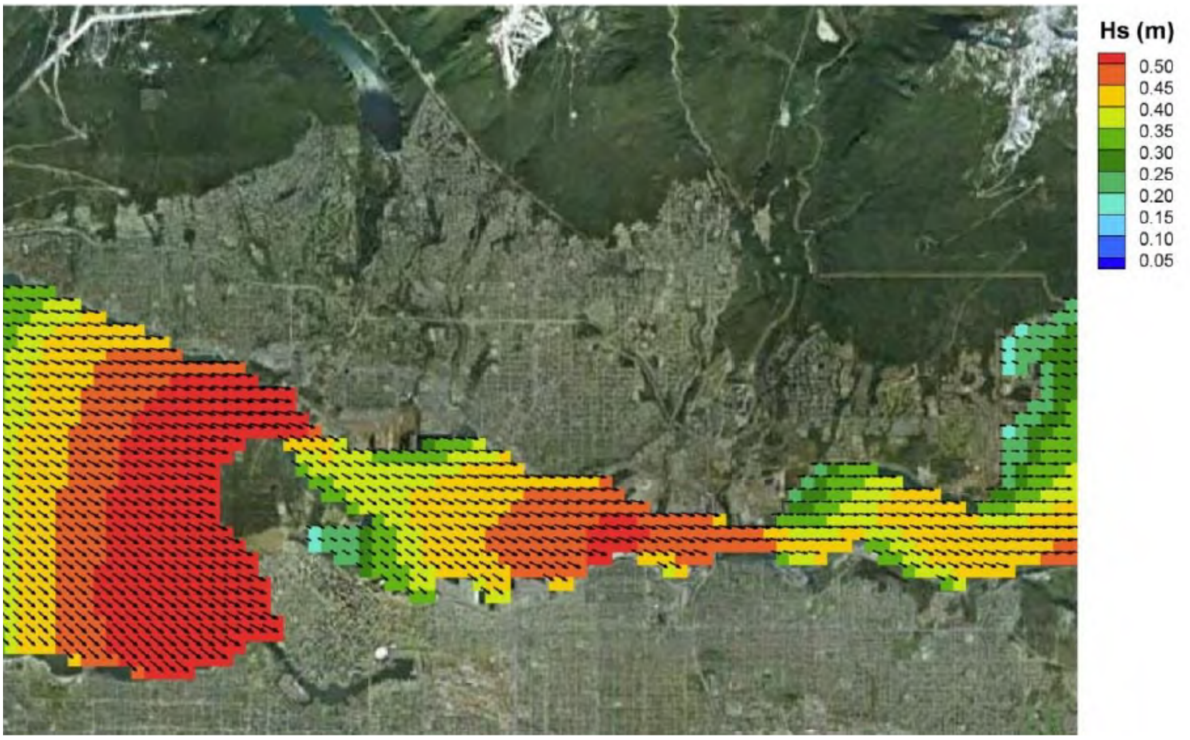



Figure B.1: Burrard Inlet Wave Model example results, University of Miami Wave Model (Muir and Menezes, 2014)

Figure B.1 shows the model output for the significant wave height for the December 19, 2012 storm event. The colour bar indicates the wave height and vectors indicate the direction of the waves. This is used as an example to make assumptions about which wave heights and directions to consider. As can be seen the wave heights at the project location are small compared to the calculated value in Chapter 3.4. The scope for this project is to look at local wind-induced and ship waves, so further research for waves coming from outside the Burrard Inlet needs to be done and will not be taken into account in this study.One can for example also determine a wave height in a 200 year storm event at the Strait of Georgia with easterly waves, heading towards the Burrard Inlet.

## B.2. General approach Peak Over Threshold method

### B.2.1. Wind frequency analyses

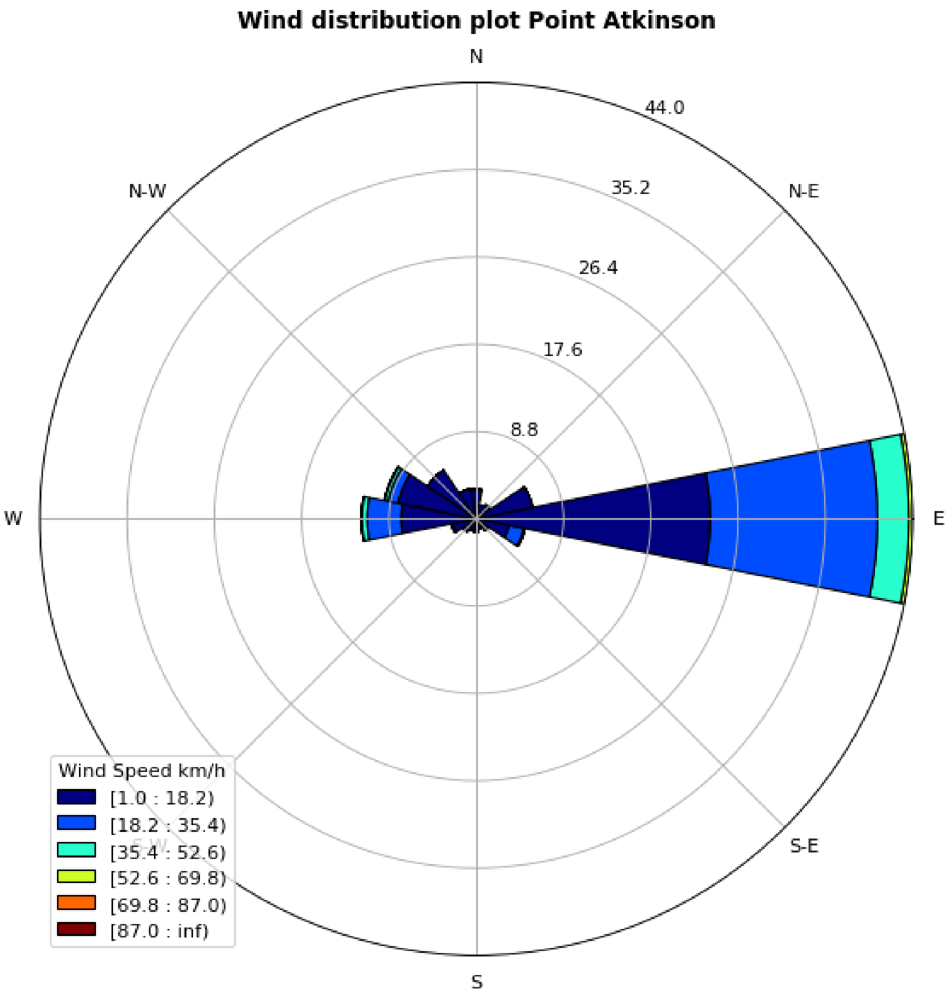



Figure B.2: Wind rose Point Atkinson. Wind speed in m/s

A peak-over-threshold (PoT) analyses is a way to process a time series of observations into a dataset of storms, which can be done either with wind speeds or wave heights. In this dataset , a storm can arbitrarily be defined as a period of time in which the observed parameter is higher than a certain chosen value. (J.P. van den bos, Edition 2018) To get a more accurate result, the data set is first filtered based on wind direction. The wind rose shows a dominant wind direction from the East.B.2 Therefore, only the waves from the East, East-North-East and East-South-East are considered, corresponding with a window of 80°- 100°.

A rule of thumb that's often used for a good first estimation is to search for a threshold level, such that an average of 10 storms per year ($N_s$ = 10) of the data remains standing. (J.P. van den bos, Edition 2018) The used data set for the frequency analyses has a value every hour for a period of 23 years, Government of Canada (1996-2019). Multiplying this with the storms per year ($N_s$), the 230 highest easterly wind speeds are taken into account. A typical storm duration is often 3-6 hours. (J.P. van den bos, Edition 2018) With a Python script the dataset is filtered to make sure only the maximum wind speed during a storm is selected. Since the dataset consists of hourly data, a so-called rolling window was programmed to pick the maximum wind speed, within a 6 hour storm duration. So for example at time X a wind speed XX is maximum, but one hour later wind speed YY is still one of the highest 230 wind speeds, wind speed YY will not be stored in the highest waves dataset, since it's during the same storm as XX.

It's important to keep in mind that it is also possible to select the highest wave-/ wind observation in each year, which leads to a $N_s$ = 1. With this list of annual maxima, the rest of the frequency analyses will be exactly the same, but with less data.

With the dataset of observations, a study of the statistical frequency analyses is done. (Goda, 1985) First the data is sorted from lowest to highest, each data point is given a ranked number, $i = 1, 2, 3, ..., N$. Therewith the exceedance ($Q_m$) and non-exceedance probabilities ($P_m$) of the dataset is calulated with the following formula:

$$P_m = \frac{m - \alpha}{N + \beta}, \qquad m = 1, 2, ...N. \tag{B.1a}$$

$$Q_m = 1 - P_m \tag{B.1b}$$

The values of constants $\alpha$ and $\beta$ are determined according to formulas from GODA (Goda, 1985) In order to translate a target return period R into corresponding design storm wind speeds $U_{ss}$, an extrapolation of the dataset is needed. This is done by fitting the dataset into four extreme value distributions: Exponential, Weibull, Gumbell, Generalized Pareto distribution. The parameters of these distributions can be found using linear regression. Linearized X-axis variables $X_E, X_W, X_G, X_P$ are calculated with translation formulas from GODA (Goda, 1985) When these X-axis variables are plotted with the remaining dataset, the parameters for the regression lines can be calculated. See Figure B.3 for the regression line $U_{ss} = A + B \cdot X$. With these values A and B, a value for $U_{ss}$ for every value of Q can be calculated, using the following formula:

$$U_{ss} = \gamma - \beta \cdot \ln Q \tag{B.2}$$

Where B = $\beta$, A = $\gamma$ and Q depends on the chosen value of the return period (R) and chosen amount of storm events in a year (Ns):

$$Q = \frac{1}{R \cdot N_s} \tag{B.3}$$

By means of a Root Mean Square Error (RMSE), which compares the original wind speed $U_{ss,i}$ to a estimated value according to the regression parameters, the most accurate fit is found. The Weibull distribution has the best fit and therefore $U_{ss}$ can be calculated according to the following formula:

$$U_{ss} = \gamma + \beta(-\ln Q)^{1/\alpha} \tag{B.4}$$

Where $\alpha$ is the shape factor of the Weibull distribution. For this parameter $\alpha$ various numbers are compared, in order to get the best possible fit. The final results of the Extreme value distribution analyses are shown in table B.1 and Figure B.3.

Table B.1: Root mean square error results

| $U_{ss} = \beta \cdot X + \gamma$ | Exponential | Gumbel | Weibull | Pareto |
|---|---|---|---|---|
| A ($\gamma$) | 15.42 | 16.21 | 14.91 | 15.55 |
| B ($\beta$) | 1.41 | 1.08 | 2.11 | 1.18 |
| RMSE | 0.064 | 0.11 | 0.061 | 0.10 |

The uncertainty in the predication is done according to the Goda method.(Goda, 1985) With a design wind speed determined with a Weibull distribution and a corresponding return period, Goda states that the uncertainty of the predicted value can be modelled like a normal distribution. The mean ($\mu$) will be the design wind speed and the standard deviation ($\sigma_H$) can be calculated according to the following empirical determined formulas: (Goda, 1985)

$$\sigma_H = \sigma_x \cdot \sigma_z \tag{B.5a}$$

$$\sigma_z = \sqrt{\frac{1 + a(y_R - c)^2}{N}} \tag{B.5b}$$

$$a = a_1 \exp a_2 * \cdot N^{-1.3} \tag{B.5c}$$

$$y_r = \ln{(N_s \cdot R)}^{1/\alpha} \tag{B.5d}$$

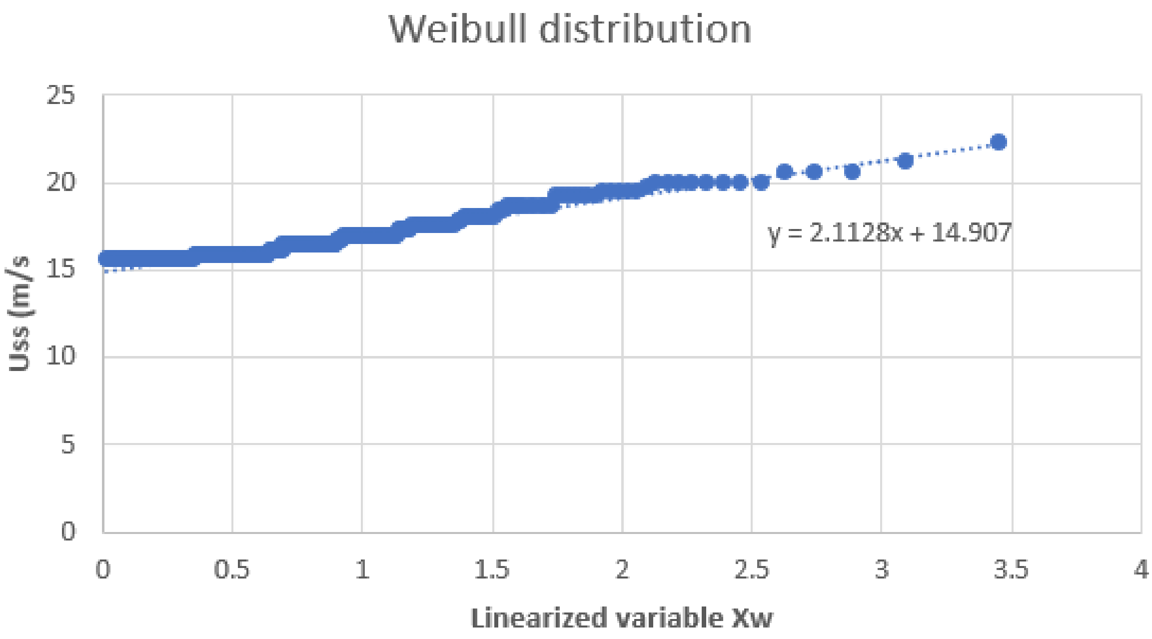



Figure B.3: Result from linear regression, dataset wind dir $80$ °- $100$ °(Government of Canada, 1996-2019)

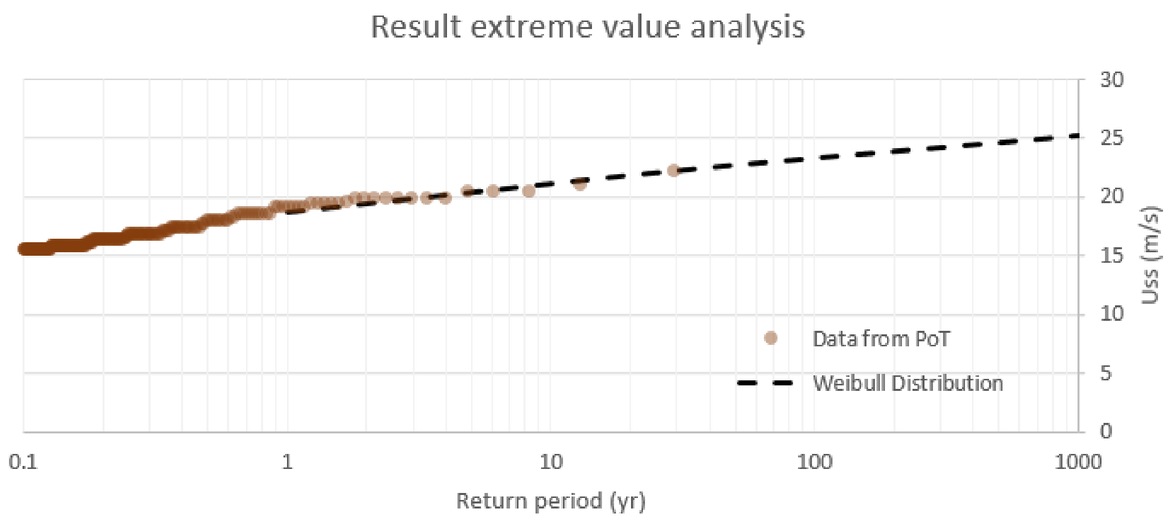



Figure B.4: Result from extreme value analysis, dataset wind dir $80$ °- $100$ °(Government of Canada, 1996-2019)

Where: $\sigma$ = standard deviation of wind speed $U_{ss}$ dataset, determined with Excel
$N$ = number of storms in dataset
$\alpha$ = shape factor Weibull distribution
$a_1, a_2, c$ = empirical determined coefficients.(Goda, 1985)
$y_R$ = reduced linearized variable $X_W$

For the confidence intervals around the calculated design wind speed, Goda determined again empirical values. For the 90% confidence level this gives for example $\mu \pm 1.64\sigma_H$. The final results are shown in Table B.2:

Table B.2: Results confidence intervals: wind speed prediction normally distributed (Goda, 1985)

| Confidence level | Return period(Yr) | Windspeed(m/s) | Lower bound | Upper bound |
|---|---|---|---|---|
| 90% | 100 | 23.31 | 23.00 | 23.62 |
| 90% | 200 | 23.90 | 23.59 | 24.21 |
| 95% | 100 | 23.31 | 22.94 | 23.68 |
| 95% | 200 | 23.90 | 23.53 | 24.27 |
| 99% | 100 | 23.31 | 22.82 | 23.80 |
| 99% | 200 | 23.90 | 23.42 | 24.39 |

### B.2.2. Frequency analyses water level

The calculation for the design water level is done in the same way as the wind frequency analyses. This data set consist of data from 1948-2018 Government of Canada (1948-2018) and contains the observed water level Chart Datum, which was −3.011 meters lower than CGVD28. The data station is located in Vancouver Harbour, which is as close as possible to the Burrard Inlet IR#3 site.


Figure B.5: location CHS Vancouver Station(Government of Canada, 1948-2018)

The used data set for the frequency analyses has a value every hour for a period of 70 years (Government of Canada, 1948-2018) Multiplying this with the assumed value for storms per year ($N_s$= 10), the 700 highest water levels are taken into account. After converting the data, again a Python script is used to make sure only the maximum water level during a storm of 6 hours is selected. Since the rest of the process is exactly the same as the wind distribution analyses, the process will not further be elaborated. The design water level ($d_{ss}$) that will be determined in the distribution analyses includes the maximum tide and storm surge. Therefore the effects of (wind-induced) waves or sea level rise will need be added to the design water level.

Table B.3: Results confidence intervals: water level prediction normally distributed (Goda, 1985)

| Confidence level | Return period(Yr) | Water level(m) | Lower bound | Upper bound |
|---|---|---|---|---|
| 90% | 100 | 2.630 | 2.617 | 2.643 |
| 90% | 200 | 2.676 | 2.663 | 2.689 |
| 95% | 100 | 2.630 | 2.614 | 2.646 |
| 95% | 200 | 2.676 | 2.661 | 2.692 |
| 99% | 100 | 2.630 | 2.610 | 2.651 |
| 99% | 200 | 2.676 | 2.656 | 2.697 |

Max fetch length

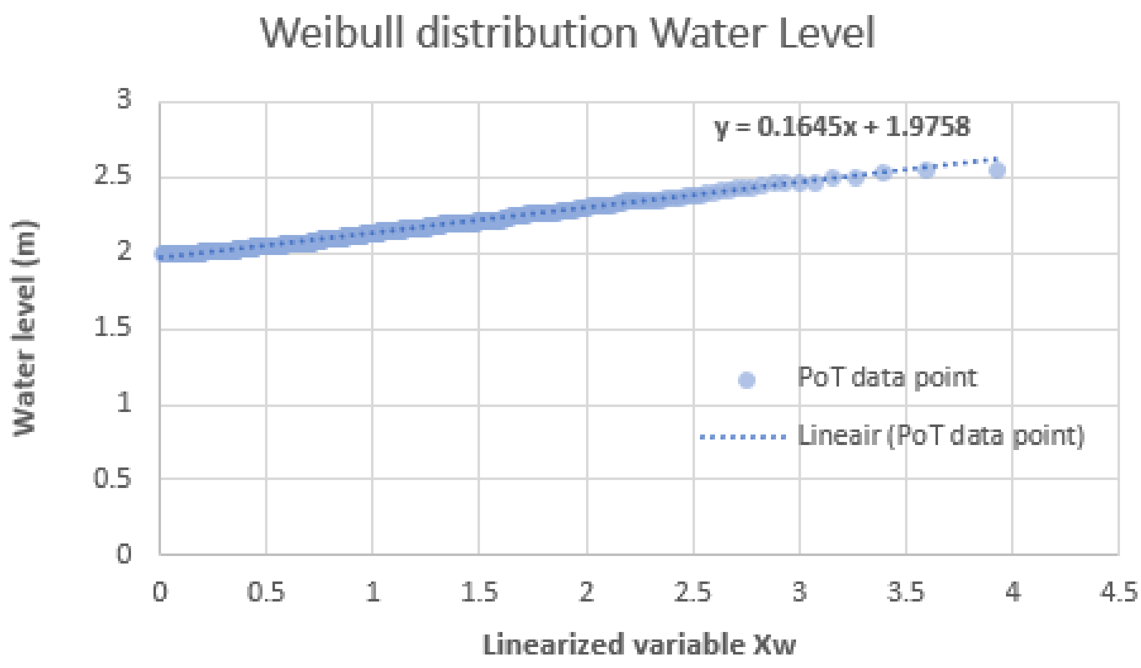



Figure B.6: Result from linear regression, dataset water level (Government of Canada, 1948-2018)

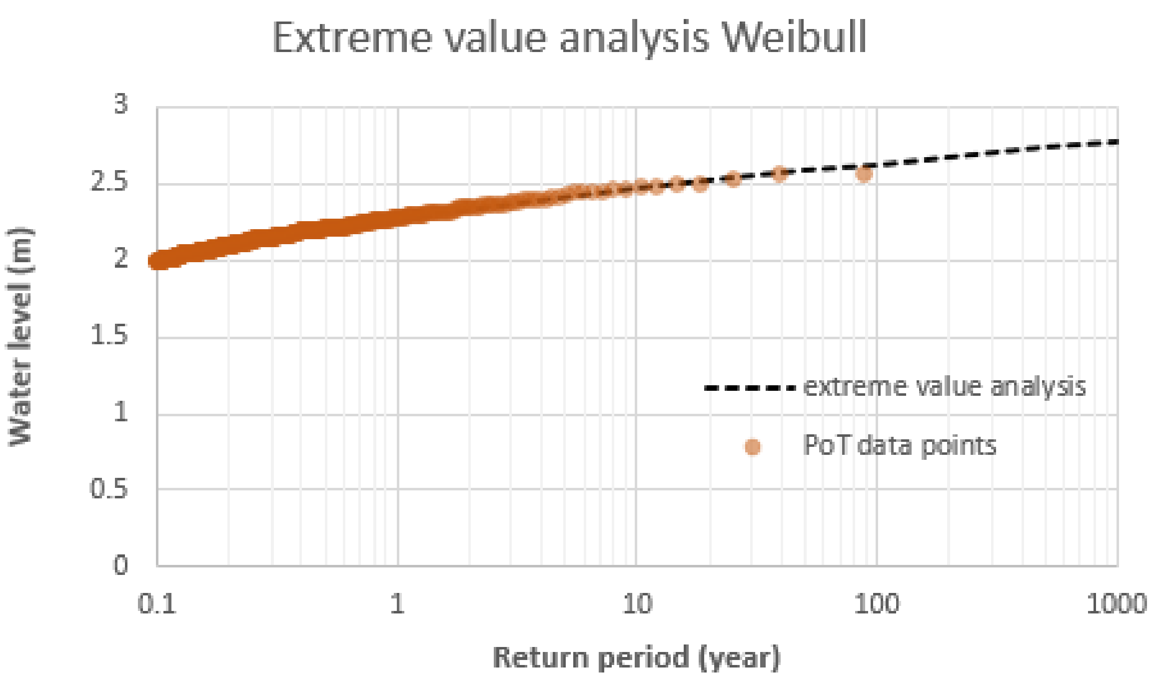



Figure B.7: Result from extreme value analysis, dataset water level (Government of Canada, 1948-2018)

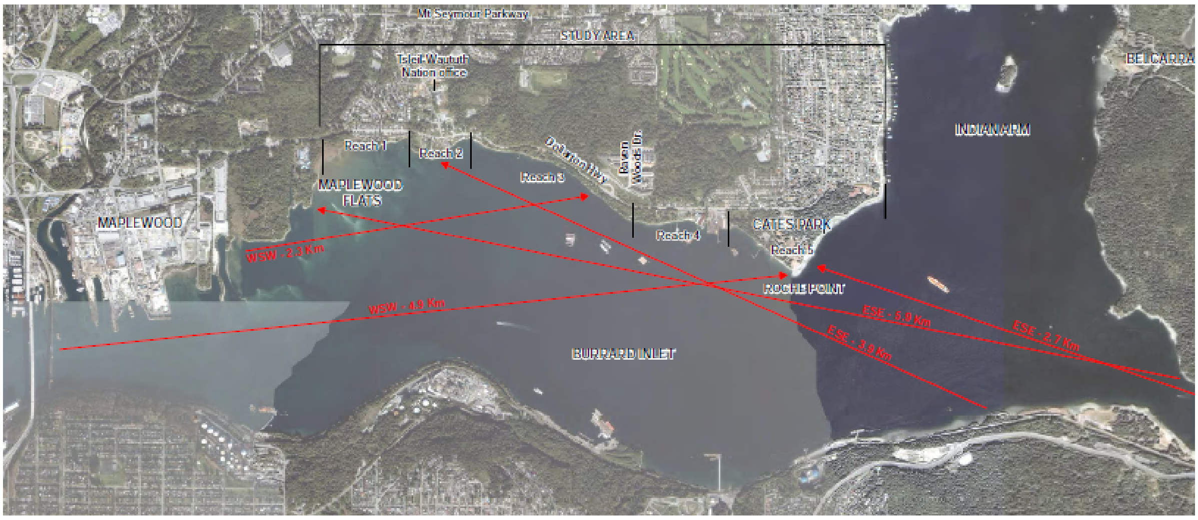



Figure B.8: Wind fetch determination(Muir and Menezes, 2014)

# C

# Ship waves

## C.1. Model options secondary waves

**Model 3 (Bhowmik 1975** Only valid for deep water waves i.e. Fr < 0.7. Hull type not defined in experiments

$$H_m = D \cdot \sqrt{0.139 \cdot V^{1.174} \cdot (x/L)^{-0.915}} \tag{C.1}$$

Where:
D = draught of vessel [m]
V = vessel speed [m/s]
x = distance from sailing line ship [m] L = length of vessel [m]

**Model 4 Gates and Herbich** Method for predicting the cusp waveheight Hm generated by large vessels moving in deep water (i.e., F < 0.7). This approach is aimed at large vessels such as cargo vessels and tankers which have a bow located fore of a long middle section having parallel sides.

$$H_b = \frac{K_w \cdot B}{Le} \cdot \frac{V^2}{2 \cdot g} \tag{C.2a}$$

$$H_{cusp} = \frac{1.11 \cdot H_b}{(2 \cdot N + 1.5)^{1/3}} \tag{C.2b}$$

B = width of vessel [m]
g = gravitational constant [$m/s^2$]
V = vessel speed [m/s]
Kw = coefficient depending on vesselspeed / length [-]
$H_b$ = wave height generated at vessels bow [m]
N = number of successive cusp points out from the sailing line
$L_e$ = (0.417 0 0.00235*L)*L = bow entrance length [m]

**Model 5 (Bhowmik, Demissie and Guo** Bhowmik, Demissie, and Guo (1982) reported measured vessel wave data from 59 barge tows consisting of from 2 to 18 barges and a tugboat operating on the Illinois and Mississippi Rivers. It does not include the wide range of distances between the sailing line and the point at which waves were measured.

$$H_m = D * \frac{0.133 \cdot V}{\sqrt{g \cdot D}} \tag{C.3}$$

**Model 6 (Blaauw et al.** Blaauw et al. (1984) present an equation that is based on Delft Hydraulics Laboratory field (canal) and laboratory measurements and employs a format similar to Gates and Herbich (1977). The height of the interference peaks (i.e., Hm)

$$H_m = A \cdot d(\frac{S}{d})^{-0.33} \cdot F^{2.67} \tag{C.4}$$

A = empirical coefficient depends on vessel type [-]
d = water depth [m]
S = distance from sailing line [m]
F = $\frac{V}{\sqrt{g \cdot d}}$ Froude number [-]
V = vessel speed [m/s]

**Model 7 - PIANC** The coefficient A" are given based on laboratory and field tests in deep water. A similar equation is presented in a paper by Verhey and Bogaerts (1989)

$$H_m = A'' \cdot d \cdot (\frac{S}{d}) \cdot F^4 \tag{C.5}$$

A = empirical coefficient depends on vessel type [-]
d = water depth [m]
S = distance from sailing line [m]
F = Froude number [-]

**Model 8 Kriebel and Seelig** Sorensen and Weggel (1984) and Weggel and Sorensen (1986) developed a vessel wave height prediction model based on the measured laboratory and field data then available in the literature. They noted some of the important limitations on the available data as far as developing a completely satisfactory wave prediction model.

$$H_m = \frac{V^2}{g} \cdot \beta \cdot (F^* - 0.1)^2 \cdot (\frac{y}{L})^{-0.33} \tag{C.6a}$$

$$F^* = F \cdot \exp \alpha \cdot (\frac{R}{d}) \tag{C.6b}$$

$$\beta = 1 + 8 \cdot \tanh 0.45 \cdot ((L/Le) - 2)^{-1/3} \tag{C.6c}$$

$\alpha$ = 2.5(1 - Cb) [-]
Cb = ship blockings coefficient [-]
$F^*$ = modified depth Froude number that accounts for vessel length and draft
y = distance from sailing line [m]
L = length of vessel [m]
$L_e$ = (0.417 0 0.00235*L)*L = bow entrance length [m]

**Final results different methods:**

Table C.1: Comparison different methods

| **Method** | Waveheight at x=30 [m] |
|---|---|
| Bhowmik (1975) | 2.26 |
| Gates and Herbich (1977) | 0.99 |
| Bhowmik, Demissie, Guo (1982) | 0.52 |
| Blaauw et al. (1984) | 0.69 |
| PIANC (1987) | 0.42 |
| Bhowmik et al. (1991) | 0.88 |
| Kriebel, Seelig (2005) | 0.61 |

# D

# Climate induced coastal hazards

## D.1. Climate change context

### D.1.1. Sea level rise

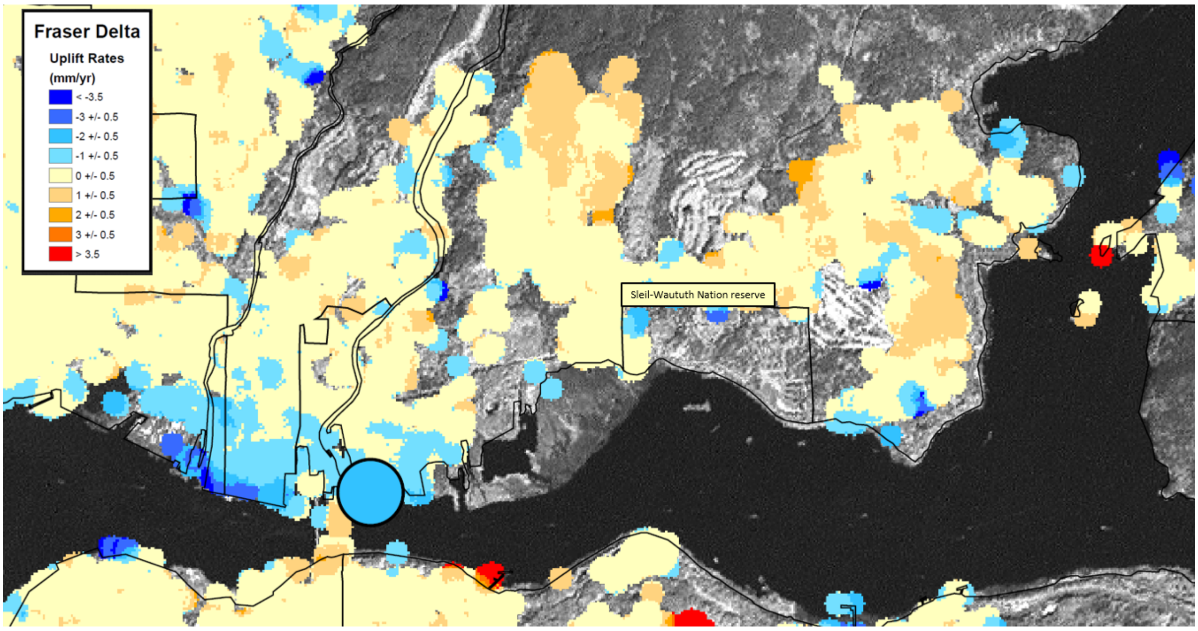



Figure D.1: Subsidence of the Fraser River Delta, North Vancouver, Britisch Columbia (Lambert et al., 2008)

## D.1.2. Ocean conditions changes

**Effects on salinity**

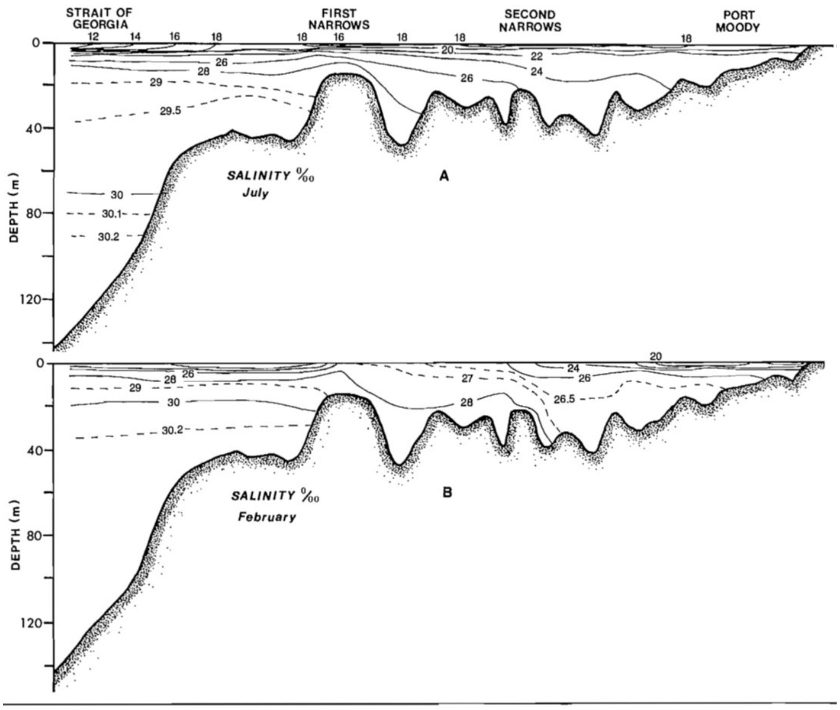



Figure D.2: Salinity distribution in mid-channel sections through Burrard Inlet in summer (A) and winter (B) (Thomson, 1981)

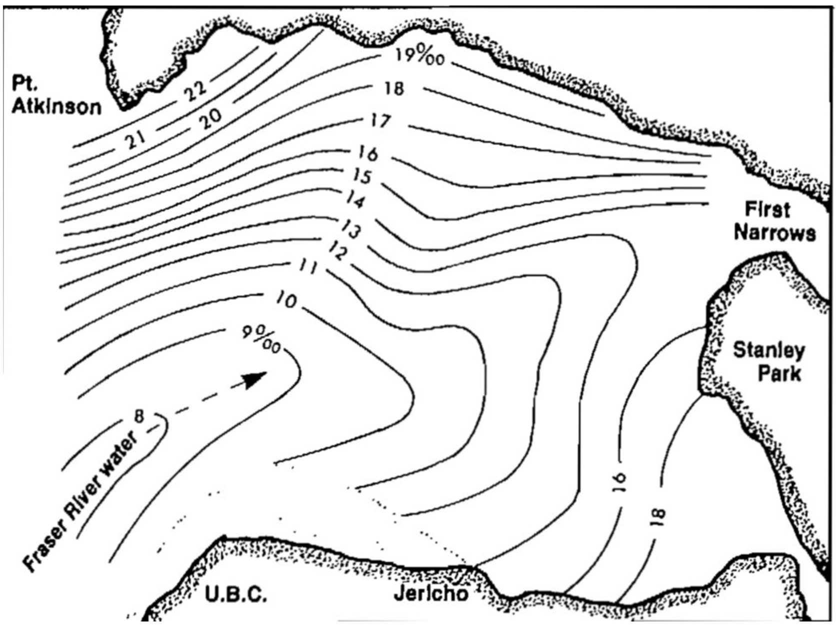



Figure D.3: Average surface distribution salinity in Burrard Inlet during large Fraser River runoff during summer (Thomson, 1981)

### D.1.3. Precipitation changes

Climate changes are expected to change the annual, seasonal and extreme event participation patterns in the British Columbia region. Higher atmospheric temperatures cause more evaporation which will result in increased precipitation in wet areas and reduced precipitation in dry areas. The metro Vancouver region will experience a modest increase in precipitation which is not evenly distributed over the seasons. Summer months will become dryer and the fall season will experience the largest increase in precipitation. The Metro Vancouver region can also expect stronger and more frequent extreme rainfall events, less precipitation falling as snow in the winter months, longer periods of consecutive days with precipitation less than 1 mm (dry spells) and the extension of the dry season into September (Metro Vancouver, 2016). The annual precipitation in the Metro Vancouver area was 2381 mm/year over the period between 1961-1990 and will increase with 7% in the 2050s and 8% in the 2080s (Murdock et al., 2019).

Next to the annual increase in precipitation in Metro Vancouver the two following changes in precipitation are expected for TWN: increased precipitation events in the wet season and decreased summer season total precipitation.

**Increasing extreme precipitation events:**
Due to climate change the intensity and frequency of extreme rainfall events will increase. For the project area of the TWN nation KWL used IDF (Intensity duration Frequency) curves to predict an increase in extreme rainfall intensity of 24% compared to the current situation between the year 2050 and 2100 (Taleghani et al., 2020). This result is in line with the findings for the Metro Vancouver region. Metro Vancouver most recent report predicted a possibly increase in single-day maximum rainfall of 17% by 2050 and 32% by 2080 compared to a past single-day maximum rainfall of 69 mm which is the average over the 30-year baseline period of 1971 -2000 (Metro Vancouver, 2016).

**Decreasing summer season total precipitation:**
The summer period is the driest period of the Metro Vancouver region and is expected to become drier and last longer. A decrease in precipitation of 19% and 29% is expected for 2050 and 2080 respectively compared to the past precipitation of 206 mm per summer season (average over the 30-year baseline period of 1971 -2000). Next to the decrease in precipitation the dry season will last longer extending to September and the duration of dry spells (number of consecutive days with rainfall under 1 mm) is expected to increase from an average of 21 days to 26 days in 2050 and 29 days in 2080 (Metro Vancouver, 2016).

### D.1.4. Air temperature changes

Atmospheric warming is mainly due to the increase in greenhouse gases in the atmosphere, globally averaged air temperatures have increased with 0.85 °C over the 20th century (IPCC, 2014). Average annual air temperatures in the Metro Vancouver area have increased with 1.3 °C over the last century. The temperatures will continue to increase with 1.7 °C in the 2050s and 2.7 °C in the 2080s compared to the annual average temperature of 8.5 °C (measured over the period from 1961-1990), with temperatures rising faster for the summer periods than the winter periods (Murdock et al., 2019).

## D.2. Hazard assessment

Different hazards have different effects on the TWN. These effects and the consequences of these elements were assessed by Kerr Wood Leidal (KWL) in a hazard- and vulnerability assessment. In this assessment, KWL aims to come up with a ranking of vulnerable elements compared to the posing hazards. This ranking is very thorough and therefore a similar hazard- and vulnerability assessment is done by down-scaling the existing work to the scope of this project, as explained in 4.3.1.

These hazards are based on literature studies such as: academic journal articles, federal, provincial, and local government reports, technical reports by global working groups and non-government organizations, and local news reports. The hazards are also based on conversations with the TWN-staff and community members. Taleghani et al. (2020)

The process of getting to a vulnerability ranking is explained in the following steps:

**Step 1: Define and refine sectors and elements** To do a vulnerability assessment, first the elements which are evaluated should be determined. An element is a feature of the community that will be impacted by climate change. Examples of such elements are community housing, cultural and archaeological sites, shellfish, beaches, etc.

A total of 34 vulnerability elements have been identified and in further studies, this number might even increase. These elements are subdivided in six sectors for clarity: Ecological Systems, Land Use & Real Estate, Infrastructure & Community Services, Archaeological & Cultural Heritage Sites, Community & Cultural Health, and Economy.

**Step 2: Screening assessment of hazards** This step looks at thirteen hazards, identified by KWL, that pose a potential impacts to TWN elements. These are the following hazards:

1. Coastal stillwater flooding
2. Coastal erosion
3. Intertidal area change
4. Creek flooding
5. Creek erosion
6. Urban flooding
7. Extreme heat
8. Wildfire
9. Vector-borne disease
10. Ocean acidification
11. Harmful algae blooms
12. Other ocean condition-related hazards
13. Invasive species

All hazards and elements were paired. Through a combination of expert judgement and knowledge shared by TWN staff and LUPWG members, the impact was assessed. Element-hazard combinations that did not pose a measurable impact were not further assessed.Taleghani et al. (2020)

**Step 3: Element-hazard vulnerability scores** In the next step a score is developed to determine a qualitative measure of the vulnerability of each element to relevant hazards. This element-hazard vulnerability score is based on the combination between the exposure, the sensitivity and the adaptive capacity of an element using the following equation:

$$\text{Element-Hazard Vulnerability Score} = \text{Exposure} + \text{Sensitivity - Adaptive Capacity} \tag{D.1}$$

In this equation the *Exposure* is the degree to which an element interacts with a particular hazard (e.g., spatial proximity, number of same type of element exposed), the *Sensitivity* is the degree to which the health or function of an element is inherently susceptible to impacts from a hazard, and the *Adaptive capacity* reflects the ability of an element to adapt to impacts from a hazard, whether due to inherent qualities (e.g., migration, evolution) or TWN's capacity to accommodate changes.

**Step 4: Overall element vulnerability scores** The element-hazard vulnerability scores have been combined to create an overall score for each element. This vulnerability score has been put into a table to create a ranked list of the TWN elements that are considerate most vulnerable to climate change, as shown in table D.4.

## D.3. Vulnerability assessment

| Element | Overall Element vulnerability score | Relevant hazards (all) |
|---|---|---|
| Social. Cultural & Spiritual well-being | 35 | Intertidal area change, Extreme heat events, Other ocean conditions, Wildfire, Invasive species, Creek flooding, Creek erosion, Coastal flooding, Ocean acidification, Harmful algae blooms, Coastal erosion, Vector-borne diseases |
| Archaeological Sites | 33 | Coastal flooding, Coastal erosion, Ocean acidification, Creek flooding, Extreme heat events, Wildfire, Intertidal area change, Invasive species, Creek erosion, Urban flooding |
| Other Cultural & Traditional Use Sites | 28 | Intertidal area change, Coastal flooding, Creek flooding, Coastal erosion, Creek erosion, Extreme heat events, Wildfire, Invasive species, Vector-borne diseases |
| Shellfish | 24 | Ocean acidification, Other ocean conditions, Intertidal area change, Coastal erosion, Harmful algae blooms, Invasive species creek erosion |
| Salmon | 23 | Intertidal area change, Other ocean conditions, Ocean acidification, Harmful Algae blooms, Creek flooding, Invasive species, Creek erosion |
| Forage Fish | 21 | Intertidal area change, Other ocean conditions, Coastal erosion, Ocean acidification, Harmful algae blooms, Invasive species |
| Roads & Emergency Access | 21 | Coastal erosion, Creek flooding, Coastal flooding, Creek erosion, Urban flooding, Extreme heat events, Wildfire |
| Beaches & Shorelines | 20 | Coastal erosion, Intertidal area change, Coastal flooding, Ocean acidification, Creek erosion, Wildfire, Invasive species, Extreme heat events |
| TWN Community Housing | 19 | Wildfire, Urban flooding, Creek flooding, Coastal erosion, Invasive species, Coastal flooding, Creek erosion |
| Employment & Productivity | 17 | Coastal flooding, Coastal erosion, Creek flooding, Creek erosion, Urban flooding, Wildfire, Extreme heat events, Vector-borne diseases |

Table D.1: Top 10 most vulnerable elements by overall vulnerability score. Scores made by Kerr Wood Lydal

**Table 6-2: Vulnerability Summary Matrix**

| | | HAZARD | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Sea Level Rise | | | Precip. Change | | | Temperature Change | | | | Ocean Changes | | | | | |
| SECTOR | ELEMENT | Coastal Flooding | Coastal Erosion | Intertidal Area Change | Creek Flooding | Creek Erosion | Urban Flooding | Extreme Heat Events | Wildfire | Vector-Borne Diseases | Invasive Species | Ocean Acidification | Harmful Algal Blooms | Other Ocean Conditions | Vulnerability Score Sum | Community Priority Score | Overall Vulnerability Score |
| Ecological Systems | Shellfish | - | 3 | 4 | - | 1 | - | 2 | - | - | 2 | 5 | 2 | 5 | 24 | 1 | 25 |
| | Salmon | - | 0 | 4 | 2 | 1 | - | 4 | - | - | 2 | 3 | 2 | 5 | 23 | 1 | 24 |
| | Forage fish | - | 3 | 4 | - | - | - | 3 | - | - | 2 | 3 | 2 | 4 | 21 | | 21 |
| | Other finfish | - | - | 2 | - | - | - | 1 | - | - | 2 | 3 | 3 | 4 | 15 | | 15 |
| | Marine birds and waterfowl | - | 1 | 4 | - | - | - | 2 | - | - | - | 3 | 1 | 4 | 15 | | 15 |
| | Marine and semi-aquatic mammals | - | 1 | 3 | - | - | - | 1 | - | - | - | 3 | 1 | 3 | 12 | | 12 |
| | Beaches and shorelines | 3 | 4 | 4 | - | 2 | - | 1 | 2 | - | 2 | 2 | - | - | 20 | 1 | 21 |
| | Tidelands and marine habitats | 2 | 1 | 3 | - | - | - | 1 | - | - | 2 | 2 | - | 4 | 15 | | 15 |
| | Marine water quality | 0 | 0 | - | 2 | 0 | 2 | 1 | - | - | - | - | 2 | 5 | 12 | 1 | 13 |
| | Upland wildlife | 0 | 1 | 1 | 0 | 1 | - | 2 | 4 | - | - | 0 | 1 | 0 | 10 | | 10 |
| | Forested areas & medicinal plants | 2 | 2 | - | 1 | 1 | - | 4 | 4 | - | 3 | - | - | - | 17 | 1 | 18 |
| | Freshwater creeks, streams, wetlands, and groundwater | 3 | 1 | - | 2 | 1 | 2 | 4 | 1 | - | - | - | - | - | 14 | 1 | 15 |
| | Air quality | - | - | - | - | - | - | 4 | 5 | - | - | - | - | - | 9 | | 9 |
| Land Use & Real Estate | Near-shore lands | 0 | 1 | - | 0 | 0 | 2 | - | 3 | - | 2 | - | - | - | 8 | | 8 |
| | TWN community housing | 1 | 2 | - | 4 | 1 | 4 | 1 | 4 | - | 2 | - | - | - | 19 | 1 | 20 |
| | Market (leasehold) housing | - | - | - | 1 | - | 0 | - | 4 | - | 1 | - | - | - | 6 | | 6 |
| | Community buildings | 2 | 0 | - | 1 | 0 | 2 | 1 | 4 | - | 2 | - | - | - | 12 | | 12 |
| | Hazardous sites | 3 | - | - | - | - | - | - | - | - | - | - | - | - | 3 | | 3 |
| | Future land use opportunities | 0 | 2 | - | 0 | - | 0 | - | 3 | - | 2 | - | - | - | 7 | | 7 |
| Infrastructure & Community Services | Water supply and distribution system | 1 | 2 | - | 3 | 2 | - | 2 | 1 | - | - | - | - | - | 11 | | 11 |
| | Sewer/Wastewater collection system | 3 | 5 | - | 4 | 2 | - | - | 0 | - | - | - | - | - | 14 | | 14 |
| | Stormwater system | 2 | 3 | - | 4 | 2 | 1 | - | 1 | - | - | - | - | - | 13 | | 13 |
| | Roads and Emergency Access | 3 | 4 | - | 4 | 2 | 2 | 3 | 3 | - | - | - | - | - | 21 | | 21 |
| | Energy and telecommunications systems | 1 | 2 | - | 1 | 2 | 1 | 2 | 3 | - | - | - | - | - | 12 | | 12 |
| Archaeological & Cultural Heritage Sites | Archaeological sites | 4 | 5 | 3 | 4 | 0 | 1 | 5 | 5 | - | 2 | 4 | - | | 33 | 1 | 34 |
| | Cemetery | 0 | 3 | - | - | - | 0 | - | 0 | - | - | - | - | - | 3 | 1 | 4 |
| | Other cultural and traditional use sites | 4 | 3 | 5 | 4 | 3 | - | 3 | 3 | 1 | 2 | - | - | - | 28 | 1 | 29 |
| Community & Cultural Health | Physical health (general population) | 0 | 1 | - | 0 | 0 | 0 | 2 | 3 | 1 | 2 | - | 2 | - | 11 | | 11 |
| | Mental health | 2 | 0 | 1 | 0 | 0 | 1 | 1 | 3 | 0 | - | - | - | - | 8 | | 8 |
| | Vulnerable populations | 1 | - | - | 1 | 1 | 1 | 4 | 3 | 3 | 2 | - | - | - | 16 | 1 | 17 |
| | Social, cultural, and spiritual well-being | 3 | 1 | 5 | 3 | 2 | - | 5 | 3 | 1 | 2 | 3 | 3 | 4 | 35 | 1 | 36 |
| Economy | Employment & productivity | 2 | 3 | - | 3 | 3 | 2 | 1 | 2 | 1 | - | - | - | - | 17 | | 17 |
| | Commercial Assets | 0 | 0 | 3 | - | - | 1 | - | 1 | - | - | - | - | - | 5 | | 5 |
| | Future economic development opportunities | 1 | 3 | - | -1 | -1 | - | - | 2 | - | - | - | 3 | - | 7 | | 7 |

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Figure D.4: Vulnerability scores per element for thirteen hazards

**Table 6-2: Vulnerability Summary Matrix**

| SECTOR | ELEMENT | Coastal Flooding | Coastal Erosion | Intertidal Area Change | Ocean Acidification | Harmful Algal Blooms | Other Ocean Conditions | Vulnerability Score Sum | Community Priority Score | Overall Vulnerability Score |
|---|---|---|---|---|---|---|---|---|---|---|
| | | HAZARD | | | | | | | | |
| | | Sea Level Rise | | | Ocean Changes | | | | | |
| Ecological Systems | Shellfish | - | 3 | 4 | 5 | 2 | 5 | 19 | 1 | 20 |
| | Salmon | - | 0 | 4 | 3 | 2 | 5 | 14 | 1 | 15 |
| | Forage fish | - | 3 | 4 | 3 | 2 | 4 | 16 | | 16 |
| | Other finfish | - | - | 2 | 3 | 3 | 4 | 12 | | 12 |
| | Marine birds and waterfowl | - | 1 | 4 | 3 | 1 | 4 | 13 | | 13 |
| | Marine and semi-aquatic mammals | - | 1 | 3 | 3 | 1 | 3 | 11 | | 11 |
| | Beaches and shorelines | 3 | 4 | 4 | 2 | - | - | 13 | 1 | 14 |
| | Tidelands and marine habitats | 2 | 1 | 3 | 2 | - | 4 | 12 | | 12 |
| | Marine water quality | 0 | 0 | - | - | 2 | 5 | 7 | 1 | 8 |
| | Upland wildlife | 0 | 1 | 1 | 0 | 1 | 0 | 3 | | 3 |
| | Forested areas & medicinal plants | 2 | 2 | - | - | - | - | 4 | 1 | 5 |
| | Freshwater creeks, streams, wetlands, and groundwater | 3 | 1 | - | - | - | - | 4 | 1 | 5 |
| | Air quality | - | - | - | - | - | - | 0 | | 0 |
| Land Use & Real Estate | Near-shore lands | 0 | 1 | - | - | - | - | 1 | | 1 |
| | TWN community housing | 1 | 2 | - | - | - | - | 3 | 1 | 4 |
| | Market (leasehold) housing | - | - | - | - | - | - | 0 | | 0 |
| | Community buildings | 2 | 0 | - | - | - | - | 2 | | 2 |
| | Hazardous sites | 3 | - | - | - | - | - | 3 | | 3 |
| | Future land use opportunities | 0 | 2 | - | - | - | - | 2 | | 2 |
| Infrastructure & Community Services | Water supply and distribution system | 1 | 2 | - | - | - | - | 3 | | 3 |
| | Sewer/Wastewater collection system | 3 | 5 | - | - | - | - | 8 | | 8 |
| | Stormwater system | 2 | 3 | - | - | - | - | 5 | | 5 |
| | Roads and Emergency Access | 3 | 4 | - | - | - | - | 7 | | 7 |
| | Energy and telecommunications systems | 1 | 2 | - | - | - | - | 3 | | 3 |
| Archaeological & Cultural Heritage Sites | Archaeological sites | 4 | 5 | 3 | 4 | - | | 16 | 1 | 17 |
| | Cemetery | 0 | 3 | - | - | - | - | 3 | 1 | 4 |
| | Other cultural and traditional use sites | 4 | 3 | 5 | - | - | - | 12 | 1 | 13 |
| Community & Cultural Health | Physical health (general population) | 0 | 1 | - | - | 2 | - | 3 | | 3 |
| | Mental health | 2 | 0 | 1 | - | - | - | 3 | | 3 |
| | Vulnerable populations | 1 | - | - | - | - | - | 1 | 1 | 2 |
| | Social, cultural, and spiritual well-being | 3 | 1 | 5 | 3 | 3 | 4 | 19 | 1 | 20 |
| Economy | Employment & productivity | 2 | 3 | - | - | - | - | 5 | | 5 |
| | Commercial Assets | 0 | 0 | 3 | - | - | - | 3 | | 3 |
| | Future economic development opportunities | 1 | 3 | - | - | 3 | - | 7 | | 7 |

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Figure D.5: Vulnerability scores per element for the six hazards

# E

# Stakeholders

## E.1. Legislative and jurisdictional framework

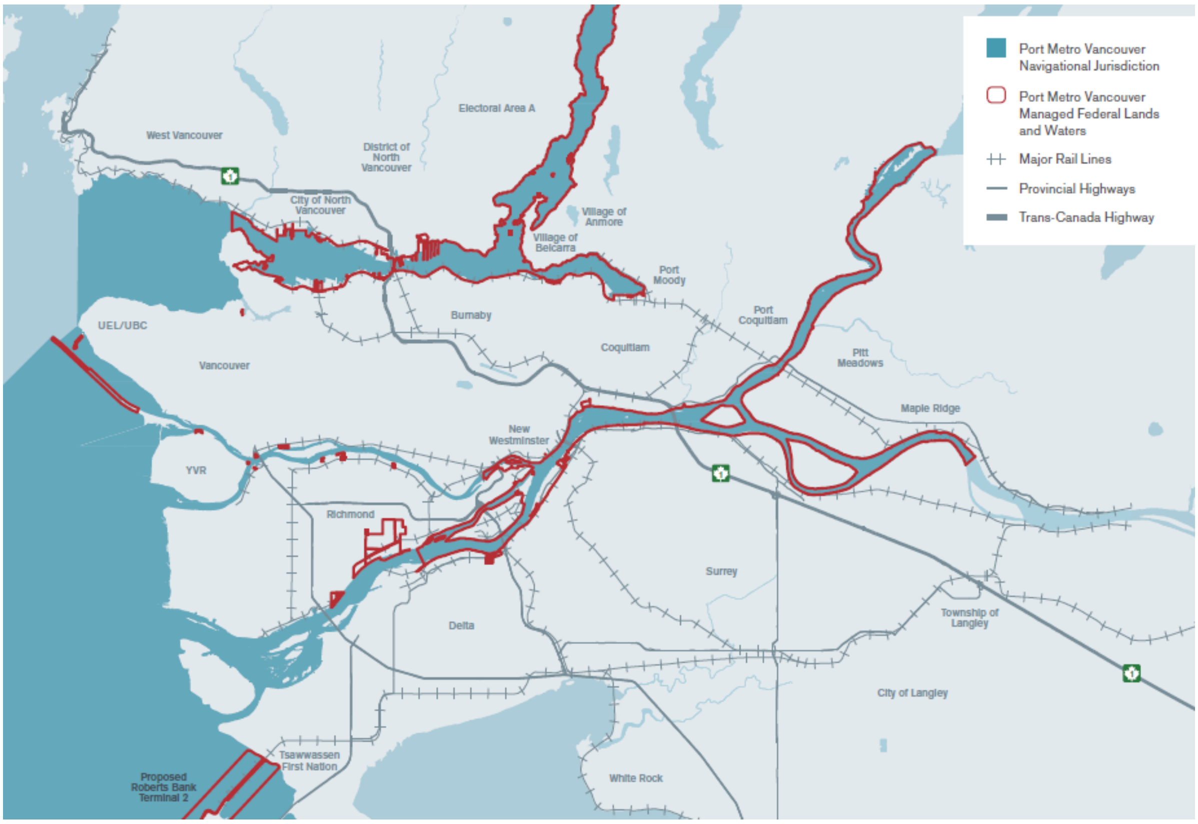



Figure E.1: Port Metro Vancouver jurisdiction E.1

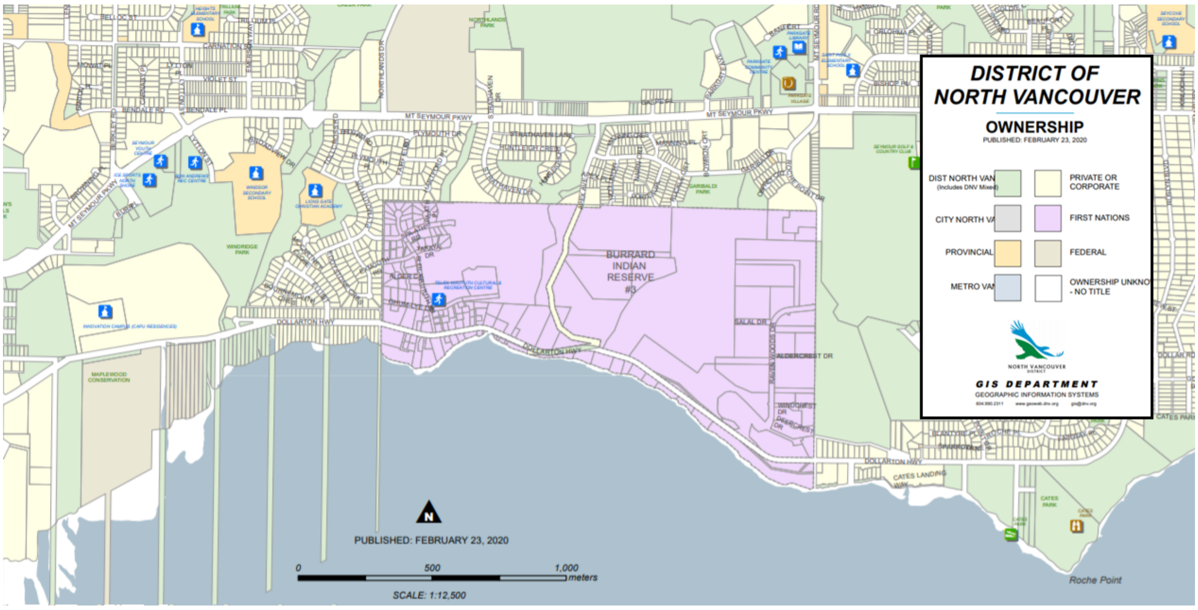



Figure E.2: Ownership of the project area and its surroundings as given by the District of North Vancouver (District of North Vancouver, 2020)

# E.2. Stakeholders

# F

# TWN principles

| Principle | Policies/Criteria |
|---|---|
| 1. **LEADERSHIP:** Stand as a leader in climate action | • Take **bold action** to build the resilience of our Lands and People.<br>• **Demonstrate leadership among communities** across BC and find opportunities to share knowledge and experience across the region. |
| **2. SELF-RELIANT:** Self-reliant and in control of our adaptation and resilience | • Climate action is driven by the Nation's leadership and **focused on the areas within our jurisdiction.**<br>• The CCCRP **helps members see their role** in climate resilience and motivates local stewardship and action at the individual and household level.<br>• Establish a mix of actions that can be **implemented at different levels**, including community leaders, staff, and members.<br>• **Keeping youth connected** to climate action and natural spaces is particularly important. |
| **3. SCIENCE-BASED:** Based on indigenous science and local knowledge | • Draws on the best available science, including **indigenous science** to understand climate change impacts and define priorities.<br>• Draw on **local knowledge** held by members and community leaders to understand where the Nation may be most vulnerable to climate change impacts.<br>• Prioritize adaptation approaches focused on addressing our highest and most **critical vulnerabilities first**.<br>• Adaptation measures are **aligned with traditional teachings** and practices.<br>• Information is shared to **keep members up-to-date** as science progresses. |
| 4. **VALUES-BASED:** Guided by community values and input. | • Decisions are **guided by TWN vision and priorities**, including the TWN Constitution, Land Use Plan, and Resilience Vision and Goals.<br>• Prioritize climate adaptation actions to focus on areas considered to be **most important to Tsleil-Waututh leadership and members**. |
| **5. STRENGTHS-BASED:** Focused on actions that support existing initiatives. | • Adaptation measures **build on and support existing TWN initiatives,** drawing on in-house expertise and systems.<br>• Focus on issues and actions we can address in the short term; "low-hanging fruit" - **what we can do, today.**<br>• **Encourage capacity-building**, implementation, and management in-house. |
| **6. COLLABORATIVE:** Build collaborative relationships. | • **Collaborate with neighbouring communities and across levels of government** to increase our scale of influence beyond what can be achieved when acting alone.<br>• **Build meaningful and constructive relationships** based on trust and accountability.<br>• **Stay aware** of issues and initiatives outside of reserve lands.<br>• Celebrate and **build on best practices** and successes in neighbouring areas. |
| **7. COST-EFFECTIVE:** Aim for realistic, cost-effective, and sustainable solutions. | • Because funding and resources are not unlimited, actions are designed to **achieve desired results as efficiently as possible**.<br>• Prioritize opportunities to **leverage available external funding** sources to build resilience (e.g. grants). |
| **8. MULTI-SOLVING:** Prioritize approaches that support the community in multiple ways | • **Seek out opportunities to adapt and thrive** under changing conditions, such as new economic development initiatives.<br>• Prioritize adaptation approaches that **promote co-benefits** (e.g. low carbon, cultural knowledge-sharing, economic growth, community health, nature-based, protect the environment) |
| **9. ADAPTIVE:** Plan actions today that are flexible to changing conditions and can be built on by future generations. | • Adaptation measures are flexible and can be **adapted over time** to address new or changing information and vulnerabilities.<br>• Lead **ongoing monitoring** to measure progress, growing resilience, and changing conditions. |

Figure F.1: List of TWN principles and their policies/criteria per principle

# G

# Design Rip rap Revetment

## G.1. Shallow water wave transformation

In this section the input parameters for the SwanOne model are given in Figure G.1, G.3, G.2 and G.4.

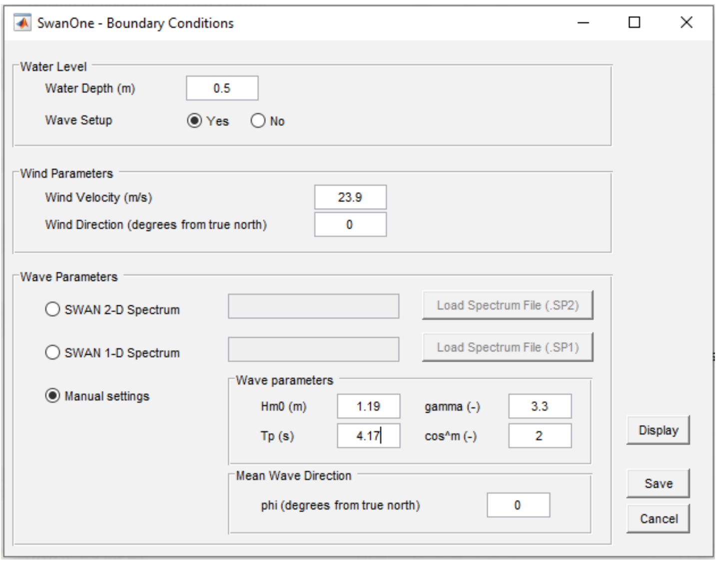



Figure G.1: Input parameters SwanOne, boundary conditions 0.5m SLR

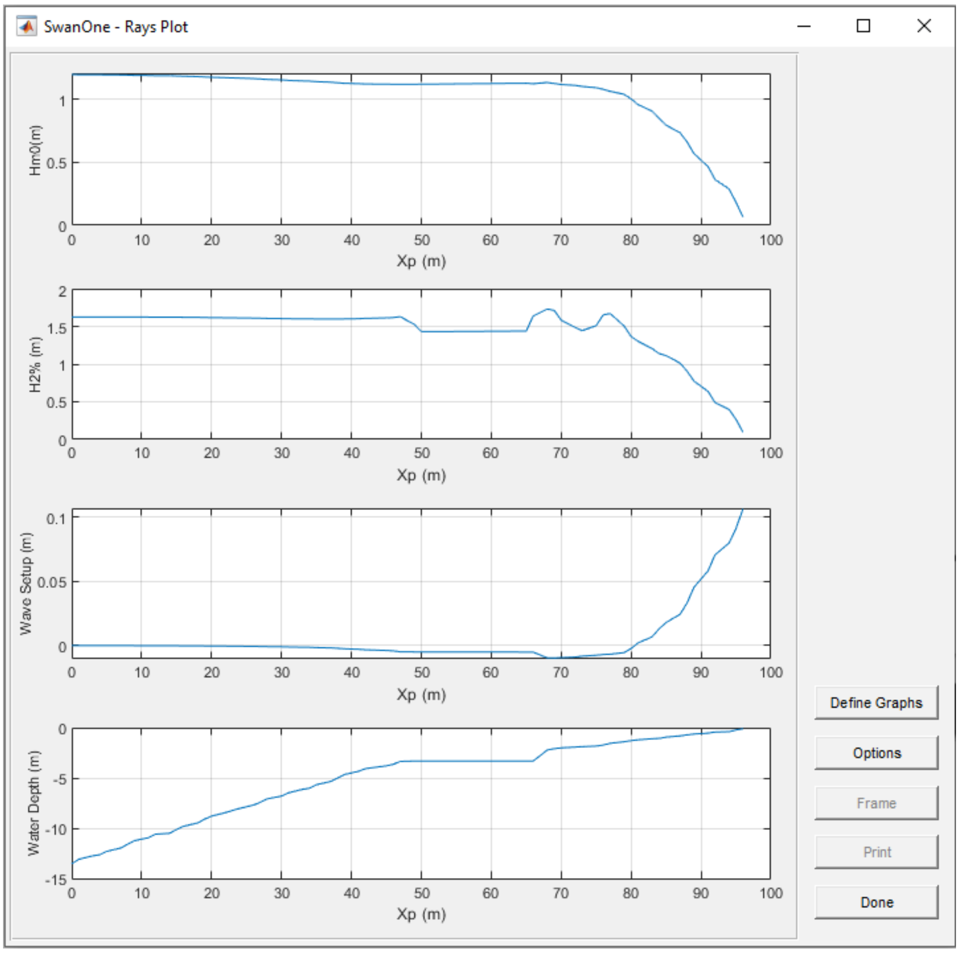



Figure G.2: Results SwanOne analyses 0.5m SLR

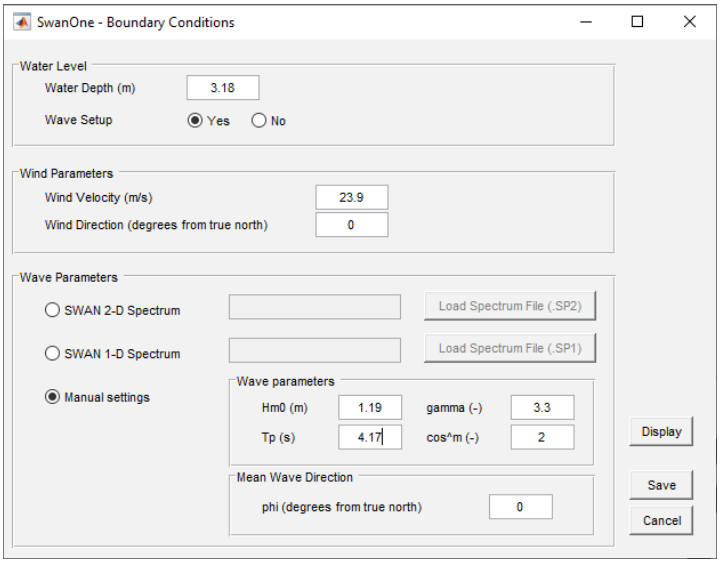



Figure G.3: Input parameters SwanOne, boundary conditions 0.5m SLR + tides + storm surge based on waterlevel analyses3.4.1

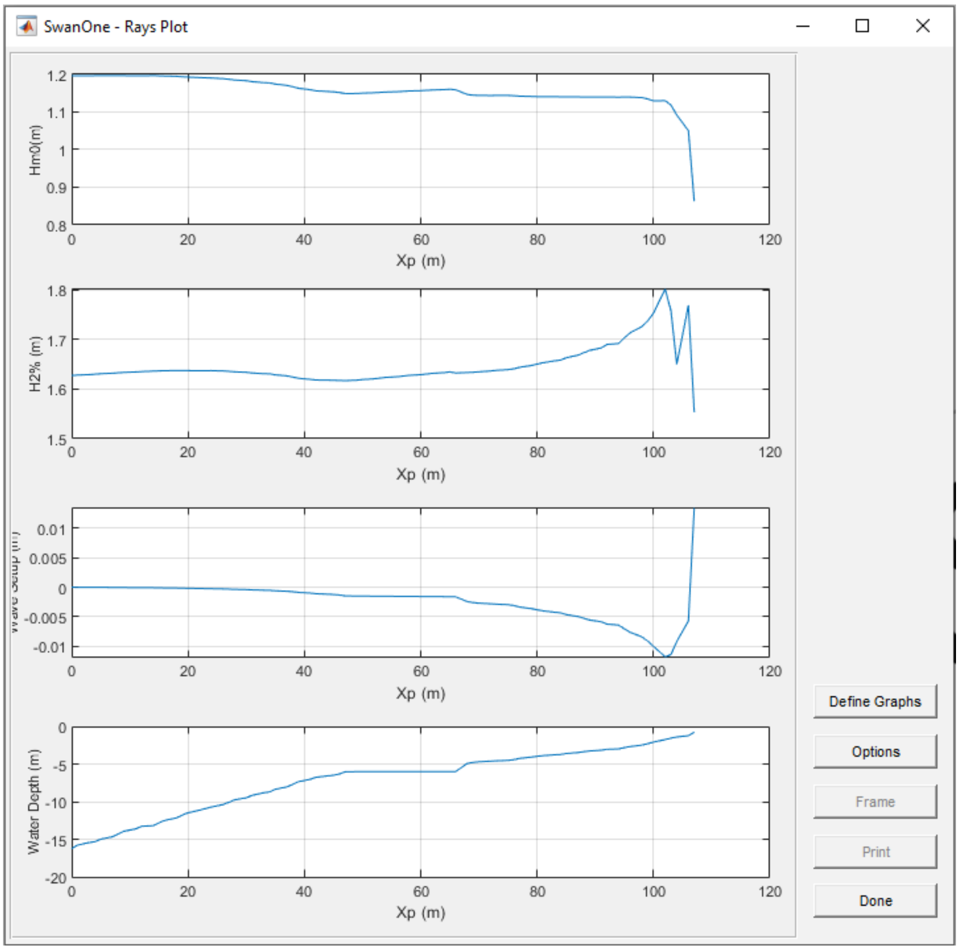



Figure G.4: Results SwanOne analyses 0.5m SLR + tides + storm surge

## G.2. Van der meer calculation

Shallow water wave conditions Van Der Meer (1990) formula:

$$\frac{H_s}{\Delta \cdot d_{n50}} = 8.4 \cdot P^{0.18} \cdot (\frac{S}{\sqrt{N}})^{0.2} \cdot (\frac{H_s}{H_{2\%}}) \cdot \xi_{m-1,0}^{-0.5} \tag{G.1}$$

$\frac{H_{sc}}{\Delta \cdot d_{n,50}}$ = Stability parameter [-]
$H_{2\%}$ = can be determined from SwanOne model or using Battjes-Groenendijk (2000) equations (J.P. van den bos, Edition 2018)
$\Delta$ = relative mass density $(\rho_s - \rho_m)/\rho_m$, $\rho_s$ is mass density of stone and $\rho_w$ is mass density of water [-]
$d_{n,50}$ = nominal median block diameter [m]
P = notional permeability coefficient
S = damage level
N = number of waves
$\xi_{m-1,0}$ = surf similarity parameter (Iribarren parameter)

As mentioned before, The Rock Manual (2007) recommends to use the deep water equations of Van Der meer only if the local water depth at the toe of the structure is more then 3 times the local significant wave height. Therefore the shallow water formulas are used as described in The Rock Manual (2007), which are based on the Van der Meer equations (1988) but additional model test data is added for shallow water conditions (Van Gent et al 2004). In the table below an overview is given of the input parameters. The deep water formulas are also used to validate the shallow water conditions and see if the solutions have similar outcomes. For the deep water wave conditions the Van Der Meer formula is given in Equation G.2:

$$\frac{H_s}{\Delta \cdot d_{n50}} = 6.2 \cdot P^{0.18} \cdot (\frac{S}{\sqrt{N}})^{0.2} \cdot \xi_m^{-0.5} \tag{G.2}$$

$H_s$ = Local wave height, determined using Swanone model
$H_{2\%}$ = An exceedance value, indicates that 98% of the waves are lower than this value. In shallow water it can be determined from SwanOne model or using Battjes-Groenendijk (2000) equations,in deep water waves follow a Rayleigh distribution, so it is a fixed value.
Δ = Relative mass density $(\rho_s - \rho_m)/\rho_m$, $\rho_s$ is mass density of stone and $\rho_w$ is mass density of water [-]
$d_{n,50}$ = Nominal median block diameter [m]
P = Notional permeability coefficient. When the permeability of a sub layer is rather low, waves can be reflected against the sub layer and therefore increase the lift force on the armour layer. Based on experiment this value is set at 0.4, which is a common value for revetments. (J.P. van den bos, Edition 2018)
S = Indication for the level of damage. For a slope 1V:2H a typical value is 2. (J.P. van den bos, Edition 2018)
N = Number of waves in a storm. For shallow water conditions The Rock Manual uses N < 3000.
$T_{m-1,0}$ = shallow water wave period $T_{m-1,0}$, determined out of spectrum in SwanOne model.
$\xi_{m-1,0}$ = $tan(1/2)/(2*\pi*Hs/(9.81*T^2))^{0.5}$ = Surf similarity parameter determined with shallow water wave period out of local spectrum Swanone (Iribarren parameter)

Table G.1: Final result armour layer $d_{n50}$

| | $D_{n50}$ [m] |
|---|---|
| Shallow water conditions | 0.43 |
| Deep water conditions | 0.38 |

In Table G.1 the final nominal median block diameter for the shallow- and deep water wave conditions are given, which shows a same order of magnitude for both shallow- and deep water conditions. For further calculations the shallow water wave conditions will be considered as legitimate. Also the used pythonscripts can be found in Figure G.5 and G.6.

### G.2.1. Standard gradings Table EN13383

```
#shallow water

Hs = H_sss
Hm0 = 1.05 #from swanone at x = 2 meters from still water level
Hs = Hm0
P = 0.4 # permeability factor armour stone + filter = 0.4
S = 2 # acceptable damage factor, for revetment typical value of 2 is used
N = 3000 # shallow water <3000
T = 3.19 # shallow water wave periode T_(m-1,0) = 2*pi*m_(-1)/m_(0)
alfa = 1/2 # slope of revetment
xi = np.tan(alfa) / np.sqrt(2*np.pi*Hs/(9.81*T**2)) # surf similarity parameter
Delta = 1.65 # relative mass density stone-water
cpl = 8.4 # coefficient Van Der Meer shallow water
H_2 = 1.77E+00 # H_2% determined from Swanone, Battjes en Groenendijk

dn50 = Hs /(Delta * cpl * P**(0.18) * (Hs/H_2)* (S/np.sqrt(N))**0.2 * xi**(-0.5))
print(dn50, 'm')

x = np.linspace(0,1,10000)
dn50 = x
H_sc = cpl * P**(0.18) * (Hs/H_2)* (S/np.sqrt(N))**0.2 * xi**(-0.5) * (Delta*dn50)
```

```
0.42563002388153803 m
[0.42554255] m
```

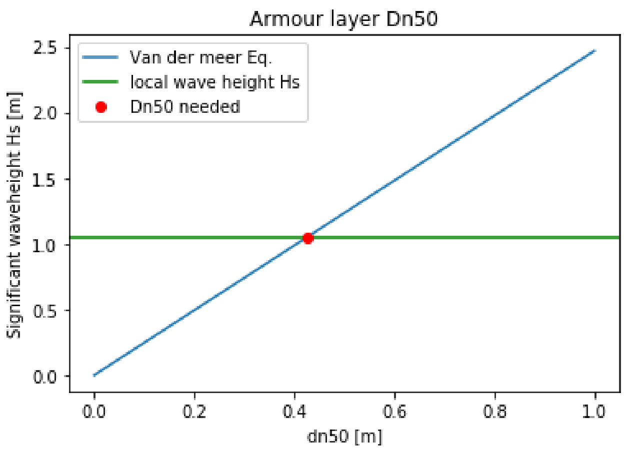



Figure G.5: Determination with python Dn50 shallow water wave conditions

## Deepwater

```
Hs = Hm0 = 1.05
#print(Hs)
P = 0.4
S = 2
N = 7000 # shallow water <3000
alfa = 1/2
Delta = 1.65
Tm = 3.4
xi = np.tan(alfa) / np.sqrt(2*np.pi*Hs/(9.81*Tm**2))
#print (xi)
cpl = 6.2

dn50 = Hs /(Delta * cpl * P**(0.18) * (S/np.sqrt(N))**0.2 * xi**(-0.5))
print (dn50)
x = np.linspace(0,1,1000)
dn50 = x
H_sc = cpl * P**(0.18) *  (S/np.sqrt(N))**0.2 * xi**(-0.5) * (Delta*dn50)
```

```
0.38439495597891815
[0.38438438] m
```

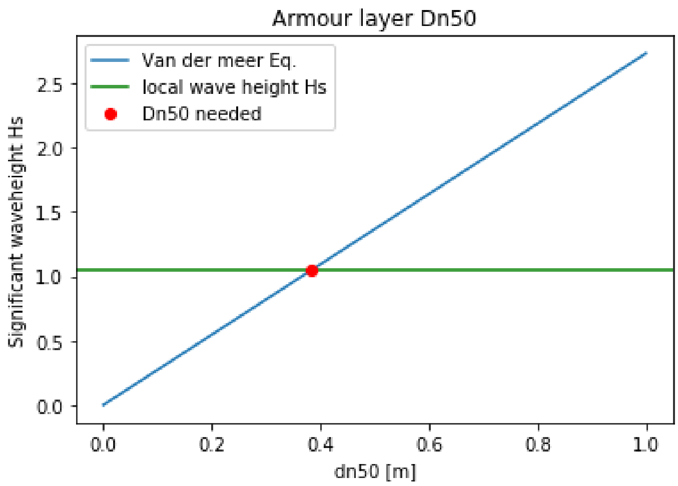



Figure G.6: Determination with python Dn50 deep water wave conditions

Table A- 2 Standard gradings in EN13383

| Class name | described in EN13383 | | $d_{50}$ (cm) | $d_{85}/d_{15}$ | $d_{n50}$ (cm) | (2) | (3) |
|---|---|---|---|---|---|---|---|
| | range | (1) | | | | | |
| CP45/125 | 45/125 mm | 0.4-1.2 | 6.3-9.0 | 2.8 | 6.4 | 20 | 300 |
| CP63/180 | 63/180 mm | 1.2-3.1 | 9.0-12.5 | 2.8 | 9 | 20 | 300 |
| CP90/250 | 90/250 mm | 3.1-9.3 | 12.5-18 | 2.8 | 12.8 | 20 | 300 |
| CP45/180 | 45/200 mm | 0.4-1.2 | 6.3-9.0 | 4.0 | 6.4 | 20 | 300 |
| CP90/180 | 90/180 mm | 2.1-2.8 | 11-12 | 2.0 | 9.7 | 20 | 300 |
| $LM_A$ 5-40 | 5-40 kg | 10-20 | 18-23 | 1.7 | 17 | 25 | 500 |
| $LM_A$ 10-60 | 10-60 kg | 20-35 | 23-28 | 1.5 | 21 | 32 | 550 |
| $LM_A$ 40-200 | 40-200 kg | 80-120 | 37-42 | 1.5 | 34 | 52 | 850 |
| $LM_A$ 60-300 | 60-300 kg | 120-190 | 42-49 | 1.5 | 38 | 57 | 950 |
| $LM_A$ 15-300 | 15-300 kg | 45-135 | 30-44 | 2.7 | 31 | 46 | 700 |
| $HM_A$ 300-1000 | 300-1000 kg | 450-690 | 65-75 | 1.4 | 59 | 88 | 1325 |
| $HM_A$ 1000-3000 | 1-3 ton | 1700-2100 | 103-110 | 1.4 | 90 | 135 | 2050 |
| $HM_A$ 3000-6000 | 3-6 ton | 4200-4800 | 138-144 | 1.2 | 118 | 177 | 2700 |
| $HM_A$ 6000-10000 | 6-10 ton | 7500-8500 | 167-174 | 1.2 | 144 | 216 | 3250 |

CP - Course gradings
LM - Light gradings
HM - Heavy gradings

(1): range of $W_{50}$ for category "A" (kg)
(2): Layer thickness 1.5 $d_{n50}$ (cm)
(3): Minimal dumping quantity with layer of 1.5 $d_{n50}$ (kg/m$^2$)

Figure G.7: Standard gradings EN12383

# H

# Salt marsh

## H.1. Design calculation

### H.1.1. Canoe shed

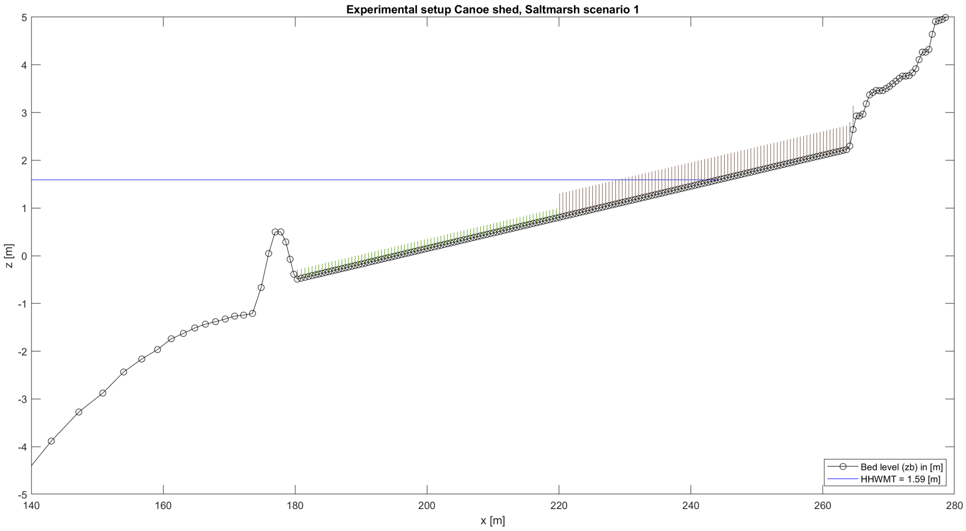



Figure H.1: XBeach model setup of the Canoe Shed cross section for scenario 1

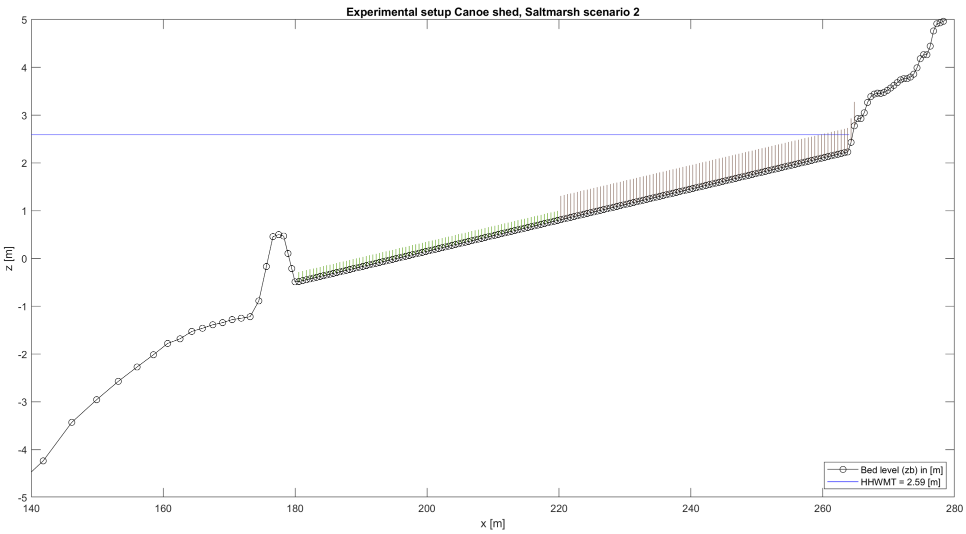



Figure H.2: XBeach model setup of the Canoe Shed cross section for scenario 2

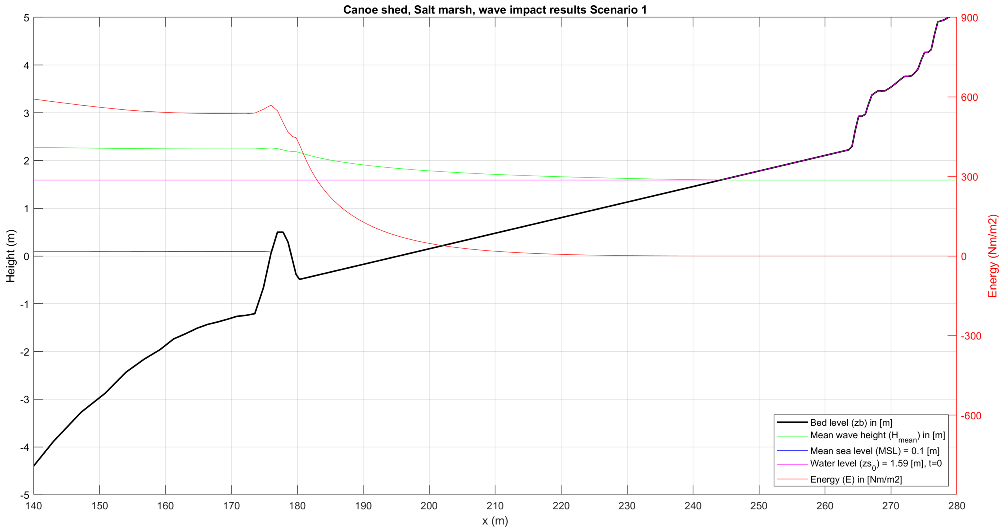



Figure H.3: Wave impact on the Canoe Shed cross section given the conditions of scenario 1

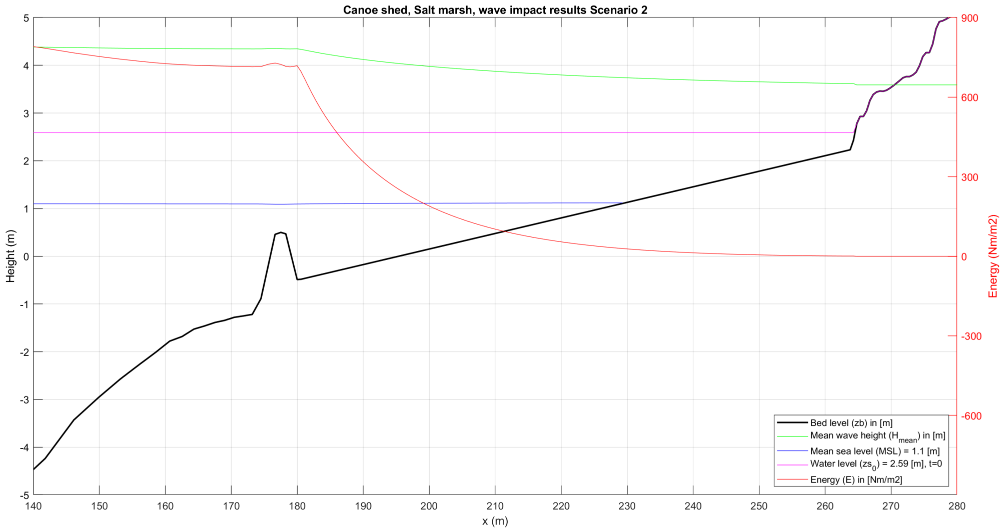



Figure H.4: Wave impact on the Canoe Shed cross section given the conditions of scenario 2

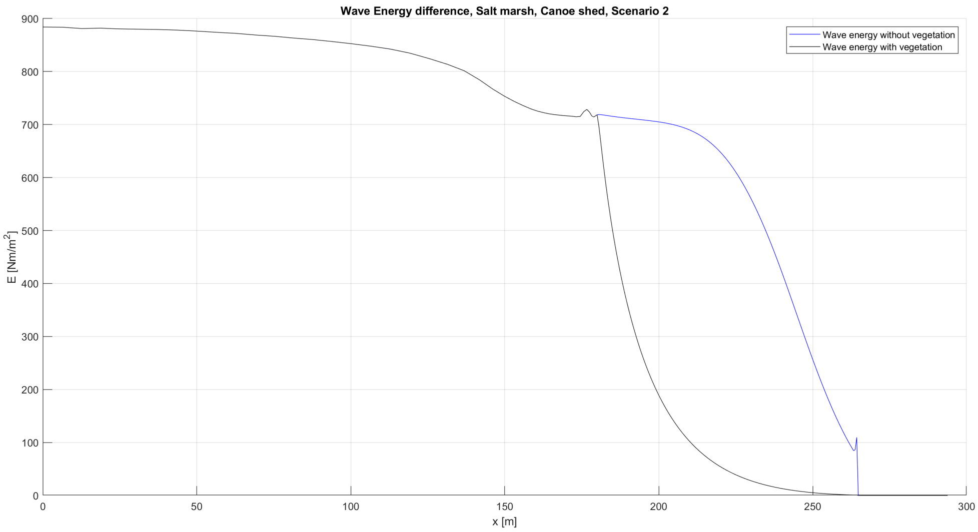



Figure H.5: Wave energy at the Canoe Shed cross section given the conditions of scenario 2

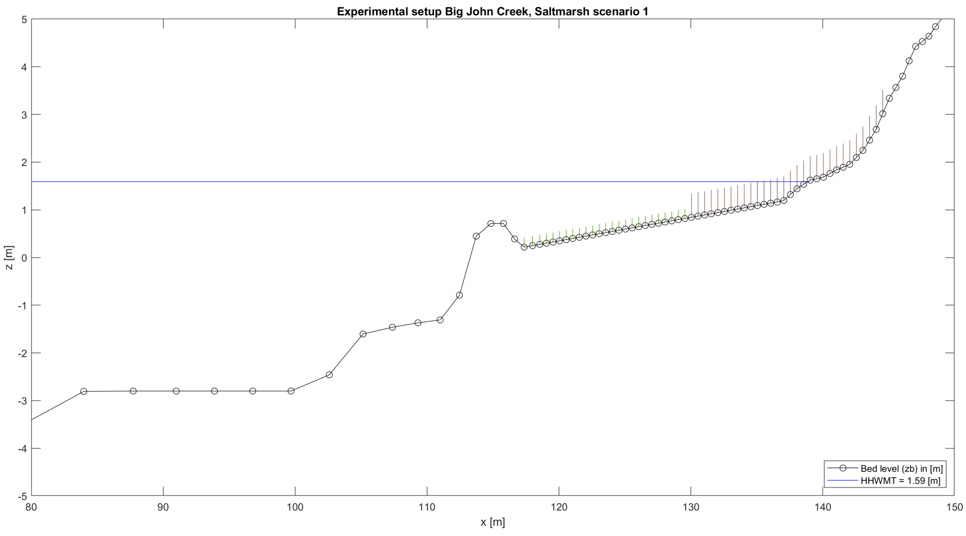



Figure H.6: XBeach model setup of the Big John Creek cross section for scenario 1

## H.1.2. Big Johns Creek

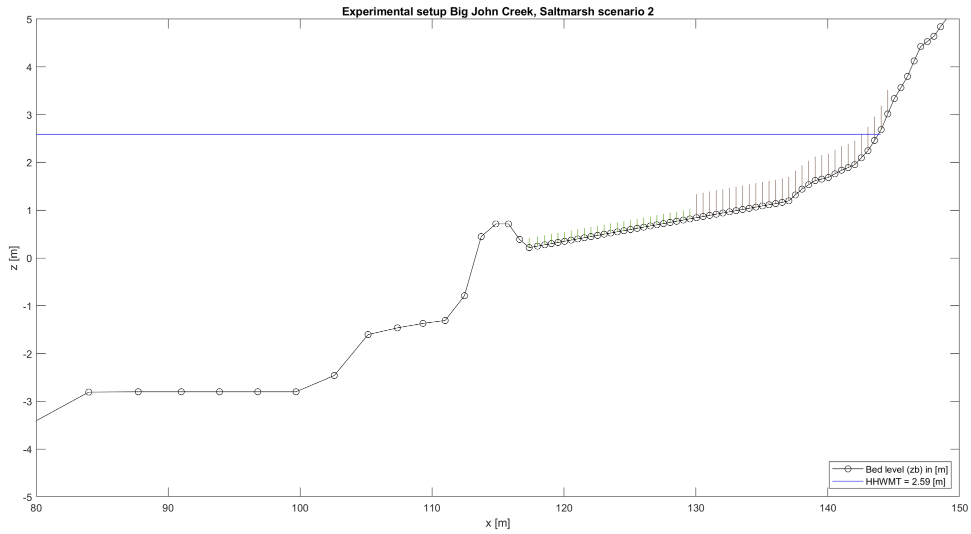



Figure H.7: XBeach model setup of the Big John Creek cross section for scenario 2

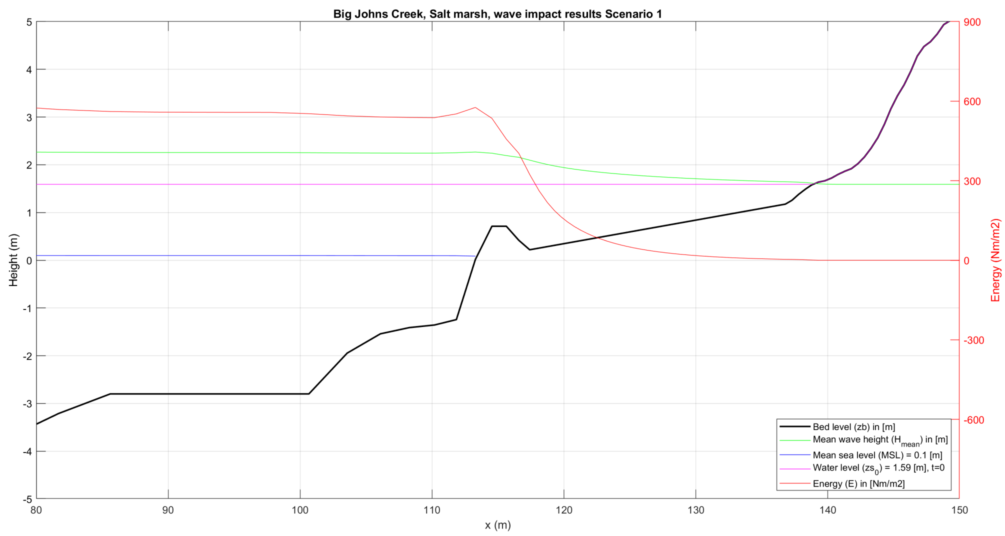



Figure H.8: Wave impact on the Big John Creek cross section given the conditions of scenario 1

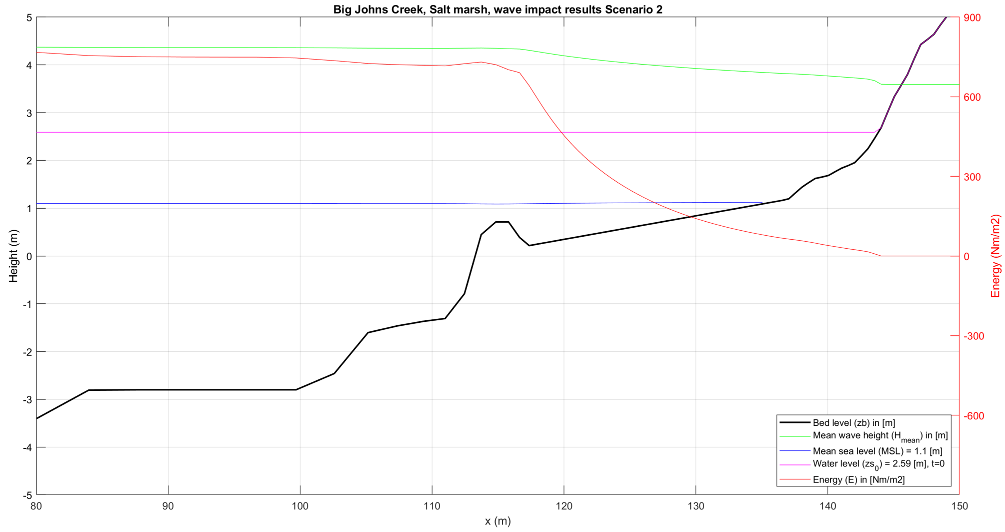



Figure H.9: Wave impact on the Canoe Shed cross section given the conditions of scenario 2

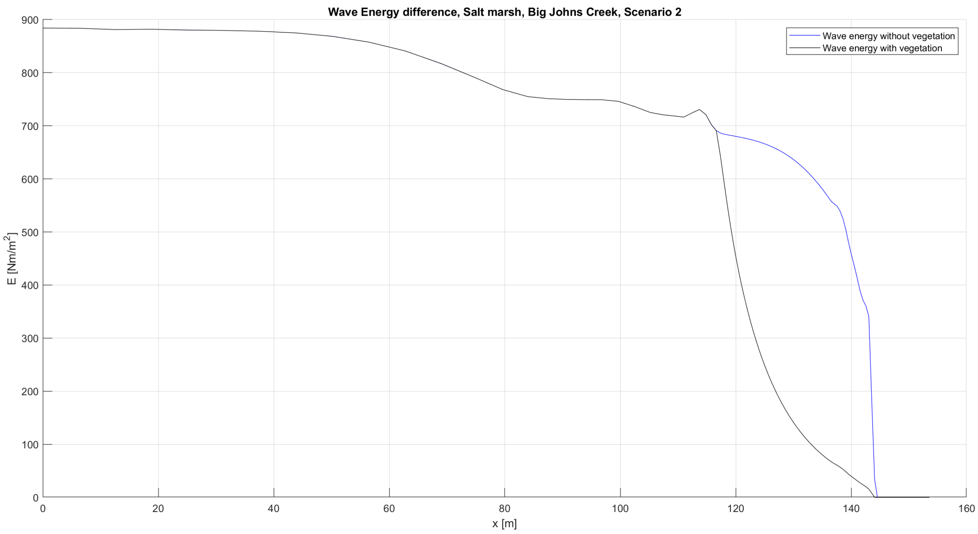



Figure H.10: Wave energy at the Canoe Shed cross section given the conditions of scenario 2

## H.2. Cost calculation

The amount of sediment that is needed to create the salt marsh is calculated. For the cross sections of the Canoe Shed and Big Johns Creek these are about 180 and 20 $m^2$/m respectively (Figure H.11 and H.12).

```
# .csv file made with 6 columns:
# X(x-coordinaten_origineel);
# Z(z-coordinaten_origineel);
# Y100(z-coordinaten_origineel + 50m)
# XX(x-coordinaten_saltmarsh);
# ZZ(z-coordinaten_saltmarsh);
# YY100(z-coordinaten_saltmarsh + 50m)

CS = pd.read_csv("bathymetry_CS_Saltmarsh.csv")
x = CS['X']
y = CS['Y100']
area1 = trapz(x,y)
print(area1)

x2 = CS['XX']
y2 = CS['YY100']
area2 = trapz(x2,y2,dx=0.1)
print(area2)

area = area1-area2
print('The added amount of sediment to create the saltmarsh at the Canoe Shed is equal to an area of:', area, 'm^2/m')
```

```
3225.0077136063464
3045.5176894862034
The added amount of sediment to create the saltmarsh at the Canoe Shed is equal to an area of: 179.49002412014306 m^2/m
```

Figure H.11: Adjusted cross section at Big Johns Creek for the creation of a saltmarsh

```
BJC = pd.read_csv("bathymetry_BJC_saltmarsh.csv")
x = BJC['X']
y = BJC['Y100']
area1 = trapz(x,y,dx=0.1)
print(area1)

x2 = BJC['XX']
y2 = BJC['YY100']
area2 = trapz(x2,y2,dx=0.1)
print(area2)

area = area1-area2
print('The added amount of sediment to create the saltmarsh at Big Johns Creek is equal to an area of:', area, 'm^2/m')
```

```
1866.3227582680834
1847.8840153062915
The added amount of sediment to create the saltmarsh at Big Johns Creek is equal to an area of: 18.43874296179183 m^2/m
```

Figure H.12: Adjusted cross section at Big Johns Creek for the creation of a saltmarsh

# I Clam garden

In this section the X-beach setup and Wave impacts for the Canoe shed and Big John creek cross section with clam gardens are discussed.

## I.1. Canoe Shed

Figures I.1 and I.2 show the X-beach model setup for the Canoe shed cross section. The surface roughness is depicted as small black elements on top of the clam garden area.

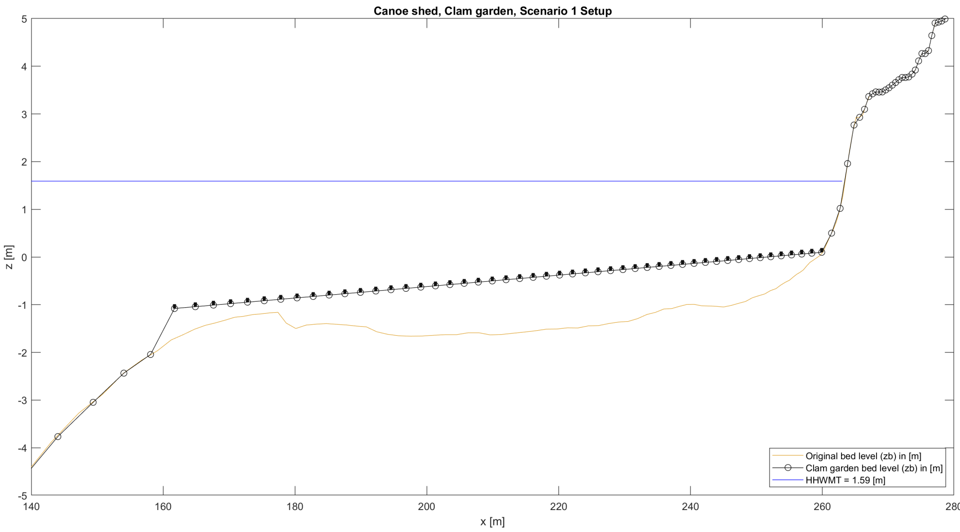



Figure I.1: X-beach model setup of the Canoe shed cross section for scenario 1. The original beach profile is depicted in yellow. The modelled clam garden is shown in black with a visual display of the shell hash surface as black elements.

Comparing Figure I.3 to the base case ( Figure 6.10a ), it is possible to observe that the mean wave height just before the breaking point (X = 263m) has decreased a little. The clam garden does not fully prevent erosion from happening but decreases it.

Figure I.4 shows the wave impact under the second scenario. Water levels have increased and the clam garden is further submerged. The wave dissipation properties of the clam garden have become less observable, but based on the observed behaviour of scenario 1, it is expected that the amount of erosion that will occur will be mitigated.

The location of the breaking point does not significantly change.

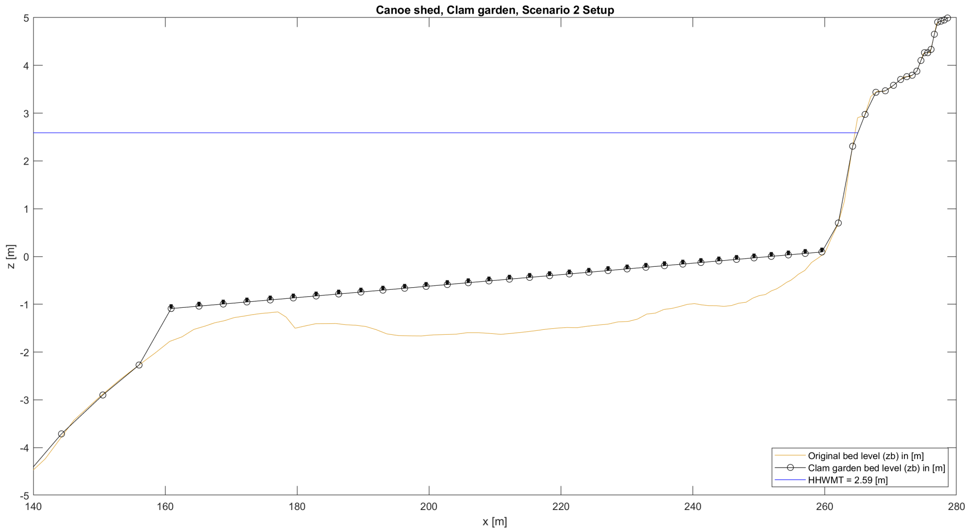



Figure I.2: X-beach model setup of the Canoe shed cross section for scenario 2. The original beach profile is depicted in yellow. The modelled clam garden is shown in black with a visual display of the shell hash surface as black elements.

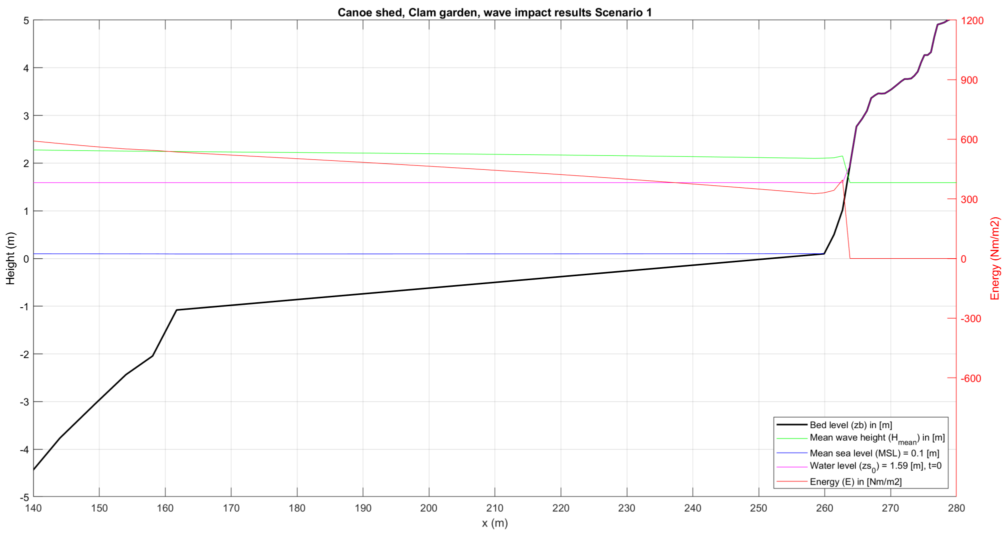



Figure I.3: Wave impact on the Canoe shed cross section in Scenario 1. The black line represents the bed level with the clam garden incorporated. The blue line indicates a MSL of 0.1m. The pink line shows the scenario specific high water level of 1.59m and the green line the mean wave height. The red line indicates the energy level

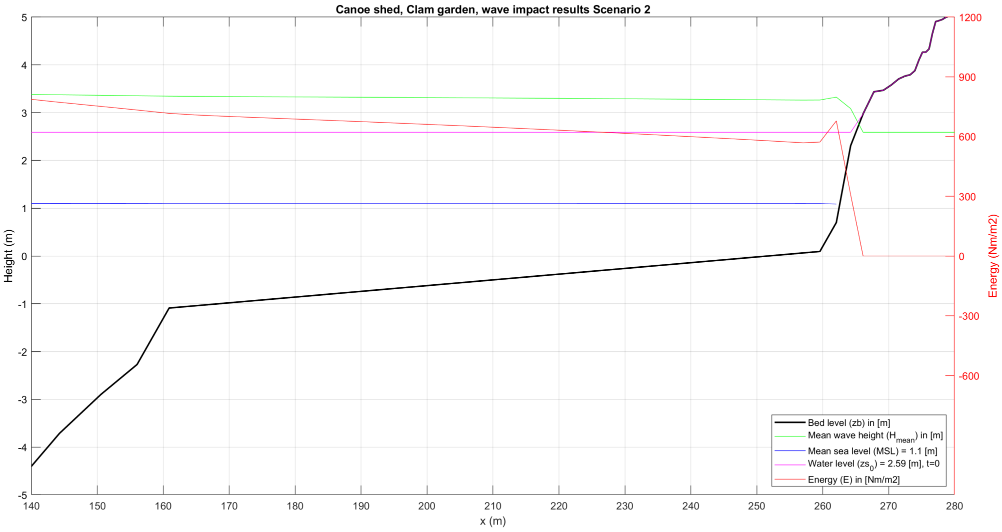



Figure I.4: Wave impact on the Canoe shed cross section in Scenario 2. The black line represents the bed level with the clam garden incorporated. The blue line indicates a MSL of 1.1m. The pink line shows the scenario specific high water level of 2.59m and the green line the mean wave height. The red line indicates the energy level

# I.2. Big John creek

Figures I.1 and I.2 show the X-beach model setup for the Big John creek cross section. The surface roughness is depicted as small black elements on top of the clam garden area.

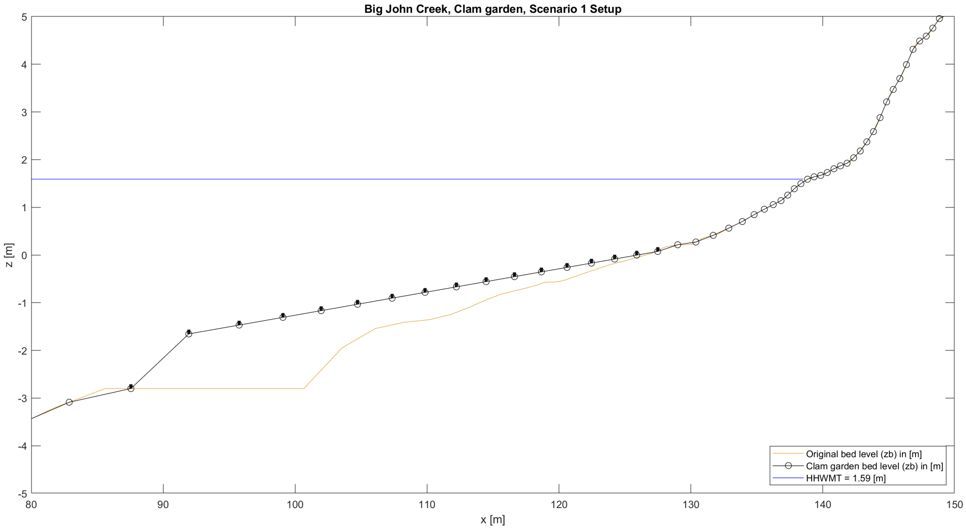



Figure I.5: X-beach model setup of the Big John creek cross section for scenario 1

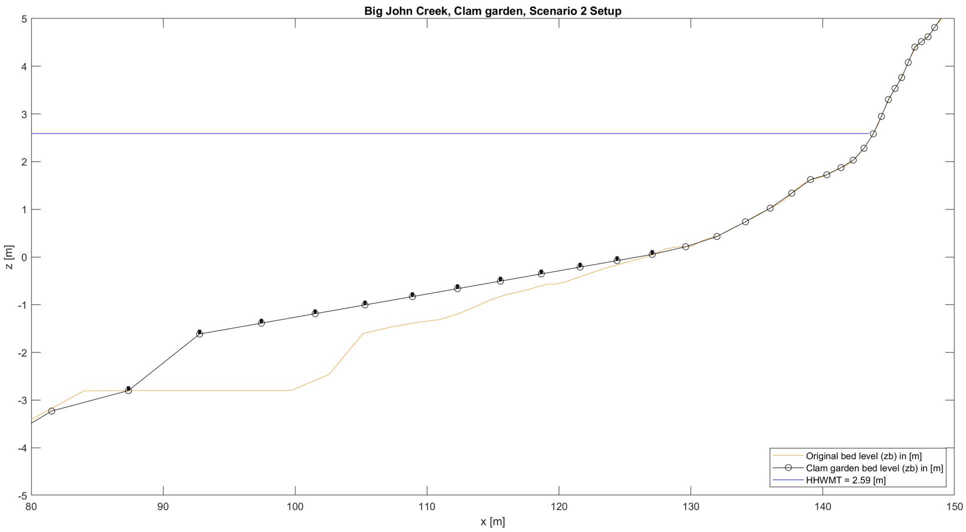



Figure I.6: X-beach model setup of the Big John creek cross section for scenario 2

Figure 6.9a displays the base case for the Big John creek with scenario 1. Comparing Figure I.7 here, a subtle difference in energy levels, indicating a decrease in erosion. The same is expected to happen in the cross section in scenario 2, which can be found in Figure I.8. The location of the breaking point does not significantly change.

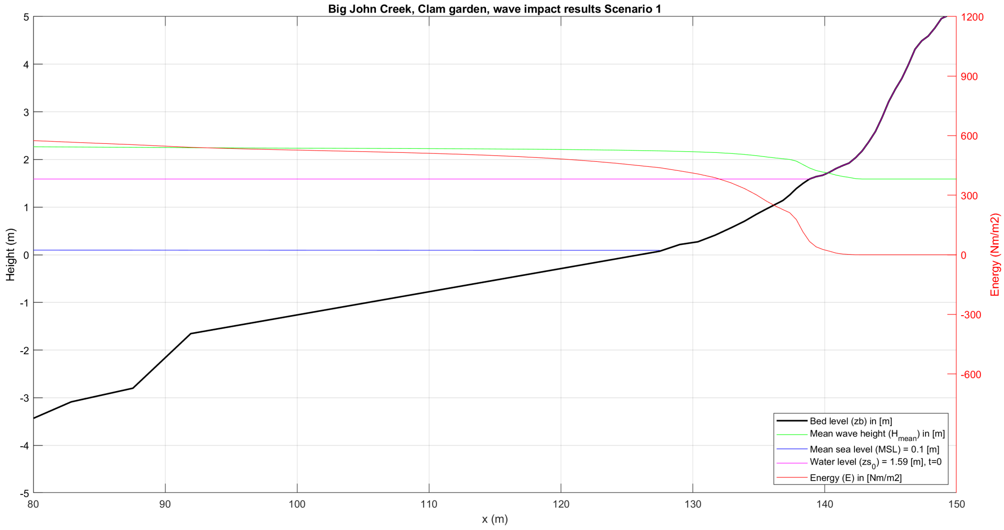



Figure I.7: Wave impact on the Big John creek cross section in Scenario 1. The black line represents the bed level with the clam garden incorporated. The blue line indicates a MSL of 0.1m. The pink line shows the scenario specific high water level of 1.59m and the green line the mean wave height. The red line indicates the energy level

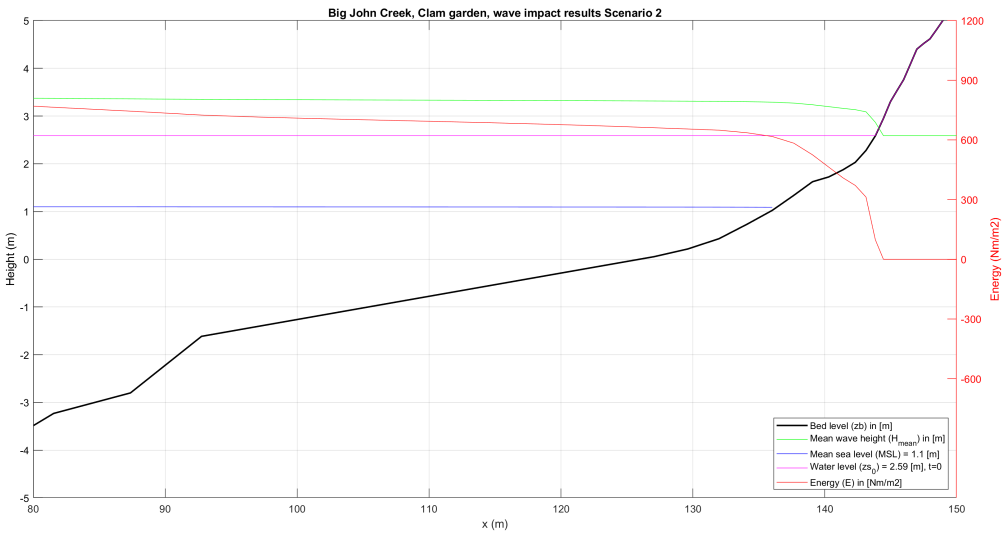



Figure I.8: Wave impact on the Big John creek cross section in Scenario 2. The black line represents the bed level with the clam garden incorporated. The blue line indicates a MSL of 1.1m. The pink line shows the scenario specific high water level of 2.59m and the green line the mean wave height. The red line indicates the energy level

# J

# Nourishment

## J.1. Definitions Coastal cross-shore profile

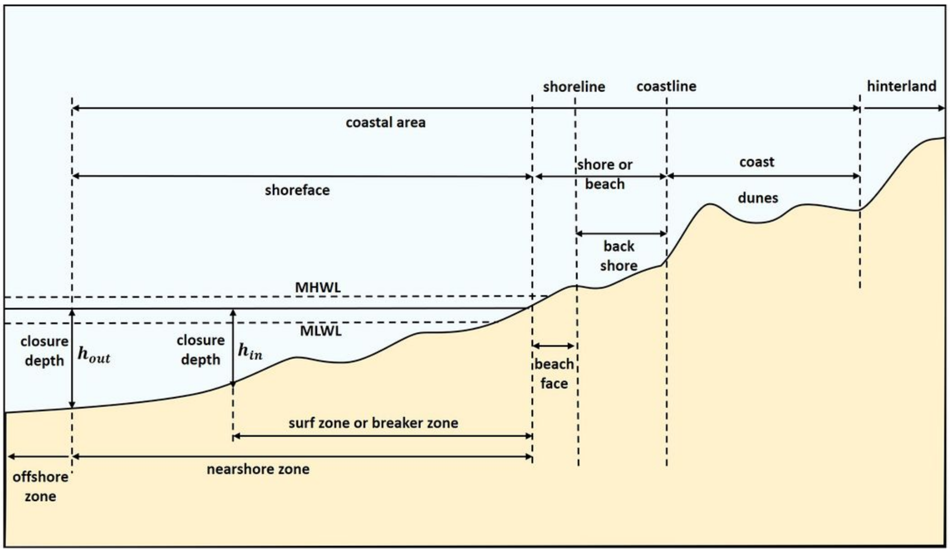



Figure J.1: Definition of coastal terms, adapted from Shore Protection Manual,1984 (Karsten, 2020; engineering Research Center, 1984)

## J.2. Active coastal zone and equilibrium profile

In cross-shore direction the zone where sediment is exchanged in cross-shore direction by natural processes is called the Active coastal zone or the active coastal profile. This profile reaches from the Closure depth until the landward limit of a hard boundary. For a soft boundary, which is the case for the TWN project area, it includes part of the bank which can be eroded by storm waves (Dronkers, 2005). In the Active coastal zone the cross-shore coastal profile for the TWN project site is assumed to be in equilibrium according to the generally accepted understanding that for an unchanged grain size and prevailing wave climate there exists a dynamic Equilibrium profile. This is the natural form that a beach would take given a volume of sediment under the prevailing wave climate. This was first proposed by Bruun (1954) and later supported by Dean (1977). The Equilibrium profile is a dynamic concept as the hydrodynamics conditions are constantly changing and therefore also the corresponding profile (Bosboom and Stive, 2015; Johannessen and Shipman, 2014; Bodegom, 2014). The Equilibrium profile tends to be concave upward with finer sediments in deeper waters and coarser sediment in shallower waters. Finer sediments result in milder slopes and steeper waves give flatter slopes for the Equilibrium profile (Dean, 1977; Bodegom, 2014).

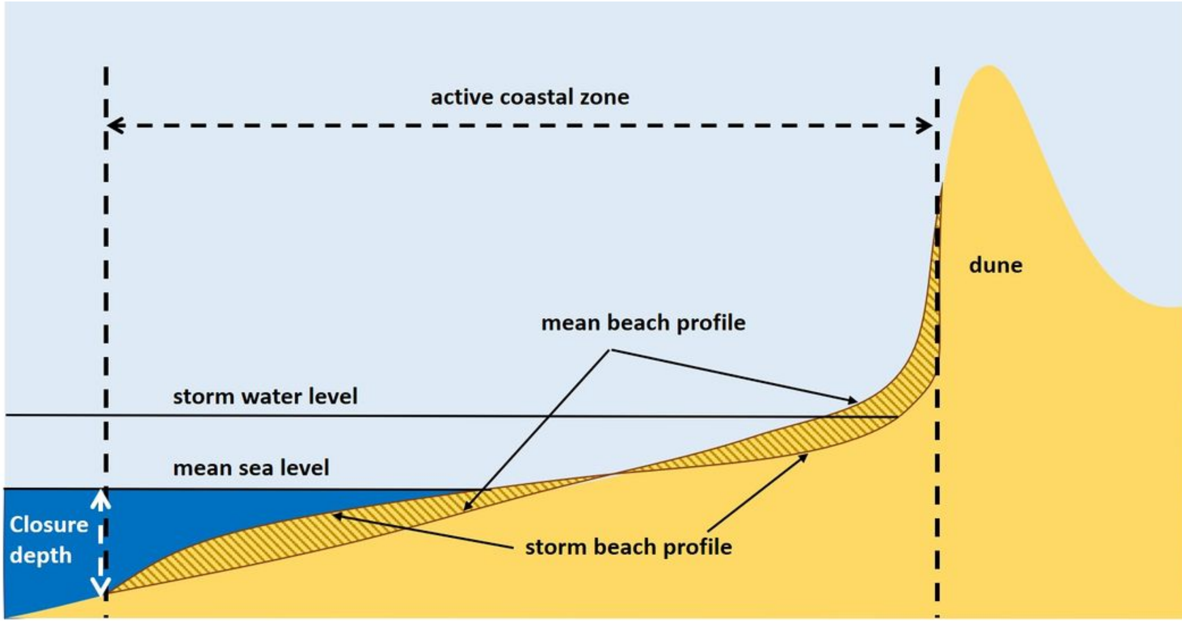



Figure J.2: Schematic illustration of the active coastal zone for a dune coast (Dronkers, 2005)

## J.3. Nourishment locations in the cross-shore profile

- Backshore nourishment
- Beach nourishment
- Shoreface nourishment
- profile nourishment

**Backshore nourishment**

A Backshore nourishment strengthens the upper part of the beach by placing the nourishment on the backshore or at the foot of the bank at the dry beach. Bachkshore nourishments are executed to strengthen the backshore/bank against erosion during storm conditions and is placed on some distance from the intertidal zone out of reach of non-storm waves. The nourishment acts as a buffer during storm conditions when the nourished material is sacrificed and large losses may occur. For the TWN a backshore nourishment could stop the bank transgression as the bank is mostly eroded during high water levels and storm conditions. The drawback is that large losses will occur during high water and storm conditions as sediment is transported from the backshore to the intertidal zone. Whether this lost sediment to the intertidal zone is moved back to the backshore by wave action during calmer conditions must be further researched for this specific site (Van Rijn, 2014; Johannessen and Shipman, 2014; Mangor, 2019).

**Beach nourishment**

A beach nourishment is the supply of sediment to the shore to increase the recreational value and/or to secure the beach against shore erosion by feeding sand to the beach. The sediment is placed in the intertidal zone up to the backshore and can be placed either directly on the shore or by means of dumping larger amounts of sediments at specific places updrift of the eroded shoreline sections. In the latter case the sediment forms a continues source of sediment which is transported by breaking waves and the longshore current to the eroded shoreline sections. In this way nature is doing the work of distributing the sediment to the right place. An example of this is the sand motor in the Netherlands. Substantial volumes of sediment that are placed in the intertidal zone are expected to be to transported down to the lower foreshore and potentially alongshore dependent on the longshore transport gradients. (Van Rijn, 2014; Johannessen and Shipman, 2014; Mangor, 2019). As the beach nourishment does not protect erosion of the bank at the backshore of the TWN project site during storm conditions a beach nourishment is not further used for the design.

**Shoreface nourishment**

In a shoreface nourishment sediment is supplied at the edge of the surfzone. The sediment is placed as a longshore artificial bar to feed sediment to the beach by onshore transport processes. If a bar is already present the sediment is usually placed at the most offshore bar. Large nourishment volumes are required for a shoreface nourishment as only part of the nourished sediment volume will reach the beach zone after a few years depending on the onshore transport processes. Therefore, a shoreface nourishment can have significant impact on sediment transport processes and can behave in the same way as an offshore breakwater by waves breaking on the bar. This process diminishes over time as the nourishment will be distributed over the coastal profile over time. A shoreface nourishment can reduce impact on the upper beaches but is not always applicable as it has negative impacts on submerged aquatic vegetation which is also present at the project site as discussed in Section 3.3 (Mangor, 2019; Van Rijn, 2014). Whether a shoreface nourishment is applicable at the TWN project site depends on cross-shore sediment transport processes which are not known in this situation. Therefore, this option is for this preliminary design not further elaborated.

**Profile nourishment**

A combination of shoreface and beach nourishment can be made in the form of a profile nourishment which is a nourishment over the entire beach profile from the backshore down to the Closure depth. It allows for less redistribution of the sediment and a longer lifetime. (Johannessen and Shipman, 2014).

## J.4. Sediment sieve analysis

Table J.1: Results from sediment analysis for Big John Creek from KWL sieve analyses. For the sub-surface truncated result grain sizes above 2 mm are excluded.

| | $D_{16}$ [mm] | $D_{50}$ [mm] | $D_{84}$ [mm] |
|---|---|---|---|
| Surface | 7 | 25 | 162 |
| Sub-surface | 0.9 | 9.1 | 22.1 |
| Sub-surface truncated | 0.3 | 0.7 | 1.5 |

## J.5. Borrow area

## J.6. Wave runup

For a first impression of the wave runup Hunts formula is used to determine the wave runup. This formula is then adapated for the heighest $2\%$ of the waves according to Equation J.3 which results in Equation J.4 for the runup exceeded by $2\%$ of the waves. This depends on the significant wave height and iribarren parameter which is determined in Equation J.1. As this is (Schierick, 2nd Edition 2012). The values for scenario 1 described in Chapter 6 are: $H_m0 = H_s = 1.03$ m, $T_p = 3.92$ s.

$$\xi = \frac{tan\ \alpha}{\sqrt{H_0/L_0}} = 0.48 \tag{J.1}$$

Where:

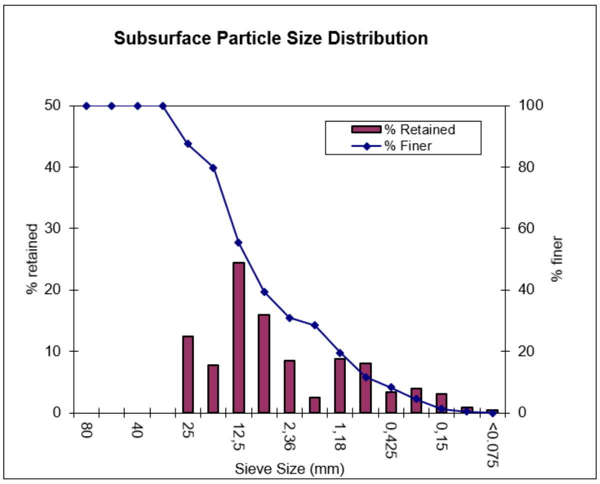
$tan\ \alpha$ = steepness of the nourishment beach (1:10)
$L_0$ = wavelength in deep water = $1.56 \cdot T^2$
$H_0$ = wave height = $H_m0 = 1.03$ m
$T_p = 3.92$ s

As the iribarren parameter is lower than 0.5 the waves are of the type spilling waves.

$$\frac{R_u}{H} = \xi \tag{J.2}$$

| Sieve Size (mm) | Percent Retained (%) | Cumulative Percent Finer (%) |
|---|---|---|
| 80 | 0 | 100,00 |
| 56 | 0 | 100,00 |
| 40 | 0 | 100,00 |
| 37,5 | 0 | 100,00 |
| 25 | 12,5 | 87,50 |
| 19 | 7,8 | 79,70 |
| 12,5 | 24,4 | 55,30 |
| 4,75 | 15,9 | 39,40 |
| 2,36 | 8,5 | 30,90 |
| 2 | 2,5 | 28,40 |
| 1,18 | 8,8 | 19,60 |
| 0,6 | 8 | 11,60 |
| 0,425 | 3,3 | 8,30 |
| 0,3 | 3,9 | 4,40 |
| 0,15 | 3,1 | 1,30 |
| 0,075 | 0,9 | 0,40 |
| <0.075 | 0,4 | 0,00 |
| | 100 | |

(a) Sub-surface sieve analysis Big John Creek




(b) Subsurface particle size distribution plot Big John Creek

Figure J.3: Sub-surface sediment analysis Big John Creek from KWL (2018)


Figure J.4: Locations of the quarry and depot for the fill material of the nourishment. Quarry: Britannia beach and (Lehigh Hanson Heidelberg Cement Group, 2020)

$$H_{2\%} \approx 1.5 \cdot H_s \tag{J.3}$$

$$R_{u2\%} \approx 1.5 \cdot \xi \cdot H_s = 0.75m \tag{J.4}$$

# J.7. Xbeach model setup and results nourishment

## J.7.1. Big John Creek

**Profile nourishment Xbeach results:**

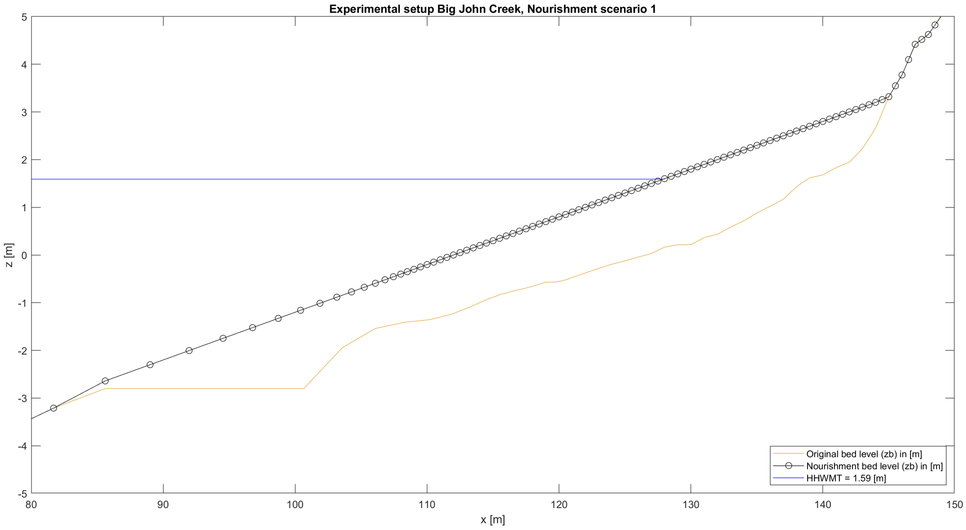



Figure J.5: Xbeach model setup of Big John Creek for the profile nourishment in scenario 1. The original profile is depicted in yellow and the modelled nourishment in black.

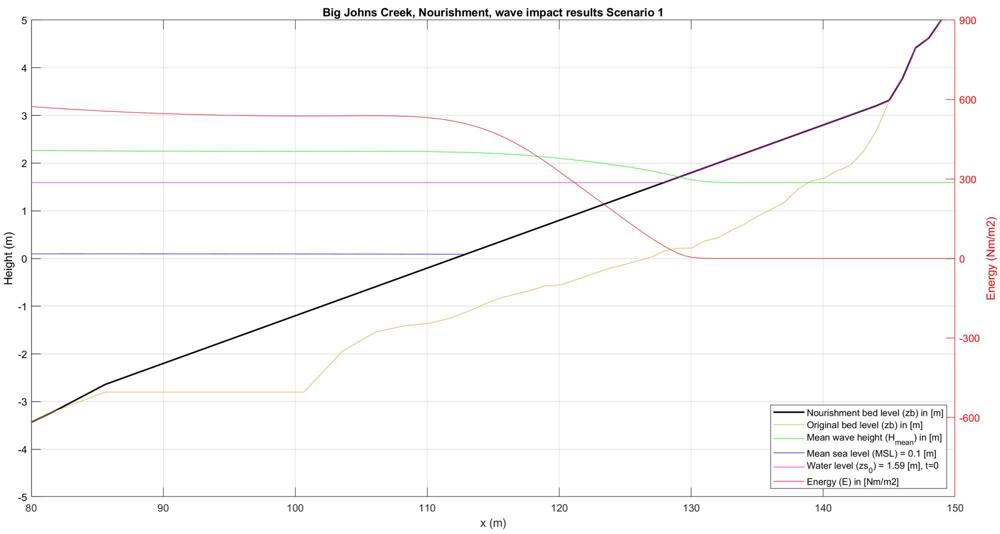



Figure J.6: Wave impact at Big John Creek for the profile nourishment in scenario 1. The original profile is depicted in yellow and the modelled nourishment in black.

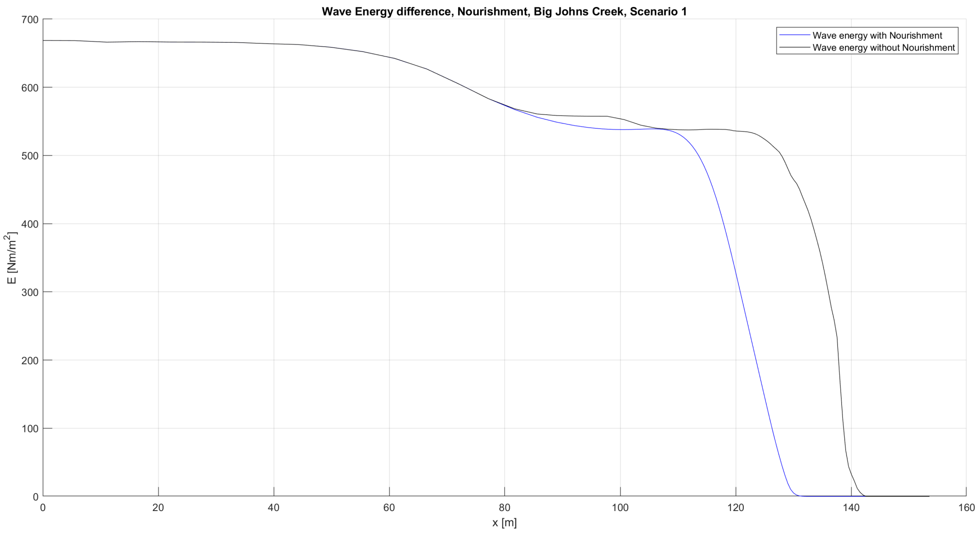



Figure J.7: Wave energy dissipation at Big John Creek for the profile nourishment in scenario 1. The original profile is depicted in yellow and the modelled nourishment in black.

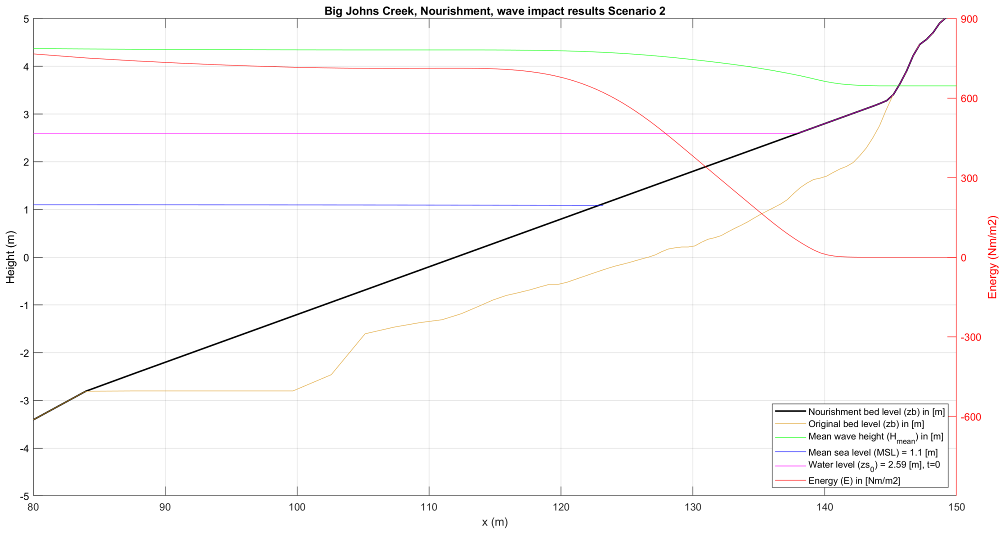



Figure J.8: Wave impact at Big John Creek for the profile nourishment in scenario 2. The original profile is depicted in yellow and the modelled nourishment in black.

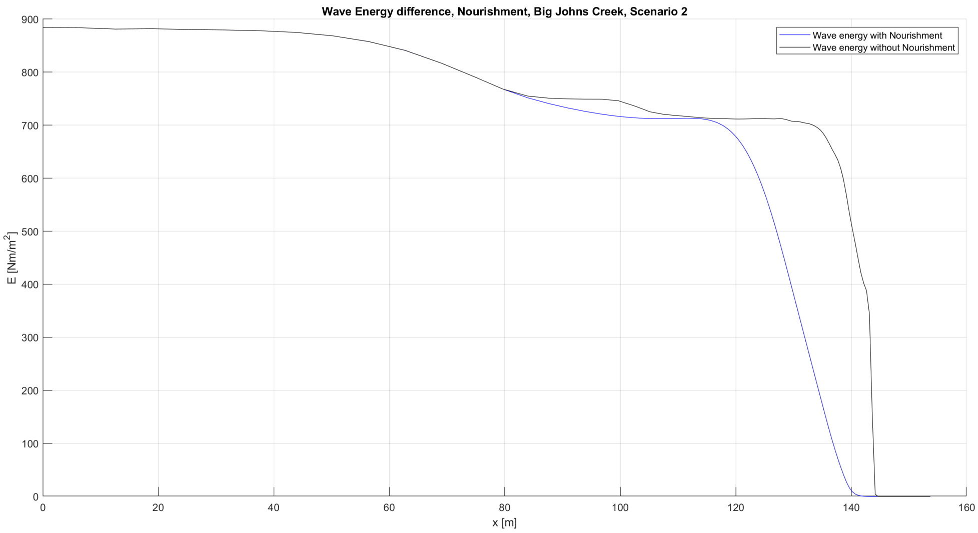



Figure J.9: Wave energy dissipation at Big John Creek for the profile nourishment in scenario 2. The original profile is depicted in yellow and the modelled nourishment in black.

## Backshore nourishment Xbeach results:

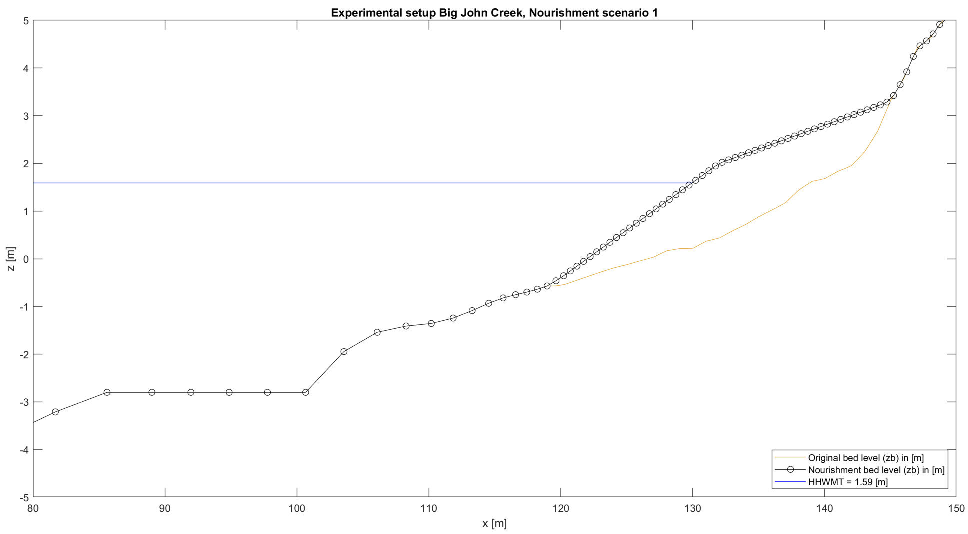



Figure J.10: Xbeach model setup at Big John Creek for the backshore nourishment in scenario 1. The original profile is depicted in yellow and the modelled nourishment in black.

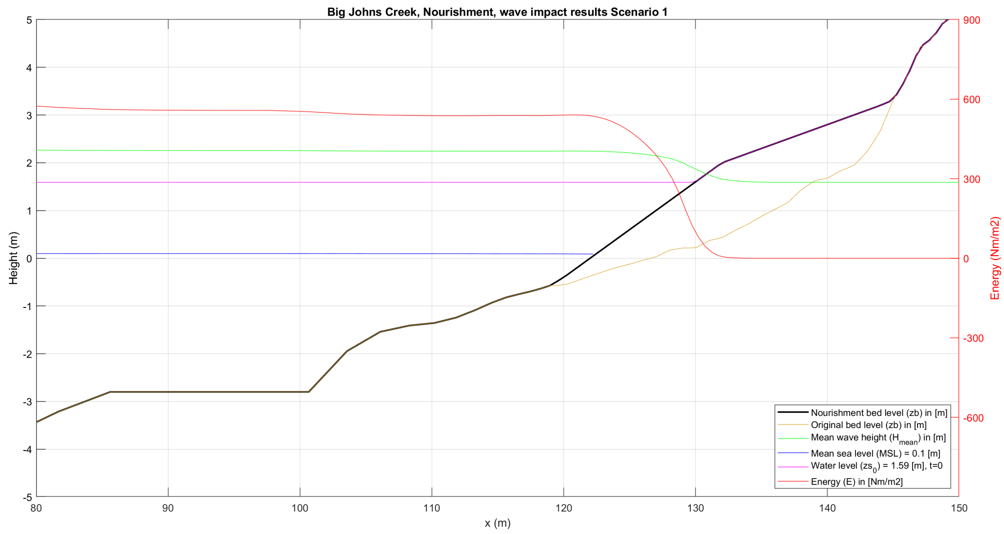



Figure J.11: Wave impact at Big John Creek for the backshore nourishment in scenario 1. The original profile is depicted in yellow and the modelled nourishment in black.

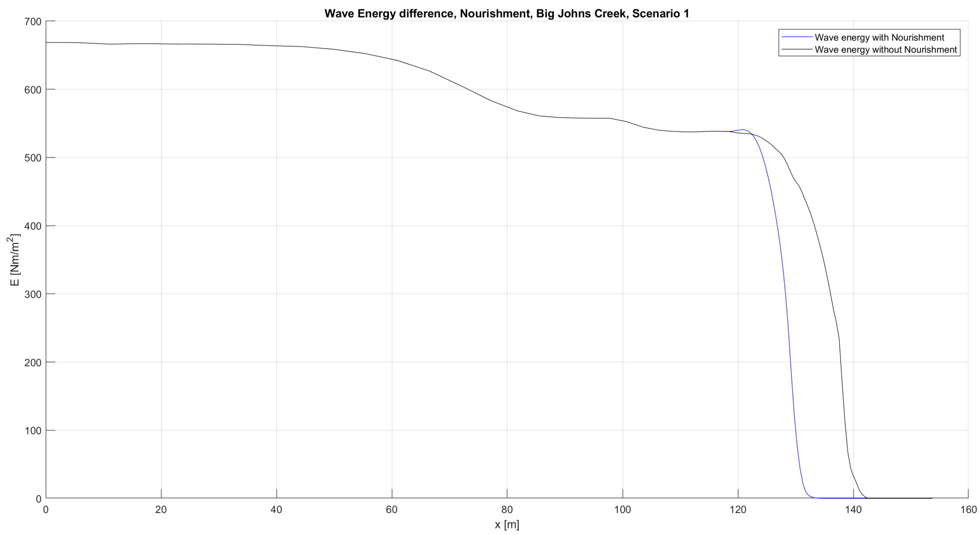



Figure J.12: Wave dissipation at Big John Creek for the backshore nourishment in scenario 1. The original profile is depicted in yellow and the modelled nourishment in black.

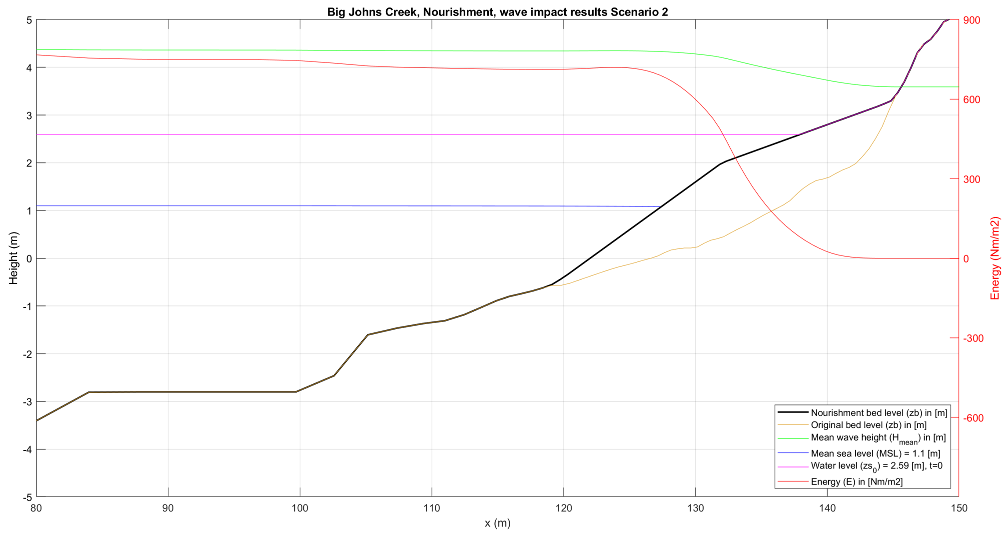



Figure J.13: Wave impact at Big John Creek for the backshore nourishment in scenario 2. The original profile is depicted in yellow and the modelled nourishment in black.

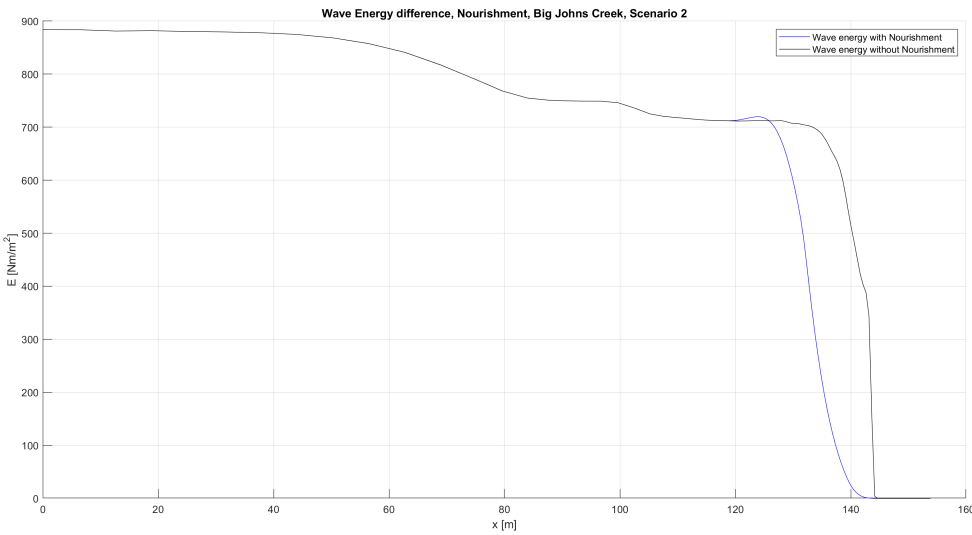



Figure J.14: Wave dissipation at Big John Creek for the backshore nourishment in scenario 2. The original profile is depicted in yellow and the modelled nourishment in black.

## J.7.2. Canoe Shed

### Profile nourishment Xbeach results:

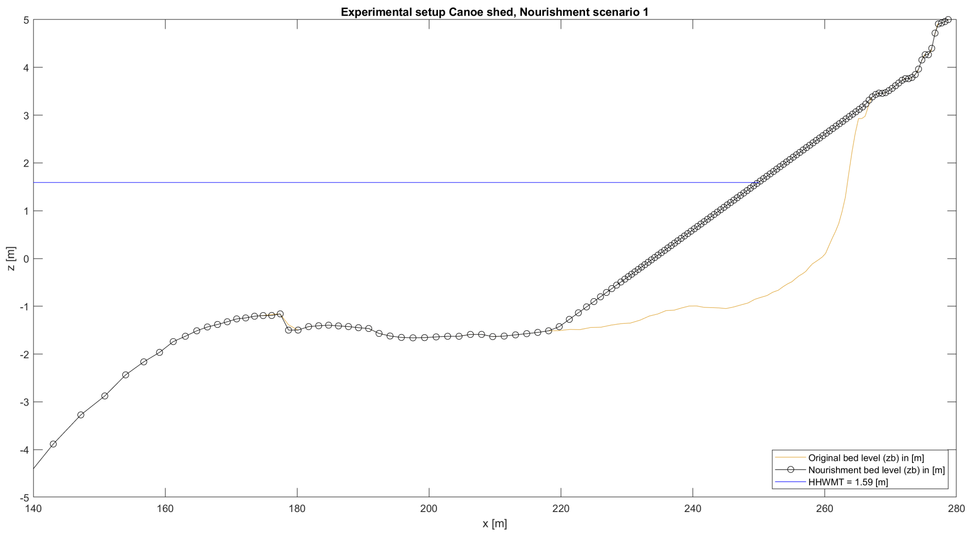



Figure J.15: Xbeach setup at Canoe Shed for the profile nourishment in scenario 1. The original profile is depicted in yellow and the modelled nourishment in black.

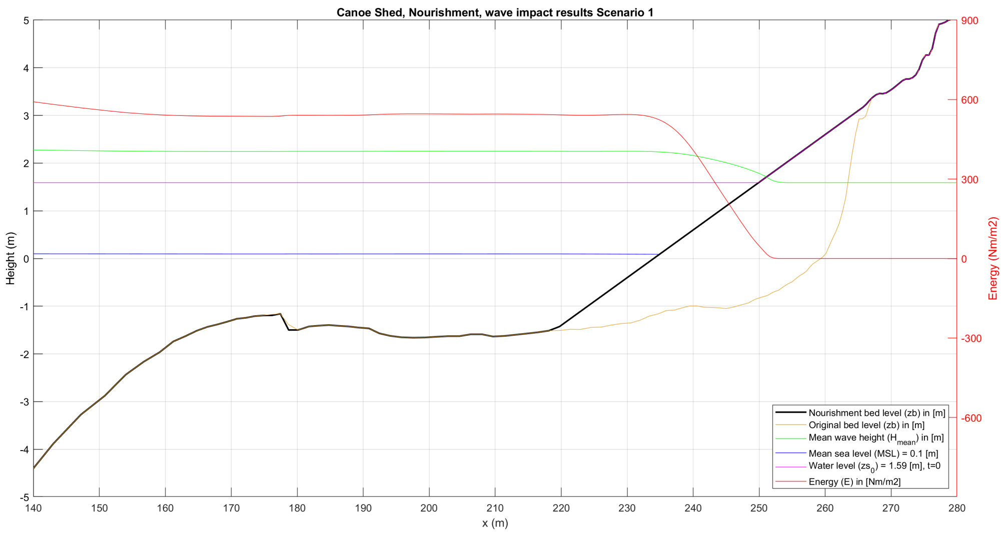



Figure J.16: Wave impact at Canoe Shed for the profile nourishment in scenario 1. The original profile is depicted in yellow and the modelled nourishment in black.

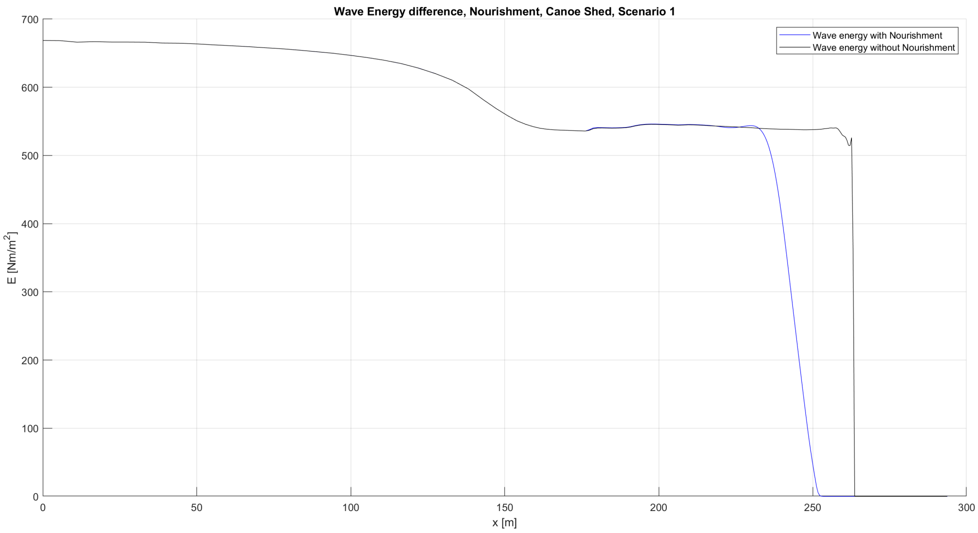



Figure J.17: Wave energy dissipation at Canoe Shed for the profile nourishment in scenario 1. The original profile is depicted in yellow and the modelled nourishment in black.

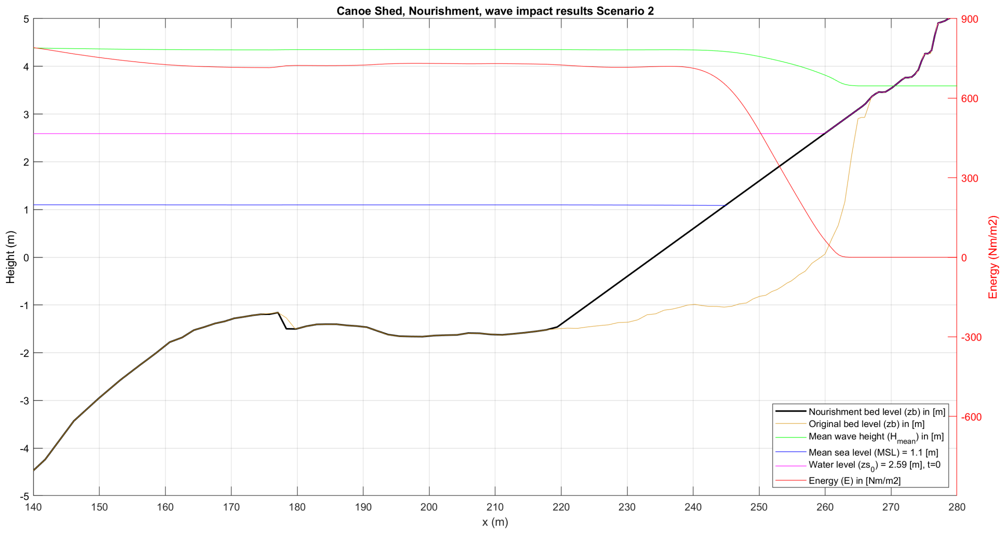



Figure J.18: Wave impact at Canoe Shed for the profile nourishment in scenario 2. The original profile is depicted in yellow and the modelled nourishment in black.

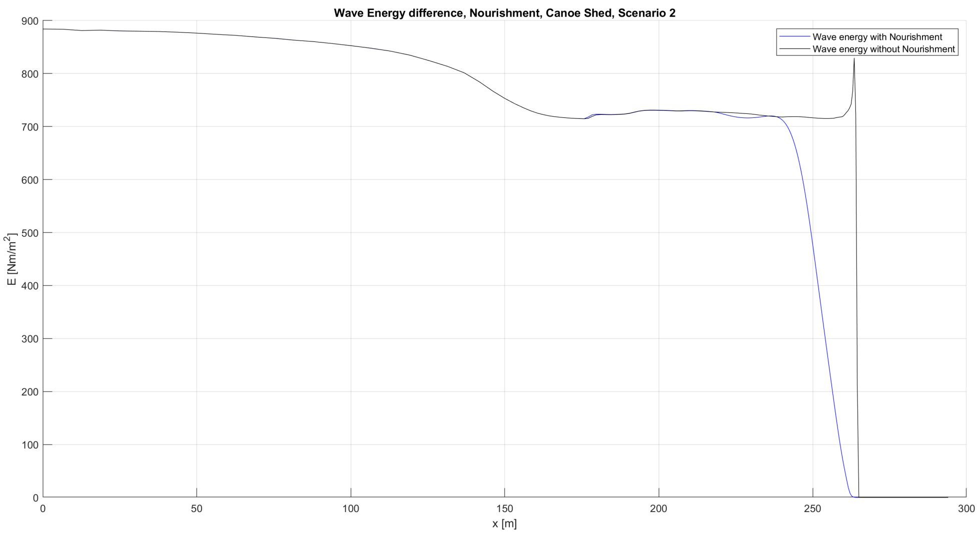



Figure J.19: Wave energy dissipation at Canoe Shed for the profile nourishment in scenario 1. The original profile is depicted in yellow and the modelled nourishment in black.

# K

# Site visit project site Tsleil-Waututh Nation Burrard Inlet IR#3

To get a feeling for the project and do some visual inspections of the project site a site-visit was made under the guidance of Micheal George, a member of the Tsleil-Waututh Nation. During our site-visit Micheal George (TWN Cultural Advisor) shared information about how over the years the shoreline had changed from being vegetated with plants to the current situation as seen in Figure K.1. Mike also told us how the shoreline has eroded over the years and keeps on eroding due to climate change induced hazards. In this section an impression is given of the site-visit with pictures that were made that day. We would also like to thank the Tsleil-Waututh Nation to invite us to there reserve with special thank you to Mike for being our guide and telling us about the history of the shoreline of the Tsleil-Waututh Nation.

Figure K.1: Site visit project site of the Tsleil-Waututh Nation; Erosion of the shoreline is clearly visible at the foot of the trees and other vegetation

Figure K.2: Site visit project site of the Tsleil-Waututh Nation; picture of the scarp where clearly the midden can be seen

Figure K.3: Site visit project site of the Tsleil-Waututh Nation; picture of previous placed rip-rap with vegetation behind the rip-rap

Figure K.4: Site visit project site of the Tsleil-Waututh Nation; picture of the Canoe Shed cross-section

Figure K.5: Site visit project site of the Tsleil-Waututh Nation; Mike showing us the erosion and scarp behind the trees used as extra shoreline protection

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