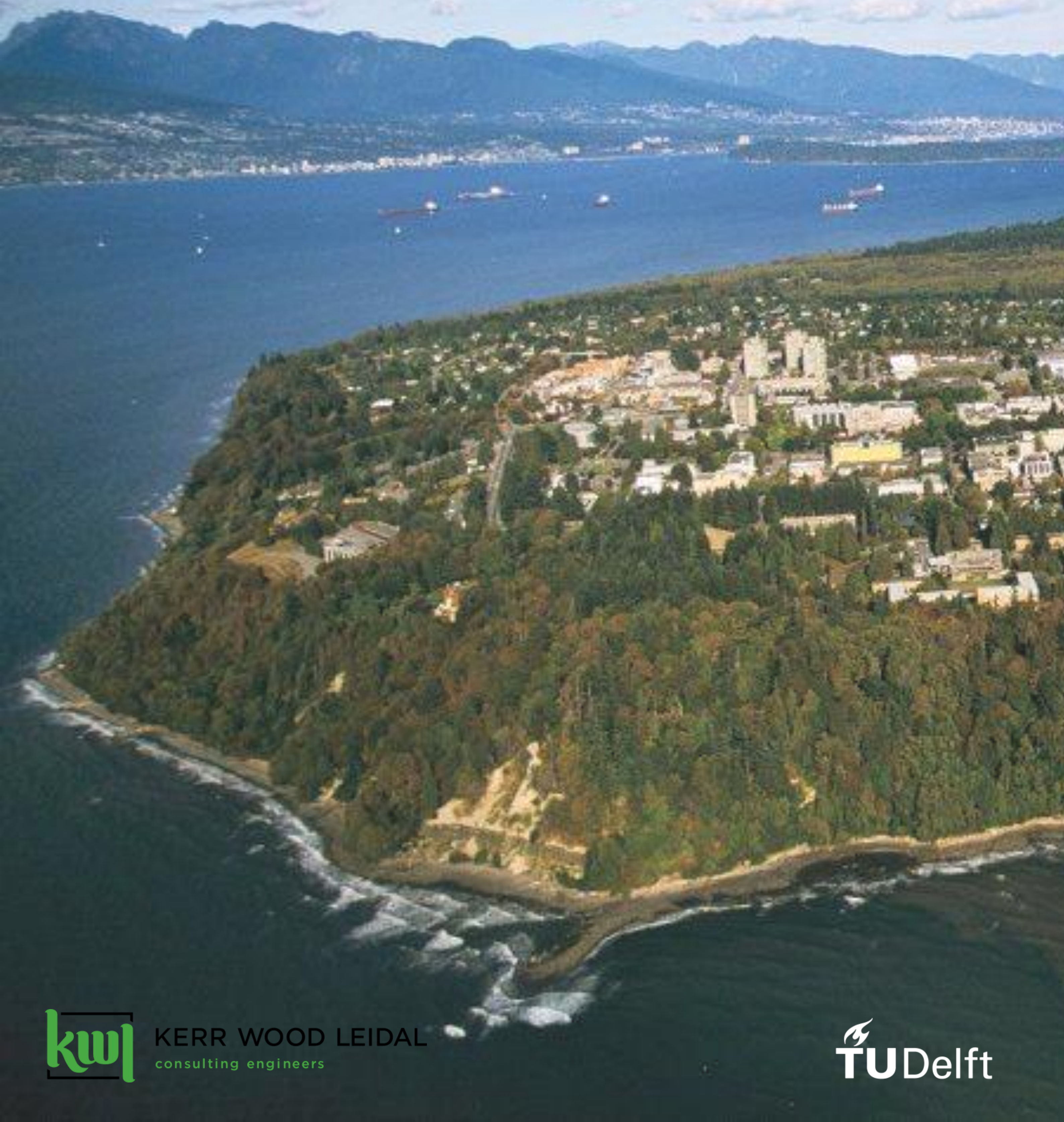
CIE 4061-09

Multidisciplinary project

Cliff Erosion at Point Grey UBC



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Cliff Erosion at Point Grey UBC

A feasibility study of preliminary concepts to deal with erosion

by

Multidisciplinary Project Team

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Preface

This report contains the results of a multidisciplinary project conducted at the University of British Columbia (UBC), wherein different concepts for dealing with cliff erosion at the Point Grey cliffs are identified and their feasibility is assessed from a holistic point of view.
It is written to fullfil the requirements of the course Multidisciplinary Project CIE4061-09, which is part of the Civil Engineering Masters Degree at the Technical University of Delft (TU Delft). The aim of a multidisciplinary project is to solve a track related problem for a client, in this case the University of British Columbia (UBC), and to deal with aspects of a design project other than of technological nature, such as taking into account stakeholders, finance and ecology. This group consist of three students from the master track Hydraulic Engineering with specializations in Coastal Engineering and Environmental Fluid Mechanics and a student from Environmental Engineering. This project was executed from November 2018 to February 2019, of which the group was present in Vancouver from November to January.
The project is commissioned by the University of British Columbia in Vancouver, Canada, as part of their larger project called Living Breakwaters, which aims to find a solution for the eroding cliffs around the UBC peninsula. As this project was commissioned by UBC, it follows the objectives and principles that are set in UBC's policies.

We are very thankful for everyone that helped us with this project. During the research time in Vancouver we have received great guidance from our supervisor in Vancouver Amir Talenghani, a representative of Kerr Wood Leidal (KWL). Without his help we would not have obtained some essential information and data for the completion of the project. Also our supervisors at TU Delft Bram van Prooijen, Stuart Pearson and Erik Mostert have provided us with a lot of support to improve the quality of this report. Lastly, we would like to thank UBC and especially Kees Lokman and Tugce Conger for providing us with this great opportunity of living and studying in Vancouver.

Glossary

- **Aeolian erosion** - Erosion caused by small particles transported by wind.
- **Aquifer** - An underground soil layer in which water is stored and water can flow.
- **Aquitard** - A soil layer that lies adjacent to an aquifer which has a low permeability.
- **Armour layer** - Layer composed of concrete units or rocks on a breakwater.
- **Bathymetry** - Map of the ocean or sea bottom, elaborated from depth measurements.
- **Beach nourishment** - Supply of sediment to a beach in order to avoid erosion and increase the available beach space. Sediment can be supplied on the beach, with land-based equipment, or in the foreshore, with waterborne equipment.
- **Clam garden** - Traditional clam harvesting method. They consist in building a boulder wall around the low water mark. Sediment deposits behind it, reducing the slope steepness and increasing clam productivity.
- **Coastal uplift** - Phenomenon where the earth surface is lifted above the sea level by tectonic forces.
- **Downdrift** - Downstream posititION according to the longhsore transport.
- **Effective shear strength** - The resistance against shear stress carried by the solid particles of the soil.
- **El Niño/La Niña oscillations** - Climatic phenomena that happen cyclically in the Pacific Ocean due to pressure oscillations.
- **Foreshore** - The part of the shore which lies between the low and high water marks.
- **Geogrid** - A synthetic material that is used to increase the stability and strength of soils.
- **Groynes** - A hard hydraulic structure located in an ocean shore or river bank to limit the movement of sediment by interrupting the water flow.
- **High energy environment** - An environment with a high energy level resulting and a high turbulent motion that prevent fine sediments to settle. The environment is created by waves and currents.
- **Intertidal area** - Area affected by the tide (between high water mark and low water mark).
- **Jetty** - A form of a breakwater installed to protect a harbour, riverbank our coastline.
- **Littoral transport** - Transport of sediment due to hydrodynamic activity (waves and currents) along the coast.
- **Live staking** - A bioengineering technique in which live stakes are put into the ground to take root and grow. This technique is used to stabilize slopes and other eroding areas.
- **Musqueam First Nations** - The Musqueam First Nations people are descendants of the original inhabitants of Canada, Vancouver, Point Grey. They lived in this area many years before the European explorers colonized Canada.
- **Native beach sediment** - Sediment that is found originally on the beach.

- **Natural boundary** - *"Visible high water mark of any lake, stream or other body of water where the presence and action of the water are so common and usual and so long continued in all ordinary years as to mark upon the soil of the bed of the lake, river stream or other body of water a character distinct from that of the banks, both in vegetation and in the nature of the soil itself"* [46].
- **Offshore** - Zone at some distance from the coast.
- **Residual water level** - The component of the water level that is not caused by astronomical effects.
- **Rip-rap** - Mixed rock material used to protect shorelines, banks, etc.
- **Rubble mound** - Structure consisting in a pile of rocks of different dimensions.
- **Salt marsh** - Coastal ecosystem situated in the tidal zone, inhabited by salt-resistant plants that can sustain to be periodically flooded by tide.
- **Saturated soil** - A soil condition in which the pores between the soil particles are completely filled with water.
- **Seepage** - The escape of slow flowing water from soil.
- **Stratigraphic profile** - A soil profile which shows the sequence of layers of different soil types in the order of which they are deposit.
- **Stormwater** - Rainwater that has fallen on the ground.
- **Storm surge** - Combination of wind stress and pressure reduction on the water surface.
- **Surf zone** - Zone close to the shore where waves break.
- **SWAN** - A wave model developed at the TU Delft.
- **Understory** - A layer of plants and bushes that is positioned underneath the canopy of a forest.
- **Wave climate** - Characteristics of waves in a certain location in direction, wave height, averaged out.
- **Wave set-up** - Raise in water level caused by variation in radiation stress due to breaking waves.
- **Wetland** - Ecosystem that is constantly or periodically flooded.
- **Well** - A narrow passage in the ground, usually bored or drilled which purpose is inject or extract water in/from the ground or monitor groundwater.

Summary

Erosion of the cliffs at the Point Grey Peninsula threatens important infrastructure and buildings at UBC. In order to tackle this problem, UBC launched a comprehensive project called Living Breakwaters. This project is part of Living Breakwaters and aims to act as a transversal element among different expertise, integrating these specializations into a holistic framework. It analyses the problem from a technical, environmental, economical, legislative and social perspective. Four concepts are proposed to tackle the erosion and their feasibility considerations are listed. Accordingly, the main goal of this report is to present a clear and holistic framework of the erosion problem at the Point Grey cliffs, both gathering and integrating existing information and contributing with innovative ideas that might open new approaches for dealing with erosion.

First, the existing conditions and context are described. The project area is important due to the presence of important assets, and its cultural and environmental significance. Regarding the hydrodynamic conditions, the zone has a semidiurnal tidal behaviour, with the occurrence of storm surge and wave set up phenomena and can be defined as a high energy environment. The wave climate is dominated by the westerly and west-northwesterly directions. The structural erosion is caused by a sediment deficit of around 15,000 $m^3/year$ to 60,000 $m^3/year$ due to human interventions on the Fraser River. Erosion on the cliffs is both natural and human-caused. The main causes of erosion are identified as marine erosion at the toe and subaerial erosion on the cliff face due to stormwater runoff and seepage.

Various stakeholders are concerned with the erosion problem. Landowners' properties are at stake and society groups such as UBC community and Musqueam First Nations risk losing land to which they are emotionally attached and where they conduct daily activities. Besides, the coastal jurisdiction in Canada is divided among federal, provincial and local government. A single intervention could therefore involve different governance levels and it has to respect the correspondent legislation, consequently needing different permits. Thus, a framework of stakeholders and legislation is lined out, aiming to help future design phases.

Since a coastal management strategy can be chosen among the approaches of Protect, Accommodate, Retreat and Avoid, these strategies are described. Protect is identified as the most suitable strategy for this project. Hard solutions, hybrid solutions and soft solutions can be used to protect the coastline: a *toolkit* of common solutions (such as breakwaters, artificial reefs, etc.) is presented. The Business As Usual approach is evaluated as not viable: the short and long-term consequences are unacceptable.

Then, four first design concepts are proposed, three concerning marine erosion and one subaerial erosion. As a traditional marine solution, a rip- rap revetment is proposed and, as more innovative concepts, an engineered beach with floating islands and a concept containing clam gardens and submerged breakwaters are introduced. The fourth concept, differently from the first three, addresses subaerial erosion at the cliff face. It consists of three measures: revegetation of the cliff face, a stormwater detention facility and inter-aquifer drainage wells. Afterwards, feasibility concerns of each concept are stated from an holistic perspective. Technical feasibility is assessed primarily on the erosion reduction effectiveness. Environmental considerations include the impact on existing ecosystem services. The economical assessment includes a rough cost estimate. The legislative analysis states the permissions and acts that need to be taken into account. Lastly, some social considerations are reviewed without the involvement of stakeholders engagement. During the project several data gaps are encountered. Therefore, recommendations are presented for next design phases and future research.

In conclusion, the Point Grey cliff erosion is a problem that has to be tackled to prevent severe damage to the adjacent lands. It is advised to combine both marine and subaerial measures. An integrated approach combining technical, environmental, legislative and social expertise is recommended in order to achieve a truly sustainable design.

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1
Introduction

Situated next to the city of Vancouver, the Point Grey peninsula is home to the University of British Columbia (UBC) and the University Endowment Lands (UEL). This Musqueam First Nation territory is characterized by its cliffs, which have been eroding for the past decades. This erosion is caused by both marine and subaerial factors and despite several erosion mitigation measures taken in the past, the cliffs are still eroding and posing a threat on the adjacent lands. These lands are mostly inhabited and valuable assets such as infrastructure and a sanitary sewer main pipeline are located near the edge of the cliffs.

Additionally, important cultural heritage as the Museum of Anthropology is located near the eroding edges. Besides, the cliffs have recreational value and are part of an ecosystem which is under pressure due to the undergoing erosion (and, therefore, loss of habitat) and aggressive human activities, such as urbanization and felling of trees. Furthermore, the eroding cliffs can lead to dangerous situations as civilians may find themselves below the cliffs during a collapsing episode, which has already led to one death in 2014 [67].

Because of these reasons, there is a great need to reduce and manage the cliff erosion. Therefore, UBC has set up a research to investigate the erosion and to come up with possible solutions. This report is part of this research and describes alternatives to deal with the cliff erosion at the UBC campus and assesses their feasibility from a holistic point of view. Additionally, this project provides basic knowledge about Point Grey Cliff erosion which can be used in further research. The study is of a conceptual design level and gives a first overview of possible solutions. The solutions have a qualitative nature and should be elaborated in further stages of UBC's research.

1.1. Problem Definition

The cliffs consist of sand with an unconsolidated nature and consequently a low shear strength. As a result, the cliffs are prone to instabilities which can result in erosion. The main factors contributing to these instabilities are coastal erosion at the toe of the cliff, heavy precipitation and human activities such as deforestation [43].

Several researches into these causes of cliff erosion have been carried out over the years, but a study that combines all of the causes to investigate solutions for the whole cliff erosion problem at UBC is missing. Additionally, the regulatory structure at the Point Grey peninsula is complex and an overview of the legislation that has to be considered when measures are taken is wanted by UBC.

1.2. Project Objectives

The objective of this study is to collect relevant information regarding the cliff erosion problems at Point Grey, from a technical, social, environmental and legislative perspective and to use this information as a basis to identify concepts for dealing with cliff erosion at Point Grey, taking into account both marine and subaerial causes of cliff erosion and and assessing their feasibility from a holistic point of view.

Specific objectives are to:

- Provide an overview of the study area
- Review factors contributing to cliff erosion and identify the main causes of this processes
- Give an outline of the stakeholders involved
- Present a legislative framework for possible erosion solutions
- Identify a toolkit of measures to tackle cliff erosion with: hard, hybrid and soft solutions
- Develop four concepts for dealing with cliff erosion, and conduct a feasibility study for each of them in terms of technical, environmental, economical, legislative and social aspects
- Give insight in the existing knowledge gaps and missing data

1.3. Approach

Several steps are taken to achieve the project objectives. Firstly, to gain a holistic understanding of the study area, the existing conditions are investigated from a cultural, ecological and technical point of view. For the latter, all causes of cliff erosion are investigated to determine the principal ones that need to be tackled and for which the concepts will be designed. Besides, to cover the social and legislative aspect a stakeholder identification is done and a regulatory framework is set up.

The design of the concepts consist of several stages. First, high level adaptation strategies are examined and the most suitable strategy is chosen. Secondly, a toolkit is designed which includes measures that are consistent with this strategy for all previously determined erosion causes. Lastly, four concepts are build with the measures of this toolkit. The life time of these concepts is 50 years. Additionally, a business as usual concept is formulated, which acts as a base case for comparison with the other concepts.

The feasibility of the concepts is reviewed from a holistic point of view in order to understand the consideration that must be taken into account while developing the concepts further. The areas under which they will be analyzed and the perspective which is taken in the different areas are:

- **Technical feasibility**, in which the effectiveness of the concept on solving the erosion problem, the time framework of the concept, the design complexity and the adaptability to changes like climate change are considered.
- **Environmental feasibility**, in which the impact of the concept on the ecosystem services is examined.
- **Economical feasibility**, which is based on the Canadian Class ’D’ Estimate. This is an order of magnitude estimate comprised of a list of requirements and based on a rough cost per measurement unit. Per concept, the costs are calculated for the whole coastline of the project area (3,140 meters). The accuracy of the cost is in the order +/- 20 to 30%.
- **Legislative feasibility**, in which the different permits and acts that have to be taken into account are given.
- **Social feasibility**, in which the social impact of the concept and the effect on safety is given. As no stakeholder analysis has been done in this phase of the project, the opinion of stakeholders can’t be taken into account.

Lastly, as this project is part of an ongoing research, it provides a gap analysis and recommendations for further steps that can be taken.

1.4. Reading Guide

In Chapter 1 the problem is defined, the project objectives are listed and the approach method is described. Chapter 2 provides an overview on the project area, describing the land infrastructure and land use, existing ecosystem and the coastal characteristics. In Chapter 3, the erosion problem is analyzed, causes of erosion are listed and the main causes at the Point Grey cliffs are identified. Previous studies on Point Grey's cliff erosion are reviewed and summarized, and it is explained how erosion attacks different cliff sections. Chapter 4 describes the social and legislative landscape: stakeholders are listed and depicted, considerations about the social impact are made and a legislative framework is laid out. In Chapter 5, general coastal management strategies are enumerated and their suitability to the project specificity is evaluated. The most suitable strategy is then identified and common measures are presented in a table. Thereafter, the concepts are introduced. Chapter 6 analyses the Do Nothing approach, pointing out the short and long-term consequences. In Chapters 6, 7 and 8, concepts are elaborated to tackle marine erosion and feasibility considerations regarding technical, environmental, economical, legislative and social aspects are made.In Chapter 7, the preliminary design of a rip-rap and rock revetment is presented and analysed. Chapter 8 is dedicated to the Engineered Beach and Floating Wetlands. In Chapter 9, the concept of Clam Gardens and Submerged Breakwater is investigated. Chapter 10 presents the concepts elaborated to address the cliff face erosion. Similarly to the the marine erosion ones, their technical, environmental, economical and social feasibility is examined. In Chapter 11, a discussion on the project is done. Chapter 12 highlights gaps and missing data in the existing knowledge, and lays out recommendations for further research and next design steps. Lastly, in chapter 12 the findings of this research are discussed and in chapter 13 a conclusion can be found.

2

Existing Conditions and Context

This chapter focuses in understanding the system in which the project will be developed. This chapter describes the location, present infrastructure and land use around the project area and the cliff sections under consideration. Besides, the local ecology and hydrodynamics conditions are outlined. All this information will be used further in the report to develop scenarios and concepts to solve the cliff erosion problem.

2.1. Project Area

Point Grey peninsula lies in the southwestern part of British Columbia between the Burrard inlet and the Fraser river, Figure 2.1. It hosts the Canadian city of Vancouver and is part of Metro Vancouver region. The project site (Figure 2.2) covers the cliffs of Point Grey peninsula. The area is enclosed by the Pacific Spirit Regional Park that also surrounds the UBC campus. On the southern side, the Point Grey peninsula faces the Northern Arm of the Fraser River. Here, inter-tidal zones consisting of mudflats can be found. On the northern side Spanish Banks beaches represent the boundary of the project zone. The Fraser River is the longest river within British Columbia and the 10th longest river in Canada. The river estuary is of hemispheric importance as a stopover for migrating shorebirds [5] and it represents the main sand and gravel sediment source for the region. UBC is built on the traditional territory of the Musqueam First Nation. The Musqueam community now lives on a small portion of the traditional territory, situated near the mouth of Fraser river.

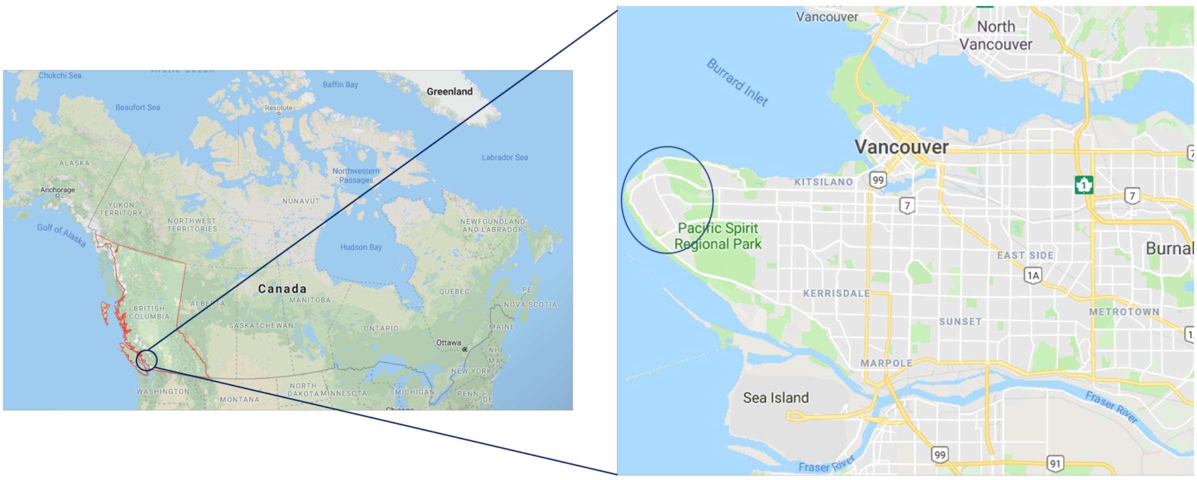


Figure 2.1: Project zone, showing outlined in red in the lift figure the province British Columbia and in the right figure Metro Vancouver and circled the Point Grey peninsula. Source: adapted from Google Maps.

Cultural Heritage

UBC campus at Point Grey is located on *"the ancestral, traditional and unceded territory of the Musqueam people"* [64], which has been occupied for thousands of years. Moreover, even though no permanent Musqueam settlements were present in the campus area, villages were all around the perimeter. Thus, acknowledgment of the past system and present relation with communities is an important part of the culture heritage of this zone. UBC works towards having a collaborative relation with Musqueam people, by understanding and acknowledging the history of the culture on campus[45]. Furthermore, UBC has taken measures such as adding Musqueam signage on campus, in order to visually represent the Musqueam language and art, and programs for promoting indigenous culture, like courses for learning the language. Therefore, before any measures are taken in the project area, it has to be a close collaboration with the Musqueam nation.

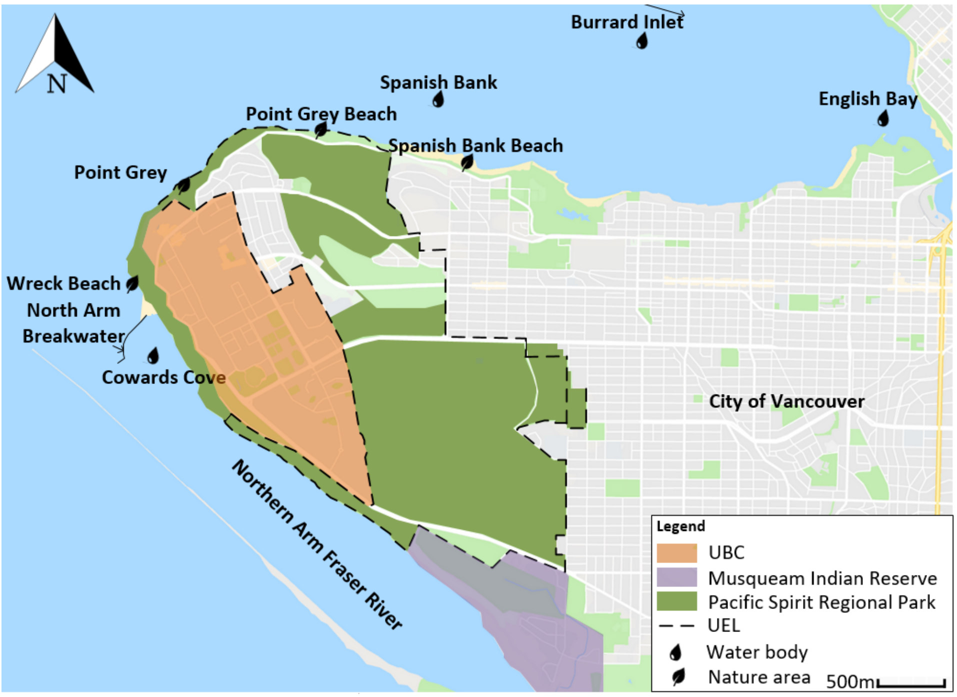


Figure 2.2: Project Area, shown are the Pacific Spirit Regional Park [69], UBC [52], UEL[48], the Musquem Indian Reserve [70] and important water bodies and nature areas.

2.2. Infrastructure and Land Use

Campus buildings and infrastructure have been developed closely to the edge of the cliffs at some locations in the peninsula. Also some of the roads along the edge of the peninsula are prone to damage if the cliff erosion will continue[15]. Particularly NW Marine Drive and SW Marine Drive are situated close to the edge of the cliffs (Figure 2.3). NW and SW Marine Drive are of great importance for the accessibility of the UBC campus as they are the main access roads. The function of the land of UBC (Figure 2.2) is mainly urban as it hosts many campus buildings, housing and sportsfields. A large part of the peninsula has a recreational function as it hosts the Pacific Spirit Regional Park and small beaches can be found at the bottom of the cliffs such as Wreck Beach (Figure 2.2.

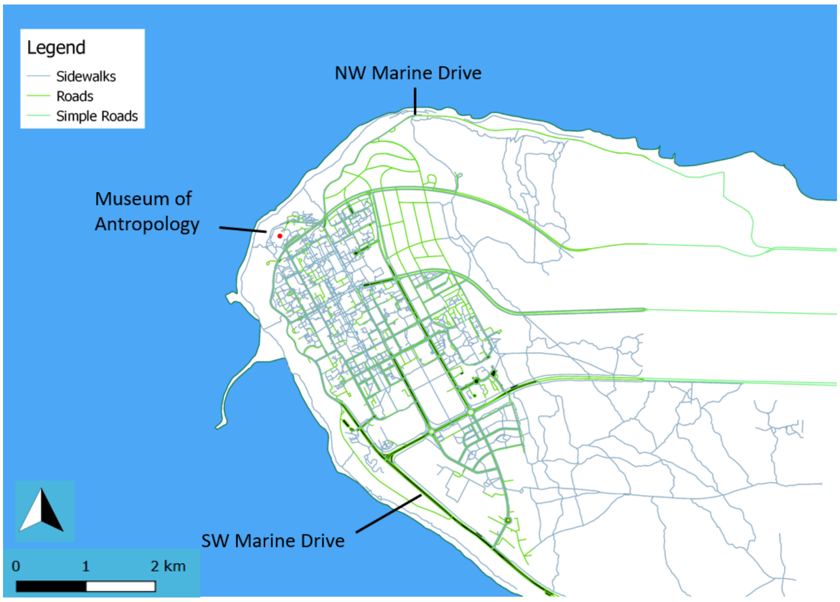


Figure 2.3: Map of the important infrastructure at UBC[65].

Stormwater Management System

The stormwater system of UBC consist of open drainage channels, a series of storm sewers and stream outfalls Figure 2.4. Besides, stormwater detention facilities such as green roofs, cisterns and water retention basins are used to decrease the runoff.

The current system operates under capacity, whereby extreme weather events can lead to overland flows and floods which endanger the cliff stability. Besides, high outflow rates of the University's outfalls lead to erosive forces on the cliffs [54]. With the increasing development of the campus and the projection of more rainfall due to climate change [68], the risk of erosion as a result of rainfall will increase. Storm water management should therefore be considered to take all aspects of cliff erosion into account.

Figure 2.4: Stormwater Outfalls and the surface flow directions [10].

2.3. Ecology

In this section the essential role of the local ecosystem for the UBC area will be explained. First a broader overview of the overarching ecosystem is given after which a more detailed description of the local habitat around UBC is provided. The importance of ecology for society can be assessed with ecosystem services, which is explained in the last section.

Description of the Ecosystem

The natural area around UBC is part of a bigger ecosystem, which covers the area of the Salish Sea[31] and its surrounding coast. The Salish Sea consists of Georgian Basin north of the international border and the Pudget Sound south of the international border and it meets the Pacific Ocean at the Strait of San Juan(Figure 2.5. The ecosystem is host to over 200 marine fish species, more than 100 marine birds, 26 species of mammals and 1000s invertebrate species [31].

Figure 2.5: Geographical Map of the Salish Sea [33].

The area of the Salish Sea is home to over 7 million people, which is expected to grow to over 9 million by 2025 [12]. The strong urbanization of the region has disturbed the delicate balance within the ecosystem, which has caused a decline in the marine and bird population over the last decades. To reverse this trend, the responsible governmental institutions of both Canada and the USA have agreed to a joint Joint Statement of Cooperation to facilitate the necessary international cooperation to reverse the downward trends [12]. Recent studies [31] show positive trends for some issues such as air quality and toxic chemicals in the food web, however, some issues such as the population of the marine species and the habitat protection still show a downward trend. In the entire Salish sea 113 marine species were considered at risk. In Section 2.3 there is an elaboration on the endangered species that are relevant to the considered area.

Habitat at the UBC Coast

There are five different habitat types present along the cliffs of UBC: mudflats, sandflats, marshes, high vegetation (trees) and low vegetation (grasses, shrubs), as shown in figure 2.6 [16]. Most natural habitat is situated along the southwest coast. According to the FREMP (Fraser River Estuary Management Program) program [22] productivity classification, the natural habitats in the Fraser estuary are classified as following [39]:

- Red (High Productivity) - The habitat is productive and diverse and supports the critical fish and wildlife functions on-site or regional.

- Yellow (Moderate Productivity) The conditions in the habitat are of moderate value in diversity and support moderate fish and wildlife functions.

- Green (Low Productivity) - The habitat includes features where functions are limited (due to e.g. a nearby port or urbanized uses).

The habitat along the cliffs are classified as red (Figure 2.7) and are therefore of significant value for the local and regional ecosystem.

Apart from that, the habitats are home to various wildlife (Table A.2) and marine species (Table A.1) that are identified as endangered by the Province of British Columbia. Additionally, the area provides relevant biological resource to varous marine species (Table A.3). An overview of the different species that are present in the habitats can be found in Appendix A.

Figure 2.6: Different habitat types present along the UBC cliffs, (BIEAP) [16].

Figure 2.7: Habitat Classification, (FREMP) [22].

Ecosystem Services

Maintaining a healthy ecosystem in the Salish Sea is essential for the survival of endangered flora and fauna, but is also of great importance for the residents of the coastal area. Therefore the concepts that are designed in this report are assessed on their environmental feasibility, with the help of their effect on ecosystem services. An ecosystem can provide many different ecosystem services of different categories such as supporting, provisioning, regulating and cultural services.

- **Supporting Services**

  These services of the ecosystem are necessary to enable the other categories of ecosystem services to do their work. These services concern the key processes that create the boundary conditions in which the other services will act [10]. Habitat provisioning is an important supporting service as the type of habitat and its components determines which species will be able to live in the habitat. A more detailed example is the wave dissipation provided by shoreline vegetation. Most species do not fare well under severe hydrodynamic conditions so wave dissipation is essential. Another supporting service is soil formation so vegetation is enabled to grow. If the soil does not accumulates enough, the land will be immersed to many times a year which are unfavourable conditions for most plant species. The ecosystem must provide the opportunity for keystone species to establish so other species can accommodate afterwards.

- **Provisioning Services**

  Provisioning services regards natural resources for provision in food and biotic materials [13]. The most important provisioning service is that of food provision for both humans and animals. Restoring an ecosystem leads to more biomass [11] and a larger biodiversity. Fishermen profit from this and more fish is provided to the public. An iconic species in the Salish Sea is the salmon [31]. It provides food for as well fauna such as bears, eagles and killer whales but also to other species as invertebrates and even plants as their carcasses provide plenty of nutrients. The large presence of commercial and recreational salmon fisheries also makes the salmon of economic importance to the region[12].

- **Regulating Services**

  An ecosystem provides biological and physical support to facilitate the reproduction of numerous species that do not necessarily spend the entire year in the region [13]. It can be a key habitat for many birds by functioning as a nursery, spawning area or as a part of their migratory route. For instance, different species of geese use salt marshes to hibernate [11]. Another important regulatory service is the maintaining of water quality. Vegetation, but also mussel and oyster beds have strong water purifying qualities as they filter the water.

- **Cultural Services**

  The Salish Sea is home to many First Nation Tribes, which have a strong connection with the environment. The coastal ecology has a significant spiritual and cultural value for the First Nations as they rely for food and clothing on resources provided by nature.

  Apart from the cultural value it provides to the First Nations, the ecosystem also provides cultural services to the general community. Recreation and tourism in the region of British Columbia is focused heavily on its beautiful nature. Examples are whale watching, recreational fisheries and national parks. Because of this, the local economy benefits from the cultural services the ecosystem provides.

Water Quality

The Salish Sea surrounding the Point Grey Cliff is experiencing a declining trend in dissolved oxygen concentration. As a result, the aquatic life is getting more vulnerable to pollution and die off. The depletion of oxygen is caused by eutrophication from runoff that contains fertilizers, failing septic systems and wastewater discharges [29]. This eutrophication can cause periods of algae boom that excrete bio-toxins, which contaminate the shellfish in the area. As a result, shellfish harvesting around Point Grey is dangerous and prohibited [34]. A large contributor to this pollution is stormwater runoff, which can contain polluting substances as pesticides, petroleum products, heavy metals and construction sediments [40]. As further water quality deterioration is unwanted, potential solutions should consider water quality effects.

2.4. Coastal System Characteristics

Hydrodynamic Conditions and Water Levels

It is important to understand the hydrodynamics conditions and water levels to gain knowledge in how marine processes can impact coastal erosion at the cliff toe. Moreover, these conditions define the design water level and wave characteristics for the assessment of different scenarios.

- **Water Levels**

  The design water level must consider mean water level, tide and residual water levels.

  - Mean sea level (MSL)

    The expected Sea Level Rise (SLR) is added to MSL according to the lifetime of the project, which is 50 years. Moreover, in this region global warming is expected to rise the sea level at least 1 m by 2100 and 2 m by 2200 [26]. The low uplift rates for the project area are considered negligible in comparison with the projection for the climate-change induced SLR [15], and therefore not considered in this report.

  - Tides

    The tides in this region are defined as mixed with mainly semidiurnal behavior[62]. The mean tidal range is 3.3 m at Point Atkins (around 6 km North from Point Grey) [15]. The significant tidal water levels are shown in table 2.1.

Table 2.1: Tide elevation at Point Atkinson [15].

Characteristic Tide	Elevation (m CGVD)
Higher High Water Large Tide (HHWLT)	1.9
Higher High Water Mean Tide (HHWMT)	1.4
Mean Water Level (MWL)	0
Lower Low Water Mean Tide (LLWMT)	-1.9
Lower Low Water Large Tide (LLWLT)	-3.2

– Residual water levels

  Residual water levels occur due to phenomena such as storm surge, wave set-up and responses to climatic changes (El Niño/La Niña oscillations). However, storm surges are the main contributing component to the extreme water level [15].

  Relevant storm surges occur when a considerable storm and high tide take place at the same time, generating a temporary surplus in the water level due to extreme meteorological conditions (low atmospheric pressure and/or strong winds). This natural hazard increases the risk of flooding, especially in winter, along the coast of the Salish Sea. As a reference, 1.03 m has been the maximum residual water level measured at Point Atkins (between 1980-2013) [59].

The extreme water levels, described above, must be related with a joint probability in order to develop scenarios with an specific probability of occurrence (inverse return period). The analysis shown in Table 2.2is retrieved by Golder Associates [15] for Point Atkinson.

Table 2.2: Extreme water level with specific return period at Point Atkinson [15].

Return period (years)	Water level (m CGVD)
2	2.1
5	2.2
10	2.3
50	2.4
200	2.5

The values of Table 2.2 are referred to present day sea level. Therefore, with the SLR influence, an analysis for a project of 50 years of lifetime should consider 1 m extra in water level. Thus, the water level for a return period of 50 years is 3.4 m and for 200 years is 3.5 m.

- **Wave Climate**

  According to the Golder Associates [15], waves are the main force responsible for the erosion and sediment transport in this area. The wave field in this location is dominated by westerly and west-northwesterly directions. The latter sets the path of the sediment transport, which in this case is in a north-eastwards direction (English bay). The wave erosion impacts can be observed in the exposed beaches North of the Wreck Beach. Southwards the impact is less due to the sheltering of the North Arm Breakwater and the presence of a jetty[15].

  For the design of erosion solutions a design wave with certain return period must be estimated. This can be achieved by carrying out a long term analysis of the wave data and fitting a distribution to it. The wave data consists of 27 years of buoy measurements (between 1992-2018) and is retrieved from the Halibut Bank[36] buoy located around 45 km northwest of UBC coast. To have the design wave conditions, a wave transformation is then conducted through SWAN. More details about the model set-up are explained in Chapter 5.

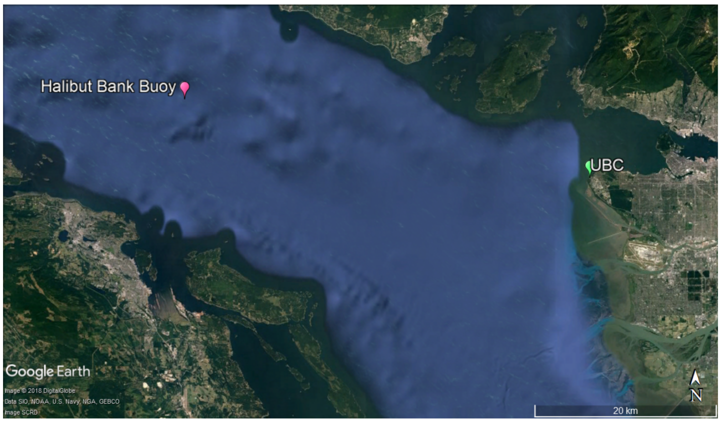


Figure 2.8: Halibut Banks buoy location with respect UBC. Source: Google Earth.

The data was filtered in terms of wave period and wave direction in order to represent the more risky scenario as well as possible. Afterwards, an exponential curve is fitted to the long term wave distribution (more details can be seen in Appendix B. The results for several return periods can be seen in Table 2.3.

Both for water levels and wave projections, and stationary assumption [1] is made. The latter refers to not take into consideration possible future changes in water levels and wave climate (only a SLR of 1 m is considered). This will have to be further researched in the next design phases, but for a first conceptual design this simplification is considered acceptable.

Table 2.3: Wave Climate at Halibut Banks.

Return period (years)	Wave Height (m)	Wave period (s)
1	2.26	5.76
50	3.73	6.94
100	3.99	7.13
200	4.25	7.30

Sediment budget

Sediment budget can be defined as the balance between the input and output of sediments in a coastal system. When the balance is positive accretion takes place and when it is negative erosion occurs. Human development can impact this sediment budget leading to an eroding coast. The latter can be seen in the UBC Cliffs, where the supply of sediments, after human interventions, reduced from 24,000 $m^3/year$ to 7,500 $m^3/year$ to the littoral system [15].

Moreover, according to a Golder estimate *"A potential net littoral transport rate of 23,000 $m^3/year$ (Kamphuis) to 70,000 $m^3/year$ (CERC) to the north east along the beaches from the Museum of Anthropology, as far as the turn in the coastline towards Spanish Banks"*[15] can be expected. Thus, as the potential net littoral transport exceeds considerably the sediments supply a deficit of around 15,000 $m^3/year$ to 60,000 $m^3/year$ can be found at the cliffs (Northwards Point Grey).

2.5. Summary

In Chapter 2 an overview of the required information of various topics is given in order to get a good idea of the conditions at project area. The information in this chapter is required to be able to develop the design concepts in later chapters. First, the spatial lay-out of the project

[1]A process is defined stationary when its properties do not change over time. Applied to this case, it means that it is assumed that the recorded wave signals are stationary

area with its most important features such as infrastructure, main buildings and the storm outfall system was explained. Also the importance of the local ecology to the UBC area is explained in terms of the ecosystem services that are provided by the ecosystem, which helps to assess the ecological feasibility of the concepts. The hydrodynamic conditions described in this chapter are used to develop the scenarios in chapter 5 and the concepts illustrated in chapters 7, 8, 9 and 10.

3
Point Grey Cliff's Erosion

This chapter gives an insight of the Point Grey Cliff characteristics and describes the different cliff erosion processes present at UBC cliffs. Additionally, it summarizes previous erosion studies conducted on Point Grey's cliffs.

3.1. Point Grey Cliff

Point Grey peninsula is characterized by steep slopes and cliffs falling to the shore. This land, according to geologists, can be described as a *"perched aquifer topology consisting of layers of glaciofluvial sand interspersed with impermeable layers"*[51]. This characteristics were acquired due to presence of glaciers above sedimentary deposits during the last ice age, followed by a warming trend. Over the time, forest developed in this area and the erosion was only due to marine forces at the toe and creek washout at the slopes [51].

The Point Grey cliffs consist mainly of Quadra Sand, which commonly forms a cohesive and compact base. However, the cliffs are unstable due to the stratification of the cliffs and the ongoing erosion [43]. Figure 3.1 shows the stratigraphic profile of the cliffs. The cliff consist of an organic topsoil layer lying on a till layer. The two sand layers form the upper and lower aquifer and in between lies an impermeable silt layer. This results in a subsurface water flow between the upper sand layer and the silt layer. Due to this interface, the cliff is prone to slope instability as a consequence of its structure. [13]

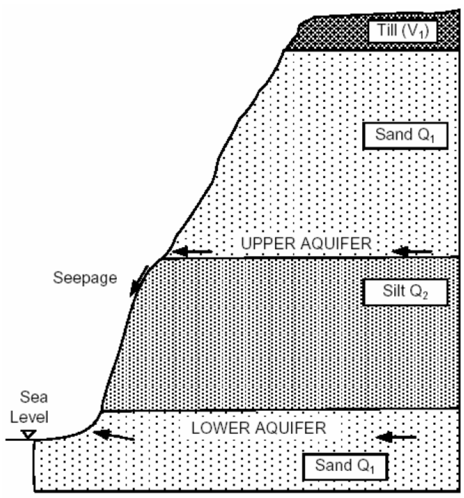


Figure 3.1: Stratigraphic profile of the Point Grey cliffs [13].

3.2. Erosion Causes

Erosion causes can be classified in natural and human causes. As mentioned in the previous section, the cliff erosion at Point Grey is mainly caused by marine erosion at the toe, and due to subaerial processes at the upper slopes. However, even though the main drivers of erosion are natural processes, its rates can be enhanced due to human activities. This increase in the erosion rates can lead to cliff instabilities and to a system imbalance.

In Figure 3.2 an overview is given of the main erosion processes that can be found at Point Grey cliffs. Additionally, in Figure 3.3 the consequences of previous erosion hazards can be noticed. Trees are present on the beach as a result of vegetative uprooting and the effect of landslides is clearly seen.

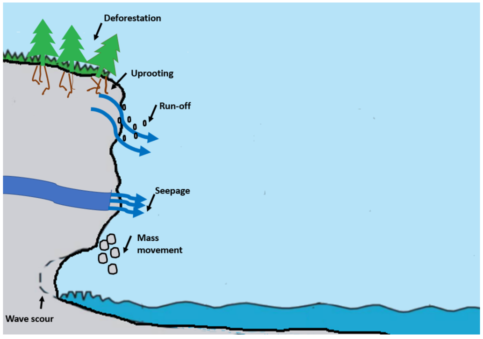


Figure 3.2: Overview of different cliff erosion processes. Source [32]: Modified by authors.

Figure 3.3: Overview of different cliff erosion processes [8].

Natural causes

- **Subaerial processes:** Subaerial processes are land based processes that can cause instability and erosion at the cliffs. The most important processes that have led to cliff erosion at UBC in the past are mass movements [15]. During these movements, parts of the cliffs slides down, often as the result of infiltrated rainwater that creates a slip plain in the soil. Additionally, storm water runoff causes washout of the cliffs when the water flows uncontrolled over the cliff face. It must therefore be prevented that stormwater concentrates and runs off as a water surge with large erosive forces. Another form of mass movement is caused by seepage from the cliff face. The change of seepage erosion increases when precipitation drains into the upper aquifer without being able to drain to the lower aquifer because of the aquitard silt layer, see Figure 3.1. As a result, the shear strength of the upper sand layer decreases, which can eventually lead to mass movements [43]. Groundwater flow from the lower aquifer is less prone to cause cliff erosion, as it is largely located below sea level [13]. It must, however, be noted that it is probable that this groundwater discharge weakens the toe for sediment removal by waves [15].
- **Marine Erosion:** This erosion is mainly caused by wave action and can be enhanced during storm conditions. Moreover, in the long term this mechanism is the principal responsible of coastal cliffs erosion [41]. Waves erode mainly the toe of the cliff, however during high water level conditions they can also generate cliff instability. Additionally, after erosion sediments are transported in an alongshore direction. Thus, the cliffs act as feeders of sediments for downdrift beaches. This is part of the sediment budget process needed to distribute the sediments along the coast . Thus, within coastal equilibrium not irreparable damage should be caused to the cliffs.
- **Tree uprooting:** This process pulls away a considerable amount of soil. Moreover, it exposes subsoil layers to erosive weather conditions, such as rain, which accelerate the uprooting.

Human causes

- **Deforestation:** In order to use an area for human activities generally deforestation is needed. However, the roots contribute to the binding of the the soil between them, leading to slope stabilization and reduction of erosion. Thus, when deforesting the exposure of the soil to instability and natural erosive processes increases.
- **Dredging activities:** As mentioned in Section 2.4 the UBC coast suffers of erosion due to a deficit in sediment budget. One cause for the increase of the deficit in the last decades are the dredging activities in the Fraser River Delta and the port [15]. Riverine sediment is supposed to be transported to the UBC coasts from the Fraser river outlets south of UBC. The dredging activities disturb this sediment supply, and the lack thereof enhances erosion in order to fulfill the sediment demand.
- **Hard solutions:** In the past decades several hard engineering solutions have been implemented along the coast of the Fraser Delta, such as the North Arm Jetty, the Iona Island Causeway, upstream flow control structures at the Fraser River and several groynes and breakwaters. A jetty induces a higher flow velocity at the outlet, which transports the riverine sediment further offshore, preventing it to reach the downstream coast. Flow control structures reduce supply of sediment to the intertidal zone of Point Grey. Groynes and breakwaters trap the upstream originating sediment, which leads to a increased sediment deficit downstream.
- **Sewage pipelines:** The ditches dug during construction of the sewage pipelines have formed a line of weakness in the former strong and impermeable soil layer. The ditches themselves act as drainage pipes as they are filled with gravel and sand [47], increasing

the seepage flow in the soil layer. Also if the sewage or storm outfalls start leaking, this will result in significant increase of erosion of the cliff due to the increased seepage.

3.3. Previous Studies on Point Grey's Cliff Erosion

Not many recent previous studies on Point Grey's Cliffs are available. The two main documents reviewed are: UBC/Pacific Spirit Park Cliff Erosion Management Planning (2000) [51] and Point Grey Cliff Erosion Study (2015) [15].

UBC/Pacific Spirit Park Cliff Erosion Management Planning is a consultation document mainly aimed at providing a management framework that finds *"acceptable and affordable ways to manage the cause of cliff erosion"* [51]. Special importance is given to to cultural and archaeological values, especially in relation with Musqueam First Nation, ecological preservation, and community involvement. The document summarizes the recent history of the site, including changes in jurisdiction and measures taken to tackle erosion. Main causes of cliff erosion are listed and described; no mechanism is identified as dominant, but an assessment of the effectiveness of the past measures is presented. In the key planning considerations, special importance is given to community and land use plans. A list of potential actions to overtake issues concerning drainage, ground water, vegetation, maintenance of existing structures (berm and drift sill), and for priority sites is listed. Identified Priority Areas are shown in 3.4.

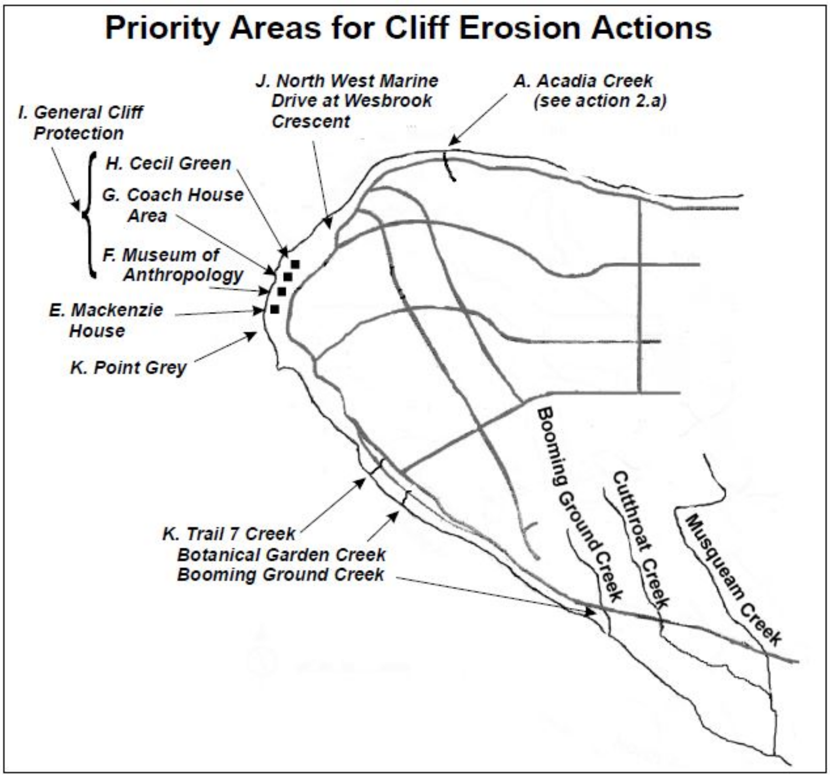


Figure 3.4: Priority areas for cliff erosion protection actions as laid out by UBC/Pacific Spirit Park Cliff Erosion Management Planning [51].

Point Grey Cliff Erosion Study is a technical report elaborated by Golder Associates Ltd in 2015, commissioned by University of British Columbia. Main aim of the study is to elaborate a focussed technical analysis on cliff erosion and provide recommendations for short-term (10 years) and long-term (50 years) measures. Special attention is given to sea level rise. The steps undertaken in order to achieve that are: data collection, both from reviewing existing data and reports and by site visit; technical assessment of coastal processes, geotechnical processes, hydrogeology, stormwater outfalls; development and assessment of strategy alternatives; and strategy and implementation plan. The project area is divided in six shoreline management units (SMU). Data collection from previous reports (Sandwell, Piteau Associates and Trow (2004) in particular) and UBC's LIDAR investigation is elaborated by Golder Associates in average recession rates. Main finding is that recession rates differ considerably among different sections and from toe to crest. An estimate of 24,000 $m^3/year$ is found for the pre-development sediment supply to littoral system by Point Grey cliffs. For the present day, this has been reduced to 7,800 $m^3/year$ due to human intervention. Golder Associates also summarize the existing hydrodynamic conditions for waves and tides. As a summary of the technical assessment, it is found that the project area consists of two areas with different timescales and mechanisms of erosion: North of Wreck Beach, where exposure to waves is significant and marine erosion is therefore dominant, resulting in higher erosion rates at the toe; and Booming Grounds, where the area is sheltered by the North Arm Breakwater and therefore the erosion (with lower rates) is concentrated on the cliffs' face. Options of hard and soft engineering solutions are evaluated through a cost-benefit analysis and a multicriteria analysis against the option of doing nothing. Main weight in the analysis is given to technical effectiveness and cost.

3.4. Considered Cliffs Sections

In Figure 3.5 the problem area undergoing cliff erosion is depicted. The region of the coastal cliffs can be divided into two different areas in terms of the dominant erosion process. Cliff erosion in the northern half of the section is dominated by marine erosion. As the southern section is sheltered for the waves, the sub-aerial processes are dominant. As the dominant erosion process is different for the different sections, they require different approaches to solve the erosion.

When assessing the feasibility of the design alternatives, a smaller area is considered, as shown in figure 3.5. Previous reports [51] identified priority sites as the ones containing the most relevant infrastructure and buildings (such as museums, heritage buildings, roads and trails). The focus area is chosen because it is considered to have the highest risk value. The cliff section is located next to important assets such as the Museum of Anthropology, trail 3 and 4, Northwest Marine Drive, Spiral Drain, Coach House and Cecil Green House and Mackenzie House. Apart from the high value (both economical and socio-cultural) of these features, the erosion rates are significant. Some cliff sections show higher erosion rates. However, as the high value assets are located further from the cliff edge or the assets are of lower value, these sections were considered less at risk.

To summarize the current condition of the focus area:

- Marine erosion is the dominant erosion process. It occurres naturally in the area, as there is relatively more exposure to wave action from the Strait of Georgia than at other sections.
- The erosion problem is exacerbated by human activities: for the area north of Wreck Beach, the historical cliff recession rates (averaged spatially and over a year timescale) are in the order of 0.1 - 0.5 m/year at the toe and 0.1 - 0.4 m/year at the crest. Local maxima can exceed 1.6 m/year at the toe and 1 m/year at the crest [15].
- Measures adopted in the past to tackle erosion are approaching the end of their lifetime. These measures consist mainly in the construction of the North Arm Breakwater at Wreck Beach (last intervention done in 1987), cobble berm and drift sills installation (1980-1981) between Tower 1 and 2, and the installation of interaquifer drains near the Museum of Anthropology (2004) [15]. Measures protecting the cliffs locally at other sections, have worsened the erosion downdrift[15] at our focus area.
- Sea level rise will aggravate the problem, and future climate changes and variability should be further investigated due to the high uncertainty [15].

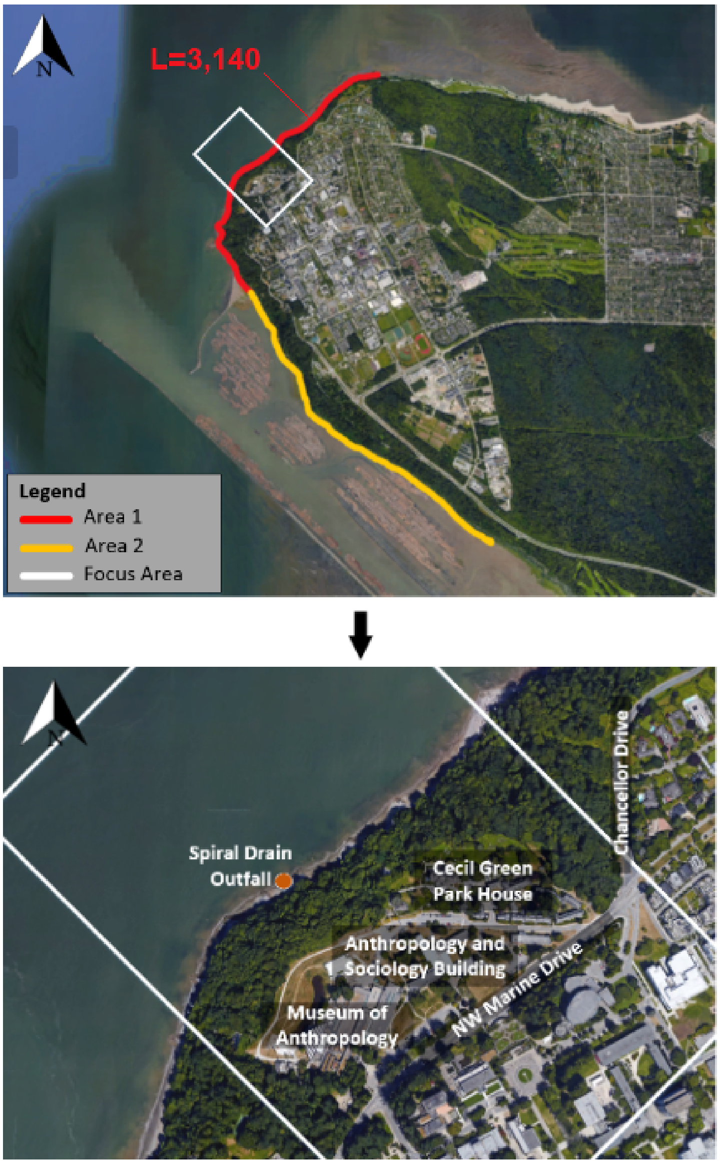


Figure 3.5: Cliff area 1, area 2 [15] and focus area of this study [43].

3.5. Summary

In Chapter 3, an overview of the current state of cliff erosion is given. Causes of erosion, both natural and human, are analyzed. Previous reports are reviewed and summarized. Although they provide a good list of previous interventions on the area and highlight successfully the areas that should be prioritized, several gaps and limitations are still present. In addition to the exiguous number of report available, none of them adopt an holistic approach. Each report is narrowed to the specific scope, either planning and management or technical assessment. In order to achieve the integrated and multidisciplinary conceptual design that is objective of this report, the vision proposed by the previous reports needs to be broadened and enriched, including aspects such as society (e.g. stakeholders) and environment.

4 Stakeholders and Regulatory Framework

This chapter gives an overview of the stakeholders that are anticipated to be involved in the project and the legislative framework that has to be taken into account.

4.1. Stakeholders

Stakeholders can be grouped in four categories depending on their main interest and impact in the project:

- *Landowners*, as the name says, will be impacted directly in their land as the project area is within their domain. University of British Columbia, University Endowment Lands, Pacific Spirit Park and private landowners belong to this category. It is important to note that different regulations and jurisdiction apply to each area of the project.

- *Society* mainly includes people or organizations that,without owning it, still make use of the land, or have an emotional attachment to it or its surroundings. UBC community members and recreational visitors are here analyzed. Another crucial issue to be taken into account is the relationship with the Musqueam First Nations. Relations between First Nations and Government of Canada are primarly regulated through the Indian Act [3], but the First Nations Management Land Act enables them to enact and administer their own land codes [2]. UBC relation with Musqueam First Nations has started to change in the recent years. With the Historic Memorandum of Affiliation, in 2006, UBC started to plant the basis for a *"long term working relationship"* with Musqueam First Nations [4]. Aboriginal Strategic Plan (2009) and its implementation reports (2009-2010-2012-2014) provide a framework for activities aimed at Indigenous people integration [9]. New Relationship Trust suggests a list of best practice to involve First Nation in Environmental Impact Assessment [30].

- *Governance* takes into account he stakeholders from which approval is needed for the project development. City of Vancouver, Port of Vancouver, Metro of Vancouver and the Department of Fisheries and Oceans are included in this category. Governance stakeholders might not have a direct stake in the project (i.e. DFO), but they provide guidelines and issue permits.

- *NGOs* include all the non governmental organization that can be involved in the project, like societies from the area or environmental organizations. Despite having usually a small economical influence and jurisdicional power, they typically have an important swing in public opinion and in professional prestige.

Is important to notice that one stakeholder can be part of more than one division. However, they are classified under the group that represents their main interest/impact. In table 4.1, a list of the main stakeholders is provided.

Table 4.1: Summary of the principal stakeholders. Source: authors.

Category	Stakeholder	Description
Landowners		
	UBC	Part of Electoral Area A of Metro Vancouver. Land use Plan is the reference policy for any action taken. Infrastructures and public realm are managed by University Neighbourhoods Association, which also represents the residents in future planning decisions.
	UEL	Unincorporated community which is also part of the Electoral Area A of the Metro of Vancouver. Directly governed by the Province.
	Private landowners	At considerable risk since some of the lands are facing directly the cliff perimeter and are within the setback lines suggested by Golder.
	Pacific Spirit Park	National park located in UEL lands. It is a nature preserve of British Columbia and part of Metro Vancouver.
Society		
	UBC community members	UBC students and staff spend a considerable amount of time in the project area.
	Recreational visitors	Touristic area mainly for visiting the cliffs, Wreck Bach and the Pacific Spirit Park.
	First Nations- Musqueam	UBC has been built on Musqueam First Nation Land, and they declare to \textit{"hold aboriginal title to the land and the rights to exercise use of land, sea and freshwaters"} and state the \textit{"intent to obtain adequate compensation for exploited land and loss of resources"} \cite{Musqueam} . Their interest in maintenance of aboriginal fisheris, hunting and cultural heritage must be protected. UBC aims at bettering the relationship between university and First Nations.
Governance		
	City of Vancouver	Municipality of the Metro of Vancouver, it's the tenure of the Spanish Banks and other beaches downdrift of Point Grey, that might be affected by measures taken updrift.
	Port of Vancouver	Responsible for a large portion of coast, its main interests are maintenance for navigation routes and economic prosperity. It has a growing concern about sustainability, reflecting in a shift of interest towards soft solutions. Dredging activities of Fraser river influence the sediment budgets of the coastal cell. Dredged sediment might become a resource.
	Metro of Vancouver	Consist of 21 municipalities, one treaty first nation and one electoral area. Measures taken to tackle erosion should comply with the Regional Growth Strategy, that aims to "Protect the environment and respond to climate change impacts". It includes GVRD parks. that form a system with the main objective of protecting and ensuring diversity of natural landscapes and habitats. The Pacific Spirit Regional park is located at the UBC area and is the principle GVRD parks affected by the cliff erosion in this area.
	DFO	Canadian government's department responsible for the protection and management of Canada's fisheries, oceans and freshwater resources. It is a stakeholder as the project area includes a water body in which endangered aquatic species live and fishery takes place\cite{DFOacts}.
NGOs		
	Wreck Beach Society	Wreck Beach is a 7.8 km long stretch of clothing-optional beach that is located near the project area.It aims at protecting the beach from threats of deforestation and contamination, and to preserve the foreshore conditions as natural as possible.
	FBC	Non-profit organization in which four government orders (federal, provincial, local and First Nations) collaborate with society and private sector to promote sustainability in the Fraser River and British Columbia in general.
	Nature trust BC	Non-profit organization focused in land conservation. Its mission is to protect the natural diversity of the province by acquiring conservation lands and preserve iconic species at risk.
	Pacific Streamkeepers Federation	Non-profit society that supports people interested in developing activities to preserve and enhance their local waterways.
	BC Conservation Foundation	Federally charity registered society. They are committed with the enhancement and protection of wildlife species and the ecosystems In British Columbia. It provides administrative, project management and technical field services for conservation projects in the area.
	Stewardship Centre for BC - Green Shores	Center with the mission of strengthen ecological management in British Columbia through capacity programs like Green Shores. The latter provides nature friendly approaches for shoreline projects.
	SalmonSafe	Leading eco-certification program in British Columbia. Its mission is to train landowners in management practices to achieve the prosperity of Pacific salmon in the West Coast watersheds.

Social Considerations

Stakeholders involvement represents only a part of the social aspects that have to be considered. In every measure taken to protect the shoreline, there is always a social impact associated. Every intervention modifies the landscape, and has an impact on the use of the project site by the community. At the same time, the different social groups present in the area have an impact: as demonstrated by human causes of erosion, society often contributes crucially to the problem. This is the reason why the society involvement has to be dual. On one side, it's necessary to include the stakeholders in the the project and try to incorporate social needs in the design; on the other, it's important to inform the community about the erosion issue and how to tackle it. Raising awareness on the problem is the only way to fully integrate the civil society in the project and to avoid damaging behaviours such as felling of trees.

4.2. Legislative Framework

Point Grey peninsula encloses several different jurisdictions: University of British Columbia owns and manages the campus; University of Endowment Lands owns the parks and natural areas surrounding the campus and is directly managed by provincial government. The whole area is furthermore a part of Metro Vancouver, not as a municipality but as an electoral section (Electoral A). City of Vancouver jurisdiction represents the eastern boundary. For a map of the area subject to different jurisdiction, refer to 2.2.

Within the Province of British Columbia, all levels of government have some role in the management of the coast. Figure 4.1 gives an overview of the jurisdiction of the different governmental institution.

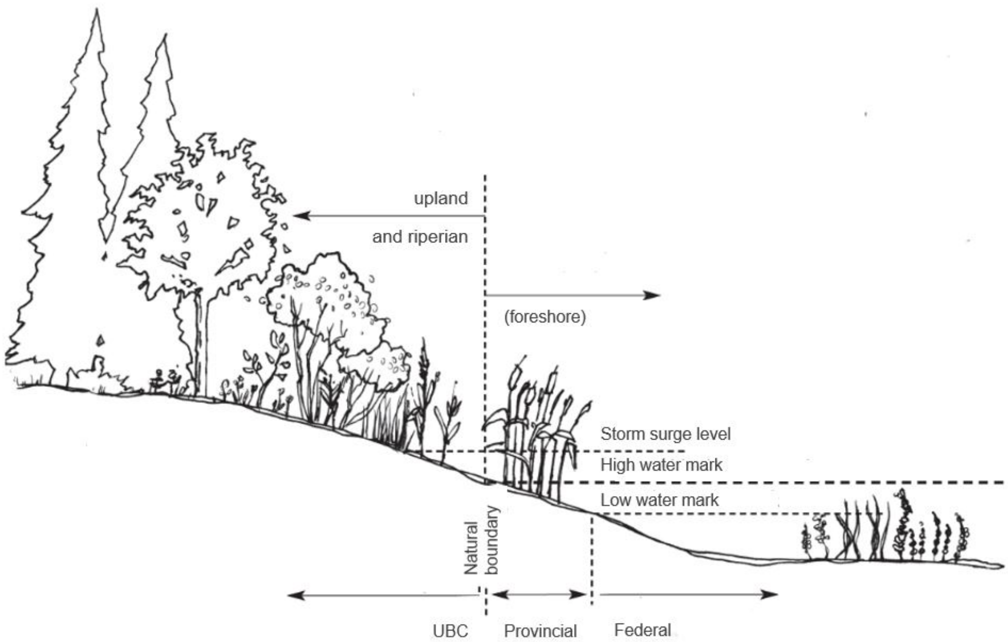


Figure 4.1: Figure showing the different jurisdictions on the coast in British Columbia Modified from: [37].

The government of Canada regulates the offshore waters from the low water mark to 12 nautilus miles along the outer coast. The DFO and the federal institution Transport Canada play a role in water related projects.Besides, the Port of Vancouver is also established under federal legislation.

The provincial government is responsible for the area between the low water level and the natural boundary. The Province of British Columbia owns the waters and the submerged lands of the Strait of Georgia, including natural and marine resources. It also manages the backshore land that is owned by University of Endowment Lands.

UBC represents the local government and is therefore responsible for the backshore, with the exception of private lands. In that case the owner is responsible for their residential land. Furthermore, consensus of the landowner of the backshore must be obtained to build on the foreshore.

In figure 4.2 an overview of the parties that have a juridical say in the project is shown. The dashed arrows show the departments within the larger body. In table 4.2, an overview of the various institutions and relevant legislation acts is shown.

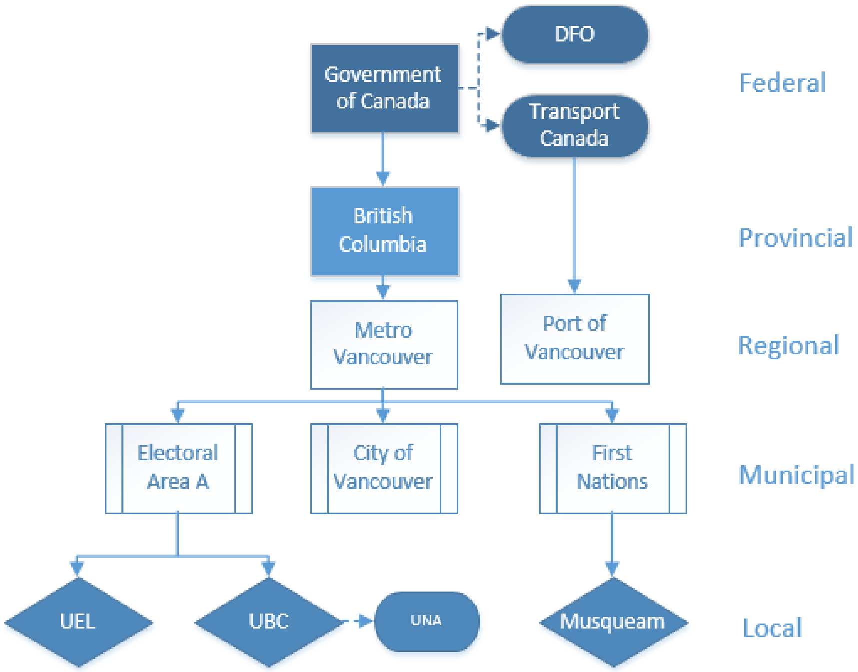


Figure 4.2: Overview of the parties that have a juridical say in the project.

Table 4.2: Overview of the federal, provincial and local legislation by institution. Source: authors.

Institution	Relevant Acts	Applicable
Federal legislation		
DFO	Fisheries Act	Water bodies that support fish, that are part of or that support a commercial, recreational or Aboriginal fishery
	Species at Risk Act	Habitat of endangered or threatened aquatic species
	Pacific Aquaculture	Projects that have a relation with aquaculture in British Columbia
Transport Canada	Navigable Waters Protection Act	Projects that can affect the public right of Navigation
Port of Vancouver	Canadian Environmental Protection Act	Prevention of significant adverse environmental effects
	Migratory Birds Convection Act	Protection of migratory birds
	Canada Marine Act	Act respecting pollution prevention of the environment and human health in order to contribute to sustainable development
Provincial legislation		
British Columbia	Land Act	Primary act used to convey lands to the community.
	Wildlife act	Aims to conservation and management of wildlife populations and habitat.
BC Ministry of Environment, Lands and Parks	Guidelines for Management of Coastal Flood Hazard	Management of lands that are exposed to coastal flood hazards, with a special focus on SLR.
	Sea Dike Guidelines 2010	Construction of sea dikes, accompanying document of Guidelines for Management of Coastal Flood Hazard.
	Riparian Rights and Public Foreshore Use in the Administration of Aquatic Crown Land	Regulates provincial defence of riparian rights and the relationship between water and the beside land.
UEL	Land Use, Building and Community	Regulates the use of land and issuance of developing permits.
	Official Community Plan 2005	Provides objectives and policies for land use management and planning of UEL. Sustaining environmental quality is one of the main five objectives.
Local legislation		
UBC	Land Use 2015	Objective of meeting GVRD Liveable Region Strategic Plan and to help sustain UBC academic mission.

4.3. Summary

In Chapter 4, an overview of the stakeholders that might be involved in the project is presented. It is important to note that stakeholders should be involved as soon as possible, in order to further understand their interests, perspective and influence on the project that should be included in next design phases. Without a stakeholders' involvement, a deep insight and a multicriteria analysis are not possible. Therefore, this chapter only adopts a descriptive approach towards stakeholders. Similarly, the social impact must be further investigated for each stakeholders though surveys and interviews. An outline of the jurisdictional and permitting landscape is also provided in this chapter, with the purpose of clarifying the different administrations present on the project site. Alas, the first conceptual design phase is not detailed enough to be analyzed from a detailed permitting and legislative perspective. The jurisdiction of each concept is therefore identified in this feasibility study, and relevant legislation listed but a further analysis of the permitting path that has to be undertaken should be conducted in the next design phases.

5
Coastal Management Strategies

In this chapter, an analysis of the general strategies for coastal management is given, along with an overview of some of the most common measures adopted.

5.1. General Strategies

Coastal hazards might be enhanced due to the impact of Sea Level Rise. The latter can cause [61]:

- Coastal inundation and reduced drainage capacity;
- Coastal erosion;
- Changes to coastal habitats and loss of wetlands such as salt marshes;
- More frequent and intense storms, storm surge and wave action.

As already explained in 2, climate change might affect storms intensity and frequency, as well as storm surge and wave action. This could lead to an increase in cliff erosion, especially if assisted by structural erosion and changes in habitat. Therefore, even if in this project these changes are not modeled, it is important to consider resilience of coastal cities when dealing with cliff erosion. According to the Sea Level Rise Adaptation Primer for Canada's Atlantic and Pacific coasts [61], coastal management can follow four adaptation strategies:

- **Protect**

  To protect is the traditional approach to deal with coastal vulnerability, where by the implementation of structural mechanism, the strategy seeks to protect people, land and infrastructures. This reactive solution may be limited for highly vulnerable coast.

- **Accommodate**

  With this strategy people habits and activities must be changed and infrastructures must be adapted to the new and future situation. This adaptation allows people to keep occupying this area.

- **Retreat**

  "Refers to any strategic decision to withdraw, relocate or abandon private or public assets"[61]. This strategy aims to limit the protection solutions and to discourage the development in vulnerable areas by relocating it in lower risk areas.

- **Avoid**

  The objective of this approach is to avoid developments in areas with moderate to high risk. For this, a mapping of land classification according to risk level must be done. This analysis also has to include possible future increases in risk.

Examples of this strategies can be seen in Table 5.1

Table 5.1: Examples measures for the different four adaptation strategies for climate change [15].

Protect	Accommodate	Avoid	Retreat
Hard solutions	Raising buildings	Potential development areas in low-risk lands	Relocation
Hybrid solutions	Flood insurance	Land acquisition	Resettlement
Soft solutions	Flood-proofing structures		Managed Retreat

Moreover, the approach of *do nothing* or going on with *business as usual* is always an option when erosion is present. Although the consequences must be thoroughly considered through a risk analysis and an asset evaluation for the buildings and infrastructure present on the spot. It's usually implemented only in non-urbanized areas, as loss of infrastructure is undesirable and often expensive.

Even though the solutions are not mutually exclusive, for the case of UBC cliff erosion is expected that retreat is a realistic approach, accommodation can help to avoid the enhancement of coastal erosion. However, for the continued usage of this area a protection strategy must be implemented.

5.2. Common Measures for Protection Against Erosion

Several examples of different solutions for coastal protection used around the world is illustrated in tables 5.2 to 5.5. The solutions are limited to the options considered suitable for this specific project and location. This list provides a *toolkit*: different solutions can be combined and mixed in order to provide a complete and holistic coastal protection design.

The first three tables correspond to toe erosion solutions and the last one to subaerial erosion solutions. Moreover, the toe erosion solutions are classified as hard, soft or hybrid solutions with the following criteria:

- *Hard solutions*: all solutions that consist in a structure and result in a fixed coast line. They include most of the traditional solutions for coastal protection, such as seawalls, breakwaters, groynes etc. The main disadvantage is the negative impact on the natural coastal dynamics, in addiction to the low flexibility of the measure with respect to changes in the initial boundary conditions (i.e. resilience to climate change), and the high capital and maintenance costs.

- *Hybrid solutions*: solutions that require some kind of structure, but don't result (only) in a fixed coastline. Main disadvantage of the considered hybrid solutions is the lack of reliability: most of them are still at experimental level and need further studies to assess the effectiveness as coastal protection measures.

- *Soft solutions*: these are solutions that maintain the natural dynamics of the coast, and mainly consist in an additional supply of natural resources (sediment, vegetation, etc.).

It is important to note that the classification of the solution is not unambiguous and it's often debated. Another distinction that can be found in the literature is *nature-based solution*. Almost all solutions can be nature-based if designed keeping in mind specific principles, such as nature conservation, and using ecosystem-based approaches. For instance, the project of a Living Breakwater proposed for Staten Island transforms a traditional solution, such as a breakwater, into an improvement of the existing ecosystem [14].

Table 5.2: Toolkit of hard solutions for cliff toe erosion. Source: authors.

Solution	Location	Description	Advantages	Disadvantages
Breakwater	Offshore	Offshore structures made of rocks or concrete armour. Can be emerged of submerged.	+Wave dissipation +Protection against erosion at the location	-Reduction of coast dynamics -Cost and maintenance -Ecosystem impacts -Erosion downdrift
Berm	Cliff toe	Berm made of sand, gravel, cobbles or mixture	+Reduction of wave attack on the cliff toe	- Disturbance of natural environment
Seawall	Cliff toe	Vertical structures that fix the coast line	+Protection against erosion	-Cost -Requires deep foundations -Enhancement of wave action due to reflection
Geotubes	Cliff toe	Permeable fabrics, shaped as bags and filled with sediment and water.	+Protection against erosion +Cheaper than hard structures +Vegetation growth	-Reduction of beach dynamics -Limited water circulation -Maintenance

Table 5.3: Toolkit of hybrid solutions for cliff toe erosion. Source: authors.

Solution	Location	Description	Advantages	Disadvantages
Hydraulic piling	Foreshore	Vertical wooden piles planted in the sand.	+Dispersion of wave energy +Deposition of sediment +Cheap and easy to implement	-Not always efficient -Could hamper recreational activities on the beach -Does not affect total sediment budget
Clam gardens	Intertidal area	Rock walls constructed in the intertidal area that creates a favorable environment for clam colonies	+Culturally relevant +Enhancement of ecosystem +Could reduce wave action	-Not enough information about effectiveness, studies necessary
Artificial reefs	Offshore	Try to imitate natural reefs. Can be built with old boats, but also with oysters and mussels	+Wave dissipation +Protection against erosion	-Effectiveness not assessed

Table 5.4: Toolkit of soft solutions for cliff toe erosion. Source: authors.

Solution	Location	Description	Advantages	Disadvantages
Beach nourishment	Foreshore	Supply of sediment to the beach or the shore	+Increase the sediment available	-Maintenance -Affects intertidal ecosystem -Sediment source
Engineered beach	Foreshore	Building of a beach	+Creation a new long-term sediment supply +Mitigation of wave action on cliffs	-Ecological issues -Cost -Sediment source
Plant debris cover	Cliff toe	Branches are used to cover the cliff toe	+Mitigation of aeolian erosion +Organic input for plants development	-Landscape issues limit extension area
Coastal wetlands	Intertidal areas	Creating a rich habitat in the intertidal area Can consist of salt marshes, seagrass bed or sand bars	+Wave attenuation +Sediment trapping +Ecosystem enhancement	-Effectiveness depends on the scale of intervention -Space required -Feasibility issues

Table 5.5: Toolkit of solutions for subaerial cliff erosion. Source: authors.

Solution	Location	Description	Advantages	Disadvantages
Plantation	Cliff face	Plantation of vegetation	+Sediment trapping +Reduction of sediment loss due to wash out or wind +Slows the velocity of the slope runoff (erosive force)	-Ecological issues (native species vs invasive species)
Plantation	Cliff top	Plantation of trees and/or small vegetation	+ Binding loose material +Increase shear strength slope +Decrease run off	-Growth time (trees)
Aquifer storage	Adjacent areas	Injection of water into the lower aquifer through wells or by surface spreading and infiltration	+Larger water storage capacity +May expand function of aquifer to meet growing urban +Agricultural water needs	-Significant cost to manage properly -Significant risks
Inter-Aquifer drain wells	Adjacent areas	Well that stimulates the drainage from the Upper Aquifer to the Lower Aquifer	+Decreases seepage erosion from Upper Aquifer on local scale	-Not appropriate for large scale -Requires regular monitoring, assessment and maintenance -Costly -Unable to deal with peaks - Performance decreases over time
Stormwater detention	Adjacent areas	Temporarily storage of stormwater to release it at a slower rate than it arrived	+Decreases risk of runoff erosion	-Large footprint area (above ground)

5.3. Concepts and Feasibility

In the next four chapters, elements from the toolkit are combined in four different concepts:

- Traditional approach: a rip-rap and rock revetment.
- Nature based concept 1: Engineered beach with floating islands.
- Nature based concept 2: Clam gardens.
- Subaerial concept: Revegetation, underground stormwater detention facility and inter-aquifer drainage wells.

These concepts are chosen with the following reasoning. First, a comparison between a traditional approach and some more nature-based solutions is sought. In the elaboration of nature-based solutions, local culture and mind set is taken into consideration. Cultural importance of clam gardens is the starting point for Concept 2, while the great use of engineered beaches in the zone inspires Concept 1. The subaerial concepts tackles erosion of the cliff face with a dual goal. On one side, a better storm-water management through detention facility and drainage wells is forsaken. Moreover, an improvement of cliff coesion through revegetation is implemented. All the concepts are designed following the profile of one specific transect, namely the one under the Museum of Anthropology, considered the one to be prioritized [43]. For each concept, a feasibility study is conducted following an holistic approach: technical, environmental, legislative, economical and social feasibility is assessed and key issues for each item are highlighted. In order to assess the effectiveness in reduction of the hydrodynamic conditions that lead to marine erosion, three scenarios are developed:

- Scenario 1: for this scenario, a water level corresponding to High High Water Mean Tide is chosen, with the addition of 1 m to take into account sea level rise. Waves with a return period of 50 years are considered.
- Scenario 2: 50 year return period waves are considered on a water level with a return period of 50 year (according to the joint probability for tide and skew surge [15]), plus 1 m of sea level rise.
- Scenario 3: finally, to test extreme conditions, 200 year return period waves are considered together with a 200 year return period water level, and 1 m of sea level rise.

Scenario 1 is elaborated to test more ordinary conditions. Scenario 2 is taken as design scenario. A return period of 50 years is considered appropriate for the timelife of the measures. The decision is taken in accordance with UBC, and considering the local engineering culture. Differently than in the Netherlands, in Canada the upper end of the probability range recommended is an average period of 200 years [20]. A particular attention in avoiding overdesign is therefore adopted. Scenario 3 is chosen in order to assess resilience of the design to extreme conditions that might occur more often than expected due to climate change. A summary of the scenarios' characteristics can be found in table 5.6.

Table 5.6: Analyzed scenarios. Source: authors.

Scenario	Water level [m]	Sea level rise [m]	Wave height [m]	Wave period [s]
Scenario 1 (HHWM and 50 years wave)	1.4	1	3.73	6.94
Scenario 2 (50 years water level and 50 years wave)	2.4	1	3.73	6.94
Scenario 3 (200 years water level and 200 years wave)	2.5	1	4.25	7.3

Each scenario is run in SWAN, including wave setup, for the original bathymetry and for the changes in bathymetry due to each concept. Thus, a comparison of wave attenuation of original bathymetry versus every concept per scenario is made. As a final note regarding the design, the waterline at Scenario 2 is chosen as the 0 for the x axis.

5.4. Summary

In chapter 5, general coastal management strategies are introduced. Protection is identified as the most suitable for the specific site; a list of common protection measures is presented. Three holistic concepts are elaborated and suggested as a first design concept. In order to conduct a feasibility analysis, three scenarios are proposed.

6 Concept Do Nothing

The option of continuing with business as usual is hereby considered as a base case of comparison for the proposed solutions. If not prevented, erosion will continue in the active areas, leading to more cliff recession both at the toe and at the crest. This usually results in considerable damage of properties and safety threats. Further studies need to be conduced to quantitatively assess economic damages and risks, but from previous studies the following short and long term issues can be summarized.

6.1. Short-term Consequences

Economical consequences

The main features endangered in the short term is the NW Marine Drive and the sewer running along it outside. The damage of this features could represent a significant economical damage. According to Golder, the timeframe for the damage of the sewer line is as short as 10 years [15].

Environmental consequences

The possible failure of the sewer constitutes a remarkable threat. The consequence is a potential environmental disaster, plus loss of habitat on the cliff face, on the beach and in the foreshore for several years.

Social consequences

Slide events that continue to carry on in the areas of active erosion represent a safety hazard for the users of the beach or of the trails [15]. Furthermore, the loss of campus land could significantly hamper the recreational use of the beach.

6.2. Long-term Consequences

Economical consequences

On the long term, significant portion of campus land could be lost due to erosion. Under the present average recession rates, buildings and infrastructure at risk are: Cecil Green House, Coach House, Old Marine Drive, and South Marine Drive.

This estimate is considered to be conservative [15]: due to sea level rise, which will potentially increase erosion rates and endanger museum of Anthropology and Mac Kenzie house too.

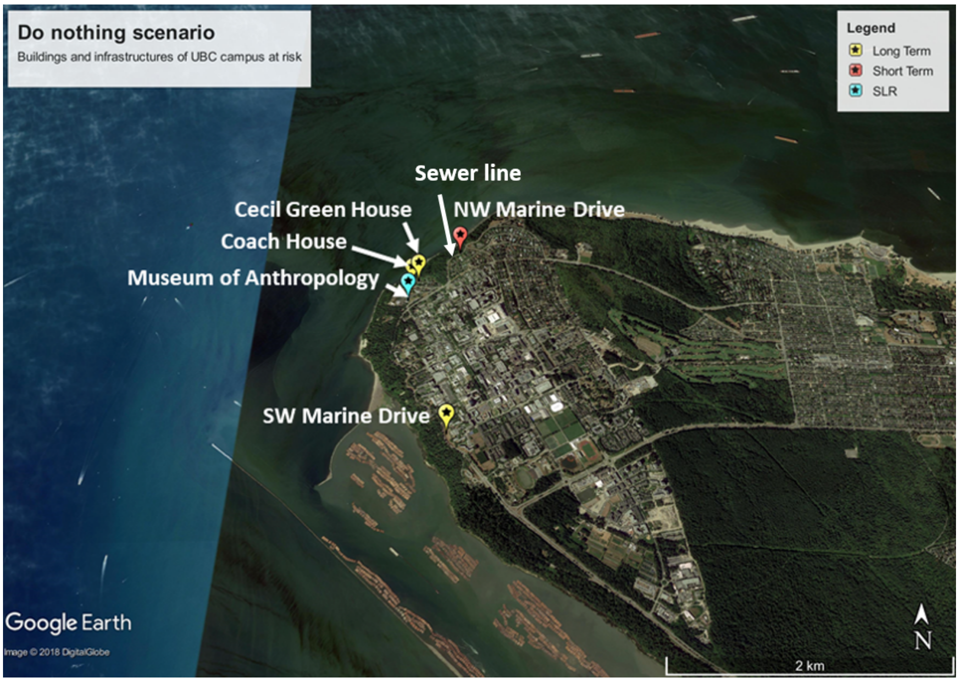


Figure 6.1: Map of the endangered infrastructure in the short and long term, and when taking into account SLR according to Golder. Source: authors.

Environmental consequences

On the long term, loss of habitat at Point Grey will affect crucially the whole environment. If erosion carries on, the whole habitat on the cliff face will eventually disappear. This will also have an impact on the marine habitat: the sediment input from the cliffs affects the turbidity of the water, which is a key element for the ecosystem.

Social consequences

The Do Nothing approach will completely disrupt the local community. For First Nations, the loss of the cliffs represents the loss of a part of their ancestral territories. UBC and Vancouver community will suffer the loss of the beach. Societies such as Wreck Beach will stop having a purpose. The whole land use of the site would change completely.

6.3. Summary

In Chapter 6, the option of Do Nothing is considered and the long and short term consequences forecast. It has to be noted that further investigation of the latter should be conduced in order to have a more detailed framework. Furthermore, an accurate risk analysis is recommended.

7

Concept A Rip-rap and Rock Revetment

This concept has a more traditional approach in dealing with cliff erosion, by constructing a rock revetment which fixes the coast. It is a well proven concept and there is a lot of knowledge available on the behaviour of the design. This more traditional approach was applied at the project site in the 1970s and 1980s when a cobble beach and groynes were constructed. However, these interventions have not prevented the cliff toe from eroding. A substitute berm with a different stone grading and slope may solve the eroding trend and successfully fixate the coastline.

7.1. Technical Feasibility

The main purpose of this approach is to fix the current coastline in order to prevent further erosion from the cliff toe. This is done by applying a sufficiently large grainsize class on the berm to ensure stability during storm conditions. The berm is constructed along the whole shoreline of the peninsula as the berm only protects the parts of the coast where it is constructed(Figure 7.1). Essential elements of the design of the revetment are explained in this section. More information on the design process can be found in Appendix D.

Revetment profile. In order to minimize the material required for the berm it's chosen to follow the slope of the cliff, which leads to a steep slope of the berm of 1:3. A steep slope leads to a reduction of construction costs. The height of the berm equals the waterlevel during scenario 3 plus half the wave height to protect the cliff from erosion from wave scour. There is a significant amount of run up due to the high offshore waves and the steep slope of the berm. The run-up during scenario 2 and 3 is reduced by the construction of a berm slightly above the scenario 1 waterlevel. The cliff profile above the top of the revetment is protected from run-up by an engineered stacked rock wall.
The stability of the bottom of the structure is essential for the stability of the entire structure. To stabilize the revetment a toe is necessary to protect the bottom of the revetment from wave scour. Also scour in front of the toe needs to be prevented which is done by applying a bottom protection. Below the armour layer a geotextile is designed to prevent the escape of cliff sediment through the revetment.

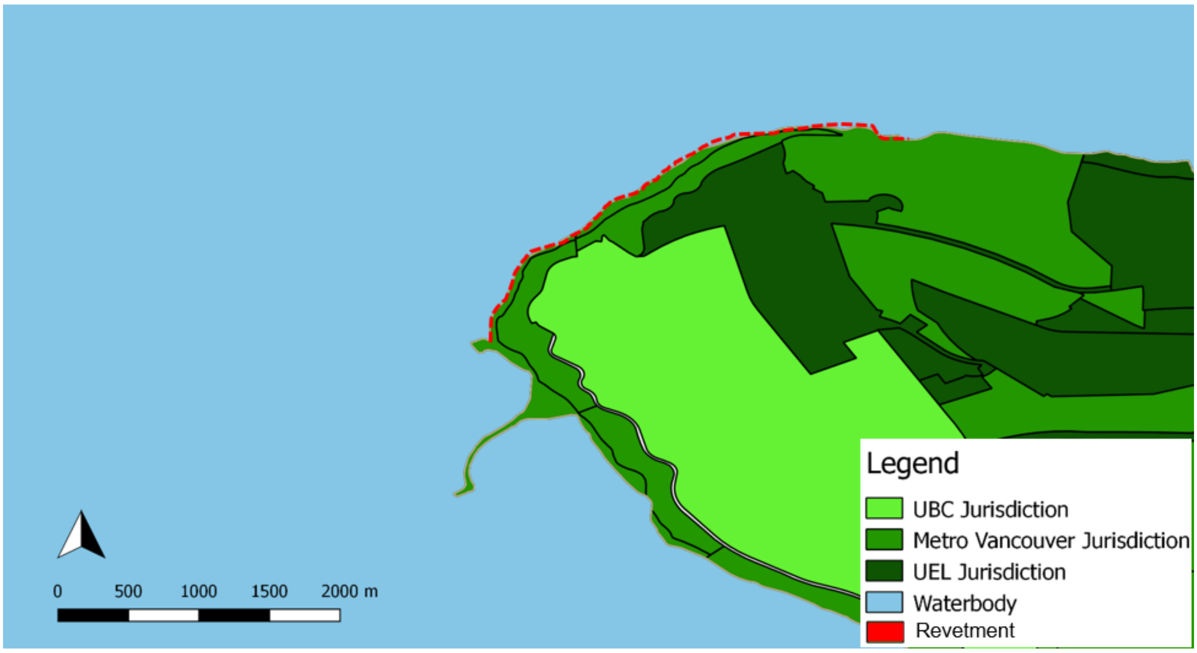


Figure 7.1: Top view of the location where the revetments needs to be constructed. Source: authors.

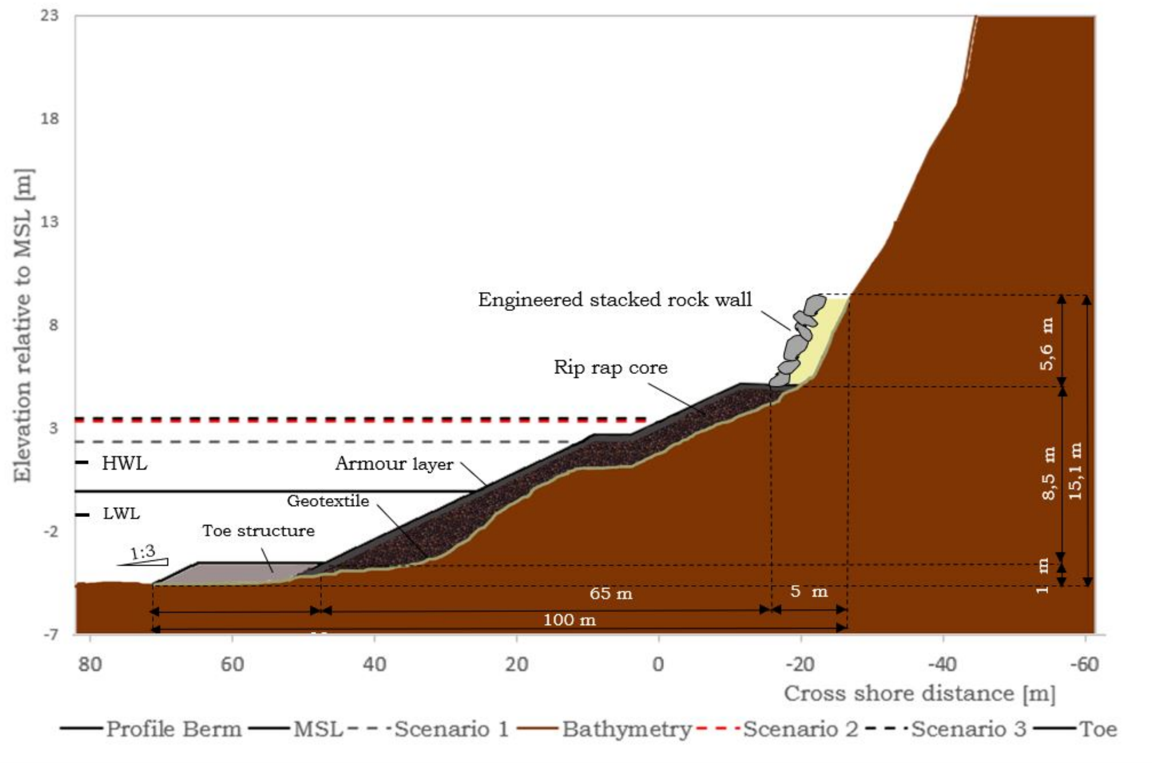


Figure 7.2: Cross section of the revetment design. Source: authors.

Stone size. In order to withstand the high wave impact during storm conditions, the armour layer requires a stone size with a $d_{n,50}$ of minimally 0.61 m. Both the Hudson formula as the Van Der Meer formula are used to determine the required stone size, as the experiments that generated the fit of both the formulas were executed under comparable circumstances (such as slope and permeability) that can be found here [42]. Hence both

formulas are applicable to this situation and the least conservative outcome is used in the design. Further elaboration on the determination of the stone size can be found in Appendix D.
The core of the revetment consists of riprap. Due to the fact that the toe structure doesn't experience much impact, it requires a smaller rock class. However, to ensure stability between the main structure and the toe structure, the rock class of the toe structure should be maximum one class smaller than that of the armour layer.
As the rocks of the armour layer are of considerable size, they are not suitable for pedestrians that visit the beach. If the client wishes to keep the shoreline accessible for visitors, it can be considered to add a thin layer of smaller grain size which is suitable for walking. The latter does not withstand extreme conditions considered in the scenarios but does make the shoreline more accessible. In the case of an extreme event, minor maintenance can replace the lost material.
Effectiveness. To assess the effectiveness in erosion control by the berm, a SWAN model to check the wave transformation is conducted. As it can be observed in figure 7.3, onshore evolution of the significant wave height H_{m0} is remarkably affected by the berm:

- Waves are breaking further offshore with respect to the original bathymetry.
- Wave height in the surf zone is reduced.
- Waterline is moved further offshore; therefore, wave solicitation on the cliff toe is reduced.

This means that the design of the revetment can be made with a lower wave height than can be found in the scenarios in Chapter 5.
Though the revetment attenuates the waves very well and is expected to fix the coastline, it does not solve the problem of the sediment deficit. One must be aware that by preventing erosion at the UBC cliffs, this will likely move the erosion problem more downstream to the beaches of Spanish Banks and Jericho.

Construction. The main issue for the construction of the revetment is the accessibility of the shore as it is positioned under a cliff with no access roads suitable for the equipment. There are two options to access the shore, which are via water or via a constructed access road. Barging the riprap to the site may not be feasible due to the wide intertidal area and high tidal range. This lead to access restrictions during parts of the day, which limit the time that can be used each day to construct the revetment. However, the other option of constructing a access road is also a very costly option. Besides the construction, it has a big impact on the cliff environment and the UBC community. A more detailed study on the construction costs and impacts is recommended to provide more insight on what would be the better option.

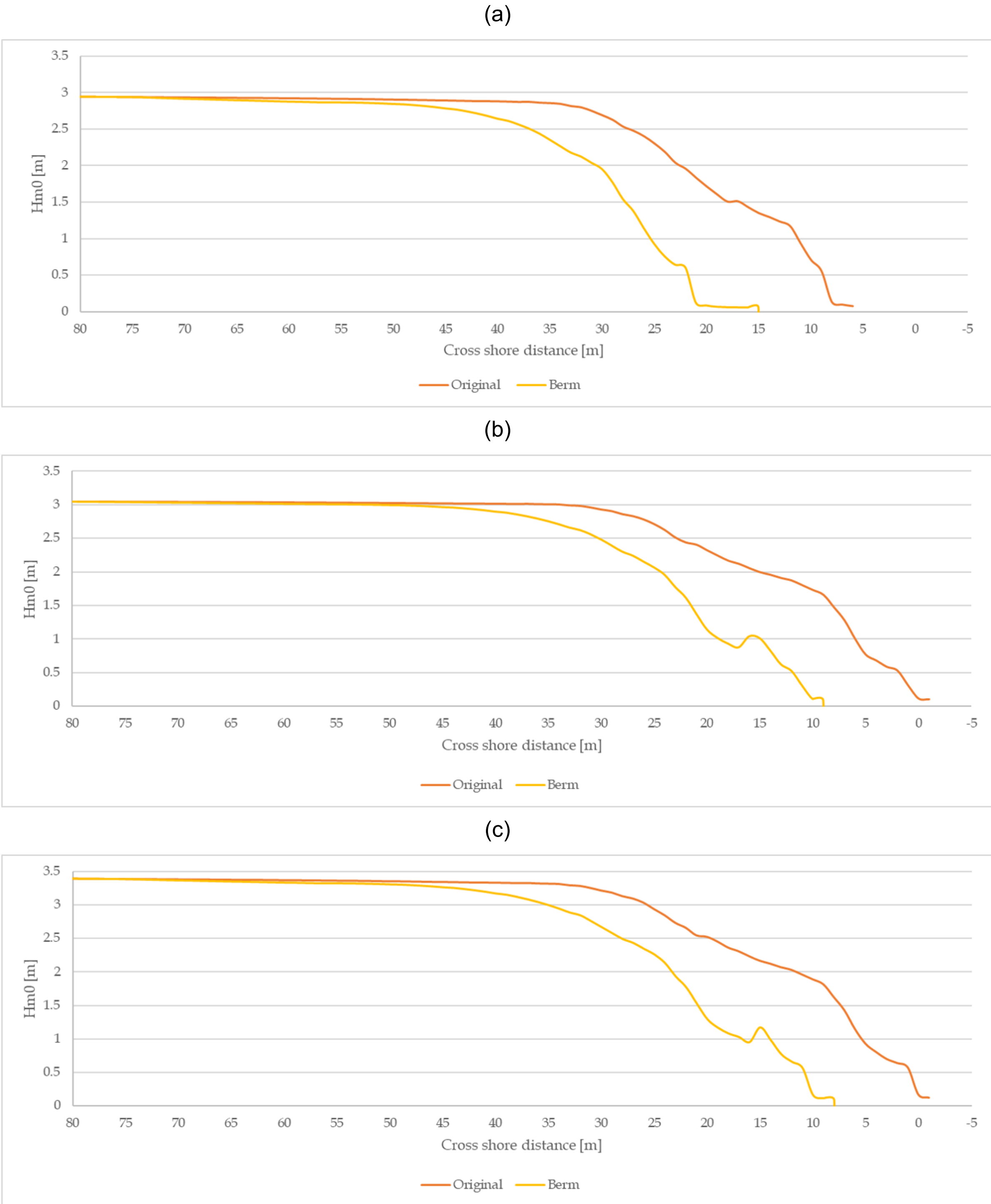


Figure 7.3: Comparison between onshore transformation of waves for the original bathymetry and the bathymetry modified by the revetment. (a) Scenario 1 (b) Scenario 2 (c) Scenario 3. Source: authors.

7.2. Environmental Feasibility

This section identifies the different impacts the construction of the revetment has on the ecosystem. It is expected that by constructing a new berm revetment on top of the current berm the quality of the habitat is not significantly changed with respect to the current situation. However, the surface area of the new berm revetment is larger than that of the current berm, as it stretches out both more seaward and more upwards up the cliff. The habitat at these locations is expected to experience impact from the construction of the revetment. Both the marine habitat and the habitat at the cliff are treated separately.

Marine habitat. The structure of the revetment including the toe reaches 50 meters offshore. The construction and dumping of rocks is expected to generate a loss of benthic species and other marine species present at the location. To mitigate this effect as much as possible, the dumping of the rocks should take place during winter when less species are present at the site. This measure helps to obtain a permit for construction as it helps to meet regulations mentioned in 7.4.

Cliff habitat. The revetment reaches up the cliff up to 11 meter above MSL, which is currently vegetated by different tree and fern species. In order to construct the revetment, this vegetation has to be removed. However, at the lower part of the cliff a large number of the trees have fallen already or are uprooted, hence this is not considered as loss of vegetation.

Ecosystem services

- Supporting and provisioning services: this option actually reduces the available habitat and hamper some other supporting and provisioning services. As suggested by BC Rip-Rap design guides, a number of modification to the initial design can be made in order to mitigate the environmental impact, such as providing eco-pockets that compensate for the lost habitat [58].

- Regulating services: The berm dissipates waves. This means that the reve me t may be more suitable for vegetation or shells as there is less wave attack.nt

- Cultural services: recreational use of the beach could be hampered by the presence of big rocks, and landscape aesthetic might be affected.

Climate change resilience. The revetment is designed taking into account 1 meter of sea level rise. According to current predictions, this suffices for the sea level rise during the next 100 years. Also relatively high extreme storm conditions of 1/200 years are considered to check how the design would perform during these extreme storm conditions. According to the long term water level analysis by Golder [15], the water level belonging to a 1/200 year return period is not much higher than the 1/50 water level. Therefore a more severe storm will not lead to a much higher water level. Therefore it is expected that this concept will be resilient for potential changing hydraulic conditions due to climate change during the next 100 years. However, there is no data available on storm frequency or intensity due to climate change near the Vancouver area to make specific predictions.

7.3. Economical Feasibility

In the table below, a class D cost analysis for materials and construction is provided. It has to be noted that important costs like maintenance are excluded from this analysis. The berm results to be an expensive protection option because of the costly materials required and the necessary space used.

Table 7.1: Cost estimate of rip-rap and rock revetment.

Rip-rap and rock revetment	Units	Quantity	Cost per unit (CAD)	TOTAL (CAD)
Supply and placement angular rock	m3	628,000	200	125,600,000
Supply and placement engineered stack rock wall	m2	17,584	400	7,033,600
Supply and placement geotextile	m2	224,856	8	1,798,846
General conditions* (5%)	LS	-	-	6,721,622
Contingency (50%)	LS	-	-	70,577,034
			TOTAL (CAD)	**211,731,103**

* Site preparation (mobilization and demobilization), surveying, insurance, bonding, quality check and quality assurance.

7.4. Legislative Feasibility

The berm is installed over the whole coast and therefore the measure should meet the jurisdictional demands of UBC, British Columbia and the government of Canada, as seen in Figure 4.1. The legal documents that are relevant for this measure are:

- The Fisheries Act from DFO as the berm is built in a water body where fishery is active.
- The Species at Risk Act from DFO as the berm is installed in an area where threatened aquatic species live.
- The Pacific Aquaculture Regulation from DFO as the project can influence the aquaculture of British Columbia.
- The Riparian Rights and Public Foreshore Use in the Administration of Aquatic Crown Land from British Columbia.

Besides, the project should be in line with UBC's Land Use Plan as the top of the berm is built on their land. The applicability of these legal documents has some direct consequences on the design and construction phase. One of them is the requirement to create compensation areas for lost habitat. Also the construction schedule can be affected, as the sprawning season of endangered species should be taken into account.

7.5. Social Feasibility

The revetment affects the aesthetic landscape as the design includes the elevation of current beach and the partial replacement of the cliff vegetation by the shore protection. However, the landscape aesthetic should not change drastically since currently there is also a berm . It has to be kept in mind that the loss of habitat can arouse opposition from environmental societies and concerned inhabitants. Before constructing the revetment a lot of attention should be paid to the public awareness to mitigate possible social unrest.

7.6. Summary

A traditional approach to prevent cliff erosion consists out of designing a revetment or breakwater. In this case a revetment is chosen to fix the coastline and prevent further marine erosion of the cliffs. It is a reliable option as it has been used frequently throughout the world and a lot of experience and knowledge is present. Even if this solution might be effective at location, it may though result in increased erosion at downstream locations in the bay. Moreover, this revetment is effective up until a certain water level and does not work as effectively with a sea level rise of more than 1 m. Hence it is not a very climate resilient option. It is expected that by constructing a new berm revetment on top of the current berm the quality of the habitat is not significantly changed with respect to the current situation.

8

Concept Engineered Beach and Floating Wetlands

This concept focuses on the stabilization of the cliff toe by introducing more sediment into the system through widening the beach. By performing a beach nourishment along the cliff a beach of the optimal slope can be constructed to reduce the wave run-up and prevent wave attack at the cliff toe. However, solely performing a beach nourishment will not reduce the shore erosion and the deposited sand will erode eventually, exposing the cliff toe again in time. To reduce the erosion rate, the design includes the placement of floating wetlands in front of the beach in order to attenuate the waves. Moreover, is important to note that this approach demands maintenance, especially for the beach. In order to keep the needed amount of sediment in the system, beach nourishment has to be an ongoing process. To estimate the amount of time between each maintenance intervention a more detailed study of erosion rate is needed, considering also the effect of the floating islands. Figure 8.1 shows a top view of this concept, and the gives an insight of the dimensions of this solution. To be effective against cliff erosion the solution must be applied in the entire study area.

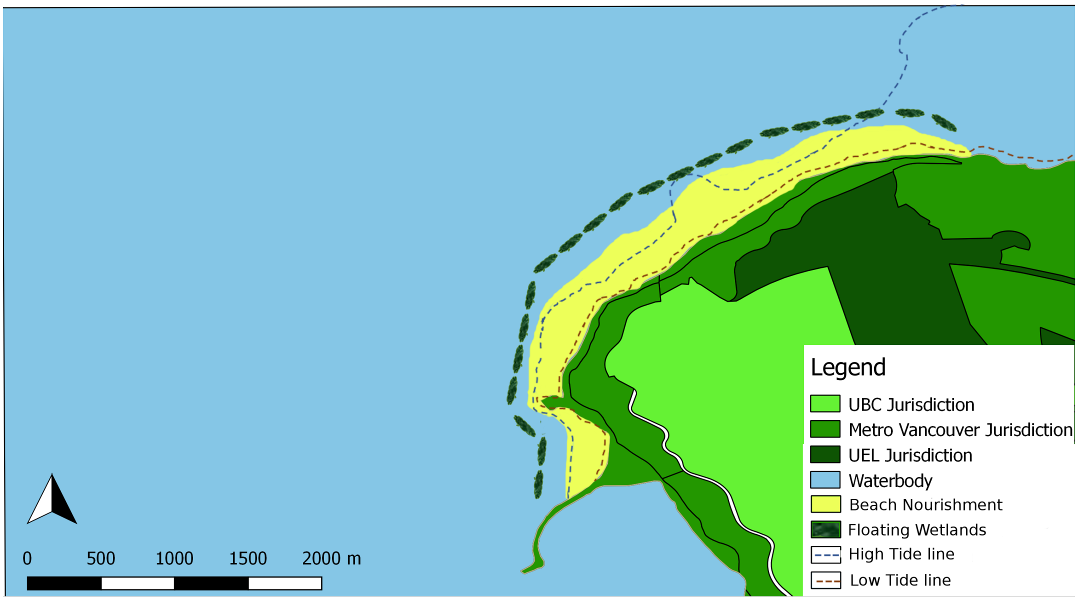


Figure 8.1: Topview of the engineered beach and floating wetlands. Source: authors.

8.1. Technical Feasibility

In order to assess the technical feasibility of the engineered beach, first, the key design aspects for the beach nourishment have to be considered.

Sediment supply characteristics. For the beach nourishment to succeed, added sediment characteristics should be close to the ones of the native beach sediment. Slightly coarser material is advisable in order to minimize sediment losses [66]. Material at the beach is consisting mainly of Quadra sand with minor silt and gravel [15]. Golder Associates estimate the sediment transport assuming a sand with a median grain size of 0.3 mm. The same assumption of a well sorted sand with a d_{50}=0.3 mm is maintained in this report, although a measuring campaign is recommended in order to obtain a sieve curve and more accurate estimates of the nourishment characteristics. 0.3 mm is also the boundary d_{50} above which the effectiveness of the nourishment increases [66]. As a possible source of sediment, the yearly dredged material by Port of Vancouver is identified. Key issues to be assessed for sediment suitability are: grain size, possible contamination and quantity.

Volume of sand. Van Rijn [66] indicates three different estimates of volume of sand (in $m^3/m/year$) depending on the level of energy of the hydrodynamic environment in which the beach nourishment is done. Point Grey is a high energy environment due to the ongoing erosion; therefore, the required volume of sand is suggested to be between 150 and 300 $m^3/m/year$ [66]. As a first estimate, a nourishment volume of around 250 $m^3/m/year$ is considered.

Beach nourishment profile. Following Van Rijn[66] recommendations and grain size characteristics, two slopes are assumed for the initial profile of the nourishment. In the upper beach, a milder slope 1:30 is assumed; in the foreshore and after the -1 m depth contour, a steeper slope of 1:20 is allowed. It's suggest not to adopt steeper slopes than the chosen ones, in order to avoid increased initial sand losses [66]. Moreover, as the slopes are mild compared to the bathymetry, a rubble mound and the corresponding bottom protection must be built at the offshore end of the engineered beach. This approach is taken, because if not the needed slope is not feasible due to the abrupt changes of bathymetry in the offshore direction. This also reduces the cost of the project due to the less sand needed. Furthermore, to protect the toe and slopes as much as possible in case of water levels between scenario 2 and scenario 3 (5.6), an engineered stacked rock wall is placed at the onshore end of the engineered beach. In Figure 8.2 the profile of this concept with its different structures can be better understood.

Effectiveness of the engineered beach. Purpose of the reshaping of the beach profile is of a double nature: supply additional sediment and contribute to wave attenuation due to the change in the bathymetry. To assess the effectiveness of the engineered beach against wave attenuation, SWAN simulations and run up calculations are conducted for the three considered scenarios. The new beach profile affects the onshore transformation of waves, as it can be seen in figures 8.3. Due to the change in the bottom profile and to the reduced water depth, waves start breaking more offshore and the significant wave height H_{m0} is reduced in every scenario. Moreover, this results are only considering the effect of the engineered beach. Thus, the reduction in wave height is expected to be even larger when the impact of the floating islands is taking into account.

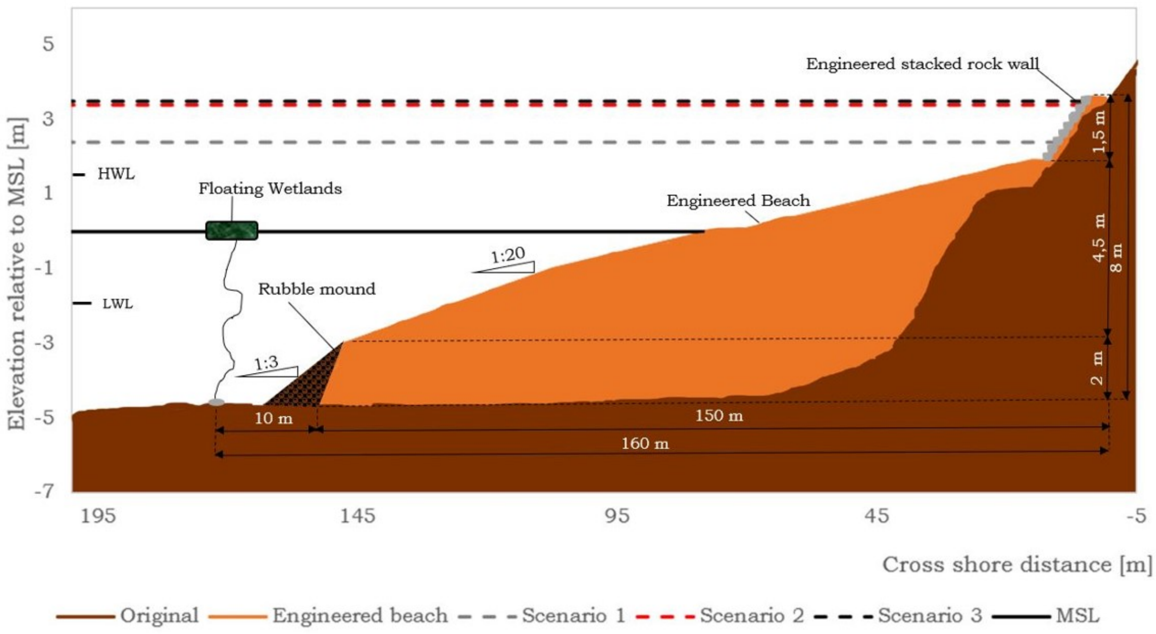


Figure 8.2: Engineered beach and floating wetlands profile. Source: authors.

The run-up is calculated according to Mase (1989):

$$\frac{R_{2\%}}{H_{m0}} = 1.86\xi^{0.71} \tag{8.1}$$

Where:

- $R_{2\%}$ is the run-up exceeded by only two percent of the wave runup values;
- H_{m0} is the wave height at x=30 m.
- ξ is the breaker parameter, calculated as

$$\xi = \frac{tan\beta_f}{\sqrt{H_{m0}/L_{m0}}}. \tag{8.2}$$

To calculate L_{m0}, peak period is used, and β_f is the slope of the bathymetry at x=30m.

Run-up calculations are conducted with the transformed wave height. Wave height at x=30 m (shoreline at MSL) is taken to do the run-up calculations. Results of the run-up calculations for the original bathymetry are shown in table 8.1, while the ones for the engineered beach profile can be found in table 8.2.

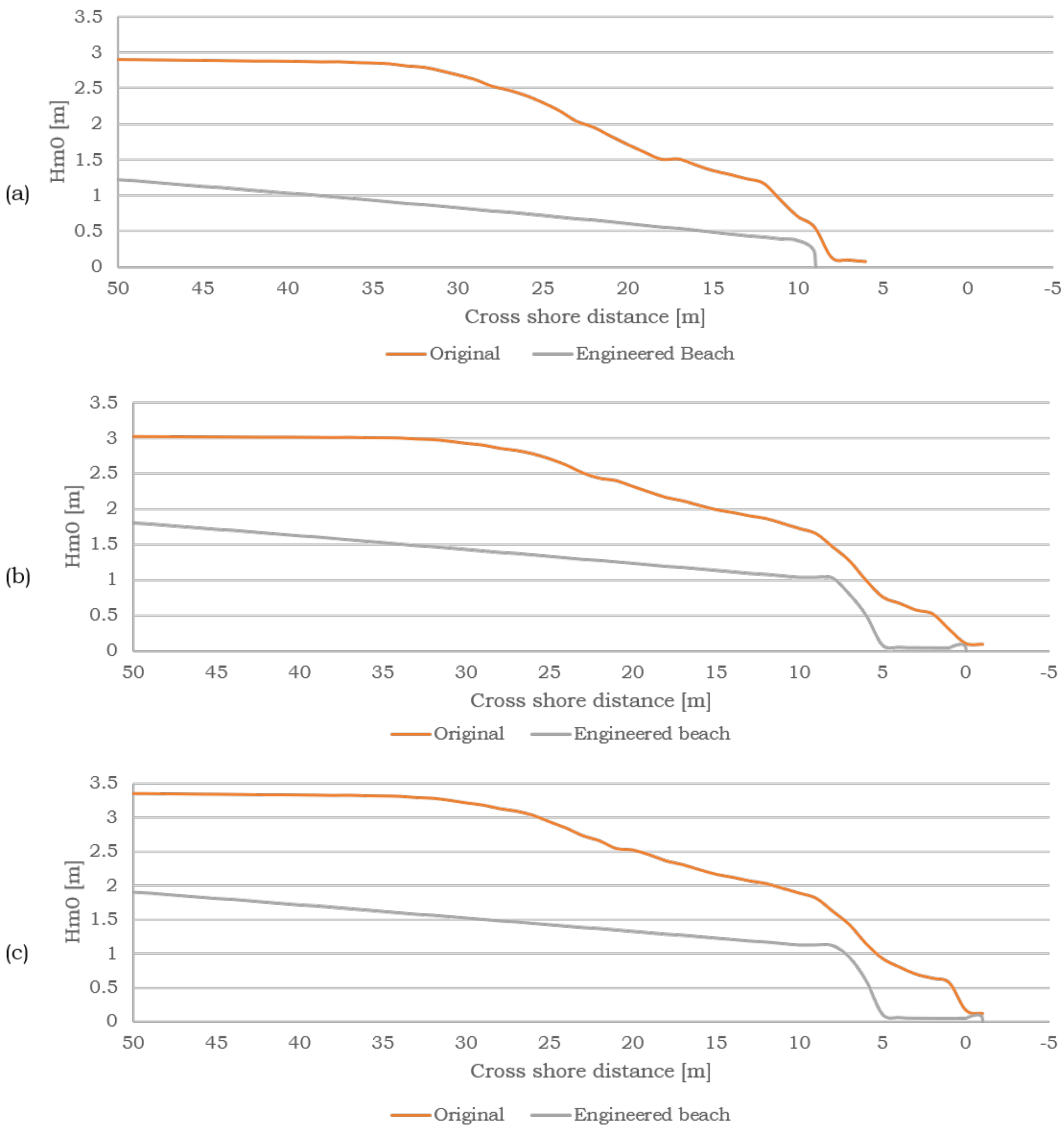


Figure 8.3: Comparison between onshore transformation of waves for the original bathymetry and the bathymetry modified by the Engineered beach. (a) Scenario 1 (b) Scenario 2 (c) Scenario 3. Source: authors.

Table 8.1: Run-up calculations for the original bathymetry, using the wave height and slope at x=30 m

Scenario	Water level [m]	Hm0 [m]	Tp [s]	L0 [m]	Slope [-]	Run-up [m]
1	2.4	2.69	7.20	80.97	0.25	2.33
2	3.4	2.93	7.20	80.97	0.25	2.26
3	3.5	3.21	7.20	80.97	0.25	2.19

Table 8.2: Run-up calculations for the engineered beach, using the wave height and slope at x=30 m

Number Scenario	Water level [m]	Hm0 [m]	Tp [s]	L0 [s]	Slope [-]	Run-up [m]	Reduction with respect to original scenario [%]
1	2.4	0.83	7.20	80.97	0.03	0.84	64%
2	3.4	1.43	7.20	80.97	0.03	0.70	69%
3	3.5	1.52	7.20	80.97	0.03	0.68	69%

As it can be observed from the calculations, the run-up is considerably reduced by the new beach profile, mainly due to its wave attenuation effect.

Floating Wetlands. Floating Islands have proven to be successful for wave energy attenuation, protecting bank and shoreline from wave erosion. According to AquaBio [60] the reduction in deep water is around 80 % and in shallow water between 58-90%, depending on the width and thickness of the island. These results refer to a controlled experiment at Alden Laboratories, with waves between 18-25 cm [60].

This technology aims to imitate the natural floating wetlands, and it consists of three basic elements: a base, an anchor and plant material. An example can be seen in Figure 8.4.

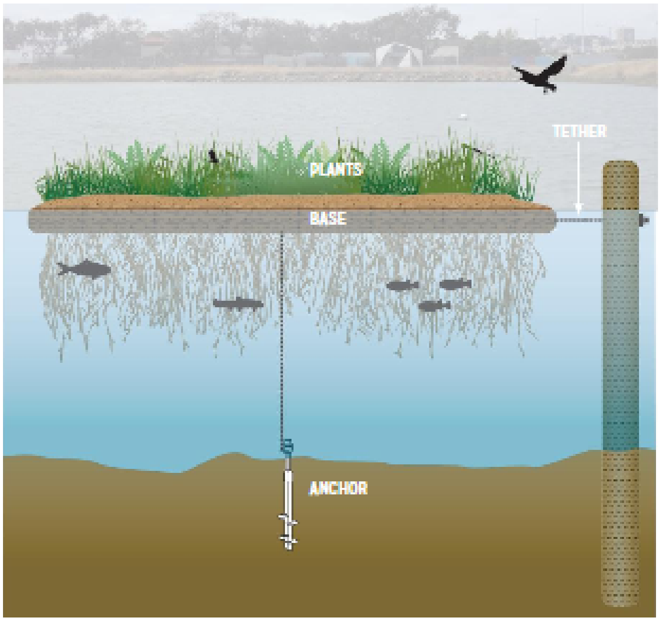


Figure 8.4: Floating Wetlands components [38].

The base must be non-toxic for the environment, resistant to salty conditions and be buoyant. The latter is achieved usually by the use of plastic tubes or polystyrene foam [63]. The materials used in the base should provide a pH between 5.0 and 6.5 [63]. The most common approach to construct it, is to build a frame that supports a mesh in which plants can grow, using peat or coconut fiber as a growth media.

The type of anchor depends on the wave activity at the location of the Floating Wetland. It can be attached to the sea bed or to a fix device such as a pole. Is important to notice that the floating capacity around a fix point allows this technology to adapt to sea level rise.

Finally, the plant material should be preferably native species, resistant to salty conditions and occasional flooding. Therefore, salt marshes are strongly recommended for this. Moreover, to avoid tilting, in the selection of the vegetation also the maximum height growth has be considered. The latter, as a rule of thumb, must be shorter than the island width [63].

8.2. Environmental Feasibility

This concept is expected to have a big impact on the environment as it alters the available habitat considerably. The following consequences should be taken into account when constructing a:

Beach nourishment

- As an initial consequence the beach nourishment results in loss of animal lives in several ways. The current surface of the beach is covered by decimeters of sand, which leads to the death of all (benthic) species living at or near the surface [23].
- A change in type of sand may change the type of habitat and therefore the suitability for present species.
- Benthic species that are lost during the construction of the beach nourishment may have served as prey for migrating birds and fish. These birds and fish require thus new locations to find food.
- There is little known about the time it takes for the ecosystem to recover from the beach nourishment. However, the recovery time is likely to be in the range of decades.
- The beach nourishment can induce (temporarily) increased turbidity in nearshore waters, smothering certain species that rely on clear water such as clams and kelps. The method of dumping the sediment has an influence in the degree of turbidity, which should be taken into account during the development of the construction plan.

Floating wetlands

- The roots of the plants in the wetlands add oxygen and nutrients to the water, providing food and thereby increasing the habitat quality [17].
- It is recommended to choose native species that fare well under local conditions. Is important to select vegetation that can develop in salty conditions, like salt marshes, and that can stand to be submerged under certain amount of time.
- The water behind a large system of floating wetlands is at risk of becoming a deadzone as there may be little water exchange with the adjacent waterbodies [63]. Some open sections or float paths are required.
- The floating wetlands should be constructed at such a depth that the floating plants don't connect with the benthic species. If the roots of the plants get attached to the bottom, the wetlands may become submerged during high tide.

Ecosystem services

- Supporting services: floating island provide a new habitat for several species. Wave attenuation caused by the floating wetlands could as well create boundary conditions for a different habitat. The increased tidal zone obtained from the milder slope of the beach nourishment offers a wider habitat for the benthic species. These additional services compensate for the initial loss of habitat caused by the nourishment.
- Provisioning services: floating wetlands offer food and shelter to several species of birds. On the other side, the initial killing of the benthic population on the intertidal zone affects birds and other animals that feeds on it. [17].
- Regulating services: water quality is increased thanks to the floating islands. Furthermore, they keep water temperatures cooler and, breaking the waves, protect the shoreline from erosion [17].
- Cultural services: an increased beach creates additional service for recreation. Moreover, the floating islands make a further contribution to the landscape quality.

8.3. Economical Feasibility

In the table below, a Class D cost estimate is provided for the engineered beach. The main factor contributing to the cost are the considerable volume of sand needed. Uncertainties connected to the cost of the floating wetlands, such as installation and maintenance costs, need to be further investigated in the next design phases.

Table 8.3: Cost estimate of engineered beach and floating wetlands.

Engineered beach and floating wetlands	Units	Quantity	Cost per unit (CAD)	TOTAL (CAD)
Supply and placement of sand	m3	2,135,200	50	106,760,000
Supply and placement of supply angular rock	m3	18,840	200	3,768,000
Supply and placement of engineered stack rock wall	m2	4,710	400	1,884,000
Supply and placement of floating wetlands	m2	6,840	400	2,736,000
General conditions* (5%)	-	-	LS	5,757,400
Contingency (50%)	-	-	LS	60,452,700
			TOTAL	**181,358,100**

* Site preparation (mobilization and demobilization), surveying, insurance, bonding, quality check and quality assurance.

8.4. Legislative Feasibility

According to Figure 4.1 the construction of the beach nourishment takes place under federal, provincial and UBC jurisdictions. The different applicable permits and acts to take into account are mentioned below.

Federal

- The Fisheries Act from DFO has as main purpose to protect the quality of water bodies containing fish[35]. Regulations of the Fisheries Act one prohibits construction which harms the fish habitat and water quality. This implies that the sediment used for the beach nourishment has to be free of contaminants and the presence of fish species should be considered.
- The Species at Risk Act focuses itself on endangered or threatened species, which are present at the cliff. During the construction of the beach these species should not be harmed.
- The Navigable Waters Protection Act protects the federal right of availability of navigable waters. The beach nourishment introduces a lot of new sediment in the system. In order to protect the navigation channels in the region, a study must be conducted of the sediment transport routes of the sediment.
- Canadian Environmental Protection Act aims at the prevention of the undesirable environmental effects in general that follow the construction of a beach nourishment.
- The Migratory Birds Convection Act impedes the available construction time during as it prevents the hampering of migratory birds.

Provincial

- Land Act (BC) regulates the conveyance of crown lands to community. In order to construct a beach nourishment as UBC at crown lands all requirements of the Land Act should be met.

- Landuse, Building and Community (UEL) regulates the use of lands and the permits on UEL grounds.
- Official Community Plan 2005 (UEL) has as one of the main objectives the sustainability of the environmental quality at UEL grounds, which is the objective possibly at stake during construction of the beach nourishment.

Local

- The Landuse plan of 2015 of UBC should be consulted. It provides criteria and policies which should be met by each project at the campus of UBC. One of the main goals in the plan is the protection of the environment and to respond to climate change.

The many different acts that are applicable and the many jurisdictions that are involved show the complexity that is correlated with granting of permits for the realization of this concept. The concept also contains relatively new technologies, which may lead to a delay in granting permits.

8.5. Social Feasibility

The construction of a beach nourishment increases the beach area available for recreation, providing a benefit for the beach and cliffs visitors. However, it is expected that the construction of a beach nourishment might result in critique from several stakeholders due to the environmental impact, especially because of the uncertainties in the recovery time. Moreover, one must take in mind that the visual landscape is affected considerably.

8.6. Summary

In this Chapter, the first building with nature concept is presented. It consists in one part of an engineered beach and in the other part of floating islands. The first one provides an input of sediments and attenuation of waves. The floating islands is expected to reduce the erosion rate while attenuating waves before reaching the engineered beach. However, this proposed combination of measures can have uncertainties in its effectiveness (due to lack of examples around the world) and in the environmental impact. Moreover, both parts of the concepts need maintenance, which might increase the project cost. The latter is already high due to the assumption of applying it in the whole project's area. Thus, more studies are necessaries to understand: the interactions between the engineered beach and the floating islands, the efficacy of the concept as a whole and the recovery time of the environment.

9 Concept Clam Gardens and Submerged Breakwater

This concept focuses on mitigating the marine erosion by the construction of a clam garden in the intertidal zone. Clam gardens are a form of shellfish management. They are traditionally used by First Nations and Native Americans to ensure a reliable food sources [6]. To create a clam garden, a boulder wall is constructed around the low water mark, creating a terrace behind it that represents the perfect environment for clams. Therefore, the clam productivity of the so maintained clam garden is increased [6]. The clam garden traps the sediment that is transported onshore. The presence of clam gardens and the boulder wall reduces the slope angle of the beach, which diminishes the wave run up and thereby also the wave attack on the cliff toe. In order to further reduce wave action and facilitate the sediment import towards the beach, the clam gardens are completed by a submerged breakwater further offshore. A cross-section can be observed in figure 9.1

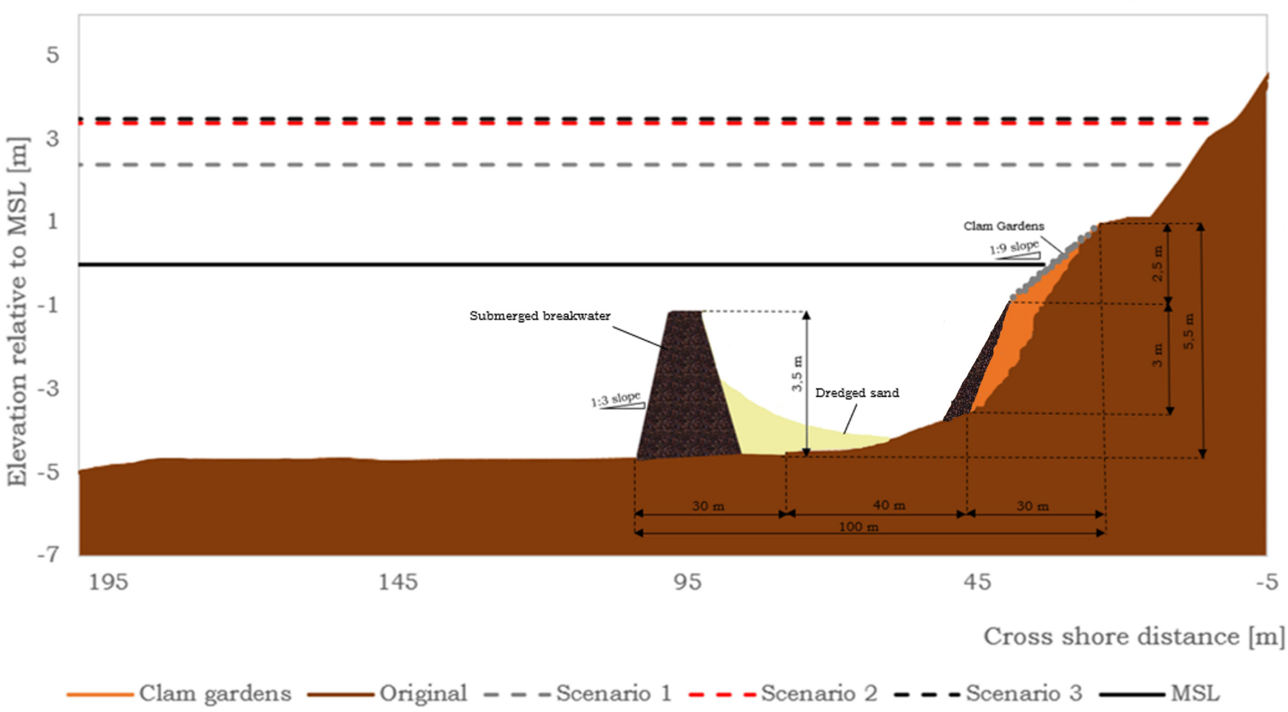


Figure 9.1: A cross-section of Concept 2, including clam gardens and a submerged breakwater. Source: authors.

9.1. Technical Feasibility

Initially, the breakwater is built offshore. Then, to create a clam garden, a rubble mound is built around the low low water (large tide) mark. Sediment is supplied behind the rubble mound, then clams are introduced in the intertidal zone.

SWAN simulations are conducted to assess the change in the onshore wave transformation. They show a slight reduction of waves if compared with the base scenario, but they don't prove to be really effective for the long-term scenario, as it can be observed in figure 9.2. The figures shows the significant wave height H_{m0} onshore transformation both for the original bathymetry and for the one modified by clam gardens. It can be observed that:

- The presence of the submerged breakwater anticipates the shoaling of the waves.
- The change in the intertidal zone steepness caused by the terrace that hosts the clam garden is also reducing the waves.
- The reduction of the waves is limited until around the high water mark, since the measure doesn't affect the beach but only the foreshore.
- Bottom roughness is not modeled by SWAN; this limitation of the model should play in favour of safety since bottom roughness is increased by clam gardens, but has still to be noted.

Since the effectiveness of the clam gardens is higher for less extreme scenarios, it is recommended to check for scenarios that are more comparable to serviceability limit state, in order to assess the effectiveness in everyday conditions. Other technical aspects that need to be further investigated are constructability and initial sediment losses of the nourishment. It is important to observe that the breakwater has to be constructed first, in order both to reduce wave action and facilitate the nourishment, and to avoid interference with the clam garden ecology.

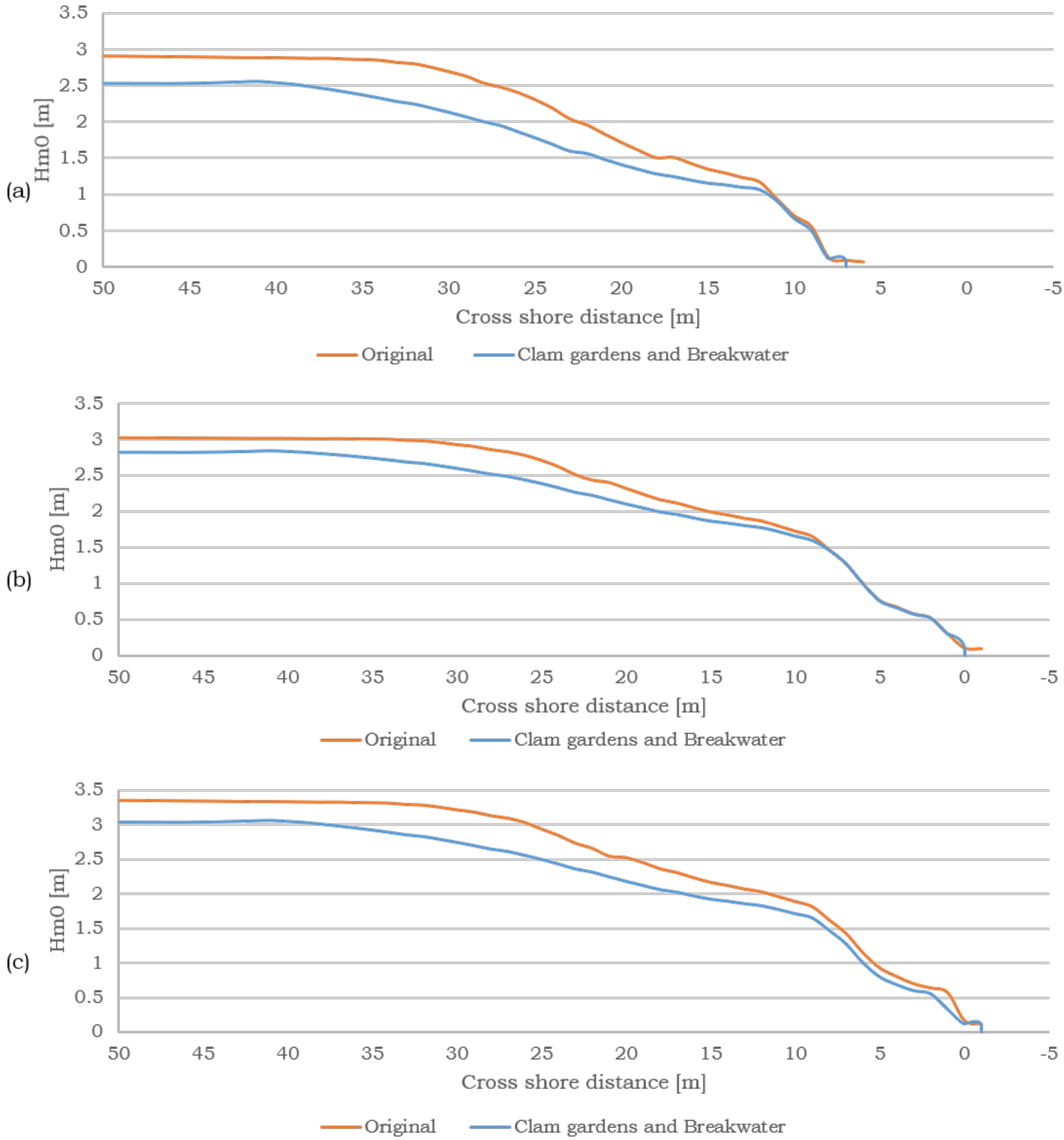


Figure 9.2: Comparison between onshore transformation of waves for the original bathymetry and the bathymetry modified by the clam gardens. (a) Scenario 1 (b) Scenario 2 (c) Scenario 3. Source: authors.

9.2. Environmental Feasibility

To assess environmental feasibility of clam gardens, the aspects that need to be taken into account are:

- Livable conditions of clams;
- Contamination issues;
- Impact on existent ecosystem.
- Provided ecosystem services.
- Climate change resilience.

Livable conditions of clams. Some common clam species in the area are listed in table 9.1. The design can incorporate a mix of these species, in order to enhance biodiversity and therefore create more ecological opportunities.

Table 9.1: Common clams species in BC and their characteristics [1].

Common name	Scientific name	Zone	Required sediment
Manila Clam	*Venerupis philippinarum*	Upper intertidal zone	Mixed mud, sand and gravel
Littleneck Clam	*Protothaca staminea*	Mid to lower intertidal zone	Mixed mud, sand and gravel
Butter Clam	*Saxidomus gigantea*	Lower third of the intertidal zone, occasionally even deeper	Porous mixture of sand, broken shells, and gravel

In addition, it has to be considered that temperature, salinity and PH of the water affect considerably the clams developing opportunities.

Contamination issues. Clams, being filter feeders, absorb contaminants in water and help to improve water quality. However, if the presence of contaminants in the water is too high, this might results in clams not being suitable for human consumption. Unfortunately, the whole area near to Point Grey peninsula is subject to a harvesting prohibition for shellfish due to contamination or paralytic shellfish poison [1]. This issue has to be addressed for the clam gardens to provide human provision as an ecosystem service.

Impact on existing ecosystem. Where clam gardens are built, the whole intertidal zone is affected. It is important to note that, despite being called 'clam gardens', these structures host many other species. A habitat that can be compared to a rocky reef it's formed by the the boulder wall, offering shelter to octopus, sea cucumbers, whelks, chiton, red turban snails and other animals [6]. This provides an enrichment to existing ecosystem. Regarding the breakwater, environmental issues similar to the cobble berm presented in Chapter 7 are present. Adopting some measures (i.e. special materials), new ecological opportunities can be created and they can compensate for the lost of ecosystem.

Ecosystem services. Clam gardens provide the following services to the ecosystem:

- Supporting services: a new habitat for clams and other marine animals is the most prominent supporting service provided. Furthermore, the construction of a clam garden helps in wave dissipation, creating a quieter environment where other species can possibly flourish.
- Provisioning services: clams could provide food, attracting other species and increasing the ecosystem diversity. Food for humans might as well be supplied, if the contamination issue is solved.
- Regulating services: acting as filters, clams increase water quality of the site.

- Cultural services: clam gardens contribute to add cultural value to the area and, due to their importance for the First Nations, to deepen and explicit the connection between the territory and its cultural roots. On the other side, clam gardens could hamper the recreational use of the beach.

Climate change resilience. Climate change is affecting the clam population due to the change in the oceanic water conditions. Raise in the temperatures alters clams reproduction cycles and their overall health, while an increased water acidity affects the calcium-based shell [7]. Furthermore, changes in hydrodynamic conditions threaten clams habitats: exacerbation of peak events might enhance erosion and sea level rise could modify the location of the intertidal zone. Sea level rise could also impact the effectiveness of the submerged breakwater.

9.3. Economical Feasibility

In the table below, a Class D cost estimate for the clam gardens is provided. Maintenance and permitting costs are not included; furthermore, cost of the clams has some uncertainties.

Table 9.2: Cost estimate of clam gardens.

Clam garden	Units	Quantity	Cost per unit (CAD)	TOTAL (CAD)
Supply and placement of sand	m3	214	50	10,675
Supply and placement of angular rock	m3	15,700	200	3,140,000
Supply and placement clams	m2	50,240	20	1,004,800
Supply and placement of armour layers	m3	52,752	200	10,550,400
Supply and placement of filter layers	m3	79,128	100	7,912,800
General conditions* (5%)	LS	-	-	1,130,934
Contingency (50%)	LS	-	-	11,874,804
			TOTAL	**35,624,413**

* Site preparation (mobilization and demobilization), surveying, insurance, bonding, quality check and quality assurance.

9.4. Legislative Feasibility

For this concept, the breakwater in built offshore and the clam gardens in the intertidal zone. According to figure 4.1, the construction of this concepts falls within federal and provincial jurisdiction. The following acts are therefore applicable.
Federal

- Fisheries Act from DFO. Since its main objective is to protect the water quality in order to prevent harm to fish habitat, care in the construction of this concept should be taken to respect its constrains. This implies that the submerged breakwater should not hamper the fish habitat; furthermore, the sediment supplied for the clam gardens should be free of contaminants and turbidity of the water should be kept under control.

- Species at risk Act: according to this act, care should be taken into prevention of harm for the species at risk present in the habitat. This is particularly true during construction.

- Navigable Waters Protection Act protects the availability of navigable waters. Submerged breakwater should then be built out of the shipping routes and navigability of the area should be protected.

- Canadian Environmental Protection Act ensures the avoidance of negative environmental effects. This should then be respected.

Provincial

- Land Act (BC) establish the transfer of lands between the crown and the community. It should then be consulted in the building of the clam gardens.
- Wildlife act constraints should be respected in order to protect the wildlife present on site.
- Riparian rights and Public Foreshore use in the Administration of Aquatic Crown Land indications should be met in order to allocate water and water access to the landowners.
- UEL Land Use regulates the use of land on UEL grounds.
- UEL Official Community Plan 2005 should be consulted and its objective of environmental quality met.

9.5. Social Feasibility

Clam gardens represent a significant value for the First Nations community, being part of their cultural heritage. According to the Haida legend, the first men were found by the Raven in a clamshell [6]. Construction of more clam gardens therefore contributes to increase the cultural value of the area, and to strengthen the relationship between UBC and First Nations. Other social impacts that have to be considered include the recreational use of the beach and the landscape aesthetics. Since the clam gardens are built in the intertidal zone, the boulder wall is visible only during low low tide, having a small impact on the overall aesthetics. Submerged breakwaters affect the local currents pattern; swimmers' safety must be ensured.

9.6. Summary

In this Chapter, the second building with nature concept is presented. It consists of a submerged breakwater and clam gardens. The main contribution brought by this measure is the cultural value of the clam gardens for First Nations. Furthermore, using clam gardens for wave reduction is an innovative solution that could open the way to new possibilities. However, effectiveness is lower than in the other proposed solutions and uncertainties are high. The huge area that would be subjected to the intervention makes also costs difficult to sustain. The best approach to this concept could be to set pilot studies in order to create a new research branch, and evaluate further the feasibility once new and more targeted data become available.

10

Concept Subaerial

This chapter describes the subaerial conceptual design. The design aims to stabilize the cliff and to reduce soil runoff and seepage erosion. It consist of three measures, which are: revegetating the cliff face, installing an underground stormwater detention facility and installing inter-aquifer drainage wells. Per measure the idea is explained and the feasibility from a technical, environmental, legalislative, economical and social point of view is addressed.

10.1. Vegetation

The first measure is revegetating the bare parts of the cliff face. The goal of planting vegetation on the cliff face is to protect the soil from surface erosion by improving the water retention capacity of the cliff and by stabilizing the ground [43]. The stabilization is caused by the root system, the increase in effective shear strength and the increase in drainage capacity of the ground [50]. It is advised to plant a combination of grasses, herbs, shrubs and trees to create a diverse ecosystem on the cliffs. Besides, the vegetation types have a different effect on the slope, see Table 10.1. Additionally, the fast growing grasses and herbs ensure an immediate reduction of cliff erosion while the shrubs and trees provide a long term stabilization of the cliff. Therefore, combining them is thought to be most efficacious.

Table 10.1: Type of vegetation with their main function to reduce cliff erosion [50].

Type of vegetation	Main function	Consideration
Grasses	Reduces surface erosion	Fast growing
Herbs	Reduces surface erosion	Fast growing
Shrubs	Soil reinforcement	Fast growing
Trees	Soil reinforcement	Slow growing

Technical feasibility

Revegetation has been used for erosion control for centuries [50] and was successfully done at UBC in the late 1980's. It was visually determined that the vegetation had grown significantly and a LiDAR review of the period 2010-2015 signifies that minimal erosion occurred in the proximity of the bio-planted slopes [15]. Revegetation is therefore thought to be efficient for this area. Nevertheless, it cannot be determined to which extent, as cliff stability depends on various factors and vegetation changes over time and thus their influence on slope stability varies over time [50].

In order to choose suitable vegetation the following things are important to consider [50]:

- The ability of the plant to grow on the cliff surface (soil, light requirement, water requirement)
- The efficiency of the root system in strengthening the soil
- Growth rate and reproduce ability (stem, roots, leafs)
- The life span of the plant
- Planting difficulties

It is advised to choose native species or dominant species that are already present on the cliffs as these are known to be able to live and grow under the cliff conditions [50]. An overview of the dominant tree species at the cliffs are given in Table A.4 in Appendix A. Further investigation is needed by field specialist to decide if these species should be chosen or other appropriate species. To ensure successful revegetation, the plantation techniques should be chosen based on the inclination of the cliff slope [50]. Previously, wattle fences were used to support the planting of the UBC cliffs. This has proven successful for all cliff sections except the steeper parts of the cliff [15]. For steep slopes and parts of the cliff where land loss has occurred, vegetated geogrids can be used. This method provides immediate soil reinforcement and creates opportunities for rapid growth [50]. The methods are shown in Figure 10.1.

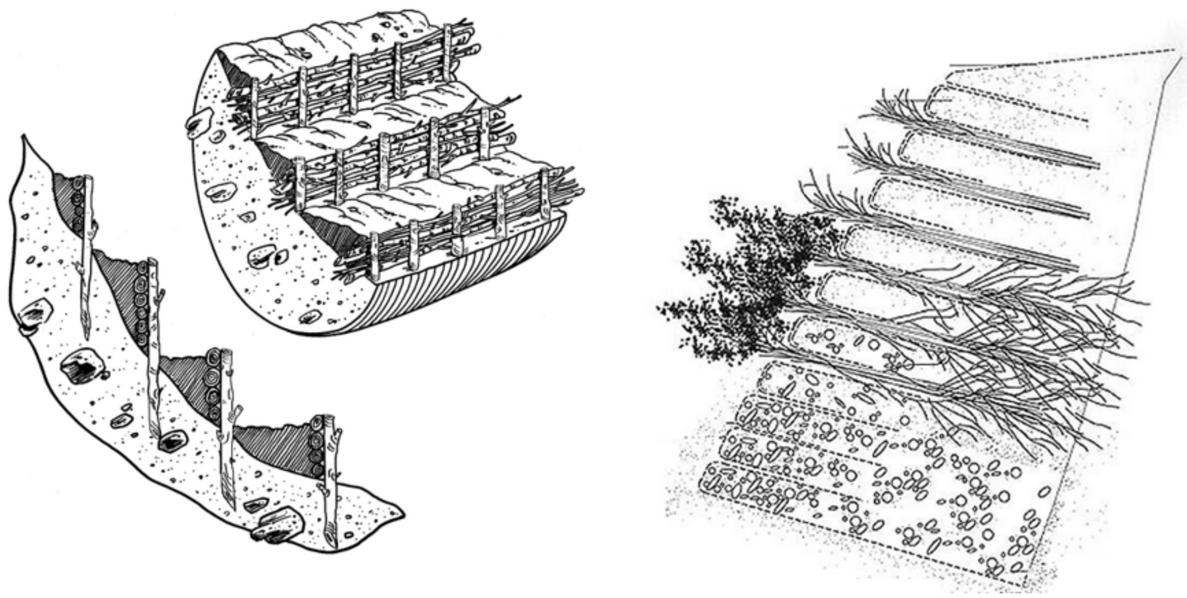


Figure 10.1: Cliff revegetation techniques. Left: Wattle fences for moderate steep slopes [55]. Right: Vegetated geogrid for steep slopes [50]

It must be noted that the cliffs supply sediment to the beach via erosion. This supply is expected to decrease significantly if the cliff face is completely vegetated. However, this sediment loss can be compensated by a marine sediment supply, as described in the marine concepts of chapters 8 and 9. Besides, the sediment input from the cliffs is thought to be significantly less than the marine sediment loss.

The cliff areas are divided by Koppes in 2016 into terrain stability classes, shown in Appendix C. As no revegation has taken place since, these cliff areas are still considered correct. Revegetation is mostly needed in the areas with larger stability problems. As new unstable areas might have arisen since 2016, an additional condition review of the cliff site is recommended.

Environmental feasibility

New habitat in the form of high and low vegetation is created by planting the cliff face. This habitat will become part of the high productivity habitat situated along the cliffs (Section 2.3) and will thus support the critical wildlife functions on the cliffs. The newly created habitat influences the ecosystem services, as described in Section 2.3, in the following manner:

- It enlarges the **supporting services** as new habitat is created. This gives the opportunity to attract animals and to expand existing populations on the cliffs.
- It expands the **provision services** as vegetation is used by many animals as food. For example, the seeds of dominant tree species such as Douglas Fir are eaten by many animals that live on the cliffs, like birds and squirrels [53].
- More **regulating services** are provided as the cliffs are used as breeding area for various birds (Table A.2).
- Vegetation has cultural value for the First Nations and the general community, as explained in Section 2.3 and revegetation thus adds to the **cultural services**.

Economical feasibility

In Table 10.2 a cost estimate for planting the cliff face is given. This estimated is based on revegetating the parts of the cliffs with large stability problems, terrain stability class IV in Figure C.2. Besides, it is based on planting 50 % of the cliff with wattle fences and 50% with vegetated geogrids.

Table 10.2: Cost estimate of revegetation. Source: authors.

Revegetation	Units	Quantity	Cost per unit (CAD)	TOTAL (CAD)
Supply and placement of geotextile	m2	8,635	8	69,080
Wattle fences *	m2	8,635	150	1,295,250
Supply and install of planting **	m2	17,270	40	690,800
General conditions*** (5%)	LS	-	-	99,303
Contingency (50%)	LS	-	-	1,042,676
			TOTAL (CAD)	**3,197,109**

* Existing of flexible branches, wooden or steel pegs
** Including dormant branches and live stake
*** Site preparation (mobilization and demobilization), surveying, insurance, bonding, quality check and quality assurance.

Legislative feasibility

As revegetation interests the upland of the cliff, the measure must meet UBC's legislation (Figure 4.1). Therefore, the concept must be in agreement with the Tree Management Plan of UBC's Land Use Plan. No provincial or regional legislation is present about revegetation. However, the Wildlife Act might have to be considered as this act manages wildlife population and habitat.

Social feasibility

Revegetation can contribute to the development of a healthy ecosystem and enhances reforestation, two things which stakeholders as UBC and UEL would probably be paying interest in [52] [44]. Besides, vegetated cliffs add aesthetic value to the surrounding. Additionally, vegetating the cliffs will result in a safer environment down the cliffs as the risk of mass movement on the cliffs will be reduced significantly [50].

10.2. Stormwater Detention Facilities

The second measure of this concept is the installation of a stormwater detention facility. The aim of this detention facility is to prevent major stormwater runoffs over the cliffs surface, to avert soil saturation and to purify the stormwater to protect the water quality of the receiving water bodies.

Detention facilities can be installed above ground in the form of ponds or swales or placed underground. As the ground at UBC is costly, limited and above ground structures require a lot of surface area, an underground vault is installed. The stormwater is temporarily stored in the vaults and is released at a much lower rate to reduce the erosive force of the water. Besides, suspended solids and floating pollutants as oil are removed from the stormwater in the vault.

Technical feasibility

The vault consist of an inlet pipe, a detention chamber with baffles, an outlet pipe and a manhole, see Figure 10.2. The needed storage volume of the chamber is predicted to be 2,600 m^3 by UBC's 100 year-storm model [54]. However, since this model was created new water management measures have been taken and it is therefore advised to create a new 100 year-storm model to determine the dimensions of the pipes and the chamber. To have sedimentation of suspended solids in the vault, it is recommended that the chamber has a length-to-width ratio of at least 1:4 and preferable of 1:6 [24].

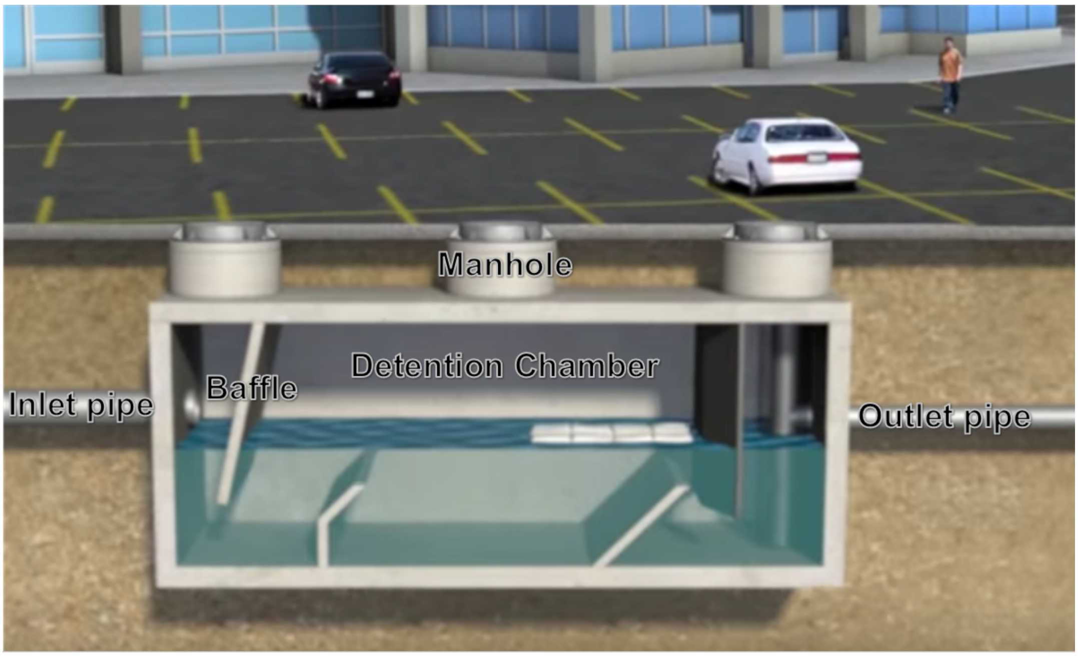


Figure 10.2: Underground storm vault with inlet pipe, outlet pipe, manhole and detention chamber. Adjusted by authors from [57].

The detention facility is installed underneath a parking area as this can easily be made into a construction site and parking areas are, next to roads, a big source for stormwater pollution [56]. In Figure 10.4 the parking lots in the project area are given. Additionally, it is important that the vault is installed in an area where floodings are expected in a 100 year-storm event, to minimize the runoff before the water enters the vault. Areas where significant surface flooding is predicted are shown in Figure 10.3 [54]. When comparing Figure 10.4 with Figure 10.3 parking lots are found in Area 2. This area is therefore thought to be the most efficient area for installing the detention vault. Additionally, it is advised to install pipes in the high risk flooding areas which lead the water to the inlet pipe of the detention vault.

Figure 10.3: Project location with areas of greatest flood risk, the no till area, the spiral drain and drainage wells and the surface flow direction. Information from [54].

Figure 10.4: Project area with parking lots, parking garages and squares.

The treated water can be released into a water body but can also be reused for, for example, flushing the toilet. Depending on the desired purpose, the location of the outlet pipes can be determined. If no reuse is wanted, it is advised to located them at the bottom of the slope so over slope water movement is prevented.

From a climate change perspective, the detention facility make the campus more resilient against the prospected climate change impact of more severe rain events [68].

Lastly, it must be noted that when building underground structures knowledge about the subsurface is of great importance to prevent settlements or uplifting of the construction. Besides, the impacts of the underground construction on the surroundings must be investigated. Therefore a subsurface geology study is needed before building the underground detention facility.

Environmental feasibility

The stormwater detention facility influences the following ecosystem services:

- **Regulating services** as the stormwater is cleaned from sediments, oil and trash via sedimentation and baffles in the vault (Figure 10.5). Floating oil and trash are stuck behind the baffle and fine sediments settle over the length of the chamber. This increases the stormwater quality and protects the water quality downstream.
- **Supporting services** as the stress on marine life is reduced by reducing the flow velocity by which the stormwater flows into the sea [40]. This is done via the controlled water outflow of the vaults.
- **Provisioning services** as less food sources of salmon are sweeped away or migrated away as a result of the lower inflow velocities [40].

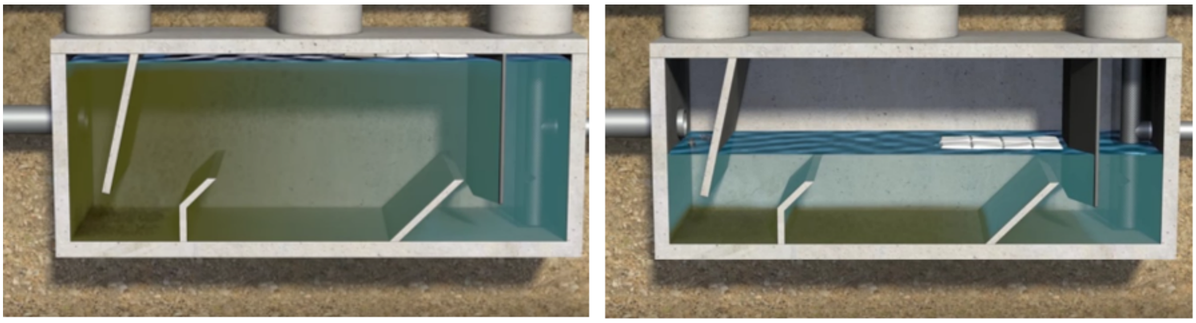


Figure 10.5: Underground storm vault. Left: Directly after a storm event. Right: 6 hours after a storm event [57].

Economical feasibility

Underground detention systems are more costly to install than surface systems [13]. However, as UBC land is valuable and the land on top of the facility can still be used with an underground system, underground detention is preferred. The maintenance of the vault includes regularly monitoring and cleaning to prevent clogging of the system. Besides, regularly cleaning is needed to prevent water quality deterioration. Significant cost goes to this practice in terms of labour hours and waste disposal taxes[28][49]. In Table 10.3 a global cost estimate of the detention facility is given. This estimate is based on a detention facility with a storage volume of 2,600 m^3. This volume is predicted by the UBC stormwater management plan as needed storage volume in the future for the project area [54].

Table 10.3: Cost estimate of stormwater detention facility. Source: authors.

Inter-aquifer drainage wells	**Units**	**Quantity**	**Cost per unit (CAD)**	**TOTAL (CAD)**
Supply and placement of detention facility	m3	2,600	1,000	2,600,000
General conditions* (5%)	LS	-	-	130,000
Contingency (50%)	LS	-	-	1,365,000
			TOTAL (CAD)	**4,095,000**

* Site preparation (mobilization and demobilization), surveying, insurance, bonding, quality check and quality assurance.

Legislative feasibility

Stormwater management in the project area is handled via British Columbia's guidelines as no legislation on municipality level exist [54]. The legal documents that are relevant for this measure are given below:

- The Fisheries Act from DFO as this act regulates the discharge to a water body containing fish [35].
- The Water Sustainability Act of British Columbia sets water quality guidelines for the release in water bodies to protect aquatic life [19]

Additionally, the detention facility is planned to be installed underneath UBC land and must therefore comply with UBC's Land Use Plan. Besides, it must be in line with UBC's guidelines of the Integrated Stormwater Management Plan.

Social feasibility

"Ensuring that developments minimize the stormwater that leaves the site and manage the outflow rates to lower levels in order to minimize the erosive forces of the discharge" [54] is part of UBC's aims to achieve their Integrated Stormwater Management Plan. The detention facility fits in closely with this aim. Besides, the facility prevents the adjacent lands from overland flooding and thus reduce the nuisance that this causes such as traffic hinder due to flooded roads and water damage of buildings. This measure is thus beneficial for all users of the adjacent lands.

10.3. Inter-aquifer Drainage Wells

The last measure of this concept is the installation of inter-aquifer drainage wells. The installation zone is between the upper and the lower aquifer with the aim to reduce seepage erosion out of the upper aquifer, see Figure 10.6. A drainage well is a perforated tube that is filled with fine filter gravel. The drains have a larger permeability than the aquitard between the two aquifers (Figure 3.1) and increases therefore the drainage over the aquitard into the second aquifer.

As periods of high intensity rainfall are predicted in the future, increased infiltration in the upper aquifer is likely to happen [68]. The purple area in Figure 10.3 is thought to especially experience a larger infiltration as no till is present there [15]. The goal of the inter-aquifer drainage wells is to prevent that the larger infiltration in the upper layer results in higher seepage erosion. Therefore, it is recommended to install the wells in the purple, more vulnerable areas.

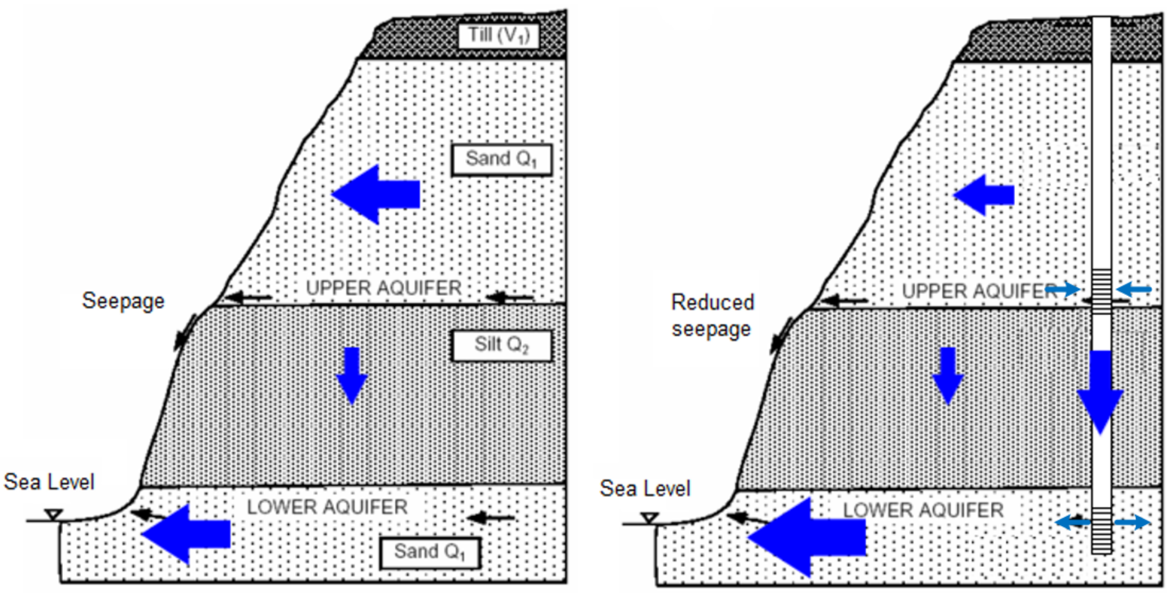


Figure 10.6: Inter-aquifer drainage well principle, adjusted from [15].

Technical feasibility

Two inter-aquifer drainage wells have already been installed on the project site. From these wells it is known that they were successful in transporting water from the upper aquifer to the lower aquifer and in enhancing the cliff stability on a local scale [10].

An AECOM research on UBC stormwater management states that inter-aquifer drainage wells are not able to handle the severe stormwater flows as the flow rate into the aquifer via a drain is much lower than the rate of stormwater accumulation during a peak storm event [11]. To gain insight to what extend the drains can infiltrate stormwater, it is therefore advised to create an infiltration model to stimulate the infiltration during a peak storm event. In this way, the amount of stormwater that is accumulating on the surface can be investigated and the amount of drains that are needed can be determined. With this knowledge, it can be investigated if other measures, such as on site stormwater storage, are needed during storm events.

If wells are installed it is recommended to install them in the purple areas in Figure 10.3 as the largest infiltration is expected in these areas. To determine the best exact location for the wells it is recommended to perform a subsurface geology study in the project area.

Via the drainage wells, the quantity of groundwater in the lower aquifer increases. This can result in a higher upward force on the aquitard if the soil in the lower aquifer gets saturated, which can lead to destabilization of the soil. Additionally, the change in groundwater on the project site can result in changes in groundwater outside the project area. These effects have to be investigated.

The effect of the drainage wells on surrounding water levels has to be monitored frequently. This can be done via monitoring wells, which are already installed in the project area at UBC. The pipe has to be maintained from clogging, which mostly occurs on the surface. In this case, the clogging can easily be removed by replacing the first layer of gravel.

Environmental feasibility

The installation of the drainage wells influences the **regulating services** of the ecosystem as the quality and the quantity of the groundwater change. If the infiltration rate is too large, the water seeping into the lower aquifer via the drain can still contain oxygen which leads to oxidation of dissolved metals in the lower aquifer. This causes deterioration of the groundwater quality and a requirement for more frequent maintenance of the wells[54]. The composition of the soil around the drainage wells must be analysed to determine if elements (for example iron) that are present in the soil could aggravate this issue.

Additionally, the soil filters the water naturally but the filter capacity of the drains can be different than the filter capacity of the surrounding soil. If this filter capacity is less, the water that infiltrates via the drain can pollute the lower aquifer. Little pollution might be solved with installing a filter cloth inside the well but if runoff water quality is largely polluted, the drainage wells should not be used. This has to be determined with a runoff water quality analysis and an infiltration model.

Economical feasibility

After installation, the wells need to be monitored and maintained at least yearly [10].Therefore, they might not be cost effective on large scale but for stabilization of the cliffs in high risk areas the benefits might exceed the cost. The estimated cost for installing 2 drains are given in Table 10.4. The estimate is based on a the cost of the previously installed drains at UBC [27].

Table 10.4: Cost estimate of inter-aquifer drainage wells. Adjusted from [27].

Inter-aquifer drainage wells	Units	Quantity	Cost per unit (CAD)	TOTAL (CAD)
Supply and placement drains	unit	2	50,000	100,000
General conditions* (5%)	LS	-	-	5,000
Contingency (50%)	LS	-	-	52,500
			TOTAL (CAD)	**157,500**

* Site preparation (mobilization and demobilization), surveying, insurance, bonding, quality check and quality assurance.

Legislative feasibility

The legal documents that are relevant for this measure are:

- The Fisheries Act from DFO as this act regulates the discharge to a water body containing fish [35].
- The Water Sustainability Act of British Columbia which includes the Groundwater Protection Act that ensures that well and groundwater related actions are performed in an environmentally safe way [21].

Additionally, UBC's Land Use Plan and Integrated Stormwater Management Plan must be taken into account.

Social feasibility

The drainage well decrease the seepage erosion and the risk of mass movement and thus increase the safety of the people walking below or on the cliffs. Besides, it must be noted that there is a change that the increase of the groundwater can lead to more frequent water nuisance in cellars.

10.4. Summary

This chapter described the subaerial concept, which consist of revegetating the cliffs, installing an underground detention vault under a parking lot and installing inter-aquifer drainage wells. The goal of the concept is to stabilize the cliffs, to reduce runoff erosion and to reduce seepage erosion.

The feasibility analysis shows that all measures can be effective in reaching the goal. The vegetation and inter-aquifer drainage wells have already been successful in the past at UBC. From the analysis, however, it is found that the inter-aquifer drainage wells can bring various risk with them and that they are presumably only effective on local scale and not during large storm water events. It is therefore thought to be a mitigating measure and most effective in short term. To have a more long term solution, integrating stormwater detention facilities in the built-up environment to reduce the infiltration can be an option. Locations where detention facilities can be installed are on roofs, squares and parking lots, shown in Figure 10.4.

11

Gap Analysis and Recommendations

As it can be seen in the previous chapter there is a gap of knowledge and data, which must be fulfilled in order to develop further the concepts presented in this report. In general the gaps identified are:

- **Bathymetry:** higher bathymetry resolution is needed for a detailed design. This project is based on a low resolution bathymetry from Navigation Charts.
- **Sediment studies**: sediment paths (where is the sediment moving), sediment budget and sediment characteristic, as sieve analysis, are not well known.
- **Current patterns:** currents studies in the area ae not available. Thus, they are not included in the analysis.
- **Morphodynamic model:** this model is needed to understand with more detail the system and to evaluate the long term impact of the different concepts.
- **Wave climate and water level predictions:** in this report stationary conditions are assumed. The only future prediction considered is sea level rise. Thus, an study predicting wave climate and water level future changes is relevant for detailed designs.
- **Construction alternatives:** the accessibility to the area is difficult. Thus, the construction approach must be studied thoroughly in order to find a viable solution. Some options can be the use of floating equipment or building a road for land base construction.
- **Vegetation data:** a classification of vegetation present at project location is been carried out by UBC. Unfortunately, this project's timeline is not compatible with the results; therefore vegetation data is only obtained via field exploration.
- **Current and predicted precipitation:** the precipitation data of the study area is unknown for this research. Therefore, high level assumptions are made.
- **Infiltration data:** infiltration data is not available for the project. Therefore, old researchis investigated (UBC's stormwater management plan) and infiltration areas are globally determined.
- **Water quality of stormwater and water bodies:** detailed water quality data is not available for this research. Therefore, only global descriptions are taken into account.
- **Stakeholders:** stakeholder meetings are planned after the hand in date of this research. Therefore, the stakeholder interest are still unknown and only a description of the stakeholders is added in this report.

Additionally,the following studies and models are recommended to tackle uncertainties specifically related with each concept:

Do Nothing

- Detailed evaluation of economical value of UBC assets is necessary to estimate the economical losses that will follow the *business as usual* approach.
- An accurate risk assessment should be conducted to identify the main safety hazard caused by active erosion.
- Long term environmental impact of the habitat loss has to be studied.
- Setback lines suggested by provincial guidance should be taken into account.
- Uncertainties related with sea level rise and climate change should be further investigated.

Engineered beach and floating wetlands

- Sieve analysis, contamination studies and specific quantity of required sand are needed while searching for potential providers (i.e. Port of Vancouver).
- Floating wetlands must be designed in detailed and tested in order to assess their real impact in wave attenuation.
- Vegetation research and testing for this specific marine conditions must be carried on to select the species for the floating wetlands.
- A morphodynamic model could help to understand how the engineered beach reshapes over time. Moreover, a long term plan, including maintenance, can be elaborated on the basis of the model's results.
- Environmental assessment of the influence of the nourishment and the habitat recovery time should be conducted.

Clam gardens and submerged break water

- Contamination studies regarding influence of polluted water in clam gardens are necessary to investigate the future possibility of human consumption.
- Hydrodynamics changes due to clam gardens should be studied. Wave attenuation and changes in current patterns have to be investigated.
- Studies about the influence of clam gardens in sediment characteristics and patterns should be conducted.
- The breakwater is only introduced as a concept for wave attenuation. Thus, more detailed dimensions must be calculated to better assess its effectiveness and investigate its impacts.

Subaerial concept

- Biogeography study to investigate which species are suitable for revegetating the cliffs and which species are present.
- Site specific study to investigate the conditions of the cliffs, to determine in which places the revegetation is needed and to determine the amount of sediments that will be loss after revegetation.
- Storm water model to take new stormwater management measures into account that were taken after the last UBC stormwater model.
- Water quality research into the stormwater and the water bodies and the polluting sources. Additionally, research into the treatment efficiency of the stormwater detention vault.

- Infiltration model to model the amount of stormwater that is infiltrating and that is accumulating on the surface.
- Subsurface geology study to investigate the physical properties and locations of the soil layers, the stability of the cliff slopes, the composition of the soil and to gain knowledge on the groundwater aquifers and the groundwater flows.

12 Discussion

This report fits in the broader context that includes a related project commissioned by UBC. The objective of this report is to present a clear and holistic framework for the erosion problem at Point Grey cliffs, both gathering and integrating existing information and contributing with innovative ideas that might open new paths. Therefore, several different disciplines are covered and a mixed quantitative and qualitative approach is adopted. After analyzing the existing system, four concepts that help in tackling erosion are presented at a conceptual design level, as an example of what can be done. The concepts are elaborated using a toolkit of possible interventions for protection measures from cliff erosion found worldwide. Key feasibility issues for each of them are highlighted, with the goal of covering all the aspects of a holistic design: technical, environmental, economical, legislative and social. Due to the different expertise needed, some aspects of the feasibility are only faced with a high level perspective and more specialized studies are recommended. Furthermore, the time line of this project is not always matching with the one of other parallel and complementary projects on the same topic: consequently, new insight can be given once other studies are completed. Specifically, the following general aspects need to be considered:

- Environmental feasibility is only assessed qualitatively as there is no recent data available on the ecology. Full ecological studies do not fit within this project time frame. However, it is important to understand how the erosion is affecting the different types of habitat and how the solutions to tackle it could also affect the environment. With the help of experts in biology and ecology, new ecological opportunities could be integrated in the solutions to create new habitat.
- Economical feasibility is drafted following the class D Canadian standard and assuming that each measure covers the whole coastal stretch of approximately 3 km. These assumptions could change in the next design phases, consequently affecting the cost. Moreover, class D analysis is only a rough estimate that can turn drastically once that design becomes more defined.
- Legislation and permitting issues are mentioned but not fully investigated due to the complexity of the jurisdiction and the innovative nature of the presented solutions. Possible complications in the permitting process might arise due to the innovative nature of some of the concepts. Further investigation should be conducted by relevant experts once that the design stage reaches a satisfying level of detail.
- Due to the sensitivity of the topic, contact with stakeholders is constrained to the UBC project team, and stakeholder meetings are planned after the completion of this report. Therefore, the stakeholders could only be identified and not engaged. As a consequence, the social feasibility has to be refined including the specific stakeholders perspective after the official stakeholder assessment. Also the design should be refined once that the stakholders' view is made more clear, in order to have a truly integrated and holistic final product.

Due to this mixed nature of the approach, both quantitative and qualitative and present knowledge gaps, it is decided to stop at the investigation of the key feasibility issues and not to proceed with an evaluation of the concepts. A multicriteria analysis would require more quantitative information and specific weighting that are not available at this moment. The multi-criteria analysis should be carried out after some gaps as the stakeholders analysis are filled in (See Chapter 11).

As a qualitative comparison and discussion of the individual concepts, the following remarks can be made:

- The cliff erosion in this report is tackled through two perspectives: marine (three concepts) and subaerial (one concept with three measures). A summary of every concept, including the approach of do nothing, can be seen in Table 12.1.
- From the three marine concepts, the revetment is a more traditional approach that fixes the coastline and attenuates waves. However, it does not solve the sediment deficit. The other two concepts have more uncertainties due to their innovative nature but they supply additional sediment to the system. The engineered beach and floating islands concept is the most effective measure for reducing waves. The clam gardens add an important cultural value but with a lot of uncertainties regarding their effectiveness.
- Evolution in time of the designs needs to be studied and forecast. This is particularly true for the nature based concepts, for which the effectiveness is highly dependent on development after building.
- Environmental impact of the proposed concepts must be evaluated and mitigated. When mitigation is not possible in a satisfactory manner, compensatory measures should be taken. Sometimes it is even possible to achieve a positive environmental impact, by creating new ecological opportunities. The clam gardens concept and the revegetation of the cliffs are the designs that seems to be more promising from this point of view. Also the use of floating wetlands helps to compensate for the initial loss of ecosystem caused by the engineered beach construction. Meanwhile, the negative effects associated with the traditional berm might require more effort to be mitigated.
- From an economical point of view, the berm results to be the most expensive solution, due to the use of costly material and the need for specialized equipment and labor. It has however to be noticed that only a rough estimate of the cost is presented. Moreover, maintenance is excluded from the evaluations while this can lead to non negligible cost. Furthermore, the constructability issue has to be taken into account: due to the nature of the project site, the construction process has to be planned in detail and could lead to extra cost, such as the necessity of tailored equipment or new infrastructure that allows to the equipment to reach the site. The steepness of the cliffs also represents a challenge.
- All the concepts, both the ones tackling the marine erosion and the one dealing with the subaerial erosion, are presented separately. It has although to be noted that, in order to provide a complete solution, measures at the cliff toe and the cliff face have to be combined. Furthermore, all the measures are designed for a specific transect and for the whole coastal stretch: a combination of different design for different cliff transects might be more effective as all the transects differ considerably in slope and profile. Therefore, this has to be further investigated.
- Several uncertainties are connected with the preliminary design. First of all, all the concepts are analyzed only in the cross-shore dimension: any effect on the long-shore transport is not investigated. This would be particularly important for the downdrift effects on Spanish Banks and Jericho Beach. Furthermore, in the clam gardens concept, the relationship between the length of the breakwaters and the gaps between them must be studied. Submerged breakwaters are responsible for complicated current patterns and they might lead to more erosion if not properly designed. The differences in

elevation profiles on the cliff face might also affect the suitability of species for revegetation, and the installation of detention facilities and interaquifer drains might affect water levels in adjacency areas.

As the project progressed, the differences between Canadian and Dutch engineering culture became clear. As a result, the shape of the more innovative marine concepts has changed during the design process to meet the desires of the local client. The effectiveness of the initial concepts relied more on the capability of nature to transport and withhold sediment, which made the two innovative solutions more uncertain than they are now. Also the timescale of effectiveness was not acceptable for Canadian standards. Instead of a more building with nature approach, the approach became more similar to bio-engineering, where the nature in the concept is built by humans in stead of letting nature do the work of the development.

It is recommendable to look at the problem from a broad perspective, thus involving the whole Vancouver coast, to ensure a long term solution. For example, when solving the erosion problem only at one location, erosion at other parts can aggravate. To realize an integrated solution, implementing a coastal management plan for the whole stretch of the Vancouver coast is advised. However, it must be noted that realizing this can be a difficult and time consuming process from a legislative perspective, as the local political framework does not facilitate this.

Additionally, it must be noted that even though this report focuses in solving marine and subaerial erosion, also the human causes of cliff erosion should be tackled. They are discussed in the report but no concepts are designed to counteract them. It is, however, of great importance to inform visitors and residents about the consequences of, for example, deforestation and climbing the cliffs. Furthermore, it is advised to generate a communication environment for understanding the consequences that different actions and projects, such as cutting a tree or building a groyne, can have in cliff erosion. With this approach, it is expected to create social awareness about how crucial it is to reduce erosion as much as possible and to take measures to counteract it.

Table 12.1: Concepts summary. Source: authors.

Concept	Technical	Environmental	Economical	Legislative	Social
Do Nothing	- Non intervention - Erosion will continue as business as usual	- Habitat will disappear as the cliff erodes - Probably new habitats will be formed	- Lost of campus land - Lost of infrastructure: buildings, roads and sewer	- Without intervention no permission is needed	- Community affected by the lost of land and cultural heritage
Rip-rap and rock revetment	- Effective protection of the toe - Does not solve the problem of sediment budget	- Reduction of the available habitat - It is recommendable carrying the most nuisance activities during winter reduce the loss of species	-Minimum maintenance - Total estimated cost is around 210 MM CAD	- Needs to meet the jurisdictional demands of UBC, BC and Canada's government	- Change of the aesthetic landscape - Beach may be not suitable for pedestrians
Engineered beach and floating wetlands	- It copes with problems of marine erosion and sediment budget - Lack of studies to ensure level of effectiveness	- Alteration of the habitat due to coverage of (new type) sand and increase of turbidity - Floating islands give a new habitat but can generate a dead zone behind -Resilient solution that can be adaptable to SLR	-Maintenance of floating wetlands and beach must be considered - Total estimated cost is around 180 MM CAD	-Federal, provincial and local jurisdictional demands must be fulfilled	- Change of the aesthetic landscape - Increase of available recreational beach
Clam gardens and submerged breakwater	-Does not solve the problem of sediment budget - Lack of studies to ensure level of effectiveness	- Alteration of habitat from beach to clam garden - Low water quality can impact in clamps contamination (not suitable for human consumption) - Increase of habitat for clams and other species -Resilient solution that can be adaptable to SLR	-Maintenance of clam gardens must be considered - Total estimated cost is around 35 MM CAD	-Provincial and local jurisdictional demands must be fulfilled	- Change of the aesthetic landscape -First Nations cultural heritage
Subaerial	- Cliff stability is aim through revegetation. Efficiency is not certain - High speed flow over the cliff is avoid through an underground stormwater detention facility -Inter-aquifer drainage wells reduce thus seepage erosion. Best location is difficult to be determined	- Revegetation provides new habitats expanding the existing wildlife population - The stormwater detention removes contaminants improving water quality - The drainage wells can influence the quality and quantity of ground water (i.e oxidation of dissolved metals)	-Maintenance vegetation must be considered - Total estimated cost is around 7.5 MM CAD	- The three approaches are in UBC land thus must be approved mainly by UBC - Storm water detention facility and drainage wells plans must follow BC guidelines	-Revegetation adds aesthetic value - Storm water facility reduces nuisances due to flooding - Revegetation and drainage wells increase safety for cliff's visitors

13 Conclusion

The Point Grey cliffs are eroding as a result of coastal erosion and subaerial erosion processes. Besides, this erosion is accelerated by human activities. Previous studies mainly focused on solving the marine erosion at the toe of the cliff, not combining marine and subaerial erosion measures. However, due to the significant contribution of the subaerial erosion processes to the cliff erosion, they cannot be ignored. Hence, this report proposes concepts to tackle both marine and subaerial erosion.

First of all a Do Nothing scenario is analysed to investigate the consequences when no interventions are made. It is concluded that the erosion will be a hazard to human and UBC equity within the coming decade. This can lead to severe environmental and economical damage. Besides, it will lead to a loss of cultural heritage that cannot be replaced. It is therefore required to develop protection concepts. To get to these concepts, an overview of possible interventions to tackle the cliff erosion is presented in a toolbox, covering both potential marine and subaerial solutions.

Marine erosion should be tackled as the erosion at the toe is the driving force for the cliff erosion at the Point Grey cliffs. For a complete solution the sediment deficit should be solved, as fixing the coastline with a hard structure will only move the erosion problem more downstream. By introducing two innovative ideas that also tackle the sediment deficit, an alternative has been proposed to the traditional hard structure. The subaerial erosion should not be underestimated, as cliff destabilization can lead to dangerous situations and with the perspective of more heavy precipitation, the cliffs are prone to erode at higher rates. This will have large financial consequences and which can lead to high risk for human life. Therefore, it is advised to implement subaerial measures that stabilize the cliffs, prevent major stormwater runoff over the cliff face and reduce seepage erosion. Hence, it is thought that both marine and subaerial erosion should be tackled to solve the cliff erosion. It is therefore recommended to combine marine measurements with subaerial measurements in a final solution. As the cliff profile is not homogeneous along the peninsula, a combination of different marine concepts at various locations can be proposed. The various cliff profiles can benefit from different solutions, according to their specificity. Additionally, to diminish human causes of cliff erosion, it is advised to set up an educational program to involve stakeholders and inform local communities. However, additional research is needed to fill the knowledge gaps and further elaborate the concepts to be able to evaluate the different concepts. With the help of the overview of the problem, the potential solutions and the gap analysis that this report provides, further steps can be taken by the UBC project team to develop a satisfying strategy to address cliff erosion.

A

Marine, Wildlife and Tree Species

This appendix gives an overview of the marine, wildlife and tree species that can be found in the project area. Table A.1 gives an overview of the marine species that are present at the Point Grey cliffs. The type of species is given, the risk level of extinction and if they are present in a certain time of the year. The level of extinction is indicated with blue (no risk, yellow (medium risk) and red (high risk).

Table A.1: Overview of the present marine species at the Point Grey cliffs. The risk level of extinction for these species is indicated with either Blue (no risk), Yellow (medium risk) or Red (high risk)[25] [18].

Locally sighted			
Name	Type	Risk level	Presence
Great Blue Heron	Bird	Blue	Not specified
Coho Salmon	Fish	Yellow	Not specified
Green Sturgeon	Fish	Red	Not specified
White Sturgeon	Fish	Red	Not specified
Sandhill Crane	Bird	Yellow	Breeding in summer
Caspian Tern	Bird	Blue	Not specified
Double-Crested Cormorant	Bird	Blue	Not specified
Alcides	Bird	Blue	Not Specified
Purple Martin	Bird	Blue	Breeding Summer

In Table A.2 an overview of the wildlife species present at the Point Grey cliffs is given.

Table A.2: Overview of the present wildlife species at the Point Grey cliffs. The risk level of extinction for these species is indicated with either Blue (no risk), Yellow (medium risk) or Red (high risk)[25] [18].

Locally sited			
Name	Type	Risk level	Presence
Chordeiles minor	Bird	Yellow	Nesting occurs on the ground on a bare site in an open are
Falco Peregrinus anatum	Bird	Red	Nest on rock cliffs above lakes or river valleys where abundant prey is nearby.
Phalacrocorax auratus	Bird	Blue	Nest on coastal cliffs (high sloping areas with good visibility)
Cypseloides niger	Bird	Blue	Breeding in summer

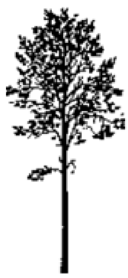
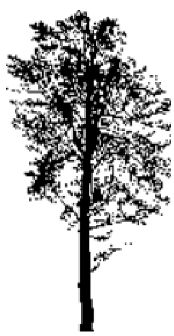
In Table A.3 an overview of the marine species is given for which the project area provides relevant biological resource.

Table A.3: This table provides an overview of the marine species for which the area under consideration provides relevant biological resources. The risk level of extinction for these species is indicated with either Blue (no risk), Yellow (medium risk) or Red (high risk)[18].

Relevant biological resource		
Name	Type	Risklevel
Black Oyster Catcher	Bird	Yellow
Blue Heron	Bird	Blue
Cormorants	Bird	Blue
Dabbling Ducks	Bird	Blue
Diving Ducks	Bird	Blue
Shorebirds	Bird	Blue
Double-Crested Cormorant	Bird	Blue
Purple Martin	Bird	Blue

In Table A.4 the dominant tree species that can be found on Point Grey cliffs are given with their appearances and their main features.

Table A.4: Dominant trees species on Point Grey Cliffs [53].

Dominant tree species	Appearance	Features
Red Alder		Life span: 40-60 years Uses: Commercial, Aboriginal, Coastal groups Roots: Extensive, fibrous root systems
Douglas Fir		Life span: Oldest known is 1400 years old Uses: Commercial, Aboriginal, Animal Roots: Combination of strong taproot, secondary supporting taproots, lateral roots and fine roots
Bigleaf Maple		Life span: Individuals may reach 300 years of age Uses: Commercial, Aboriginal Root: Shallow and wide spreading

B

Long Term Wave Analysis

This analysis was based on the criteria of Extreme Value Analysis, where the lower threshold of a storm was defined to be a wave of 1.4 m. With the latter, 11.2 storms are expected to occur every year (close to the aim of 10 storms per year for a breakwater design[42]).
Moreover, the data was filtered to take into account the most relevant wave climate. Thus, the waves were considered while having a period between 0 and 7 seconds, and a wave direction between 50° and 200°with respect to the North. Finally a exponential curve with a coefficient of determination of 99.29% was fitted for the long term wave distribution. The latter can be seen in figure B.1.

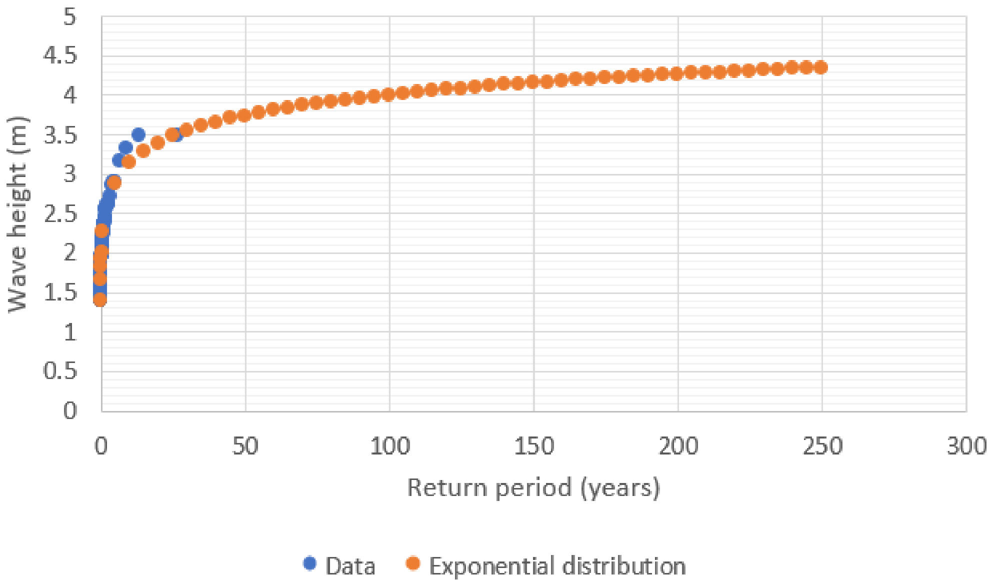


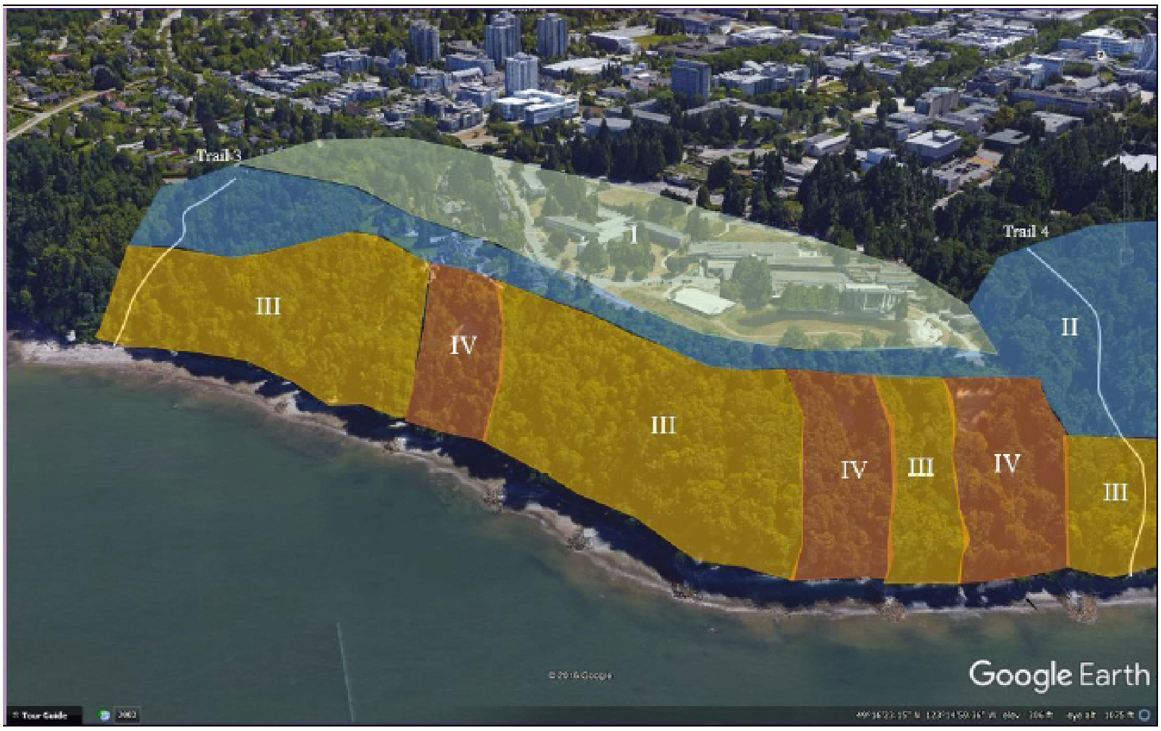
Figure B.1: Wave height long term distribution.

C

Terrain Stability Map

This appendix shows the terrain stability map at the project location from the Koppen Research. In this map the cliff is divided in 5 terrain stability classes, showing the likelihood of slope failure at that location. Figure C.1 shows the location where Figure C.2 is located and the view point from which Figure C.2 is seen.

Figure C.1: Terrain stability map location and view point from Figure C.2 shown with the yellow arrow [43].



Terrain Stability Class	Interpretation
I	No significant stability problems exist.
II	Low likelihood of slope failure.
III	Minor stability problems with moderate likelihood of slope failure.
IV	Larger stability problems with a moderate likelihood of slope failure.
V	High likelihood of slope failure.

Figure C.2: Terrain stability map at the project location, taken from Koppes research on the stability of UBC Point Grey Cliffs and the effects of vegetation on slope stability [43].

D

Revetment Design

In order to calculate the required stone size both the Hudson formula(D.1) as the Van Der Meer formula(D.2) are consulted. The Hudson formula is more popular in North America and the Van Der Meer formula is more popular in The Netherlands. Both formulas are highly depending on empirical relations and have little physical meaning[42]. Because of the dependence on experiments, the circumstances of the design should be comparable with the experiment's for a formula to be applicable. As it considers a steep, permeable revetment both formulas can be applied[42]. Table D.1 shows the results for both the Van Der Meer as the Hudson formula with the used parameters. A slope of 1:3 is used, and a wave height of 2 m is derived from Figure 7.3 in Chapter 7. The wave period used to calculate ζ follows from Table 2.3.

$$\frac{H_{\mathrm{sc}}}{\Delta d} = \sqrt[3]{cot(\alpha)K_{\mathrm{D}}} \tag{D.1}$$

$$\frac{H_{\mathrm{sc}}}{\Delta d_{\mathrm{n,50}}} = 6.2P^{0.18}\frac{S}{\sqrt{N}}^{0.2}\zeta^{-0.5} \tag{D.2}$$

The Hudson formula gives the smallest required stonesize of d=0.61 m, but the result from the Van Der Meer formula does not differ much. They likely both result in the same required stone class.

The wave run-up and the required freeboard to prevent overtopping are determined with with Hunt's formula D.3 and formula D.4[42]. This determines the required height of the revetment and the height of the engineered stacked rock wall.

$$\frac{R_{\mathrm{u}}}{H} = \zeta \tag{D.3}$$

$$Freeboard = R_{\mathrm{u}}\zeta H_{\mathrm{sc}} \tag{D.4}$$

Table D.1: Results of the required stone size for the Van Der Meer formula and the Hudson formula. Source: authors.

Parameters	Van Der Meer	Parameters	Hudson
Hsc [m]	2	Hsc [m]	2
ζ	1.413815	cot(α)	2.888057
δ	1.6	δ	1.6
P	0.1	Kd	3
S	5		
N	7000		
$d_{n,50}$ [m]	0.637427	d [m]	0.608603
R [m]	2.8		
Freeboard [m]	8.0		

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