The exploration of solution strategies for the mitigation of coastal erosion by applying the BwN design process

A case study at Long Bay, Jamaica

Master thesis

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A case study at Long Bay, Jamaica

By

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Abstract

Coastline regression is a significant threat to many coastal zones. Being able to mitigate the erosion while simultaneously improving nature development is something that is increasingly strived for in coastal projects. This report utilizes the building with nature philosophy to explore integrated solutions for a coastal erosion problem in Negril, Jamaica. Erosion of the coast is threatening the many hotels and resorts along the beach near Negril. The hotel owners and the local community are looking for a sustainable solution to the erosion problem.

The building with nature approach starts with the system in mind, not the intervention. First the cause of coastal erosion is better understood. A combination of factors is responsible of which the intensification of storm events and degradation of the environment are two of the main causes. A reduction of the sediment production rates could also have led to increased coastal erosion. Due to the lack of data in this phase of the project, the exact reason cannot be identified. Therefore, both scenarios are considered. From there, different solution strategies are explored and alternatives are identified. The strategies range from environmental solutions to soft, hard and hybrid solutions. These designs are simulated to understand their effectiveness by relative comparison. Alternatives that do not work as intended are excluded.

The evaluation of the remaining alternatives shows what the strengths and weaknesses are of the different solution strategies. A social evaluation method is also applied to assess the applicability of this type of evaluation method and gain a broader perspective on the alternatives. If restoration of the natural sediment production leads to large production rates and a large improvement in overall environmental quality, then this solution strategy could be very positive. Nourishment strategies work well from a social and technical point of view but less ecologically. The nourishment strategies can be improved by adding environmental improvements to the alternatives. A hybrid solution has the potential to provide a positive effect on the technical, ecological as well as social aspects of Long Bay. However, this depends on the applicability of Reef Balls in breakwater designs and the effectiveness of coral transplantation.

The BwN approach ensures that a wide range of solutions is considered. The results give more insight in the cause of the coastal erosion and possible solution strategies for Negril. Using the knowledge gained in this thesis, more detailed alternatives can be obtained in the future.

Preface

This thesis reports on my graduation work for the master program Hydraulic Engineering at Delft University of Technology. I have been fascinated by coastal engineering for as long as I can remember and is the reason why I decided to a bachelor in Civil Engineering. My other interest is nature and during my study I became interested in understanding how to find natural solutions for coastal engineering problems. During my Master program I learned about Building With Nature. Their philosophy speaks to me and was glad to hear that my personal interest is nowadays seen as important in engineering projects.

For my thesis I looked for a study case in which I could apply the Building with Nature design process. A conversation with Stefan Aarninkhof pointed me towards Arjen Luijendijk who introduced me to a case study in Jamaica. I found the project interesting since the focus was on finding sustainable solutions. I enjoyed working on the project and learned a lot about the Building with Nature approach and the research process in general. I hope that my contributions help to find a feasible solution strategy for Long Bay, Jamaica.

I would like to express my gratitude for the members of my committee at the TU Delft. First of all, I would like to thank Arjen Luijendijk for giving me the opportunity to work on this project as well his for his supervision and constructive feedback. I would like to thank professor Stefan Aarninkhof, head of my graduation committee, for his contributions during meetings and useful feedback. Thanks to Jeroen van den Bos for his advice on the design process and sharing his experience. I want to thank Alexander van Oudenhoven for sharing his knowledge about ecosystem services and involvement in the project. Finally, I want to thank everyone who supported me this last year.

Jorrit Horst

Delft, June 2017

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source: https://iamajamaican.net/travel/2016/01/view-jamaica/

Chapter 1

Introduction

This chapter first gives an overview of the project site and its development over the years. The next section explains the main problem that the area faces. The chapter is concluded by proposing the research question for this thesis.

1.1 Project location

Jamaica is home to a varied landscape from a central mountain chain to limestone hills, low-lying coastal plains and interior valleys. This study focuses on the most western tip of the island. This is the area within the red box in figure 1.1.

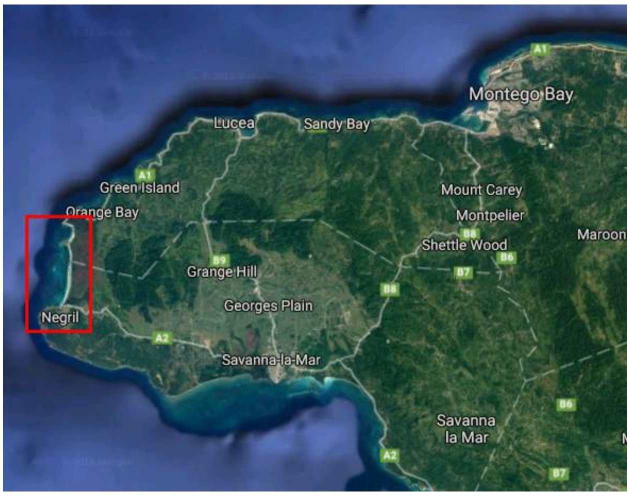


Figure 1.1: The project location on the island of Jamaica

The western tip of the island is a low-lying area. Near the small city of Negril lie two bays, Long Bay and Bloody Bay. These two bays hold the most beautiful white sandy beaches of Jamaica. Off the coast of Long Bay lies a large coral reef. To the east of the coast lies a large wetland. Figure 1.2 gives an impression of the area.

Figure 1.2: Beach of Long Bay Negril (left), Coral reef off the coast of Long Bay, Negril (right)

The area of Long Bay was very underdeveloped until the late 60s. Negril was just a remote fishing village. The white sandy beaches and large coral reef in a remote location makes Long Bay very attractive for tourists. However, the area was difficult to reach due to the lack of proper infrastructure so only few tourist came to this part of the island. Figure 1.3 shows Long Bay in the early 1950s on the left. During the late 60s the tourism development started and the first resorts and hotels were built near the beach. This development was assisted by the improvement of the road between Montego Bay and Negril. Figure 1.3 on the right shows the road which was constructed. Because of the roads, it became easier to travel along the bays. This led to an increasing tourism industry. As can be seen in the figure, the road was placed close to the coastline. This way, hotels near the beach became very accessible.

In 1976 the airport, the Negril Aerodrome, was constructed providing a link between Negrils resorts and Montego Bay. This led to a large growth of the tourism industry, which caused rapid construction of resorts through the years. The tourism industry became the main economic activity in the area. The beaches along with the flora and fauna in the area attract many tourists. Most of the medium to large scale hotels and resorts are built along the beach of Long Bay. Bloody Bay

Figure 1.3: Long Bay before the road was built, early 1950s (left), The road from Negril to Montego Bay along the coastline of Long Bay (right)

has a similar white sandy beach but is a bit more secluded. It offers smaller-scale boutique hotels and cottages. At Long Bay most resorts are constructed between the road and the beach. The primary reason for this is that tourists value a resort which is directly on the beach. The other reason is that a large wetland lies on the eastern side of the road. Construction is more challenging here so most resorts are built on the sandy ridge between the wetlands and the waterline. Figure 1.4 clearly shows the wetlands and the resorts built between them and the coastline.

Figure 1.4: Resorts built on the sandy ridge between the wetlands and the coastline

Due to weak policies and enforcement a lot of unlicensed construction occurred. Hotels are built far too close to the coastline as can also be seen in figure 1.4. The construction of buildings like these along with sea walls causes a stronger wave reflection, thereby increasing erosion in front of the structure. Also, the government allows the construction of four story resorts even though the height of hotels and resorts was restricted to two stories. The rapid development and lack of regulation also attracted illegal beach activities like drug use, visitor harassment and motorbike and horse riding. Currently, Negril is still a popular tourist destination. The white beaches and reef, for snorkeling and diving attract a lot of visitors to this part of the island. More than 20 percent of Jamaicas total visitors come to Negril. The many hotels and resorts provide many jobs for the local community. The airport is now also used for para sailing. Although the tourism industry keeps growing, Negril remains a small city. It is a city of about 7000 inhabitants with a population density of 193.6 persons/km2. It is home to one health center and one police station. There are no public or private hospitals in Negril. [CL Environmental, 2014]

1.2 Problem description

Negrils pristine beach, Long Bay, is in trouble. Erosion of the coast is threatening the many hotels and resorts along the beach. The coastline is very dynamic. The coastline changes are an issue for the expanding tourism industry. Large scale erosion-accretion cycles are present in the bay. This causes a large fluctuation in beach width. Apart from this, structural erosion is observed at Long Bay. Because the resorts are built close to the beach, erosion is an imminent threat. Figure 1.5 shows the beach width before, and after a large storm. Sand bags are used in an effort to prevent further erosion of sediment at one of the resorts. The coastline has regressed so much that the other building is already partly in the water. This shows just how vulnerable the resorts are to beach erosion. The region thrives on tourism. It is therefore very important to mitigate the erosion problem. The reason for the erosion seems to be a combination of different factors. Increased frequency of hurricanes, degrading coral reefs, construction of sea walls have been mentioned as possible contributors to the problem.

Figure 1.5: Preferred beach width (Left), Beach erosion after a storm (Right)

Apart from the changing coastline, the environment is also changing. It is under pressure from different sources. Overfishing, pollution and the expansion of the tourism industry are part of the cause. Since the development of the region, the coral reef has degraded significantly according to the local community. The increasing development also puts pressure on the wetlands. Because of the importance of the region, the government of Jamaica implemented the "Enhancing the resilience of the agriculture sector and coastal areas to protect livelihoods and improve food security" project. This project consists of three components covering the areas of coastal erosion, water and land management and raising awareness. One of the sub-projects is the "construction of break water structures offshore Negril (Negril Breakwaters)". The construction consisted of two large offshore breakwaters between the reefs to reduce wave impact on the shore. The total length of the breakwaters would be around 1 km long with crest level at MSL. The local community was heavily against the plan. Hotel owners and local inhabitants feared the negative effects on the environment and the tourism industry. "The government should consider a cheaper and more efficient beach nourishment system instead" (Opposition Spokesman on Environment, Aug. 2014). This project was eventually canceled due to the objections from hotel owners and local inhabitants. The hotel owners and the local community recognize all the issues and strive for sustainability. Currently, the tourism industry is still heavily involved in finding a solution for the erosion of Long Bay. If nothing is planned by the government, they will start themselves. The tourism industry needs short-term results as well as a long term solution. By inviting research institutions they are looking for environmentally friendly alternatives, like beach nourishments, without being dependent on governmental projects. Apart from this, they are also proposing a beach maintenance tax to the government. The tax can help sustain and maintain beaches across the island. The government is not involved at this moment. So far, there has been no significant contact between the invited research institutions and the authorities.

1.3 Research question

The current erosion rates are threatening the beach of Long Bay, Jamaica. The hotel owners and the local community are looking for a sustainable solution to the erosion problem. The goal of this thesis is to explore possible solution strategies for Long Bay. The Building with Nature philosophy will be followed instead of the traditional approach. Building with nature is a design process that integrates nature and development goals, uses natural processes and creates added value for nature and society. If you build, do it in a sustainable way. Use the force of nature and promote nature development if possible. An integral approach is required from the start. The solution should not only be an engineering solution. A combined solution is required which covers multiple levels of the project site to come to an overall improvement of the area. Since the focus is on finding sustainable solutions, following the BwN approach could lead to more preferred solution strategies than the traditional approach. The following research question is to be answered in this report:

How can the erosion of the coastline of Long Bay, Jamaica be mitigated while simultaneously improving nature development in the area?

source: https://iamajamaican.net/travel/2016/01/view-jamaica/

Chapter 2

Describing the coast

This chapter describes what is known about the features of the project site. The first section describes the framework of the project site. The coastline is affected by several components, which are defined. The following sections describe each component. The first component is climate. The average and extreme conditions are described in this section. Next, the social system is explained. This section describes the economic activity, societal issues and stakeholders in the region. The last component is the ecosystem. In this section the most important natural features within the region are described along with their ecosystem services. The environmental impact in the region is also explained along with the preservation actions that are taken. The last section describes the observed coastline changes in history. It is explained what is currently understood about the coastline erosion in the bay. Then, what is currently known about each component of the sediment balance is described. By the end of this chapter it will be clear what is understood about the coastal erosion and what should be further researched.

2.1 Framework

Figure 2.1 gives the framework of the project site. The framework includes not only Long Bay, but also some of the surrounding area that may be of importance to the project. This framework lies within two parishes, Hanover and Westmoreland. The figure shows the main areas of the project site. It consists of Long Bay (yellow), the city Negril in the south (orange), and Bloody Bay (purple) in the north. A small airfield exists near Bloody Bay (blue). To the east of Long Bay lies a large wetland area (Green).

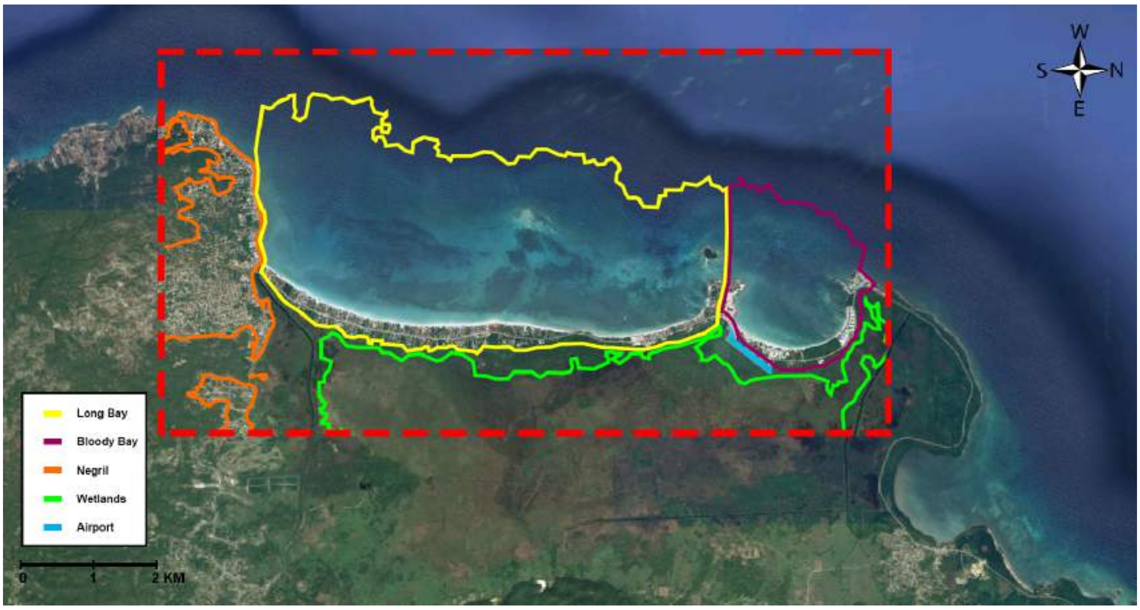


Figure 2.1: Framework project site

The coastline of long bay is affected by many factors. The factors can be categorized in three main components: Climate, the social system and ecosystem. The social system and ecosystem components directly affect each other. Climate affects both other components. The three components can contribute to coastline changes. The connections are represented in figure 2.2. The components and the coastline changes are described in the following paragraphs.

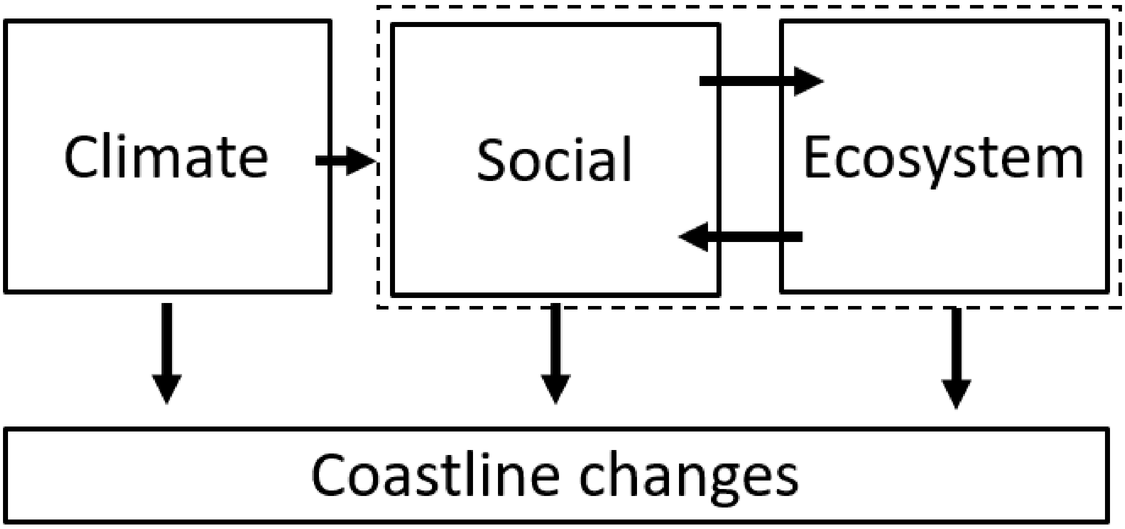


Figure 2.2: Effect diagram of the main components within the framework

2.2 Climate

Jamaica has a tropical climate. Trade winds reach the island from the east to north-east. The mountain range causes most of this rain to fall in the north and east of the island. Because of this the south-western side of the island receives less rain causing a more semi-arid climate. The raining season is between May and November with the most rainfall during September and October.

2.2.1 Average condition

The western side of Jamaica is subject to a mild daily climate. Since the bay is also very sheltered, the wave conditions entering the bay area are very mild. Waves which do enter the bay then approach the coast on the inner shelf which has a very gentle offshore slope. This allows the waves to refract causing them to reach the coast nearly perpendicular. This is likely the reason for the small longshore sediment transport that is observed.

2.2.2 Extreme events

The island is situated in the Atlantic hurricane belt. Most hurricanes move past the island on the north. Only few of them actually go over Jamaica. Hurricane season is from June through November. In the Caribbean, an average hurricane season consists of 10 tropical storms. Six of these reach hurricane intensity. [McKenzie, 2012] The hurricanes often cause significant damage. They also cause high storm waves traveling from the north towards the island. These waves can reach the western coast and enter Long Bay. Figure 2.3 shows the past hurricane events near Jamaica.

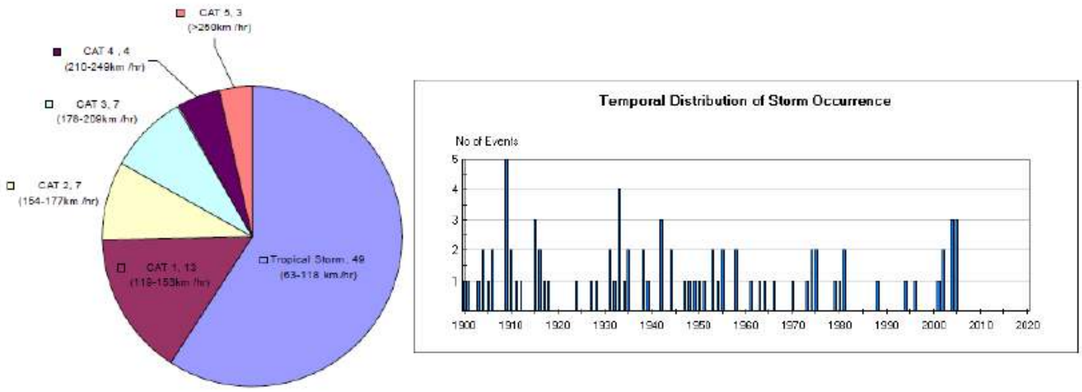


Figure 2.3: Hurricane events within 30 km of Jamaica since 1900
Source: [Smith Warner, 2007]

2.2.3 Sea level rise

Due to climate change, the sea level is rising. The global sea level change between 1970 and 2008 has been recorded and gives a rise of about 9.5 cm. [Richardson et al., 2009] The sea level rise in the Caribbean appears to be near the global mean. [IPCC, 2007] Future expectations differ among studies but all indicate an increasing rate of sea level rise.

2.3 Societal system

The area of long bay changed significantly over the last 45 years and so did the societal system. In the 70s, Negril was a small community. The main economic activity was fishery. Over the years Long Bay and the surrounding area became Jamaicas tourist hot spot. Many new jobs became available for the local community. This rapid increase also led to illegal activities causing societal issues. This paragraph discusses the current situation at the project site. It also explains which stakeholders are involved in the coastal protection project.

2.3.1 Economic activity

There are two main economic activities at Long Bay. The most dominant one is the tourism industry. This drives most of the development in the region. The other economic activity is fishery.

Tourism industry

Negril has 25 percent of all available hotel rooms on the island. Tourism provides many jobs for the local community. The average number of employees per room was 1.23 in 2011 and is increasing since then. Another 18,730 indirect jobs are generated in the area due to the tourism. For instance watercraft rental beach activities and tours to the 48 snorkel and dive sites within Long Bay and Bloody Bay. [CL Environmental, 2014] The largest all-inclusive resorts are found in the northern section of the coastline. The section to the south contains smaller hotels and restaurants. The most southern part of Long Bay is public beach. There are no hotels or resorts at this location. Figure 2.4 illustrates the different areas. The largest risk is at the northern section of Long Bay. This area contain the largest resorts so the consequences of erosion is the largest. Also, the resorts are built very close to the coastline. For the most part, the beach width is only around 10 meters. This means that the probability of damage caused by erosion and storm events is high. Since risk can be defined as probability multiplied by consequence, this means that the risk is the highest at this section of coast.

Figure 2.4: Tourism along the beach of Long Bay

Fishery

Fishing is another economic activity in the area. Fisheries generate a large variety of employment, ranging from fishermen to boat builders and retailers. Fish is available year round and provides an important food source for the community. Not only does it generate income, but it is estimated that about 10 percent of the total catch goes to household consumption. This is often lower quality fish which is not suitable for retail. In Negril over three-quarters of households live from fishing. There are mostly male fishers. Women are more often involved in the process of selling fish. Fisherman used to fish from their homes on the beach but once the tourism industry started expanding most of them moved away. Near the mouth of the South Negril River lies a small fishing village. In the past fisherman were able to get their fish in the bay. There was a large variety of fish. Especially near the reefs. Reef related fisheries capture fish that depend directly on the reef or habitat such as sea grass beds. [Waite, 2011] However, due to illegal fishing practices such as dynamite fishing the reef is not able to support the fish anymore. More about this is explained in chapter 2.4.

2.3.2 Societal issues

The rapid expansion of the tourism industry led to issues. Even though the amount of tourists increased, Negril remains the small city of only about 7000 inhabitants. With only one police station, law enforcement becomes difficult. Additionally, governmental policies are not regulated well. Because of this, the area attracted illegal activities. These activities range from unlicensed beach services like motorbike and horse riding to visitor harassment and drug use. Even though the tourism industry creates a large amount of income, Negril still only has one health center, one police station, and no public or private hospitals.

2.3.3 Stakeholders

Many stakeholders are involved at the project location. In this analysis the most important stakeholders are determined. Stakeholders with similar interests are grouped. The power of influence for each group and their general interests are used in the evaluation of designs in order to determine the most feasible solution.

Stakeholder groups

In appendix A, the most important stakeholders are described along with the connection between them. The stakeholders are divided into 8 groups. The stakeholders within a group have common interests. The groups are given in table 2.1.

Table 2.1: Stakeholder groups

Stakeholder group	**Stakeholders**
Government	The Government of Jamaica (GOJ)
	Planning Institute of Jamaica (PIOJ)
	The National Environment and Planning Agency (NEPA)
	Urban Development Corporation (UDC)
	Fisheries Division, Ministry of Agriculture and Fisheries
Tourism industry	Negril Chamber of Commerce (NCC)
	Jamaica hotel and tourism association (JHTA)
	Negril Water Sports Operators Association
	Retail and other services associations
Fishing industry	Negril Fishermens Cooperative
	National Fisheries Advisory Board
Environmentalists	Negril Coral Reef Preservation Society
	The Jamaica Environment Trust (JET)
	Negril Area Environmental Protection Trust (NEPT)
Residents	CBO or community associations
Visitors	Tourists / Beach visitors and users
Academia	TU Delft/Leiden University/Nature Coast project
	University of the West Indies
	Smith Warner

Interests

Different stakeholder groups will have different interests. Understanding the interests of stakeholder groups is important since they can indicate whether a stakeholder will support or oppose an intervention in the region. For this thesis, the interests are based on the coastal zone functions defined by Waterman. Waterman defined 22 specific functions in the coastal zone which represent the development of integrated and sustainable coastal areas. [R.E., 2010] Every coastal zone will contain a number of these functions and each stakeholder will value them differently. First, the functions present at Long Bay are determined. Based on the 22 coastal zone functions, 9 are defined for Long Bay. The first function is Safety. In the case of Long Bay, the function safety refers to protection against coastal erosion, sea level rise and natural disasters. The second function is water resources management. This relates to drinking water quantity and quality. Waste water processing and sewer systems are also part of this function. The third function is fishery. This is based on the function agriculture, fishery and aquaculture. At Long bay, the most dominant aspect of this function is fishery. The fourth function is Recreation and tourism. This is the most prominent function of the coastal zone at Long Bay. This function also contains land- and seascape conservation and development since this is an important factor which attracts tourists to this part of the island. The fifth function is nature. Nature refers to all flora and fauna in the region and focuses on nature conservation and development. The sixth function is environmental quality. With this function the focus is on air, water and soil quality as opposed to nature, which focuses on biodiversity. The seventh function is transport. The function contains infrastructure, transport modules and transfer/distribution centers. At Long Bay, the airport and the main road along the beach are the two main components of this function. The eighth function is culture and history. This function consists of cultural, religious and historical aspects which shape and influence the development of the region. The final function of Long Bay is education and research. This function refers to the value a region has for research purposes. Long Bay can be an interesting project site for both morphological and ecological studies. Based on the information provided in appendix A, the interests of the stakeholders are determined as shown in table 2.2.

Table 2.2: Interests of stakeholder groups

	Government	Tourism industry	Environ-mentalists	Fishing industry	Residents	Visitors	Academia
Safety	x	x			x		x
Water resources management	x	x			x	x	
Fishery	x			x			
Recreation & tourism	x	x				x	
Environmental quality	x	x	x	x		x	x
Transport	x	x			x	x	
Culture & History				x	x		
Education & research			x				x

Power of influence

The power of influence is the ability of a stakeholder group to change, affect or influence a region or project. In this analysis the stakeholder groups are ordered from most influential to least influential, where the most influential is given a (7) and the least influential a (1). Based on the information provided in appendix A, the power of influence is determined as shown in table 2.3.

Table 2.3: Power of influence of stakeholder groups

	Power of influence
Government	7
Tourism industry	6
Fishing industry	4
Environmentalists	5
Residents	3
Visitors	2
Academia	1

Stakeholder alignment

The stakeholders are not aligned. The governmental agencies that are involved only care about economic growth by the development of tourism. They do not know much about environmental issues. There is also a lack of technical knowledge about costs and benefits of coastal interventions. The other stakeholders do value the environment and see the benefits it has to offer. There is no agreement between the authorities and other stakeholders on which solution would benefit the region the most. Governance seems to be the main issue. The coastal problem needs to be solved physically but also governmental. Governance is needed for a technical solution to work, otherwise the approval of a project may take a very long time. This is why the government should see the value of a project. The focus can be put on the right attributes by understanding what the government desires.

2.3.4 Finances

Financing is a very important aspect of a project. Without money a project can never be realized. The breakwater project was going to be financed partly by the government of Jamaica and partly by a fund. Government of Jamaica had 9.9 Million USD available for Agriculture and Coastal Areas of which 5.4 Million USD was reserved for Negrils offshore breakwaters. Funding came from the United Nations Climate Change Adaptation Fund (2012). The government reserved a large amount of money for the breakwater project. If the government can be convinced to support a new environmentally friendly solution, then they might help fund the project. The adaptation fund only provides funding to projects with concrete, sustainable solutions. A project needs a large certainty of success. Funding is not given to beach nourishment projects. This is why they funded the breakwater proposal. A building with nature solution to the problem might not fit in with this requirement. The tourism industry may also be able to help fund future projects. The tourism enhancement fund specifies a 20 USD fee for incoming airline passengers and 2 USD for cruise passengers. [Ministry of Tourism, 2016] This money is used for implementation of the Master Plan for Sustainable Tourism Development of 2002. Part of the money from this fund could be used for future coastal protection projects. Along with donations from hotel owners this can be of great help. The Negril Chamber of Commerce also requested the government to create a beach maintenance tax, charging beach usage on a per person basis. The collected money can be used to help maintain the beaches on the island. [the gleaner, 2016]

2.4 Ecosystem

The ecosystem at Long bay is diverse. There are several important natural features which will be discussed in this section. Each natural feature adds specific ecosystem services to the bay. The environmental system is under impact from different sources. They are discussed along with preservation measurements taken to protect the environment.

2.4.1 Natural features

The coastal system at the project site has several natural features. The most significant ones are given in Figure 2.5. The natural features are coral reefs, sea grass beds, the sandy beach, the wetlands and two small river systems. The natural features are explained in detail in appendix B.

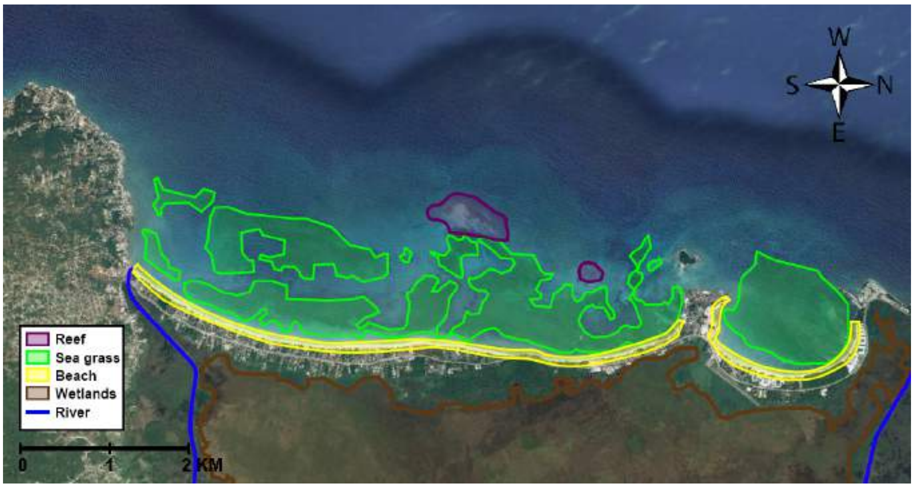


Figure 2.5: Ecosystem features

2.4.2 Ecosystem services

An ecosystem affects the environment on location. The affecting processes are called the ecosystem services. These ecosystem services can be represented by two levels, as seen in figure 2.6. The bottom level represents the supporting services. These services are the base of the ecosystem since they support the development of the ecosystem. The top level of the figure represents the services the ecosystem can provide when it flourishes. These are the provisioning, regulating and cultural services. The supporting services are necessary for the production of these services. The provisioning services are the products that can be gained from the ecosystem (food provision and the provision of certain biotic materials). Regulating services are benefits from the regulation of ecosystem processes (water purification, coastal protection, climate regulation). The cultural services are all the non-material benefits an ecosystem can provide (tourism, aesthetic). [Liquete et al, 2013]

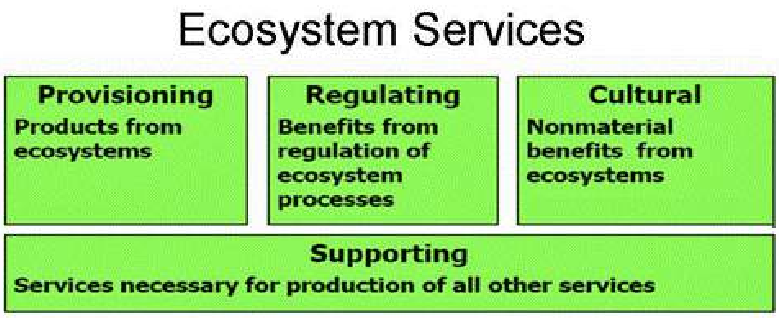


Figure 2.6: Description of ecosystem services
Source: [Liquete et al, 2013]

The reef, sandy beach, sea grass beds and wetlands all provide ecosystem services. The services each natural feature provides are explained in appendix B. Table 2.4 gives a summary of these services.

Table 2.4: Ecosystem services of features at projectsite

		Reef	Beach	Sea grass	Wetlands
Provisioning services	Food provision	x			x
	Raw or biotic materials and biofuels	x		x	x
Regulating services	Coastal protection	x			
	Coastline stability			x	
	Life cycle maintenance	x	x	x	x
	Water purification			x	x
	Air quality regulation				x
Cultural services	Symbolic and aesthetic values	x			x
	Recreation and tourism	x	x		
	Cognitive effects	x			x

2.4.3 Environmental impact

The environment is under pressure. The climate and the societal system both affect the ecosystem. The climate does this due to accelerated climate change. The societal system does this by polluting the environment, the development of the tourism industry and by harmful fishing practices.

Climate change

Climate change affects the environment. The two primary changes are an increasing water temperature and sea level rise. A warmer climate means higher water temperatures. The higher temperatures put an environmental stress on coral reefs which can result in the coral algae leaving the polyp. Since the algae provides the color, the coral turns white. This is called coral bleaching. Higher water temperature, in combination with an excess of nutrients, also creates a higher possibility of increased algae and phytoplankton growth. Algae grows over the coral and kills it. A large growth of the algae and phytoplankton production could even induce eutrophication, where oxygen is depleted from the water. A rising sea level can affect the coral reef. As mentioned earlier, a healthy reef grows upward up to a water depth which holds the best growth conditions. As the sea level rises, the coral reef grows with it. This is a very useful property when considering the coastal protection properties of the reef as it can be seen as a submerged breakwater which adapts itself to new conditions without the need of human intervention. As long as the coral reef can keep up with the rising sea level, there is no problem. However, when the reef accretion is not fast enough the water column above the reef increases due to the rising sea level and growth conditions become less favorable. This situation often occurs when coral mortality is increasing while coral recruitment is decreasing. [WAVES, 2016]

Pollution

The hotels and resorts at Long Bay cause pollution. When flood water runs of into Long Bay, it brings in pollutants from the resorts. This is however not the largest form of pollution. Another large forms of pollution is caused because hotel owners dump waste water into the wetlands. Not only does this hurt the wetlands but the pollution in the wetlands runs off into the Negril River which ends in Long Bay. The water coming into the bay is of poor quality and can be visibly brown in color. Polluted water blocks light, increases toxicity and creates a good environment for algae and phytoplankton growth. This causes issues as already mentioned in the previous section. Until recently, the highest average biochemical oxygen demand, phosphate and faecal coliform values were measured at the influence of the south Negril River. This is partly due to the pollution from the hotels, but is also likely the result of the outflow from the sewage plant which was built in 1991. [CL Environmental, 2014] The sewage plant caused issues because the treatment ponds were sinking. This caused contaminated water to flow into the wetlands. In 2012 a new waste water treatment plant was constructed costing 278-million dollar. Whether this solved the issues, is not clear.

Tourism industry

The tourism industry has a great effect on the environment. Since the industry is quickly developing, the pressure on the environment will keep increasing. The use of boats, jet skis and other watercraft in the bay negatively affects the environment. The use of these watercraft can damage the reef in shallow water. They may also stir up sediment smothering the coral. Anchors can also cause damage when dropped without consideration. Although snorkeling and diving promotes environmental awareness it must be done responsibly. Touching coral with hands or scuba fins damages the polyps. The tourists also affect the environment by leaving waste on the beach and in the water. Most hotel owners removed the sea grass at their section of the beach to make it safer and more aesthetically attractive for tourists. Tourists usually dont value sea grass. Animals like sea urchins hide in the sea grass making walking into the water dangerous. Hotel owners only care about pleasing their guests but fail to recognize the benefits sea grass has to offer. Land use of the tourism industry greatly affects its surroundings. The increase of land use in the area is one of the main factors which caused a change in the vegetation line. The tourism industry keeps developing but the beach ridge barrier between the waterline and the wetlands is small. The increased land use on the beach leaves less space for safe turtle nesting areas. Since the hotels will continue to expand, the wetlands will be put under pressure.

Fisheries

Fisheries directly impact the environment. If done in a sustainable way, the negative effects can be minimized. The use of poor fishing practices is harmful to the environment. Using nets results in unwanted by-catch and can also damage the coral reefs. Overfishing has a big impact on the environment. Overfishing near the reefs resulted in a decline of herbivorous, algal-grazing fish. This led to a reef which is dominated by algae reducing the health of the reef. [CL Environmental, 2014] The use of dynamite for fishing is the most harmful practice. This method of fishing causes serious harm to coral reefs. Dynamite is thrown into the water which detonates several meters below the surface. The explosion kills a large number of fish which float up to the surface. This way many fish can be collected from the surface with minimal effort. This harmful practice also kills fish that are not needed for consumption. The collateral damage is not the only issue. Dynamite fishing is done where there is a high density of fish to gain maximum profit. For this reason, dynamite fishing is mostly done near coral reefs. The explosion does not only kill many fish species but destroys the reef in the process. It is a damaging, unsustainable method which destroys the environment. At Long Bay, this technique has been used in the past which resulted in loss of large areas of reef. Whether some fishers currently still use dynamite, is not clear.

2.4.4 Preservation

Several actions are taken in order to reduce the impact on the environment. The local community recognizes many of the issues and voices a strong opinion on the subject. A lot of publicity is given to the issues so the will to do something about these issues is strong.

Policies

Multiple environmental policies have been established over the years such as the Negril/green island development order of 1991, which describes the coastal marine resources in Negril and the dynamic ecological balance near the coral reef. Another is the Negril environmental protection area. The protection area guides environmental planning and decision making within the area. It establishes all the goals of the Negril EPA. The most significant are:

- Negril Marine Park
  The Negril Marine Park was established by the government of Jamaica in 1998. The Natural resources Conservation order 1998 describes the exact area of the park. Long Bay is within the park. The establishment of the park enabled a ban on dredging, excavating, discharge

of pollutants, littering, use of explosives and poisons and fishing within the protected area boundaries except when a permit is provided. [CL Environmental, 2014]

- Zoning plan
  The zoning plan is created by The National Environment and Planning Agency and divides the Negril Marine Park into different sections. The plan seeks to realize sustainable use of natural resources. Zoning prevents overuse of resources, thereby protecting them. A zone specifies the allowed activities and limits of acceptable use. [NEPA, 2012] Figure 2.7 shows the zones in which Negril Marine Park has been subdivided. From the coastline to offshore Long Bay consists of the following zones:

Swimming sub-zone:	0	-	91.4 m (300 ft)
Non-motorized craft sub zone:	91.4 m	-	182.8 m (600 feet)
Motorized craft sub-zone:	182.8 m	-	424.6 m / 487.6 m (1400 / 1600 ft)
Diving sub-zone:	424.6 m / 487.6 m	-	outer shelf
Multiple-use zone:	outer shelf	-	end of boundary

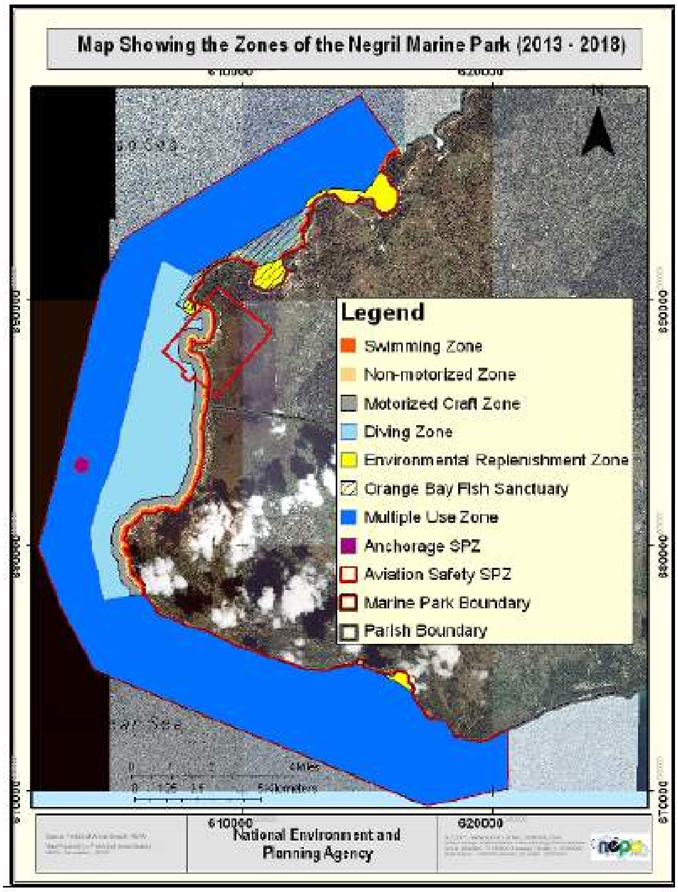


Figure 2.7: Negril Marine Park
Source: [NEPA, 2012]

Regulations

The only way that these environmental protection areas and zoning rules work, is when they are regulated properly. As mentioned in chapter 2.3.3, the policies are not well regulated at this moment. There is no strict regulation to prevent misuse of the region. This is very important to realize because when finding a nature friendly solution to the erosion problem it is an absolute requirement that environmental protection is guaranteed.

2.5 Coastline changes

The coastline of Long Bay changed over time. This section first describes the coastline changes which are observed over the years. Then, the components which form the sediment balance are described. This leads to an understanding about the system and which components require further research.

2.5.1 Coastal erosion

The shoreline changes in history can be estimated using aerial photo images and satellite imagery. Robinson et al measured the distance between the beach toe and the vegetation using photo images from 1971 and 1991, and satellite imagery up to January 2008 for 65 points from south to north along Long Bay. [Robinson et al, 2012] The results are given in figure 2.8. The results show zones which are dominated by erosion and zone which are dominated by steady accretion. The overall change over time is that the average annual recession increases.

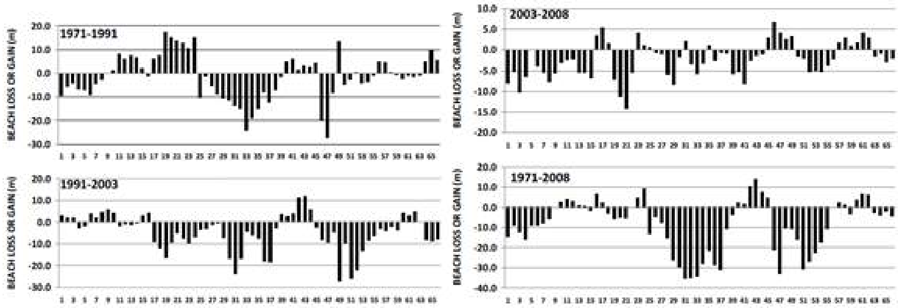


Figure 2.8: Bar graph indicating relative recession or progradation of the shoreline between 1971 and 2008 for each of the 66 measured transects
Source: [Robinson et al, 2012]

Smith Warner has measured shoreline changes in a similar matter. [Smith Warner, 2007] It was also found that the beach is very dynamic. The beach width may fluctuate more than 30 m during a given year. There are large erosion and accretion cycles. Their results also show dominant erosion and accretion zones which match the results of Robinson et al. The zones are shown in figure 2.9.

Figure 2.9: Erosion and accretion zones along Long Bay
Source: [Smith Warner, 2007]

The measured rate of erosion differs between papers. Robinson et al estimated a rate of change between -0.23 m/yr and -0.59 m/yr depending on the location on the beach. Smith Warner measured an erosion rate of around 1 m/yr. Table 2.5 gives the complete list.

Table 2.5: Rate of coastline change from different sources

(Robinson et al, 2012)

	Period	Rate of change
Mean rate of past coastline change	1971 2008	-0.23 m/yr
Mean coastline change after development	1991 2008	-0.41 m/yr
Mean coastline change at hotspot	1971 2008	-0.59 m/yr

(Smith Warner, 2007)

	Period	Rate of change
Mean rate of past coastline change	1968 1980 1980 1991 1991 2006	0.8 m/yr 1 - 2 m/yr 1 m/yr
Mean rate of past coastline change	1968 2006	1 m/yr

(CL Environmental, 2014)

	Period	Rate of change
Overall level of erosion	No specifics	0.2 - 1.4 m/yr

2.5.2 Sediment balance

The coastline changes are caused by a change in the sediment budget. The sediment budget is given in figure 2.10. It consists of longshore sediment transports, cross shore sediment transports, sediment production (both natural and nourishments) and sediment extraction. In a system that is in balance, an even amount of sediment enters the system as leaves of the system. Since the coastline suffers from structural erosion there must be an imbalance. This subsection explains what is currently known about the components which comprise the sediment budget.

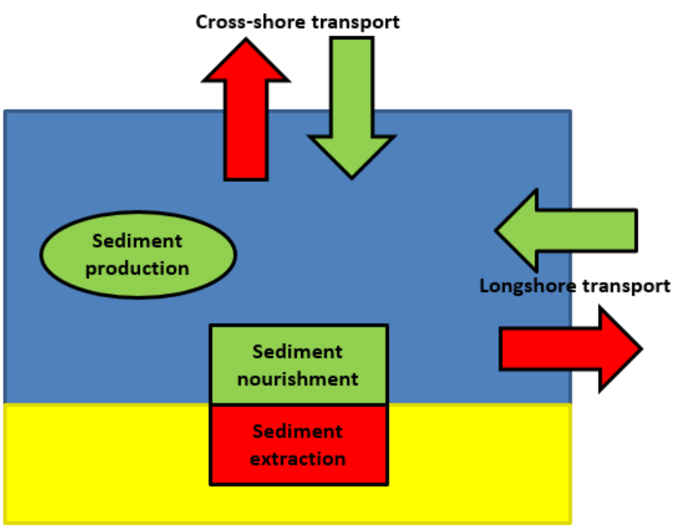


Figure 2.10: Simplified sediment budget

Longshore sediment transport

Longshore transport is driven by daily wave action on the coastline. Most of the sediment is transported within the breaker zone. Smith Warner modeled longshore transport leading to an annual sediment transport. The longshore sediment transport rate is not very high. Their results indicate that long Bay and Bloody bay are two independent systems. [Smith Warner, 2007] Sediment does not pass by the headland as is evident by the lack of sediment along the edge of the bay and near the headland. An important conclusion is that longshore transport does not seem to transport sediment in or out of the system. It only redistributes it within the bay.

Cross-shore sediment transport

Cross-shore sediment transport is driven by both daily wave action on the coastline and long period swell storms. Daily wave action transports sediment onshore while long period swell waves, originating from offshore storms, transport sediment in offshore direction. Smith Warner modeled cross-shore sediment transport using data from swell waves. The measured beach profile was after a storm so the original profile was assumed and then calibrated using the measured profile. Significant erosion from swell storms was observed during modeling. [Smith Warner, 2007] McKenzie collected beach profile data for nine years between 2000-2008. [McKenzie, 2012] During this time four hurricanes (Michelle 2001, Ivan 2004, Wilma 2005, Dean 2007) occurred. Data was collected at regular intervals on the beach. Two data locations are Negril Gardens Hotel and Native Sons Villas. Figure 2.11 gives pre- and post-hurricane beach profiles for the two locations. The results give an average of around 15 meters of coastline regression, based on the high water mark. It also shows less erosion at the northern part of the Beach and more in the south. The report states that the beach requires a minimum of 3-4 years to recover from a category 4 storm event. [McKenzie, 2012] The results indicate the impact of extreme events but do not say anything about the amount of sediment that is lost out of the system due to the event.

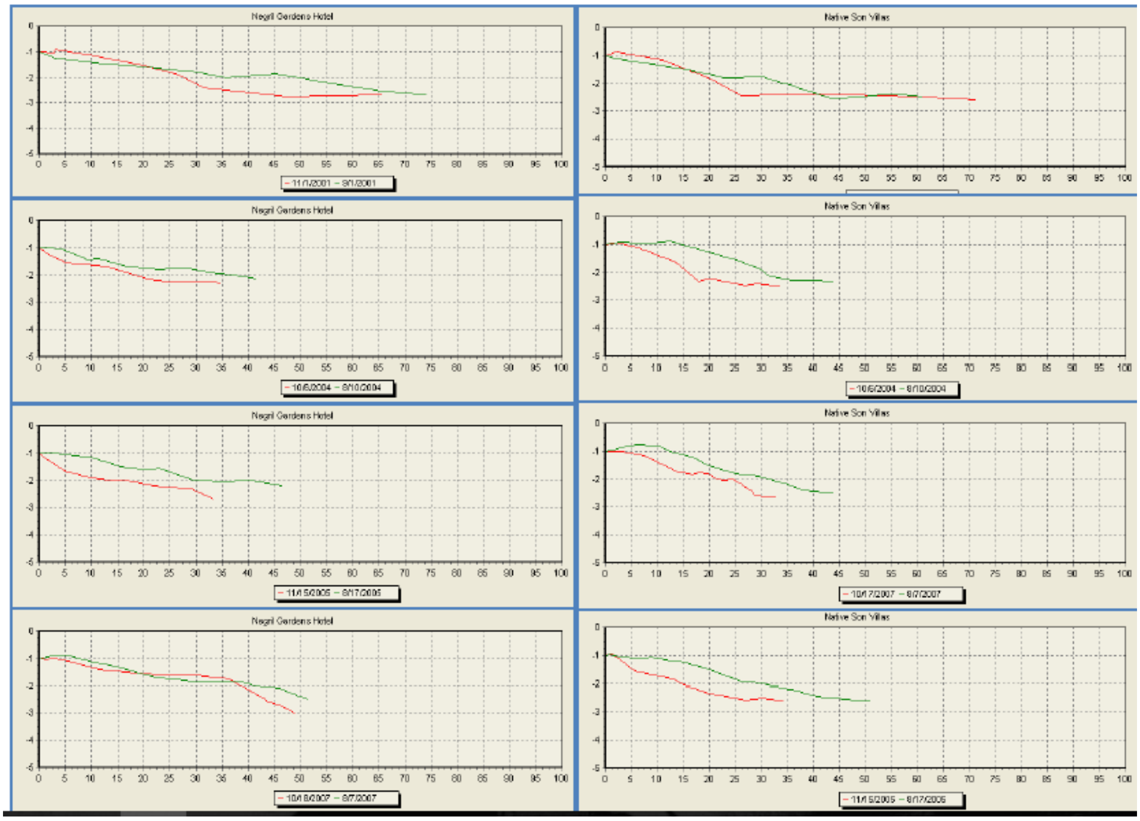


Figure 2.11: Pre- and post-hurricane beach profiles at Negril Gardens Hotel and Native Sons Villas Source: [McKenzie, 2012]

The sediment is moved offshore by wave action and currents. Daily wave action slowly moves sediment back towards the beach. The sediment moved by storms must remain within the littoral system or daily wave action will not be able to transport it back towards the beach. Hurricanes might be able to transport sand away beyond this point. This causes erosion which cannot recover naturally. Evidence of sand is found between the 20 m and 50 m depth contours on the outer shelf by NCRPS divers and dredging company Van Oord. However, no official reports have been published at this point. This suggests sand eroding from the beach due to storm events is deposited at this location. If it is known where most of the sediment goes then more can be said about the driving mechanisms and main flow directions of the sediment.

Natural sediment production

As mentioned in chapter 2, sea grass produces sediment. The reef can also be a source. They add calcium carbonates to the sediment. Sediment production might be an important source of sediment. The previous paragraphs explained that there is no longshore sediment transport into the system. It is also possible that the cross-shore transport moves the sediment offshore but is unable to transport it back onshore during calm wave conditions. If that is the case then the natural sediment production is the only supplier of sediment, making it very important.

Nourishments and sediment extraction

Nourishments are a human intervention which adds sediment to a system. It is a way to compensate for the sediment imbalance in the system. So far, only small nourishment projects have been done. Most of these nourishments are done without detailed analysis and research. This led to situations where an unsuitable type of sediment is used or placed at the wrong location. The opposite of nourishments is sediment extraction. This can occur for instance when sediment is needed for projects at a location outside the system. It can also occur when sediment is not wanted at a location, for instance when a certain depth is required for vessels. At Long Bay, no large scale sediment extraction by the government, local community or other groups occurred in the past. Therefore, sediment extraction is not considered.

In conclusion, the most important components in the sediment balance are cross-shore sediment transport and sediment production. The quantities of sediment are not certain at this point. Cross-shore transport seems significant at the coastline during extreme events but the amount of sediment lost out of the system is unknown. Sediment production seems to be the only source of sediment in the bay since there is no significant longshore sediment import into the system. The significance of this production is not known at this point.

2.6 Conclusion

Long Bay is an area which is dominated by the tourism industry. Most of the large hotels and resorts are placed at the northern part of the bay. They are placed very close to the shoreline making them vulnerable to coastal erosion. The climate consists of a yearly hurricane season which causes an impact on the coastline. The impact due to hurricanes seems severe but needs to be better understood. Sea level rise is around the global mean at Jamaica. The bay is very shallow so a rise in the mean sea level has likely had an effect on the coastal erosion. How significant this effect is must be further understood. The long term erosion rate is caused by an imbalance in the sediment balance. By understanding all components in the sediment balance it will become clear why the erosion occurs. This requires the yearly cross-shore sediment losses and sediment production in the bay. This will show how much is lost every year. A complete understanding of the sediment transport is gained by also determining the pathways that the sediment follows. The most prominent components of the ecosystem are the coral reefs and the sea grass fields. Both are in decline. The coral reefs have declined significantly in size due to destruction by illegal fishing practices and boats. The sea grass is removed nearshore in front of the resorts. This may have caused a reduction in sediment production. Furthermore, the reduction of the reef also reduced its coastline protection ability. This likely increased wave impact on the coastline. The significance of the decline of the ecosystem also needs to be better understood. In summary, the hotel and resorts are at risk due to coastal erosion. The reason for the erosion is not clear at this point. The cause of the erosion may be a combination of factors mentioned above. These components need to be better understood before a solution to the problem can be found.

source: http://www.dredgingtoday.com/2014/06/11/picture-of-the-day-keansburg-beach-replenishment-usa/

Chapter 3

Methodology

In this chapter the research methodology is explained. The chapter starts by formulation of the design requirements and assumptions. This is the starting point of the design process. The next section describes this design process. The process is based on the Building With Nature design process. By following the steps explained in this section the research question can be answered.

3.1 Design requirements and assumptions

The goal of this thesis is to explore solution strategies for the mitigation of the erosion problem by following the BwN design process. Chapter 2 showed the complexity of the project site. Based on this chapter design requirements and assumptions can be formulated.

3.1.1 Design requirements

Every design that is proposed should at least meet the following minimum requirements. If not, the design either not feasible or does not provide a solution to the problem.

- Short term safety
  On the short term, prevent erosion of the coastline where this forms an immediate threat to safety.
- Long term durability
  On the long term, maintain a beach width which is safe and wide enough for tourism and recreation along the entire bay.
- Sustainability
  The design should not have a long term negative impact on the environment. The aim of this study is to actually find a design which provides new opportunities for the environment.
- Navigability
  Boasts should not be completely obstructed by the design. They should still be able to leave and enter the Bay and beach.

3.1.2 Preferences

Preferences are design objectives which are desired in the project but not required. By considering them in a design, the solution will be more accepted by the stakeholders and therefore more likely to be implemented.

- Environment
  Optimal ecological integration is desired.
- Disturbances
  Minimal disturbances to tourists during construction is preferred.
- Fisheries
  Improved fishing conditions are desired.
- Limit design cost
  The project should not have to depend on subsidies.

3.1.3 Design assumptions

The designs made in the thesis are based on a number of initial assumptions. These assumptions are given in this section.

Representative storm

Smith warner used a parametric model to generate deep water wave conditions during hurricanes. Hurricane records from NOAA are used in the parametric model. The significant wave height calculated with a return period of 10 years and 50 years are transformed to nearshore conditions. A return period of 50 years leads to a significant wave height of 9.2 meters. [Smith Warner, 2007] These are very high wave height which leads to design requirements which are very difficult to meet. For this thesis the representative wave height is found based on a certain wave return period. The data used is yearly wave data as used by van Arkel. [van Arkel, 2016] This leads to a representative nearshore wave height which can be used in the required simulations.

Wave return period

The wave return period is used as a basis in designs. The return period is based on a certain life expectancy of the design and an allowable probability of failure during this lifetime. The probability of failure can be determined using a Poisson distribution. [Verhagen and d'Angremond, 2012]

$$p = 1 - exp(-f * TL) \tag{3.1}$$

In which:

p = probability of occurrence of an event one or more times in period

TL = considered period (e.g. the lifetime of the breakwaters) in years

f = average frequency of the event per year

An economic lifetime in the order of 50 years is commonly used coastal defenses. This leads to failure probabilities for different storm frequencies as illustrated by figure 3.1. This assumes that the over-exceedence of the chosen storm event leads to failure of the design.

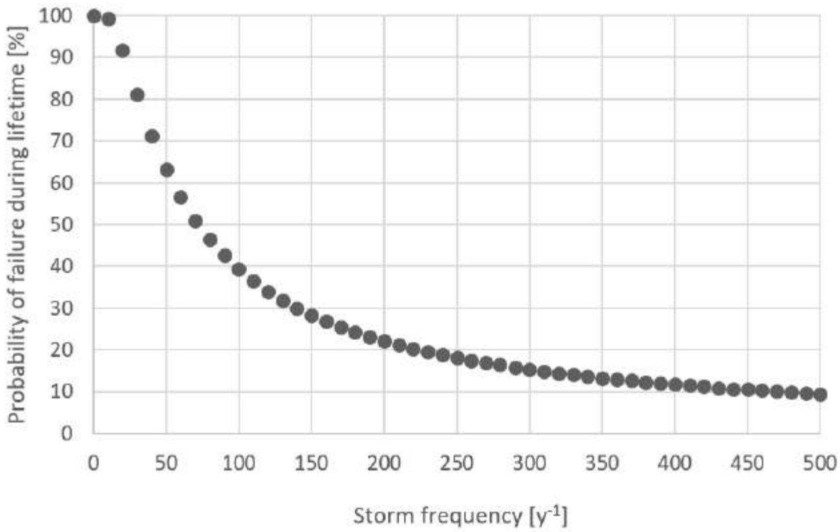


Figure 3.1: Failure probabilities for different storm frequencies

The choice of a certain return period for the design does not only depend on the probability of failure but also on the consequences. In this case, failure of the design would mean that the erosion rates go back to the current erosion rates. This causes some immediate consequences during hurricane events, but other than that short term consequences are manageable. The second consideration is based on the choice between investment and maintenance. A design based on a very low storm frequency, e.g. 1/500 years, will require a large initial investment. However, the probability of failure of this design is low so little maintenance will be necessary. When the initial investment is expected to be relatively higher than maintenance cost, a higher probability of exceedence may be allowed. This means the focus will be on regular maintenance. In the Netherlands, the economic optimum lies between 5 and 20 percent accepted exceedence of design parameters. This optimum rarely applies to other countries and using this optimum in a different country often leads to over dimensioning of a design, making the project too expensive. This results in a proposed design which will never be implemented. Studies in Jamaica and the Caribbean generally use a 50-year return period for coastal design. [Smith Warner, 2007] This would lead to a probability of failure during lifetime of 63.2 percent. Based on the above considerations, the designs in this thesis are based on a wave return period of 1/100 years. This leads to a probability of failure during lifetime of 39.3 percent. This storm frequency is low enough to generate a durable design and high enough to reduce the initial investment costs.

3.2 BwN approach

The research is performed following the BwN approach. This approach is different from the traditional approach and should lead to a broader range of solutions with the focus on utilizing ecosystem services while delivering engineering services.

The traditional approach for hydraulic projects is to first plan a project once the general objective is identified. At this point, the general solution has already been chosen. After that, the effects of the design on the ecosystem are described. The design is optimized to reduce the effects on the environment. Any nature loss is compensated by building of nature. Then, the project is executed according the the norms and regulations. The BwN approach is to first understand the system. Then, the envisioned functions are identified and the project is planned accordingly. The following steps are to determine how natural and governmental processes can be stimulated to achieve the project goals. After this, the final two steps are to monitor the environment during execution and after completion. The monitoring is done so that the execution and management can be adapted if necessary. So, the main difference from a project development perspective is that the BwN approach starts with the system in mind, not with the intervention. The BwN philosophy shows a shift in environmental approach. The traditional approach plans a project and then minimizes negative impact on the environment. This is building in nature. This approach is improved by compensation of losses by building of nature. This leads to a neutral approach. The BwN approach is the next step by optimizing a project to create opportunities for the development of new nature. This goes beyond the neutral approach. The strategic objective for Building with Nature projects is therefore to deliver engineering services while delivering and/or utilizing ecosystem services.

3.3 Design process

When following the BwN approach several steps are generally taken when developing designs. Building with Nature Design process consists of five general steps that can be followed in any phase of a project. The strategy follows these five steps:

1. Understand the system
2. Identify realistic alternatives
3. Valuate the qualities of alternatives and preselect an integral solution
4. Elaborate selected alternatives
5. Prepare the solution for implementation in the next phase on the road to realization

Chapter 2 showed that there is erosion of the coastline but that the reason for this erosion is still not certain. The components climate, social and environment influence the coastline but to what extend is not clear at this point. Before a way can be found to mitigate erosion, we must first understand the cause of it. This is the goal of the first step. The next step is to come up with alternatives which addresses coastal protection, environment and social policies. The integral aspect of these alternatives is important to keep in mind. Step 3 evaluates the alternatives. The valuation is based on technical, ecological, legal and social feasibility. The valuation leads to the most promising design which can then be elaborated on in step 4. In this step the execution and timing aspects are taken into account. The final step prepares the solution for implementation in the next phase. This involves creating a technical design and translating the solution to a request for proposals or contract.

In this phase of the project, the evaluation will not lead to a final design which can be elaborated on the the following steps. In the initiation phase the results indicate the pros and cons of different solutions strategies but the restricted data limits the accuracy of the designs effectiveness. Therefore it is not possible to say that one design is the best solution and should be implemented. For this reason, step four and five are not performed.

3.3.1 Understand the system

As explained in chapter 2, several aspects of the coastal system are not yet fully understood. The chapter 'understanding he system' will treat these subjects.

Impact of extreme events

The impact of extreme events on the coastline needs to be understood. Extreme events tend to cause large cross-shore transports. Hurricanes occurred frequently in the past. For this reason hurricane events are assumed to be a primary factor in the coastline erosion. The severity of beach impact during hurricanes is examined using the modeling program Xbeach. XBeach is a two-dimensional model for wave propagation, long waves and mean flow, sediment transport and morphological changes of the nearshore area, beaches, dunes and backbarrier during storms. (https://oss.deltares.nl/web/xbeach/) It can be used to simulate the impact of waves on sandy coasts on the time scale of storms. The results give the amount of coastline retreat after a storm. This indicates the severity of a storm event and the overall threat to safety.

Sea level rise

A rising sea level affects the coastline. Generally, as the sea level moves upward the shoreline moves inland changing the location of the beach system. At long Bay, the hotels and infrastructure are located prevent this inland movement. This causes degradation of the beach width. For this reason sea level rise is considered as part of the reason for the erosion of the beach over the years. Using the Bruun rule gives an estimate for the amount of beach degradation caused by sea level rise. The coastal retreat is estimated for the entire coastline. The results can be compared to the retreat caused by long term sediment loss. This shows how significant the retreat caused by sea level rise is.

Sediment balance

The sediment balance is not yet completely understood. Chapter 2 explained that cross-shore sediment transport and sediment production are not known at this point. The sediment pathways, along which the cross-shore sediment transport moves, also need to be understood.

Sediment transport pathways The sediment eroding from the coast during storms travels towards the outer shelf by moving with the currents. In this report two scenarios are considered about the general direction of the sediment flow towards the outer shelf. The first scenario assumes that the eroded sediment is moved offshore by cross shore transport where it is quickly picked up by the currents in the bay. This slowly moves the sand towards the point close to the bay where the sea bed deepens the fastest, see the left illustration of figure 3.2. From there it moves towards the outer shelf. In the second scenario the reef, acting as a submerged breakwater, causes a current flow as shown in the right illustration of figure 3.2. When the beach erodes due to a storm event, it is transported between the reefs along with the currents. The sediment ends up between the 20 and 50 m depth line, where it is unable to be transported back onshore. The actual sediment pathways are found by looking at sediment transport magnitudes and directions in the simulation made in Xbeach.

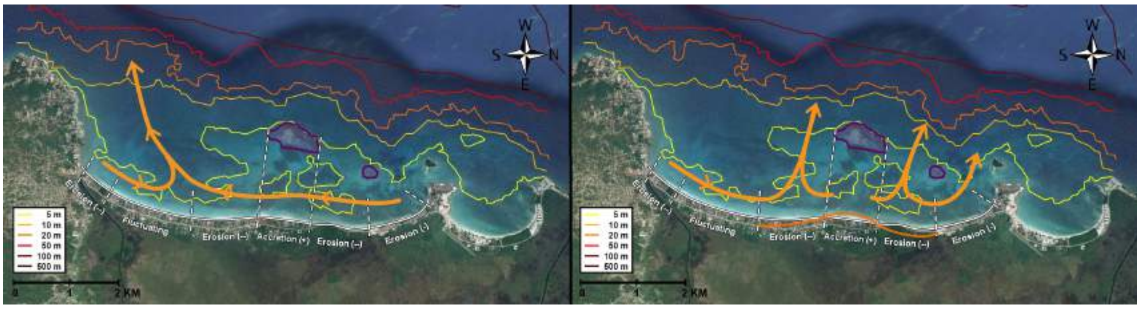


Figure 3.2: Expected sediment transport direction scenario 1 (left) and scenario 2 (right)

Long term sediment transport The long term sediment transport is determined by calculating the amount of sediment that is transported so far offshore that it is unable to be transported back to the beach during normal conditions. This is calculated for different types of storms, each with a different frequency of occurrence. Using this information the long term volume loss per year can be estimated.

Sediment production Sediment production seems to be mainly from sea grass and reefs. The composition of the sediment at Long Bay is examined first. The composition will tell where the sediment comes from. The sediment production can be estimated once it is understood what the primary producers are. After doing this, it becomes clear if the degradation of the environment actually influences the sediment production, and whether this reduced sediment production is an important cause of the observed coastline change.

Reduced coastal protection by reef

Coral reefs can protect the coastline from incoming waves by dissipating wave energy. The energy is dissipated because waves may break on the reef and dissipate due to friction from the coral cover. The reduced waves have a smaller impact on the beach leading to less erosion than when there would not be a reef. Before the development of the region, the coral reef at Long Bay was much larger and healthier. The two coral reef patches were still connected and the coral species diversity was much higher according to the local community. The reef is under stress from fisheries and reduced water quality and significantly reduced in size over the years. The reduced size of the reef allows storm waves to travel into the bay more easily. This leads to increasing shoreline erosion. The reduction of the coastal protection capability of the reef is found by simulating a situation with a healthy reef, as it was before the activity in the region. For this historical reef, total coastline change is estimated. The difference between this scenario and the reference scenario indicates the amount of extra erosion that is caused due to the degrading of the reef.

3.3.2 Identify realistic alternatives

Once the reason for the coastal erosion is better understood, a solution to the problem can be found. The chapter 'understanding the system' will conclude with the most important contributors to the erosion problem. This is the starting point for creating alternatives. There are many ways to mitigate erosion. First, the main solution strategy is formulated. From there the type of solutions for each strategy is discussed. The type of solutions can be applied in many different ways. The range of possibilities for both types of solutions is given. This range of solutions is modeled to understand how the solution performs compared to the reference scenario. Based on the performance, ineffective solutions are excluded. The remaining alternatives are evaluated in the next step.

3.3.3 Evaluation

In this step the quality of the alternatives determined in the previous section is evaluated. The evaluation of the alternatives is based on ecosystem services. A social evaluation method is also applied to assess the applicability of this type of evaluation method and gain a broader perspective on the alternatives. At the end of this chapter it is clear what the strengths and weaknesses are of the different solution strategies. These results can be used in the next project phase.

Evaluation of alternatives This evaluation shows which ecosystem services are affected by the alternatives and in what way. The effect can be positive or negative. The ecosystem services are grouped in technical, ecological and social aspects. The result is a clear overview of the positive/negative effects of the alternatives on the ecosystem services. This can be used to see on what aspects an alternative scores well and where it can be improved.

Social evaluation method In this evaluation the alternatives are valuated based on the needs of the stakeholders. The alternatives positively or negatively affect the interests of the stakeholders. The evaluation results in the score for each alternative representing their potential value. The goal of this type of evaluation is to put the results in a broader perspective. The potential value of the alternatives should not be used for a final determination of the most feasible design. For this, the data is too uncertain at this phase of the project.


source: https://iamajamaican.net/travel/2016/01/view-jamaica/

Chapter 4

Understanding the system

This chapter contains the first step in the design process. The aim of this chapter is to understand what causes the coastal erosion. This is done using the methods described in chapter 3. In the first section the impact of extreme events is explained. This is the short term impact after a storm event. The results show how significant the impact is. The next section describes the importance of sea level rise. After that, the components which make up the sediment balance are described. The sediment pathways are identified along with the long term cross-shore sediment loss and possible sediment production. The results describe the balance and annual sediment loss. After that, the effect of the historical healthy reef on the coastal protection is explained. The conclusion of the chapter is a description of the cause of the erosion at Long Bay.

4.1 Impact of extreme events

Chapter 2 already indicated the effects of a hurricane event on the coastline. Cross shore transport due to hurricanes seems to be significant. The data from mckenzie indicates the amount of erosion. However, more detail is required to understand the impact of hurricane events on the coast. This is acquired by simulating a storm event in Xbeach as explained in appendix E.

The results from the Xbeach simulation are used to find the coastline impact after the storm. The method to determine the retreat is also explained in appendix E. Appendix J gives the complete results of the simulation. Figure 4.1 gives the results about the beach width before and after the storm. The retreat of the beach differs along Long Bay. At some places there is regression of the shoreline while at other places the coastline advances. What is clear is that the reefs help to prevent coastline retreat of the beach. The coastline actually advances slightly behind the reefs. Between the reefs the retreat results in large impact. The width of the beach at this location is already small and the erosion caused by the storm is significant here. This causes the lower level of the beach width to retreat beyond the upper level. In other words, the beach completely disappears. Towards the south the retreat fluctuates. At the final section the retreat is significant. The beach also completely disappears. As chapter 2 explained, the largest hotels and resorts are situated in the northern section of the bay. The hotels are only 10 meters away from the waterline so even small amounts of retreat can have significant consequences. The southern section, where the retreat is very large is public beach. There are less buildings and they are placed further from the water line. This means that the risk is less even though the retreat is the largest.

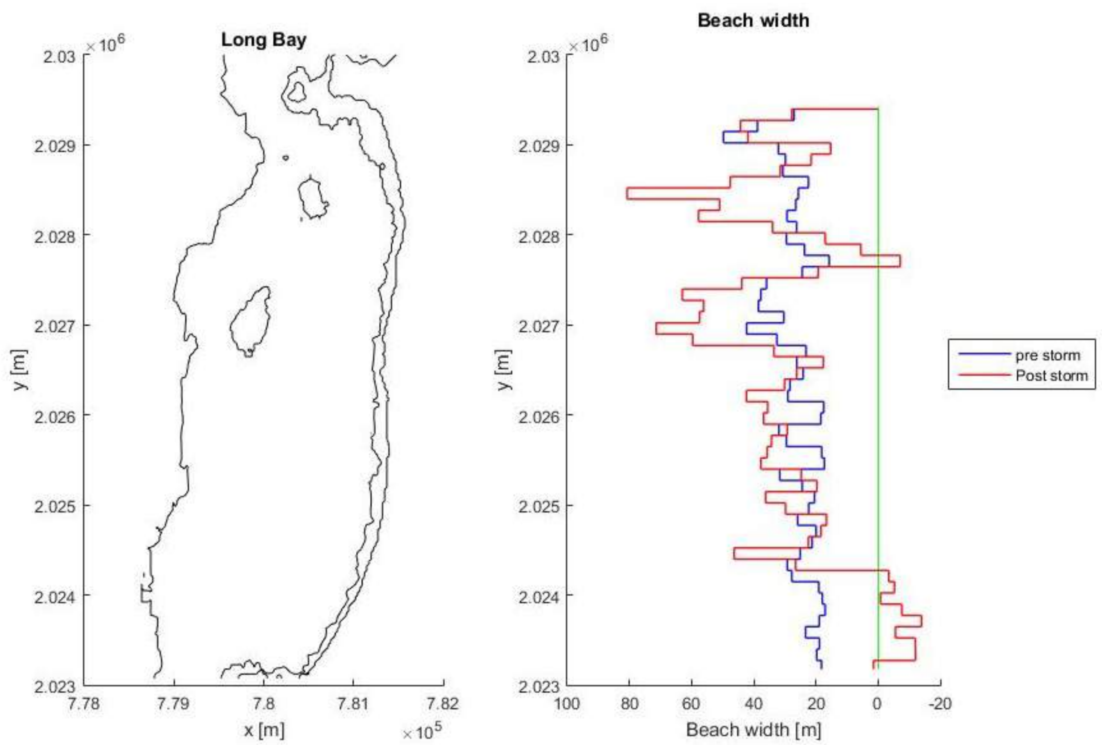


Figure 4.1: Coastline retreat after an extreme event

4.2 Sea level rise

The onshore area where most of the hotels and resorts are situated is only about 1 meter above mean sea level. Because of this, and the fact that the coastline has a very shallow slope, sea level rise will impact the position of the coastline. This section determines the importance of sea level rise on the coastal retreat.

4.2.1 Bruun rule

To get an idea about the importance of sea level rise on the coastline the Bruun rule is used. The Bruun rule estimates the response of the beach profile to sea level rise by assuming that the equilibrium profile of the beach moves with the sea level. [Bosboom and Stive, 2015] This causes the profile to move land inward and upward. The Bruun rule is given as:

$$R = S * L/(B + h) \tag{4.1}$$

In which:

R = Shoreline retreat

S = Sea level rise

L = Cross-shore width of the active profile

B = Elevation of the beach or dune crest (maximum height of sediment transport)

h = Closure depth (maximum depth of sediment transport))

Sea level rise was 0.095 m between 1970 and 2008 as mentioned in chapter 2. This is equal to 0.0025 m per year. The closure depth is at -3 m and the maximum height of sediment transport is at +1 m. The left illustration of figure 4.2 shows the position of the two along the coast. The width of the active profile is the distance between the two.

4.2.2 Results

The right illustration of figure 4.2 shows the results of applying the Bruun rule along the coastline of Long Bay. The results show an average of 0.14 m of retreat per year. The areas that show higher amounts of retreat reach values of around 0.23 m per year. The retreat is significant and is caused by the shallow slope of the beach. Especially in the north, the distance between the +1 m above MSL line and -3 m below MSL becomes large.

Robinson linked past sea level rise to past shoreline changes. This results in a yearly coastline retreat of around 0.28 m/y. The use of the Bruun Rule gave the same average retreat of 0.14 m/y as found in this report. The difference may be because of factors such as variation in long-shore sediment supply, carbonate sediment supply and changes in the drainage characteristics of the wetlands which are not considered in the Bruun Rule. The difference indicates the uncertainty of the results and the effect of sea level rise could be more significant.

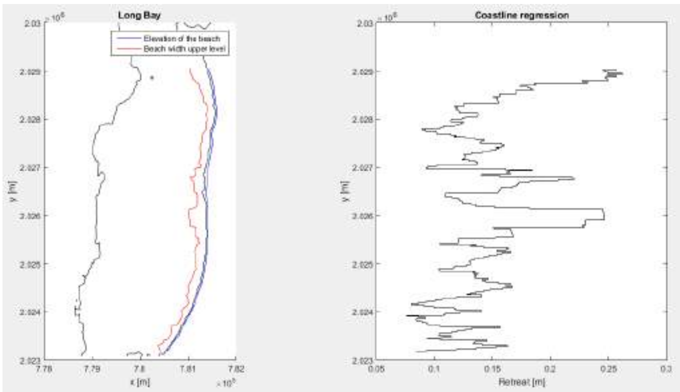


Figure 4.2: Recession or progradation of the shoreline caused by sea level rise [m/y]
Source: [Robinson et al, 2012]

4.3 Sediment balance

Sediment balance needs to be understood. Chapter 2 explained that offshore sediment losses and natural sediment production need to be understood in order to make up the sediment balance of Long Bay. In case of the offshore sediment losses we are interested in the pathways along which the sediment flows and the amount of transport.

4.3.1 Sediment pathways

The left illustration of figure 4.3 shows Eulerian velocities and flow directions of the water near the end of the simulation. Flow velocities of around 1 m/s are observed between the two reefs and north of the smaller reef. Shoaling over the reefs is visible. Along the beach behind the bay the general direction is towards the south and then towards the section between the reefs. South of the bay the flow first moves in northern direction along the beach. At a certain point the direction moves offshore. Further off the coastline the flow turn to the south. This causes disturbed flow patterns between the two opposite flows. The rising and falling tide have little to no influence on the flow magnitude or direction. The right illustration of figure 4.3 shows the magnitude and direction of sediment transport integrated over bed load and suspended and for all sediment grains throughout the bay at the same time step as the right illustration. The magnitude and direction strongly correlate with the Eulerian velocities. Where the flow velocities near the bed are higher than the critical velocity of the sediment, sediment transport occurs.

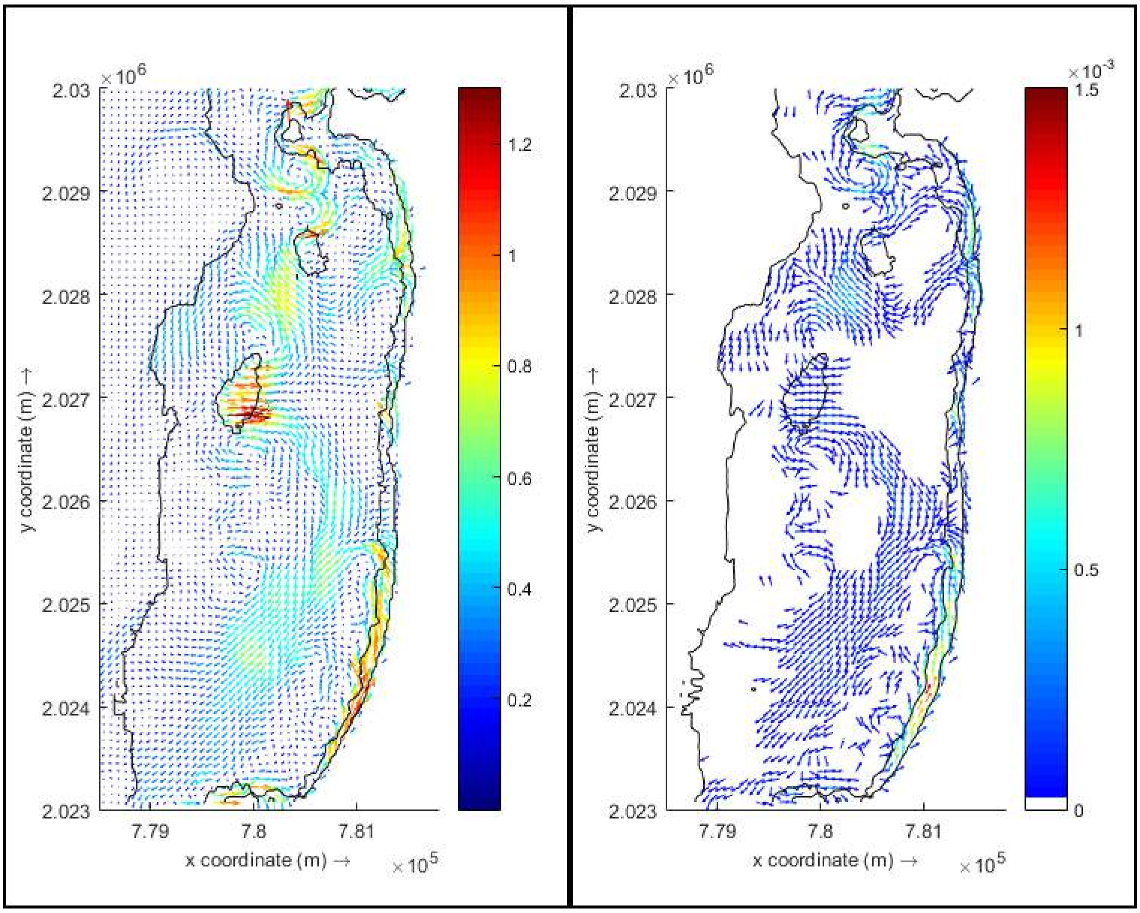


Figure 4.3: Eulerian velocities in m/s (Left), Sediment transport integrated over bed load and suspended and for all sediment grains in m/s (Right)

4.3.2 Long term sediment transport

The figures in the previous paragraph indicate the sediment pathways but do not show how much sediment is lost on the long term. Sediment is moved offshore during a storm event. During normal conditions sediment is pushed back onshore. This means that sediment does not necessarily have to be lost. However, waves are only able to affect the sediment up to a certain depth. This depth, where there is no significant net sediment transport anymore is referred to as the closure depth. Any sediment that lies beyond this depth will not be transported onshore during normal conditions. So in case of a storm event, any sediment that is transported offshore beyond the closure depth will be lost. For this coastline the closure depth is assumed to be at 3 m. Smith Warner used a depth of 2.99 m. [Smith Warner, 2007] Robinson et al 2012 used a similar closure depth of 3 meters. [Robinson et al, 2012] They based this on the boundary between the mobile sand carpet in front of the beach and the sea grass beds. Because the sea grass stabilizes the sediment it was assumed that this point is the maximum point of sediment transport. This is a reasonable assumption. The left illustration of figure 4.4 shows the closure depth for Long Bay. The right illustration shows the amount of volume lost along the coastline. This is the volume of sediment which is moves from the beach to a depth lower than 3 m below MSL. It is calculated by integrating the pre and post storm for each cross-shore profile between the closure depth and the last gridpoint onshore. The difference between the two surface areas is the amount of sediment which moved beyond the closure depth. This is multiplied by the y-dimension of the grid to get the volume in m3. The pattern found is similar to the coastline retreat which was expected.

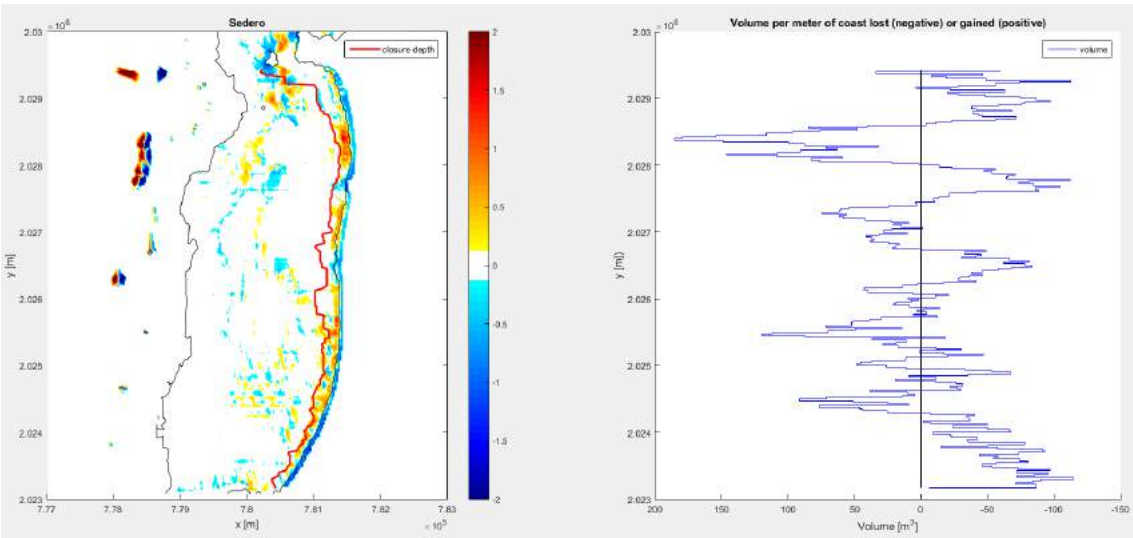


Figure 4.4: Cumulative sedimentation/erosion and closure depth (left) and amount of volume lost along the coastline (right)

The total volume lost from this event is 48,263 m3. This is caused by a storm event with a probability of exceedence of 1/100 years. The goal is to find long-term sediment losses expressed in volume per year. This means that this extreme event causes a yearly sediment loss of 482.63 m3. However, this is not the only type of storm event that occurs. Smaller storm events will cause less sediment loss but occur more frequent. This means that the yearly sediment losses caused by these storms can still be significant. Three types of storms with different intensities are simulated. The total volume lost after a storm is determined and translated to a yearly sediment loss per storm type. The total of these values is the total volume of sediment lost per year. Table 4.1 shows that this results in a total of around 6,000 m3 sediment loss per year.

Table 4.1: Total volume loss

Type of storm	**frequency [years]**	**Hs [m]**	**Tp [s]**	**Total lost volume [m^3]**	**Volume loss per year [m^3]**
Extreme	1/100	2,91	9	48263	483
Medium	1/10	2,34	6	21864	2186
Small	1/5	2,17	6	16523	3305
				Total	5974

4.3.3 Sediment production

Another part of the sediment balance which needs to be further understood is sediment production. By understanding sediment composition and the primary producers an estimation of the production quantity can be made.

Sediment characteristics and primary producers

Sediment can be produced by the local environment. The sediment properties given in appendix C show that the sediment at Long Bay is carbonate sand. The composition shows that the sediment consists of about one third bioclast, one third amorphous grains and one third recrystallized grains. Bioclast are skeletal fossil fragments of once living marine or land organisms in a marine environment. They range from coral fragments to echinoid fragments or halimeda and red algae. Amorphous grains can be formed by the micritization of bioclasts. In other words, the sand on the beach consists for a large portion of once living organisms from its own environment. The composition of the bioclast shows that it consists for the largest part of foraminifera, bivalves, halimeda and red algae. Foraminifera is the biggest contributor. Almost 50 percent of the bioclast consists of it. Comparing the composition of 1991 to 1980 shows that percentage of foraminifera declined and red algae increased. Foraminifera is epifauna living on the sea grass and its decline is likely due to the removal of sea grass beds or increased pollution caused by the development of the tourism industry. The percentage of bioclast as a whole within the sediment composition declined by about 3 percent. [Department of Geology and Geography, 2002] Only a very small percentage of bioclast comes from echinoids and corals. So there is hardly any reef material present in the sediment. Reef material comes from dead coral colonies. When these colonies are not used as new framework for the reef they disintegrate and are transported away. The dead colony then becomes part of the sediment. Whether it becomes part of the framework or not depends on its size, shape and hardness, the location of the colony and outside exposure such as the impact of storm waves or human contact. [Goreau, 1959] The small percentage of coral material in the sediment of Long Bay might be due to the orientation of the reef. Since the reef lies on the edge of the inner shelf, only the landward directed section of the reef could provide material into the lagoon. The seaward side of the reef is not likely to provide the bay with sediment. Comparing data from 1980 and 1991 shows that porites remains a very small percentage even though the coral would have been of better health in 1980. [Department of Geology and Geography, 2002] The lack of reef material in the sediment in both 1980 and 1991 means that the degradation of the reef through the years did not have an effect on the sediment production. The composition of the bioclast and lack of reef material also indicates that the production of sediment is mainly in the shallow lagoon area since that is where the main contributors flourish.

Production quantities

The previous paragraph showed that the production of sediment comes predominantly from bioclast. Foraminifera, bivalves, halimeda and red algae. Sediment production quantities are uncertain for most types of bioclast. For halimeda some research is done and it is estimated that this type of bioclast generates between 80 g CaCO3/m2/y and 2 kg CaCO3/m2/y depending on the conditions at the location. [Department of Geology and Geography, 2002] Smith Warner estimated that the total surface area of sea grass in Long Bay is around 4,000,000 m2. [Smith Warner, 2007] Assuming a sand density of 2,000 kg/m3 this would lead to a production of between 130 m3/y and 3,300 m3/y. So, under optimal conditions halimeda could possibly provide 3,300 m3/y. Halimeda is only part of the total bioclast so the total production could be higher. Under lesser conditions halimeda barely produces sediment. Whether this is the case for the rest of the bioclast as well is uncertain.

The exact amount of production at a certain point in time is difficult to quantify. Under optimal conditions, the total sediment production could be very significant and possibly be in the same order as found for cross-shore sediment losses. However, this does not have to be the case and sediment production under optimal conditions could be low and insignificant. There is not enough information to claim one or the other. The other uncertainty is the exact environmental conditions at Long Bay. It is not possible to accurately estimate the quality of the specific environmental conditions which constitute to sediment production. What we can say is that the environmental conditions in the past were good and better than in the present. The tourism industry was not present. Therefore, the pollution and other negative effects on the environment caused by this industry as mentioned in chapter 2 were not there. The local community also speaks of better environmental conditions during this time, most notably that the reefs were still connected as one large section. For this reason, the assumption is that in the past the environmental conditions were favorable. How much the environmental conditions degraded over the years cannot be said with confidence.

4.3.4 Balance

Analysis of the Xbeach simulations showed that the sediment pathways will be similar to figure 4.5. The annual sediment loss along these paths is around 6000 m3 per year. The sediment at Long Bay consists of bioclast, amorphous grains and recrystallized grains. The bioclast consists predominantly of foraminifera, bivalves, halimeda and red algae. They live on and around sea grass beds. Almost no material from coral is found in the sediment composition. This concludes that sediment production is mainly from sea grass and not from the coral reef. The production quantity cannot be easily assessed. There are two uncertainties, the quantity of sediment production under optimal conditions and the amount of degradation of the environment, specifically of the conditions which constitute to sediment production. This leads to different possible situations. If the optimal production is small, then the influence of the sediment production in the sediment balance for both past and present is not significant. In this case, the only remaining component of the sediment balance is the cross-shore losses of around 6000 m3/y. If the optimal production is large then there are two possibilities. If optimal production is large then this means that in the past the sediment production was significant. In the sediment balance, the sediment production might even have completely balanced the cross-shore losses. Over the years, the reduced environmental quality led to lower sediment production rates. This reduction leads to a more negative sediment balance meaning increased erosion rates. How much the production rate has lowered is not known it this point. If this reduction is significant then this means that the sediment balance changed from a situation where sediment production balanced the cross-shore losses to a situation where the cross-shore losses are the only significant component in the sediment balance. The other possibility is that the degradation is not that significant. This means that the sediment production in the present is lower than in the past but still significant. This means that sediment production is still a significant part of the sediment balance.

The most negative situation in the present is where environmental degradation was very high and there is no significant sediment production anymore. In this case, sediment losses are around 6000 m3/y. Long bay is around 6.5 km long. Assuming that the sediment redistributes evenly along the bay during normal conditions, the coastal line loses sediment in the order of 1m3/m/year. With an active zone between -3 MSL and +1 m MSL, the structural retreat is in the order of 0.25 m per year.

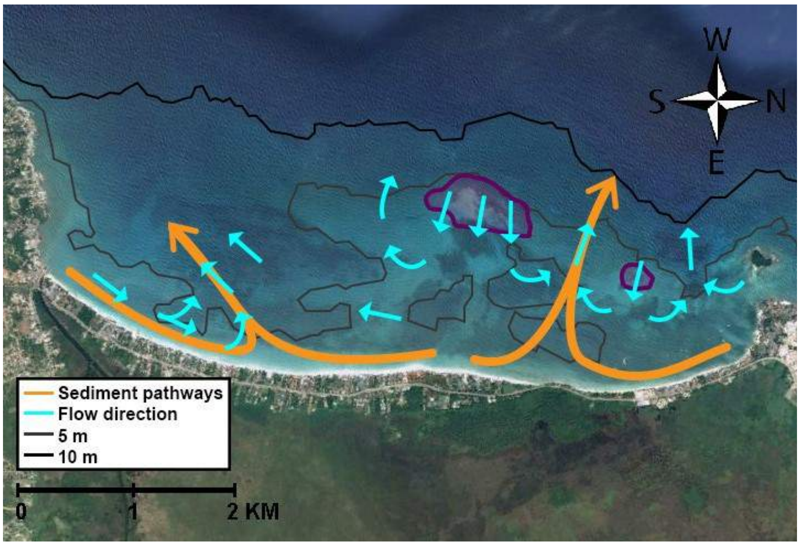


Figure 4.5: Sediment pathways and directions of flow

4.4 Reduced protection by reef

As mentioned in chapter 2 the environment is under pressure. The reef is a clear example of this. Among others, unsustainable fishing practices and the development of the tourism industry have degraded the reef from one large flourishing reef into two small reefs with low biodiversity. This change also reduced the coastal protection capacity of the reef. A reduction of the coastal protection capacity of the reefs has likely increased the amount of erosion at Long Bay. In the 1970s the reef was bigger, healthier and more diverse. In order to understand the impact of a degrading reef on the erosion of the coast, the historical reef is compared to the current state of the reef. This is done using Xbeach.

4.4.1 Xbeach simulation

The comparison of the two different reefs is made by modeling the historical reef similar to the simulation made in appendix E. In other words, the same simulation is made only now with a bathymetry conform the historical reef. The bed friction and non-erodible layer are also changed accordingly. All other parameters are left unaltered. The difference between this simulation and the original can then be compared.

Limited detailed information is available about the quality of the historical reef. The local community explains that the two reefs used to be bigger and connected to each other. The reef was also more diverse. Based on this information a modification of the bathymetry was made. The changes can be seen in figure 4.6. The reef is larger, connected to each other and higher. The shallowest part is only 0.5 m below mean sea level. This value is based on flourishing conditions for reefs. Changes to the non-erodible layer and the bed friction layer are made accordingly. The friction factor of 0.2 for a healthy reef is used instead of the 0.14 used in the reference scenario. The complete results of the simulation is given in appendix J.

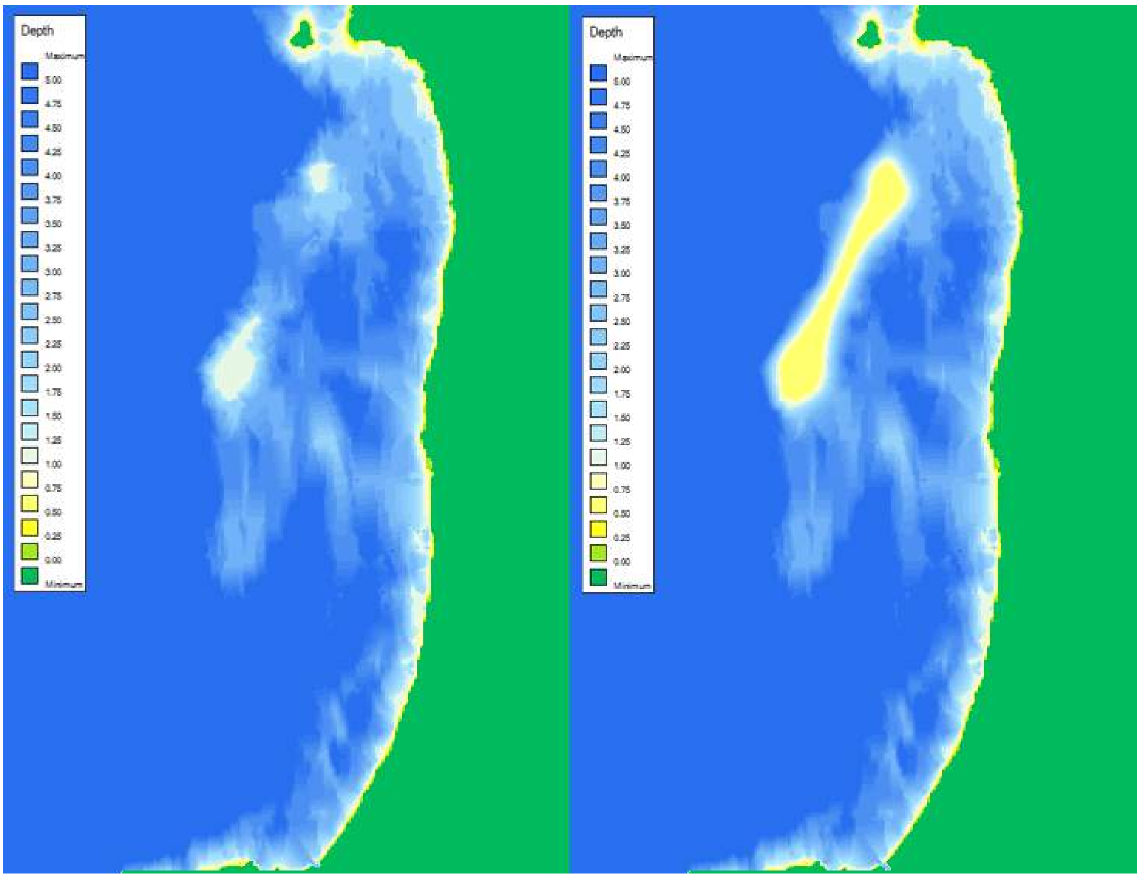


Figure 4.6: Bathymetry for reference scenario (left) and historical reef scenario (right)

4.4.2 Impact of extreme events

The change results in a different coastline retreat compared to the reference simulation. Figure 4.7 shows the coastline retreat of this situation. This can be compared to the reference scenario. The southern sections of coastline do not show significant change on the coastline compared to the reference model. This was expected as the conditions remained almost unchanged along these sections of coast. The section behind the healthy reef shows a reduction in erosion of the coastline. Most noticeable is the reduction in the middle, where there was no reef in the original situation. In the reference simulation there was a large amount of erosion at this location. The coastline just south and north of the reef shows a slight increase in retreat. The historical reef reduced the impact of the coast locally but is not able to prevent erosion sufficiently.

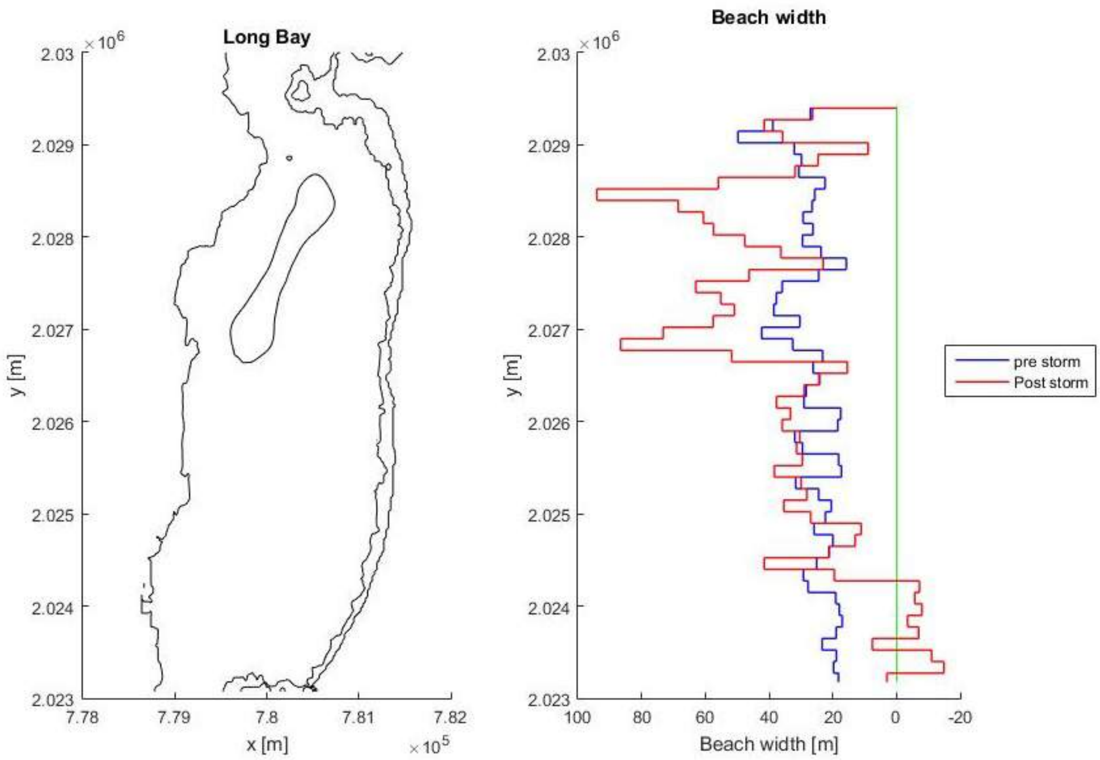


Figure 4.7: Cumulative sedimentation/erosion after storm event

4.4.3 Sediment Balance

The sediment pathways and volumes have likely changed due to the altered scenario. A lower sediment loss shows whether the historical reef helped to maintain the sediment balance.

Sediment pathways

Figure 4.8 shows the Eulerian velocities (left) and the sediment transport integrated over bed load and suspended and for all sediment grains, both in m/s. The direction of flow changed a lot compared to the reference scenario. Since the reef is now one large area there is no offshore flow between the two sections anymore. The flow over the entire reef area is now onshore directed. On both sides of the reef the flow changes back offshore due to shoaling. Since the offshore flow between the reefs is no longer present, the offshore directed water has to find another path. This is clearly visible as the flow between the southern end of the reef and the coastline increased. The flow velocities north of the reef also increased. Just as with the reference scenario, the sediment transport and magnitude strongly correlates with the flow velocities and direction. This means the sediment transport mostly changed just as the Eulerian flow did. A notable change is that in this case there is slight sediment transport towards Bloody Bay which was not present in the reference scenario. Another difference between this simulation and the reference scenario is that the wave height behind the reef is lower. The result is a smaller magnitude of sediment transport behind the reef.

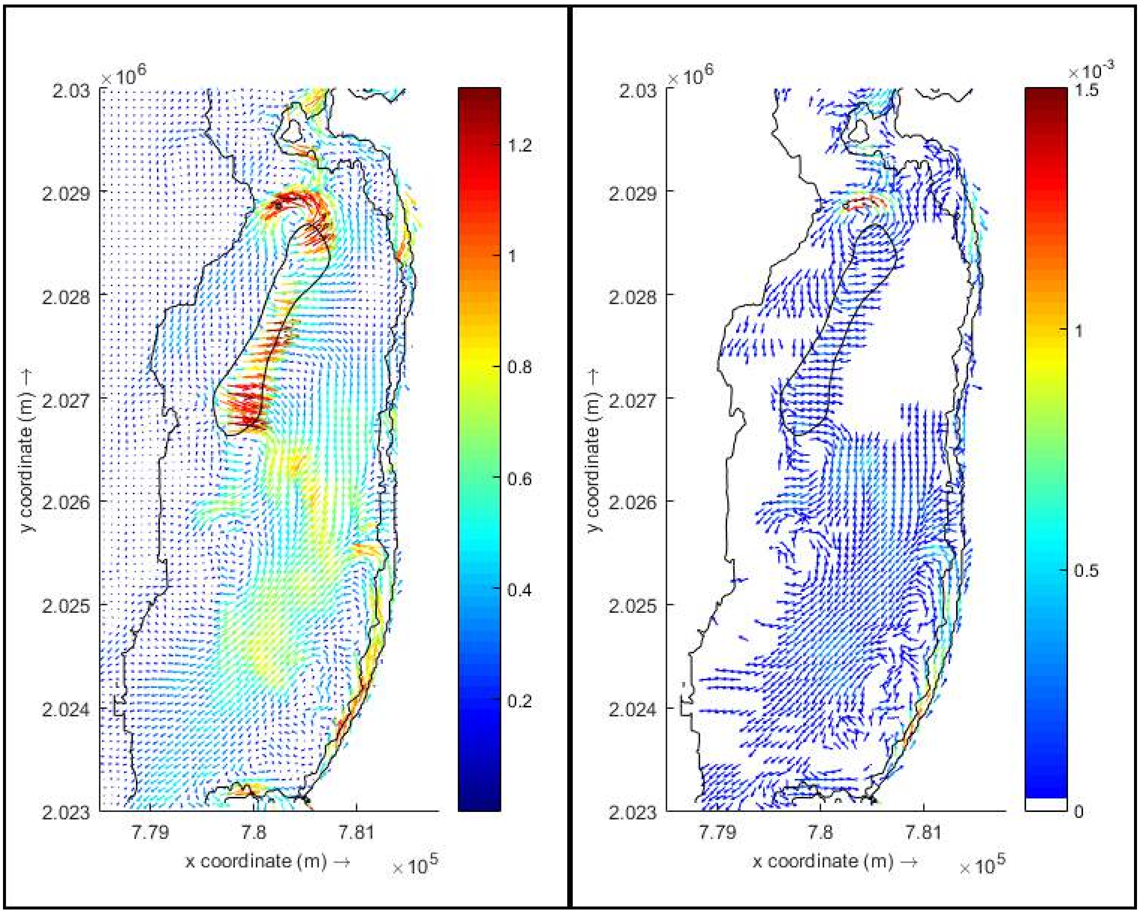


Figure 4.8: Eulerian velocities in m/s (Left), Sediment transport integrated over bed load and suspended and for all sediment grains in m/s (Right)

Long term sediment transport

The long term sediment transport is determined in the same way as for the reference scenario explained in the previous section. The right illustration of figure 4.9 shows the amount of volume lost for this scenario in pink compared to the reference scenario in blue. The pattern is similar to the coastline retreat. Again, the coastline behind the middle section of the reefs is affected less than for the reference scenario.

Table 4.2 gives the total sediment loss per year. This is determined in the same way as for the reference scenario. For this case, the total loss equals 5685 m3/y. Compared to the reference scenario, which was 6000 m3/y, this is not a considerable reduction.

Table 4.2: Total volume loss

Type of storm	**frequency [years]**	**Hs [m]**	**Tp [s]**	**Total lost volume [mˆ3]**	**Volume loss per year [mˆ3]**
Extreme	1/100	2,91	9	46836	468
Medium	1/10	2,34	6	19760	1976
Small	1/5	2,17	6	16204	3241
				Total	5685

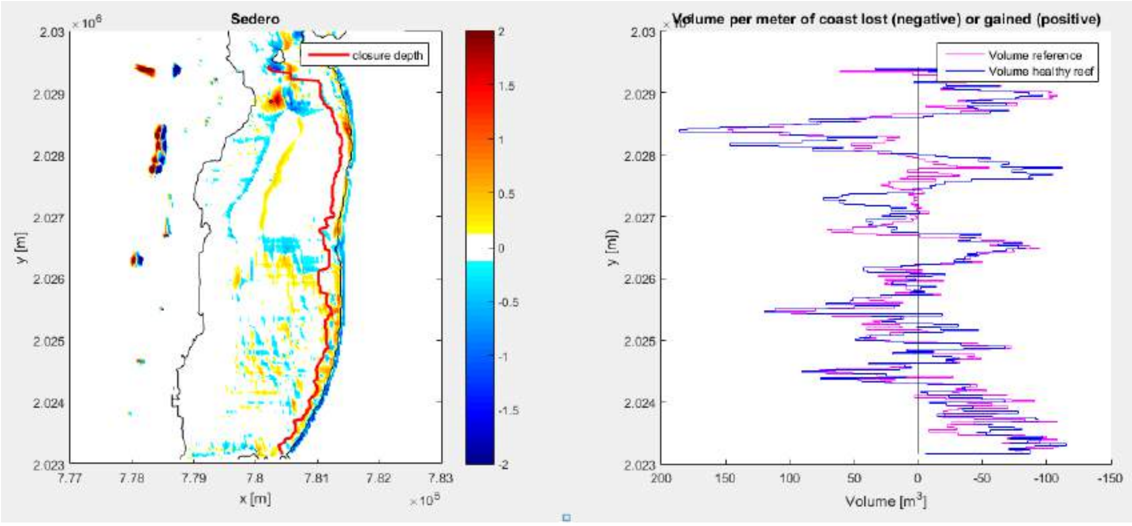


Figure 4.9: Cumulative sedimentation/erosion and closure depth (left) and amount of volume lost along the coastline (right)

4.4.4 Significance of reef

In conclusion the historical reef was on average better at protecting the coast behind the reef than the current situation at Long Bay. Coastline retreat is reduced behind the reef. Sediment loss is only reduced by a small amount. Because of the reef, the sediment pathways and flow directions changed to what is illustrated in figure 4.10. The healthy reef does not completely prevent erosion. So, from a coastal protection point of view a healthy reef offshore is not sufficient to mitigate the erosion problem by itself. This does not mean that there are no benefits to potentially restoring the reef. The wave impact on the coast is definitely reduced. Furthermore, chapter 2 explained that a healthy reef provides more ecosystem services than just coastal protection.

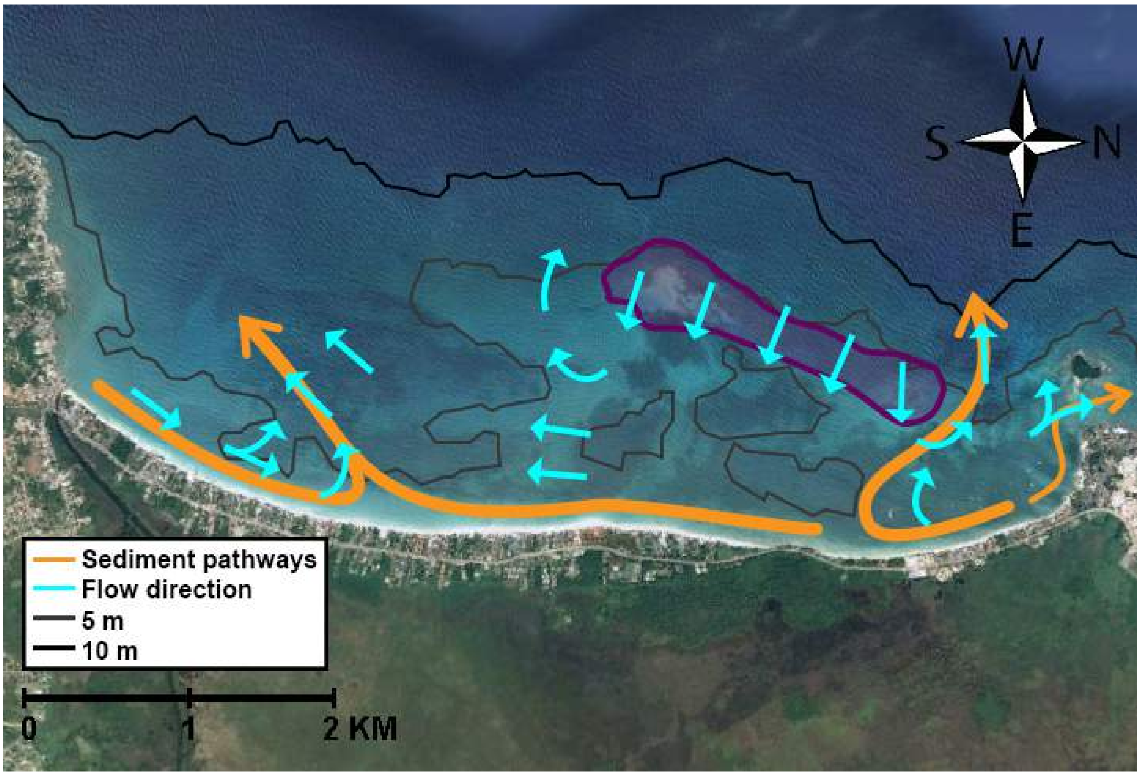
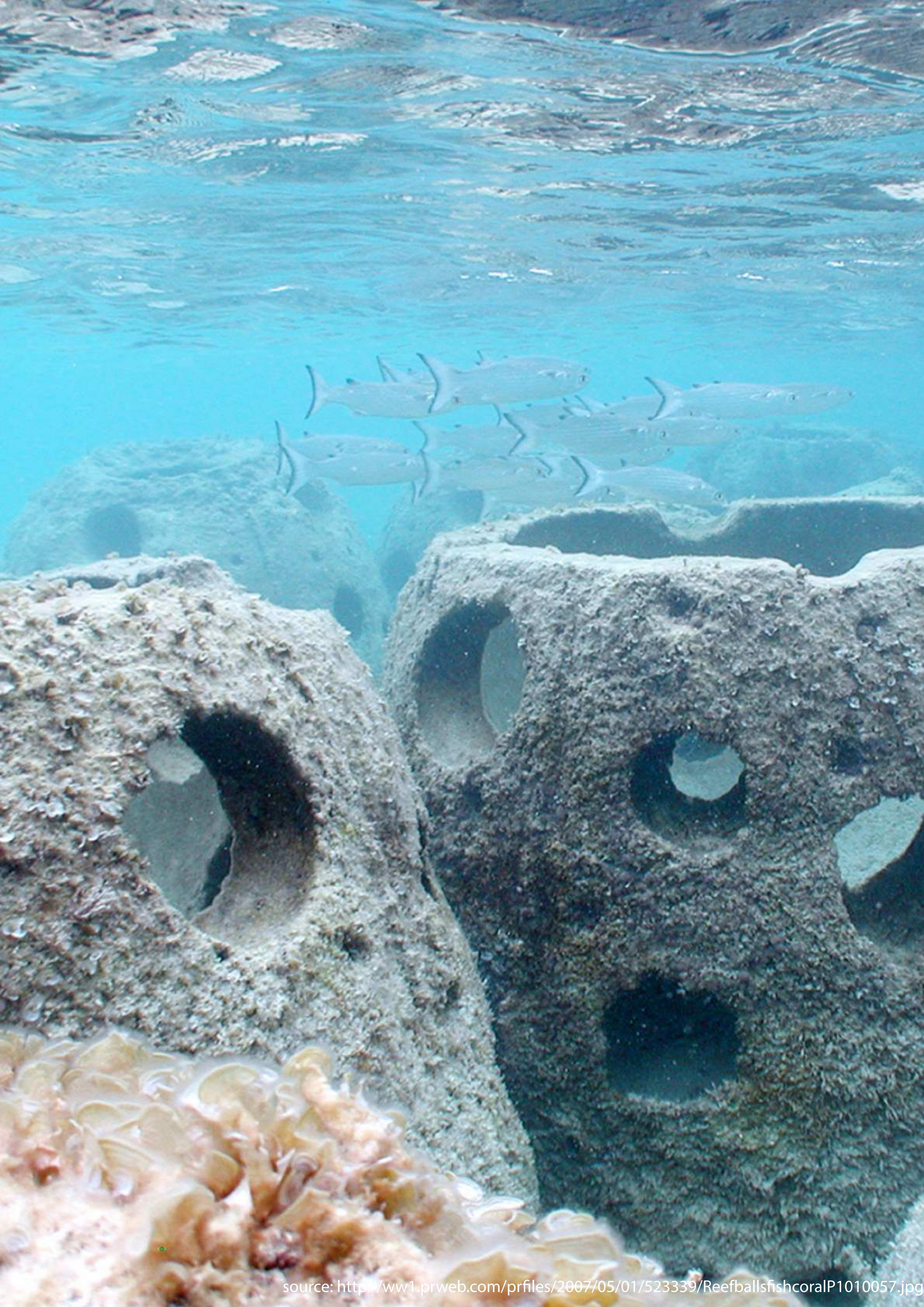


Figure 4.10: Sediment pathways and directions of flow

4.5 Conclusion

In conclusion, the erosion occurring at Long Bay through the years is caused by a combination of factors. Hurricane events lead to large amounts of erosion. The short term impact is a danger to the hotels along the beach. Most of this sediment is not transported beyond the closure depth during one event, so sediment is not immediately lost. On the long term, it is expected that this sediment redistributes along the beach during normal conditions. However, sediment that travels beyond the closure depth will travel offshore following two main sediment pathways. The amount is estimated to be in the order of 6000 m3/y. The degradation of the reef is not one of the primary cause of the current erosion problem at long bay. The coastal protection capability of the historical reef was better but it did not completely prevent the erosion. The long term sediment losses remain similar in this scenario compared to the reference scenario. The impact of extreme events is reduced locally. The sediment balance also includes sediment production. The production quantity cannot easily be assessed leading to different possible scenarios. A scenario where the optimal sediment production is low and one where this production is high. Since there is not enough information to disclose one of them, both will be taken into account. If the sediment production under optimal conditions is low, then the sediment balance will not be strongly affected by a change in sediment production. In that case the difference between past and present must be caused by intensification of the storm intensity. This would then have been lower in the past. A combination of degradation of the reef and intensification extreme events caused increased sediment loss. For this scenario the sediment balance is equal to -6000 m3/y. This is equal to a coastline retreat in the order of 0.25 m/y. Sea level rise also causes regression of the coastline. An average of 0.14 m/y is estimated. This makes the total coastline retreat around 0.4 m/y. The accuracy of the sediment losses is low due to the limited wave data and fact that the simulation is of storms with one wave condition. Still, this coastline retreat that is found is similar to values found in literature which were already stated in chapter 2. Sea level rise is responsible for about 35 percent of the total coastline retreat which is a significant amount. The other scenario is that the sediment production under optimal conditions is large. This means that in the past, the sediment production was a significant part of the sediment balance. The added sediment could have been in the same order of quantity as the cross-shore losses. Over the years, the reduced environmental quality led to lower sediment production rates. This reduction leads to a more negative sediment balance meaning increased erosion rates. How much the production rate has lowered is not known at this point. In this case, lowering of the sediment production due to environmental degradation is at least part of the cause of the increased erosion rates and possibly even the most dominant aspect. Under this scenario, it is also possible that the sediment budget is actually in balance because production rates still make up for the losses. This means that the erosion rates found at Long Bay could be primarily due to sea level rise. Both scenarios will require different solution strategies. Now that the system is understood different alternatives can be found to mitigate the erosion problem at Long Bay. On the short term, the impact of extreme events needs to be reduced. On the long term, the coastline retreat caused by the sediment imbalance and sea level rise should be minimized.



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Chapter 5

Identify realistic alternatives

The system analysis shows that a large contributor to the problem is the extreme event. Sea level rise also caused coastline regression. The environmental degradation of the coral reef slightly increased erosion and changed the flow patterns in the bay. The degradation of sediment producers might have been a cause of the increased erosion rates. The future perspective is that these causes continue to occur. Sea level rise and the occurrence of extreme events is expected to get worse due to climate change. Sea level rise is expected to continue and even accelerate. Extreme events are expected to become more frequent with increased intensity. The environmental degradation will likely continue in the future if no action is undertaken. This means further degradation of the reef leading to a reduced coastal protection capability and further degradation of the sediment producers leading to a less stable system. Furthermore, the tourism industry will continue to expand putting more pressure on the system. The goal of this chapter is to generate a number of alternatives which meet the objectives defined in chapter 3. Determining alternatives requires a strategy which ensures that a large range of possibilities is explored in an efficient way while still focusing on the objective. To do this, general solution strategies are used as a guideline together with the Building with Nature design guideline. This leads to a range of solutions from passive to active coastal protection and from no BwN to full BwN solutions. The alternatives are simulated to better understand their effectiveness.

5.1 Strategy

This section explains the main strategy for generating alternatives. The strategy is to apply the building with nature design guidelines within general solution strategies. The first section explains what a full building with nature design consists of. The second section explains which solution strategies are considered.

5.1.1 Building with nature design guideline

A design is Building with nature when it is utilizing natural processes (utilizing services) as well as creating opportunities for the development of new nature (delivering services). Solutions which utilize natural resources use this resource to for instance lower construction and maintenance costs, or make a solution more sustainable by using less energy or less material. Solutions which create more opportunities for the development of new nature strengthen the functioning of the system. When these two are both acquired in a design, you can call it a full BwN design. [van Raalte,] When finding alternatives, this will be looked for.

5.1.2 Solution strategies

There are several different solution strategies to follow. The 4 main strategies are the do nothing scenario, managed retreat, hold the line and advance the line. The do nothing strategy means no intervention is made. The do nothing scenario is used as a reference scenario. It is used to compare other solutions with. The other solution strategies are discussed.

Managed retreat

The strategy managed retreat means that the erosion is allowed to continue and focuses on compensating the affected stakeholders and relocation. If the scenario occurs where sea level rise is the primary cause of the erosion then managed retreat is a viable option. Coastal erosion due to sea level rise can only be mitigated by retreating or raising the ground level where the hotels are situated on. As mentioned in chapter 2, the hotels are built on a very narrow strip of sand between the water line and the wetlands. This means that there is little space to retreat. This solution also means that the sandy beach, which is the main tourist attraction of the area, will continue to regresses. If sea level rise is not the main cause of the erosion then other solutions will be more preferable. The impact because of this solution strategy will have a very negative effect on the tourism industry, will be costly on the long term and is not a sustainable solution.

Hold the line using soft solutions

A solution strategy can be holding the line by using nourishments. Regular nourishments restore the coastline where sand is lost. These can be called soft solutions. The new sediment can be placed in various locations in the cross-shore profile with different results and impact.

Hold the line using hard solutions

These are solutions which mitigate the erosion of the beach by reducing the natural dynamics. This can be done in a number of ways, such as sea walls, offshore breakwaters, revetments, groynes, etc. The structures can be classified based on their position in the coastline. They are generally perpendicular to the coastline or parallel to the coastline onshore, nearshore and offshore.

Perpendicular to the coastline refers to groynes. Two groynes guide the South Negril River into the bay. Several groynes have been placed at Long Bay by hotel owners. They are not desired as they break the continuous coastline which is part of the aesthetic attraction of Long Bay.

Parallel to the coastline onshore are structures such as seawalls or revetments. Sections of seawall are built on the northern part of Long Bay and in front of several hotels. [Smith Warner, 2007] Seawalls often cause a negative effect on the coastline. Waves which reflect off the seawall cause scouring holes in front of the structure.

Parallel to the coastline nearshore refers to breakwaters which are situated relatively close to the coastline. They reduce wave impact on the section of coastline behind it. Multiple breakwaters of this kind are often placed next to each other with some distance between them. The change of currents usually results in either a tombolo or a salient. Smith Warner proposed a solution using nearshore parallel breakwater on the southern half of the coastline which resulted in a strong reduction of the erosion. [Smith Warner, 2007] However, the use of these type of breakwaters has several downsides. First of all, a lot of material is needed for a coastline of this length. Secondly, the breakwaters obstruct water sports operators and other boats leaving from the beach. Lastly, the breakwater must be constructed submerged to not ruin the aesthetics. And even then, a submerged breakwater may still be visible in the clear water. For these reasons nearshore parallel breakwaters are not recommended. A variation to this type of structure is creating low parallel walls at minor depth. They can prevent sediment from traveling offshore. These are not considered for the same reason as for nearshore parallel breakwaters.

Parallel to the coastline offshore refers to breakwaters which are built further away from the coastline. The solution proposed by the government is an example of this, using an offshore breakwater as coastal protection. This type of structure is most suitable for Long Bay as it does not impact the beachfront. Depending on the type of breakwater the impact on the environment and aesthetics can be minimized.

Hold the line by restoring natural sediment production

Chapter 4 showed that there is a possibility that the sediment production reduced over the years and that this phenomena is part of the cause of the increased erosion rates. If this is the case, then restoring the natural sediment production could be a solution. This strategy focuses on improving the environment to create the optimal conditions for sediment production.

Advance the line

Advancing the line means moving the coastline seaward. This creates a buffer. More room between the water line and the beach front development means a reduced probability of damage. The added beach can be positive for tourism. The cause of erosion is not stopped with this solution so, depending on the nourishment strategy, some form of maintenance is required.

Hybrid solutions

Finally, a hybrid approach is possible which combines hard and soft solutions. Hybrid approaches often score well because they utilize the positive effects of both hard and soft solutions. However, this comes at the cost of them often being the most complex and expensive.

The possible strategies for this case are restoring the natural sediment production, using a nourishment to either hold or advance the line, using a breakwater to hold the line, or creating a hybrid approach by combining these strategies. Managed retreat will not be further considered. The expectation is that sea level rise is not the primary cause of the erosion. The erosional hot-spots and accretion zones show that the coast is influenced by more than just sea level rise. However, further research needs to be done on this topic to better understand the influence of sea level rise on the erosion of Long Bay. This means that, in a new design cycle, the managed retreat solution strategy might need to be reconsidered. The following sections will discuss the possibilities of the remaining solution strategies and narrow down solutions.

5.2 Restoration of the natural sediment production

Chapter 4 showed that sediment production mainly comes from sea grass. Restoration of the sediment production can be achieved by an overall improvement of the environment. This creates better conditions for sediment production but also improves other natural features such as the coral reefs and the wetlands. These features provide additional ecosystem services.

5.2.1 The cause of degradation

Chapter 2 explained how the environment at Long Bay is impacted. Pollution from the hotels is one of the sources. Pollution of the wetlands remains an issue. Water coming into the bay from the South Negril River is of poor quality. This leads to a high biochemical oxygen demand. This pollution negatively affects the growth conditions for the sea grass and the reefs. How far this pollution extends into the bay is uncertain. If the polluted water does not travel far then the affected area remains limited. This will depend on the currents in the bay and the amount of polluted water. The simulation results in chapter 4 show a northern directed flow near the river outlet. This means that it could be possible that the pollution travels away from the source further into the bay. More detailed research would be needed to support this. Sea grass beds are also impacted by hotel owners removing sea grass at their section of the beach. This reduces the total surface area where sediment can be produced. Water sport practices and fishery impacts the reefs.

5.2.2 The improvement

Reducing pollution can be achieved by establishing proper waste disposal for the hotels and resorts. This means that the wetlands are not polluted because they will not dump this in the wetlands anymore. A well-functioning waste water treatment plant will reduce pollution significantly. The wetlands should be preserved with clear regulations. As mentioned in appendix B, healthy wetlands provide many ecosystem services. The sustainable waste disposal means that no polluted water enters the bay. This means that the water quality will improve. The sea grass beds should be preserved. Preferably, the sea grass beds near the coastline are also allowed to regrow. Not only does this equal more surface area for sediment production, but the sea grass also stabilizes the bottom. This leads to a more resilient coastline. For this to succeed, it is important that the hotel owners understand their impact on the environment and are willing to make a change. The quality improvement also benefits the reef. This could enable the reef to restore itself to a degree. To further allow this to happen strict regulations on fishing and water sport practices are needed. Without this preservation natural restoration of the reef becomes less probable. Improvement of the reef could improve its wave reduction capability. The solutions show that most of the improvement comes down to more strict policies and regulation. This should be combined with creating increased awareness. Understanding why the environment needs to be protected is just as important as the actual regulations. Once the environmental conditions improve, the restoration process can be accelerated by planting.

The growth opportunities of the sea grass can be improved by reducing pollution and allowing sea grass beds to develop. This leads to larger and healthier sea grass beds. Under these conditions the sediment production rates will increase. It is uncertain how big the effect of improving the environment is. As explained in chapter 4, the effectiveness of the method depends on the actual production rate under optimal conditions and the amount of improvement caused by environmental restoration. Nevertheless, the improvement will provide more services than just sediment production.

5.2.3 Costs

The cost of the restoration of the natural sediment production is assumed to be low. The actual costs cannot be quantified. No indication is available for the cost of improving waste disposal and restoring sea grass beds. It is also uncertain what the current stat of the waste water treatment plant is. This uncertainty along with the unknown effectiveness of the method means that this strategy requires more research before potentially becoming a viable solution.

5.3 Nourishments

Placing nourishments is a common method to counteract structural coastal erosion. The sediment can be placed in different ways and at different locations within the coastal zone. Each method has its own strengths and weaknesses. Appendix F explains the different ways a nourishment can be applied. Around 42,000 m3 of volume is estimated to be required. This is based on the yearly sediment loss as determined in the simulations. The actual required volume can differ but this serves as an initial indication. An additional buffer volume of 48,000 m3 is placed on the northern section of coastline to obtain a safe and wide beach. In the following sections four types of nourishments are treated as possible solutions. The designs are compared to each other to understand which once are most suitable.

5.3.1 Designs

The following section elaborates on possible nourishment schemes for Long Bay. Based on the information given in appendix F, four nourishment designs are determined. These are a beach nourishment, shoreface nourishment, concentrated nourishment and a nourishment at the edge of the bay. All nourishment designs are based on the same lifetime of 7 years. The large scale nourishment is not explicitly considered as a design. However, based on the results of the concentrated nourishment it can be said if upscaling that design into a large scale nourishment could be feasible. Figure 5.1 shows the nourishment locations for the different designs.

Figure 5.1: Nourishment designs

1. Beach nourishment

The first nourishment design is a beach nourishment. Placing it just above high water is the most economical. This results in a high, wide beach. Discharge pipelines are placed. The initial beach advancement is lost in a short amount of time due to redistribution of the sediment. However, the sediment itself it not lost as it is merely redistributed. For the public this may seem like the nourishment has failed. So, shaping the nourishment so that this change of slope is small is preferred. The location and quantity along the coast is conform the distribution as described in appendix F.

2. Shoreface nourishment

This design focuses on shoreface nourishments. The nourishment should be placed within the shoreface. This is the area between the closure depth and the mean low water level. So the nourishment should be placed in an area that is less deep than -3 m below MSL. The berm needs to be parallel to the beach with a minimum length of 10 times the local wave length, or 100 times the local water depth. The crest width should be about 5 to 10 times the local water depth. Side slopes are around 1 to 30/50 and the end slopes around 1 to 100. [van Rijn L.C. and Walstra D.J.R., 2004] The total volume and distribution of the sediment is the same as for the beach nourishment. A total of 42,000 m3 is divided over the 7 sections along the coastline.

3. Concentrated nourishment

The third design places concentrated nourishments where applicable. The sections specified in the beach and foreshore nourishments is used as a basis for the nourishment locations. The same amount of sediment needs to be supplied to Long Bay only now more concentrated. Concentrated nourishments cannot be placed anywhere. In order to be effective, currents should redistribute the sediment towards the correct longshore direction. Together with the identified sediment pathways as given in figure F.2, a possible nourishment scheme can be found. The volume of section 1 is placed at the most northern point as a concentrated nourishment. The sediment pathways show a southern directed transport along this part of the coast so the nourishment will likely redistribute along this section of coast. The volume of section 5 and half of section 6 can be placed at the northern side of section 5. The volume of section 7 and the other half of section 6 is placed at the most southern point as a large scale nourishment.

4. Edge of the bay nourishment

The final nourishment design is called the edge of the bay nourishment. As the name suggests, the nourishment is not placed in the active zone but is placed on the outer edge of Long Bay. Three nourishment locations are defined. The locations are given in figure 5.1. The first two are placed in the south. The first one at the edge of the bay and the second one a bit further east. This is done to determine whether this makes a large difference in effectiveness. The third location is in the north. Based on the sediment pathways the most suitable location is south of Booby Cay. This is still near the edge of the bay and the sediment pathways are directed towards the coast. Since a percentage of the nourishment will not reach the coast more is placed than determined in the previous section. A volume of 84,000 m3 is placed at the locations. This is double the required amount for the coastline. As a first simulation this is enough to understand the effect of this type of nourishment.

5.3.2 Costs

The costs of the nourishment alternatives depends on the availability of local sediment sources and the method of implementation. Appendix F indicated methods of implementation and the possible local sediment sources. The cost of placing a nourishment is between 25-40 USD/m3 if the sediment comes from a local source. If third party material is required, then the costs could go up to 120-150 USD/m3. The nourishment alternatives places 42,000 m3 of sediment every 7 years and an initial 48,000 m3 for the buffer zone. For this project it is assumed that the sediment can be obtained between the 20-50 meter depth lines offshore of Long Bay. This would make the initial costs for placing the first nourishment and the buffer zone between $2.25 - $3.6 million dollars. After that between $1 and $1.7 million dollars is required every 7 years. This is equal to an investment of between 150,000 and 240,000 dollars per year. If the sediment cannot be obtained locally then the costs go up significantly. There are some differences between the alternatives. A large part of the costs is the mobilization and demobilization. Concentrated nourishments for instance will not require the extensive amounts of pipelines that beach nourishment will require so they are likely less expensive. The edge of bay nourishments could be most cost effective. More sediment is placed but the placement method is far less complex. The specified costs are a rough estimation. Contractors would have to be approach in order to obtain a realistic estimation of the total costs.

5.3.3 Simulation results

All nourishments are simulated in Xbeach. The fourth design has three nourishment locations which are modeled separately. The results of the simulations are given in appendix J. The simulation uses the same settings as for the reference scenario. The effectiveness of the designs is based on the sediment transport during an extreme event. In reality, onshore directed sediment transport is generated under normal wave conditions. These conditions cannot be easily modeled. Therefore, the results from storm events are used. The sediment transport directions that occur during an extreme event are assumed to indicate long term sediment pathways. The results can be compared to each other to determine the most promising design.

Yearly sediment loss

A nourishment adds a sum of sediment to the location. This amount compensates the yearly sediment for a number of years. So, the goal of the nourishment is not to reduce the yearly sediment loss, it merely compensates for it. However, when the nourishment scenario causes a large increase in yearly sediment loss, the nourishment may be inefficient. This means that a large portion of the nourished material is quickly lost or that the change of currents due to the new coastline configuration results in increased sediment loss at other parts along the coast. The yearly sediment losses for the different nourishment scenarios, as given in table 5.1 show that the yearly sediment loss remains similar to the reference scenario. The largest increase happens in case of a beach nourishment. Still, this increase is only 4 percent.

Table 5.1: Yearly sediment loss for all nourishment designs

	Reference	Beach	Shoreface	Concentrated	Edge 1	Edge 2	Edge 3
Yearly erosion [m3/y]	5974	6212	6124	5922	6033	5960	5572
Average retreat per year [m/y]	0.24	0.25	0.24	0.24	0.24	0.24	0.22
Erosion reduction [%]	-	-4%	-3%	1%	-1%	0%	7%

Beach nourishment

The beach nourishment does not cause large changes in sediment transport directions. The change in beach width after a storm improved compared to the reference scenario meaning not all sediment is washed away after one storm. Long term sediment loss did increase slightly. This could be expected since the coastline is moved close to the closure depth. This means that the sediment is transported offshore more easily. Furthermore, the initial beach width gained from the nourishment will reduce naturally due to redistribution of the sediment over the active profile. This sediment is not lost because it remains in the system but the beach width does reduce. The main flow of currents and sediment transport is not changed by the nourishment. This means that on the long term, the nourishment will be transported south and then offshore.

Shoreface nourishment

The sediment transport magnitude and direction near the concentrated nourishments is given in figure 5.2. The northern nourishment shows a sediment transport directed towards the beach and to the south. This means that the sediment gets redistributed and will move onshore. The second nourishment, near the beach between the two reefs, also shows transport directed onshore. The third nourishment will not work well. The sediment transport directions change often. This causes part of the nourishment to move offshore. The vicinity of the large offshore directed flow south of the nourishment further increases offshore flow. The southern nourishment shows sediment transport in alongshore direction. There is no clear onshore directed sediment flow. A feeder berm should show this for it to be effective. Redistribution of sediment still occurs but this type of nourishment is not effective at this section of beach. In conclusion, the shoreface nourishment may work for the northern section of beach and the area between the reefs.

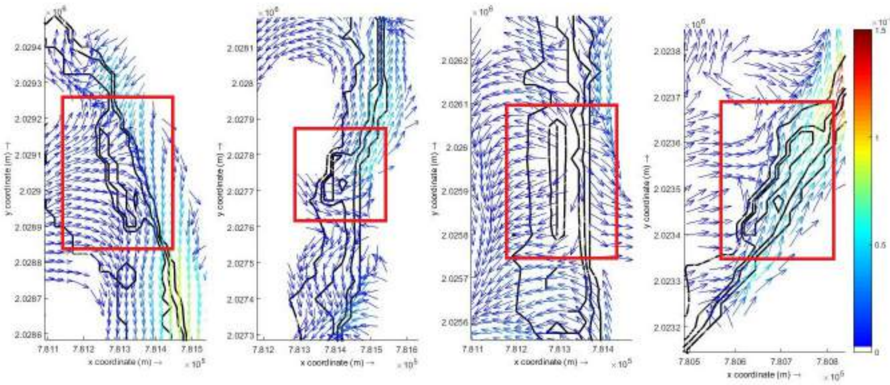

Figure 5.2: Sediment transport magnitude and direction for the four shoreface nourishment in order from north to south

Concentrated nourishment

The sediment transport magnitude and direction near the concentrated nourishments is given in figure 5.3. The concentrated nourishment in the north shows a southern directed sediment flow as intended. North of the nourishment the flow moves in the other direction. This means that the nourishment is spread out in both directions. The simulation shows positive results. An optimal location could be found which benefits as much coastline as possible on the long term. The nourishment placed in the center of the bay does not perform as desired. It is supposed to supply the beach to the south of itself with sediment. However, the sediment transport directions at this location are not consistent and often change direction. Furthermore, the point where the flow from the south moves offshore is not far from the nourishment site. This means that the length of coastline this nourishment could supply to is relatively small. This further reduces its use. The southern placed concentrated nourishment shows sediment transport occurring in northern direction. This is desired. The bathymetry changes during this storm show that almost all of the nourished sediment is redistributed by the end of the storm for all three nourishment locations. This also applies to the smaller simulated storms. For this reason it is assumed that the sediment is spread out over the section of beach in a short time after the nourishment. In conclusion, the concentrated nourishment is promising for the southern and northern section of beach. The sediment seems to redistribute in a short time.

Edge of the bay nourishments

This nourishment design contains three locations modeled separately. The sediment transport magnitude and direction near the nourishment locations is given in figure 5.4. The first nourishment location results in some sediment transport directed towards the bay. This flow is local. The simulation shows that the sediment moves east. This is a positive result. On the long term the sediment may travel all the way towards the coastline. The second nourishment is transported towards the coast. The simulation shows the nourishment moving a significant distance towards the coastline. On the long term this nourishment will definitely supply the coast with sediment. This location is much more effective than the first location. However, it is also further into the bay than the first one so the advantages created when placing a nourishment far away are reduced. The northern nourishment location shows sediment transport directed towards the bay. This seems like a positive results. However, the sediment pathways show that the direction of flow quickly

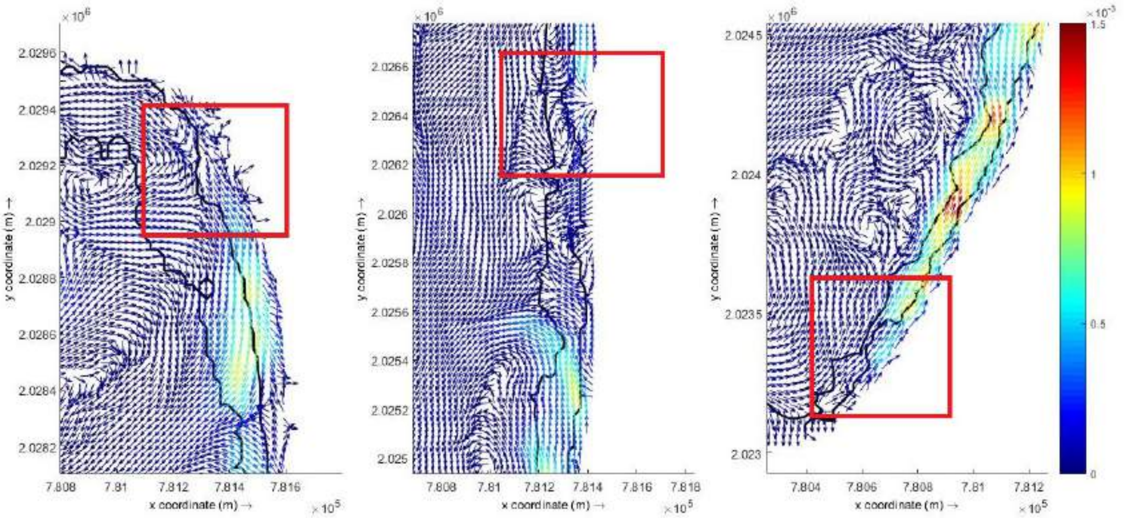

Figure 5.3: Sediment transport magnitude and direction for the northern (left), center (middle) and southern concentrated nourishment(right)

changes to an offshore directed flow between the northern reef and Booby Cay. Most sediment is going to follow this path and never reach the coastline. This makes it an unsuitable location. In conclusion, the location with the most effect on the coastline is the second location. Still, this does not necessarily make it a suitable solution for Long Bay as the sediment pathway that is created reaches the South Negril River. The nourishment may block the river's flow. Two small groynes guide the river into the bay. These groynes could further prevent the sediment flow. This means most of the sedimentation occurs in the mouth of the river where the fishing village is. This is not desired.

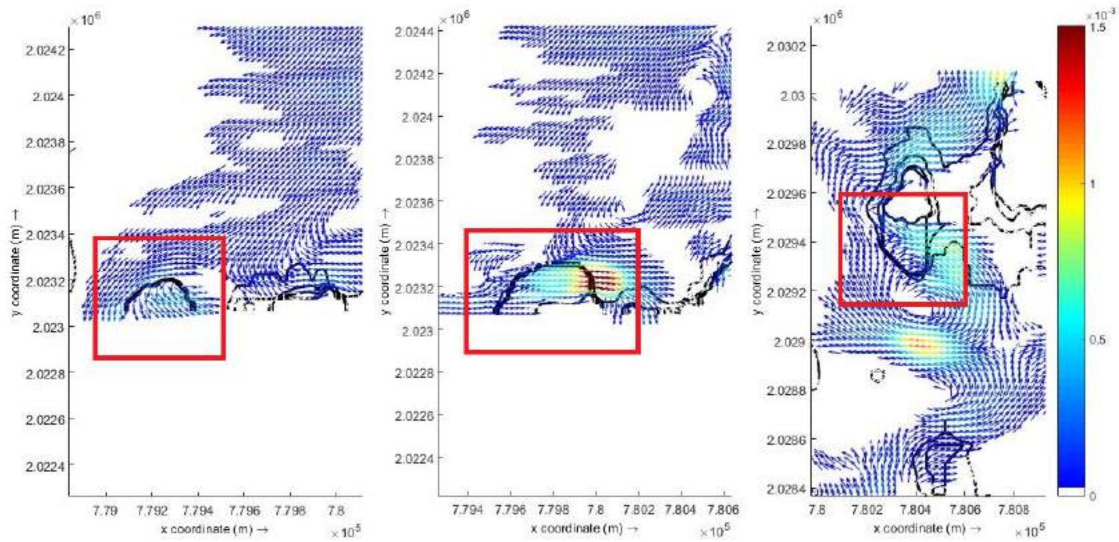

Figure 5.4: Sediment transport magnitude and direction for location 1 (left), location 2 (middle) and location 3 (right)

5.4 Offshore breakwaters

An offshore parallel breakwater can be constructed to reduce wave impact on the coastline. Creating a functioning offshore parallel breakwater at Long Bay can be done in many ways. Appendix G elaborates on the possible ways a breakwater can be constructed. Having established the range of possible solutions, several breakwater designs are determined for Long Bay. The designs are compared to each other to understand which once are most suitable.

5.4.1 Designs

The following sections elaborates on possible designs for Long Bay. Three designs are determined based on the information given in appendix G. Figure 5.5 shows the three designs. Design 3 has two situations. This is because it focuses on restoring the reef. This takes time so there is a short term situation shortly after construction and a long term situation. The long term situation shows the reef after complete restoration. Design 1 and 2 do not have this as they do not change significantly over time. All designs are simulated in Xbeach. The simulation uses the same settings as are used for the reference scenario. The results are given in appendix J. The results of the simulations can be compared to each other and to the reference scenario.

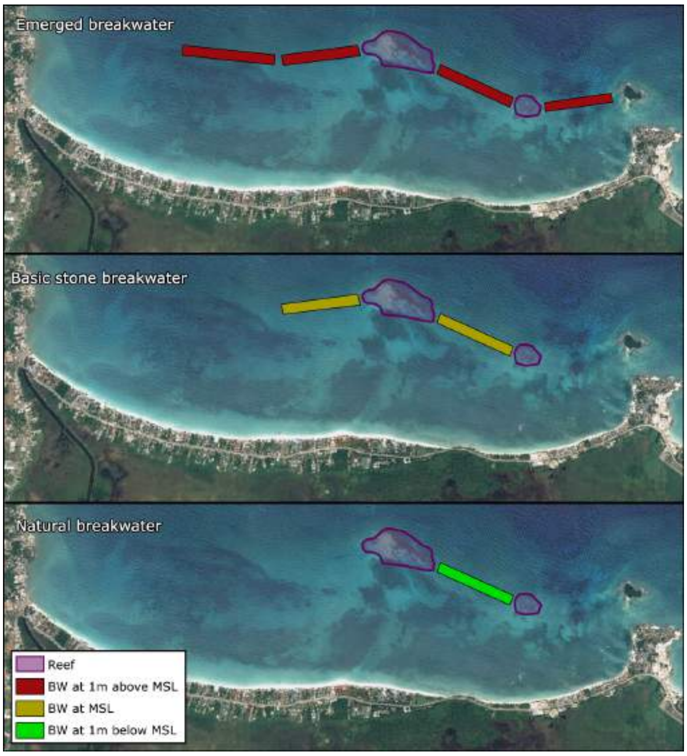

Figure 5.5: Breakwater designs

1. Emerged breakwater design

The goal of the first design is to mitigate the erosion issue as much as possible for the entire bay. Chapter 4 showed that a submerged breakwater is not enough by itself to prevent erosion completely. So, the first design is an emerged breakwater which protects as much of the bay as possible. Since boats still need to be able to leave the bay uninterrupted, it is not possible to completely close off the bay. The design is a total of four breakwaters stretching the coast from north to south as indicated in figure 5.5. The existing reefs and Booby Cay are used as connection points. The south of the bay is left open intentionally to allow vessels to enter and leave the bay. In the north, the vessels can move through the section between Booby Cay and the coastline. The breakwaters are basic types made out of armor stones or concrete units and have a crest height of 1 meter above MSL.

2. Basic stone BW design

The second design closely resembles the breakwater proposal made by the government. The design connects the two reefs with a breakwater. Another section of breakwater is placed south of the southern reef. The breakwaters are made out of stones and have a crest height at MSL. The difference between this design and the government proposal is that this design is longer. The total length of the design is 1800 m as opposed to the 938 m of the government proposal.

3. Natural reef design

The third design focuses on restoring the reef to its historical situation. This means that the goal is to restore the state of the current reefs and reconnect them. As appendix G explained, pure natural restoration takes time. This makes this not a suitable method since the design should provide a short term beach protection. Therefore, the design consists of a breakwater between the two reefs made out of reef balls. By using reef balls between the two reefs the designs provides short term wave reduction. The reef balls promote coral growth which can be accelerated by applying coral transplantation. The regrowth rate can possibly be further increased at the existing reefs by using ecoreefs. The full effect of the reef will take effect when the reef is completely restored on the long term. For this reason, two designs are considered. One design which represents the short term situation after construction and one which represents the long term outcome. The short term design is a breakwater between the two reefs with the crest at 1 meter below sea level. Coral transplantation is applied to the reef balls and the current reefs. The long term situation is equal to the healthy reef described in chapter 4. The reef has grown in size and the crest now reaches to 0.5 m below MSL. The possible design of a reef ball breakwater is given in appendix H. This gives an indication of what this design could look like. More research is required to determine a viable design.

5.4.2 Costs

The cost of the breakwater used for the basic stone BW alternative can be based on the proposal made by the government. The government proposal was going to cost 6.9 million USD. [CL Environmental, 2014] The total length of the two breakwaters would be around 940 m. This leads to about 7500 USD per meter of breakwater. The basic stone breakwater is longer than the government proposal. The two breakwater sections are 1,000 and 800 meters long. This would lead to a total cost of around $ 13.5 million dollars. Maintenance could be required during its lifetime but will be only after large hurricane events so this will not significantly affect the total cost.

The emerged breakwater is longer and has a higher crest height. The additional breakwater sections are both around 700 meters long. This means a total increase in length of about 1.8 times. Including the increased crest height, the total cost for this breakwater is expected to be at least twice the cost of the basic stone breakwater.

The natural reef alternative applies a submerged breakwater made out of reef balls. It is generally said that the use of artificial reef modules in a design leads to higher construction costs because the units are expensive. The largest Reef Balls have a retail price of around 450 USD. [Reef Ball Foundation, 2017b] For medium sized projects, the cost per unit can be reduced by about 20 percent due to the advantage of ordering and shipping in large quantities. [Reef Ball Foundation, 2017c] For this initial estimate this is not taken into account. Deployment of the units by barge costs around 7,000 USD per day. Including bottom survey and monitoring of 500 USD per day and pre / post deployment survey of 500 USD per day, the total deployment costs by barge is 8,000 USD per day. It is estimated that a barge can carry 50 units. Assuming that deployment can take a full day, the total number of Reef Balls that are placed in a day is 50. This means that deployment cost is about 160 USD per unit. This brings the total cost to 610 USD per unit for supply and placement. These units occupy a space of 1.93*1.93*1.9 = 7.1 m3 (L,W,H). This means that the Reef Balls cost around 86 USD/m3. The coral transplantation is not included yet. Also, the costs varies a lot depending on how the Reef Balls are obtained and the project requires trained professionals. If 20 percent is added to cover this cost then the Reef Balls cost around 100 USD/m3. The cost of supplying and placing common armour stones is between 80-100 USD/m3. [CL Environmental, 2014] So the Reef Balls are is actually in the same order of costs as more expensive concrete armour units. This means that the artificial reef will not necessarily have to be more expensive than the traditional breakwater. Therefore, the same estimated cost of 7,500 USD per meter is used for the artificial reefs. The natural reef alternative is 1000 meters long meaning that the total cost of construction is around $ 7.5 million dollars. This is clearly a very rough estimate and would have to be further researched. For this, more detailed submerged breakwater design is required. The costs for the artificial reef also greatly depend on the final breakwater design. Appendix G gave an initial indication. Further research is required to obtain a more detailed design.

5.4.3 Simulation results

The function of the breakwater is to reduce wave impact on the coast during storms. This results in a smaller impact during extreme events and less sediment loss on the long term. So a well-functioning breakwater solution helps to reduce both short term impact as well as long term erosion. The results of the breakwater designs are given in appendix J. This section compares the technical effectiveness of the designs to each other. The effectiveness is based on the remaining beach width after an extreme storm and the yearly sediment loss. The remaining beach width after an extreme storm gives short term impact reduction and yearly sediment loss indicates long term effectiveness.

Beach width

Table 5.2 shows the change of beach width after an extreme storm in percentage for all breakwater designs. The areas are the same as defined for the nourishments. The results for area 1 and area 3 are the most important. Area 1 is important because this is the area with the highest risk due to the many resorts close to the beach. Area 3 is important because the main road is very close to the waterline at this position. North of long bay is best protected by the emerged breakwater. These two designs place a breakwater in front of this part of the beach so they have the largest effect. The beach retreat between the reefs completely disappears for all breakwater designs.

Table 5.2: Change of beach width after extreme storm for all breakwater designs

Area	Reference	Type 1	Type 2	Type 3	Type 3
				Short	Long
1	-13%	29%	-8%	-11%	-19%
2	117%	35%	133%	128%	166%
3	-67%	37%	62%	60%	66%
4	61%	26%	33%	60%	74%
5	5%	103%	126%	12%	19%
6	4%	27%	5%	-3%	-4%
7	-143%	-126%	-117%	-132%	-123%

Yearly sediment loss

The yearly sediment loss for each breakwater design is given in appendix J. A summary of the results is given in table 5.3. The reduction of yearly sediment loss is the greatest for the emerged breakwater. The breakwater reduces yearly sediment loss by 84 percent. This is a very large reduction. This was expected since the breakwater greatly reduces wave impact along most of the coastline. The basic stone BW design reduces yearly sediment loss by 30 percent. The last design has different results for its short and long term situation. As explained in the previous sections, this is because the natural long term scenario is not realized immediately. The results differ since the natural design is modeled higher and larger than the initial construction. The initial construction is governing for the effectiveness of the design since the design should be a short term solution. The natural breakwater design is the least effective, both short term and long term. This was already found in chapter 4. It reduces the sediment loss by less than 10 percent. It is also the smallest design so the effect on the coastline was expected to be the smallest.

Sediment transport pathways

The sediment pathways for each design can be found by looking at the Eulerian velocities and sediment transport directions in the same way as is done for the reference scenario in chapter 4.

Table 5.3: Yearly sediment loss for all breakwaters

	reference	type 1	type 2	type 3	
				short	long
yearly erosion [m3/y]	5974	967	4183	5447	5685
average retreat per year [m/y]	0.24	0.04	0.17	0.22	0.23
erosion reduction [%]	-	84%	30%	9%	5%

The figures of the Eulerian velocities and sediment transport directions are given in appendix J. The emerged breakwater design shows the largest reduction of sediment transport. The northern and middle section of the bay show almost no sediment transport. Southern area still affected. The main sediment pathway is from the southern beach moving offshore through the only remaining exit. The Eulerian velocities over the breakwater are high. The breakwater is 1 meter above MSL and surge is 0.5 m. This means that the waves of 2.91 m are just able to flow over the breakwater. This causes large flow velocities over the crest. The basic stone BW design shows sediment pathways in the northern half of the bay similar to the pathways for the healthy reef scenario as described in chapter 4. Now that the section between the reefs is closed off, the sediment finds a new way between the northern reef and Booby Cay. Sediment is now also getting transported to Bloody Bay. One of the differences between this design and the healthy reef scenario is the breakwater extension to the south. This causes larger flow velocities directed offshore compared to the healthy reef scenario and the reference scenario. The natural reef design placed an artificial reef between the existing reefs. The long term version of this design is the same as the healthy reef scenario. The short term version shows no significant changes in sediment pathway orientation. This is expected since the configuration of the breakwater is not different short or long term.

5.5 Hybrid solutions

The previous sections showed different possible solution strategies. The following section uses the results to create hybrid solutions. The hybrid solutions are a combination of soft and hard solutions.

5.5.1 Designs

Two hybrid designs are determined. Figure 5.5 shows the two designs.

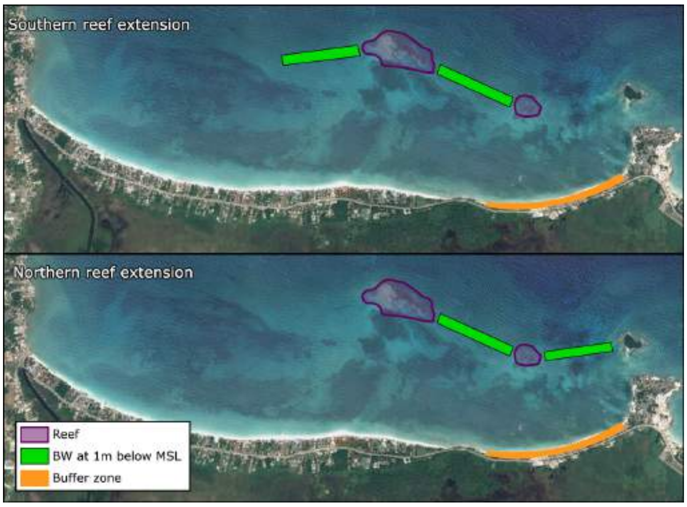

Figure 5.6: Hybrid designs

1. Southern reef extension design

The aim of this design is to also restore the reef similar to the natural reef design. The effectiveness of the natural reef is already explored in the previous section. The reef helps to locally reduce the short term impact of extreme events but does not help to reduce sediment losses significantly. So, to improve the effectiveness of the design the reef is extended. This way, the design protects a larger section of coastline. For the short term design, two breakwaters are constructed using reef balls with the crest at 1 meter below MSL. Again, the reef balls immediately work as a breakwater. On the long term the breakwater turns into a more natural reef. The breakwaters are placed at the same location as for the basic stone BW design. So, one is placed between the reefs and the other is placed south of the southern reef. For the long term situation, the reef grows in size just like the natural breakwater design did. The crest is now at 0.5 meter below MSL. The basic stone breakwater showed significant beach impact during storms at the northern section of the coastline. For this reason, the buffer zone as used in the nourishment designs is also applied. This means that the northern section of the coastline becomes much wider creating a larger buffer and more recreational possibilities.

2. Northern reef extension design

This design is similar to the previous design. Again, the goal is to restore the reef to its historical state while also extending it. This time the extension is created in the north instead of the south. The crest height is at 1 meter below MSL for the short term situation and at 0.5 meter below MSL for the long term situation. The extension in the north will improve protection of the northern section of the coastline against wave impact. On top of this, the beach is advanced just as is done with the previous alternative.

5.5.2 Costs

The cost of constructing an artificial reef has already been estimated for the 'natural reef' alternative. The initial estimate for the costs is around $ 7,500 USD/m. The southern reef extension design is 1,000+800 meter long and the northern reef extension design is 1,000+700 meter long. The total cost of the designs would then be around $ 13.5 million dollars for the southern reef extension alternative and $ 12.75 million dollars for the northern alternative. Both alternatives place a sediment buffer of 48,000 m3 on the northern section of the coastline. For the nourishment alternatives a cost of 25-40 USD/m3 is assumed leading to a cost between $ 1.2 to $ 1.92 million dollars for the initial placement of the buffer zone. If erosion is not completely prevented by the reef extensions, then re-nourishments on the northern section might be required in order to maintain the buffer zone. Depending on the newly established sediment losses, the maintenance would be a certain fraction of the volume used for the buffer zone ones every 10 years. So the total cost of initial construction and placement of the buffer zone is around $ 15 million dollars for the southern reef extension alternative and $ 14.25 million dollars for the northern alternative. Additional investments might be required for maintenance nourishments to maintain the buffer zone.

The same applies for this cost estimate as for the other alternatives, that this is a very rough estimate and requires more detailed designs and simulation in further design steps along with approaching contractors in order to obtain a realistic estimation of the total costs.

5.5.3 Simulation results

The results of the hybrid designs are given in appendix J. This section compares the technical effectiveness of the designs to each other. Just as with the other alternatives, the effectiveness is based on the remaining beach width after an extreme storm and the yearly sediment loss.

Beach width

Table 5.4 gives the results for the beach width after a storm event. North of long bay is best protected by the northern reef extension design. Just as with the emerged breakwater, the design places a breakwater in front of this part of the beach so they have the largest effect. The beach retreat between the reefs completely disappears for both hybrid designs.

Table 5.4: Change of beach width after extreme storm for all breakwater designs

Area	Reference	Type 4 Short	Type 4 Long	Type 5 Short	Type 5 Long
1	-13%	-10%	-15%	26%	50%
2	117%	124%	164%	118%	117%
3	-67%	58%	69%	60%	73%
4	61%	41%	57%	64%	73%
5	5%	71%	92%	33%	20%
6	4%	9%	12%	-1%	-1%
7	-143%	-138%	-123%	-132%	-136%

Yearly sediment loss

The hybrid designs have different results for their short and long term situation. Table 5.5 gives the results. As explained previously, this is because the natural long term scenario is not realized immediately. The southern extended reef design is similar to the basic stone BW design in terms of orientation. The difference between this design and the basic stone BW design is the crest height, being at MSL for the basic stone BW design and at -1m MSL for this design. Generally, a lower crest means a smaller reduction in wave height so less wave impact reduction. Despite this fact, the southern extended reef design is as good as the basic stone BW design. On the long term, the design becomes even better at reducing sediment loss. The reduction goes up to 40 percent in this case. So even though the crest height is lower, the design performs equally well or even better. The difference is in the flow and sediment transport directions. The northern extended reef design performs less well than the southern alternative. Around 13 percent reduction is achieved.

Table 5.5: Yearly sediment loss for all breakwaters

	reference	type 1	type 2	type 3		type 4		type5	
				short	long	short	long	short	long
yearly erosion [m3/y]	5974	967	4183	5447	5685	4310	3606	5175	5215
average retreat per year [m/y]	0.24	0.04	0.17	0.22	0.23	0.17	0.14	0.21	0.21
erosion reduction [%]	-	84%	30%	9%	5%	28%	40%	13%	13%

Sediment transport pathways

The southern reef extension design has the same configuration as the basic stone BW design. There is no significant difference between the short and long term version of this design in terms of sediment pathway orientations. The northern reef extension design shows sediment pathways in the southern half of the bay similar to the pathways for the healthy reef scenario as described in chapter 4. Sediment from the beach first travels north until it moves offshore and travels out of the bay in southwestern direction. The northern section is closed off in this design so the velocities are reduced here. The velocity increases between Booby Cay and the coast. This transports sediment from Long Bay to Bloody Bay.

The results of the sediment pathways for these alternatives and the breakwater alternatives show that the direction of the pathways is mostly determined by the configuration of the breakwaters. The crest height is of lesser influence. A crest height at 1 meter below MSL results in similar sediment pathways as a design with a crest height at MSL. The fact that the breakwater blocks of a possible flow path is the dominant factor. Nevertheless, a higher crest results in lower Eulerian velocities near the coastline and lower sediment transport quantities. So the amount of sediment transport will be affected, just not the sediment transport pathway directions themselves.

5.6 Conclusion

This chapter gives a range of solution strategies. The solutions range from an environmental solution to soft solutions, hard solutions and hybrid solutions. The simulations performed in this chapter reveal which alternatives work well and which do not. Alternatives that do not work are not considered in further steps of the process. From the simulations can be concluded that two alternatives do not give the desired results. These are the shoreface nourishment and the 'edge of bay' nourishment. The shoreface nourishment does not supply the beach with sediment as intended. The 'edge of bay' nourishment could potentially work on the southern side of the bay but the sediment flow is directed towards the river outflow. The nourishment may block the river's flow. Two small groynes guide the river into the bay. These groynes could further prevent the sediment flow. This means most of the sedimentation occurs in the mouth of the river where the fishing village is. This is not desired. The effectiveness of the restoration of the natural sediment production is not certain at this point. However, improving the environment is a no-regret solution. Even though it might not provide the intended increase in production rates, the alternative is still beneficial for Long Bay. The other alternatives do improve the situation at Long Bay. In conclusion, the alternatives that remain are: one environmental solution, two soft solutions, three hard solutions and two hybrid solutions. These alternatives are evaluated in the next chapter.

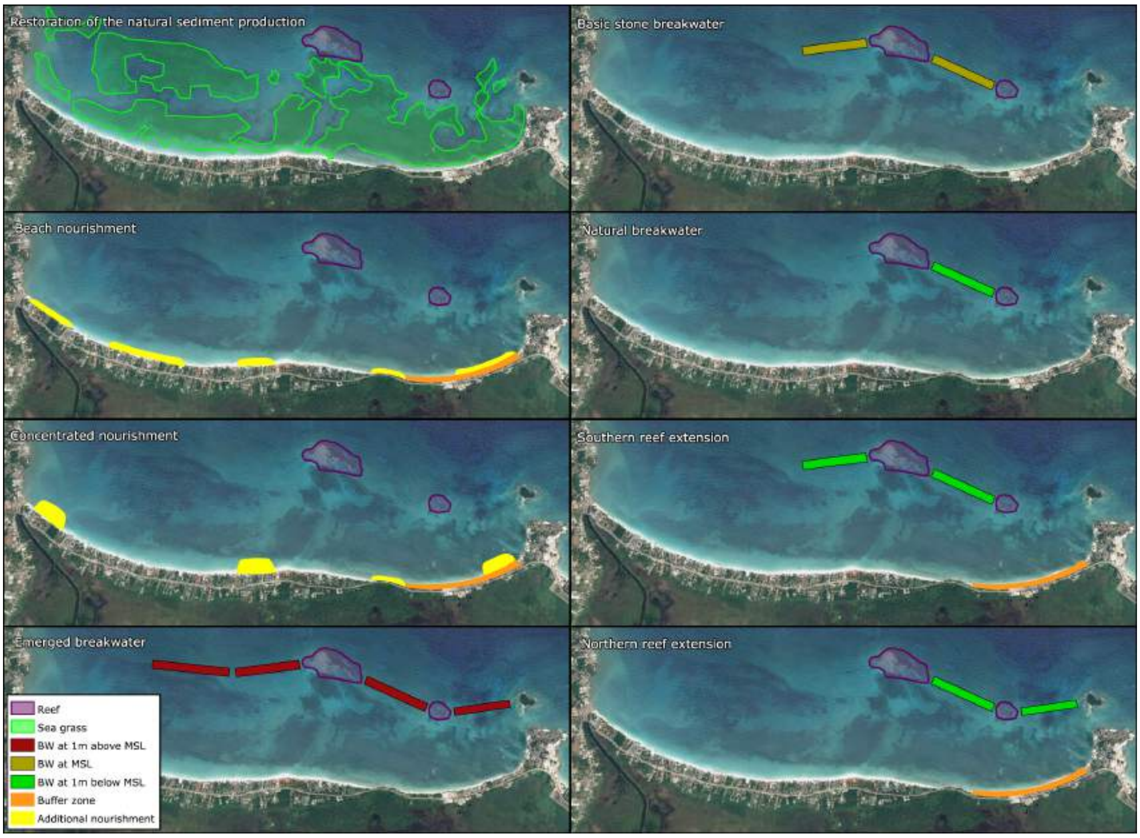

Figure 5.7: All designs

source: http://lennievacationdestination.blogspot.nl/

Chapter 6

Evaluation

The previous chapter provided a large range of possible designs. Ineffective solutions have been excluded based on the simulation results. The remaining alternatives are evaluated in this chapter. The first section of this chapter consists of an evaluation based on ecosystem services. The alternatives can affect the ecosystem services. This effect can be positive or negative. This evaluation shows which ecosystem services are affected by the alternatives and in what way. The ecosystem services are grouped in technical, ecological and social aspects. The result is a clear overview of the positive/negative effects of the alternatives on the ecosystem services. This can be used to see on what aspects an alternative scores well and where it can be improved. In the second section of this chapter a social evaluation is performed. In this evaluation the alternatives are valuated based on the needs of the stakeholders. The alternatives positively or negatively affect the interests of the stakeholders. The evaluation results in the score for each alternative representing their potential value. The goal of this type of evaluation is to put the results in a broader perspective. The potential value of the alternatives should not be used for a final determination of the most feasible design. For this, the data is too uncertain at this phase of the project. At the end of this chapter it is clear what the strengths and weaknesses are of the different solution strategies. These results can be used in the next project phase.

6.1 Evaluation of alternatives

This evaluation is based on ecosystem services. The ecosystem services provided by the different ecological features were given in the chapter describing the coast. They can be grouped in technical, ecological and social aspects. The alternatives that are considered are found in the previous chapter. A reference scenario is also considered. In this scenario, no alternative is implemented. The figure below shows the effect of each alternative on the ES at the project site.

The scores are neutral if the alternative does not impact the ecosystem service. Other possible scores are 'positive', 'very positive', 'negative' and 'very negative'. More detailed scaling options would imply a higher accuracy of results than we have. This is not realistic. Whether a result is 'positive' or 'very positive' differs per ecosystem service and depends on the indicators. Figure 6.1 clearly shows what aspects an alternative scores well on. Appendix I explains the complete reasoning behind the chosen scores.

				nourishments		BW			Hybrid	
		Reference	Restore sediment production	Beach	Concentrated	Emerged	Basic stone	Natural reef	Southern reef	Northern reef
Technical	Coastal protection, north	-1	0	1	1	1	0	0	1	2
	Coastal protection, middle	-1	1	0	0	2	2	2	2	2
	Coastal protection, south	-1	0	1	1	0	0	0	0	0
	Coastline stability	-1	2	2	2	2	2	1	2	1
Ecological	Food provision	0	2	0	0	-1	-1	1	1	1
	Material and biofuels	0	2	0	0	-1	-1	1	1	1
	Life cycle maintenance	0	2	-1	-1	-1	-1	1	1	1
	Water purification	0	2	-1	-1	0	0	0	0	0
	Air quality regulation	0	2	0	0	0	0	0	0	0
Social	Symbolic and aesthetic values	-1	1	1	1	-2	-2	1	2	2
	Recreation and tourism	-1	1	1	1	-1	-1	1	2	2
	Cognitive effects	0	2	0	0	-1	-1	1	1	1

++
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Figure 6.1: Evaluation of alternatives based on ecosystem services

6.1.1 Restoration of the natural sediment production

Restoration of the sediment production offers the most ecological benefits out of the alternatives. It may potentially provide technical benefits in terms of coastline stability. The increased sediment production creates a neutral or even positive sediment balance. This means a stable coastline is created. The improved quality of the sea grass beds means services such as stabilizing the sediment are also improved. A nourishment might be needed to increased the beach width and create a stronger buffer against storms. Since the effectiveness of improving the environment on the sediment production rates is uncertain, this solution type should not be considered as final possible solution at this point. However, the environmental improvement made in this alternative does provide ecological benefits with little effort so can be seen as a no-regret solution that can be implemented in any case.

6.1.2 Nourishment strategies

Nourishments work well from a social and technical point of view but less ecologically. The nourishments create a stable coastline by compensating for the lost sediment and the extra beach width creates a buffer to protect against short term storm impact. The added beach width also creates more recreational opportunities and is aesthetically pleasing. The alternatives do not focus on environmental improvement so no increased services are created due to the alternatives. The nourishment can actually have a negative effect on several ecological ecosystem services since the fines in the nourishment can be harmful. The negative effects can be reduced by reducing spillage and turbidity as mentioned in appendix F. Beyond mitigation, the alternatives could positively affect the ecological aspects if the environment is improved in the same way as is done for the 'restoration of the sediment production' alternative. The effects of environmental improvement would make the nourishment alternatives very positive solutions since a positive effect is created for technical, ecological as well as social aspects. The two nourishments obtain a similar overall score. However, there are some differences between the two. The negative effects on life cycle maintenance and water purification are likely less for the concentrated nourishment. Since the nourishment is placed at one location the negative effects will be more local. Also, the construction method is less complex and does not require the large amounts of pipeline that the beach nourishment requires. This also reduces the disturbance for the tourism industry during implementation. These differences make the concentrated nourishment more favorable than and beach nourishment. More detailed modeling would be required to optimize the design.

6.1.3 Breakwater strategies

The emerged breakwater and the basic stone breakwater perform very well technically but not on ecological and social aspects. The emerged breakwater protects both the north and the middle section of coastline very well. Both alternatives improve coastline stability by reducing the yearly sediment loss caused by storms. The emerged breakwater does this almost completely. The negative effects on the ecosystem services occur due to the poor integration into the environment. The construction will likely damage the existing reefs and does not promote restoration. This impacts ecological aspects as well as recreation & tourism and aesthetic values. So the main issue is the lack of environmental integration. The 'natural reef' alternative does integrate by applying an artificial reef design instead of a traditional breakwater. The natural reef alternative scores a little less on technical aspects compared to the basic stone breakwater but scores better on ecological aspects. This makes it an overall more preferable alternative than the more traditional breakwaters. The benefits of this alternative come from the active restoration of nature while simultaneously protecting the coastline. Appendix H showed what the implementation would entail. The effectiveness of the coral reef restoration is uncertain. Whether coral transplantation and overall restoration will be successful cannot be said at this point so the results should be interpreted with caution. Improving the environmental conditions in the bay increases the likelihood of success.

6.1.4 Hybrid strategies

The hybrid solutions are a combination of positive aspects of different alternatives. They create an artificial reef like the 'natural reef' alternative and extend it to protect a larger section of coastline like the traditional breakwaters. Furthermore, they place a buffer zone at the northern section of coastline for recreational purposes, aesthetic value and extra safety like the nourishments. Hybrid solutions offer the most benefits all-round due to this combination. Between the two, the southern variant results in the strongest reduction of the yearly sediment loss. The northern variant results in the most coastal protection on the northern beach. The southern reef extension protects more of the middle section and a slight improvement on the south. It creates the largest sediment buffer along with the strongest wave reduction at this section.

Similar to the 'natural reef' alternative, the success of these alternatives depends on the success of implementation of the artificial reef. The likelihood is increased by improving the environmental conditions in the bay. If it turns out that the sediment production rate is able to increase significantly when the environmental conditions are improved, then the environmental improvement required for the success of the artificial reefs will also improve the sediment production rates of the sea grass beds. If that is the case then the coastline stability becomes very positive for both alternatives. This also applies to the 'natural reef' alternative.

In conclusion, restoring the sediment solution could be a solution strategy accompanied by a beach advancement. This strategy is only feasible if improving the environment leads to a significant increase in sediment production. Whether this is the case requires further research. Nourishment strategies may provide a solution as they give positive results for technical and social aspects. The negative effects on the ecological ecosystem services can be partially mitigated by adjusting the implementation methods. Improving environmental conditions could even provide positive benefits beyond mitigation. The concentrated nourishment is more promising than the beach nourishment although more detailed simulations are required to further understand the applicability. Traditional breakwaters are not preferred due to their lack of environmental integration. The 'natural reef' alternative provides active restoration of the reef which gives it technical, ecological and social benefits. The technical aspects score lower than the traditional designs so some nourishment would be needed to overcome this. The hybrid solutions creates a positive effect on all three aspects by combining solution strategies.

6.2 Social evaluation method

A method that can be applied in project is a social evaluation method. This method determines the potential value of alternatives based on the power of influence and interests of the involved stakeholder groups. The previous section showed the effect of the alternatives on the ecosystem services. The goal of this evaluation method is not to state that the alternative with the largest potential value is the optimal design. There are too many uncertainties to claim this. The method is applied in order to gain a broader perspective on the results and the importance of the stakeholders.

In chapter 2, the different stakeholder groups are identified. Their power of influence and interests in the region have also been indicated. The interests are ranked for each stakeholder. From this, the importance of each interest is determined. The alternatives affect the region and the coastal functions. They have a positive or negative effect on the interests. A score can be determined for each. This is done by relating the interests to the ecosystem services used in the previous section. The scores are multiplied by the importance of the stakeholder. A total score is found by adding the scores of all the interests per alternative. This final score indicates the potential value of the alternative. This can be compared to the other alternatives to find the most promising solution.

6.2.1 Interests

The method uses the interests of the stakeholders for the determination of the potential value of the alternatives. The stakeholder interests are already defined in the chapter describing the coast. The interests that are affected by the different alternatives are safety, fishery, recreation & tourism, environmental quality and education & research. Each alternative will have an effect on the interests. The alternative which affects the interests the most positively is the alternative with the most potential value. In order to be able to assign a score for each interest per alternative, indicators are needed. The interests relate to ecosystem services. The previous evaluation showed how the alternatives affect the ecosystem services. So by knowing how the ecosystem services relates to the interests it is possible to score the alternatives. Figure 6.2 shows the relation between interests and ecosystem services. For instance, safety relates to coastal protection and coastline stability. The relations are used to valuate the alternatives per interest.

		Safety	Fishery	Recreation & tourism	Environmental quality	Education & research
Technical	Coastal protection, north	x				
	Coastal protection, middle	x				
	Coastal protection, south	x				
	Coastline stability	x				
Ecological	Food provision		x			
	Material and biofuels					
	Life cycle maintenance		x		x	
	Water purification		x		x	
	Air quality regulation				x	
Social	Symbolic and aesthetic values			x		
	Recreation and tourism			x		
	Cognitive effects					x

Figure 6.2: The relation between interests and ecosystem services

6.2.2 Valuation of alternatives per interest

Now that it is clear which ecosystem services relate to the different interest, it is possible to assign scores to the alternatives. The scores are based on the determined impact on the ecosystem services as given in figure 6.1 of the previous section. In this evaluation the alternatives were given a score between -2 and +2 depending on their positive/negative impact on an ecosystem service. For the social evaluation the scores per interest are the average of the scores given to the ecosystem services relating to that interest. So for instance, environmental quality relates to life cycle maintenance, water purification and air quality regulation. The 'natural reef' alternative is given 1 point for life cycle maintenance and no significant improvement to the other two ecosystem services. Therefore, the score for environmental quality becomes $(1+0+0)/3 = 0.3$. The complete results for the alternatives is given in figure 6.3.

			nourishments		BW			Hybrid	
Interests	Reference	Restore sediment production	Beach	Concentrated	Emerged	Basic stone	Natural reef	Southern reef	Northern reef
Safety	-1,0	0,8	1,0	1,0	1,3	1,0	0,8	1,3	1,3
Fishery	0,0	2,0	-0,7	-0,7	-0,7	-0,7	0,7	0,7	0,7
Recreation & tourism	-1,0	1,0	1,0	1,0	-1,5	-1,5	1,0	2,0	2,0
Environmental quality	0,0	2,0	-0,7	-0,7	-0,3	-0,3	0,3	0,3	0,3
Education & research	0,0	2,0	0,0	0,0	-1,0	-1,0	1,0	1,0	1,0

Figure 6.3: Scores for each alternative per interest

6.2.3 Importance

Not all interests are as important as others. Each stakeholder groups will value some interests over others. The groups also have different powers of influence. The main interest of a stakeholder with a large power of influence will be more important to consider.

Based on the indicated interests a ranking is made for each stakeholders of the five interests defined in the previous section. The lowest interest is given a (1), the highest interest a (5). The importance of each interest can now be obtained by multiplying the power of each stakeholder by their value of the interest and adding the results. Figure 6.4 illustrates this for the interest 'Safety'.

Stakeholders	Power	Interest in safety	Power*safety
Government	7	5	35
Tourism industry	6	3	18
Environmentalists	5	1	5
Fishing industry	4	3	12
Residents	3	3	9
Visitors	2	3	6
Academia	1	3	3
		Total	88

Figure 6.4: The importance of the interest of safety based on stakeholder groups

The obtained value indicates the importance relative to the other interests. Figure 6.5 gives the results for all interests. The importance of each interest is used to determine the potential value of the alternatives.

Stakeholders	Power	Interests				
		Safety	Fishery	Recreation & tourism	Environmental quality	Education & research
Government	7	5	3	4	2	1
Tourism industry	6	3	1	5	4	2
Environmentalists	5	1	2	3	5	4
Fishing industry	4	3	5	1	4	2
Residents	3	3	5	2	4	1
Visitors	2	3	2	5	4	1
Academia	1	3	1	2	4	5
	importance	88	77	95	103	57

Figure 6.5: The importance of interests based on stakeholder groups

The values given for the interests are scaled to values between 0 and 1, where 1 is equal to the highest given score and 0 to the lowest given score. A power-interest framework can be made which shows the interest of each stakeholder in a particular subject. This gives a quick visual representation of the importance of each interest. The figure is given in figure 6.6.

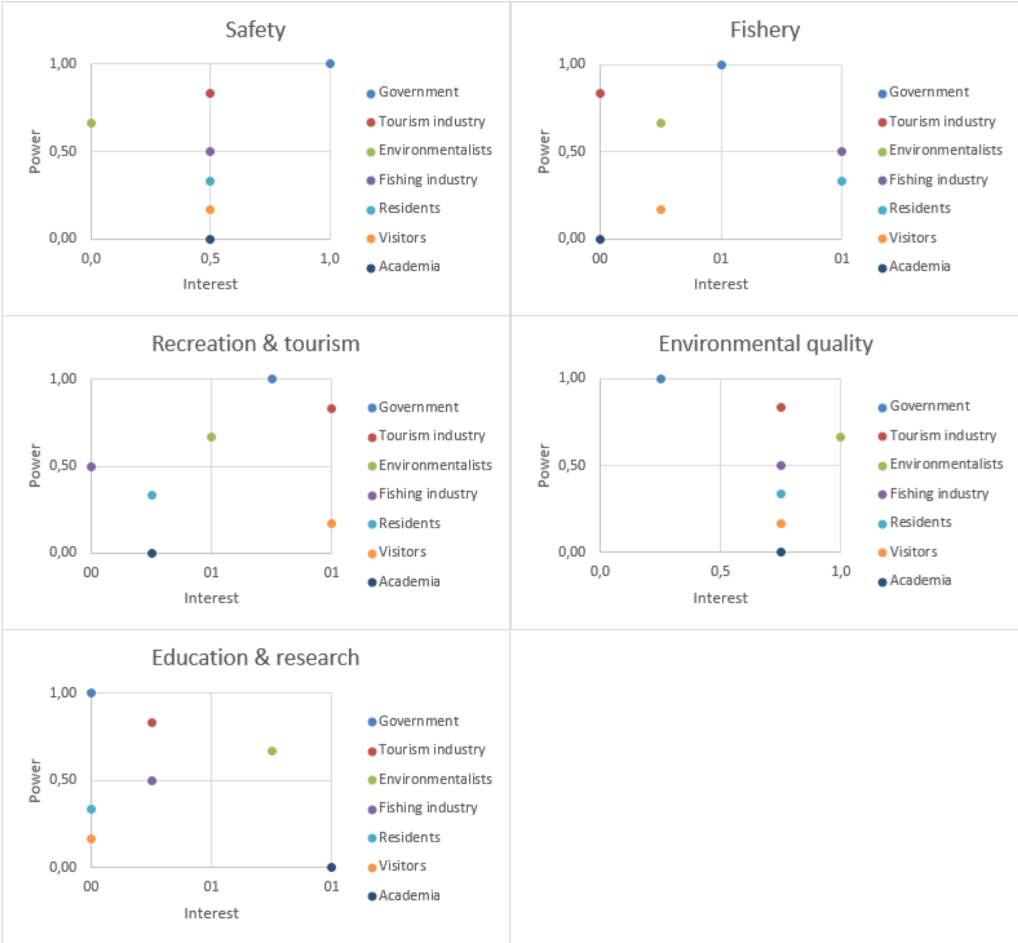

Figure 6.6: Power-interest frameworks for each interest

6.2.4 Potential value

The potential value of each alternative can be found now that the alternatives have been valuated by interest and the importance of each interest is known. The potential value of each alternative can be obtained by multiplying the importance of each interest by their score of that interest and adding the results. Figure 6.7 illustrates this for the 'Natural reef' alternative.

Interests	Importance	Score	Importance*score
Safety	88	0,8	66
Fishery	77	0,7	51
Recreation & tourism	95	1,0	95
Environmental quality	103	0,3	34
Education & research	57	1,0	57
		Total	304

Figure 6.7: Potential value of the 'natural reef' alternative

Table 6.8 gives the complete results for all alternatives. The results correspond well with what is found in the first evaluation. The 'restoration of the natural sediment production' alternative obtains the highest potential value. Just as explained in the previous section, this results strongly depends on the sediment production capability as well as the effectiveness of environmental improvements to the system. The nourishments are valued positively but not nearly as high as the artificial reefs. This is because the interest 'environmental quality' is most important. The nourishment alternatives do not actively improve the environment. As the matter of fact, the placement can actually be harmful to the environment. The nourishments do score well for the interests 'safety' and 'recreation & tourism' which is why the potential value remains positive. The traditional breakwaters do not score well. There are too many negative effects on the ecological and social ecosystem services. The good score for 'safety' does not make up for this. The Basic stone breakwater actually obtains a more negative value than the reference scenario. This result correlates well with what happened in reality. The government proposal, which is similar to the basic stone alternative, was feared to cause more harm than good. The artificial reef alternatives score high potential values. Especially the hybrid solutions score very well. This is because these solutions provide a positive effect to technical, ecological as well as social ecosystem services.

				nourishments		BW			Hybrid	
Interests	Importance	Reference	Restore sediment production	Beach	Concentrated	Emerged	Basic stone	Natural reef	Southern reef	Northern reef
Safety	88	-1,0	0,8	1,0	1,0	1,3	1,0	0,8	1,3	1,3
Fishery	77	0,0	2,0	-0,7	-0,7	-0,7	-0,7	0,7	0,7	0,7
Recreation & tourism	95	-1,0	1,0	1,0	1,0	-1,5	-1,5	1,0	2,0	2,0
Environmental quality	103	0,0	2,0	-0,7	-0,7	-0,3	-0,3	0,3	0,3	0,3
Education & research	57	0,0	2,0	0,0	0,0	-1,0	-1,0	1,0	1,0	1,0
	Potential value	-183	635	63	63	-175	-197	304	443	443

Figure 6.8: Potential value of alternatives

6.2.5 Stakeholder opinion

The highest potential value does not necessarily mean that this is the most feasible design. If a design has a high potential value but the stakeholder with the largest power values a different design, than the design with the highest potential might still never be realized. Whether this might happen can be made clear by creating a power-opinion framework. This framework determines a value for the opinion that the stakeholder has towards a design. This opinion is calculated by multiplying the value a stakeholder gave for an interest by the score a design got for that interest. By adding the outcomes a score is generated which indicates the opinion of the stakeholder towards the design. Figure 6.9 illustrates this for the governments' opinion on the 'natural reef' alternative.

Government interests		**Natural reef score**	**Interest*score**
Safety	5	0,8	3,8
Fishery	3	0,7	2,0
Recreation & tourism	4	1,0	4,0
Environmental quality	2	0,3	0,7
Education & research	1	1,0	1,0
		total	11

Figure 6.9: Opinion of stakeholders towards alternatives

The lowest possible score is -30, the highest possible score is 30. These extremes are obtained when a design scores the minimum minus two or maximum two points for every single interest. Any stakeholder with an opinion lower than zero will likely oppose the design proposal. Table **??** shows the complete results.

				nourishments		BW			Hybrid	
Stakeholders	Power	Reference	Restore sediment production	Beach	Concentrated	Emerged	Basic stone	Natural reef	Southern reef	Northern reef
Government	7	-9	20	6	6	-3	-5	11	18	18
Tourism industry	6	-8	21	5	5	-8	-9	11	18	18
Environmentalists	5	-4	26	-1	-1	-10	-11	11	14	14
Fishing industry	4	-4	25	-2	-2	-4	-5	10	12	12
Residents	3	-5	24	-1	-1	-5	-6	10	13	13
Visitors	2	-8	21	4	4	-7	-8	11	17	17
Academia	1	-5	24	2	2	-6	-7	11	15	15

Figure 6.10: Opinion of stakeholders towards alternatives

The results can be visualized in a power-opinion framework. Figure 6.11 illustrates this for a selection of alternatives. The power-opinion frameworks result in the same conclusion as the potential value determination did. The artificial reef designs and the restoration of the sediment production are most favored. The framework gives more insight in the different opinions on an alternative.

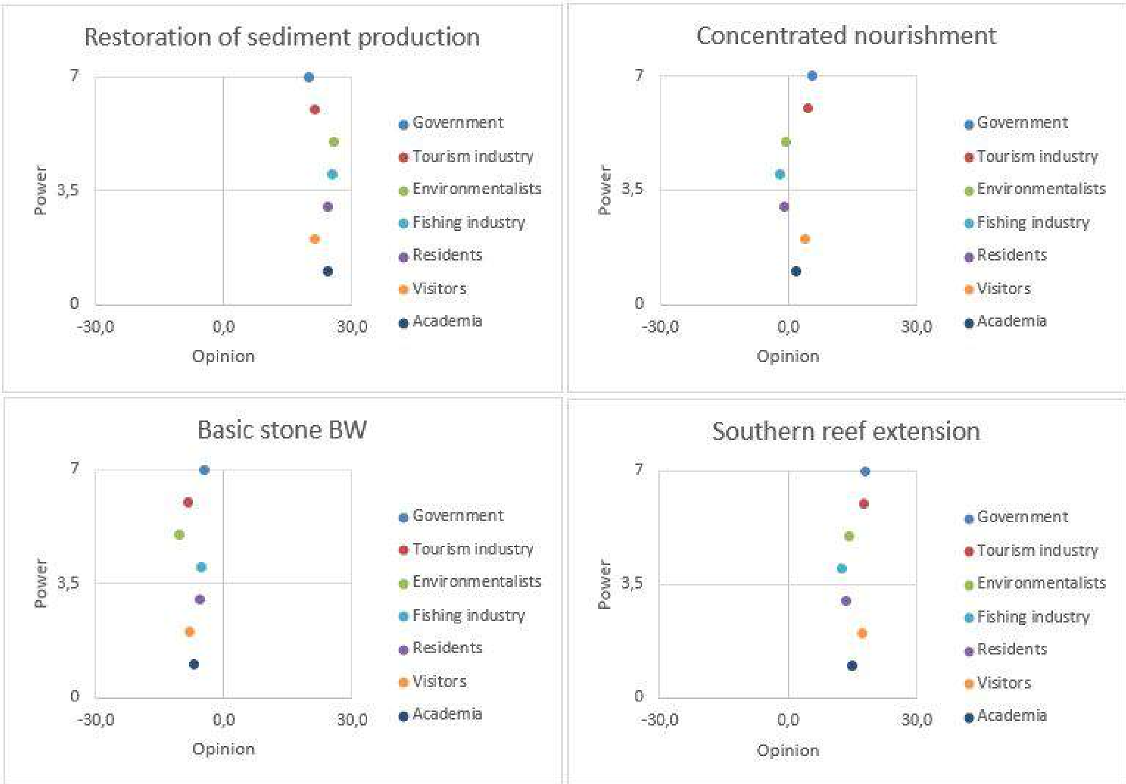

Figure 6.11: Power-opinion frameworks for each alternative

6.2.6 Reflection on social evaluation method

The social evaluation method aims to implement the interests of the stakeholder groups to the evaluation of the alternatives. In theory this is useful since this means that alternatives only score well if the stakeholder groups are actually interested in the benefits it creates. However, there are several downsides to this evaluation method.

First of all, the interests require indicators in order to determine a score for the alternatives. Which indicators are used determines how the alternatives are valued for the interests. This means that the accuracy of the indicators is important. Furthermore, if more than one indicator relates to an interest then determining a score becomes more complex. For this case, each indicator, in this case the ecosystem services, is given the same weight. So for instance, coastal protection is just as important as coastline stability. However, it is also possible to put more weight on one of them. This could be done if one aspect is more important than the other. It could also be done if one indicator is more reliable than the other because the data is more accurate. These type of weight factors are not included for this evaluation but could improve results.

A second downside to this social evaluation method is the interest themselves. Relating the ecosystem services to the interests, as is done in this case, is not logical. Many interests are actually ecosystem services themselves. This social evaluation should ideally be about ecosystem services. This requires a ranking of importance by ecosystem services for each stakeholder. A downside of doing so is that assigning the rankings for each stakeholder becomes more challenging. A detailed understanding of the interests of the different stakeholder groups is needed in order to obtain a reliable ranking.

The third downside of this social evaluation method relates to the previous notion. The risk of these type of evaluations is that they become subjective. Ranking defined interests for stakeholders and ordering the stakeholders by power is something which will never truly represent the complex stakeholder connections, conflicts and desires. However, it does give an indication of the potential value of different alternatives. The accuracy of the evaluation can be improved by obtaining a better understanding of the interests and power of influence of the stakeholder groups. For this thesis, the interests and power of influence is based on the goals and values of stakeholders within each group and conflicts between stakeholder groups in the past. This judgment can be improved by communicating with the different stakeholder groups. An example of how the ranking system in this method can lead to unrealistic results can be found in the power-opinion framework. The power-opinion framework shows that the government is not likely to support the basic stone BW design. This seems like an unrealistic result. When looking at the power-opinion framework of the basic stone BW the results show that the government supports this the most out of the stakeholders. The tourism industry and visitors support it less than the government. This is because they value the safety it creates but do not like the poor environmental integration. This difference corresponds well with reality but the government would be expected to favor this alternative more. The fact that the government does not do this is because of the method. The interests of the stakeholder groups are ranked from (1) to (5). In reality the interests will not likely be distributed this way. The government might only be interested in 'safety' and not care much about other interests. This would mean that the opinion towards the alternatives changes. A different type of ranking for the interests could indicate this better. For instance, distributing 100 point over the interests could represent the interests better. If a stakeholder group is mostly interested in one aspect than this interest could be given most of the 100 points. For this thesis, this way of distributing scores is not applied as it requires a more detailed understanding of the interests of the different stakeholder groups.

The method can be improved by improving the accuracy of the indicators. This requires more accurate simulations and more environmental data. Secondly, by ranking ecosystem services directly instead of general interests. This requires more understanding of the stakeholder groups. And finally by adjusting the ranking system to a weighted distribution.

6.3 Conclusion

The first evaluation shows the effect of the alternatives on the ecosystem services. The second evaluation places the results in the broader context by considering the interests of the stakeholders to estimate a potential value of the alternatives.

The first evaluation shows what aspects an alternatives likely has a positive effect on and where it has a negative effect. The three main aspects are technical, ecological and social. This gives a broad view of the impact of an alternative. What the evaluation does not show is which aspect is most important when considering the most feasible solution. For this phase of the project that is not too relevant. Obtaining an indication of the strong assets of an alternative and where it could improve is more important. The evaluation shows that traditional breakwaters only provide technical benefits but have a negative effect on ecological and social aspects. Restoring the natural sediment production could possibly positively affect all aspects. However, the effectiveness is highly uncertain. Nourishments work well on technical and social aspect. However, they do not actively improve the environment and could actually harm the environment depending on the implementation method. Artificial reef alternatives potentially have a positive effect on all aspects. The hybrid solutions in particular. The social evaluation method also determines them as most favorable. However, their effectiveness depends on the applicability of reef balls as a breakwater as well as the success of coral transplantation. Furthermore, they are the most expensive type of solution. The second evaluation method gives a broader perspective on the results. The difference between this method and the first one is that here the importance of different aspects are also considered. The results show that artificial reef solutions and 'restoration of the sediment production' are most favorable. These are also the alternatives which showed the least negative impacts and an overall positive effect on the ecosystem services in the first evaluation. The results depend greatly on initial simulations and assumptions. In theory, the evaluation method could give a decent indication of the potential value of the alternatives but it requires several improvements as stated in the previous section. For now, the determined potential values cannot be used as a concluding measure.

What comes forward is the importance of environmental quality for the success of an alternative. The artificial reef alternatives as well as the 'restoration of the natural sediment production' score well because they provide a technical solution while also improving the environment. The nourishment alternatives lack this environmental improvement which results in lower overall scores. The fact that the impact of the alternatives on the environment is still uncertain means that the results can only be indicated as positive or negative. This eliminates smaller differences between alternatives making it difficult to for instance compare the beach nourishment with the concentrated nourishment. The choice of the ecosystem services themselves also impacts the results. The used ecosystem services are based on the services that the main natural features at Long Bay provide. This gives a reasonable list of ecosystem services. However, it is very possible that some may be overlooked. This can have an effect on the results.

So what can be concluded from the evaluation? The most important conclusion is that not one design can be determined as the best solution in this phase of the project. What can be said is which strategies offer potential, what can be improved about those type of solutions and what remains uncertain about them. This shows which solution strategies should be considered in a new design cycle, how they can be improved and what needs to be further researched in order to obtain higher accuracy. If restoration of the sediment production leads to large production rates and a large improvement in overall environmental quality, then this alternative could be very positive. This effectiveness should be further researched to reduce uncertainty. Nourishment strategies should be further explored. Concentrated nourishments in particular for their advantages in terms of implementation over beach nourishments and their smaller ecological footprint. The nourishment strategies can be improved by adding environmental improvements to the alternatives. What needs to be further researched is the optimal configuration of the nourishment volumes and their expected distribution over time. According to the evaluations, a hybrid solution provides has the most positive effect on Long Bay. However, this depends on the applicability of Reef Balls in breakwater designs and effectiveness of coral transplantation. This type of strategy should be taken into the next design cycle but cannot be pointed out as the best solution to the issues at Long Bay at this point. With improved data and more research on the different topics, a new design loop will provide more certainty about the effectiveness of the above mentioned solution strategies.

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Chapter 7

Conclusion & recommendations

The final chapter of the report gives the conclusion of the thesis as well as a discussion and recommendations for further research. The recommendations focus on improvements for the model, further research on environmental conditions and recommendations for the evaluation of the alternatives and stakeholder involvement.

7.1 Conclusion

The research question of this thesis is "How can the erosion of the coastline of Long Bay, Jamaica be mitigated while simultaneously improving nature development in the area?" The Building with Nature approach is applied to explore possible solution strategies. This approach starts with the system in mind, not the intervention. The BwN approach aims to optimize a project to create opportunities for the development of new nature. This goes beyond the neutral approach. The strategic objective for Building with Nature projects is therefore to deliver engineering services while delivering and/or utilizing ecosystem services.

This thesis showed that the cause of the erosion is a combination of factors. Extreme events have a large impact on the coastline causing significant short term coastline regression. The sediment balance is used to understand long term changes. The two main components of the sediment balance are long term erosion by storms and sediment production. Storm events cause a yearly sediment loss that is estimated around 6000 m3/y. The coastal protection capability of the historical reef was better but it did not completely prevent this sediment loss. The impact of extreme events is reduced locally. Sediment production can provide a positive input in the sediment balance. The production quantity cannot easily be assessed leading to different possible scenarios. A scenario where the optimal sediment production is low and one where this production is high. Since there is not enough information to disclose one of them, both are taken into account in this thesis. If the sediment production under optimal conditions is low, then the sediment balance will not be strongly affected by a change in sediment production. In that case the difference between past and present must be caused by intensification of the storm intensity. For this scenario the sediment balance is equal to -6000 m3/y. This is equal to a coastline retreat in the order of 0.25 m/y. Sea level rise also causes regression of the coastline. An average of 0.14 m/y is determined. This makes the total coastline retreat around 0.4 m/y. The other scenario is that the sediment production under optimal conditions is large. This means that in the past, the sediment production was a significant part of the sediment balance. The added sediment could have been in the same order of quantity as the cross-shore losses. Over the years, the reduced environmental quality led to lower sediment production rates. This reduction leads to a more negative sediment balance meaning increased erosion rates. In this case, lowering of the sediment production due to environmental degradation is at least part of the cause of the increased erosion rates and possibly even the most dominant aspect. Both scenarios require different solution strategies.

On the short term, the impact of extreme events needs to be reduced. On the long term, the coastline retreat caused by the sediment imbalance and sea level rise should be minimized. The thesis explores different solution strategies. Based on simulations, alternatives which do not perform as intended are excluded. The alternatives that remain are one environmental solution, two soft solutions, three hard solutions and two hybrid solutions. The environmental strategy focuses on the scenario that the sediment production rates can be increased significantly by environmental restoration. The effectiveness of the restoration of the natural sediment production is not certain at this point. However, improving the environment is a no-regret solution. Even though it might not provide the intended increase in production rates, the alternative is still beneficial for Long Bay. The nourishment strategies focus on compensating for the imbalance in the sediment budget and improving safety against short term impact by storm event. The breakwater alternatives focus on reducing the yearly sediment loss by storm events thereby improving the sediment balance. The hybrid strategy combines aspects of the previously mentioned strategies.

The alternatives are evaluated based on the ecosystem services. This evaluation shows what aspects an alternatives likely has a positive effect on and where it has a negative effect. The three main aspects are technical, ecological and social. This gives a broad view of the impact of an alternative. What the evaluation does not show is which aspect is most important when considering the most feasible solution. To also consider this, a social evaluation method is performed. The social evaluation method is applied to place the results in a broader context. This evaluation method includes the interests of the involved stakeholder groups in order to determine the most important aspects of a project. An alternative which mainly improves the most important interests will be more likely to be supported. Involving stakeholders in the evaluation process can benefit the design process. However, it also comes with more uncertainty and requires a clear view of the needs of the stakeholder groups. This increases the unreliability of the results. For this thesis the results are used as a rough indication of strategy preferences along with the first evaluation. Together the evaluations show the potential of the different strategies. One design cannot be determined as the best solution in this phase of the project. If restoration of the sediment production leads to large production rates and a large improvement in overall environmental quality, then this alternative could be very positive. Nourishments work well from a social and technical point of view but less ecologically. Nourishment strategies should be further explored. Concentrated nourishments in particular for their advantages in terms of implementation over beach nourishments and their smaller ecological footprint. The nourishment strategies can be improved by adding environmental improvements to the alternatives. A hybrid solution has the potential to provide a positive effect on the technical, ecological as well as social aspects of Long Bay. However, this depends on the applicability of Reef Balls in breakwater designs and effectiveness of coral transplantation.

The three types of strategies should be taken into the next design cycle. It is known what their potential is, how they can be improved and what needs to be further researched in order to obtain higher accuracy. With improved data and more research on the different topics, a new design loop will provide more certainty about the effectiveness of the above mentioned solution strategies.

7.2 Discussion & Recommendations

This section discusses several important components of the thesis. The first section reflects on the Building with Nature approach. After that, the technical, environmental and societal components are discussed.

7.2.1 BwN approach

The Building with Nature approach aims to deliver engineering services while delivering and/or utilizing ecosystem services. The design process starts with the system in mind instead of the intervention. Understanding the environmental and societal system can lead to a wider range of solution strategies. There is a risk that engineers are more likely to consider physical designs than non-structural alternatives such as managed retreat or social solutions. Therefore, a wide scoping of alternatives is needed which is what this approach strives towards. This is not something that the BwN approach could improve on but is something that should be changed in the mindset of the engineer. Not every issue requires an engineering solution. This different point of view can be difficult. Even though I focused on using this BwN approach I still almost went back to designing traditional interventions.

What I consider very positive about the BwN approach is the strong connection between the system understanding and proposed alternatives. This allows for a wide range of solution strategies. The difficulty of this lies in obtaining the required information about the physical and natural system. In the traditional way, the intervention can be found more quickly and with less required data. The natural environment is more challenging to quantify with certainty. Often small scale experiments need to take place to see whether a natural solution works as intended such as for instance coral transplantation or the effectiveness of environmental improvements. This asks for a more adaptive type of project smaller scale implementation is performed. Monitoring the effects throughout the different project phases is then required to adapt the project if necessary. So there are two paths to follow. Either the system understanding is improved until it is accurate enough to select an alternative, or focus on adaptive strategies. Adaptive strategies can prevent costly and unnecessary constructions based on too limited data. However, projects on a smaller scale can become more expensive overall due to the cost of mobilization and demobilization. So in that sense, implementing a large scale project is more cost-effective.

The BwN design process explains to valuate the qualities of alternatives and preselect an integral solution in step 3. However, this is not always possible. The BwN approach could be improved by creating a clear assessment of whether the system understanding is accurate enough to pre-select an alternative. Whether the assessment concludes that the accuracy is sufficient or not determines how the project should continue. If the system understanding is accurate enough then it is possible to narrow down the alternatives and evaluate their quality. A cost-benefit analysis can be applied and the selection of alternatives can be ranked to find the most promising design. If the system understanding is not accurate enough then the alternatives should not me narrowed down. A wide range of solutions should still be considered. An evaluation based on ecosystem services then indicates the strengths and weaknesses of different strategies. After doing so, another assessment needs to be made. This second assessment should shows whether an adaptive approach should be followed or knowledge should be increased by additional measurements. When the latter is chosen, the system understanding is improved. This cycle can continue until a certain amount of accuracy is met. The choice of which path to take depends on the results of the design process. A combination of the two could also be possible as the adaptive approach leads to a further understanding of the system and effectiveness of alternatives. For instance in this study case, the environmental improvements can be implemented while going through a new design cycle. The costs of environmental improvements are likely relatively low with no negative effects. This means low risk and small investments. The effects of the improvement can be used to gain a more reliable assessment of the alternatives.

Figure 7.1 shows the new design process. If the accuracy assessment gives an sufficient result, then the process is the same as the first three steps of the BwN design process. First the system is understood, then alternatives are identified which are evaluated and a alternative is selected as the most promising design. If the other path is followed then the steps as explained before are followed. What the accuracy assessment and the second assessment of the results should consist of needs to be further researched.

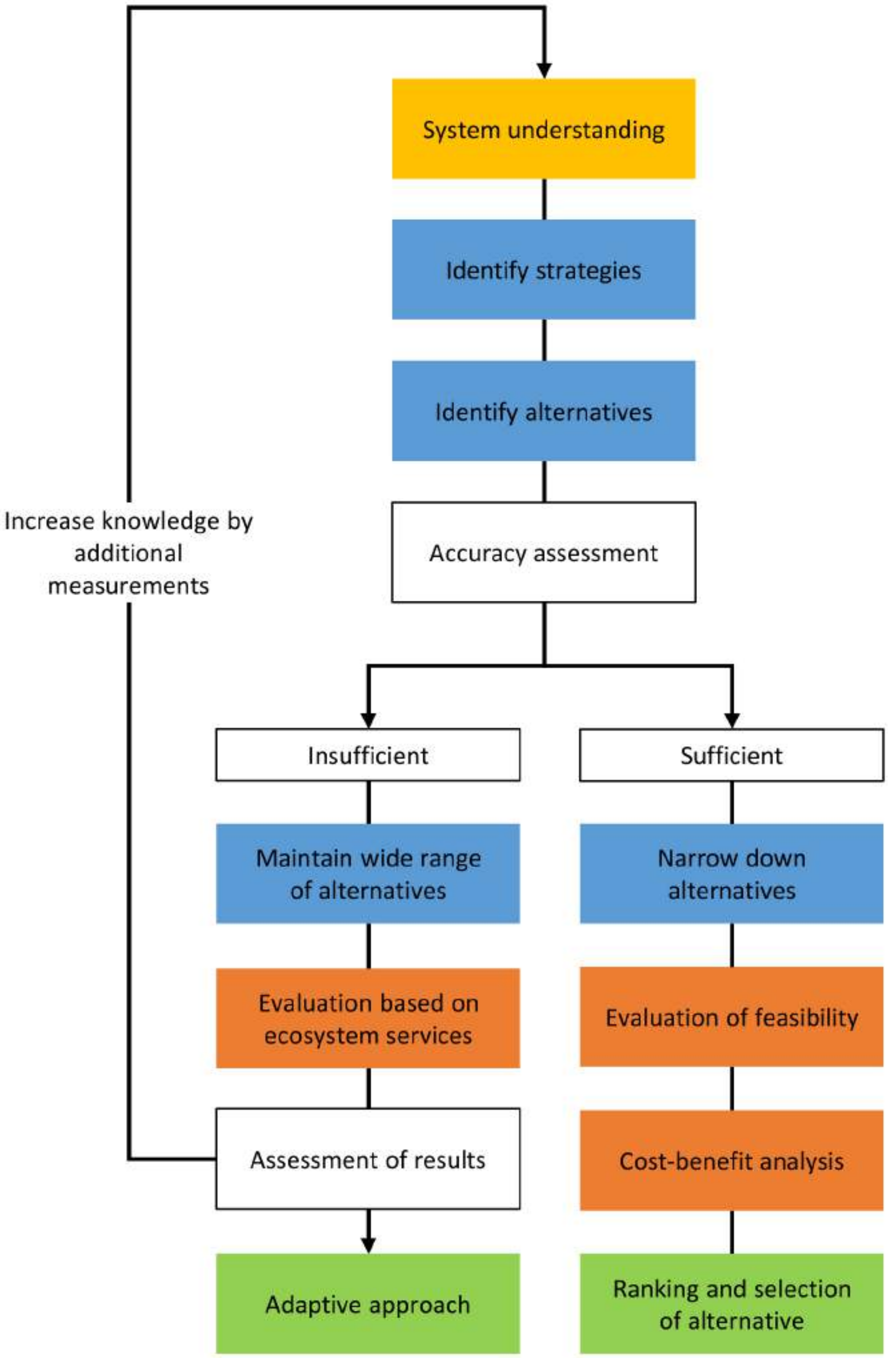

Figure 7.1: Proposed adjustment to the BwN design process for the first three steps

7.2.2 Technical

The estimate in this thesis leads to 0.25 meter of retreat due to storms and 0.14 m/y due to sea level rise. Overall estimates vary between 0,2 and 1 m/y. This indicates the uncertainty. The uncertainty also relates to identified sediment pathways and effectiveness of alternatives. The nourishment strategies require more knowledge about the optimal configuration and long term redistribution of the sediment. This means more detailed simulations are required. The hybrid solutions require more research on artificial reef design. The design largely determines the expected effectiveness of the structure.

Model improvements

The effects on the coastline are uncertain. The simulations are of low accuracy and serve only as an rough indication and relative comparison. The results are based on the simulation of one storm condition. This is not realistic and needs to be improved in further design cycles. Knowledge needs to be increased on wave angles, normal wave climate conditions, nearshore wave conditions and hurricane paths and frequencies. The closure depth and active profile also need to be defined in more detail. The wave data used in this report is the same as Van Arkel used. [van Arkel, 2016] This is offshore data which is translated to nearshore conditions. The wave conditions used in this report could be improved if nearshore measurements are done with buoys. This does not only improve the wave conditions but also gives more detailed data about storm durations and surge levels. This will improve the simulations significantly. The bathymetry measurements used in the simulations is of good quality. However, what currently lacks is clear bathymetry data before and after a hurricane event. This will significantly improve calibration of the model. McKenzie measured this but provides limited detailed information in the report. [McKenzie, 2012] Either this data is collected or new measurements should be done. The solid sediment density and porosity are assumed in the simulations in this report. No detailed information is available but they can be measured to improve the simulation. The D50, D15 and D90 are based on measurements from Smith Warner. When determining the solid sediment density and porosity, the grain size should also be determined. That way the chosen density and porosity corresponds to the right grain sizes. Also, the sediment layer between the 20 and 50 meter depth line needs to be better quantified. This will show whether there is actually enough sediment for the nourishment and if it is of good quality. The model setup can be improved by using a smaller grid size. The grid used in the simulations has a size of 25x25 meter. This is good to gain an understanding of the system and develop alternatives at this stage, but future design loops will require more detail so a smaller grid size should be used. A smaller grid requires more computational power so should be used only where needed. Xbeach is sensitive to calibration parameters. The model simulation assumes no alongshore gradients and currents in the bay. Because of the complex bathymetry in Long Bay this simplification might cause some unrealistic answers. For future simulations Delft3D could provide more realistic results.

Artificial reef

Design The design of artificial reefs needs to be further researched. Appendix G gave an indication but more detail is required before it can be considered as a feasible solution. The design an the artificial reef affects the performance.

Permeability The artificial reef simulated in Xbeach is created by altering the bathymetry and applying a non-erodible layer. This means that the created breakwater is non-permeable. This causes unrealistic results. In the simulations, the wave reduction of the reef is significant. On the onshore side of the reef, the waves reduce to a height of about one meter. The coefficient of transmission C_t is defined as the relation between the incident and the transmitted wave height, or $C_t = H_i/H_t$. For the simulation this gives $C_t = 1/2.91 = 0.34$. Following the simplified prediction method for wave transmission this would correspond to the same transmission coefficient as a breakwater with a crest height of 1.16 m above MSL. [CUR, 2007] This does not correspond well to what should be simulated and causes an overestimation of the wave impact reduction of the artificial reef. The alternatives formulated in chapter 5 all contain this overestimation. They are compared relatively to each other in chapter 6 which is why this evaluation still holds. However, when more detailed simulation of the final design are made in the future it is important to make the wave transmission of the artificial reef more realistic. Armono estimated wave transmission of submerged breakwaters made out of Reef Balls using hydraulic model tests. [Armono and Hall, 2003] Several Reef Ball configurations were tested among which designs similar to the artificial reef design in this report. The report proposes an equation for wave transmission. Equation 7.1 gives this empirically based equation. The equation is valid for structures which range between: $H_i/gT^2 = 0.001 \quad 0.015$, $h/d = 0.7 \quad 1$ and $h/B = 0.35 \quad 0.583$.

$$K_t = 1.616 - 31.322\frac{H_i}{gT^2} - 1.099\frac{h}{d} + 0.265\frac{h}{B} \tag{7.1}$$

The artificial reef design proposed in this report gives an K_t of 0.84. The parameters give $H_i/gT^2 = 0.004$, $h/d = 0.7$ and $h/B = 0.358$ so are all valid. The equation is applicable as a first estimate of the wave transmission. A submerged breakwater of the same height as the artificial reef design results in the wave transmission coefficient of 0.56 when following the simplified prediction method for wave transmission. This shows that the artificial reef is less effective at reducing wave heights then a traditional rubble mound submerged breakwater. This is as expected since the Reef Ball modules are much more permeable.

The results indicate that the artificial reef has a higher transmission coefficient than occurs in the simulation. This causes an over-estimation of the wave reduction which leads to an over-estimation of the effectiveness of the design. More detailed research is required to better estimate the transmission coefficient of Reef Ball breakwaters. This information should be correctly implemented in future simulations.

Sea level rise

The relative importance of sea level rise also needs to be verified. The calculation in chapter 2 gives an indication but the expected future sea level rise needs to be further researched. Also, sand demand due to sea level rise is not included in the simulations and required nourishment volumes. One should keep in mind that the coastline regression due to sea level rise will continue no matter what design is implemented. The average 0.14 meter of yearly coastline regression will remain and possibly increase due to climate change. On long timescales this might eventually become an issue. This type of coastline regression cannot by halted by basic nourishments since it is the MSL that rises. So the only way to ensure safety is to raise the ground level or relocate. Relocating is challenging considering the small dune strip on which they are placed. This is important to consider.

Priority

Hydraulic measurements, sediment properties and bathymetry measurements offer the most significant improvement on the model input. The buoy data gives wave heights, storm durations and surge levels. The bathymetry measurement provides a pre and post storm bed level. This can be used to calibrate the model accurately. The measurements take time but the data is very useful. The other measurements improve the model less significantly. Still, measuring the upper level of the beach and the sediment properties can be done in a relatively short amount of time.

7.2.3 Environment

The effect that alternatives have on the environment is uncertain. The construction of Breakwaters can harm the reefs but to what extent is not clear. The impact of nourishments and how far the range of effect is is also unknown. These are important aspects for the evaluation of the alternatives. The evaluation based on many assumption for this reason. This also makes it difficult to distinguish more subtle differences between alternatives. This knowledge needs to be increased if an alternative is to be selected from the evaluation.

Coral reefs

As mentioned in the previous section, the exact location of the existing reefs should be defined with more accuracy. Also, more information should be found regarding the orientation and state of the reef before the tourism industry came to Long Bay. This information needs to be obtained from the local community as there is no data or reports of this time available. The current state of the reef is also important. This should be clearly understood when considering restoration possibilities. There are many reports available on this subject so most information can be obtained from literature.

Sea grass

As shown in chapter 2, sea grass can offer multiple ecosystem services. From a technical point of view, the most interesting features are the ability to stabilize the bed by slowing down currents near the bed and the ability to produce sediment due to organisms living on them. The bed stabilization capability is not added to the simulations in the report. A feature to add the effects of vegetation exists and could be added to future simulations. More detailed information is required about the locations of the sea grass beds, the height of vegetation section relative to the bed, the drag coefficient, stem diameter and vegetation density per vegetation section in order to add sea grass beds to the simulation. [Deltares, 2017] The unknown sediment production capabilities are also an important uncertainty during the design process. This, together with the uncertainty of the simulations makes it difficult to determine the cause of the erosion at Long Bay. This is why multiple scenarios are considered. However, this means that the effectiveness of the alternatives is uncertain. This should be further researched to gain a more accurate indication. The amount of sediment production per square meter of sea grass bed should be quantified with more accuracy.

Wetlands

The environmental quality of the wetlands also needs to the better understood. It is unknown whether the waste water treatment plant functions as intended. This is important to know for further considerations of alternatives.

This thesis showed the importance of environmental protection for a successful integral project. Chapter 2 explained the environmental impact of the tourism industry and other factors on the region. For instance the water quality at Negril is an important factor which determines the living conditions for the ecology in the bay and wetlands. Monitoring and educational programs can benefit environmental protection and increases knowledge on the state of the environment.

7.2.4 Societal

The societal system is important to the project.

Stakeholder involvement

Proposing a building with nature design requires awareness of the public and government. It is very important that they understand the benefits that the design creates. Often stakeholders find it difficult to grasp that some implementations have indirect benefits or benefits that take time before they take effect. For instance, artificial reefs takes time to restore to a functioning coral reef. This means that the benefits created by coral reefs do not take effect immediately. Also, the coastal protection capacity improves over time for the same reason.

Involving stakeholder groups in the project can be very beneficial to the design process. Chapter 6 showed that this does require a good understanding of the different stakeholder groups. The social evaluation method cannot be used effectively because a lack of understanding leads to subjectivity. Furthermore, involving stakeholders early in the design process helps to convey the benefits of different building with nature alternatives. Stakeholders who are not active in the engineering fields often value straight forward solutions. Building with nature designs are often innovative ideas with many indirect and long term benefits. Making the stakeholders and the public understand the effects of different alternatives helps to proceed with an innovative idea without great opposition. Stakeholder groups may actually favor the design once they realize the benefits it brings.

The involvement can be achieved by information panels, media coverage, workshops and guided excursions. Information panels and workshops are very useful to get a better understanding of the interests of the different stakeholder groups. At the same time, the stakeholders can gain a better understanding of possible alternatives and their benefits. Media coverage helps to spread this information and open attitude to a wider public. Following this thesis, it is useful to share the gained knowledge about possible solutions to the stakeholder groups in the form of a workshop. Not all stakeholder groups responded to workshop invitations in the past. However, it is expected that many stakeholder groups will be attracted to the workshop when concrete morphological results are presented along with possible solutions to the problem. The response to the different alternatives can be used to assess the interests of the stakeholder groups with more certainty. Furthermore, it will open the idea to less traditional alternatives. The results of this workshop can be used in a new design loop to further detail alternatives to the interests of the stakeholders.

Policies and regulations

In order to ensure that Long Bay becomes a sustainable environment, policies are required. As mentioned in chapter 2, several environmental preservation policies exist. The policies need to be renewed to better fit the envisioned future. Policies by themselves are not enough. Regulations are also required. At the moment there is no strict policy regulation at Long Bay. This means there are little to no consequences when policies are not followed. The regulations are required to make sure no illegal practices occur which damage the environment. For instance, harmful fishing practices impacted the reef in the past. It is important that conservation of the reefs is ensured. A restored coral reef provides benefits for the fishermen. When fishermen start to go back to the reefs for their catch, it is crucial that they understand the importance of the reef and learn to catch fish in a sustainable way.

Financial

What has not been significantly touched upon is the costs of the projects and investment costs. In order for a project to succeed funds need to be raised. How the government proposal was funded is explained in chapter 2. For different solution strategies other investments might be needed such as tourism taxes. The costs of alternative also need to become more accurately indicated. This needs to be further explored in order to better understand the viability of the projects. When this is achieved, a cost benefits analysis can be performed which

7.2.5 Summary

So, the net step in the process can be to adopt an adaptive approach or to do a new design cycle. In this case, a combination of the two is possible. As an adaptive measure, environmental improvement can be implemented. This is a no-regret solution that is always going to be beneficial to the region for a small investment cost. The effect of the improvement can be used in the system understanding. The new design cycle requires additional measurements to increase knowledge. This improves the system understanding leading to more feasible and accurate alternatives. To increase knowledge three main components need to be improved: simulations, environmental quality assessments and stakeholder understanding. Better simulations improve the accuracy of coastal effects and the assessment of the impact of alternatives. Having a better understanding of the environmental quality and the impact of alternatives on the environment increases the certainty of the effect on solution strategies. Understanding the stakeholder groups better means that the social evaluation method will become a workable evaluation method. It also improves the formulation of the requirements of the project.

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Appendix A

Stakeholders

In this appendix the stakeholders involved in the project are described. First, all stakeholders are introduced. Their main interests and power of influence is indicated for each stakeholder group. This is based on past events such as the breakwater proposal from the government. In the next section, the connection between the stakeholders is explained.

A.1 Stakeholders

The stakeholders are divided into 8 groups.

A.1.1 Government

The government consists of many departments. The most important ones for this project are given below. The main interest of the government is economic growth and sustainability. In this region, the government focuses on the tourism industry to achieve this growth. As with most governments, safety of the inhabitants is one of their responsibilities. Environmental protection is also important for the governmental stakeholders.

- The Government of Jamaica (GOJ)
  The current government composition consists of mainly two parties; Jamaicas Labour Party and Peoples National Party which combined hold 98,6 percent of the votes. [Wikipedia, 2016] The government is a stakeholder with a large power of influence. They mainly want the area of Long Bay to keep developing. Their focus is on tourism development as it helps to provide economic growth for the region and Jamaica. Since Long Bay attracts 20 percent of all the tourism on the island, the governments interest in the region is high. Due to their large power of influence, the government can quickly start the implementation of a new project. This became most clear when the government proposed a breakwater project to prevent the erosion of Long Bay.

- Planning Institute of Jamaica (PIOJ)
  This institute leads policy formulation on economic and social issues. Their mission is to do this while achieving sustainable development for the people of Jamaica. Its function ranges from advising the government on issues relating to different policies, to providing technical and research support. It also serves as the implementing entity for Jamaicas adaptation fund project. [Planning Institute of Jamaica, 2016] The institute does not have the same power as the Government of Jamaica as its has a supporting function for the government. Nevertheless, the advice that they provide to the government relating to policies and research may influence the government in its decision making.

- The National Environment and Planning Agency (NEPA)
  This agency carries out the administration of three other statutory bodies. Their mission is to promote sustainable development by protecting the environment and careful development of Jamaica. Other functions are policy and program development, spatial planning, public education and outreach, and compliance and enforcement. [NEPA, 2016]

- Urban Development Corporation (UDC)
  This governmental corporation controls a large portion of the land in Negril, including part of the beach and wetlands. The corporation leases and sells land but also aids in the development of properties. [Olsen, 1997]

- Fisheries Division, Ministry of Agriculture and Fisheries (government)
  This part of the government is responsible for managing fish resource. For years, the fisheries division had limited presence and effectiveness in the field. The state of the division has improved over the years. It managed to create fish sanctuaries and passed a new fisheries law. The law seek to create sustainable development of the fisheries industry. [Waite, 2011]

The government has a large power of influence. Due to this power, the government can quickly start the implementation of a new project. This became most clear when the government proposed a breakwater project to prevent the erosion of Long Bay. The breakwater proposal was going to be implemented by both PIOJ and NEPA.

A.1.2 Tourism industry

The tourism industry consists of businesses which depend on tourists for their income. The main actors are the hotel and resort owners, the water sport operators and retail. The most influential organization is the Negril Chamber of Commerce, which represents the hotel and resort owners. The tourism industries main interest is further development by attracting more tourists and expanding business. The environment is very important for the tourism industry since this is what attracts the most tourists. The most prominent concern of the hotel owners is safety against coastal erosion.

- Negril Chamber of Commerce (NCC)
  The Negril Chamber of Commerce was founded in 1983 and currently has sixty members. Their mission is to create a sustainable environment in which the tourism product is improved and promoted through the development of projects, educating, lobbying and action. [Negril Chamber of Commerce, 2016] The main goal/needs for the tourism industry is to have a sustainable environment which attracts many tourists. They also want the ability to further develop and expand the industry.

- Jamaica hotel and tourism association (JHTA)
  This association represents hotels and other accommodations as well as suppliers of services to the tourism industry. They promote cooperation between bodies of the tourism industry and encourage its development. http://www.jhta.org/index.php/about-us

- Negril Water Sports Operators Association
  Water sports operators consist of dive instructors, snorkel and dive tour guides and people renting boats, jet skis and other watercraft. Watersport operators depend on the environment and tourism for their income. Because the environment is so important, dive operators formed a non-governmental organization focused on the protection of the reef. This NGO is discussed later.

- Retail and other services associations
  These associations represent people selling art and craft, souvenirs, clothes, cigarettes and other goods and services. They are small associations with not that much power of influence but together they represent a working group which cannot be neglected. Several noteworthy associations are the Rutland Point Craft Market Association, Itinerant Vendors Association and the Negril Craft Market Association. [CANARI, 2001]

Because the tourism industry is the largest economic sector in the region, they have a decent amount of influence. This became evident during the breakwater proposal. This project was strongly opposed by among others the Chamber of Commerce. Their opinion was that the breakwater design was not environmentally friendly and would have a negative impact on tourism. The environmentalists and the local community agreed with the Chamber of Commerce. Their voice turned out to be strong enough and the Jamaica Labour Party government decided to scrap the breakwater project. During the protests and meetings both PIOJ and NEPA were invited to attend on multiple occasions but never attended them.

A.1.3 Fishing industry

The fishing industry is represented by the Negril Fishermens Cooperative and the governmental actor mentioned earlier, the fisheries division. The fisheries main interest is food resource and environment. Sustainable development is important to the fishermen.

- Negril Fishermens Cooperative
  The cooperative was created to improve the involvement of fishermen in the development of the Negril area. They mostly work with the NCRPS on different projects like shrimp farming projects, learning new fishing technique and others. [CANARI, 2001]

- National Fisheries Advisory Board
  The fisheries division is supported by the National Fisheries Advisory Board which monitors fishing activities and advises the Minister of Agriculture and Fisheries. The board consists of fishermen, ecologists and other representatives.

The power of influence of the Negril Fishermens Cooperative is not large. However, the National Fisheries Advisory Board which supports the fisheries division, also consists the fishermen. This way, the fishermen are able to influence the fisheries division in their decision making. The Fisheries Division has been struggling for years and does not have a strong position within the government.

A.1.4 Environmentalists

There are three important environmental stakeholders. Two are NGOs and one is a large consortium. Their function and services slightly vary but they all have similar interests. Their general interests are environmental protection and sustainable development.

- Negril Coral Reef Preservation Society (NCRPS)
  Diver operators formed the NCRPS in 1990 to protect the reef. They focus on damage caused by among others, divers, snorkelers and anchor damage. They installed mooring buoys at dive sites and launched awareness campaigns. [CANARI, 2001]

- The Jamaica Environment Trust (JET)
  JET is a non-governmental non-profit organization which mains to protect the natural resources of Jamaica by using law and advocacy, education and conservation.

- The Negril Area Environmental Protection Trust (NEPT)
  The Negril Area Environmental Protection Trust is a large consortium with a broad membership ranging from government agencies to NGOs and local community associations. The first activity of NEPT was developing the protection plan for the Negril environmental protection area (EPA). Most stakeholders are represented in NEPT. This can makes it difficult to coordinate and make decisions. [CANARI, 2001]

These organizations mainly provide advice and support. They have a reasonable power of influence.

A.1.5 Residents

Residents are generally most affected by new development. Their main interests are human well-being, water quality and food resources. Residents also want enough jobs available.

- CBO or community associations
  There are two community associations which represent the local inhabitants called Little Bay Citizens Association and Whitehall Citizens Association. [CANARI, 2001]

This stakeholder group contains a large group of people but does not have a large amount of influence. Having a community association improves their position. The local community was strongly against the breakwater proposal. They initiated many protests but only with support of the tourism industry and environmentalists were they able to prevent the project.

A.1.6 Visitors

Visitors are those who come to Long Bay for a short period of time. Most of the visitors come for pleasure. The main interest of visitors is recreation and nature. They want an aesthetically pleasing natural landscape. Visitors also want good infrastructure. Airports and good quality roads make it easier for visitors to travel to Long Bay.

- Tourists / Beach visitors and users
  This stakeholder consists of anyone coming to the beach for recreational purposes. These people can be both Jamaican tourists, international tourists, and local beach users. Tourists will have individual wishes and interests. The tourism industry will try to cater to thee wishes as good as possible.

The wishes and interests of tourists are very important for the region. The tourism industry will always try to please the tourists. So even though tourists have a low power of influence directly in the region, they do have a large indirect influence.

A.1.7 Academia

This stakeholder group consists of different research institutions. They provide technological support to other organizations. Their interests are mainly gaining and sharing knowledge. The environment is important to them. The institutions which provided/provide the most support are listed below.

- TU Delft/Leiden University/Nature Coast project
  This group of institutions is currently working with the chamber of commerce to find a solution to the erosion problem at Long Bay. Their focus is on finding a sustainable, environmentally friendly solutions.

- University of the West Indies
  The University of the West Indies is the largest university in the English speaking Caribbean. [UWI, 2016] Research is being done on a variety of topics. The Department of Geography and Geology conducted research on the coastal erosion at Long Bay. This research was often done independently for research purposes. The department also provided technical support for governmental institutions.

- Smith Warner
  In 2006, Smith Warner did a study for the Negril Coral Reef Preservation Society about the erosion problem at Negril. They came with a recommendation on how to revere the erosion trend. [Smith Warner, 2007]

Academia have a low power of influence. They offer a supporting function and can give advice but do not have the power to make decisions. They can only convince other groups to follow a certain direction.

A.2 Stakeholder connections

In figure A.1, the connections between the stakeholders are visualized. The right side of the figure shows three layers: the government, businesses (tourism and fishery industries) and people (visitors and residents). To the left are the environmentalists and academia. The green arrows represent stakeholders working together. These cooperations have been mentioned in the previous section. The red arrows between stakeholders represent conflicts. Apart from the given collaborations and conflicts between stakeholders, there are also collaborations and conflicts between stakeholder groups. The most important collaborations and conflict between groups occurred during the breakwater proposal of the government and have already been mentioned in the previous section.

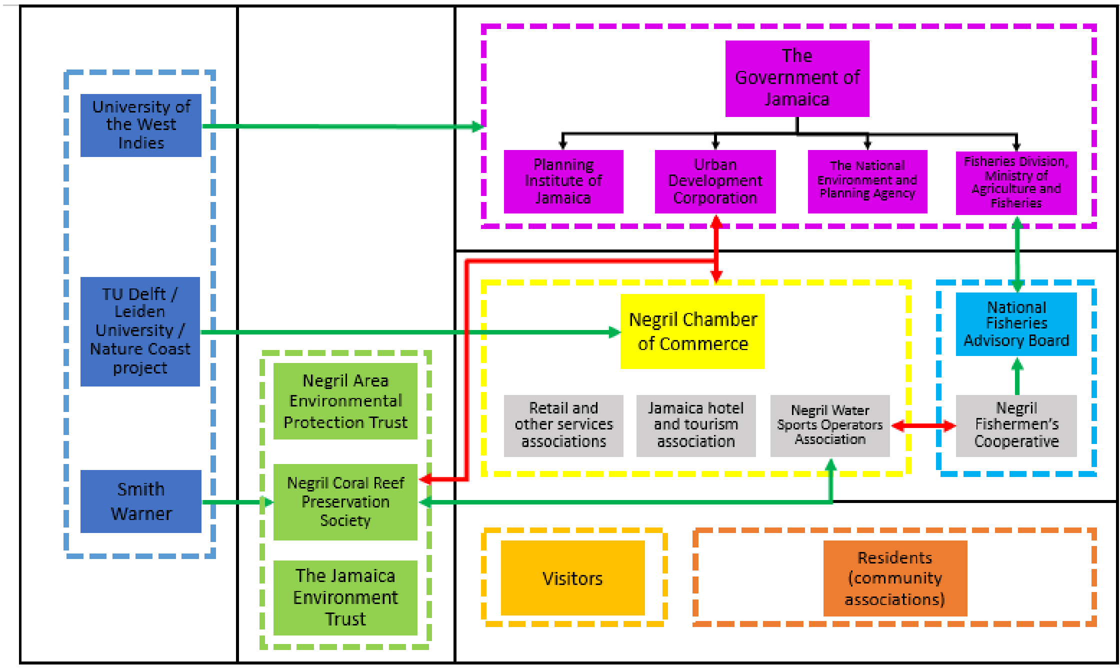

Figure A.1: Connections between stakeholders

A.2.1 Conflicts between stakeholders

Conflict between fishermen and water sport operators is mostly about the use of the bay. Fishermen and water sport operators use the same area and fishermen feel like the operators are using the area too much and dont get enough time to fish. They also complain about operators damaging their equipment. Most of the conflict is due to the main concern about the declining amount of fish in the region. Fishermen blame the tourism and agricultural industry for this. [CANARI, 2001]

The urban development cooperation owns a large section of the beach and morass. Their development plans caused conflicts with the NCC and NCRPS when the government used the last area of wilderness along the beach for hotel development. In order to preserve the ecology, the opposing side wanted to turn this area in a public park. In the end, the UDC only used a small section for a public park to please the community. This attempt has unsuccessful since the opposing side remained displeased. [Olsen, 1997]

A.2.2 Internal conflicts

Apart from conflicts between different stakeholders, there are also internal conflicts. These are usually caused due to the competitive nature of the industries. For instance, all hotel owners want a wide beach in front of their hotel. Constructing interventions to accomplish this, such as groins, can have a negative impact for hotel owners alongshore. Fishermen also have internal conflicts. Competition increased due to the reduced amount of fish in the bay. Services focused on tourist have the same issue.

Appendix B

Ecosystem

This appendix explains in detail what the most important natural features at Long Bay are and what ecosystem services they provide

B.1 Reef

On the edge of the inner shelf lies a coral reef. In the past this was one large reef but currently it consists of two separate smaller areas. Coral reef grows in shallow waters in tropical and subtropical regions around the world and supports thousands of different species. Corals, reef fish, sponges, urchins, mollusks, turtles, crustaceans and many more form a large biodiversity. The biodiversity provides the reef with the nutrient, food and shelter to sustain itself. Coral species form the basis of the reef life. Coral exists due to a symbiotic relationship between algae and polyp. Polyp provides a place for the algae to live. The algae provide food and color through photosynthesis for the polyp. Polyp excretes an exoskeleton made from calcium carbonate. The polyp itself mostly feeds on micro-plankton A coral reef is a limestone formation build up from the remains of coral polyps and coralline algae. The outside layer consists of living coral colonies. This way of growing causes the reef to grow upward. The coral reef at Long Bay is a fringing reef. Fringing reefs are shallow reefs with a flat zone or lagoon between land and the reef. Figure B.1 illustrates the general layout of a fringing reef.

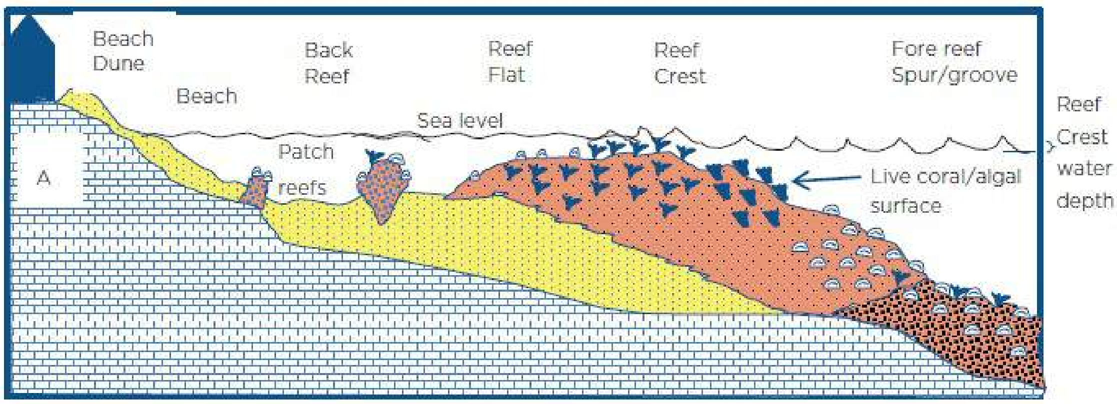

Figure B.1: Coral reef
Source: [WAVES, 2016]

The reef crest is the shallowest part of the coral reef. This part is most influenced by the tides and wave action. The reef is only several meters below mean sea level at this point and waves to break on the reef. These conditions are good for the ability of the coral to feed on plankton. Also, the shallow depth allows for a lot of light to reach the corals. Generally the growth conditions for coral are sunlight, clear water, low level of nutrients, warm water temperatures over 18C, high salinity, low carbon dioxide concentrations and supply of food and oxygen. The reef crest has all of these requirements so the coral usually flourishes at this region. The area from the back of the reef to the shore is called the reef flat zone. It is usually a sandy area containing random coral rocks. It may also contain an enclosed lagoon. In case of long bay the reef is located about 1.4 km offshore. The zone between the reef and the shoreline is not an enclosed lagoon. It is a sandy area consisting mostly of sea grass fields. There are only small patches of coral in this area with low diversity. The fore reef is very small at Long Bay. Since the reef is located at the end of the inner shelf, the sea floor quickly drops to over 50 meters behind the coral reef.

B.1.1 Ecosystem services of reef

The reef can provide many services. Food provision relates to fisheries. The reef attracts many species of fish which are caught for human consumption. A healthy kilometer of reef may yield 5-15 tons of fish per year. [Jamaica Environment Trust, 2016] The second provisional service refers to biomass or biotic elements for non-food purposes. A reef may add to the sediment production by providing material. It also supplies corals and shells which can be used for ornamental purposes. The regulating and maintenance services that the reef provides are coastal protection, coastline stability and life cycle maintenance. A risk and vulnerability study showed that the reef helps to reduce the amount of erosion on the coastline. The reef reduces storm impact. Without the reef the shoreline erosion significantly increased. [CL Environmental, 2014] This leads to the assumption that the reef acts as a detached submerged breakwater. Life cycle maintenance means the biological and physical support that the reef gives to facilitate the healthy and diverse reproduction of species. Cultural services of the reef include symbolic and aesthetic values, recreation and tourism and cognitive effects. Coral reefs provide an obvious aesthetic value due to existence and beauty of the charismatic habitat and species. Tourism greatly benefits from the reef. As mentioned before, the tourism industry is the main source of income in the region. The reef is a great tourist attraction which is evident by the 48 snorkel and dive sites. The cognitive effects trigger mental processes like knowing, developing, perceiving, or being aware resulting from natural landscapes or living organisms. In this case the coral reef induces awareness and a respect for nature. It also provides material for research and education.

B.2 Sandy beach

The beach of Long Bay is the longest continuous stretch of white sandy beach in Jamaica with a length of about 7 km. Bloody Bay is a separate piece of coastline. The two are divided by a headland made out of limestone. The beach lies on limestone bedrock, clay and peat deposits. Long Bay has a very small loping profile. The sandy beach is a known sea turtle nesting area. [NEPA, 2016]

B.2.1 Ecosystem services of sandy beach

The services that the beach provides are regulating and maintenance services and recreation and tourism. The sandy beach is a known sea turtle nesting area. [NEPA, 2012] This way the beach facilitates the healthy and diverse reproduction of species. The sandy beach is the main reason for the tourism development in the area. It provides many opportunities for relaxation and amusement.

B.3 Sea grass beds

Sea grasses grow in shallow coastal waters with sandy or muddy sea beds. They come in many species all of which have long and narrow leaves. The shallow water allows for plenty of light to reach the leaves for photosynthesis. Other requirements for growth are calm currents and wave action, low level of nutrients, high salinity and supply of food and oxygen. They form large beds consisting of one or several species of sea grass. Sea grass provides habitat for many species ranging from fish, turtles, manatees and sea urchins to macro- and micro algae, mollusks and nematodes. At Long Bay, sea grass grows abundantly in the inner shelf. Thalassia testidium and syringodium filiforme can be observed in large fields.

B.3.1 Ecosystem services of sea grass beds

One of the main advantages off sea grass fields is that the sea grass is capable of trapping and holding sediment. The sea grass slows down currents near the bed, increasing sedimentation. This makes it very valuable for stabilizing the bed and reducing erosion. Sea grass is also thought to produce raw material. Organisms which grow in the sea grass beds produce sediment. The quantity of this production is uncertain. Additionally, it can remove dissolved nutrients from the water. Since they also trap sediment the sea grass beds help improve water clarity as well. Lastly, sea grass beds act as nurseries and spawning areas for many species of fish. It is also a primary food source for many organisms such as the green sea turtle and the manatee.

B.4 Wetlands

Wetlands are an important habitat for local to migratory avifauna and many other species of animals, plants, birds and fish. Wetlands maintain fresh water supplies by storing rain water, refilling reserves and protecting it from saline intrusion. They also hold flood water, putting less pressure on other areas. Wetlands protect marine ecosystems by acting as a barrier that filters water before it reaches the sea. This way it helps in protecting the fragile coral reef. For a wetland to properly grow it requires sunlight for photosynthesis, nutrient cycling and a recurring water cycle. The soil needs to be inundated at least most of the year. The wetland near Negril is called the great morass. The great morass is a large protected wetland area of round 21 km2. It is a low lying area, consisting mostly of peat, which is separated from the bay by a sandy barrier. This sandy barrier is where the hotels and resorts are built on.

B.4.1 Ecosystem services of wetlands

In terms of provisioning services, the wetland can provide food due to the diverse species of plants and animals. Raw material such as peat and mangrove wood can also be gained. The regulating services are that the wetland improves water quality, provides oxygen and provides living conditions for many species. It holds a strong aesthetic value, triggers awareness and knowledge. It is also a place for tourists to explore using boats or canoes.

B.4.2 Rivers

The rivers form the connection between the wetlands and the bays. The southern river was constructed first. It was built to drain the wetlands allowing the construction of the road between Montego Bay and Negril. By connecting the morass to the coast salt water started to intrude into the wetlands. The fishing village which was already present before the construction of the river, further developed in the river outflow.

Appendix C

Sediment properties

This appendix covers the sediment characteristics at Long Bay. This includes basic sediment properties and the sediment composition.

C.1 Sediment properties

The department of Geology and Geography collected samples from different parts of the beach along Long Bay and Bloody Bay. The grain size analysis they performed determined the mean, the sorting and skewness. The results show an increase in mean grain size from the south of Long Bay to the north. The sorting is typical for sandy beaches which are attacked by waves. The skewness shows weak to moderate negative skew. This is also typical for sandy beaches. The grain size distribution remained similar when comparing data from 1991 and 1980. Soil classification by CL Environmental revealed a poorly graded particle size with a uniformity coefficient less than 6. The samples were well sorted which indicates a relatively high wave energy at the shoreline. Smith Warner also took samples of sediment. The results are summarized in figure C.1. The sediment is also classified as well sorted, poorly graded sand.

Table C.1: Sediment classification by Smith Warner

Sample number	D15 (mm)	D50 (mm)	D90 (mm)
S1.1	0.28	0.51	0.85
S1.2	0.18	0.32	1.20
S4.1	0.1	0.37	0.75
S4.2	0.24	0.51	0.95
S9.1	0.15	0.26	0.55
S9.2	0.15	0.24	0.40
S10.1	0.40	1.06	1.90
S10.2	0.16	0.25	0.40
S12.1	0.19	0.42	0.85
S12.2	0.15	0.25	0.49
S13.1	0.36	0.59	1.00
S13.2	0.15	0.25	0.42
S14.1	0.29	0.54	1.00
S14.2	0.16	0.28	0.49
S16.1	0.18	0.29	0.57
S16.2	0.18	0.27	0.48
S18.1	0.40	0.73	1.70
S18.2	0.40	0.81	1.80

Source: [Smith Warner, 2007]

C.2 Composition

The department of Geology and Geography also determined the composition of the sediment. The results are given in table C.2. It shows that over 32 percent of the sediment is bioclast, over 37 percent amorphous grains and almost 30 percent recrystallized grains.

Table C.2: Sediment composition
Source: [Department of Geology and Geography, 2002]

		1980 [%]	**1999** [%]
Bioclast	bivalve	4.01	3.58
	echinoid	1.13	1.14
	halimeda	6.23	7.73
	red algae	3.54	5.90
	gastropod	0.91	0.62
	forams	19.31	13.28
	worm tube	0.00	0 .00
	porites	0.65	0.02
	intraclast	0.00	0.21
Amorphous		34.80	37.34
Recrystallized		29.25	28.41
Cement		0.35	1.58
Total		100.00	100.00

The results show that amorphous and recrystallized grains form a large percentage of the total composition. The mean values are 37.3 percent for amorphous grains and 28.4 percent for recrystallized grains. Amorphous grains are formed by micritization of bioclasts and faecal pellets. Recrystallized grains are formed by neomorphic replacement of grains in diagenesis (from activities of marine organisms). Beach nourishments with imported sand can also add to the amorphous and recrystallized grains. The bioclast in the sediment mostly comes from foraminifera, bivalves, halimeda and red algae. Only a very small percentage of bioclast comes from echinoids and corals. In this case, foraminifera is mostly epifauna living on the sea grass. The bivalves are mostly infaunal species living close to shore. The halimeda and red algae are expected to live in the shallow shelf.

Appendix D

Hydrodynamic processes

D.1 Wave data

Van Arkel used hindcasted wave data for modelling of the Negril coastline. [van Arkel, 2016] The report evaluated two different data sources; The European Centre for Medium-Range Weather Forecasts and The National Oceanic and Atmospheric Administration. A comparison was made between measurements and modeled nearshore wave characteristics for both NOAA and ECMWF waves. The results from ECMWF were proven to be more accurate.

Transformation method Two methods can be used to transform offshore wave characteristics to nearshore. These are by using the linear wave theory or the wave energy balance. The main differences between the two are given in figure D.1.

Origin of difference	Linear wave theory	Wave energy balance
Size of wave input	Typically ~ 1000 – 10000 waves (time series)	Typically ~ 100 waves (wave climates)
Wave input	Waves at 1 location Only onshore directed waves considered	Varying offshore wave boundaries All wave directions considered
Wind input	No wind considered	Varying wind fields
Bathymetry	Alongshore uniform slope, with one constant cross-shore profile	Bathymetry
Coral reef	No reef height considered	Reef height considered
Processes	Only linear processes included	Both (non-)linear processes included
Computational time	Around 20 seconds	Around 7-20 hours

Figure D.1: Difference between linear wave theory and energy balance
Source: [van Arkel, 2016]

In general, linear wave theory can only be used in very simple cases. Accuracy decreases for variable bathymetry, refracting waves, influence of wind and other non-linear processes. Van Arkel showed that applying linear wave theory for the Negril coast leads to large inaccuracies. The (de)-focusing of waves due to the variable bathymetry seems to be the main cause of the differences. [van Arkel, 2016] The wave energy balance is the preferred method. A numerical wave model like SWAN can transform the offshore wave characteristics to nearshore. Due to the non-linearity this model requires an Eulerian approach. A special grid with bathymetry is required. The wave climate is imposed at the boundaries of the grid in deep water. Wind conditions can be imposed on a separate grid. The offshore wave climate is transformed to nearshore conditions by solving the wave energy balance on the grid.

Reduced wave climate Reducing the dataset reduces computation time considerably compared to using the full dataset. The reduction may decrease the accuracy of the results. The input reduction method determines the decrease in accuracy. Reduced wave climate must still give similar results as the full wave climate in order to be useful. Reducing wave conditions can be done by reconstructing offshore time series to a nearshore time series. This is done by first determining a reduced wave climate from the offshore wave database. This selection is transformed to nearshore wave conditions. The time series of the offshore data can be transformed to a nearshore time series (For this, statistical methods can be used). This time series can be validated by comparing it to nearshore measurements. The reduction of wave data can be done by two methods, single reduction or repeated reduction. Single reduction reduces the wave dataset only once, where repeated reduction this is done for every model execution. The selection for the wave input reduction method for the Negril coast is based on several considerations:

- The specific target for the wave input reduction is the bulk alongshore sediment transport
- The models compute the average conditions, hence the wave chronology does not affect the resulting bulk alongshore sediment transport rates. Therefore, a reduced offshore wave climate can be constructed, without taking into account sequencing.
- Olij (2015) investigated algorithms to reduce an offshore wave climate. He recommends using the K-harmonic means method. To reproduce the bulk alongshore transport rates with the Kamphuis formulation. Therefore, this method is the starting point of the wave input reduction.

  [van Arkel, 2016]

Van Arkel used the K-harmonic means method. This is a clustering method, meaning that similar wave conditions are bundled in one cluster. It is an inconsistent input reduction method. Inconsistent input reduction methods are likely to introduce inaccuracies. To improve the method, Van Arkel combined the K-harmonic means with the maximum dissimilarity algorithm. This makes the method consistent and increases performance. Because the computational time of reduction method is considerable, the single reduction is used. Figure D.2 shows the results of applying this method.

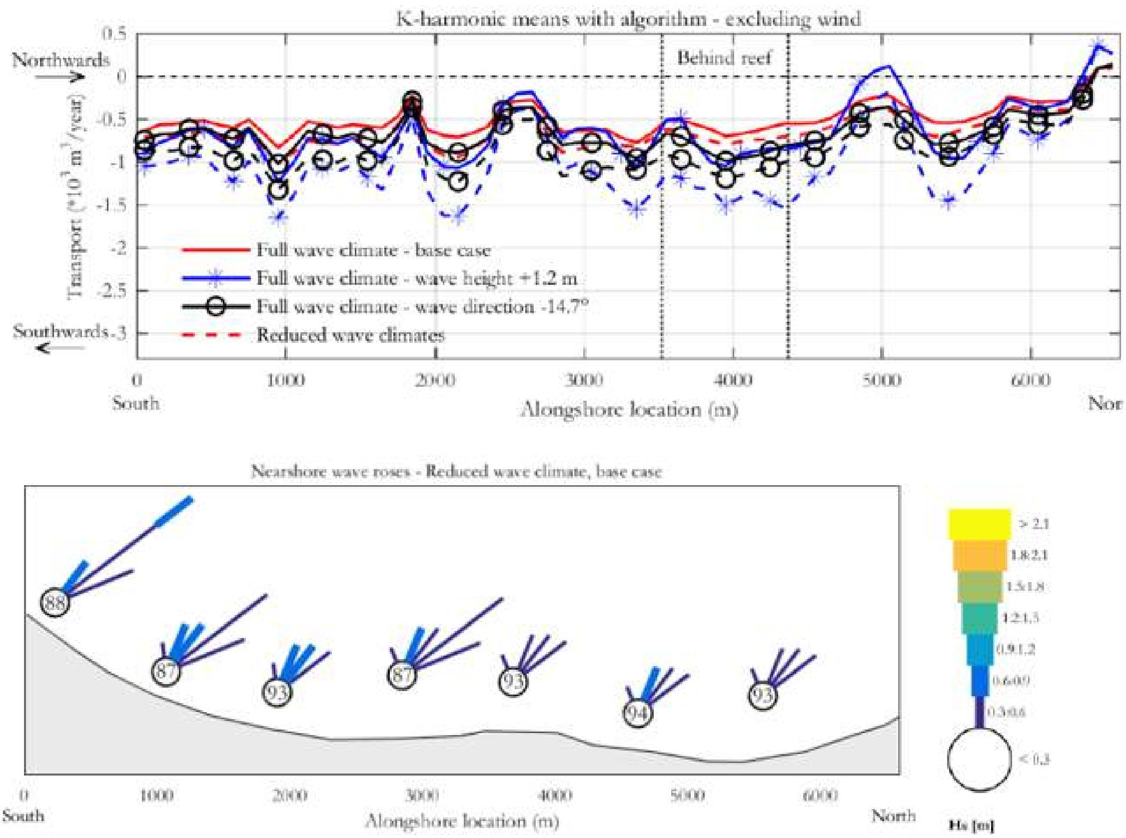

Figure D.2: reduced wave climate and near shore wave roses
Source: [van Arkel, 2016]

The results from Van Arkel represent 132 scenarios. Using quickplot, nearshore wavedata is obtained from the smallest grid. The left graph of figure D.3 shows the percentage of occurrence in bins of 0.2 m. Waves are most common between 0 and 1 m. When looking at the right graph of figure D.3 , this can be seen since the probability of exceedence of wave higher than 1 meter is already below 3 percent.

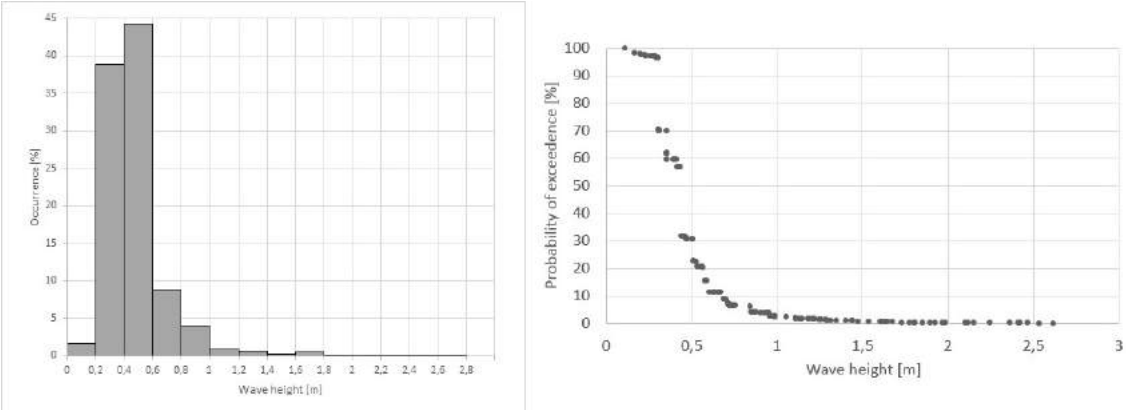

Figure D.3: Wave height occurrence (left), Wave height probability of exceedence (right)

D.2 Wave period

Similar to the wave height data, wave periods are extracted from the Delft3D model made by Van Arkel. [van Arkel, 2016] Figure D.4 gives the relation between the wave height and wave period. The data set contains wave periods which rarely exceed 9 seconds. These kind of waves are wind driven waves. There seems to be almost no swell.

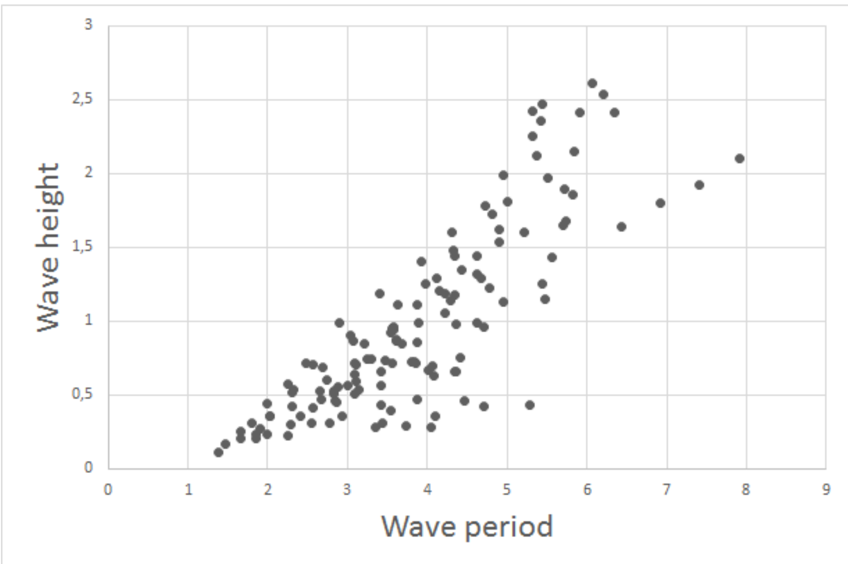

Figure D.4: Relation between wave height and wave period

D.3 Wave direction

Offshore waves predominantly travel from the northeast to southeast direction. This is the cause of trade winds. When translating the offshore to nearshore only offshore wave which are able to reach the coastline are considered. This results in nearshore waves with a directional distribution as indicated in figure D.5. [Smith Warner, 2007]

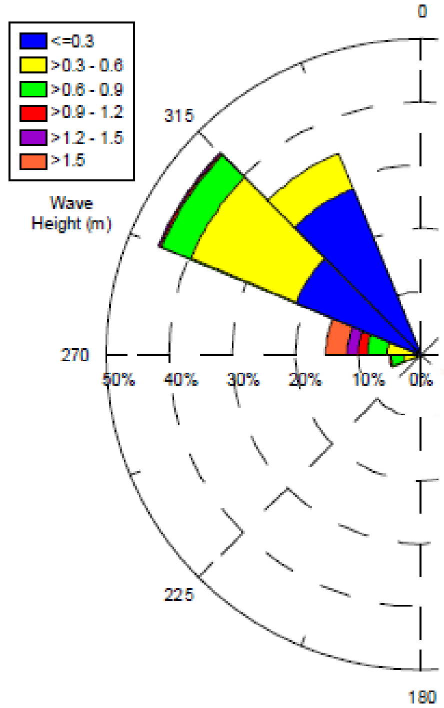

Figure D.5: Nearshore wave rose
Source: [Smith Warner, 2007]

D.4 Tides and currents

Negril is subject to small tidal ranges. CL Environmental measured a spring tidal range of 0.345 m. [CL Environmental, 2014] The tide signal recording from their measurements shows that two tidal cycles a day occur, or one every twelve hours.

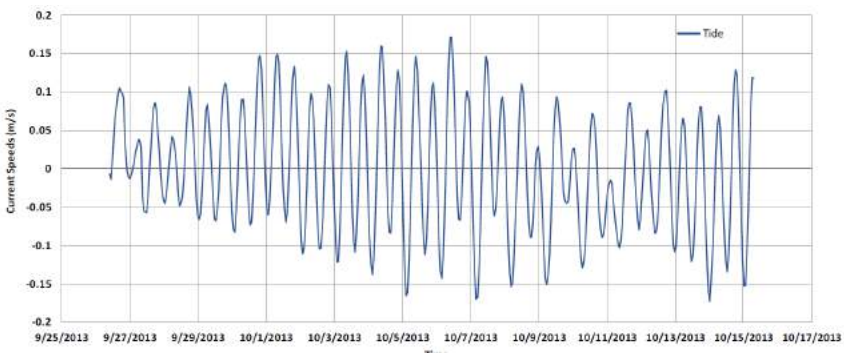

Figure D.6: Tidal signal at Negril, Jamaica
Source: [CL Environmental, 2014]

D.5 Wind

The data provided by van Arkel shows a clear correlation between wind and wave direction. [van Arkel, 2016] This relation further supports this claim that the waves are mostly sea waves. Wind speeds are generally low with an average of 5 m/s.

Appendix E

Xbeach modeling

This appendix contains all detailed information about the Xbeach simulations. The first section explains how the basic model is set up. It is explained how the calibration is done and which model input is used in the end. The information given in the model input represents the reference scenario. Other simulations are a variation to this where the bathymetry, non-erodible layers and friction layers are different. The other parameters remain unaltered. The following sections explain how the results are computed after simulation. Sediment loss and coastline regression are calculated using the simulation results.

E.1 Simulation

This section explains how the Xbeach model is set up which is used to simulate storm events on the coast of Long Bay. Other Xbeach simulations are a variation of this model, where the original is used as reference scenario.

E.1.1 Model Setup

The model simulates a significant hurricane event impacting the coast in its current state. Setting up an Xbeach model requires a grid and bathymetry, boundary conditions and morphological conditions. A 1/100 year storm event is simulated as explained in chapter 3. It is assumed that the waves resulting from the passing hurricane impact the coastline for approximately 48 hours.

E.1.2 Calibration

In order to establish whether the simulation made by Xbeach represents reality in a correct way, calibration is required. Calibration is done by comparing the model results with the data from chapter 2. The pre- and post-hurricane beach profiles at the location of Negril Gardens Hotel and Native Sons Villas must be of similar magnitude as the information provided by McKenzie. [McKenzie, 2012] If this is the case, the model represents reality close enough to be valid. Another criteria is that the hotel, situated around 2 meter above MSL, should not be completely eroded away after one storm. This has not happened in the past and would be unrealistic. In other words, erosion at 2 meters above sea level should be low.

The following section gives the complete model input used to simulate a hurricane event on the coastline after calibration of previous results. The resulting simulation shows erosion patterns similar to data from McKenzie. [McKenzie, 2012] The cross-shore bed level at the two locations used for calibration are similar to that data. Furthermore, erosion above the +2 m MSL line is not significant so the simulation is considered valid.

E.1.3 Model input

Each parameter used in the reference model is discussed. For every parameter not mentioned the default value is used in Xbeach.

Grid The grid used for this model is based on the smallest grid used in the model by van Arkel. This grid is cropped to give it a rectangular shape. The final grid is 228x369 (MxN).

Wave direction Xbeach uses a directional grid for short waves and rollers. This grid requires a minimum (thetamin) and maximum (thetamax) angle and a directional bin size (dtheta). In this case the angles are defined according to the Cartesian convention. The values depend on the wave direction. Appendix D showed that the largest waves occur between 270 and 315 degrees. The simulation uses a wave direction of 270 degrees. Other simulation at 260 and 280 degrees have also been made. The different angle did not cause large changes in currents and sediment loss. This is why the simulations all use 270 degrees as wave direction. The chosen parameters for the directional grid are Dtheta = 180, thetamin = -90 and thetamax = 90.

Bathymetry The bathymetry is generated by triangular interpolation of the bathymetry data on the grid using Delft3d - QUICKIN. Figure E.1 shows the bathymetry from +5 up to -10 m below sea level using contours for every meter of depth. As can be seen, Long Bay is a shallow bay. Most of the bay is not deeper than 5 m below sea level. This inner shelf extends up to 2 km offshore. Beyond the 10 meter depth line the sea bed quickly drops. The area along the beach where the main road and most of the resorts are situated is around 2 m above sea level. Other simulations use a modified version of this bathymetry file.

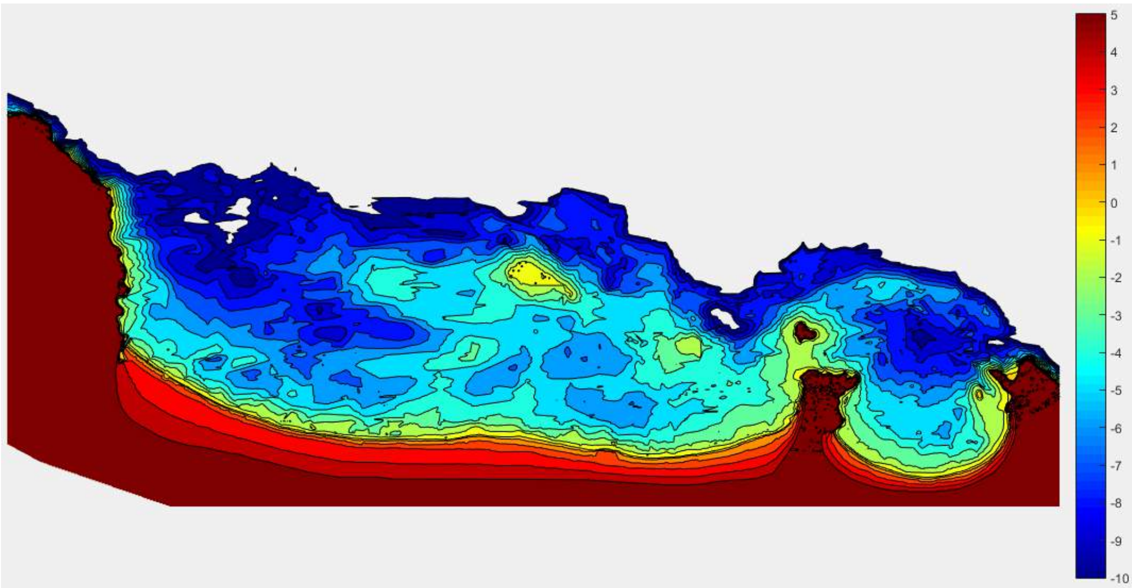

Figure E.1: Bathymetry contours Long Bay

Wave boundary conditions It is necessary to use surfbeat mode to input waves when the focus is on swash zone processes. This mode solves the variation of short-waves envelope on the scale of wave groups. The lateral wave boundary condition is generally set to Neumann. For surfbeat mode, this leads to shadow zones in the groupiness. Setting the gradient along the wave crests of the wave energy to zero reduces this effect. [Deltares, 2017] The significant storm wave height for a return period of 1/100 years is determined from the data given in appendix D. A threshold value of 1 m is applied on the dataset. Anything below 1 m is not considered a storm wave. Using the remaining wave data, the significant storm height Hss is determined using an Exponential, Weibull and Gumbel distribution. The results are illustrated in figure E.2. The Weibull distribution is chosen as most fitting result. The Weibull distribution has the following parameters: beta = 0.509, gamma = 0.889 and alpha = 1.45. These parameters lead to a correlation of 0.992. For a 1/100 year storm this distribution leads to an Hss of 2.91 m. Based on information given in appendix D, a peak wave period of 9 s is chosen with this storm wave height. The significant wave height for other return periods is determined in the same way. The wave condition is simulated using a jonswap spectrum. Due to the lack of data, the actual wave spectrum is not known. For this reason, not all parameters for the jonswap spectrum can be determined and default values are used. The parameters specified in Xbeach are Hm0 = 2.91, Tp = 9.0, mainang = 270 and fp = 0.11 where fp is approximately 1 / Tp.

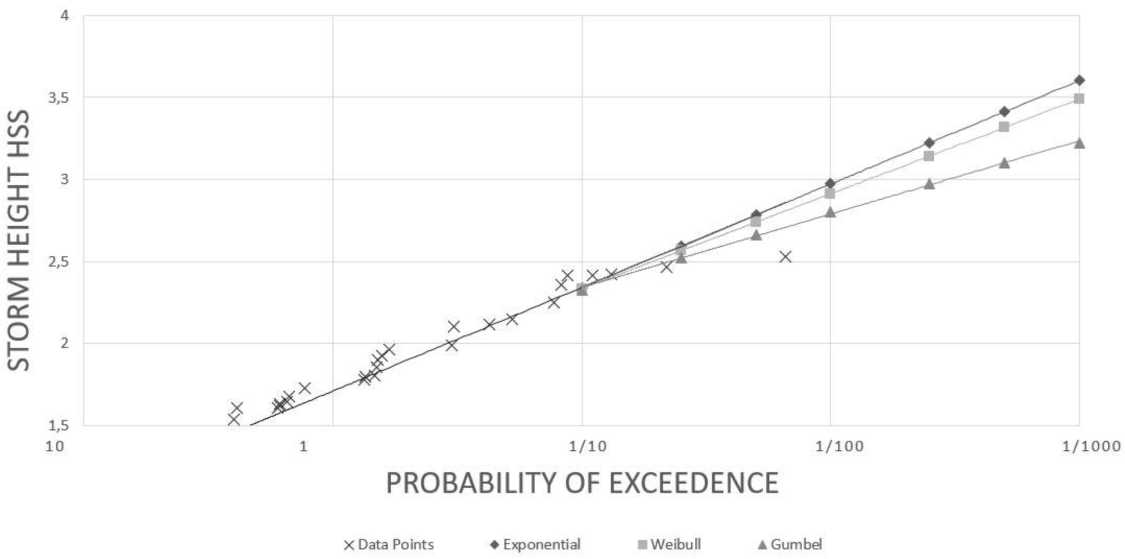

Figure E.2: significant storm height estimation for different distribution type

Flow boundary conditions A Neumann boundary condition is prescribed at the left and right boundary. This condition means that there is locally no change in the surface elevation and velocity. The front and back boundary use a weakly-reflective boundary in 2D, which is the default value in Xbeach. Obliquely-incident and obliquely-reflected waves can pass through this boundary. The epsi parameter, which determines which part of the particle velocity is part of the current and which part is due to the wave, is computed automatically by Xbeach.

Tide and surge Based on appendix D, a tidal cycle of twelve hours with a tidal range of 0.345 m is used. No concrete data about surge levels during hurricane conditions is available. Surge levels are assumed to be present during hurricane conditions and a surge of 0.5 m is used in the model.

Sediment properties The sediment properties defined are D15, D50 and D90. The D50 that is used is based on the data given in appendix C. The lower grain size of 0.00025 m is used and D15 and D90 are scaled accordingly. This leads to D15 = 0.15 mm, D50 = 0.25 mm and D90 = 0.45 mm. Other parameters specified are a solid sediment density of 2400 kg/m3 and a porosity of 0.4. These two parameters are an estimation as there is no data available.

Morphology A morphological updating factor of 10 is used for this simulation. Setting morphological updating to 10 means that for every hour, the model runs for 6 minutes after which the bottom changes are multiplied by 10. This reduced the computation time significantly. The time series can be specified in real time since the input is divided by the morphological updating factor internally. The hydrodynamic boundary conditions cause large Eulerian velocities near the coastline during the first 6 hours, causing large amounts of erosion. This is not realistic so a spin-up time of 6 hours is applied to the simulation. Non-erodible layers are added for locations in the bay that do not contain sand, such as coral reefs and rocky beds. These are the red and orange locations given in figure E.3. An external file provides the location of these non-erodible layer. This file is of the same format as the bathymetry file, only now the values represent the thickness of the sand layer. When there is a non-erodible layer the value is zero. On other locations a large value of 30 m is used to make sure that at this location the non-erodible layer is never reached.

Friction caused by the coral is also added to the simulation. Wave dissipation due to bottom friction contains the coefficient fw. This friction coefficient affects the wave action equation. By default, this bed friction factor is zero for Xbeach simulations. [Sheppard et al, 2005] determined

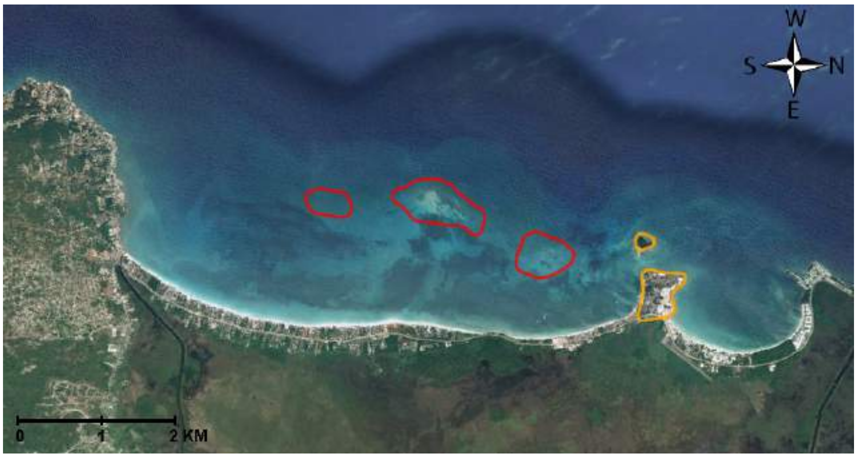

Figure E.3: Locations with specific layer properties

friction factors for different types of corals within the reef flat zone. Healthy coral has the largest friction factor. Figure E.4 gives his criteria. Since the reefs are in poor condition, a friction factor of 0.14 is used for the two main coral reefs and the patch further south indicated by the red locations in figure E.3. Other locations have the default friction value of zero. In Xbeach, an external file with the same format as the bathymetry file provides these values.

Friction factor selected for each reef flat zone

Criteria	f_w (friction factor)
75%−100% sand	0.08
75%−100% smooth rock or coral pavement. 75%−100% seagrass or algal turf	0.10
Smooth rock or coral pavement with 50%−100% coral rubble	0.12
10%−25% live coral or dead uneroded coral or tall (>30 cm) boulders	0.14
25%−50% live coral or dead uneroded coral or tall (>30 cm) boulders	0.16
50%−75% live coral or dead uneroded coral or tall (>30 cm) boulders	0.18
75%−100% live coral or dead uneroded coral or tall (>30 cm) boulders	0.20

Figure E.4: Friction factor based on quality reef
Source: [Sheppard et al, 2005]

Hydrodynamic simulation A storm event of 48 hours is simulated. This leads to a model time of 194400 s when including the six hours of spin-up time.

E.2 Sediment loss

This section explains how sediment loss is calculated. Any sediment which travels beyond the closure depth will not be able to return onshore during normal conditions. The sediment loss is calculated by determining the volume/m of sediment between the closure depth and a point far onshore each cross-section between the 5th and 255th grid point. This is done for the first time step representing the pre storm situation and the final step representing the post storm situation. The difference between the two values is the amount of sediment gained or lost in this particular section. The volume of sediment lost/gained is found by multiplying the value of the cross-section by the width of the grid for every cross-section. The result is the volume of sediment lost/gained after occurrence of the simulated storm.

E.3 Coastline regression

This section explains how the coastline regression is calculated. The determination of the beach width is explained. From follows the beach regression after a storm.

The beach width is determined by defining a upper and lower level of the beach for each cross-section between the 5th and 255th grid point. The beach width is equal to the length between the upper level and lower level of the beach. The upper level is set at 1 meter above MSL. The lower level is set at MSL. Using MSL for the lower level can lead to unrealistic results. This is because this location is subjected most by the incoming waves. For this reason, the location of the lower level could be defined as the average of the x-coordinate for 1 m below MSL and 1 m above MSL. This method was implemented but lead to results which do not represent reality well. This is due to the shallow slopes in the bay. That is way MSL is used as lower level. The exact X-coordinate is defined for the two points of interest. The difference between the two is the beach width for that cross-section. The defined length represents the beach width well when the beach travels perpendicular to the X-axis. However, when the beach is not oriented perpendicular to the X-axis, the beach width is over-estimated. This happens because the cross-sections are based on the rectangular grid. Figure E.5 illustrates this.

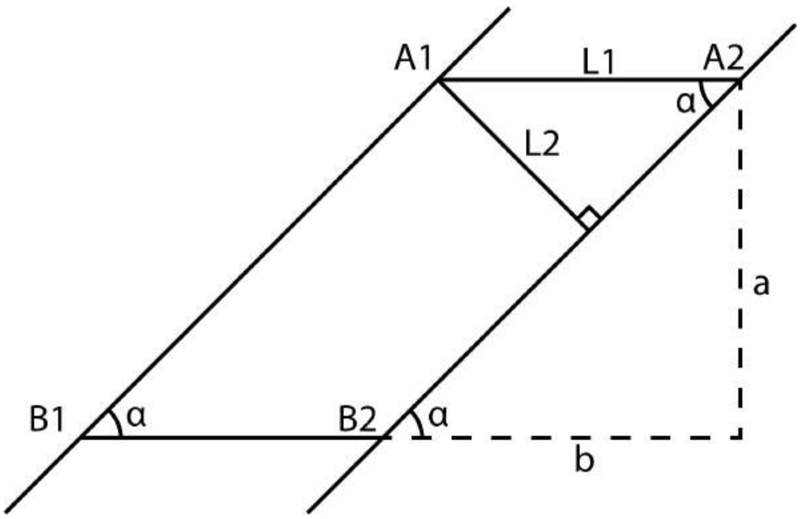

Figure E.5: Beach width correction

If A1 and A2 are the lower and upper level respectively on a certain cross-section, then L1 represents the determined beach width. B1 and B2 are the levels for a cross-section further south. If the angle α is 90 degrees, L1 is the correct beach width. If this angle is not 90 degrees then L2 gives a better representation of the beach width. The beach width can be expressed by function E.1. In the calculations, the cross-section B is a cross-section two grid points south of cross-section A. This means a is always 50 m.

$$L2 = \sin\left(\tan^{-1}(a/b)\right) * L1 \tag{E.1}$$

This beach width calculation is first performed for the first time step. This gives the beach width before the storm. The calculation for the beach width after the storm uses the same upper level as the previous calculation. The lower level is determined with the last time step of the simulation. The beach width that follows represents the width after a storm. The difference between the two beach widths is the regression caused by a storm.

Appendix F

Nourishment design possibilities and considerations

This appendix explains which types of nourishment are possible at Long Bay. The required volume of sediment is determined along with the required material properties. The results from this appendix are used to specify a selection of nourishment alternatives. The second part of this appendix explains how a nourishment could be placed. The work method is explained along with ways to reduce the environmental impact of the process and several timing aspects.

F.1 Hold or advance

When placing a nourishment the focus can be on holding the line by mitigating any further erosion or advancing the line by shifting the coastline seaward. Both strategies have different pros and cons. Holding the line means that the structural erosion of the coast is mitigated by applying nourishments. The losses are replenished. The occurring sediment transports are not influenced so the erosion does not stop. This is why periodic nourishments are required. Re-nourishment is necessary when the beach has eroded up to a defined limit. Only if the nourishment sediment is approximately the same as existing sand will the sediment transport remain the same. The erosion rate and volume of nourished sand determines the lifetime of the nourishment. Lifetimes of 5 to 10 years are generally strived for from an economic point of view. [Bosboom and Stive, 2015] Advancing the line means widening of the beach. This is beneficial for recreational purposes. Apart from this, it also increases the buffer. The nourished sand is redistributed along the cross-shore profile over time. For this reason the initial increased width is partially lost. Only if the entire cross-shore profile is shifted seaward can this redistribution be prevented. This requires large volumes of sediment. For both types of nourishment applies that maintenance is required if structural erosion is not prevented and the coastline is to be maintained. Whether a nourishment is feasible in a project depends mainly on the required frequency of maintenance and the availability of local sediment sources. As explained in chapter 2, the largest hotels and resorts are situated in the northern section of Long Bay. Chapter 4 showed that the beach width along this section of beach is on average around 30 meter wide measured as the distance between the 0 m MSL line and the +1 m MSL line. This is not necessarily a small beach width. However, at this section the hotels and resorts are built very close to the shoreline. This means that the actual functional beach width is only 10 meter or less for most of the beach along this part of the coast. The hotel owners at this section desire an increased beach width on the short term. Since the tourism industry is one of the dominant stakeholders with the financial capacity to implement a buffer zone, it is assumed that this buffer zone will be implemented. Beach width along this part of the coast is increased to an average of 55 meter. This means an increase of around 25 meters. This requires a total of 48,000 m3. This initial increase will reduce to some degree as the sediment redistributes over the active profile. This means that the final beach width will be less but still sufficient. The new beach width after implementing the buffer zone is used as the starting point for the design of other nourishment solutions.

F.2 Material

The sediment that is used is important to the success of the nourishment. The sediment should be as similar as possible to the sediment at the beach. The supplied sand forms a blanket over the existing sediment. When the grain size of the nourishment differs from the existing sand the morphology is impacted which can lead to changes in the slope. This is why not every source is suitable. Using a smaller grains size for your nourishment than the existing sediment means increased erosion rates. When this happens the nourished sediment is often quickly eroded and very inefficient. [Bosboom and Stive, 2015] The source of sand is also important for the cost of the project. The more local the source the better as this will reduce the cost of the project. The sediment for the nourishment can come from local sources, inland material or imported from further away. A source of interest is the possible sand layer just beyond the out shelf as mentioned in chapter 2. The possible sand layer between the 20 and 50 meter depth line could be a good source of sediment. This sediment originally came from the bay so will have similar properties. Based on the sediment pathways identified in chapter 4, the area with the highest possibility of a thick sand layer are estimated. Figure F.1 indicates these locations. It is where the main pathways leave the bay. These locations could be used as borrow areas. For this thesis, it is assumed that these areas indeed contain large volumes of sediment. Whether this is actually the case should be further researched. If not, sediment would have to be obtained from other sources. Other bays on Jamaica or sources on other Caribbean islands could provide the required sediment.

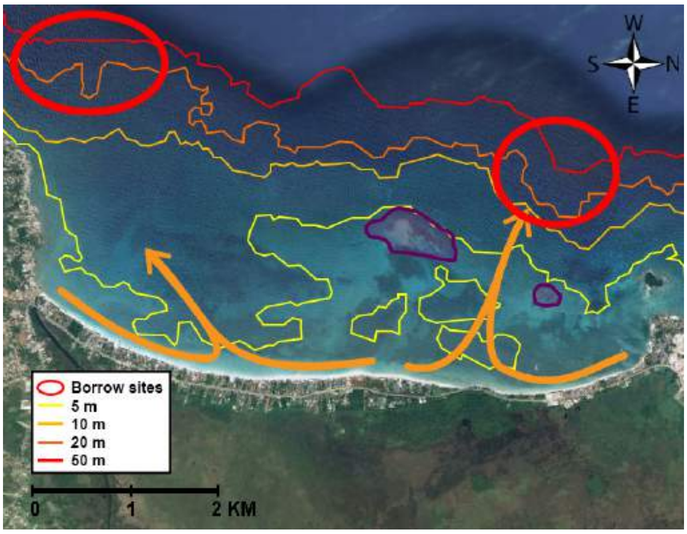

Figure F.1: Most probable locations of sediment to be used as burrow sites

F.3 Environmental impact

The disturbances caused by placing nourishments are harmful to the environment. Silt content in the nourished material, which is brought into the water through the overflow system of the dredger, can have a negative impact on the environment. Fines in the nourishment material may also harm the environment. In the existing material most fines are usually washed out making the water relatively clear. The nourishment may increase the turbidity in the bay which is harmful to the ecological system. [Bosboom and Stive, 2015] Furthermore, the ecological life at the nourishment site, such as seagrass, is suffocated by the new sediment layer. Once the nourishment is finished, the local environment may reappear. The newly created bed layer provides new opportunities for nature. This means that the nourishment might benefit the environment on the long term. Seagrass is known to have a fast growth rate so the local environment is assumed to recover relatively quick. Still, these problems could be prevented if a nourishment is placed some distance away from the project site. If the sediment is still able to enter the bay then the structural erosion can be compensated.

F.4 Quantity and longshore distribution

Chapter 4 showed that some cross sections gain sediment and some lose sediment. The sum equals a loss of around 6000 m3/y. This is a sediment loss of 1 m3/y per meter of coastline when the total amount of sediment lost is divided by the length of the beach. In other words, this applies when all the sediment redistributes evenly along the bay during normal conditions. This is not likely to completely occur. The sections which gain sediment after a storm will redistribute most of this sediment during normal conditions but not all. They will to retain some of the gained sediment. This leads to accretion at these positions over time. Two clear locations where this happens are behind the reefs. When looking at the current bathymetry, this effect is visible. When considering the nourishment locations it is not going to be effective to place the total volume equally over the entire beach since areas which gain sediment during storms are not going to require nourishments. This would be an inefficient placement. So, the placement is based on the areas which lose sediment during storms. The left illustration of figure F.2 shows the sediment loss or gain per meter of coastline in black if there is no redistribution of sediment. The blue line simplifies this to 50 sections of 125 m length. Each section gives the average of the values within the section. The total nourishment volume should be divided over the sections which lose sediment. If this is done by ratio then the result is the blue line at the right illustration. For instance, the most southern section should be nourished with 4.8 percent of the total volume. This nourishment scheme would require different volumes every 125 m. This is why the sections are further grouped together. This is indicated by the pink line on the right illustration. The coastline is divided in 7 sections. The nourishment volume is based on the yearly loss of sediment, which is around 6000 m3/y. This quantity should be multiplied by the lifetime of the nourishment. A lifetime of 7 years will be chosen for this thesis. So, the total volume to nourish is 6000*7 = 42,000 m3 per nourishment. The volume of sediment that has to be placed in the seven sections specified in figure F.2 are given in table F.1, with (1) being the northern most section and (7) the southern most section.

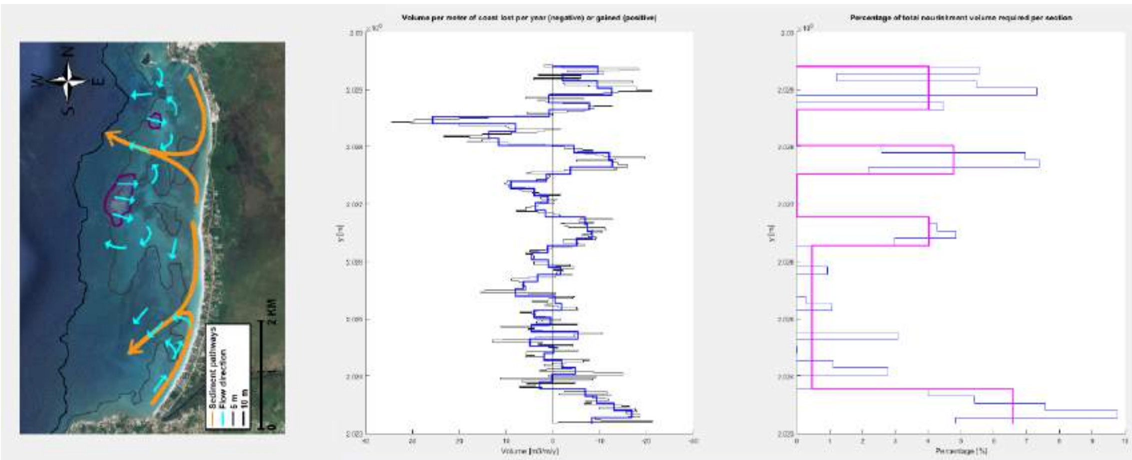

Figure F.2: Sediment pathways (left), Volume lost during storms (middle) and nourishment distribution (right)

Table F.1: Nourishment scheme

Section	Percentage [%]	Volume [m3]	Length [m]	Volume [m3/m]
1	24.1	10108	750	13.5
2	0	0	625	0
3	19.1	8017	500	16
4	0	0	750	0
5	16.1	6752	500	13.5
6	9.2	3860	2500	1.5
7	31.6	13262	600	22.1

F.5 Type of nourishments

In general, there are 4 types of nourishments. The first two are nourishments on the inner slope or on the outer slope of the dunes. The third nourishment type is nourishments on the dry beach. Sand is placed between the low water line and the dune foot. The final nourishment type is nourishments on the shoreface. The nourishment location is within the active zone. The waves will redistribute the nourished sediment along the beach. Dune nourishment is not considered since there is no dunes area at Long Bay. So this leaves the beach nourishment and the shoreface nourishment. A variation of the beach nourishment is the concentrated nourishment and large scale nourishment. Finally, a nourishment is considered further away from the coastline. This type of nourishment has several advantages which may outweigh the downsides.

In case of a beach nourishments, the quantity of sediment should be placed on the beach between the dune foot and the low-water-minus-1-meter line. The new beach cross section after nourishment is often steeper than the equilibrium slope. The material redistributes over the active profile. Because of the natural redistribution, it does not matter too much where the sediment is placed as long as it is landward of the breaker line. [H.J., 1992] So, the placement should be based on cost, environmental impact and placement method. If the beach erodes beyond a minimum then it is re-nourished. The advantage is immediate beach restoration. A negative effect is the increased disturbance for tourists.

Shoreface nourishments are generally the most economical nourishments. Shoreface nourishments do not immediately widen beach. They are used to maintain the beach or for widening over time. [Bosboom and Stive, 2015] The nourishment can have different purposes. In this case, the design is of an active feeder berm. This is a berm which disperses its sediment within a couple of years and is placed nearshore in relatively shallow water. It feeds the adjacent beach. The berm causes longshore and cross-shore effects. Longshore effects are updrift sedimentation and downdrift erosion due to the calmer wave climate behind the berm. The cross-shore effects are increased onshore transport and decreased offshore transport. Onshore transport is increased because waves break on the nourishment. This generates transport due to wave asymmetry over the nourishment. Offshore transport is decreased because the smaller waves have less impact on the coast. [van Rijn L.C. and Walstra D.J.R., 2004] The advantage of this type is that there is less disturbance for tourism during placement compared to a beach nourishment type.

The goal of the concentrated nourishment is to supply the same amount of sediment as with for instance a beach nourishment, only this time the sediment is placed at one location. The sediment is redistributed alongshore over time. This way only a small area of coast is impacted while the entire coast still benefits from the nourishment. Large scale nourishments are a combination between advancing the coastline and maintaining the coastline. They are a concentrated nourishment but use a larger quantity of material. At the location of the nourishment a large amount of sand is deposited. This advances the coastline providing new area for recreational purposes. However, instead of maintaining the new established coastline the goal of this nourishment is to redistribute the sand over a long period of time. This helps to maintain the coastline next to the nourishment site. This type of nourishment would in theory require far less maintenance. Instead of nourishing a small amount every 5 years, a large amount is nourished once every 20 years or longer depending on the size. Large scale nourishments are still in an experimental phase. The best example of a large scale nourishment is the 'zand motor' in the Netherlands. The results are very promising but to apply the concept anywhere else requires a tailor made solution.

The final type of nourishment is a nourishment at the edge of the bay. This nourishment is placed away from the coastline near deeper waters. The environment is not disturbed since the placement is not in the bay itself. During storms the sediment may be transported into the active profile, thereby supplying sediment to the coast. This may compensate for the yearly sediment loss. Because the sediment is placed further away, only a small amount of the nourished material may actually reach the coast. For that reason, this type of nourishment will require much more sediment than the other nourishments. However, this does not necessarily mean that this type of nourishment is less suitable as a solution. Since this nourishment is placed at the edge of the bay, it is much simpler to reach. This will reduce the cost significantly making it more feasible to re-nourish large quantities. It also means that the bay is not disturbed during placement which is beneficial to the environment as well as the tourism industry.

F.6 Implementation

The way of implementation depends on the chosen type nourishment. The buffer zone places a total of 48,000 m3 at the northern section of the coastline. On top of this, one of the alternatives is applied with a volume of 42,000 m3 along the coastline. This section explains the work method for the buffer zone. The final work method depends on the type of nourishment for the remaining volume.

F.6.1 Equipment

The sediment has to be dredged from the burrow sites indicated in the previous section and transported to the beach. The most common type of dredgers are the cutter suction dredger (CSD) and the trailing suction hopper dredger (TSHD). Cutter suction dredgers or plain suction dredgers can work in low water depths and use a swinging motion to dredge the sediment. The dredgers are most effective when breaching thick layers of sediment. The material can be transported by a separate barge or directly transported via a pipeline to the beach. The material can typically be pumped 4.5 km or even 10 km using a booster pump. [National Research Council, 1995] A TSHD dredges material using a drag head connected to a suction tube. The sediment is collected in the hopper. The vessel can dump the sediment in multiple ways. Bottom doors can directly dump the sediment at a location. A method called rain-bowing can be used to discharge the sediment onto the beach. Rain-bowing is difficult to control accurately. The vessel can also be connected to a pumpout facility. The material is pumped out from this location to the beach using pipelines. Distances of up to 9 km can be covered this way. [Dean, 2003]

Cutter suction dredgers are more vulnerable to wave attack than trailing suction hopper dredgers. TSHD's can work under most weather conditions. TSHD's require a deeper draft than suction dredgers. The water depth needs to be greater than the loaded draft. Depths in the order of 10 meters are required for operation depending on the size of the dredger. Suction dredgers can operate in depths less than 5 meters. The TSHD's are more suitable for this project since the depths at the burrow sites are large and are located offshore.

F.6.2 Work method

This section shows what the work method could be for the buffer zone. Due to the shallow depth of the bay, the TSHD is not able to reach the coastline. For this reason Rain-bowing is not possible. The TSHD will be connected to a pumpout facility. From there a pipeline will transport the sediment to the beach. This pipeline can be made floating or submerged. Submerged is more expensive. Floating is preferred but is more vulnerable to wave attack so should only be used during calm conditions. TSHD can sail distances of around 10 km to reach a pumpout facility. So, a facility offshore of Long Bay will definitely meet this requirement as long as the water depth is sufficient for the dredgers. Figure F.3 shows the location of the pumpout facility and connection to the northern part of the coastline. It is located beyond the 10 m depth line to ensure sufficient draft clearance. On the beach, the pipeline is placed above the HW line. The sediment is distributed using bulldozers.

A nourishment at the edge of the bay does not require pipelines. If other sections of the coastline are considered, different methods would be required. It is also possible to transport the sediment to the coastline by barges. A barge unloading dredger near the coastline can dump the sediment from the barges into the beach. The unit cost for barges is lower than for pipelines so this could be a possible solution. Another method could avoid environmental disturbance completely in the bay. With this method, the TSHD dumps the material further away from the two bays. From there, trucks transport the sediment to the beach. This way, no pipelines or barges are needed in the bay. A downside is that the trucks disrupt traffic and can damage roadways due to their large weight. Furthermore a suitable location needs to be found that can be reached by both the TSHD and the trucks. In summary, there are many ways to get the sediment to the beach. In a further project stage, the optimal solution should be determined in more detail.

F.6.3 Reducing environmental impact

The two most dominant environmental impacts are spillage and turbidity. Spillage is loosened soil which is not removed during dredging. This soil can become aerobic and pollute the region. Spillage

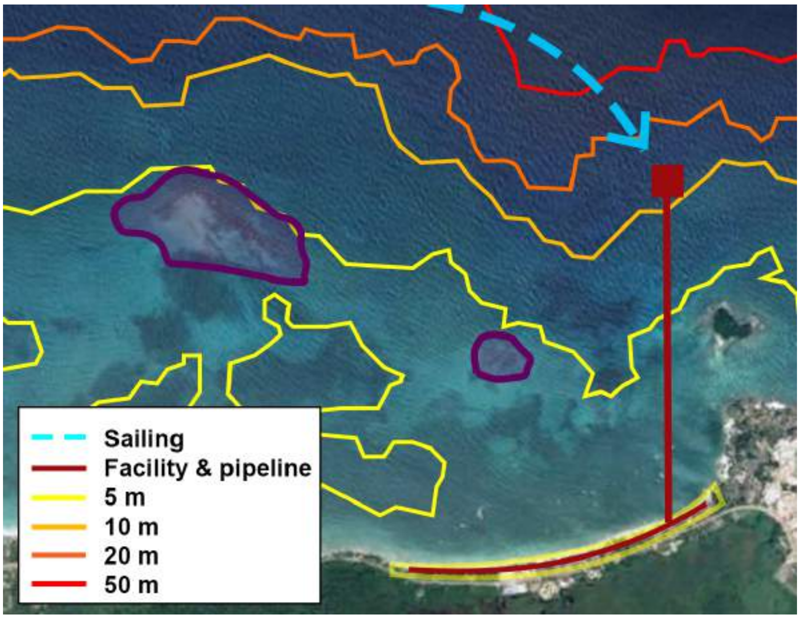

Figure F.3: Location of pumpout facility and pipeline

can be reduced by proper matching of the cutting and pumping capacities. [van der Schrieck, G.L.M., 2015] Turbidity caused by a TSHD can be reduced by not using the overflow and light mixture overboard systems. These systems maximize the density on the hopper but pump out a mixture of water and fine sediment in the process. Not using these systems means that less sediment is collected per run and the process will take more time. The process water can also be recirculated to the bed or the drag head. [van der Schrieck, G.L.M., 2015] On the beach, turbidity can be limited by constructing shore parallel berms which constrain the water. This increases the deposition of fine fractions so there is less turbidity nearshore.

F.6.4 Timing

The total volume of sediment used for the buffer zone is 48,000 m3. The Dutch design method for nourishments recommends using a surplus of 40 percent of sediment when nourishing. This is based on losses in longshore direction, washout of finer particles, and profile adaptation. [H.J., 1992] This is for the dutch coast with a large tidal difference and tidal currents along the coastline. For long bay 40 percent is unnecessary. A surcharge of 10 percent will likely be enough. This needs to be further researched. For most TSHD's, this amount of sediment can be produced in 10 cycles or less. So the dredging will not take a long time and the total project time depends mostly on the time it takes to assemble and disassemble the pipeline and pumpout facility. The nourishment should take place outside of the tourist season since the beach will not be accessible to the public during construction. Doing this during the tourist season would lead to a lot of disturbance. Also, a floating pipeline obstructs boats traveling to or coming from the north. The disturbance caused by this should be announced to the public well in advance. The actual time frame and disturbances caused by the nourishment depends on the type of nourishment that is chosen and the work method that is applied.

Appendix G

Breakwater design possibilities and considerations

In this appendix the range of possible breakwater solutions is given. Breakwaters can be constructed in many shapes and sizes. Since the goal is to find a Building with Nature solution, a range of breakwaters is determined from basic stone breakwaters to full environmentally integrated breakwater designs. This range of solutions is used to determine the possible breakwater alternatives for Long Bay.

G.1 Shape

The first mayor distinction is constructing an emerged or submerged breakwater. Submerged breakwaters are preferred considering the past objection of emerged breakwaters from stakeholders. However, emerged breakwaters are more effective at reducing wave impact on the beach.

G.2 Material

A breakwater can be made from different materials. The most common are breakwaters made from armor stones or concrete units. These breakwater are not well integrated in the environment. Using nature-based materials can improve the environmental integration. PH-neutral concrete or lightweight concrete with an organic matter matrix which accelerate biological colonization are examples of this. [WAVES, 2016] One could also use natural limestone blocks or locally available rocks and stones.

G.3 Environmental impact

Even more natural breakwaters can be obtained by restoring the natural function of coral reefs. The reef is a natural breakwater. Chapter 4 showed the coastal protection capability of a flourishing reef. The reef in itself is not enough to prevent erosion but in combination with other solutions it may become beneficial. Active restoration of coral reefs can be done biologically or physically. Biological restoration means rebuilding the coral reef by in-situ transplantation of coral species. The use of coral nurseries improves this technique. The transplantation restores the reef diversity and structure of degraded reefs. The critical species in a reef, which provide the main structure, are stony coral populations. [WAVES, 2016] CARIBSAVE and the Coral Restoration Foundation International have successfully established coral nurseries and transplantation at multiple sites in Jamaica. [CARIBSAVE , 2017] Natural coral recovery rate depends on many factors and many take as little as five years to centuries. Coral transplantation places established colonies speeding up the growth rate. Coral transplantation is an expensive procedure which is usually only applicable in high commercial areas. [Harriott V.J. and Fisk D.A., 1988] Physical restoration means repairing the structural integrity of the reef. Using concrete or limestone, part of a reef can be restored physically. This enable corals to regrow on the restored area. Artificial reefs are a form of physical restoration. They mimic the natural structure of coral reefs. This means coral can regrow easier.

The structures can be made from concrete, natural stones and rock in the form of cubes, blocks and pipes. Artificial reefs can also be formed using other materials such as wood, tires or steel. Artificial structures can be used to repair or extend a reef. The most commonly used modules are Reef Balls, Ecoreefs and BioRock. Reef Balls are made out of ph-neutral concrete and are used in more than 70 countries. They are large structures which immediately provide physical structure to the reef. [Eternal Reefs, 2017] Ecoreefs are made from ceramic and are designed to promote biological growth. They are relatively small structures. BioRock is a company which makes steel cage-like structures on which coral can grow. They can be made in any shape. By flowing an electric current through the steel minerals accrete to the structure. This way biological restoration is accelerated. Each of these artificial reefs has its pros and cons. Reef Balls quickly improve the structural integrity. Ecoreefs look aesthetically most integrated in the existing reef and BioRock has a flexible shape accompanied by relatively quick biological restoration. One general downside of artificial reefs is the fact that they are expensive which makes them less applicable in any situation. Also, restoring reefs requires professional expertise. Many of the techniques are still in an experimental phase. For instance, Royal Boskalis Westminster N.V. is currently developing 3D printed artificial reefs. [Royal Boskalis Westminster N.V. , 2017] There is less certainty with experimental methods. Still, Long Bay provides an interesting location to test new innovations.

G.4 Type of breakwaters

Figure G.1 shows 8 different types of breakwaters ordered from low environmentally integrated to high integration. The first three types on the left are the most common type of breakwaters made from armor stones or concrete units. They provide no integration into the environment. The difference between the three is the height of the crest. The submerged breakwater is the most integrated of the three since it stand out the least within the surroundings. Type two is the type of breakwater that the government proposed as a solution. Type four takes the submerged breakwater but uses ph-neutral concrete in order to promote coral growth on the structure. Coral transplantation further increases the biological restoration. Breakwater type 5 through 7 make use of artificial reef structures in combination with coral transplantation Reef Balls (type 5) are most similar to the concrete armor units of the first four breakwater types. The difference is that the shape of the cubes promotes coral growth. The steel structures used by BioRock focus more on fast coral restoration and less on immediate increase of the structural integrity. As the reef restores the coastal protection ability increases. The same applies for the use of EcoReefs (type 7). The difference is that EcoReefs uses structures which are aesthetically well integrated in the existing reef. It is used as an aid in repairing and restoring the existing reef while BioRock can also extend sections of reefs. Breakwater type 8 is the most natural breakwater. No artificial structures or materials are used. Only biological restoration is applied to restore and repair an existing reef. This solution is the most natural but will also be the most time-consuming. In conclusion there is a range of breakwater types to choose from.

	1	2	3	4	5	6	7	8
Description	Basic breakwater	Basic breakwater	Basic breakwater	Breakwater with nature based materials	Artificial reef using Reef Balls	Artificial reef using BioRock	Artificial reef using EcoReefs	Reef bio restoration
Shape	Emerged	MSL	Submerged	Submerged	Submerged	Submerged	Submerged	Submerged
Materials	Large armor stones or precast concrete units	Large armor stones or precast concrete units	Large armor stones or precast concrete units	PH-neutral concrete or lightweight concrete with an organic matter matrix	Reef Balls	Natural reef + BioRock	Natural reef + EcoReefs	Natural reef
Short term increase in structural integrity	Yes	Yes	Yes	Yes	Yes	No	No	No
Biological restoration	No	No	No	Coral transplantation	Coral transplantation	Coral transplantation	Coral transplantation	Coral transplantation
Complexity	Low	Low	Low	Medium	High	High	High	High

Figure G.1: Properties of breakwater

Appendix H

Artificial reef design

Using artificial reefs instead of traditional breakwaters can create many benefits. Appendix G showed different types of artificial reef structures. All structures help to restore or create coral reefs. Of these structures, Reef Balls provide immediate wave reduction. For that reason they are preferred over the other methods. This appendix shows what a breakwater design using Reef Balls could look like and explains the most important aspects of implementing this type of breakwater. It discusses what further research is required in order to make a detailed design.

H.1 Design

This section outlines the basic design of a Reef Ball breakwater. It first illustrates what the basic design could look like. Then it elaborates on the requirements for the Reef Balls and the other components of the breakwater.

H.1.1 Reef Balls used as a breakwater

Reef Balls are mostly used for habitat enhancement. The Reef Balls are placed directly on the sandy bottom grouped together in specific orientation and sizes that best imitate the natural system at the project site. Using Reef Balls for breakwater purposes is less common. Contractors do promote the units for their breakwater applicability but there are currently no clear design guidelines. There are some cases where they have been used as submerged breakwaters to protect beaches. [Reef Ball Foundation, 2017a] Several rows of Reef Balls are placed to reduce wave impact on the coastline. If an artificial reef is to be chosen for Long Bay, then this reef will be located near the existing reefs. The artificial reef will be used to reconnect or extend the reefs. The depth at this location goes down to around 4.5 meters. Reef Balls are available in different sizes. The largest ones are nearly 2 meters high. Smaller sizes are made easily stackable so that the required height can be met. For breakwater purposes, the largest sizes are recommended due to their weight and stability during storm conditions. Artificial reefs have a crest height below sea level. At around 1 meter below sea level are the optimal growth conditions for most coral species. This will be the crest height of the design. This means that, with a water depth of 4.5 meters, the height of the structure should be around 3.5 meters. This is higher than the largest Reef Balls. To obtain the height, the Reef Balls can be stacked or placed on a berm. Stacking units is not considered as their stability during storm conditions cannot be guaranteed. Reports such as Armono place the Reef Balls on a berm. [Armono and Hall, 2003] This allows the breakwater to reach the required crest height.

So, the basic artificial reef that will be considered for Long Bay consists of 5 rows of Reef Balls on top of a rubble mound berm. This way the breakwater is of sufficient width. More rows would make the design less feasible since the cost will keep increasing. The berm is wider than the crest width. This is to ensure that the outer Reef Balls are also properly supported. The crest height is at 1 meter below sea level and the water depth is 4.5 meters. Figure H.1 illustrates the situation. It should be noted that, although this type of design is found in multiple research papers, no example of a large breakwater made out of Reef Balls and a berm is found that is implemented in a real-life project.

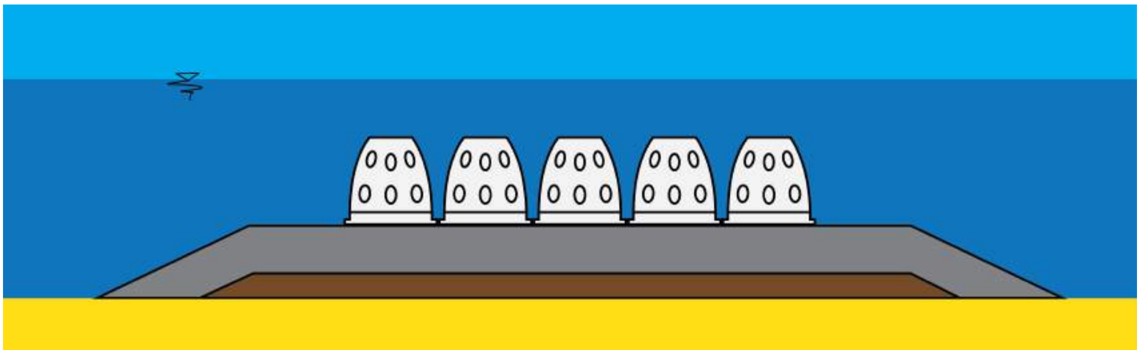

Figure H.1: build up of artificial reef

H.1.2 Reef Ball weight requirement

As explained in the previous section, 5 rows of Reef Balls are placed on top of a berm. The units will be impacted by the waves. Contractors offer different sized Reef Balls. They offer units which are, according to them, specifically made for breakwater purposes. The largest available module is the 'Goliath breakwater base'. This module weighs around 12,000 lbs or 5443 kg and is around 1.9 m tall. The large weight and height as well as a low center of gravity would make it very suitable. There no clear design criteria formulated for Reef Balls. The research that is done primarily focuses on ecology and permeability of the units. Harris performed a stability analysis for submerged artificial reef breakwaters. [Harris L.E.,] The analysis is based on the horizontal forces acting on the unit and the resisting forces due to friction with the surface. The analysis resulted in stability curves for Reef Balls as given in figure H.2.

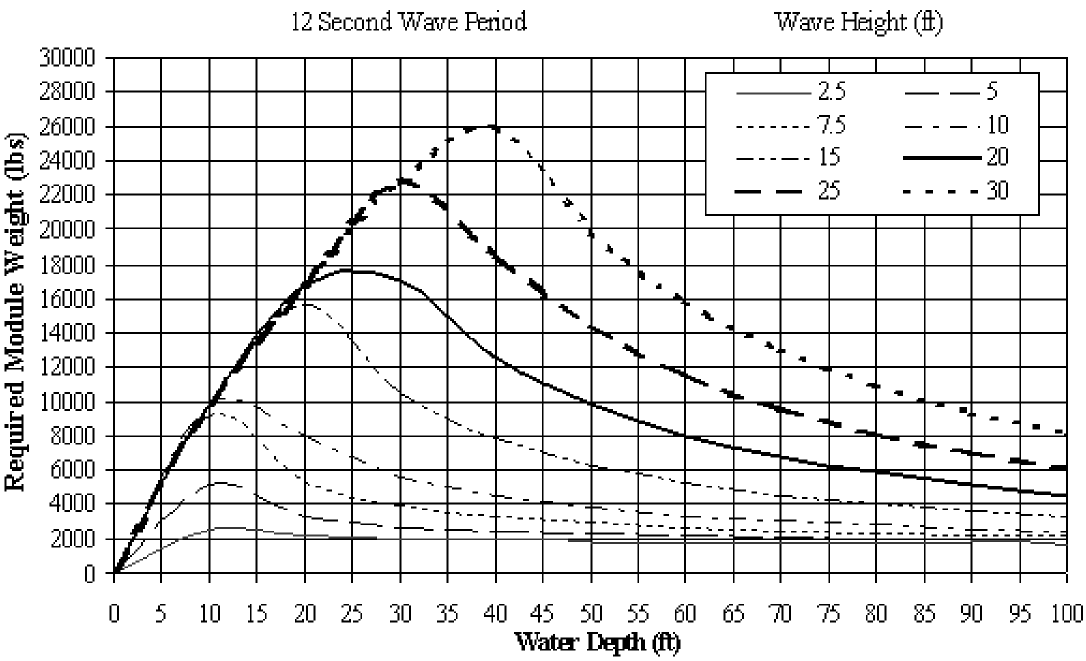

Figure H.2: Hurricane events within 30 km of Jamaica since 1900
Source: [Harris L.E.,]

Assuming the Reef Balls are around 2 meters tall, the required weight according to Harris can be determined. The Reef Balls are placed at 3 meters below mean sea level so that the crest is at 1 meter below MSL. The stabilities of the units should be guaranteed for the largest wave conditions. Displacement of the units mean that the effectiveness cannot be guaranteed. Therefore, the required weight is based on H_{max}. H_{max} is approximately 2*H_s so 2*2.91 = 5.8 m. During this wave condition surge will be present, which as 0.5 m. This results in a total water depth of

3.5 meters. Based on the figure the required module weight is around 10,000 lbs or 4,500 kg. This would mean that the 'Goliath breakwater base' of 12,000 lbs or 5443 kg suffices. The stability curves in this figure are determined using waves with a period of 12 seconds. For our scenario, the significant wave period is nine seconds. The stability calculation of Harris is based on the drag force and inertia force. A lower period results in a higher drag and inertia force acting on the Reef Ball. This means that the actual required weight will be somewhat higher. A required weight of 4,500 kg for units being attacked by waves with a wave height of 5.8 m in a water depth of 3.5 m seems unlikely. The forces are large and the units are not interlocked in any way. Replication of the applied method is not possible since the used coefficients of drag and inertia are not given. According to the research paper, the coefficient of drag is determined by wave and wind tunnel tests but the results are not included. The units can be connected to each other by cables. This can improves the overall stability of the structure. Another possibility is the use of anchors. Specific anchors are developed by the same company that develops the Reef Balls. These methods improve the overall stability of the Reef Balls. The stability of multiple rows of 'Goliath breakwater base' units is questionable at Long Bay. The exact unit requirement and possible use of cables or anchors should be further studied. The complexity of the units require scale model tests. This is out of the scope of this thesis. What can be determined is the berm on which the Reef Balls are placed. This is done in the following section.

H.1.3 Berm calculation

The previous section tries to give a weight requirement for the Reef Balls. More research is needed to obtain a reasonable design estimate for the Reef Balls. For the berm calculation it is assumed that about 2 meters of height is needed for the Reef Balls, leaving a berm height of 1.5 meters with a crest at 3 meters below MSL. What type of reef Ball is used, how they are configured is left unspecified.

Rock stability

The berm is calculated as if it is a submerged breakwater by itself. For submerged breakwaters the crest is most vulnerable. For statically stable structures many formula are available to determine the stability for start of damage. For a first estimate of the nominal diameter in a conceptual design phase a rule of thumb can be used. This rule of thumb is:

$$d_{n50} \geq 0.3d \quad for \quad \frac{H_s}{h} = 0.6, \quad cot\alpha_s \geq 100 \quad and \quad \Delta \approx 1.6 \tag{H.1}$$

where:

d = height of the crest measured form the bottom

h = Water depth at the toe of the structure

α_s = the slope of the foreshore

For H_s=2.91 m with surge of 0.5 m the formula gives a d_{n50} of 0.45 m. The requirement for H_s/h gives 0.6. There is also the possibility of a storm without surge. This storm will have a lower H_s of say 2 m. This situation results in the same d_{n50}.

A D_{n50} of 0.45 m means that a rock class of HmA 300-1000 is required according to Table A-2 of Introduction to bed, bank and shore protection. [Schiereck and Verhagen, 2012] This rock class has a D_{n50} of 0.59 m. This is equal to a D_{50} of about 0.7 m. The minimum design layer thickness of a rock layer is 1.5 times the rock diameter. [CUR, 2007] This is based on two layers of rock to ensure sufficient cover. So with a D_{50} of 0.7 m, the minimum height of the rock layer is 1.05 m.

Filter layer

A possible failure mode is when the sediment underneath the construction is able to flow out. This may cause the design to settle or collapse. To prevent this a filter layer is used. For this design a geometrically open filter is used. This implies that the grains of the base layer are able to pass through the filter layer, but gradient related to the velocity within the layers is below the critical value. A geometrically open filter is designed as opposed to the geometrically closed filter because the size of the underlayer would require either multiple layers of different rock classes or a geotextile. Multiple layers of rock classes are avoided to reduce construction complexity and geotextile is avoided because of the poor environmental integration and more complex implementation. The required thickness of the filter is calculated using the adaptation by Van de Sande of the new filter formula. [van de Sande S.A.H., 2013]

$$\frac{D_f}{d_{f50}} = \alpha_d \ln\left(\frac{\Delta_f d_{f50}}{\Delta_b d_{b50}} \frac{\Psi_{cf}}{\Psi_{cb}} \frac{(1-\gamma V_{Gf})}{(1-\gamma V_{Gb})}\right) \tag{H.2}$$

Where:

D_f = Thickness of the filter

d_{50} = Nominal stone diameter

α_d = Dimensionless parameter

Δ = $(\rho_s - \rho_w)/\rho_w$

Ψ_c = Shields parameter

γ = 0.625 for allowable transport

V_G = Non uniformity coefficient = $1 - d_{15}/d_{50}$

The properties of the bed are given in appendix C. If the rock layer as determined previously is placed directly on the soil then the minimum layer thickness would have to be over 4 meter following from formula H.2. This is clearly not feasible so a filter layer is placed in between. Using a filter layer means that the filter should meet the thickness requirements so that the soil does not wash out. At the same time, the filter material should not be washed out of the rock layer. For this, the same equation applies. Using a certain D_{n50} for the filter leads to a minimum required thickness for the filter and for the rock layer. Table H.1 gives he results. Using a smaller D_{n50} for the filter means that a smaller filter thickness is required but a larger rock layer thickness. The rock layer thickness is minimally 1.05 m as determined previously. Therefore, as long as the required rock layer thickness remains below this value the filter meets the criteria. The sum of the two should be around 1.5 meter. Table H.1 shows that a filter with a D_{n50} of 0.09 m is the optimal design. This is a rock class of CP63/180. A filter thickness of 0.48 m is minimally required. This is rounded up to a thickness of 0.5 m.

Table H.1: Filter thickness requirements for different nominal diameters

Filter Dn50 [m]	0.31	0.21	0.17	0.10	0.09	0.06
Filter thickness [m]	1.96	1.26	0.98	0.52	0.48	0.32
Rock layer thickness [m]	0.31	0.51	0.61	0.88	0.91	1.08
Total thickness [m]	**3.01**	**2.31**	**2.03**	**1.57**	**1.53**	**1.37**

H.1.4 Discussion

The previous sections shows that there is not enough information available on the application of Reef ball units in breakwater designs to make a reasonable estimate for Long bay. Some research is performed about the stability requirements of Reef Balls but this research focuses on the stability of a single Reef Ball on sandy soil. There is a lack of guidelines about artificial reef designs using Reef Balls.

It is very possible that the largest available Reef Balls fail to hold up against the wave attacks at Long Bay. If so, other solutions need to be found. Cables and anchors have been mentioned as ways to increase stability. Research on the stability of interconnected modules and implementation consequences of these designs should be done. If cabled designs are equally feasible then different sizes of Reef Balls could be combined without compromising stability of the breakwater. One may think of a solution where the outer Reef Ball modules are made smaller in size. They can be connected to the large modules using cables to ensure their stability. This offers ecological benefits. Reefs made out of a combination of different sizes offer the best matching of species and population densities to natural reefs. [Barber, 2000] So, if these type of solutions are feasible they may offer better ecological integration. It is also possible that Reef Balls on a berm is simply not feasible. In that case, a regular submerged breakwater could be used to reduce wave impact. The Reef Ball modules could then be placed behind the submerged breakwaters in more sheltered waters. This way, the Reef Balls are not directly impacted by the waves but still fulfill their function.

In conclusion, there are a number of ways that artificial reef using Reef Balls can be made. Providing a detailed design is not possible at this point due to the lack of guidelines and clear stability requirements. Once this is further researched it becomes possible to specify the artificial reef design in more detail.

H.2 Implementation

This section explains how a artificial reef design would be implemented. First the construction of the breakwater is explained. Then the coral transplantation method is described along with the requirements for successful transplantation.

H.2.1 Construction

The breakwater design consists of a filter layer, an rock layer and several rows of Reef Ball modules. First, the filter layer and rock layer are placed. The material can be obtained from quarries in the mainland. Quarries which provided material for similar projects are within 50 kilometers of the project site. [CL Environmental, 2014] Different waterborne equipment can be used to place the material. Pontoons with cranes are useful for controlled placement but have a low capacity. Split barges can dump large quantities of stone but with low accuracy. Side stone dumping vessel is most commonly used and will be applied for this implementation. The dumping is controlled reasonably well. The deviation of the dumping location and the vessel depends on the velocity and the water depth. [Schiereck and Verhagen, 2012] Construction will be done during normal conditions so the velocity of the currents will be low. The depth is on average 4.5 meters below MSL. Under these conditions the deviation will remain low. Vessels can operate under current velocities of up to 1.5 to 2 m/s and wind wave conditions of 1 to 1.5 m. Swell waves can cause more issues for vessels. Waves of 0.5 m can already cause problems. [Schiereck and Verhagen, 2012] There are several ways to deploy reef balls. Pontoons with fold down extended decks can place reef balls in shallow water. Placement from shore is also possible using cranes. In this case, the location of the reef is too far offshore for onshore deployment. The top of the reef balls are placed at 1 meter below MSL. For this large scale artificial reef project larger vessels are more efficient. The area is at around 4 meter below MSL so vessels with a shallow enough draft are able to deploy the reef balls. Reef balls can be placed using a barge only. If the placement is more delicate then the reef balls can be placed in a different way. The Reef Balls have a patented internal bladder which can be inflated. This makes them float making maneuvering the concrete structures relatively simple. Divers can then place the reef balls on the sea floor. This may be necessary near the existing reefs to avoid damage. [Reef Innovations, 2017]

H.2.2 Coral transplantation

Once the breakwater is constructed, the coral can be transplanted. Both hard and soft corals can be transplanted. Coral fragments can be attached by using cement, epoxy, cables, mails, wedging of by using lines/ropes. With Reef Balls, epoxy is generally used. Coral is divided into smaller fragments. These fragments are embedded in base plugs. These plugs are made out of PH neutral cement. The coral is put into the cement which sets in thirty seconds. Afterwards the coral fragment is put back underwater. After a 24 hour recovery period the fragments can be placed onto the Reef Balls. Reef Balls contain so-called adapter receptor plugs. The base plug can be fixed on these locations using an underwater epoxy. [Reef Ball volunteer services division , 2017a] Experts can teach local volunteers how to grow and plant corals. As much as 10,000 coral colonies and be transplanted in 14 days using 15 volunteers if they are properly trained. Coral fragment survival are over 80 %. [Reef Ball volunteer services division , 2017b] Some of the most successful coral species for transplantation are Elkhorn, Staghorn, Acropora and Finger coral. They are often used due to their fast growth rates, high survival rates and aesthetic value. The coral used for transplantation comes from adult colonies. These colonies can be obtained from nearby reefs, coral farms or nurseries. Transplantation success is generally higher when corals are transplanted from habitats similar to the project site. The turbidity, depth and water movement should be similar or the success rate goes down. The removal of coral from a location should be done carefully to not endanger the reef at that location. Suitable transplantation corals are specific target species of the correct size which have a base which can easily be broken. This means that only a small percentage of corals is suitable. The removal of the coral should be done spread out over the reef to minimize the impact at a specific location. [Harriott V.J. and Fisk D.A., 1988] Coral can also be grown specifically to be used for transplantation purposes. Coral fragments are grown in a so-called nursery until they are ready for transplantation. This can be done in an aquarium or near the project site in a shallow protected area. This is a less common practice that can be useful for large scale projects but requires expertise. [C.N., 2012] A final consideration is the timing aspects. Once the Reef Balls are placed, there is a short period of time where the coral fragments can be transplanted. If the time between these steps becomes too long then the reef Balls become overgrown by other marine life and transplantation becomes less successful, especially when using small coral fragments. Another timing consideration is climate seasons. rough sea conditions greatly reduce survival rate. When a storm occurs shortly after transplantation it is likely that a large percentage of the coral fragments is destroyed.

Appendix I

Evaluation considerations

This appendix explains the reasoning behind the chosen scores for the first evaluation of the alternatives in chapter I. It first explains which indicators are used relating to the ecosystem services. Then it gives the reasoning for the given scores per ecosystem service.

I.1 Indicators relating to the ecosystem services

The score of the alternatives given for each ecosystem service is based on indicators. Seven indicators are defined. Some are measurable using the simulations. Others cannot be specifically quantified at this point. However, for these indicators it can be said if the alternative will positively of negatively affect them. Relative comparison between the alternatives is possible. The indicators are storm resilience, yearly sediment loss, the quality of the reef, the quality of the sea grass beds, the quality of the wetlands, lack of disturbances by nourishments and the recreational beach width. Together, these indicators cover all ecosystem services.

I.1.1 Storm resilience

Storm resilience means the ability of the beach to withstand the short term impact caused by a storm. This indicator relates to coastal protection. If the resilience increases then coastal protection improves. Storm resilience is measured by the remaining beach width after a storm event as found during simulations.

I.1.2 Yearly sediment loss

The yearly sediment loss is found during simulations. A lower yearly sediment loss positively affects the sediment balance. This indicator relates to coastline stability.

I.1.3 Quality of the reef

The quality of the reef relates to the ecosystem services associated with coral reefs. Therefore, this indicator relates to food provision, material and bio fuels, life cycle maintenance, cognitive effects, aesthetic value, recreation and tourism and coastal protection. The service of providing coastal protection is already included in the measured storm resilience. This indicator consists of two aspects, the environmental conditions required for a good quality reef and the amount of surface area that is created/restored/destroyed due to the alternative. The first aspect promotes growth. The exact impact on the environmental conditions cannot be obtained at this point but it can be said is an alternative aims to improve conditions or not. The second aspect can be compared between alternatives.

I.1.4 Quality of the sea grass

This indicator relates to the ecosystem services associated with sea grass beds. The ecosystem services obtained from sea grass are material and bio fuels, life cycle maintenance, water purification and coastline stability. The comparison between alternatives is made in the same way as for the quality of the reef.

I.1.5 Quality of the wetlands

The quality of the wetlands relates to the ecosystem services associated with the wetlands. The ecosystem services obtained from the wetlands are food provision, material and bio fuels, life cycle maintenance, water purification, air quality purification, symbolic and aesthetic value and cognitive effects. The comparison between alternatives is made in the same way as for the quality of the reef.

I.1.6 Lack of disturbances by nourishments

Lack of disturbances by nourishments indicates the possible negative environmental effects of nourishments. The environmental impact of nourishments has already been explained in appendix F and shows that the fines in the nourishment can be harmful to the environmental system. This means it relates to life cycle maintenance and water purification. Sea grass is known to recover quickly so the focus is on the reefs. Therefore, the impact of the nourishment mainly depends on the amount of fines reaching the reefs. Reefs are fragile and the closer the nourishment location is to the reefs the higher the risk. The exact impact cannot be estimated at this point and requires further modeling. Therefore, this indicator is based on the distance between the nourishment sites and the reef. This give a comparable indication.

I.1.7 Recreational beach width

This indicator relates to recreation & tourism and symbolic and aesthetic value. A wider beach means more possibilities for recreation and looks more aesthetically pleasing. A large recreational beach width is more valuable where there are many hotels and resorts. For this reason, the recreational beach width is measured for the northern section of the coastline.

I.2 Considerations

This section gives the reasoning for the scores given in figure 6.1.

I.2.1 Coastal protection

Coastal protection is divided in the northern, middle and southern part of coastline. When defining the nourishment alternatives, the coastline was separated in seven sections. The northern part contains the first two sections, the middle part contains the third, fourth and fifth section and the southern part refers to the sixth and seventh section. The previous section explained that coastal protection is related to the indicator storm resilience.

With the reference scenario, the storm resilience is thought to decrease. The beach width continues to reduce making the coastline more vulnerable. Restoring the sediment production does not immediately improve coastal protection. The impact will remain similar. Sea grass helps to stabilize the bed but to what extend this prevents the loss of beach width after a storm is uncertain. The middle section might become better protected if the reef is able naturally restore itself due to the increased environmental quality. Whether this improvement is noticeable in a reasonable time frame is questionable since natural restoration usually takes a very long time. The beach and concentrated nourishment both improve the northern and southern section of coastline. The increased beach width creates a larger buffer to protect against storms. The simulations shows that the protection of the middle section is not improved by a nourishment. The wave attack is significant and the offshore directed flow exiting the bay between the reefs further enables the sediment to be transported offshore. When comparing the beach nourishment and the concentrated nourishment, both nourishments improve the situation about equally. The emerged breakwater improves the northern and middle section very well. In particular the middle section is improved significantly. The southern section shows no great improvement. This is due to the lack of breakwater at the southern end of the bay. The basic stone breakwater and the natural breakwater also improve the middle section very well. These alternatives do not improve the northern section due to their configuration. The hybrid solutions protect the northern and middle section. Again, the middle section shows great improvement. The southern reef extension alternative has the same configuration as the basic stone breakwater. However, this alternative also creates a buffer zone for the northern section. This is why coastal protection for the northern section is improved. The northern reef extension alternative protects this section of coast even more by placing a buffer zone as well as a submerged breakwater. This greatly improves coastal protection for the northern section.

I.2.2 Coastline stability

The previous section explained that coastline stability is related to yearly sediment loss and the quality of the sea grass.

For the reference scenario, coastline stability will likely continue to decrease. The cause could be intensification of storm events, degradation of the environment or a combination of both. Further research will determine the expected future state of the bay but it is thought that the stability of the coastline is keep declining as it has been doing for the past 40 years. Restoration of the sediment production could possibly lead to a great improvement of the coastline stability. The coastline stability is related to the yearly sediment loss and the quality of the sea grass. This alternative improves the quality of the sea grass and the environment in general. This could lead to a large increase in sediment production thereby creating a neutral or even positive sediment balance. This means a stable coastline is created. The improved quality of the sea grass beds means services such as stabilizing the sediment are also improved. The nourishment alternatives both neutralize the sediment balance by compensating for the yearly sediment loss. This way a stable coastline is created. Since the sea grass is able to quickly recover from the nourishment, the negative effects on the sea grass beds is small. The emerged breakwater, the basic stone breakwater and the southern reef extension all reduce the yearly sediment loss very well. The natural breakwater and the northern reef extension also reduce the yearly sediment loss but less significant. For this reason, they are scored 'positive' and the other three as 'very positive'.

I.2.3 Food provision

Food provision is improved when the quality of the reef and the wetlands goes up.

The reference scenario does not significantly affect this ecosystem service in the future. The restoration of the natural sediment production results in an overall environmental improvement. This means that the quality of the reefs and the wetlands will increase. So, this ecosystem service will be very positively affected. The other alternatives do not affect the wetlands. They do affect the quality of the reefs. The emerged breakwater and the basic stone breakwater do not integrate well with nature. The quality of the reef will likely be negatively affected during construction. The natural reef alternative and the hybrid alternatives actively restore the reef and create new nature. This positively affects food provision. The nourishment alternatives do not affect this ecosystem service since they do not significantly affect the quality of the reef or the wetlands.

I.2.4 Material and biofuels

This ecosystem service is similar to food provision in that it is also improved when the quality of the reef and the wetlands goes up. Sea grass beds also provide this service. The results of this service are te same as for food provision. Restoring the natural sediment production has the most positive effect. the nourishments do not impact the service, the emerged and basic stone breakwaters have a negative effect on the ecosystem service and the natural reef alternative and hybrid alternatives have a positive effect on the service by restoring and creating reef.

I.2.5 Life cycle maintenance

Life cycle maintenance is similar to the previous service. The difference is that this service is also related to the disturbances caused by nourishments. This means that the scores are the same as for the previous ecosystem service except for the nourishment alternatives. Their disturbance negatively affects life cycle maintenance.

I.2.6 Water purification

Water purification is improved by a lack of disturbances by nourishments and high quality sea grass beds and wetlands.

The breakwater and hybrid alternatives do not affect water purification. The nourishment alternatives, have a negative effect on this ecosystem service due to the disturbance caused by the nourishment. The restoration of the natural sediment production leads to a positive effect due to the improvement of the sea grass beds and wetlands.

I.2.7 Air quality regulation

This ecosystem service relates to the quality of the wetlands. The only alternative that improves the quality of the wetlands is the restoration of the sediment production. The other alternatives do not significantly affect this service.

I.2.8 Symbolic and aesthetic values

Symbolic and aesthetic values relate to the quality of the reef, the wetlands and the recreational beach width. The aesthetic value of a wide sandy beach and coral reefs with a large biodiversity is the main appeal of this bay. The wetlands offer a large variety of flora and fauna.

In the reference scenario, this appeal will reduce because the beach width will continue to diminish. The restoration of the sediment production mitigates further reduction of the beach width and improves the environmental conditions which will benefit the reef and the wetlands. This will positively affect the aesthetic value. The nourishments both create a nice wide beach. They do not affect the wetlands or the reef. The natural reef breakwater and hybrid solutions restore the reef and create new nature. This positively affects the aesthetic value of the bay. The hybrid solutions also create a buffer zone, making the area more aesthetically attractive by increasing beach width. The emerged breakwater and the basic stone breakwater have a strong negative effect on the aesthetic value of the bay. The designs damage the reefs. Furthermore they do not integrate with nature and are visible above water. This is seen as a large impact on the aesthetic value of the bay by hotel owners and the local community.

I.2.9 Recreation and tourism

Recreation and tourism is related to the indicators 'quality of the reef' and 'recreational beach width'. A higher quality reef will attract tourists for snorkeling/diving. A wide recreational beach is one of the main reasons for visiting Long Bay.

In the reference scenario, Long Bay will become less attractive for tourists. Further reduction of the beach width and possible degradation of the reefs will mean tourists are less likely to be drawn to Long Bay. Restoring the natural sediment production means that the environment will be in good condition. This means the reef becomes more attractive for snorkeling/diving. Also, the erosion rate is mitigated by the sea grass beds. So, although the beach width remains as it is now, recreation and tourism is still positively affected. The nourishments both positively affect the tourism and recreation by increasing the recreational beach width. The quality of the reef is not improved for these alternatives. The emerged breakwater and the basic stone breakwater negatively affect the reef as mentioned before. No nourishment is placed so the beach width remains the same as it is now. The natural reef alternative and the two hybrid solutions restore the reef and create new opportunities for nature. is will positively affect tourism. The hybrid solutions also increase the recreational beach width at the northern section. For this reason they both score 'very positive'. It should be noted that the effectiveness of reef restoration projects is still uncertain.

I.2.10 Cognitive effects

This ecosystem service relates to the quality of the reefs and the wetlands. It is quite similar to the ecosystem service 'symbolic and aesthetic value'. The difference is that the cognitive effects do not relate to the recreational beach width.

The reference scenario and the nourishments do not improve the reef or wetlands. The restoration of the sediment production improves both with leads to a very positive effect. The emerged breakwater and the basic stone breakwater score negatively for damaging the reef. the remaining alternatives score positively as they restore and improve the reef.

Appendix J

Xbeach model results

This appendix gives the results for all simulations made in the report. First, the extreme storm impact is illustrated and presented in a table. Then the long term sediment loss is given. the last illustration gives the information needed to understand the sediment pathways. The figure shows the Eulerian velocities and sediment transport magnitudes and directions in the bay during an extreme event. The list below can be used to quickly find the desired simulation

Understanding the system

H.1 Reference scenario
H.2 Healthy reef scenario

Soft solutions

H.3 Buffer zone
H.4 Beach nourishment
H.5 Shoreface nourishment
H.6 Concentrated nourishment
H.7 Edge nourishment - style 1
H.8 Edge nourishment - style 2
H.9 Edge nourishment - style 3

Hard solutions

H.10 Emerged breakwater design
H.11 Basic stone BW design
H.12 Natural reef design - short term

Hybrid solutions

H.13 Southern reef extension design - short term
H.14 Southern reef extension design - long term
H.15 Northern reef extension design - short term
H.16 Northern reef extension design - long term

J.1 Reference scenario

J.1.1 Extreme storm impact

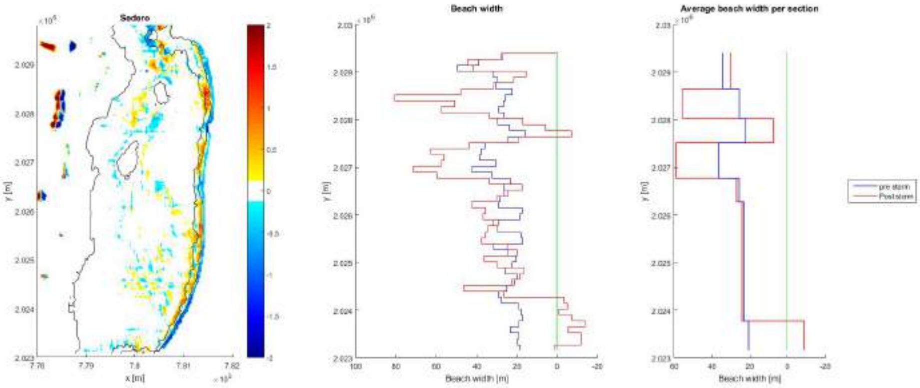

Figure J.1: Cumulative sedimentation/erosion after extreme storm (left) and Coastline retreat after extreme event (right)

Table J.1: Beach width pre and post storm

Area	Breach width pre storm [m]	Beach width post storm [m]	change [%]
1	34	30	-13%
2	26	56	117%
3	22	7	-67%
4	37	59	61%
5	26	27	5%
6	23	24	4%
7	21	-9	-143%
Average	27	28	-5%

J.1.2 Long term sediment loss

Table J.2: Sediment loss

Type of storm	Frequency [years]	Volume loss per storm [m^3]	Volume loss [m^3/y]	
Extreme	1/100	48263	483	
Medium	1/10	21864	2186	
Small	1/5	16523	3305	
			5974	Total erosion [m3/y]
			0.24	Average retreat [m/y]

J.1.3 Sediment pathways

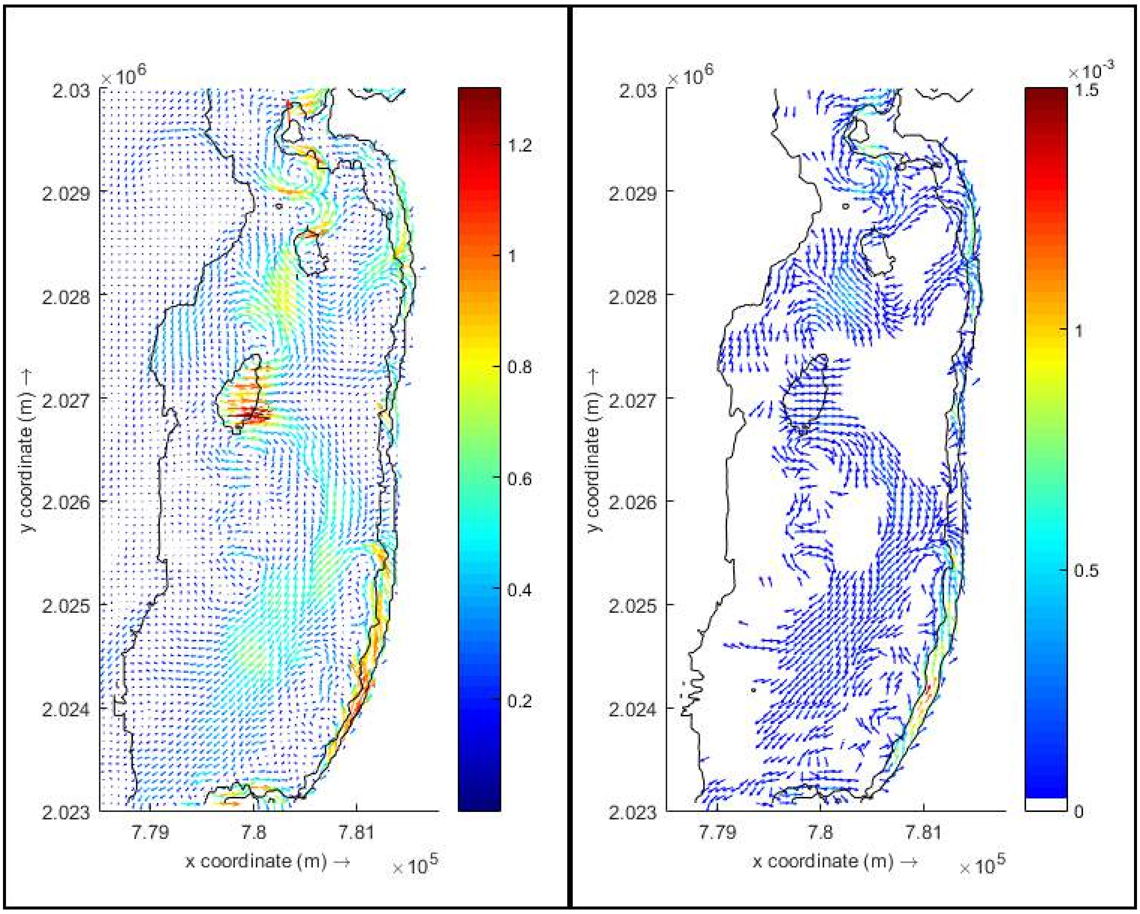

Figure J.2: Eulerian velocities in m/s (Left), Sediment transport integrated over bed load and suspended and for all sediment grains in m/s (Right)

J.2 Healthy reef scenario

J.2.1 Extreme storm impact

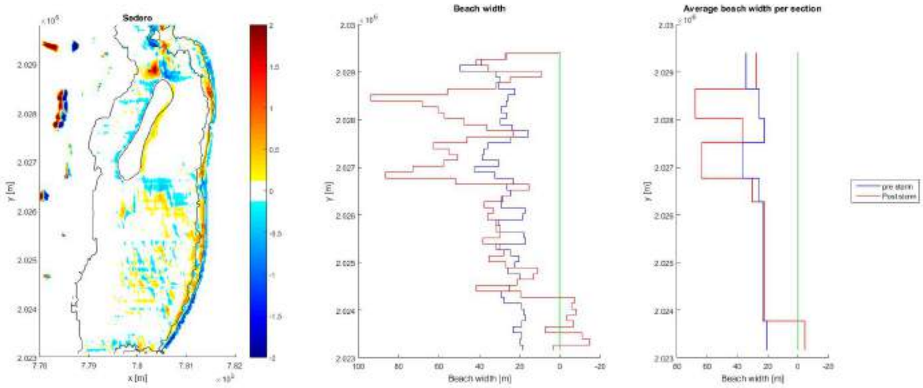

Figure J.3: Cumulative sedimentation/erosion after extreme storm (left) and Coastline retreat after extreme event (right)

Table J.3: Beach width pre and post storm

Area	Breach width pre storm [m]	Beach width post storm [m]	change [%]
1	34	28	-19%
2	26	68	166%
3	22	37	66%
4	37	64	74%
5	26	31	19%
6	23	22	-4%
7	21	-5	-123%
Average	27	35	26%

J.2.2 Long term sediment loss

Table J.4: Sediment loss

Type of storm	Frequency [years]	Volume loss per storm [m^3]	Volume loss [m^3/y]	
Extreme	1/100	46836	468	
Medium	1/10	19760	1976	
Small	1/5	16204	3241	
			5685	Total erosion [m3/y]
			0.23	Average retreat [m/y]

J.2.3 Sediment pathways

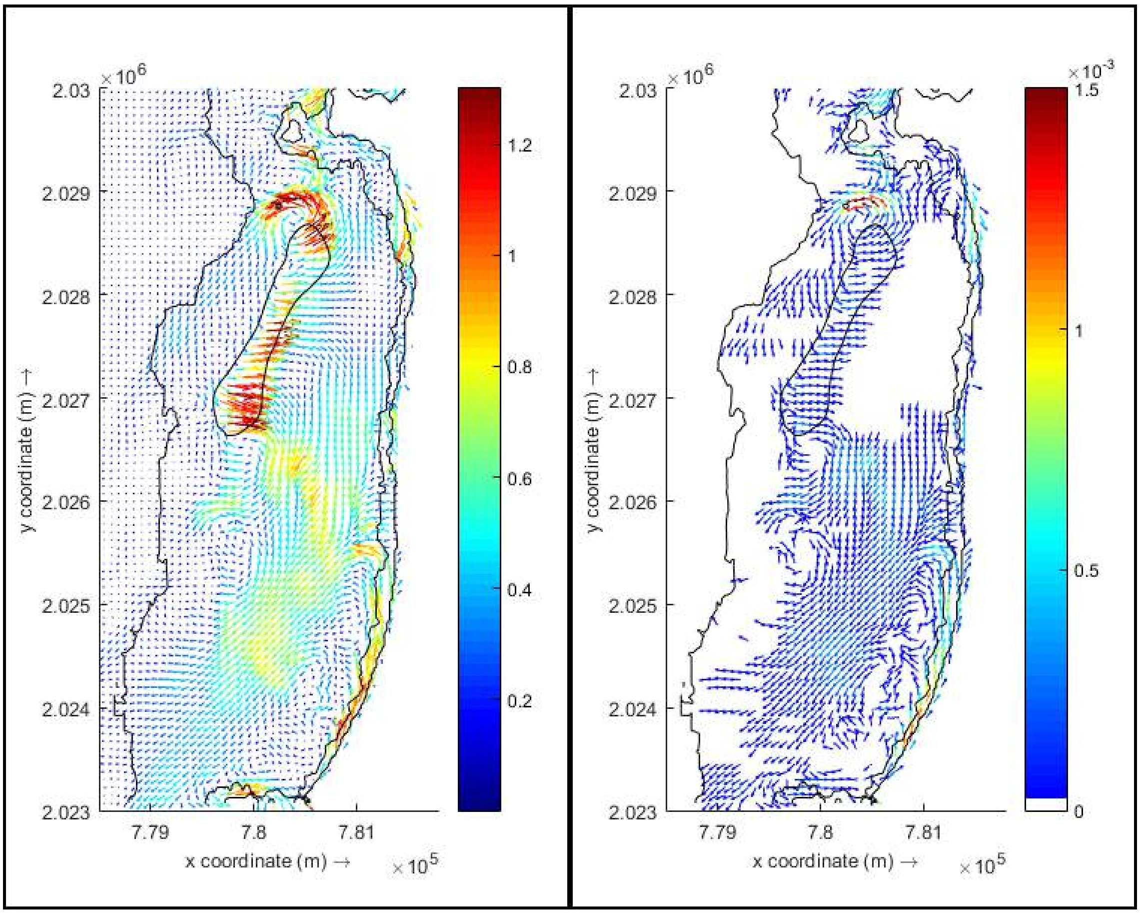

Figure J.4: Eulerian velocities in m/s (Left), Sediment transport integrated over bed load and suspended and for all sediment grains in m/s (Right)

J.3 Buffer zone

J.3.1 Extreme storm impact

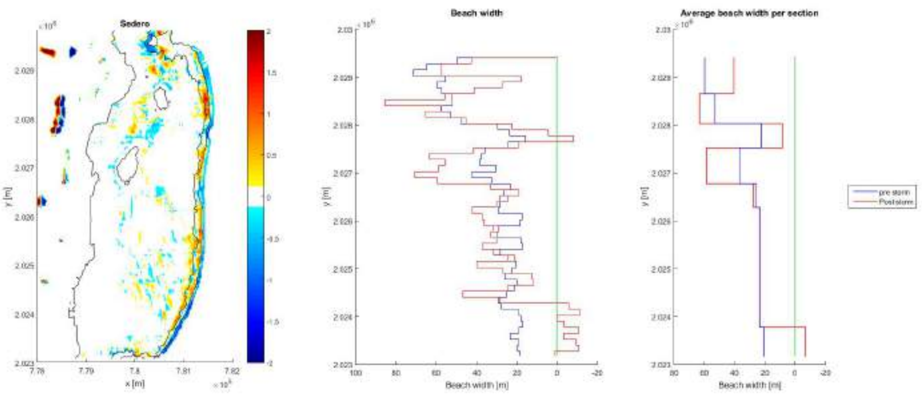

Figure J.5: Cumulative sedimentation/erosion after extreme storm (left) and Coastline retreat after extreme event (right)

Table J.5: Beach width pre and post storm

Area	Breach width pre storm [m]	Beach width post storm [m]	change [%]
1	60	41	18%
2	53	63	147%
3	22	8	-63%
4	37	59	60%
5	26	28	8%
6	23	24	1%
7	21	-7	-133%
Average	34	31	5%

J.3.2 Long term sediment loss

Table J.6: Sediment loss

Type of storm	Frequency [years]	Volume loss per storm [m^3]	Volume loss [m^3/y]	
Extreme	1/100	47473	475	
Medium	1/10	19053	1905	
Small	1/5	17284	3457	
			5837	Total erosion [m3/y]
			0.23	Average retreat [m/y]

J.3.3 Sediment pathways

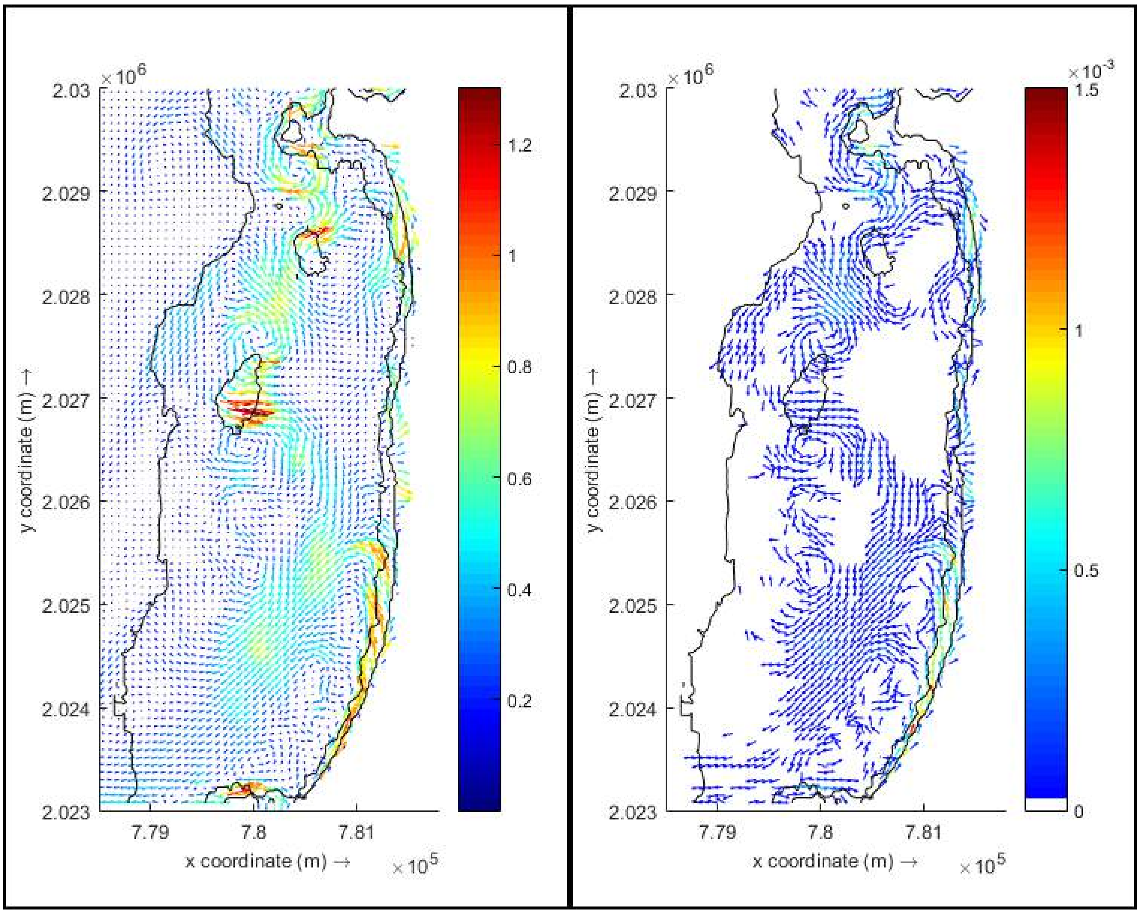

Figure J.6: Eulerian velocities in m/s (Left), Sediment transport integrated over bed load and suspended and for all sediment grains in m/s (Right)

J.4 Beach nourishment

J.4.1 Extreme storm impact

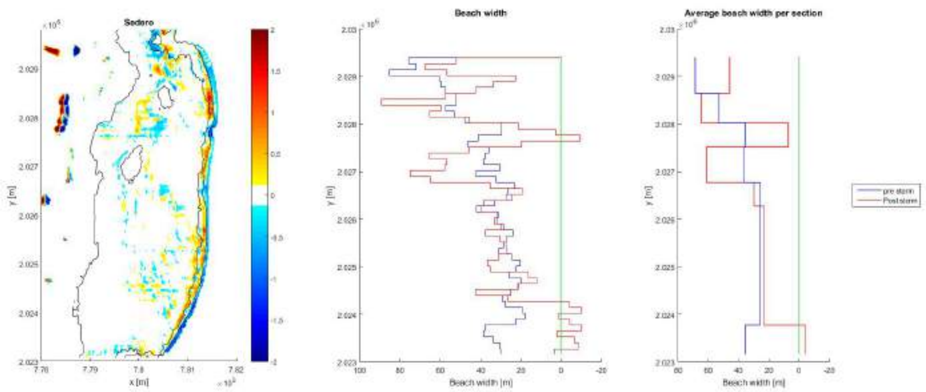

Figure J.7: Cumulative sedimentation/erosion after extreme storm (left) and Coastline retreat after extreme event (right)

Table J.7: Beach width pre and post storm

Area	Breach width pre storm [m]	Beach width post storm [m]	change [%]
1	69	46	33%
2	53	65	153%
3	36	7	-68%
4	37	61	68%
5	26	30	17%
6	26	23	0%
7	36	-4	-120%
Average	40	33	12%

J.4.2 Long term sediment loss

Table J.8: Sediment loss

Type of storm	Frequency [years]	Volume loss per storm [m^3]	Volume loss [m^3/y]	
Extreme	1/100	49521	495	
Medium	1/10	22921	2292	
Small	1/5	17122	3424	
			6212	Total erosion [m3/y]
			0.25	Average retreat [m/y]

J.4.3 Sediment pathways

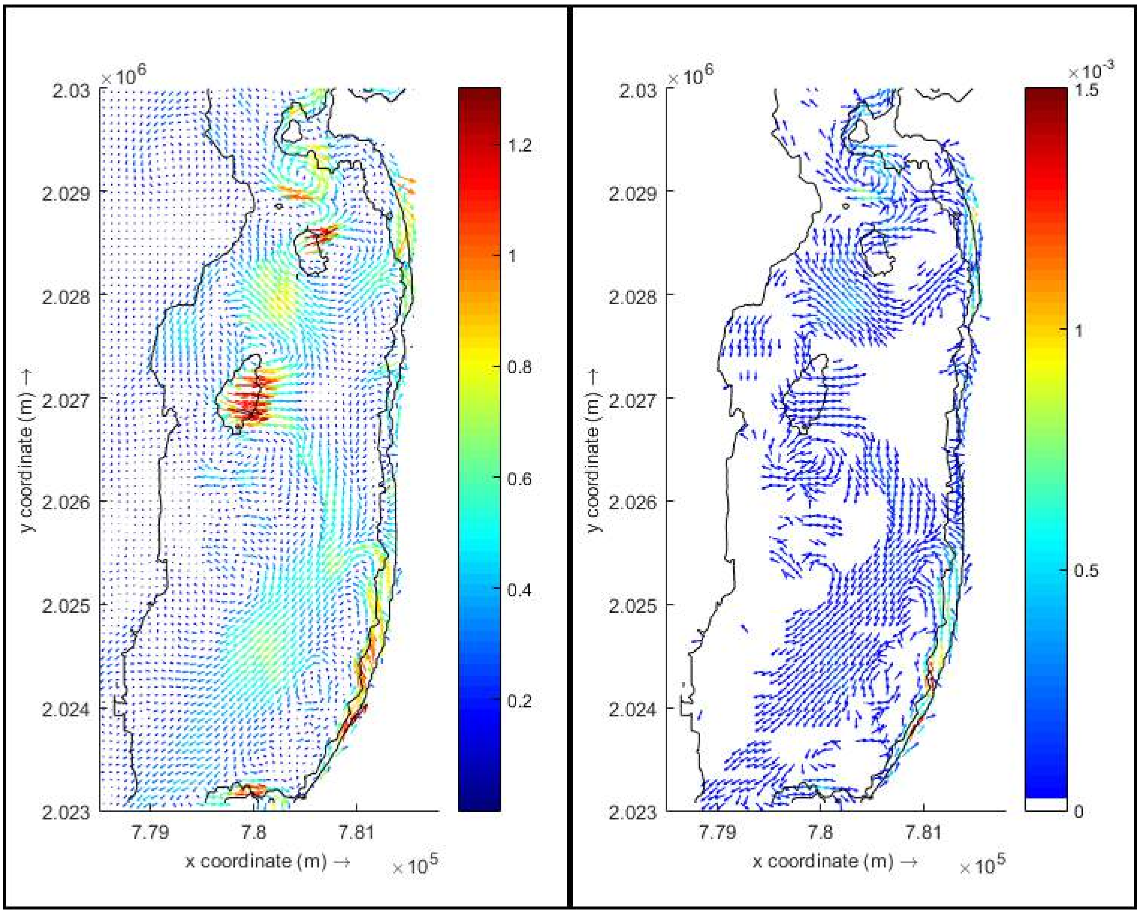

Figure J.8: Eulerian velocities in m/s (Left), Sediment transport integrated over bed load and suspended and for all sediment grains in m/s (Right)

J.5 Shoreface nourishment

J.5.1 Extreme storm impact

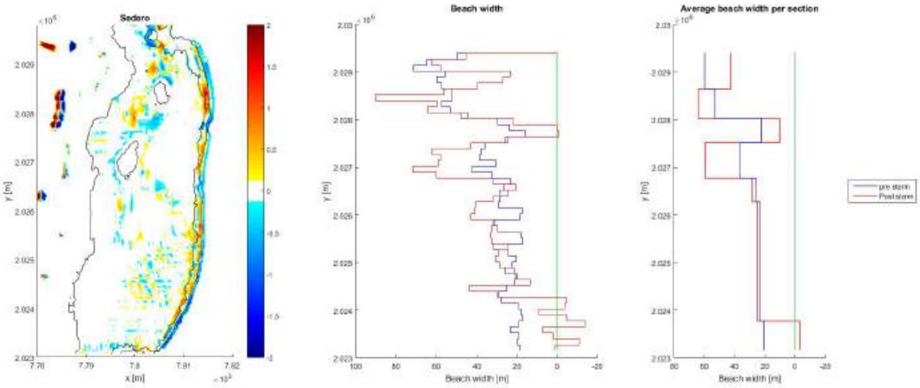

Figure J.9: Cumulative sedimentation/erosion after extreme storm (left) and Coastline retreat after extreme event (right)

Table J.9: Beach width pre and post storm

Area	Breach width pre storm [m]	Beach width post storm [m]	change [%]
1	60	42	23%
2	53	64	151%
3	22	10	-53%
4	37	59	62%
5	26	28	10%
6	23	25	7%
7	21	-3	-115%
Average	34	32	12%

J.5.2 Long term sediment loss

Table J.10: Sediment loss

Type of storm	Frequency [years]	Volume loss per storm [m^3]	Volume loss [m^3/y]	
Extreme	1/100	51363	514	
Medium	1/10	22877	2288	
Small	1/5	16612	3322	
			6124	Total erosion [m3/y]
			0.24	Average retreat [m/y]

J.5.3 Sediment pathways

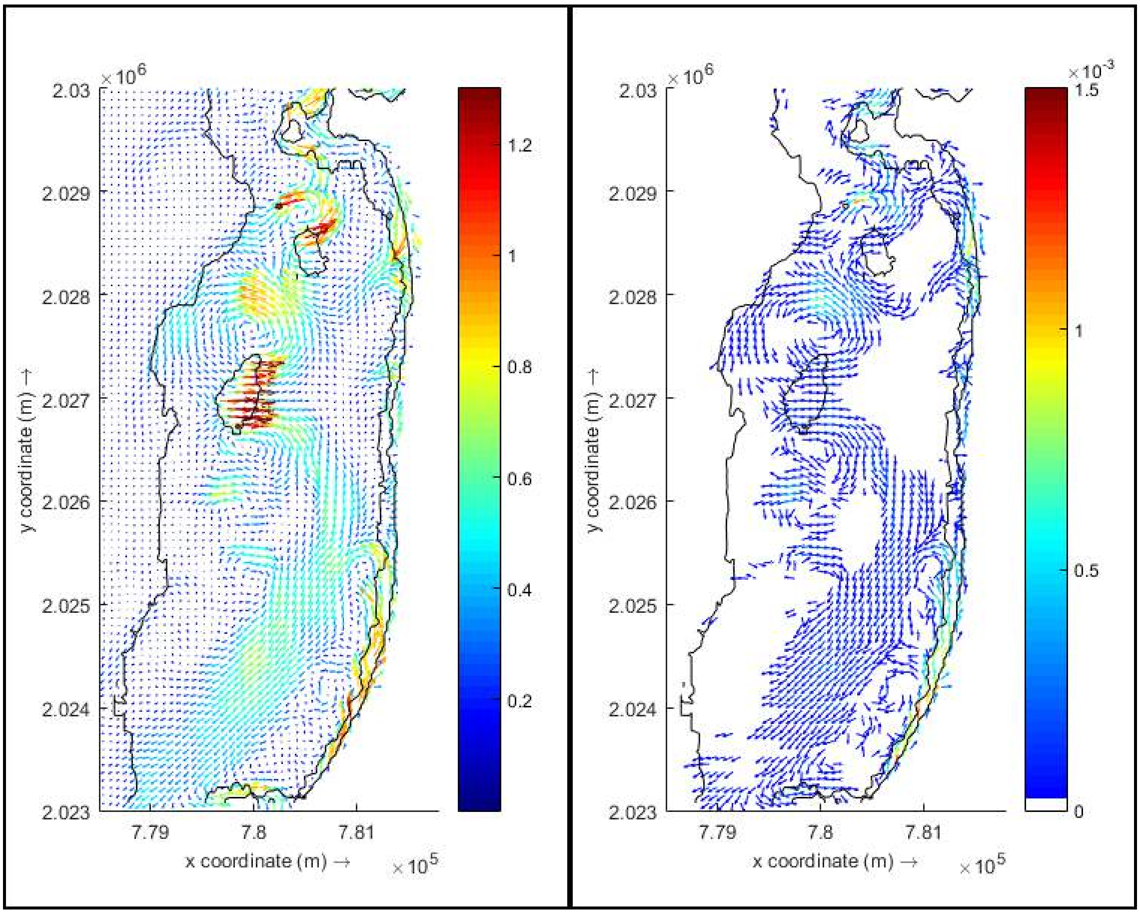

Figure J.10: Eulerian velocities in m/s (Left), Sediment transport integrated over bed load and suspended and for all sediment grains in m/s (Right)

J.6 Concentrated nourishment

J.6.1 Extreme storm impact

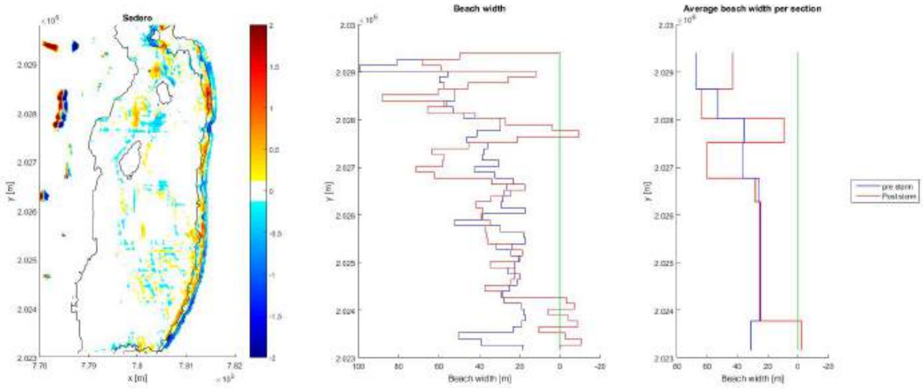

Figure J.11: Cumulative sedimentation/erosion after extreme storm (left) and Coastline retreat after extreme event (right)

Table J.11: Beach width pre and post storm

Area	Breach width pre storm [m]	Beach width post storm [m]	change [%]
1	67	43	25%
2	53	64	150%
3	36	9	-58%
4	37	60	64%
5	26	28	10%
6	25	25	6%
7	31	-2	-112%
Average	39	32	12%

J.6.2 Long term sediment loss

Table J.12: Sediment loss

Type of storm	Frequency [years]	Volume loss per storm [m^3]	Volume loss [m^3/y]	
Extreme	1/100	48770	488	
Medium	1/10	22098	2210	
Small	1/5	16120	3224	
			5922	Total erosion [m3/y]
			0.24	Average retreat [m/y]

J.6.3 Sediment pathways

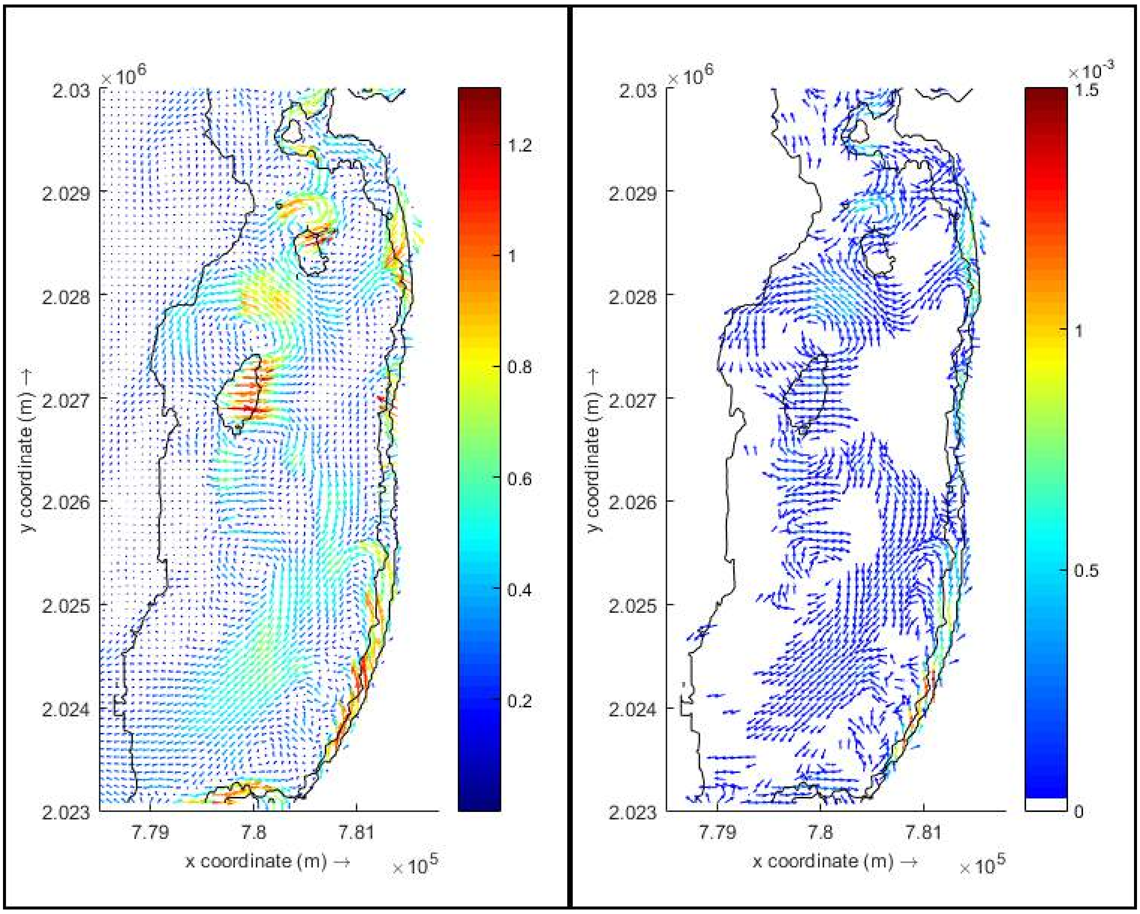

Figure J.12: Eulerian velocities in m/s (Left), Sediment transport integrated over bed load and suspended and for all sediment grains in m/s (Right)

J.7 Edge nourishment - style 1

J.7.1 Extreme storm impact

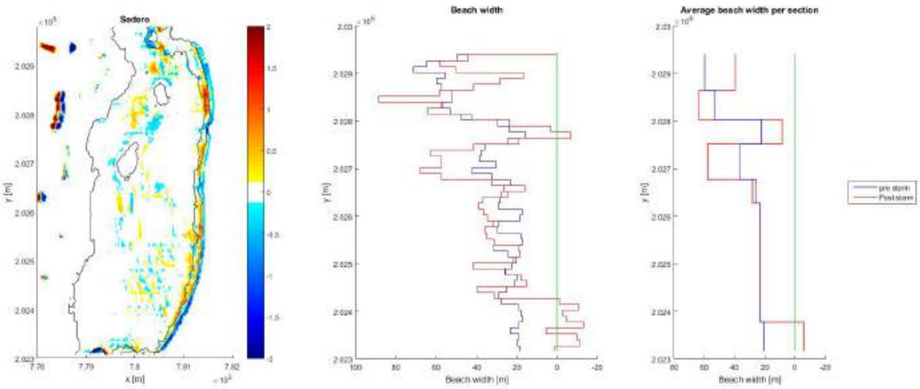

Figure J.13: Cumulative sedimentation/erosion after extreme storm (left) and Coastline retreat after extreme event (right)

Table J.13: Beach width pre and post storm

Area	Breach width pre storm [m]	Beach width post storm [m]	change [%]
1	60	39	15%
2	53	63	148%
3	22	8	-62%
4	37	58	58%
5	26	28	10%
6	23	23	-1%
7	21	-6	-128%
Average	34	31	6%

J.7.2 Long term sediment loss

Table J.14: Sediment loss

Type of storm	Frequency [years]	Volume loss per storm [m^3]	Volume loss [m^3/y]	
Extreme	1/100	52321	523	
Medium	1/10	22236	2224	
Small	1/5	16433	3287	
			6033	Total erosion [m3/y]
			0.24	Average retreat [m/y]

J.7.3 Sediment pathways

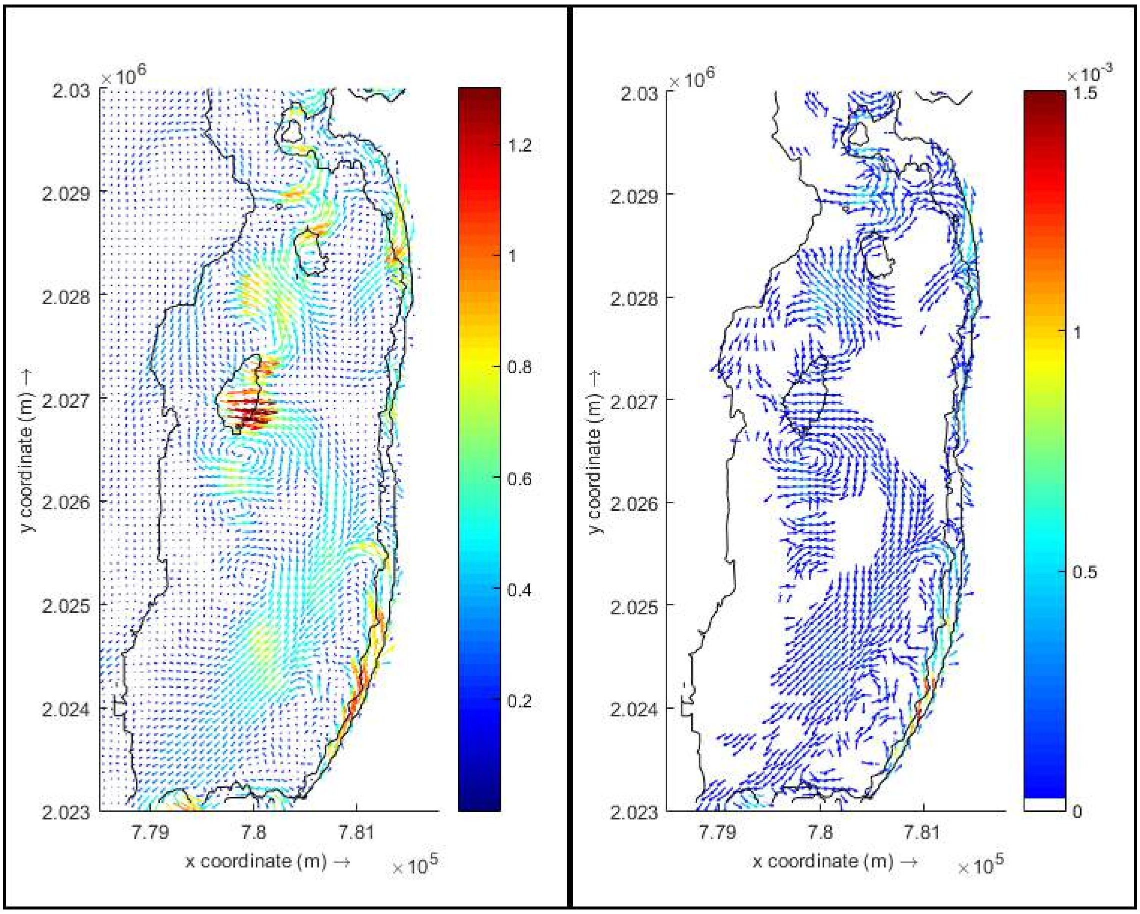

Figure J.14: Eulerian velocities in m/s (Left), Sediment transport integrated over bed load and suspended and for all sediment grains in m/s (Right)

J.8 Edge nourishment - style 2

J.8.1 Extreme storm impact

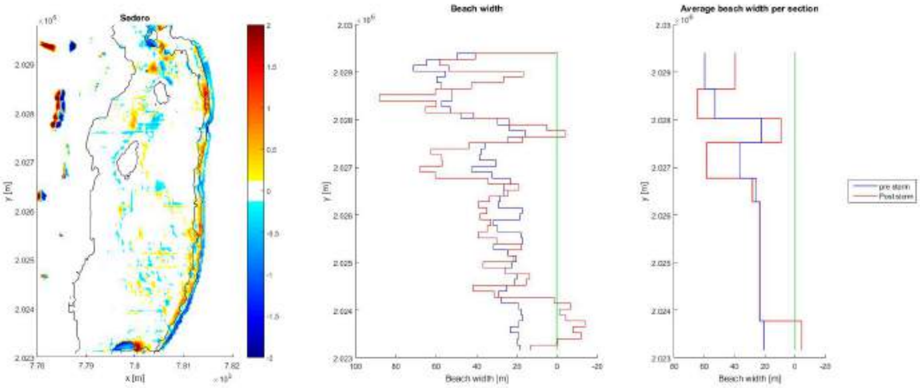

Figure J.15: Cumulative sedimentation/erosion after extreme storm (left) and Coastline retreat after extreme event (right)

Table J.15: Beach width pre and post storm

Area	Breach width pre storm [m]	Beach width post storm [m]	change [%]
1	60	40	15%
2	53	65	153%
3	22	9	-57%
4	37	59	60%
5	26	28	10%
6	23	24	2%
7	21	-4	-121%
Average	34	31	9%

J.8.2 Long term sediment loss

Table J.16: Sediment loss

Type of storm	Frequency [years]	Volume loss per storm [m^3]	Volume loss [m^3/y]	
Extreme	1/100	54278	543	
Medium	1/10	20917	2092	
Small	1/5	16628	3326	
			5960	Total erosion [m3/y]
			0.24	Average retreat [m/y]

J.8.3 Sediment pathways

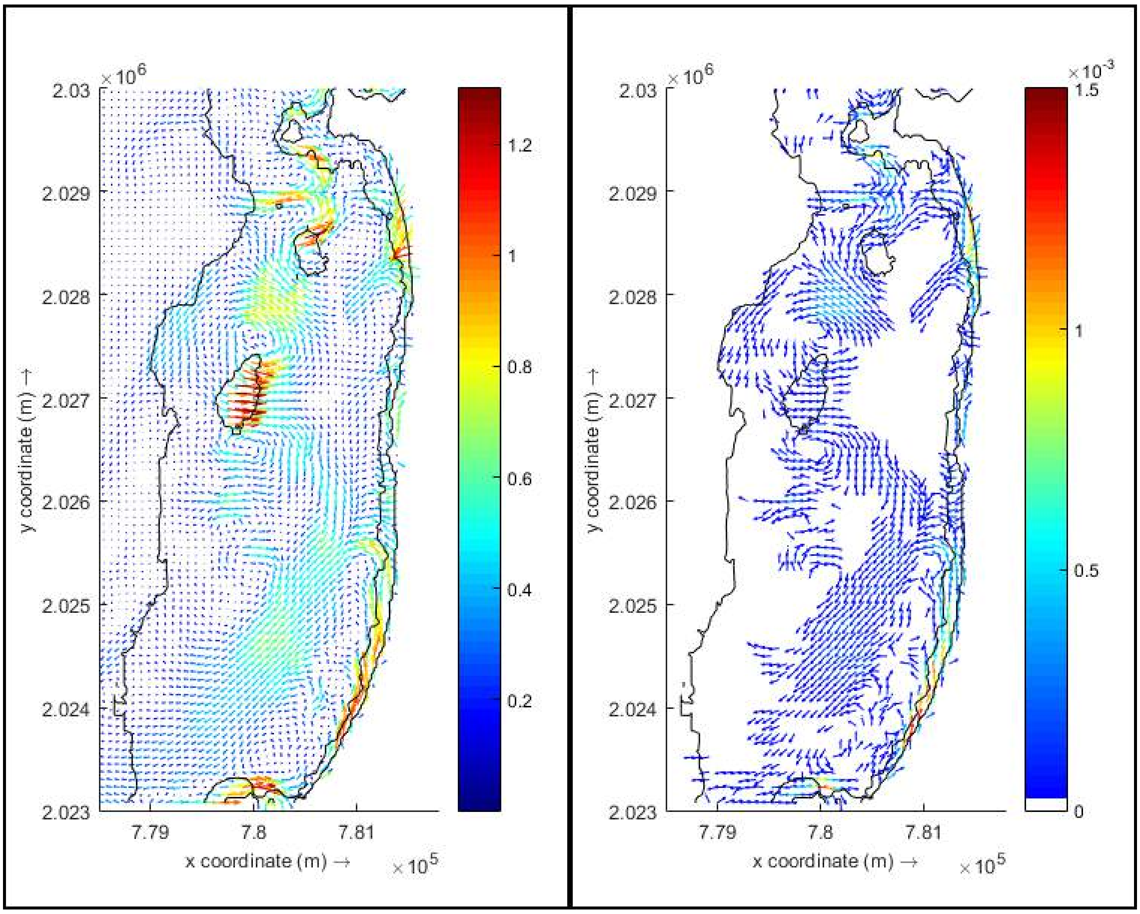

Figure J.16: Eulerian velocities in m/s (Left), Sediment transport integrated over bed load and suspended and for all sediment grains in m/s (Right)

J.9 Edge nourishment - style 3

J.9.1 Extreme storm impact

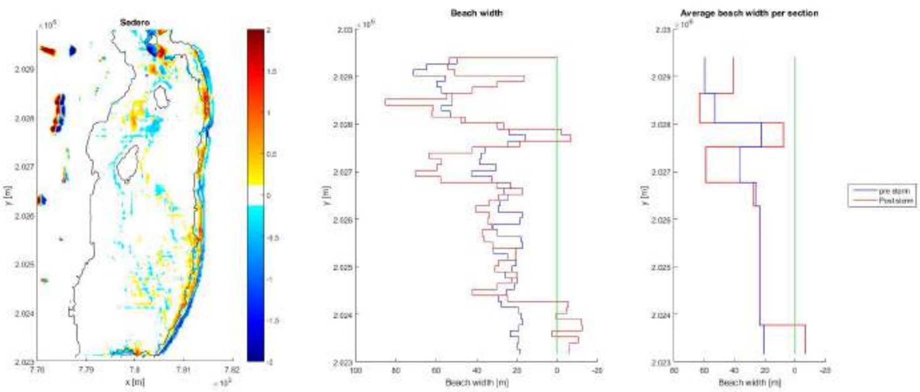

Figure J.17: Cumulative sedimentation/erosion after extreme storm (left) and Coastline retreat after extreme event (right)

Table J.17: Beach width pre and post storm

Area	Breach width pre storm [m]	Beach width post storm [m]	change [%]
1	60	41	19%
2	53	63	147%
3	22	8	-65%
4	37	59	61%
5	26	27	7%
6	23	24	2%
7	21	-7	-133%
Average	34	31	5%

J.9.2 Long term sediment loss

Table J.18: Sediment loss

Type of storm	Frequency [years]	Volume loss per storm [m^3]	Volume loss [m^3/y]	
Extreme	1/100	48962	490	
Medium	1/10	20765	2077	
Small	1/5	15028	3006	
			5572	Total erosion [m3/y]
			0.22	Average retreat [m/y]

J.9.3 Sediment pathways

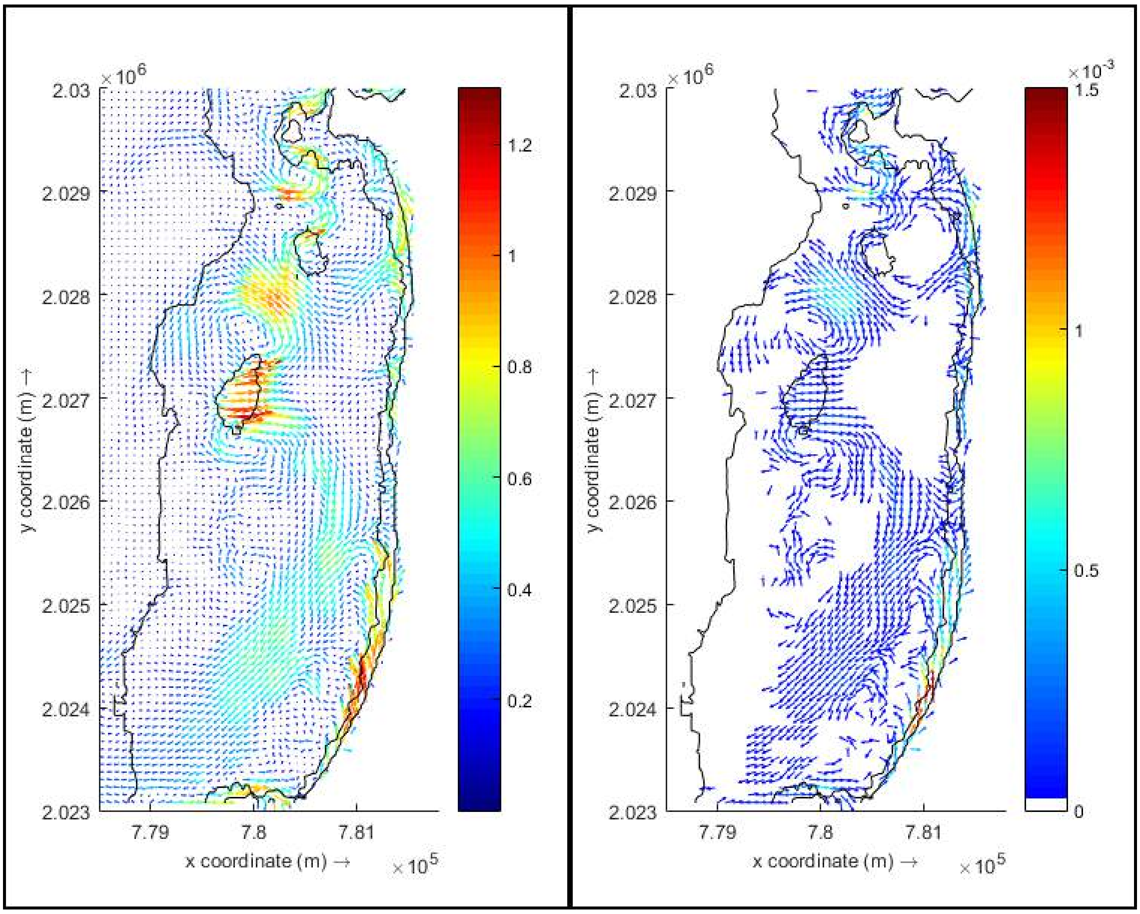

Figure J.18: Eulerian velocities in m/s (Left), Sediment transport integrated over bed load and suspended and for all sediment grains in m/s (Right)

J.10 Emerged breakwater design

J.10.1 Extreme storm impact

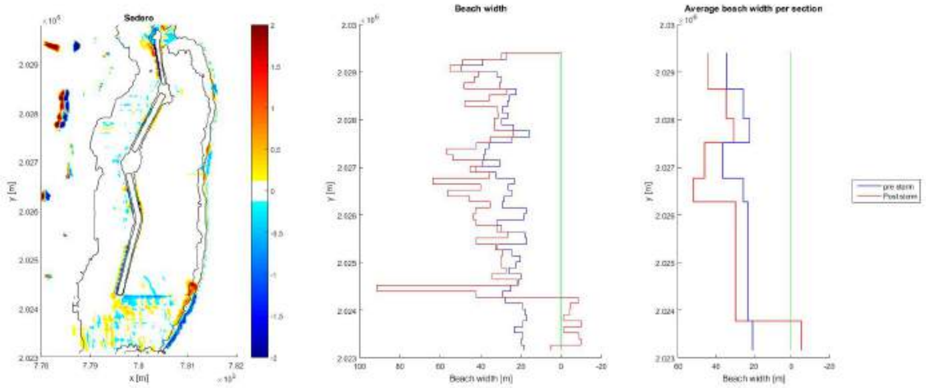

Figure J.19: Cumulative sedimentation/erosion after extreme storm (left) and Coastline retreat after extreme event (right)

Table J.19: Beach width pre and post storm

Area	Breach width pre storm [m]	Beach width post storm [m]	change [%]
1	34	44	29%
2	26	35	35%
3	22	30	37%
4	37	46	26%
5	26	52	103%
6	23	30	27%
7	21	-5	-126%
Average	27	33	19%

J.10.2 Long term sediment loss

Table J.20: Sediment loss

Type of storm	Frequency [years]	Volume loss per storm [m^3]	Volume loss [m^3/y]	
Extreme	1/100	16341	163	
Medium	1/10	4111	411	
Small	1/5	1963	393	
			967	Total erosion [m3/y]
			0.04	Average retreat [m/y]

J.10.3 Sediment pathways

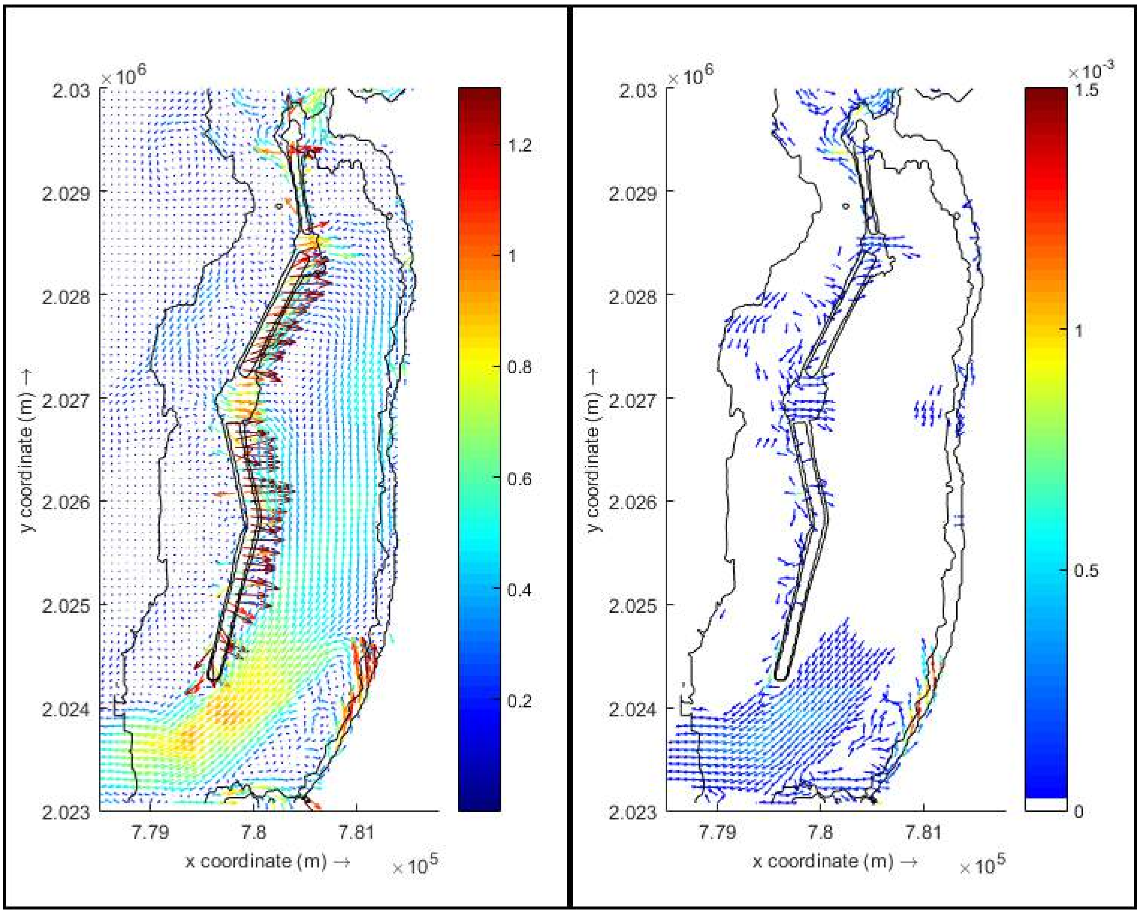

Figure J.20: Eulerian velocities in m/s (Left), Sediment transport integrated over bed load and suspended and for all sediment grains in m/s (Right)

J.11 Basic stone BW design

J.11.1 Extreme storm impact

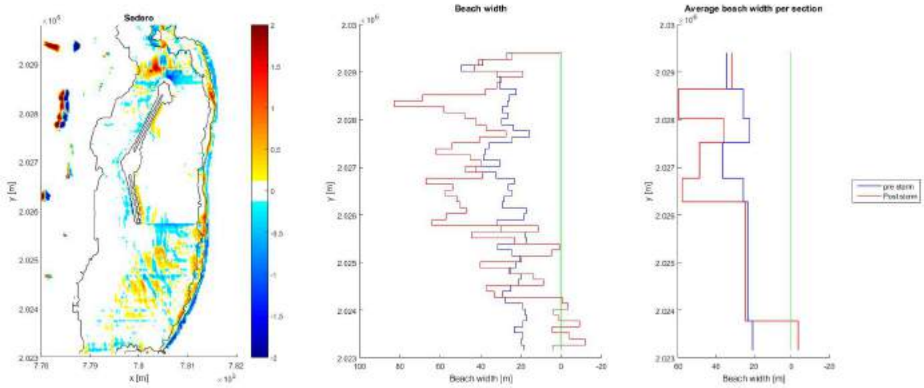

Figure J.21: Cumulative sedimentation/erosion after extreme storm (left) and Coastline retreat after extreme event (right)

Table J.21: Beach width pre and post storm

Area	Breach width pre storm [m]	Beach width post storm [m]	change [%]
1	34	32	-8%
2	26	60	133%
3	22	36	62%
4	37	49	33%
5	26	58	126%
6	23	24	5%
7	21	-4	-117%
Average	27	36	34%

J.11.2 Long term sediment loss

Table J.22: Sediment loss

Type of storm	Frequency [years]	Volume loss per storm [m^3]	Volume loss [m^3/y]	
Extreme	1/100	35132	351	
Medium	1/10	16164	1616	
Small	1/5	11075	2215	
			4183	Total erosion [m3/y]
			0.17	Average retreat [m/y]

J.11.3 Sediment pathways

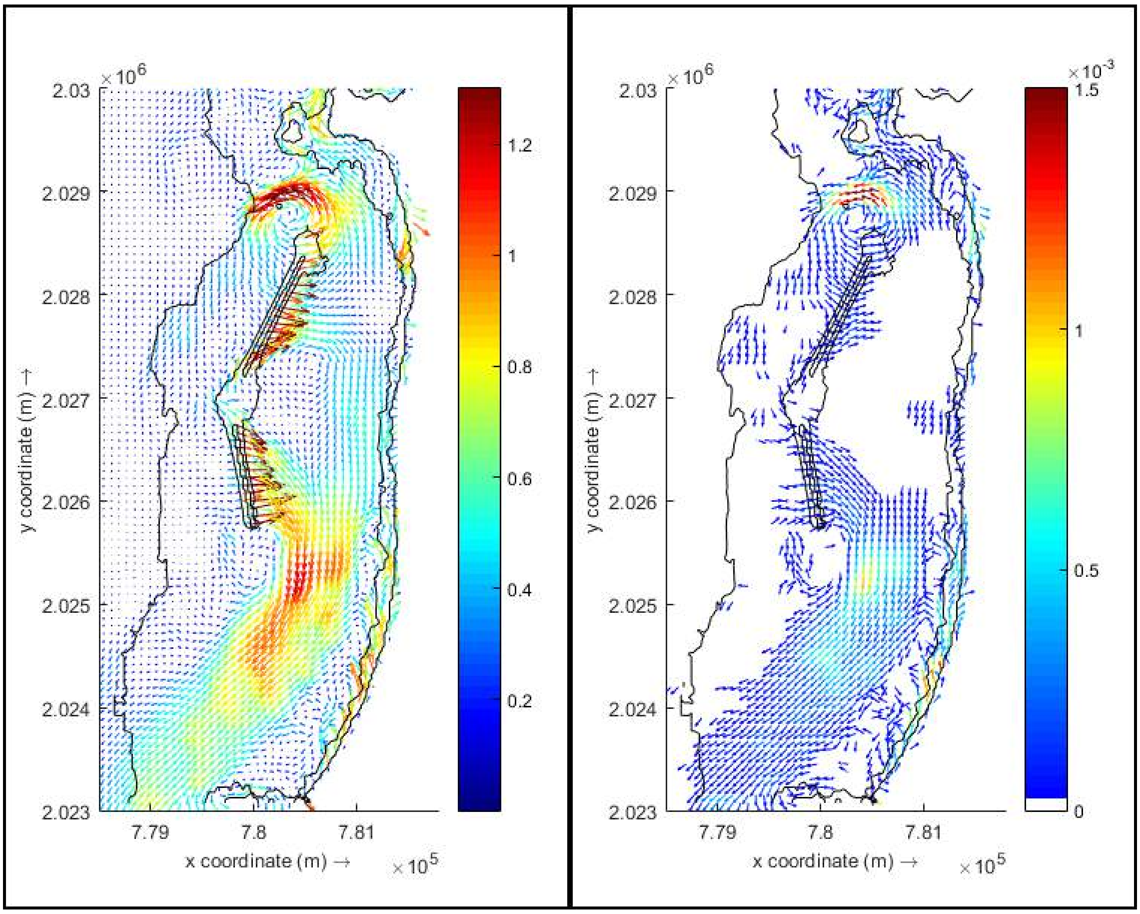

Figure J.22: Eulerian velocities in m/s (Left), Sediment transport integrated over bed load and suspended and for all sediment grains in m/s (Right)

J.12 Natural reef design - short term

J.12.1 Extreme storm impact

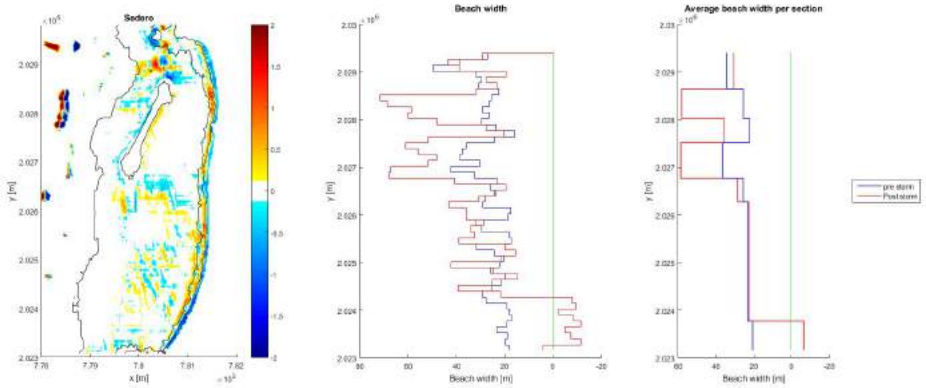

Figure J.23: Cumulative sedimentation/erosion after extreme storm (left) and Coastline retreat after extreme event (right)

Table J.23: Beach width pre and post storm

Area	Breach width pre storm [m]	Beach width post storm [m]	change [%]
1	34	30	-11%
2	26	58	128%
3	22	36	60%
4	37	59	60%
5	26	29	12%
6	23	23	-3%
7	21	-7	-132%
Average	27	32	16%

J.12.2 Long term sediment loss

Table J.24: Sediment loss

Type of storm	Frequency [years]	Volume loss per storm [m^3]	Volume loss [m^3/y]	
Extreme	1/100	48705	487	
Medium	1/10	19737	1974	
Small	1/5	14929	2986	
			5447	Total erosion [m3/y]
			0.22	Average retreat [m/y]

J.12.3 Sediment pathways

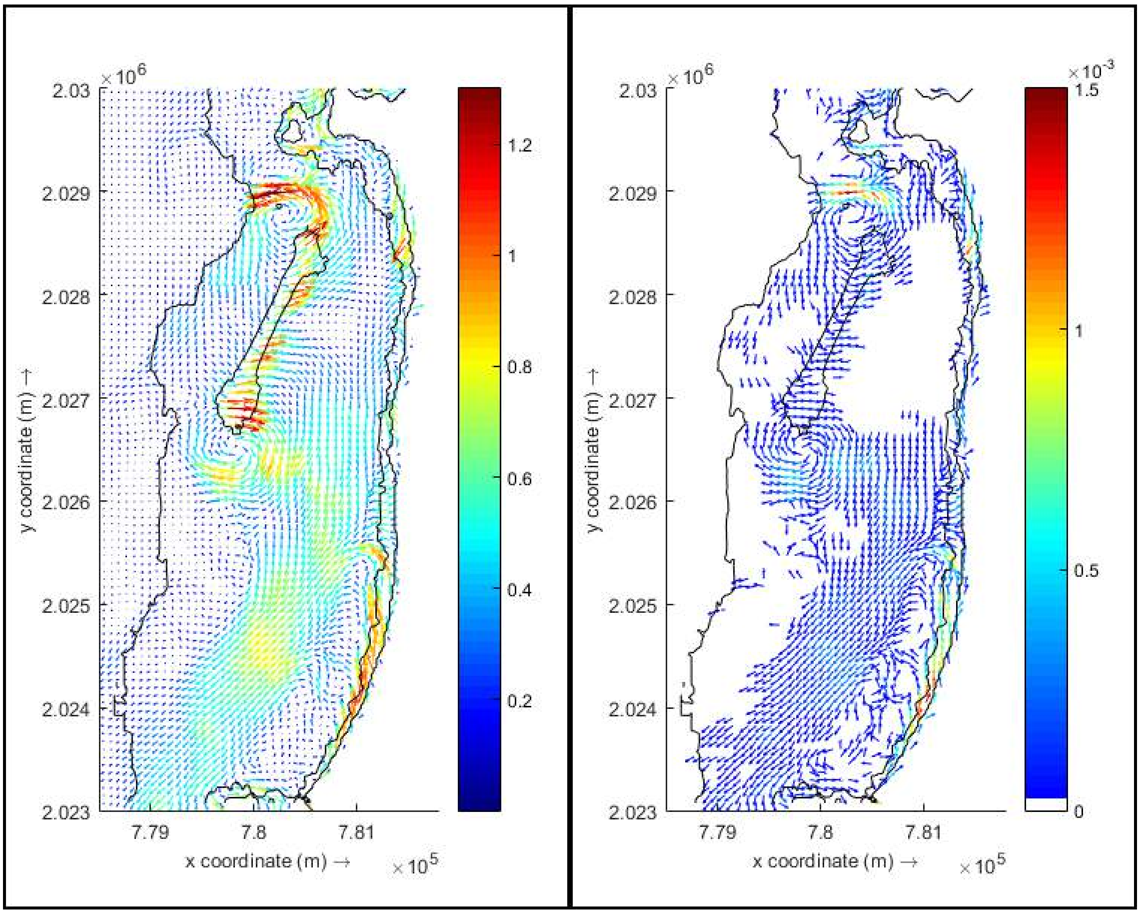

Figure J.24: Eulerian velocities in m/s (Left), Sediment transport integrated over bed load and suspended and for all sediment grains in m/s (Right)

J.13 Southern reef extension design - short term

J.13.1 Extreme storm impact

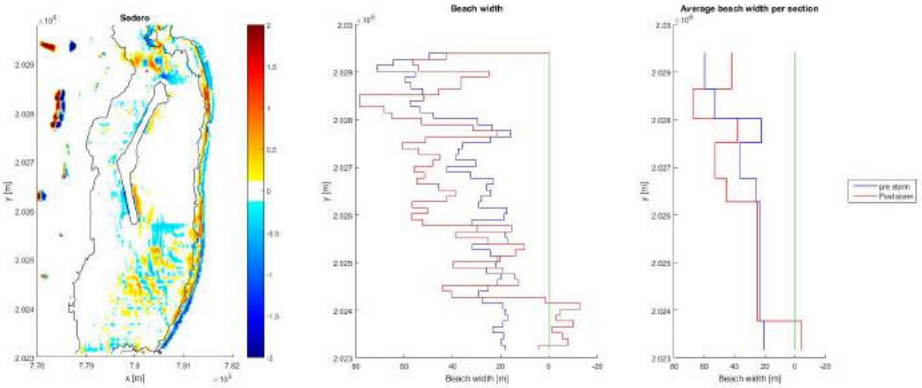

Figure J.25: Cumulative sedimentation/erosion after extreme storm (left) and Coastline retreat after extreme event (right)

Table J.25: Beach width pre and post storm

Area	Breach width pre storm [m]	Beach width post storm [m]	change [%]
1	60	42	22%
2	53	67	163%
3	22	38	71%
4	37	53	44%
5	26	45	78%
6	23	25	7%
7	21	-4	-121%
Average	34	38	38%

J.13.2 Long term sediment loss

Table J.26: Sediment loss

Type of storm	Frequency [years]	Volume loss per storm [m^3]	Volume loss [m^3/y]	
Extreme	1/100	37105	371	
Medium	1/10	16895	1690	
Small	1/5	11752	2350	
			4411	Total erosion [m3/y]
			0.18	Average retreat [m/y]

J.13.3 Sediment pathways

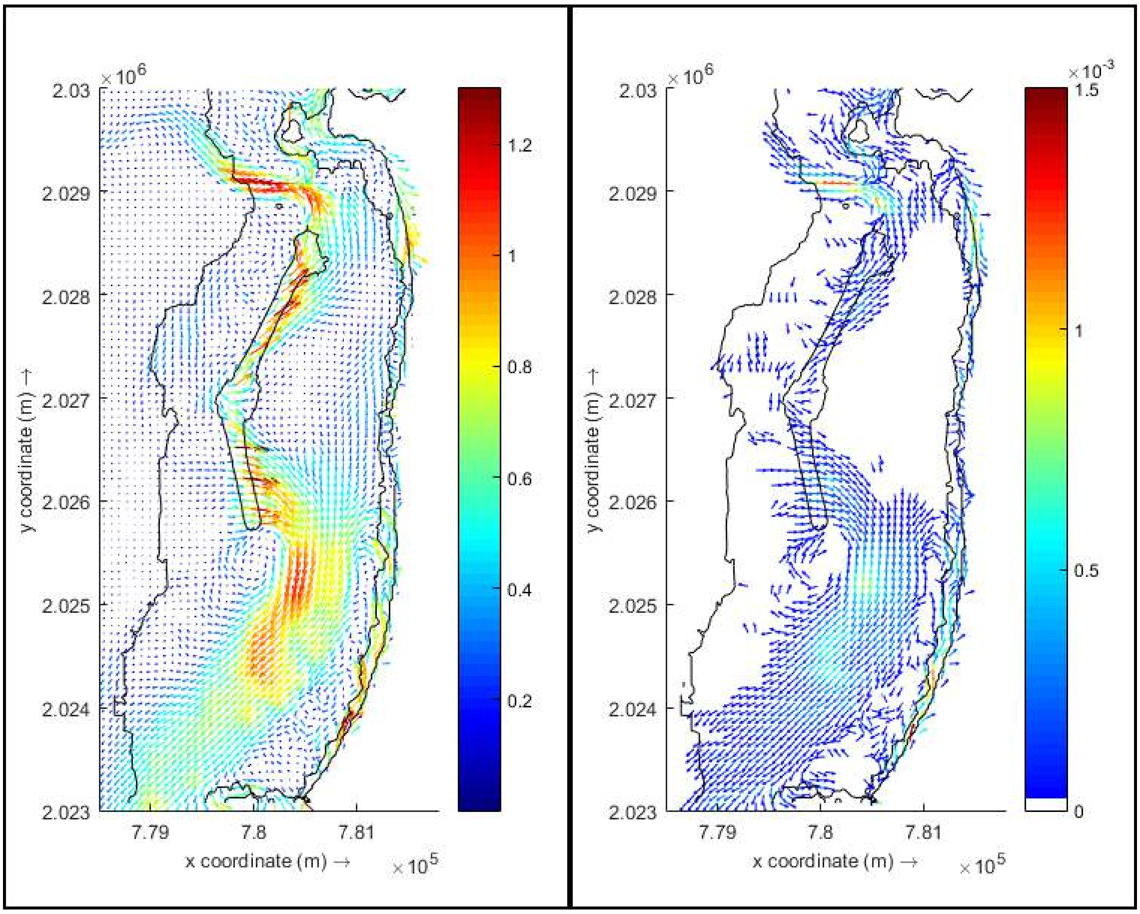

Figure J.26: Eulerian velocities in m/s (Left), Sediment transport integrated over bed load and suspended and for all sediment grains in m/s (Right)

J.14 Southern reef extension design - long term

J.14.1 Extreme storm impact

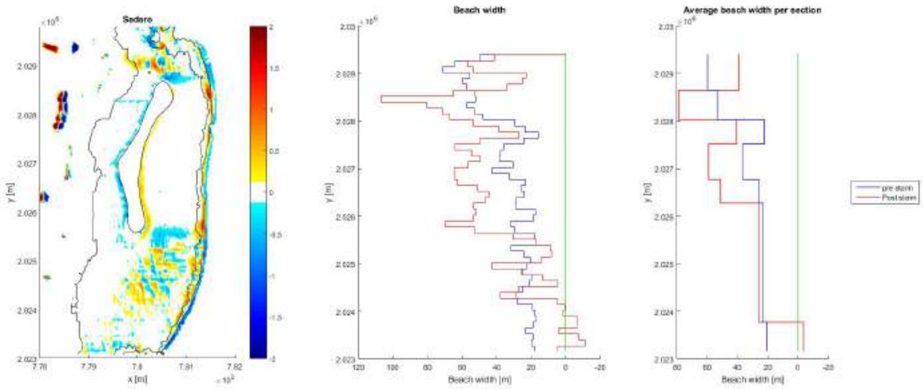

Figure J.27: Cumulative sedimentation/erosion after extreme storm (left) and Coastline retreat after extreme event (right)

Table J.27: Beach width pre and post storm

Area	Breach width pre storm [m]	Beach width post storm [m]	change [%]
1	60	39	13%
2	53	79	208%
3	22	41	84%
4	37	59	61%
5	26	51	100%
6	23	26	11%
7	21	-4	-117%
Average	34	42	52%

J.14.2 Long term sediment loss

Table J.28: Sediment loss

Type of storm	Frequency [years]	Volume loss per storm [m^3]	Volume loss [m^3/y]	
Extreme	1/100	25702	257	
Medium	1/10	12975	1298	
Small	1/5	9988	1998	
			3552	Total erosion [m3/y]
			0.14	Average retreat [m/y]

J.14.3 Sediment pathways

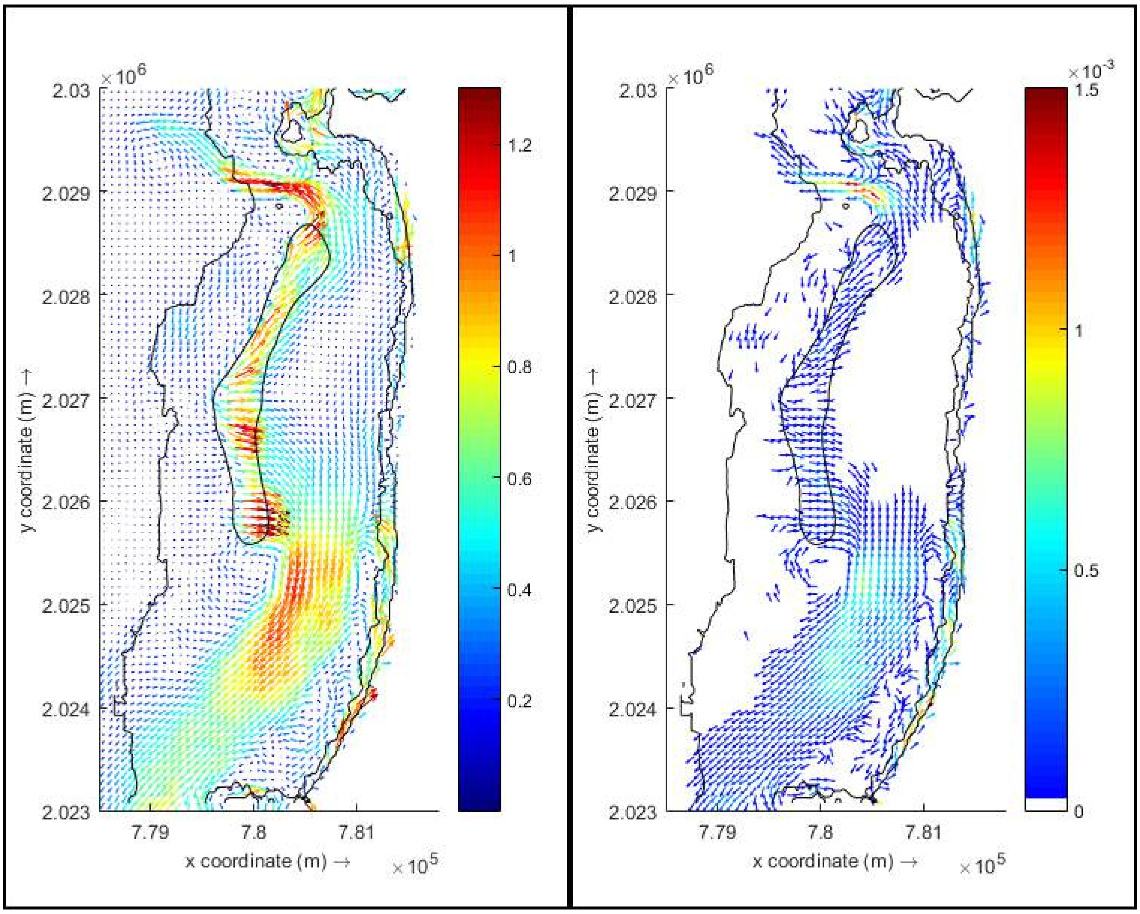

Figure J.28: Eulerian velocities in m/s (Left), Sediment transport integrated over bed load and suspended and for all sediment grains in m/s (Right)

J.15 Northern reef extension design - short term

J.15.1 Extreme storm impact

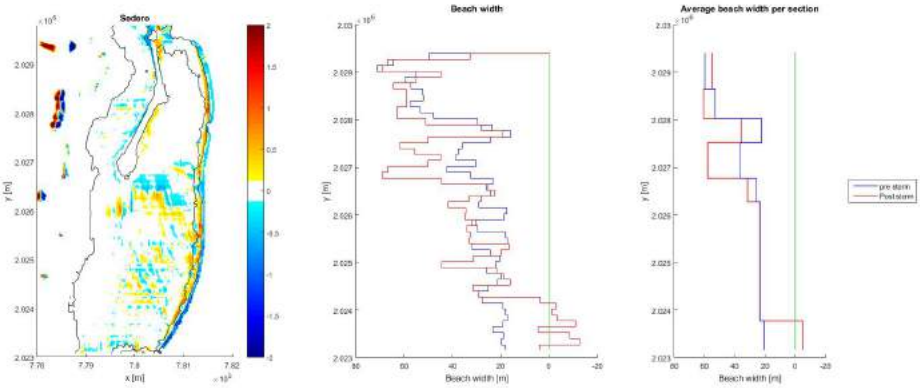

Figure J.29: Cumulative sedimentation/erosion after extreme storm (left) and Coastline retreat after extreme event (right)

Table J.29: Beach width pre and post storm

Area	Breach width pre storm [m]	Beach width post storm [m]	change [%]
1	60	55	60%
2	53	61	137%
3	22	36	61%
4	37	58	59%
5	26	32	23%
6	23	24	2%
7	21	-5	-125%
Average	34	37	31%

J.15.2 Long term sediment loss

Table J.30: Sediment loss

Type of storm	Frequency [years]	Volume loss per storm [m^3]	Volume loss [m^3/y]	
Extreme	1/100	43765	438	
Medium	1/10	19823	1982	
Small	1/5	13172	2634	
			5054	Total erosion [m3/y]
			0.20	Average retreat [m/y]

J.15.3 Sediment pathways

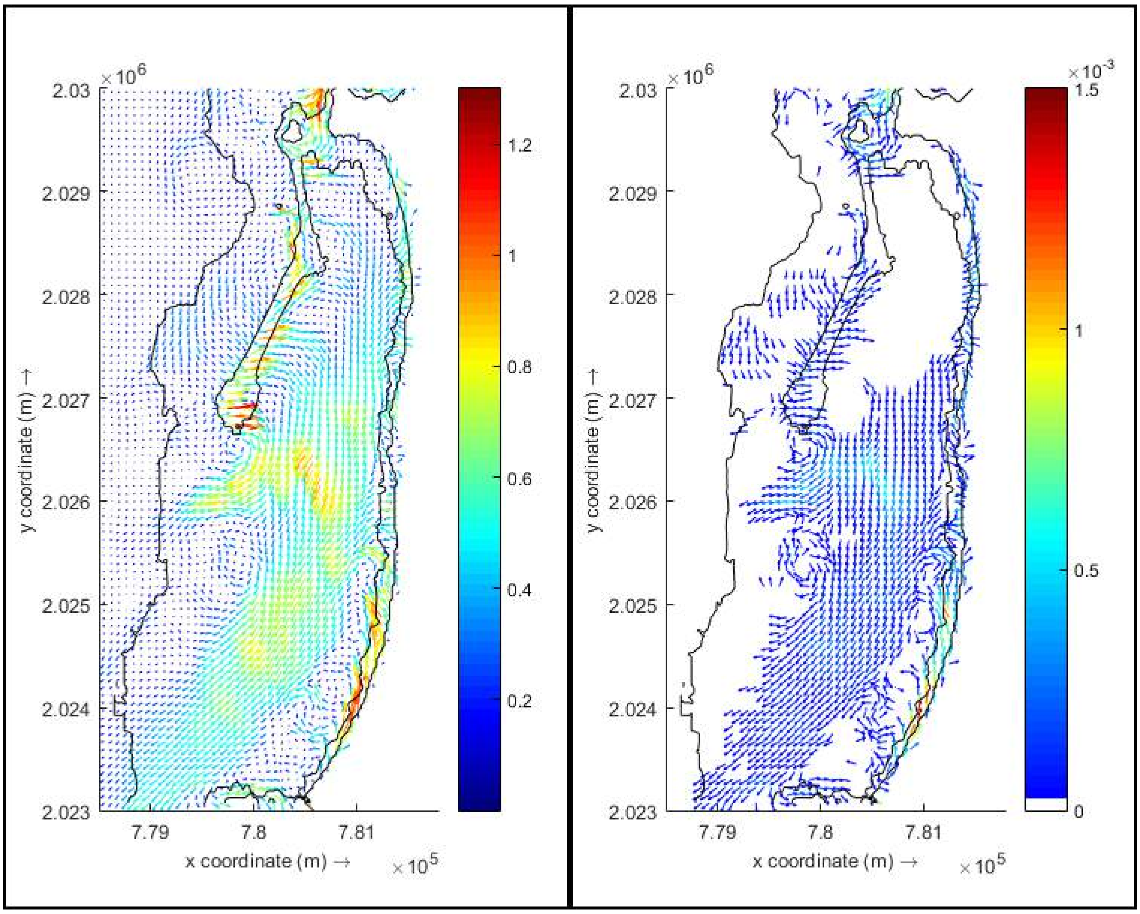

Figure J.30: Eulerian velocities in m/s (Left), Sediment transport integrated over bed load and suspended and for all sediment grains in m/s (Right)

J.16 Northern reef extension design - long term

J.16.1 Extreme storm impact

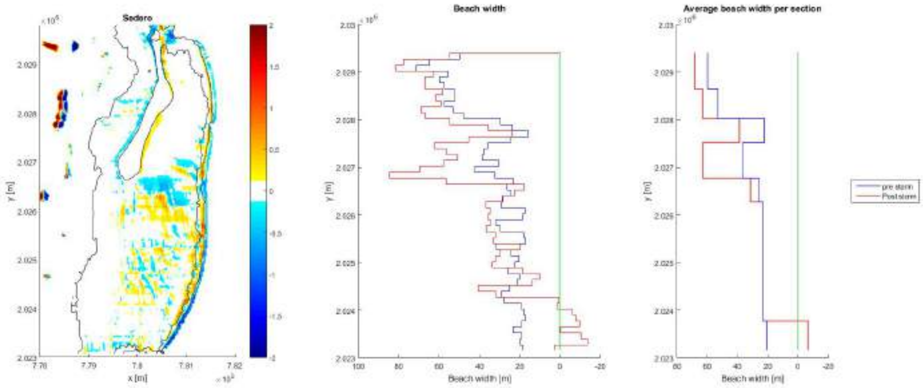

Figure J.31: Cumulative sedimentation/erosion after extreme storm (left) and Coastline retreat after extreme event (right)

Table J.31: Beach width pre and post storm

Area	Breach width pre storm [m]	Beach width post storm [m]	change [%]
1	60	68	99%
2	53	63	146%
3	22	39	74%
4	37	63	72%
5	26	31	23%
6	23	23	0%
7	21	-7	-132%
Average	34	40	40%

J.16.2 Long term sediment loss

Table J.32: Sediment loss

Type of storm	Frequency [years]	Volume loss per storm [m^3]	Volume loss [m^3/y]	
Extreme	1/100	49265	493	
Medium	1/10	20355	2036	
Small	1/5	13711	2742	
			5270	Total erosion [m3/y]
			0.21	Average retreat [m/y]

J.16.3 Sediment pathways

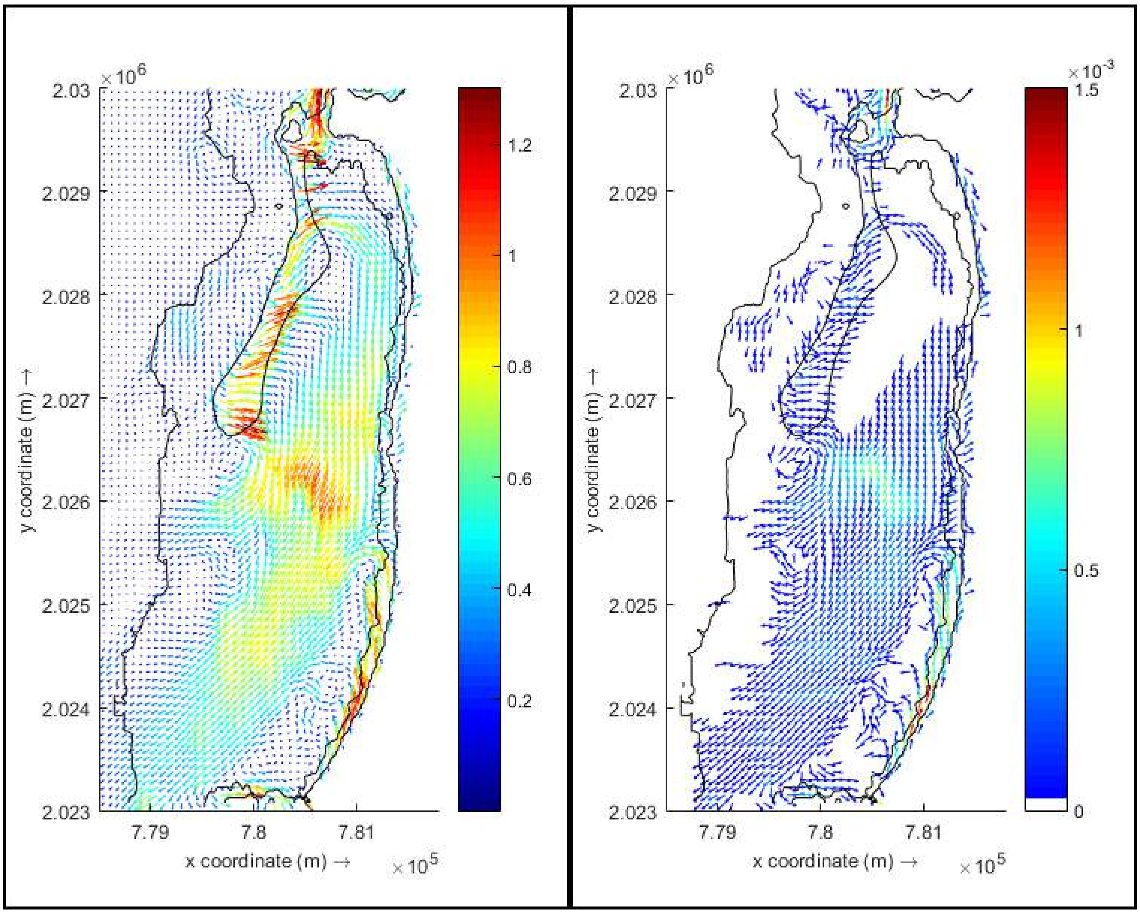

Figure J.32: Eulerian velocities in m/s (Left), Sediment transport integrated over bed load and suspended and for all sediment grains in m/s (Right)