Provision of Consultancy Services for Engineering and Safeguards Assessment of Proposed Interventions in the coastal areas of the Monrovia Metropolitan Area (MMA) in Liberia

Annex 2.B: Vulnerability Sub-assessment

27 JUNE 2019

for

UNDP in Liberia
Environmental Protection Agency
Government of Liberia

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Document	: PART I – Vulnerability Assessment
Status	: Final
Code	: B1804-07-LBR-UNDP-R002
Revision	: 4.0
Date	: June 27nd, 2019

Rev.	Description	Prepared	Approved	Date
1.0	Draft (Interim report)	Staff CDR	D. Heijboer	January 11th, 2019
2.0	Draft (Revised Interim)	Staff CDR	D. Heijboer	February 22nd, 2019
3.0	Draft Final	Staff CDR	D. Heijboer	May 3rd, 2019
4.0	Final	Staff CDR	D. Heijboer	June 27nd, 2019

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0. EXECUTIVE SUMMARY

Protection against the Impacts of Climate Change on the Monrovia Coast

Coastal communities and infrastructure in Monrovia are vulnerable to climate change induced coastal hazards. Up to 2018 over 670 households are reported to have been displaced due to coastal retreat, which is the main coastal hazard causing impact.

The vulnerability to climate change of the Monrovia coastal zone will be discussed extensively in this Vulnerability Report (PART I). At the end of this report, a set of climate resilient strategies is proposed to decrease the vulnerability of the coastal communities. The technical and socio-economic feasibility of these strategies are elaborated in the Feasibility Report (PART II). A third report is dedicated to an Environmental and Social Assessment (PART III) to capture the full context and impact of the project on the Monrovian society. All reports should therefore be read in conjunction.

The Setting and the Threat

Rising sea levels and retreating shorelines are threatening the coastal communities of Monrovia. For several years, valuable land is lost due to structural erosion problems. Combined with an increasing population rate, serious issues start to rise for Liberia's capital city. Besides a continuous loss of space to live, the dense population puts a high pressure on the environment and ecosystems on which the lives of many Liberians depend. Especially the poor communities are highly vulnerable to their rapidly degrading living environment, and their future perspectives are even worse. The effects of climate change are expected to cause an exponential increase in the loss of land and pressure on the indispensable ecosystems on which their livelihood and food security depends.

In this report emphasis is laid on the Kru and Fanti ethnic communities. They are traditional artisanal fisherfolks who derive livelihoods from the coastal waters. Catching the fish that is nurtured by the extensive inland mangrove areas, their way of life has been sustainable until now. It is also sustainable economically, using a low level of technology and locally available resources. However, to ply their trade in small open boats, these communities live on low-lying sheltered beaches which are currently subjected to structural erosion problems. Modelling the impacts of climate change show that without safeguard measures, a large part of these fishing communities will not be able to thrive in the nearby future. This is not only disastrous for these people; it would mean the destruction of key parts of the Monrovian society and economy. The Kru and Fanti fishing communities are part of the broader society and businesses that support the food trade and supply for Monrovia. Their way of live should be preserved, and therefore protected against the effects of climate change.

Socio-economic Context

Monrovia's geography has had a profound effect on its spatial development. The original city grew up on a peninsula between the open Atlantic and the broad, mangrove-filled estuary of the Mesurado river. For the largest part of the Southern beaches of Monrovia, waves are highly energetic for landing open boats for much of the year. However, northward of the Cape of Monrovia, the low-lying land is more sheltered from the Atlantic Ocean. In these sheltered coastal areas, around the mouth of the Mesurado basin and the St Paul river, most of the fishing communities are situated. The low surface elevation means that the beachfront has always been vulnerable to storm waves, still habitable with low cost and unsustainable protection measures albeit reducing the land values. Areas of higher value land are along the peninsula of the original city and in the extensive hinterland beyond the Mesurado estuary.

Liberia's society is still recovering from the civil wars that lasted from 1989 to 2003. The population is expanding at a rate of about three percent which, with the wartime disruption, means that there is a large youth element. Monrovia's population was also greatly increased by the internal migration of people displaced in rural areas during the civil wars, such that its development was not properly planned but created at a time of national crisis. The economy is also recovering, having been hampered additionally by an epidemic of Ebola virus in 2014. Formal jobs remain in short supply, and Monrovia consequently has a large informal sector, dominated by small traders and service providers.

The Changing Environment

The impacts of global climate change need to be seen in the context of a country that, by the time that the second civil war ended in 2003, had a relative low carbon footprint due to the extensive damage to its infrastructure and economy. Extensive logging of Liberia's forests occurred through the wars but since then efforts have been made to certify that all timber exports are sustainable. The country is still home to 40 percent of the remaining Upper Guinea Rain Forest that once stretched from Senegal to Cameroon. Liberia has therefore contributed little to the drivers of climate change at a global level.

The report shows how some areas of Liberia's coast are marginal at present in terms of vulnerability. The seaboard on the central Atlantic is one of high energy swell waves and east-to-west longshore drift. Coastal retreat has occurred along most densely populated parts of the coastline of Monrovia coastline, which is further clarified below, resulting in the relocation of people.

Future climate-related impacts change the environment altogether. Even the most optimistic projection of sea level rise shows that the low-lying communities behind the fish landing beaches become critically vulnerable. Sea level rise projections do not show extensively high values around Liberia (probably 0.5 to 0.75 metre by 2100), however the impact on this currently marginal location can be very large. This change will be exacerbated significantly by the stronger waves combined with more intense storms caused by small rises in global temperatures.

Overview of Vulnerability

All modelling of the potential impacts of climate change point to one conclusion: without safeguard measures the existence of the coastal communities of Monrovia cannot continue. The fishing communities will disintegrate as the climate-induced changes force them off the shores. They will settle inland haphazardly, as further land losses, higher wave impact and fiercer storms make climate change impacts a reality. Displaced from their traditional livelihoods and impoverished, they will seek whatever alternatives can be found. But the fishery will die.

Project Rationale

The report provides a detailed rationale for the project. This describes the situation regarding the resilience of the Monrovia coastal and fishing communities, and the fragility of the location in which they are based in the face of rising sea level and increased (storm) wave energy (the main impacts of climate change affecting this coast). It also explains how the fisheries industry uses very low levels of energy and how its longevity would be positive in terms of limiting the drivers of climate change. It forms the basis for the livelihoods that underpin much of the capital city's economy.

The approach to resolution represents a paradigm shift in the management of coastal areas in Liberia. The project is to be based on socio-economic and institutional reforms and strategic actions, rather than on purely engineering-based model. Given that the effects of climate change are due to cause significantly greater impacts on the coastal communities and the wider urban society, a significantly different approach is required.

The solutions proposed to be implemented by the project, focus on measures that will ensure continuation of the existing long-standing, low energy, biologically and economically sustainable fishery that helps to ensure Monrovia's food security. To do this, it will employ eco-based solutions that include both soft engineering measures and capacity development initiatives. Resilience to the impacts of climate change will be the outcome.

Socio-economic Analysis

For the period of 1990 to 2017, the GDP of Liberia grew at an average pace of about 5 percent (GDP in current prices). In 2017, real GDP growth was 2.5 percent. The growth was mainly driven by the mining sector (gold and iron ore). Iron ore exports almost tripled between 2012 and 2014, albeit from a low base as the industry was restored after the civil wars. By the end of 2014, iron ore represented over 62 percent of Liberia's total exports. Liberia ranks 177th out of 188 countries in the World Bank's Human Development Index. Although poverty has declined since 2007, it remains high overall.

The study area consists of a variety of communities. Population has been growing in Monrovia at about 3 percent per year, also due to rural-urban migration. Especially in the West Point area and New Kru Town, the communities are poor and their livelihoods depend on fisheries, shops and open markets. The fisheries sector is an important provider of food in Liberia. Fish is the second most purchased food commodity and provides approximately 15 percent of total animal protein supply. About 60 percent of persons active in the sector are women, especially in the fields of marketing and distribution. The beaches of the project's target coastal sections (especially section 2 "New Kru Town" and section 3 "West Point") serve as important landing sites for the canoes of the Kru and Fanti fishing communities. The Atlantic shore (coastal sections 4 and 5) is more composed of middle-class inhabitants and formal economic activities (hotels, shops, restaurants etc.).

Climate Change

Over the last decade the most pronounced environmental threat at the Monrovia coast has been coastal retreat. Along large stretches significant coastal retreat has took place leading to loss of land, valuable assets and recreational beaches.

The coastal stretches with the worst observed coastal retreat were section 2 (New Kru Town) and section 3 (West Point). Figure 0-1 shows an example of the coastal retreat in West Point over the last decade, where the coastline position in 2008 (left, red) and 2018 (right, blue) is shown.

Figure 0-1: Observed coastal retreat at West Point, showing the coastline in 2008 (red) and 2018 (blue)

Based on this study it has become apparent that the observed coastal retreat has been caused by natural processes and has significant climate change attribution: it has been and will be amplified due to climate change. More important, since the effect of climate change will accelerate during the next decades, the coastal retreat and subsequent damage is expected to worsen significantly over the coming decades (up to 2 times in 2100). Both from observations and projections for the future, it is clear that section 2 and 3 suffered and will suffer the most from coastal retreat.

The basis for assessing the climate change impact has been the fifth assessment report of International Panel on Climate Change (IPCC - AR5 2014). The most and least conservative climate change scenario of IPCC has been used: RCP 4.5 and RCP 8.5, in order to show the bounds of the climate change effects.

These scenarios include all the relevant climate drivers (e.g. global warming and increase of radiation) to assess the climate change impact.
In this area coastal retreat is caused by:

- Shift in equilibrium profile due to Sea Level Rise ('Bruun Effect')
- Chronical erosion due to sediment deficit[1] caused by long-shore sediment transport and Sediment exchange with rivers and estuaries
- Storm Erosion

These processes are all forced by are a) sea level rise, b) (changing) wave impact and c) change in sediment exchange of rivers and estuaries (forced by change in run-off, temperature and sea level rise) . All these processes are prone to climate change and have been included in this assessment.
The outcome of state of the art models, such as Global Circulation Models (GCM's) and Global wave models are used to assess the effect of climate change on waves and the sediment exchange of rivers and estuaries in the study area. Based on the analysis of the observed sea level rise and wave climate over the last two decades it is evident that climate change has impact and that the projected climate change scenarios are in line with the present trends:

- The sea level rise is very much comparable with the projected sea level rise (see Figure 0-2);
- Waves, especially extreme waves, are getting higher. Wave are getting longer and the wave direction is changing;
- Storms are getting more frequent and are increasing in magnitude;
- Sediment demand ('sediment hunger'[2]) of the Mesurado basin is increasing.

[1] Misbalance of sand in a specific coastal cell: a deficit or lack of sediment (sand) will ultimately lead to erosion and subsequent coastal retreat.
[2] Due to rise of mean sea level the bed level of the Mesurado Basin will adapt, i.e. increase of accommodation space and hence its demand for sediment will increase. This means that sediment will be imported into the Mesurado basin. This 'sediment hunger', will increase with accelerating rising sea levels.

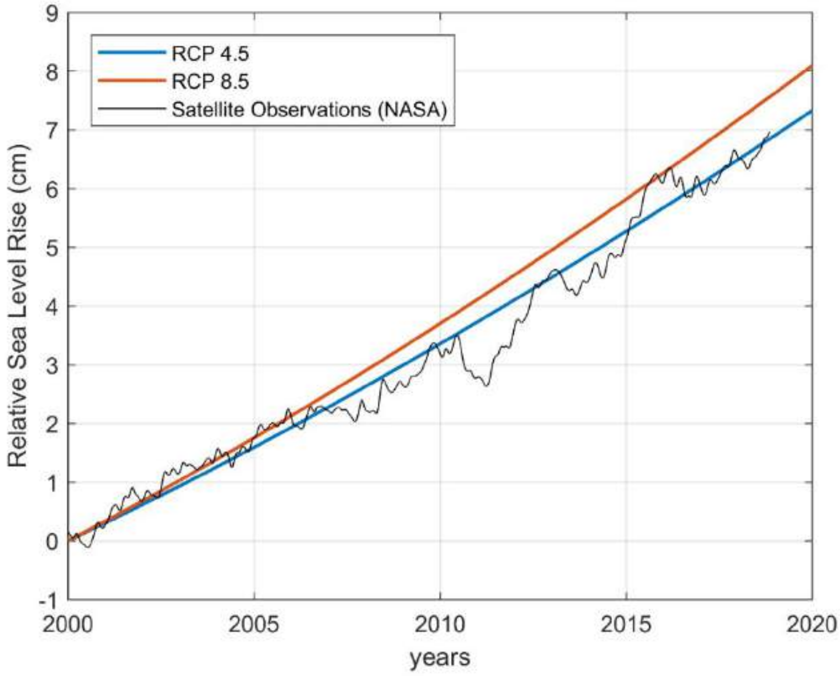


Figure 0-2: Comparison between projected sea level rise and observed sea level rise over the last decades[3]

The above effects have been included in an analysis of the total past, present and future expected coastal retreat of each section. This has resulted in a presentation of the average expected coastal retreat values with and without the effect of climate change along the different sections of the study area. Figure 0-3 provides the structural coastal retreat with climate change, based on the scenario RCP 8.5.

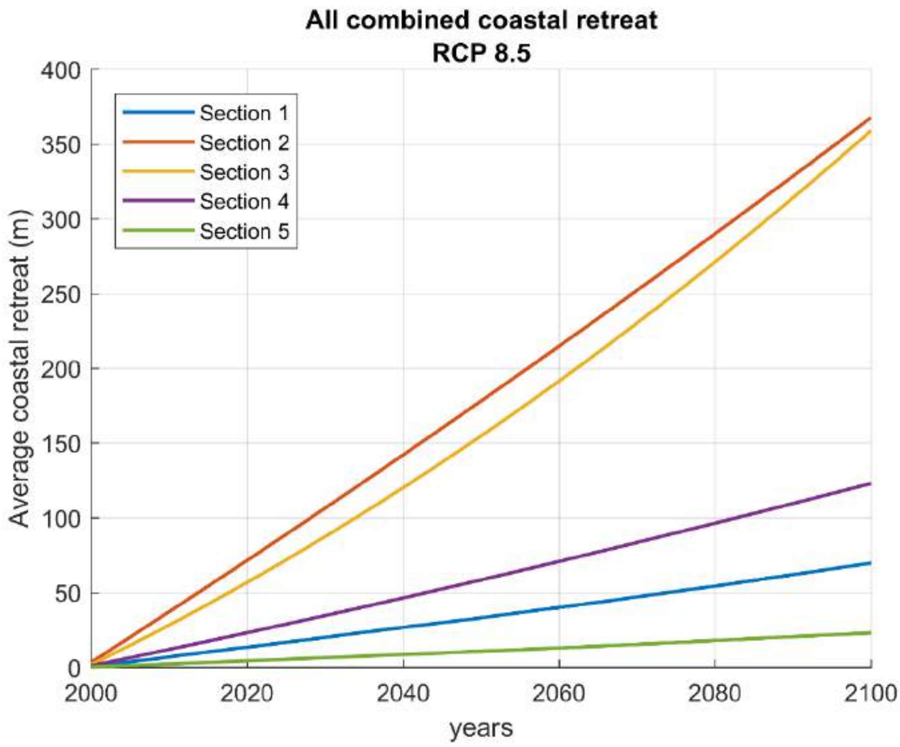


Figure 0-3: Average Coastal retreat of each section for RCP 8.5

[3] NASA Goddard Space Flight Center

It is clear that the section 2 and 3 show both the worst coastal retreat. These values have been compared to the observed average coastal retreat between 2008 and 2018 and are shown in the table below. It is clear that the observed coastal retreat is very much in line with the calculated coastal retreat. Especially the calculated values including the effect of climate change are in line with the observations, which substantiates that the observed coastal retreat is also driven by climate change.

Table 0-1: Observed and projected coastal retreat at each section between 2008 and 2018

	Average coastal retreat 2008-2018 (m)			
	Observed	No Climate Change	RCP 4.5	RCP 8.5
Section 1	6.5	5.4	6.6	6.8
Section 2	37.3	33.0	34.2	34.3
Section 3	32.5	17.1	28.2	28.2
Section 4	9.3	10.0	11.0	11.1
Section 5	2.9	1.4	2.4	2.1

Climate change attribution

Climate change worsens the coastal retreat significantly as can also be observed in the table below where the additional structural coastal retreat due to climate change is shown for the coming decades. Especially section 3 (West Point) shows significant additional coastal retreat due to climate change, which can be declared by the increasing sand hunger[2] of the Mesurado basin due to Sea Level Rise.

Table 0-2: Additional structural coastal retreat due to climate change

	Additional structural coastal retreat due to climate change			
Section	2020	2050	2070	2100
1	18.0%	19.7%	22.5%	27.5%
2	3.2%	5.8%	7.5%	10.3%
3	58.4%	77.6%	89.9%	108.0%
4	9.7%	14.2%	17.2%	21.4%
5	48.7%	52.8%	57.7%	66.3%

Storm erosion

Storm erosion is treated separately as it should be considered as *additional* coastal retreat after an extreme event with a specific return period (probability). As storm conditions occur more frequent and get more intense the storm erosion increases due to climate change. The table below shows the expected additional storm erosion due to climate change after an extreme event with a return period of 100 years. Also here it is clear that especially section 3 (West Point) shows the highest climate change attribution with respect to storm erosion.

Table 0-3: Additional storm erosion due to climate change

	Additional storm erosion due to climate change		
Section	2050	2070	2100
1	9.0%	13.6%	23.8%
2	4.0%	10.7%	20.7%
3	10.9%	19.5%	26.1%
4	9.6%	12.2%	22.7%
5	7.1%	8.6%	18.7%

Vulnerability Analysis

In this report the impacts of the hazards on coastal retreat are shown for coastal retreat and additional storm erosion. Impacts on coastal retreat are shown for the high climate change scenario (RCP 8.5), given the current shoreline and assets in Monrovia. As an example, on the maps of Figure 0-4 and Figure 0-5, the impacts for section 2 and 3 are shown. The coastal retreat due to erosion is expected to be largest in 2050 in coastal sections 2 (New Kru Town) and 3 (West Point). Storm erosion affects coastal sections 2, 3 and 4 most heavily. Sections 2, 3 and 4 can be regarded as the main hotspots in terms of vulnerability with respect to all hazards.

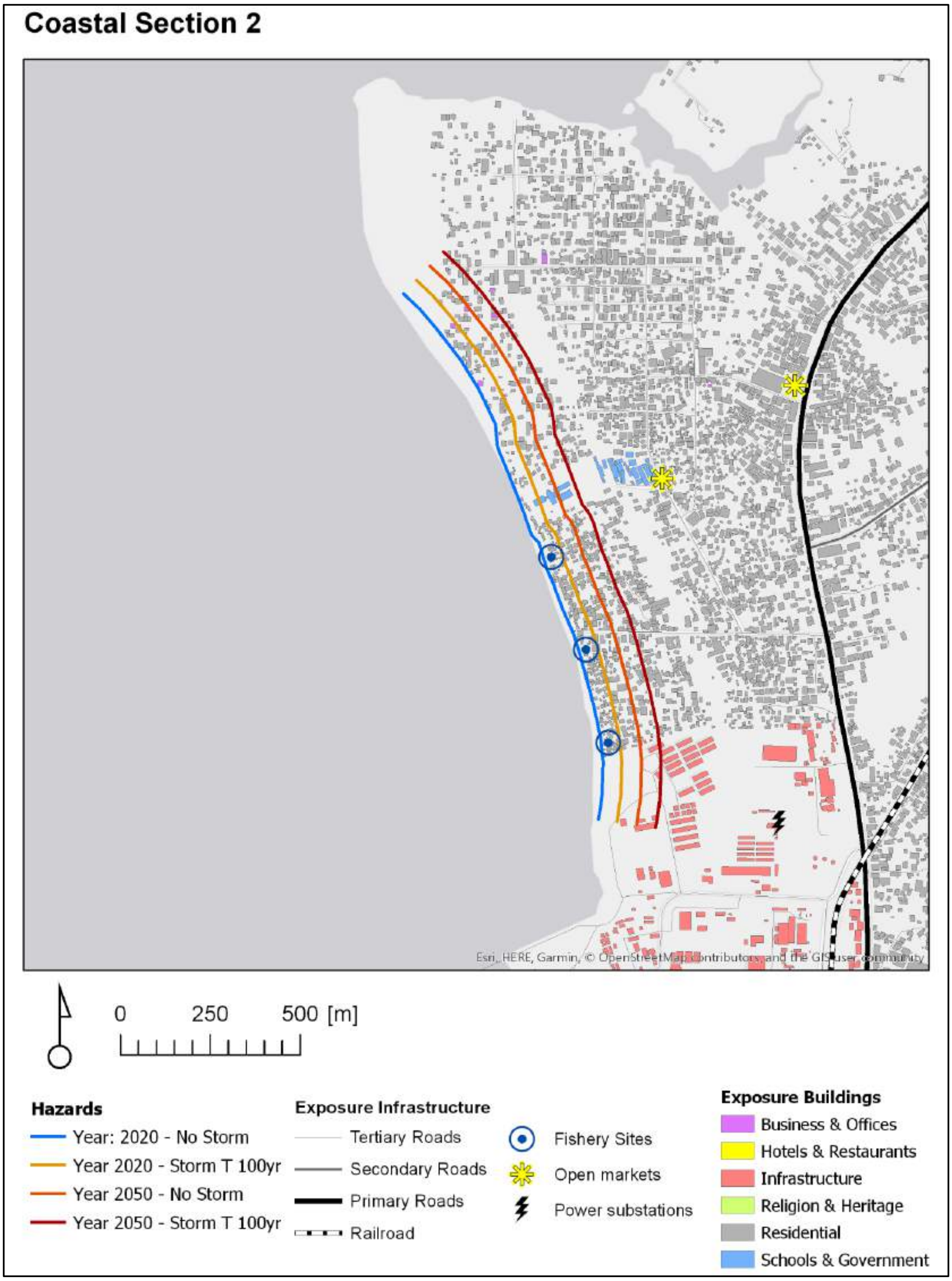


Figure 0-4: Vulnerability map Coastal section 2

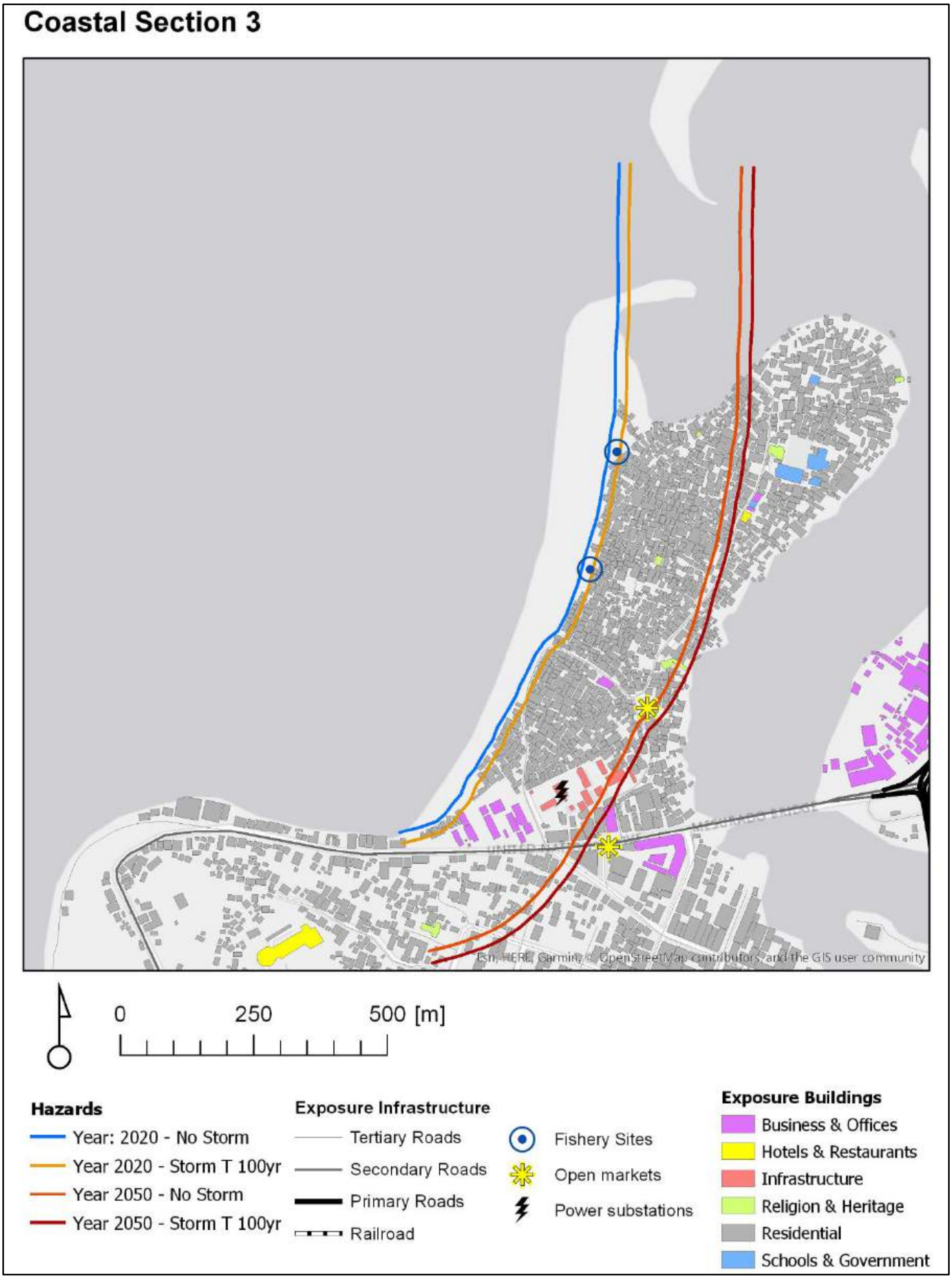


Figure 0-5: Vulnerability map Coastal section 3

Different type of assets and critical infrastructure are vulnerable to the hazards. In particular, residential buildings, informal economic activities (shops etc.), fishing sites, roads and a power substation are exposed and vulnerable. Apart from this, the beaches – which have a significant recreational value for the inhabitants of Monrovia – will be lost by 2050 in the high climate change scenario.

Damage Assessment

The tangible estimated direct and indirect damage is highest in sections 2 and 3 (in the year 2050) and more moderate in section 4. In New Kru Town and West Point respectively, around 1100 and 900 dwellings (6000 and 5500 people) are at risk in 2050 due to coastal retreat. These communities are relatively poor and dependant on the ocean and beaches in sections 2 and 3. Therefore the people's livelihoods are very seriously at risk for these two coastal sections. In sections 1, 4 and 5 there might be significant lost opportunities for urban and leisure development.

In below table the vulnerability is presented for the five coastal sections. In terms of damage, damage costs of the hazards are highest in the sections 2,3 and 4. The livelihoods of communities (fisheries, others) are especially at risk in West Point and New Kru town. Regarding tangible damage costs due to coastal retreat and storm erosion the results are presented in terms of present values of damage (2020-2100) discounted to the year 2019.

Vulnerability and damage intensity assessment coastal sections, Present value 2020-2100 in million USD (high climate change IPPC 8.5, optimistic socio-economic scenario)

Damage	**Section 1**	**Section 2**	**Section 3**	**Section 4**	**Section 5**
Tangible direct & indirect damage (assets, economic) Present Value 2020-2100 in million USD in 2019	***3,1***	***30,6***	***47,6***	***28,0***	***16,6***
Intangible damage (health, recreation)					
Livelihood coastal communities (fisheries, etc)					
Opportunities leisure & real estate					
Total damage					

Note: Orange implies small damage to assets and communities from coastal erosion and storms. blue = moderate damage by erosion or storm erosion. Red = large damage of assets and communities affected by erosion & storm erosion.

Strategies towards Climate Resilient Coastal Communities

For this project the "building with nature" principles are followed, rather than looking into hard engineering solutions only. With this integral approach, socio-economic, environmental and technical measures are combined into climate resilient strategies. The main objective of these strategies is to:

- Reduce the vulnerability of Monrovia's coastal communities to climate change;
- Protect and enhance their livelihoods;
- Safeguard the food security;
- Enhance the local ecosystems.

As further coastal retreat is considered unacceptable, the focus is laid to protect and adapt the coastal communities and their environment towards a prosperous future. Based on feasibility aspects, a first selection is made from a long list of all kind of adaptive, ecosystem-based, nature-based, and technical solutions. A second selection round to converge towards climate resilient strategies was done by means of stakeholder consultation (MCA-workshop), in which lots of information and feedback was gathered from all relevant stakeholders of this project. This selection process is visualised by Figure 0-6.

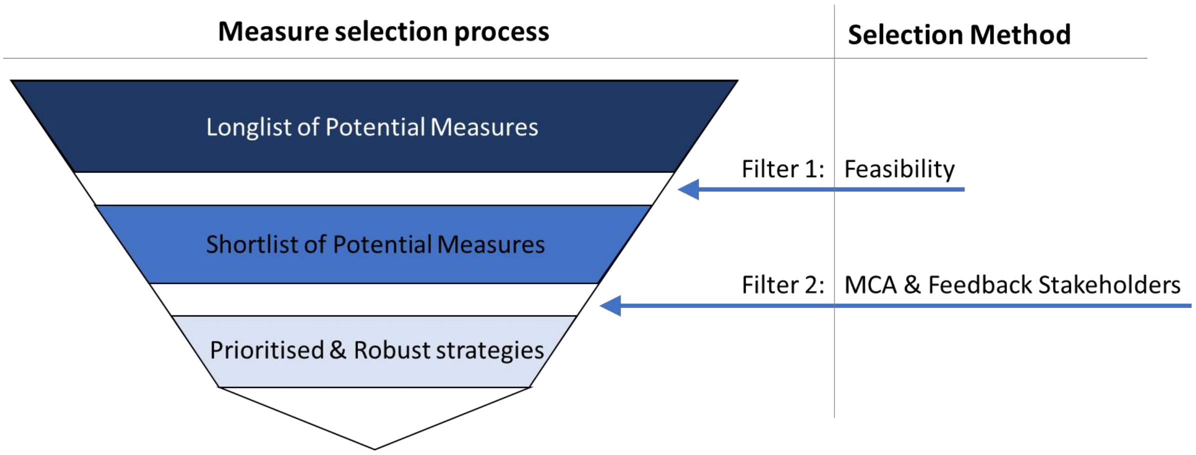


Figure 0-6: Schematization of the measure selection process

Finally a set of adaptive and protective measures has been selected most suitable for the project. Besides adaptive measures on a community-based level, also broader institutional and governmental capacity building measures are proposed. Most adaptive measures are therefore not linked or attributed to certain coastal sections. In general the relevant adaptive measures can be caught by three main strategies:

1) Strengthening the Governance
2) Enhancement of Livelihoods and the Environment
3) Improving Infrastructures

With the proposed adaptive measures, a foundation is laid to construct and maintain sustainable coastal protection measures. As the Monrovian beaches are subjected to a high energy wave climate, there is no opportunity that soft ecosystem-based measures only will result in sustainable solutions against the effects of climate change. Therefore soft protection measures are combined with more robust protective structures in the proposed designs. Of the more robust protective measures, revetments and groynes combined with beach nourishments are considered best applicable.

The protective measures are location specific and proposed for the most vulnerable coastal sections 2, 3 and 4 only. For section 2 (New Kru town) the ongoing construction of a revetment created a precondition for further revetments. For section 4 the large beach area with extensive use for social gathering, recreation and fisheries favoured the groyne with beach widening as preferred alternative. For section 3 (West Point) the both types of protective alternatives (groyne + beach widening or revetment) remained feasible from a technical, socio-economic and safety perspective.

The proposed adaptive and protective measures together form the strategy towards a climate resilient future of the coastal communities of the Monrovian Metropolitan Area. The synergy between these two type of measures will result in the preservation and enhancement of their livelihoods, food security and surrounding ecosystems. The intention therefore is that both types of measures must go hand in hand with each other.

The climate resilient strategies are further elaborated in the Feasibility Report (Part II), in which the emphasis is laid on the technical, economic and social implementation of the proposed measures.

1. RATIONALE FOR THE PROJECT: BETWEEN RISING SEA AND THE GROWING CITY

Climate change has been generating higher sea levels since at least the start of 20th century and has been accelerating over the years. More intense storm-driven waves are pushing the marginal shorelines of the Monrovia Metropolitan Area out of equilibrium. This will lead to the disintegration of a number of poor communities that form perhaps 20 percent of the city's population. They include large communities of artisanal fisherfolk from three main ethnic groups, who utilise the rich inshore fishing grounds of the coast. This fishery is key to the food security of the greater Monrovia area, as well as underpinning the livelihoods of many other people engaged in micro-enterprises. The fishery is sustainable, very low energy and resilient. The position of the fishing communities on the low-lying shores is essential to the operation of this livelihood, as their canoes are launched from the beaches and the catches are marketed close by in the city. However, the rising sea levels, with high tides becoming ever higher, coupled with storm waves of increasing intensity, is leading to coastal retreat, the collapsing of buildings and housing, salt intrusion into wells, and pollution from disrupted sewerage and city drains. There will be consequent impacts on small businesses and markets as people are progressively forced to move elsewhere. Food security will deteriorate markedly as the fishery collapses because the fishermen are no longer there.

Yet, as long as it can be continued from the beaches, this fishery is a resilient industry that is minimalist in its contributions to the drivers of climate change. Ensuring its survival is also key to the maintenance of a sustainable food source for a large city, through methods that are very low in carbon emissions. It lies at each end of the climate change spectrum: it barely contributes to the causes of global warming, but it is a victim of its growing effects through rising sea level and intensifying storms. Keeping the industry operational on a low carbon basis requires a number of adaptations in the ways that the industry itself and the land of the coastal fringe are managed, as well as providing protection against the threat of increased inundation.

The project proposes solutions based on ecologically sound control measures and management interventions. These use nature-based techniques to control the encroaching sea, with soft engineering measures added where necessary. A key aspect of the project will be to protect the low-lying land occupied by the fisherfolk and their neighbouring communities. Other actions will address the health of the mangroves, making space for their survival as sea level rises. These management-based activities will focus on improving land use planning and reducing encroachment into the large, highly biodiverse mangrove-filled inlets close to Monrovia. Coastal management capacity will be expanded to encompass these inland but tidal zones.. Ensuring the long term health of the mangroves, including its resilience to the impacts of climate change, is itself a nature-based solution to low energy food security, since these areas are the breeding grounds for the inshore fish and crustaceans that keep the artisanal fishery both highly productive and sustainable. Hence this strategy is central to sustaining the fishery.

Liberia's Coastal Fishery

The Liberian coastal waters are a dynamic tropical marine environment. The inner zone of six nautical miles is reserved for artisanal fishing. Evidence suggests that this has been successful all along the Liberian coast, in that fish landings are sustained while surveys show a broad marine biodiversity, including a number of threatened species of fish, marine turtles and marine mammals. Coral reefs are scarce because of the coastal bathymetry, but beds of sea grass are found. Extensive mangroves in inlets, estuaries and lagoons along the low-lying coast provide the spawning grounds and nurseries for many nearshore species.

Fishing Communities in Liberia

Two main ethnic groups dominate the artisanal fishing in Liberian waters. They live in neighbouring communities scattered along the coast and complement each other through different approaches and different targeted species. Most numerous are the Kru, a people who originated in the Maryland area of south-eastern Liberia and who have a long tradition of dwelling on the coast and deriving their livelihoods largely from fishing. They have a reputation for fiercely defending their independence. Kru fishermen mostly use non-motorised wooden canoes (see Figure 1-1) either alone or in small numbers, using hook-and-line and bottom-set net techniques. The other group are the Fanti, originating from Ghana but naturalised in a number of locations on the Liberian coast. Fanti fishing boats are typically much longer and broader canoe-shaped vessels (see Figure 1-2) than those of the Kru, but still open in plan and built of wood, powered by outboard motors and crewed by eight to twenty people. These fishermen use drift nets further offshore to catch the shoaling smaller fish like sardines and flying fish.

In New Kru Town, there is also a community of Popoe (or Popoh) fishing people, whose ancestry derives from Benin and Togo. This group tends to use beach seine nets for small shoaling fish.

Figure 1-1: Kru fishing canoes

The low energy artisanal fishing industry requires its workers to live close to their launching sites, which are beaches in relatively sheltered locations. The main extent of the generally south-facing coast of Liberia is exposed to a dominant regime of strong swell waves that approach from the south-south-west. This leads to a high energy foreshore where steep beaches of coarse sand develop. These extensive locations are too exposed for boat landings, so fishing communities have settled on beaches where the coastline deviates from the general east-west trend. Such places are found notably at the locations where the cities of Greenville, Buchanan and Monrovia lie – themselves located in the same places because of the essential requirement of safe anchorages and landing sites for the early settlers in the first half of the nineteenth century.

Figure 1-2: A typical Fanti fishing boat.

Monrovia's Fishing Communities

The city of Monrovia has developed around a rocky peninsular close to the first settlers' landing site of Providence Island in the sheltered estuary of the Mesurado River. The layout is shown in Figure 1-3. This estuary forms a large tidal basin occupied by extensive mangrove forest, protected from the ocean by the rocky and sandy coastal peninsula to the south. The outlet of the Mesurado is westwards, where the coast trends north and then north-west, beyond the mouth of the St. Paul River that enters the sea about 5 km from the end of the peninsula at the rocky headland of Mamba Point.

Within this setting, the relatively sheltered beaches between Mamba Point and the mouth of the St. Paul River offer suitable locations for the safe landing of the wooden canoes used by the artisanal fishermen. As a result, both Kru and Fanti people live in West Point, which is located on a large sand spit on the western fringe of the Mesurado estuary. A little further north, beyond the Monrovia Freeport that was opened in 1948, lies New Kru Town, forming a large community. A smaller Kru village is also situated further north, at Seesee Beach, beyond the mouth of the St Paul; and another is at Bernard Beach, about 7 km east of Mamba Point, where the coastal form provides a relatively gentle beach on the exposed Atlantic shoreline. The two main locations have been used by these communities for a long period, and pre-date the expansion of the city of Monrovia beyond its original position on the peninsula to the south. Over the last fifty years, Monrovia has grown to occupy the land all around the mangrove-filled basin of the Mesurado estuary (see Figure 1-3), to the extent that there is no longer any waterfront land left undeveloped. Meanwhile, the two big fishing communities have continued to live immediately adjacent to the beaches on which their canoes are drawn up, or on the shore on the eastern side of West Point, where the larger Fanti boats are anchored.

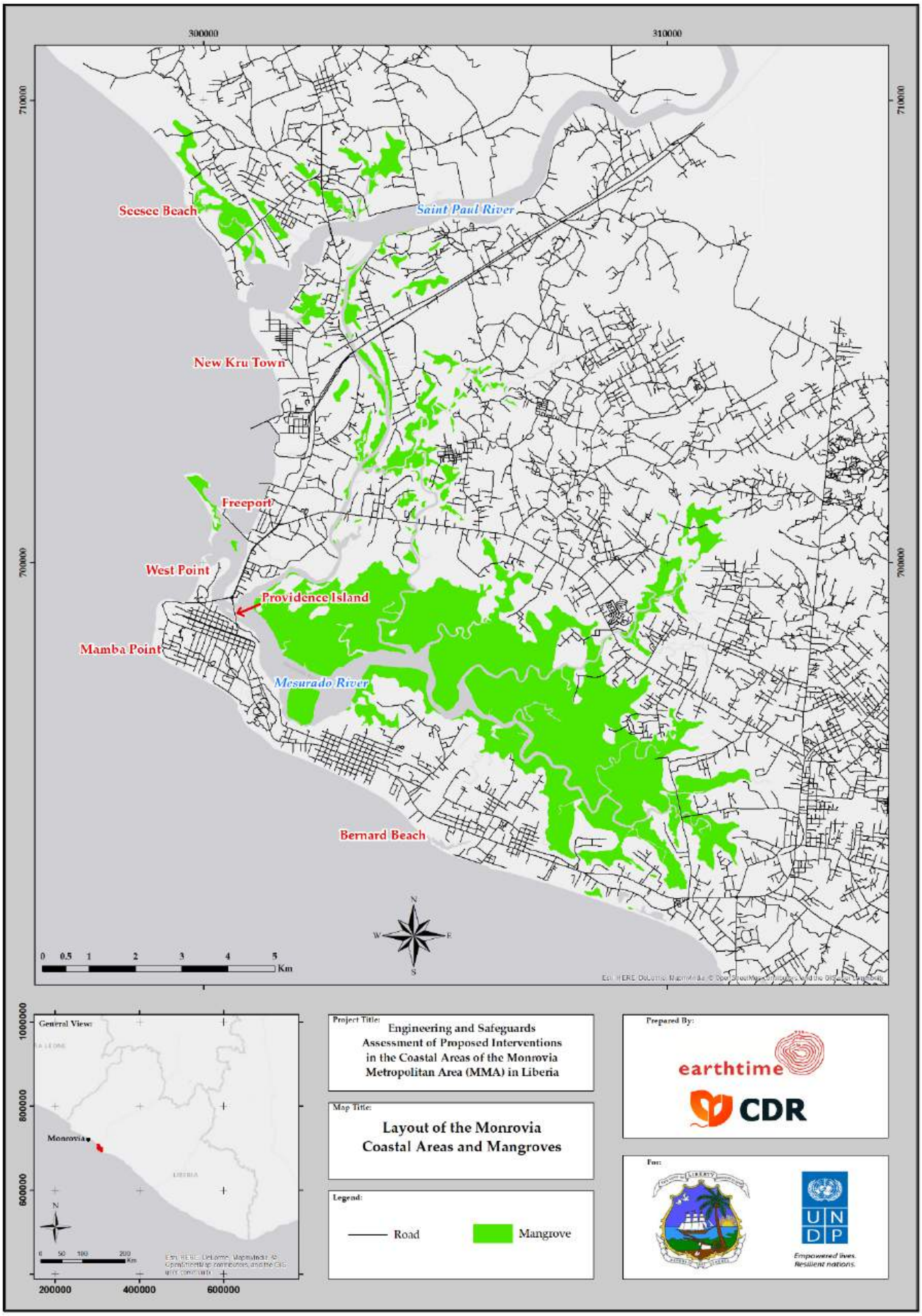


Figure 1-3: Layout of Monrovia, showing the locations mentioned in the text.

Beaches in the City
Although the beaches used for the fish landings are relatively sheltered and have clearly been home to a sustainable livelihood for numerous people (see below), it is now clear that the shoreline is out of its equilibrium which is aggravated by climate change. The instability of the area, particularly the shorelines of West Point and New Kru Town, is evident from the studies that the project consultants have undertaken using site investigations and historical data. Nevertheless, it is clear that they are locations for the basis of the current fishery, since low-resource measures used by the communities themselves (see Figure 1-4), added to by occasional government support such as the stone pitching used in 2018 at New Kru Town (see Figure 1-5), are have maintained a fragile security albeit unsustainable.

Beaches are not only important for economic livelihoods, but they are also part of the social capital of the city's people. This is especially true for the poorer communities, where people live on small, densely packed plots. Beaches act as the main recreational site for a significant proportion of the population. Every urban beach in West Africa acts as a football pitch, but they are also the sites for most large community events. Behind the beaches, among the fisherfolk's houses and fish sorting areas, are numerous small service industries, particularly those selling food and drink. Liberia's markets are thronged with small traders, often carrying their wares in wheelbarrows or in large plastic bowls on their heads. These micro-enterprises are highly mobile and migrate through the day between market, streets and beaches, following their customers. Recreation on the beach therefore comes with its own economic livelihoods capital.

Figure 1-4: Low cost wave protection on dwellings at West Point.,.

Figure 1-5: Stone pitching of the foreshore at New Kru Town in 2018. Although stated as a revetment, resource constraints are such that this structure lacks the characteristics of a genuine revetment as normally defined in civil engineering. Nevertheless, it is adequate to protect the settlement for at least some years under present sea conditions.

Climate Change Impacts

It has become evident, based on the observed accelerating sea level rise that the projected change in sea level has become real. Although the rise to date might look marginal (approximately 7 cm since 2000, see Figure 1-6), the effects of climate change are already notable. Waves have intensified and more intense and frequent storms arise, leading to an increase of morphological activity and coastal retreat. Due to changes in run-off, temperature and sea level rise the sediment budget of the nearshore system will become out of balance, leading to an increase of sediment deficit and coastal retreat. Based on the projections it is clear that even for the most optimistic projection (i.e. currently the IPCC's Representative Concentration Pathway, RCP 4.5 scenario) these effects are very likely to increase, which will ultimately impact the coastline of Monrovia significantly and will worsen over time. This means that the fragility of the fish landing beach locations, existing in an equilibrium that can only be described as marginal, are highly vulnerable due to climate change. All modelling of the potential impacts of climate change point to one conclusion: the existence of the communities on the beaches and adjacent low-lying land of Monrovia cannot continue for more than a few decades at most; and even that will come with increasing damage, and destruction of boats and houses during rougher periods and higher tides.

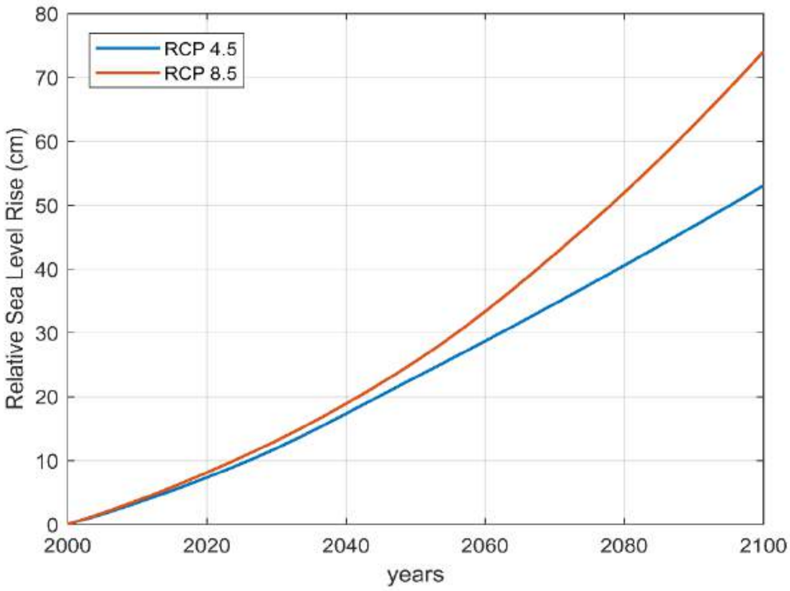


Figure 1-6: Past and projected sea level rise for the least and most optimistic scenario (RCP 8.5 and 4.5 respectively)

Livelihoods on the Monrovia Coast

According to data provided by the National Fisheries and Aquaculture Authority (NFAA) in January 2019, West Point Beach was home to 387 fishing boats, employing approximately 1,808 fishermen. Point Four Beach at New Kru Town had 185 boats and about 423 fishermen. NFAA considers that there are on average three fish mongers (receivers, processors and marketers of fish) for every fisherman. This suggests perhaps 5,425 and 1,275 respectively in the two communities, or around 6,700 in total. Given the average household size of a little over five persons, it can be assumed that, with some 8,900 people employed in the fishery, altogether around 44,500 people could benefit directly. However, there is known to be overlap (for example where fishermen's wives are among the fish mongers), and the total populations of New Kru Town and West Point are estimated by the ward chairmen to total around 46,000 people. There are other livelihoods in the communities, but it is clear that the fishery supports the majority of people directly in these communities. Estimates of the total catches are difficult to fix accurately, but it is clear that there is a strong informal economy driven by the fish landings. Surveys showed that there are also numerous other livelihoods thriving, that are related to the presence of the fisheries and fishing communities, and indirectly owing to them. These cover a wide range of small scale manufacturing and service enterprises in the same vulnerable zones, and will survive or disintegrate along with the fisherfolk.

There is a strong gender pattern in the Liberian artisanal fisheries. Fishermen are almost exclusively male, while fish mongering is dominated by women. This is an important fact in a country where gender equality is not assured, especially as in this case the distribution of labour means that it is the women who are placed in the most powerful economic position as the receivers of revenue at the point of sale. Consequent on this is the fact that the fishery supports the communities in a relatively equitable manner.

The West Point and New Kru Town fisheries have proven their resilience and sustainability. Through the political turmoil and disruption of the civil wars between 1980 and 2003, the industry kept functioning because it was self-sufficient and did not require the external inputs that caused many secondary industries to stagnate or collapse. The survival of the city through this period is owing to a considerable extent on the food supply from the fishery.

Food Security

Liberia pursues a pro-poor policy as described in the Liberia Rising – National Vision 2030. This follows five pillars, which include human development and economic transformation. Food security is a subset of one of the pillars. While most of this is focussed on agriculture, it is expected that the fisheries subsector will focus on community-based resource management to improve catches in a sustainable way: artisanal fishing is therefore embedded in the national strategy for food security.

The fact that climate variability and change have an impact on food production is well recognised in relation to agrarian food sources, frequently with a side reference to fisheries. The International Panel on Climate Change (IPCC) identified three principal components of food security (in the Fourth Assessment Report of Working Group 2, Chapter 9: Africa; 2007):

- the *availability* of food (through the market and through own production);
- adequate purchasing and/or relational power to acquire or *access* food;
- the acquisition of sufficient nutrients from the available food, which is influenced by the ability to digest and absorb *nutrients* necessary for human health, access to safe drinking water, environmental hygiene and the nutritional content of the food itself.

In the context of these components, the linkages with climate change in Africa were identified. Again, that focussed on terrestrial agriculture with only a small mention of fisheries. However, an attempt is made in Figure 1-7 to define the food security - climate change linkages in relation to inshore fisheries food sources, following the model used in the IPCC report. While this provides an indicative guide, the dearth of hard evidence of Liberian economic, health and nutrition issues to support the assumptions means that they largely still remain unproven. Gaining the data to prove the extent of each element would require substantial research.

Despite uncertainties, the rationale is clear that there is a need to provide support to food security in the targeted coastal communities, and the wider society of Monrovia. This must be achieved both by ensuring that the mass food source can be sustained without contributing significantly to the drivers of climate change, as well as through direct measures to mitigate the effects of climate change. With the linkages established in general terms in Figure 1-7, and explained in specific terms for the Monrovia fishery, there is an additional case for intervention by the project.

This rationale provides for support to food security in the targeted coastal communities, and the wider society of Monrovia, through direct measures to mitigate the effects of climate change. With the linkage clearly established in general terms in Figure 1-7, and explained in specific terms for the Monrovia fisheries, there is an additional case for intervention by the project.

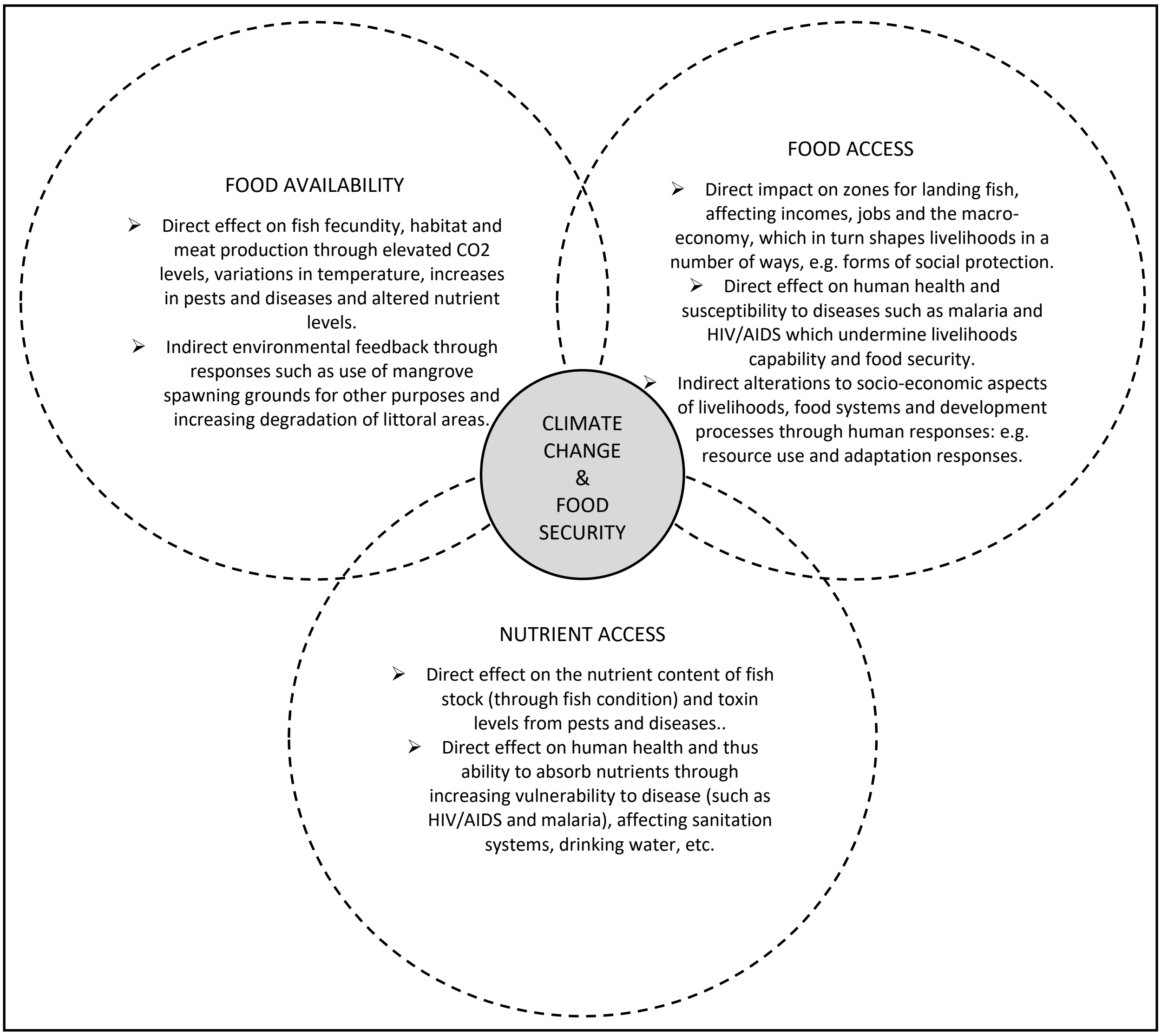


Figure 1-7: Linkages identified between climate change in Africa and three major components of food security. Adapted for the Liberia inshore fisheries subsector from Figure 9.6 in the Fourth Assessment Report (2007) of Working Group 2 of the International Panel on Climate Change. Note, however, that the nature of impacts are frequently still uncertain

Responses to Climate Change

Displacement of the communities backwards into the city is not possible as the sea level rises. This is because there is simply no land available for development behind the beaches (see Figure 1-8). Displacement to other locations is difficult for three main reasons: there are no other suitable landing beaches nearby, on account of the high energy coastal environment and the lack of sheltered shorelines; even if translocating the fishing boats were possible, the processing and marketing of the catches in the current low energy, high employment model would not be possible, since the industry relies on close proximity to the large urban market; and all possible translocation scenarios would lead to a change of practices that would be less energy efficient, more vulnerable to economic forces and less sustainable.

Figure 1-8: A view over West Point, looking towards the south, showing how the fishing communities living in the low-lying area in the foreground are constrained between the sea and the rest of the city behind. The higher ground at the back is the rocky headland *of* Mamba Point that forms the westerly end of the peninsula between the Mesurado estuary and the ocean.

It is most likely, if nothing is done, that the fishing communities will disintegrate as the climate-induced changes force them off the shores. They will settle inland haphazardly, as successive higher tides and fiercer storms make climate change impacts a reality: the initial impacts of this effect can be seen in the central foreground of Figure 1-8, where the shore has retreated in an unprotected location. Displaced from their traditional livelihoods and impoverished, they will seek whatever alternatives can be found. But the fishery is very likely to decline markedly, although it might not die completely. Canoes might be kept in the Mesurado estuary and use motors to cover the greater distances to the fishing grounds and alternative landing sites. Some fishermen might move elsewhere in Liberia to exploit less vulnerable fisheries, but with a resultant need for more processing, storage and transport. There is likely to be an increase in the influx of commercial fishing that is already present nearby, such as the large cold-store ships that come from Senegal with Fanti-style boats to collect catches and export them. Liberians without access to locally caught fish rely on imported frozen fish of low quality. There would be an increase in the consumption of this food that is produced with a far greater carbon footprint.

Around the large tidal inlets of the Mesurado and St Paul estuaries, a different impact will occur. Pressure for land in the greater Monrovia area has led to encroachment into the edges of the mangroves. As Figure 1-9 shows, the distinction between land and sea is not clear when the tide is high during the wet season. It is obvious that rising sea level will flood the lower lying houses more and more frequently, until the occupiers are forced to move. However, if the mangroves are to survive as the major ecological unit that they still represent, they will need to migrate inland as the water deepens; only then will the breeding grounds for the inshore fish species be safeguarded. With so much construction around their periphery, it is difficult to see how this will be allowed to happen without positive action to improve the governance behind the utilisation of land.

Figure 1-9: A view over part of the Mesurado estuary in August 2018. The impacts of heavy rain meeting a high tide show the marginal nature of the encroaching dwellings. Intact mangroves remain extensive in the middle distance

The Way Forward – a New Paradigm

The project proposed in this report, based on this rationale, moves away from the "business-as-usual" model. Up to now, coastal erosion in Liberia has been addressed through the use of standard civil engineering measures (i.e. simple rockfill revetments and small structures made with timber and old tyres). These have worked to a large extent, with effectiveness related to the quality of design and construction. In the investigations that led to the preparation of the project concept and feasibility study, it became clear that the environment is to change significantly with the onset of new effects generated by climate change. The existing response model would deal with these to only a limited extent. Instead, a new approach is required to resolve new problems.

The new paradigm adopted for the project uses a socio-economic and institutional model rather than an engineering-based approach. The first of these aspects is that it focuses on enabling vulnerable poor communities to develop resilience to climate change in ways that do not contribute to it; the second aspect is the way in which it is done, using capacity development and management interventions as far as it is possible to do so. Some of the solutions require physical works, but even these principally use "soft" engineering, with vegetation elements added wherever possible. However, the engineering measures are only employed in the context of better management of coastal resources that ensures continued use of low carbon emission systems, responsibility for which will be developed and shared by local communities and government authorities.

Solutions – the Proposed Project

The project as proposed in this report therefore focusses on measures that will sustain the existing long-standing, low energy, biologically and economically sustainable fishery that helps to ensure Monrovia's food security. To do this, it will employ eco-based solutions that include both capacity development initiatives and soft engineering measures.

The project's strategy is to implement the minimum and most environmentally sensitive measures that are required to ensure the longevity of the Kru and Fanti fishing communities at the West Point and New Kru Town beaches in the heart of metropolitan Monrovia, and the nearby Bernard Beach. With the protection of these communities, there will automatically also be the protection of the wider communities of houses and small businesses. These measures will include the physical protection of the landing beaches and the settlements behind them. This will be achieved using long term, low maintenance structures that ensure security against sea level rise and increased wave energy resulting from climate change. These measures all include the use of green infrastructure or nature-based solutions. Examples are the stabilisation of sediment using mangroves in sheltered areas and the protection of storm wave-breaking areas using bio-engineered slopes that combine community recreational spaces with plant-stabilised surfaces.

Protection and management of the wetlands in the nearby inlets and estuaries, and the crucial carbon stores and fish breeding grounds of the mangroves, will be enhanced through the development of capacity to regulate and beneficiate the quality and integrity of these ecosystems. . This is a key nature-based component of the project, since it will not only ensure that the mangroves continue to act as a carbon sink, but will also improve their ecology as settlement is kept back from the tidal areas.

Additional interventions through the community capacity building elements of the project are expected to include ensuring that the fishing communities maximise social inclusion and continue to use the current, apparently equitable, gender balance in the industry. Improved access to energy will also be promoted, with the project supporting subsidised photo-voltaic systems for lighting and refrigeration (especially for fish-handling), these being the two main uses of electricity in these communities. Fish smoking methods in Liberia use wood biomass inefficiently and unhealthily, with the smokers in particular (who are mostly women) and local communities in general exposed to excessive levels of carbon dioxide and smoke containing polycyclic aromatic hydrocarbons. The project will therefore also support the use of more efficient, low emissions smoking ovens, which have been promoted by a number of UN-supported projects elsewhere in West Africa.

Security of land tenure is a serious concern for many poor communities in Liberia. With the eco-based protection of the coast, the values of land will be raised. Many members of the coastal communities do not have formal title to the land they occupy, having settled there either with customary rights allocated by a traditional Chief, or because of displacement during the civil wars. A component of the coastal management capacity building part of the project will therefore support the government in developing its ability to improve the processes of formal land registration in the low-lying community lands: this is an enabling function on the part of the project, acting as a catalyst by providing government agencies with the tools and knowledge needed to resolve pressing issues that can only be undertaken by a sovereign government.

Outcomes
The anticipated main outcomes of the project will be the assurance of continuity of the Monrovia artisanal fishery through a period of climate change, helping the city to maintain its food security using low energy production. The sustainability of the fishery is demonstrated by its longevity to date. The Kru fishing canoes are wooden, and propelled by sail and paddle, and therefore do not generate greenhouse gases at all. The larger Fanti boats are wooden, with petrol-driven outboard motors that generate greenhouse gases but at a lower level than from larger mechanical trawlers. The processing of catches on the shore is mainly low energy, with most sales happening with 24 hours of landing, and therefore requiring minimal refrigeration or ice production. This benefit is enabled by the landing sites being located within walking distance of the large urban market. These outcomes cannot be attained without addressing both the management of the fishery and the safeguarding of the crucial low-lying land base that allows it to continue as a low carbon emission industry.

Timing
The project is to be set up in 2020 and implemented in the period of 2021 to 2027, with the effects of both the developed capacity and the protection measures designed to last for thirty years – effectively the lifespan of a generation. With greenhouse gas concentrations already significantly raised, the project is timed to meet and mitigate the effects of rising sea level as it occurs after a time lag (as the global oceans warm and expand, enhanced by additional meltwater from the polar ice caps). The project focusses on the parts of Monrovia’s coast which are already affected by marine erosion and are expected to encounter significant coastal retreat. It is expected that, with an increasingly rapid rise in sea level as global warming continues, a measurable impact will occur by the early 2020s, in terms of an ever-increasing loss of beach, and number of structures flooded and damaged.

Failure to implement the project would mean that Monrovia’s fishing communities would be first impoverished and then displaced altogether by the effects of climate change. This will occur as the rising sea level causes the shoreline to retreat at rates that cannot be contained by low input measures as they have been up to now. Structures will be damaged and boats lost on the foreshores, until the communities are forced to move away. With no other available landing beaches, and no unoccupied space behind the beaches, the Kru and Fanti communities will be dispersed far inland, making it impossible to continue fishing and forcing them to seek different livelihood options. With the demand for fish continuing in the city, investors would take the opportunity to bring in industrial fishing boats that use high levels of hydrocarbon-derived energy to replace the wooden canoes. This is likely to result in destabilising fish stocks since it would be a new approach for which the regulatory parameters and sustainable quotas are unknown. Monrovia would see its food security affected, while it became more reliant on hydrocarbon energy, a causal driver of the climate change responsible for removing some of its most important communities.

2. SCOPE

2.1 Project area

Figure 2-1 shows the entire shoreline of Monrovia. In agreement with the Client and based on site visits made during the Inception Phase, the coast of Monrovia is divided into five coastal section. The numbers of the coastal sections are indicated in Figure 3-1, together with a description of recognizable places of each section in Table 2-1. Within these coastal sections, hotspots will be identified that require measures to decrease the vulnerability to the assessed coastal hazards.

Table 2-1: Overview table coastal stretches

SECTION	Name	**Approx.** Length (m)
SECTION 1	Hotel Africa	2,200
SECTION 2	New Kru Town – St. Paul river mouth to Freeport of Monrovia	2,400
SECTION 3	West Point	1,500
SECTION 4	American Embassy to Barclay training center	2,600
SECTION 5	JFK Hospital – Barclay training center to Bernard's Beach	4,700
Total		***13,400***

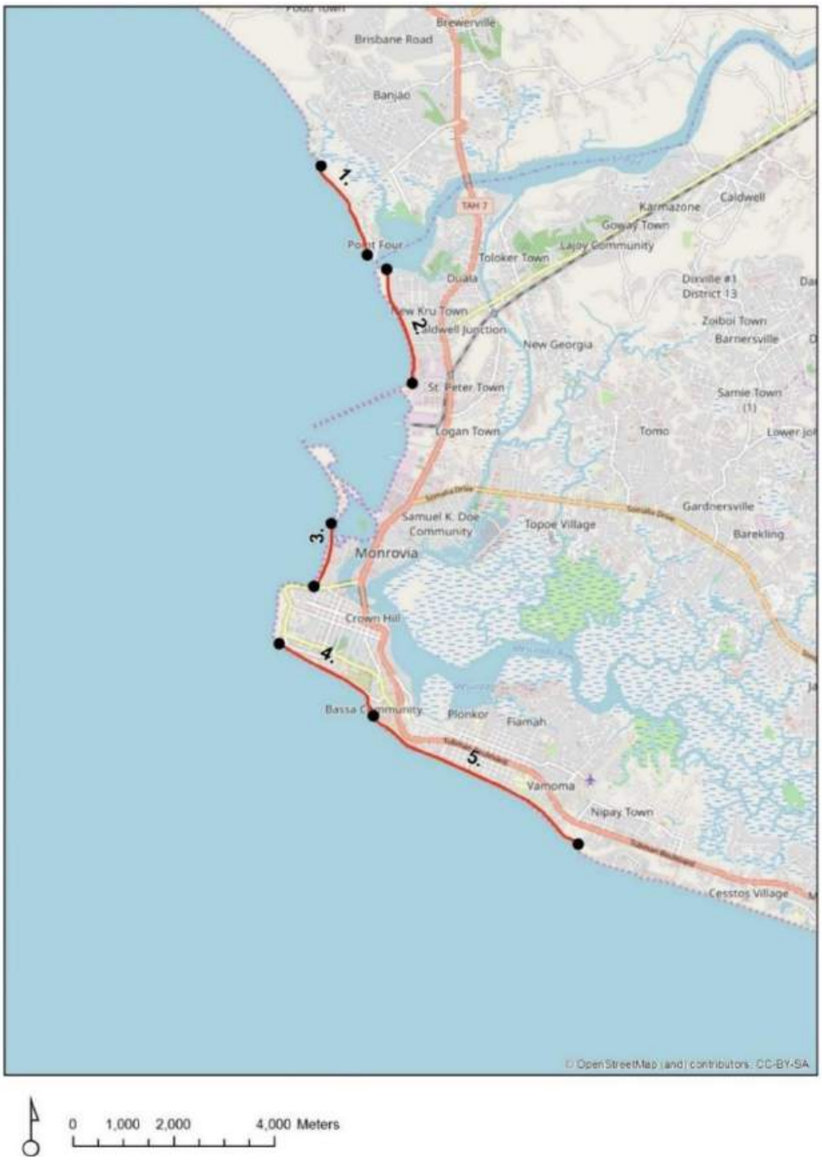


Figure 2-1: Overview map coastal stretches

2.2 Approach

The overall approach, being reflected in the build-up of this reporting, is based on the assessment of the impact by Climate Change on the socio-economic situation of Monrovia and the selection of environmentally acceptable strategies to adapt for the Climate Change effects, which will result in designs that will finally sustain and enhance the socio-economic situation.

Much focus is on sustaining the fishery activities in particular on the West Coast, where, as envisaged by those knowing the Monrovia setting, the overall threats are most evident.

First, the socio-economic context is mapped for Liberia in general, thereafter for Monrovia and more finetuned for the selected coastal sections.

Figure 2-2: Business impression in West Field

Parallel to this, the condition of the existing coastline is reviewed in the perspective of pre-defined Climate Change scenarios that are affecting the shoreline, viz. sea level rise, the wave impact on the general behaviour of the beaches, the impact of particular strong storms and the sediment exchange with the debouching rivers and estuaries. The sediment balance on the beaches play a dominant role and they are subject to the parameters mentioned above. The Climate Change scenarios are translated into numbers and figures with respect to coastline retreat and loss of land, property and infrastructure indicating the magnitude of the potential hazard.

Next, on the basis of the gathered knowledge the vulnerability assessment is performed following a strict methodology to identify the areas of highest need for measures that mitigates and protects against the Climate Change impacts and subsequently defines the focus areas or “hotspots”. The main categories of exposure are (i) population and assets, (ii) critical infrastructure and (iii) livelihoods and coastal communities, for which the vulnerability levels are assessed. At this moment, these systems are already under pressure due to a mixture of anthropologic and climate change induced factors. From the vulnerability analysis it will appear and documented based on best knowledge and engineering skills that future threats to the coastal sections will increase as a result of the Climate Change.

Next potential climate resilient strategies and solutions are presented which might decrease the vulnerability for climate change of coastal communities along the pre-selected five coastal sections of Monrovia. Based on a longlist of potential solutions, each measure is assessed on its pros and cons and only those measures are pre-selected which are technically feasible and serve as sustainable protection of the local communities for the identified hazards. From the shortlist of measures providing sustainable protection, several alternatives are further developed into potential resilient strategies (options). These have been discussed with key stakeholders in a workshop in Monrovia 30 January 2019. The stakeholders have presented their feedback regarding a number of criteria on these options. Based on their feedback several preferred strategies for the most vulnerable coastal sections (the hotspots) are proposed.

Figure 2-3: Stakeholder workshop 30 January 2019

The strategies as defined need to be aligned with the objectives of the UNDP. UNDP Liberia aims as to contribute to the country's national development priorities set out in the National Vision 2030 (Liberia Rising) and the Government's newest Pro-Poor Agenda (PPA). The focus in the presented resilient strategy is clearly on safeguarding and supporting the poor communities in the most vulnerable coastal sections (fisheries, other), which is precisely in line with the Government of Liberia's Pro-Poor Agenda.

Finally, the proposed climate resilient strategies for the hotspots have been defined. Based upon the outcomes of the stakeholder consultation organized 30 January 2019 in Monrovia a first pre-selection of potentially feasible and sustainable strategies is presented. Due to sustainability considerations it became clear that most stakeholders do not favour beach nourishment only due to the continued maintenance needed and potential risks regarding funding and implementation of regular maintenance. Moreover, set-back lines (safety zones) were not regarded as feasible and sustainable due to enforcement problems and lessons learnt from the past (people came back to the set-back zones).

From the vulnerability analysis it became clear that the hotspots in terms of number of vulnerable assets and people and damage are the coastal sections 2, 3 and 4. For this reason a preliminary selection of strategies (combinations of measures) is presented for these three hotspots.

2.3 Reader's guide

The role of this Revised Interim Report is to define the development of the project concept as the feasibility study moves forward. It is not a final report, but describes work in progress. This Revised Interim Report follows on from valuable inputs made by the United Nations Development Programme (UNDP) and the Environmental Protection Agency (EPA), as well as by the participants of a stakeholder workshop, and by other key stakeholders in further meetings.

The final report will be an extended version of this report as such this will be a standalone report.

This report is structured as follows, thus following the project rationale and the approach:

1. Socio – Economic context
2. Climate Change
3. Potential climate resilient strategies
4. Proposed climate resilient strategies

The relevant Appendixes have been attached.

Figure 2-4: Part of the Study team in Monrovia

3. SOCIO-ECONOMIC CONTEXT

This chapter describes the socio-economic context of the project. It treats the socio-economic developments and conditions in Monrovia and Liberia.

3.1 Socio-economic developments Liberia

Population

Currently, Liberia approximately has 4.7 million inhabitants (2017) of which about 1 million people live in the capital Monrovia. In Figure 3-1 a graph of the yearly population growth of Liberia is shown. The population growth was heavily disturbed by the two Civil wars between 1989 - 2003 and the accompanying political instabilities before and after the wars. The past few years the population growth is quite strong again with about 2.5% to 3% per year.

Figure 3-1: Yearly population growth rate (Ref [2])

In accordance with the growing share of Liberia's population living in urban areas (from 2016 urban population share exceeds 50%), the population within the project area (Monrovia) is also growing with a growth rate of at least 3% (Ref [3]). Liberia's population is relatively young, with more than 70% younger than 35 years of age.

Table 3-1: ***Liberia: selected socio-economic indicators Sources: Ref [1]***

Social-economic data	1990-2017	2009-2017	2017
Economic growth (GDP annual in %)	5,03%	2,32%	2,50%
Income per capita (GNI) growth (annual)		1,45%	1,64%
Population growth Liberia (annual)	3,06%	2,00%	2,55%
Population growth urban	2,30%	3,66%	3,40%

Economic development & poverty

For the period 1990-2017 GDP grew with average pace of about 5% (GDP in current prices). In 2017 real GDP growth by 2,5%. The growth was mainly driven by the mining and quarrying sectors (gold, iron ore). Iron ore exports almost tripled between 2012 and 2014. By the end of 2014, iron ore represented over 62 percent of Liberia's total exports

Liberia ranks 177th out of 188 countries in the World Bank's Human Development Index. Although poverty has declined since 2007, poverty remains overall high, and even more profound in rural areas. Unfortunately, in the years 2012-2014 the share of population with poverty increased due to slowing economic growth, rising prices of imported food and the impact of the Ebola crisis.
Liberia's poverty rate decreased from 54.1 percent in 2014 to 50,9 percent in 2016 (Ref [4]). Poverty is higher for families with a head without any formal education.

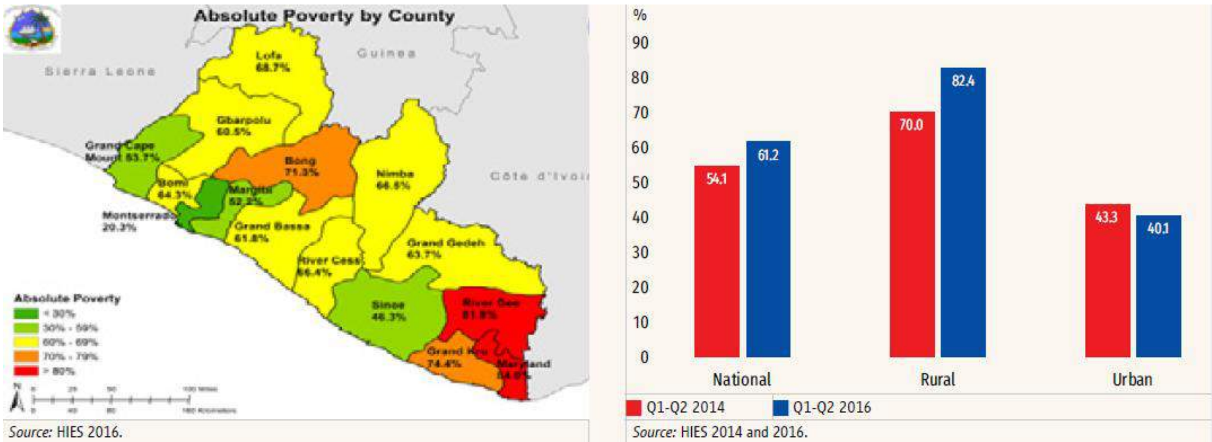


Figure 3-2: Absolute poverty and poverty rates Liberia (by type of area)

Livelihood and economic structure

Still agriculture is the main source of income for the largest part of the Liberian society (Ref [5]). Moreover, a large part of Liberia is covered by forest. Together with rubber and mineral resources as iron ore, gold and diamond, these can be considered as the main sources of economic development.
In 2017 a workshop was organised to divide Liberia into different "livelihood zones". The result is shown in the map of Figure 3-3.

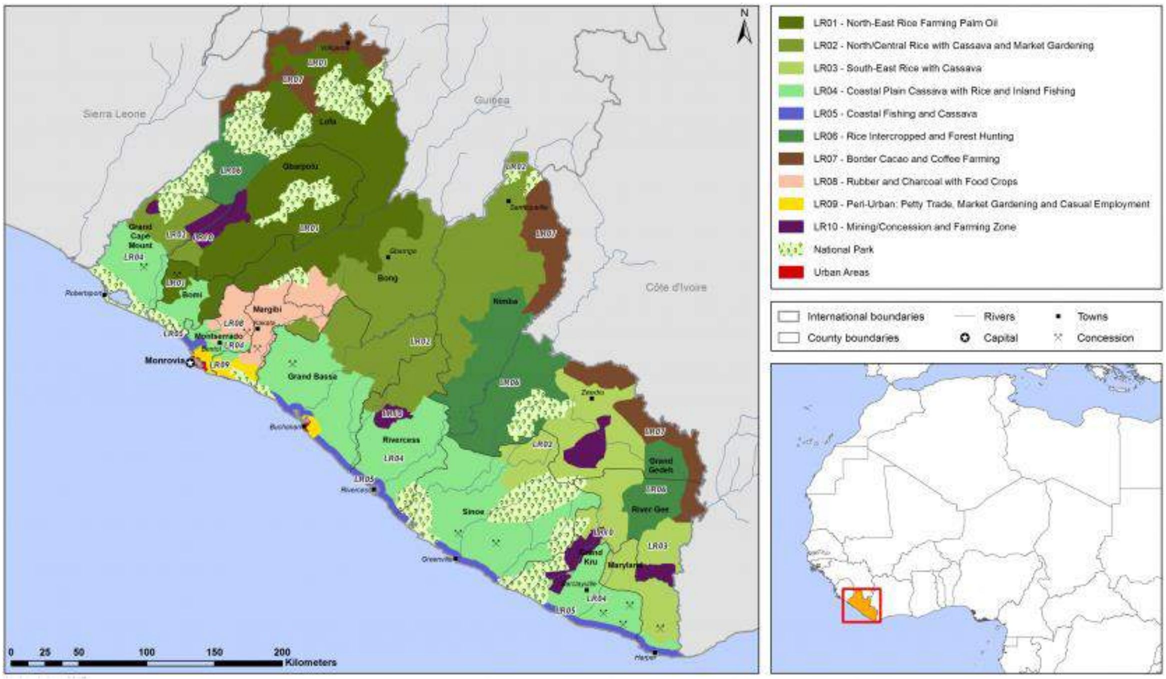


Figure 3-3: Liberia divided into different livelihood zones (Ref [6])

The map of Figure 3-3 also shows that for the largest part of the inhabited coastal stretch of Liberia (not indicated as National Park) the main source of income is subscribed to "coastal fishing and cassava". On the map of Figure 3-3 Monrovia is indicated as "urban area", hence also here a significant part of the population acquires income from coastal fishing.
In below table the distribution of employment over the different economic sectors is shown as from official statistics (NSI). As the informal economy is lacking in official statistics, the structure of total formal and informal jobs might be different. The reason is that often informal jobs are present in sectors such as retail, fishing and agriculture.

Table 3-2: Distribution employment over economic sectors (Ref [7])

Sector of economic activity ISIC rev 4	Liberia	Rural area	Urban area
	Share in total employment in %		
Agriculture, forestry, fishing	47.3%	72.5%	15.9%
Wholesale / retail trade	25.1%	11.8%	42.1%
Manufacturing	6.5%	5.6%	7.5%
Education	3.7%	2.6%	5.2%
Construction	2.4%	0.8%	4.6%
Transportation, storage	2.3%	0.6%	4.3%
Accommodation & food	2.6%	1.5%	4.1%
Remaining sectors	10.1%	4.6%	16.3%

Table 3-2 shows that in the urban areas of Liberia, by far the largest part of the population is employed in the 'Wholesale / retail trade' sector. As expected from the site visit in Monrovia, also the number of people employed in the 'agriculture, forestry, fishing' sector is significant for the urban areas.

Food security and fisheries

Fisheries are important as provider for food in Liberia. Fish is the second most purchased food commodity and provides approximately 15% of total animal protein supply. Per capita fish consumption is estimated at around 9 kilo per capita in 2018 (Ref [9]). The fishery sector contributes around 10% to the country's Gross Domestic Product (GDP). The sector provides full- or part-time employment for about 37,000 people in Liberia. About 60% of persons active in the sector are women, especially in the fields of marketing & distribution.

3.2 Socio-economic conditions Monrovia

Overall, there are limited statistics available for Monrovia city. However, there are some statistics for the county Montserrado in which Monrovia is located. In general Monrovia shows a larger population growth than most other towns, due to rural-urban migration and inter urban migration towards Monrovia. The upswing of population growth started already in the civil war period when people fled to Monrovia when the UN peacekeepers arrived.

Labour market and poverty

Poverty is lower in Monrovia compared to the national average poverty rate of 50,9%, but it is still substantial (20,3% for the Montserrado county (HIES 2016)). About 6,5% of population is registered to be unemployed in Monrovia. However, the number of inactive persons is much larger due to lack of registration and the informal economy. Therefore, in Table 3-3 also the informal employment rates are given. Vulnerable employment can be defined as work for which no salary, pension, sickness benefits are assured. Also, the future perspective of the job itself is insecure. The informal employment rates and vulnerable employment rates provide more insight in the condition of the Liberian labour market.

Table 3-3: Employment rates of 2010 and 2016 (Ref [7] and [8])

	Unemployment rate	Informal employment	Vulnerable employment
Liberia (2010)	3.7%	68.0%	77.9%
Liberia (2016)	3.9%	79.9%	79.5%
Greater Monrovia (2010)	6.5%	56.6%	63.2%
Montserrado (2010)	5.9%	60.1%	-
Montserrado (2016)	8.0%	69.0%	64.1%

As can be noted from these figures a substantial share of the labour force is either unemployed, informal employed or active in vulnerable jobs in Monrovia. For this reason, job security and safeguarding livelihoods is of utmost importance given the climate change threats for coastal communities in Greater Monrovia.

Communities in the five coastal sections

In below table an overview is provided of the types of communities for each of the five coastal areas.

Table 3-4: Overview sections, type of communities and exposed population and assets

Coastal section	Typology community	Assets exposed to climate change and hazards	Total exposed population and no of residential buildings
1. Hotel Africa	Poor, fishermen and women as market sellers (North), low density	Fishing sites, dwellers, beachfront restaurants	4208 inhabitants 1052 residential buildings
2. New Kru town	Poor – lower middle class, fishermen and women as market sellers, vulnerably employed, shops & markets	Residential buildings, roads, churches, schools, shops & marketplaces, fishing sites, beach	16020 inhabitants 2670 residential buildings
3. West Point	Slum area, high density, poor, unemployed / inactive, vulnerable employed, fishermen and women as market sellers	Slum / informal dwellings, fishing sites, beach, road, marketplaces, LEC power substation	10872 inhabitants 1812 residential buildings
4. Atlantic shore: US embassy	Middle class to upper class area, employed, offices, hotels, mall	Cement residential and office buildings, road, beaches	13488 inhabitants 3372 residential buildings
5. Atlantic shore: JFK hospital	Middle class to upper class area, employed, offices, hotels, mall	Cement residential and office buildings, road, beaches, Bernard beach fishing site	5412 inhabitants 1353 residential buildings

Fishery communities

Fishing is an important livelihood of families in at least three sections: section 1 (West Point), section 2 (New Kru town), section 5 (Bernards beach) and the area in section 1 north of Hotel Africa. Most fishermen in Monrovia use the small Kru canoes in the artisanal sector. They are used by the Kru and Popoh and propelled by paddle and sail. Kru fishermen set off to fish in the morning with an offshore breeze and return in the afternoon or evening with the onshore breeze. The beaches serve as important landing sites for the canoes.

In below table the fishing sites in Montserrado county are shown.

Table 3-5: Fishery sites in Montserrado county

Beach	*Location*	*No. of fishing canoes*	*No. of fishermen*	*No. of mongers*	*Fish sales in USD per day (from upcoming survey)*
Banjor beach	Virginia	59	134	402	
Pont four beach	New Kru town	185	432	1269	
West Point beach	West Point	387	1808	5424	
Bernard beach	Congo town	48	112	336	
King Gray beach	King Gray	77	156	468	
ELWA beach	ELWA Community	102	185	555	
Kpekor beach	Browerville	47	140	420	
Totals		**905**	**2958**	**8874**	

Artisanal fishing is depending on the season, depth of water and type of fishing craft used. Fishermen employing the dug-out Kru canoe cannot operate in rough sea conditions. Thus, there are large seasonal fluctuations in catch (rainy season, dry season) and depending on the wind speed (storms etc.). The fishery sector has strong backward and forward economic linkages in boat materials, net materials (inputs) and processing and market sales (forward). Many women are active in fish processing and selling fish on fish markets. The fishermen are heavily depending on the beaches as landing sites for canoes. Climate change and hazards can have negative impacts on the livelihoods of these communities with repercussions on related activities and food security outside the coastal area (fish provide approximately 15% of the country’s animal protein supply).

Figure 3-4: Fishing boats trips from Monrovia and women selling fish on market

Exposed critical infrastructure

In the coastal zone relevant for this study there are a number of critical infrastructures:

- *Freeport of Monrovia*: the international port providing access to other ports and linking Liberia to international trade flows;
- *Landing sites for fisheries:* in sections Hotel Africa (1, North), New Kru town and West Point there are a number of landing sites for canoes of fishermen.
- *Railroads* - Railway line 2 and are in service. Railway line 2 mainly serves transportation of mined minerals to the port of Monrovia for export.
- *Roads* Nearly all transport of people in Monrovia is road-based. One asphalted trunk road is running through Monrovia that connects the city with other cities and surrounding villages. Inside the centre of Monrovia itself, also (nearly) all roads are paved. In the vulnerability analysis these roads are assessed as important assets to protect.
- *Power stations and substations* – Within Monrovia there is one active power station, located north of the seaport. However, the main power station providing electricity to Monrovia the Mount Coffee Power Station (64MW), located at approximately 22 km’s upstream in the St. Paul River. There is a number of substations spread over the city, of which one is located close to the shoreline at coastal section 3, West Point.
- *JFK Hospital* This is the national medical centre of Liberia and the complex consists of a number of relatively large buildings. It is located at less than 150m from the shoreline at coastal section 5.
- *Educational buildings:* a number of schools are located in the coastal sections and are potentially at risk. This is especially apparent in New Kru town (section 2).

- *Religious buildings*: a number of churches are located in the sections: especially in sections New Kru town, and on the Atlantic shore.

In below map the infrastructure is shown.

Figure 3-5: Overview map of critical infrastructure assets along Monrovia's coastline

The communities in New Kru town, West Point and Hotel Africa sections consist of a variety of vulnerable groups. The livelihood of the inhabitants of these sections is heavily dependent on activities related to the coast and sea: fisheries, shops& retail (fish markets, textile & food).

4. CLIMATE CHANGE

This section elaborates on the climate change impact at the coast of Monrovia. To assess the impact of Climate Change reference is made to the fifth assessment report of International Panel on Climate Change (IPCC - AR5 2014).

Over the last decade the most pronounced environmental threat at the Monrovia coast has been coastal retreat. Along large stretches, especially New Kru Town and West Point, significant coastal retreat has took place leading to loss of land and recreational beaches.

Figure 4-1 shows the coastline position in 2008 (left, red) and 2018 (right, blue), showing the observed coastal retreat in the last decade for the coastal sections 1 and 2 (Hotel Africa and New Kru Town). It is clear that especially at New Kru Town the coastal retreat has been significant: approximately 37 m on average along the section. At Hotel Africa the coastal retreat has been less: approximately 6.5 m on average along the section.

Figure 4-1: Coastline positions in 2008 (left, red) and 2018(right, blue) at coastal sections 1 and 2.

Figure 4-2 shows the coastline position in 2008 (left, red) and 2018 (right, blue), showing the observed coastal retreat in the last decade for the coastal sections 3 (West Point). Significant erosion has took place, especially at the southern part of West Point, while at the northern part some accretion has took place. However along the complete section (from Mamba Point to the southern breakwater) on average approximately 33 m coastal retreat is observed.

The remaining sections (4 and 5) the observed coastal retreat over the last decade was less significant compared to section 2 and 3, with an average coastal retreat of about 10 and 2.5 m respectively.

Figure 4-2: Coastline positions in 2008 (left, red) and 2018 (right, blue) at coastal section 3

Based on this study it has become apparent that the observed coastal retreat has been caused by natural processes which has been and will be amplified due to climate change. More important, due to climate change the coastal retreat and subsequent damage is expected to worsen significantly over the coming decades. Both from observations and projections for the future it is clear that section 2 and 3 suffered and will suffer the most from coastal retreat. The paragraphs below describe briefly the underlying processes and the causes for the worsening of coastal retreat due to climate change. Any relevant environmental baseline information can be found in Appendix A.

In this area coastal retreat is caused by:

1. Shift in equilibrium profile due to Sea Level Rise ('Bruun Effect')
2. Chronical erosion due to sediment deficit caused by long-shore sediment transport and Sediment exchange with rivers and estuaries
3. Storm Erosion[4]

Although the above mentioned processes are assessed independently they are driven by similar forces which are all prone to climate change. The main forcing mechanisms in this coastal system that affect the processes depicted above are:

- Sea Level Rise
- Wave impact
- Sediment exchange with rivers and estuaries: changes in run-off and temperature (which together with sea level rise results in change in sediment exchange between coast and rivers and estuaries)

[4] Storm erosion is a different process with respect to the other two types of coastal retreat and should be considered as coastal retreat after a storm event with a specific return period *additional* to the structural retreat due to the other processes.

The above forcing mechanisms and the effect of climate change over the last decade and in the future are briefly described below. All projections and effects of climate change have been assessed by using the climate change scenarios developed by the International Panel on Climate Change (IPCC).

4.1 Climate Change Scenarios

The global forecasts of the fifth assessment report of the International Panel on Climate Change (IPCC 2014) show various types of scenarios for the climate change in the future, the most recent set of scenarios are Representative Concentration Pathways (RCPs). The RCPs describes four different 21st century pathways of greenhouse gas (GHG) emissions and atmospheric concentrations, air pollutant emissions and land use, see Figure 4-3. The RCPs have been developed using Integrated Assessment Models (IAMs) as input to a wide range of climate model simulations to project their consequences for the climate system (IPCC Synthesis report, 2014). RCP 2.6 assumes that global annual GHG emissions (measured in CO2-equivalents) peak between 2010–2020, with emissions declining substantially thereafter. Emissions in RCP 4.5 peak around 2040, then decline. In RCP 6.0, emissions peak around 2080, then decline. In RCP 8.5, emissions continue to rise throughout the 21st century.

Although IPCC clearly states that the scenarios do not have an associated probability of occurrence, it is noted that lack of sufficient mitigation efforts before 2020 has made the scenario of RCP 2.6 very unlikely. It is already known that the Paris agreement won't be met in time and hence the GHG emissions have risen up to now and won't likely decline until 2020. This scenario has therefore been omitted in further reporting.

In order to show the bounds of the climate change effects, in this study the most and least conservative climate change scenario among the 3 other RCP scenarios has been assessed: RCP 4.5 and RCP 8.5,. All relevant effects of these scenarios, such as the impact on the mean sea level, (extreme)wave conditions and sediment exchange of the rivers has been taken into account in this assessment.

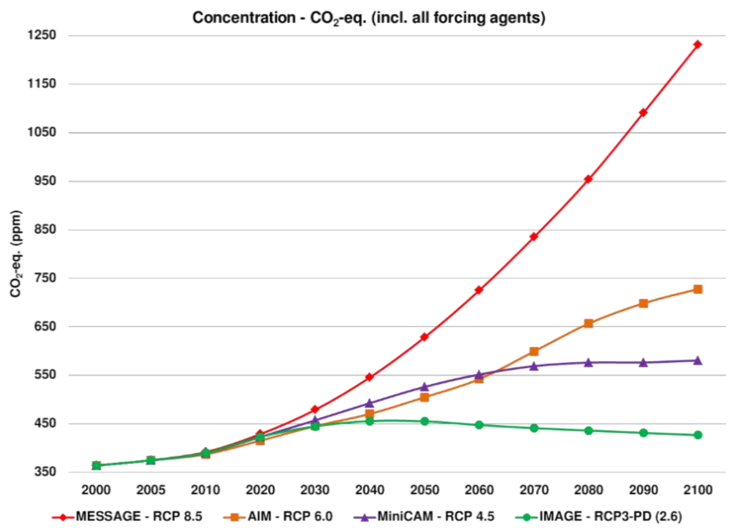


Figure 4-3: RCP scenarios - GHG emissions

4.2 Methodology

The impact of the climate change on the coastal retreat hazard has been assessed by assessing the impact of climate change on the forcing mechanisms as described in the previous section.

Two types of coastal retreat are treated: (i) structural or chronical coastal retreat which are affected by sediment deficit and the Bruun rule and (ii) storm erosion. The first is a continuous progressing process while the latter is storm erosion which is the retreat after an extreme storm event with a specific return period (probability). This storm erosion should be considered as *additional* coastal retreat to the structural coastal retreat and is therefore also treated separately.

The interrelation between the forcing mechanisms and the coastal retreat is shown in the diagram below (Figure 4-4). The two boxes in the middle shows the most important processes that are important to assess the chronical erosion due to sediment deficit and are also treated separately. It is clear that Sea Level Rise is one of the most important forcing agents as it affects all identified coastal processes and as such the hazard coastal retreat.

For each forcing agent in the diagram below the climate change impact has been assessed. The sections below describes the methodology for this impact assessment for each forcing separately.

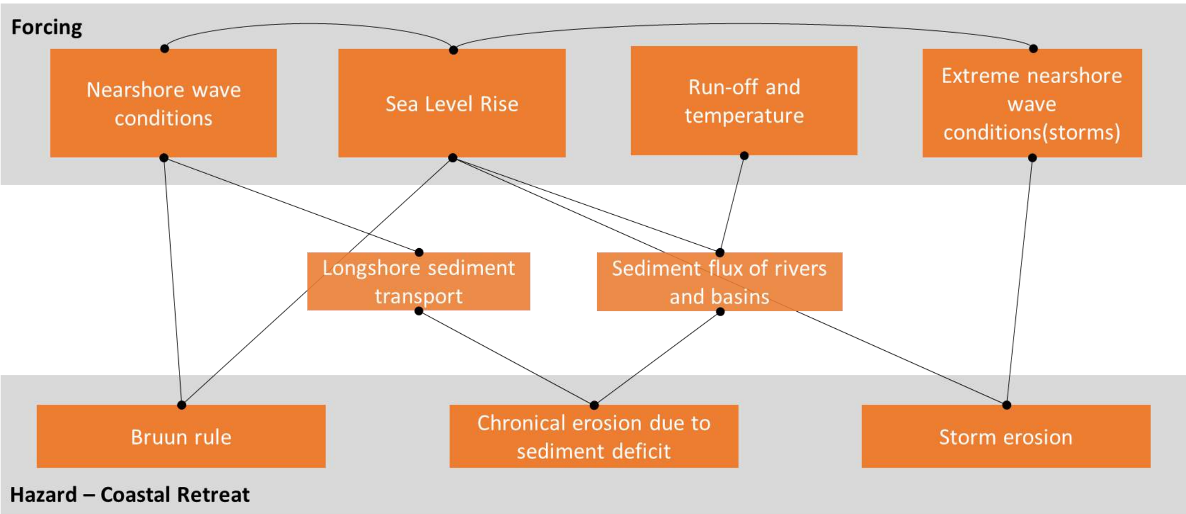


Figure 4-4: Interrelation between forcing mechanisms, coastal processes and the hazard coastal retreat

For the assessment of the effect of climate change on the wave conditions, run-off and temperature the main sources that are available are Global Circulation Models (GCM's). There are more than 60 difference GCM's developed and used by many different research institutes around the world. There are efforts to bring these models together and evaluate them in a more structured way by developing global programs. Most successful of which is Coupled Model Inter-comparison (CMIP) Project run by World Climate Research Programme (WCRP - Ref[30]). These models are developed based on different principles; they have very different global resolutions and have used different global climate change scenarios; time spans of the simulations carried out by different models are different and most importantly their performances varies spatially as well as on land and on sea. A long list of these models can be found at Ref [31]. The evaluation of the global performances and uncertainty of these different models are still ongoing and the 6th edition of CMIP is already started.
The output of GCMs are usually 'standard' climate variables such as surface (air and/or sea) temperature, wind, precipitation etc. and not wave characteristics. Therefore the output of the GCM has been used as input for global wave models to assess the wave conditions, which is described in more detail in section 4.3.2.
Table 4-1 shows the applied GCM's and methods for the assessment of the impact of climate change.

Table 4-1: Applied GCM's and methods for assessment of climate change impact

	AR5 Representative Concentration Pathway	
	RCP 8.5	**RCP 4.5**
RSLR	IPCC AR5 projection for RCP 8.5 (Church et al., 2013 – Ref [28]) with the 'intermediate' methodology of Nicholls et. al. (2011) (Ref [47])	IPCC AR5 projection for RCP 4.5 (Church et al., 2013– Ref [28])) with the 'intermediate' methodology of Nicholls et. al. (2011) (Ref [47])
Wave	Output of global wave models forced by surface winds taken from GCMs (4 EC-EARTH Runs)	Output of global wave models forced by surface winds taken from GCMs (7 GCM Models)
Run-off and Temperature	Output of GCM model with most output points in the studied catchments : MRI-CGCM3 (Yukimoto, et al. 2012 - Ref[52]). And output from other GCM's (GFDL, GISS and NorESM) for sensitivity analysis	Output of GCM model with most output points in the studied catchments: MRI-CGCM3 (Yukimoto, et al. 2012 - Ref[52]). And output from other GCM's (GFDL, GISS and NorESM) for sensitivity analysis

4.3 Impact on forcing

4.3.1 Sea level rise

It has become evident that the sea level is globally rising as a cause of global warming. Since at least the start of the 20th century, the average global sea level has been rising and accelerating. The three main reasons warming causes global sea level to rise are: expansion of oceans, ice sheets lose ice faster than it forms from snowfall, and melting glaciers at higher altitudes. The relative sea level rise (RSLR) is the sum of two major components: global-mean sea-level change, regional (local) spatial variations in sea-level change and land movement (subsidence and tectonic).

The RSLR is based on different climate models are already provided by IPCC AR5 (Church et al., 2013; Ref [28]). These projections are available for all for RCPs and as time series. Methodologies for developing regional and local scenarios are stablished and has been used widely. Here the 'intermediate' methodology from Nicholls et. al. (2011; Ref [29]) has been applied.

Appendix B provides a detailed description about the relative sea level rise projections. Figure 4-5 shows the resulting relative sea level rise projections for the two RCP scenarios for the period 2000 to 2100 (which is the average of the lower and upper bound). The worst case scenario (RCP 8.5), shows a projected relative sea level rise up of almost 75 cm for the year 2100.

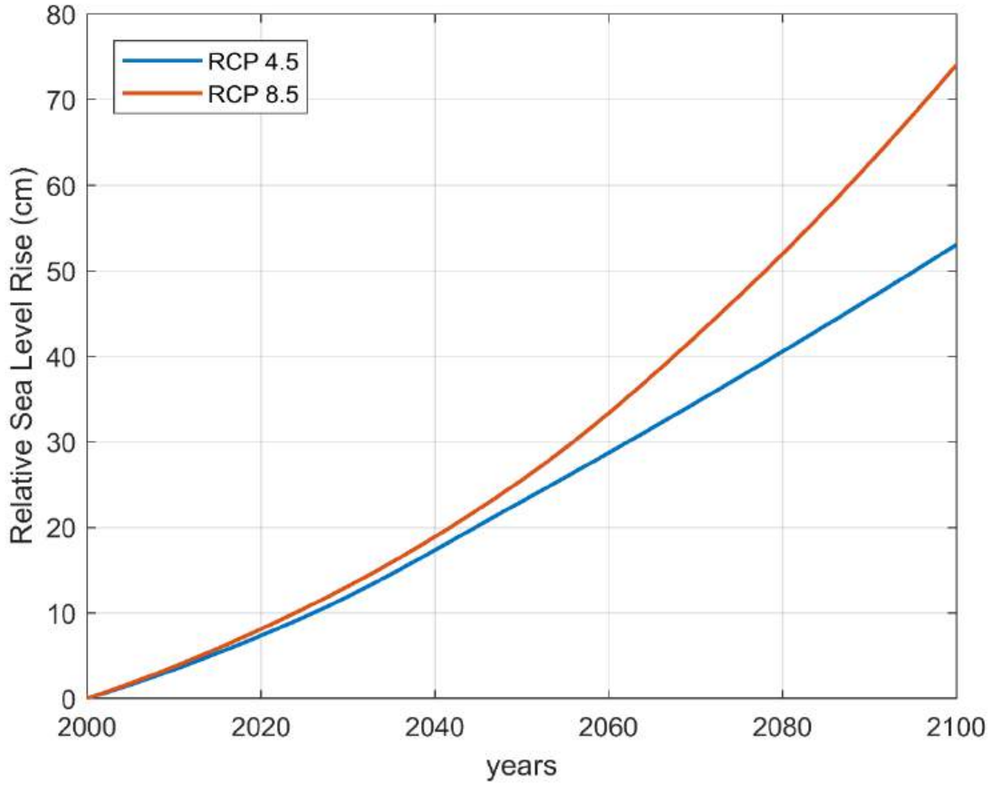


Figure 4-5: Projected relative sea level rise for RCP 4.5 and RCP 8.5

The projected relative sea level rise over the last two decades (2000-2018) has been compared to the actual satellite global sea level rise observation(NASA – Ref [10]). The regional variation in sea level rise in this area is relatively small (see Appendix B) and comparison with global sea level rise is therefore justified. Figure 4-6 shows the comparison of the projected sea level rise and the observed sea level rise. It is clear that the sea level rise is very similar to the projections and the present sea level rise is in between the least and most conservative scenario.

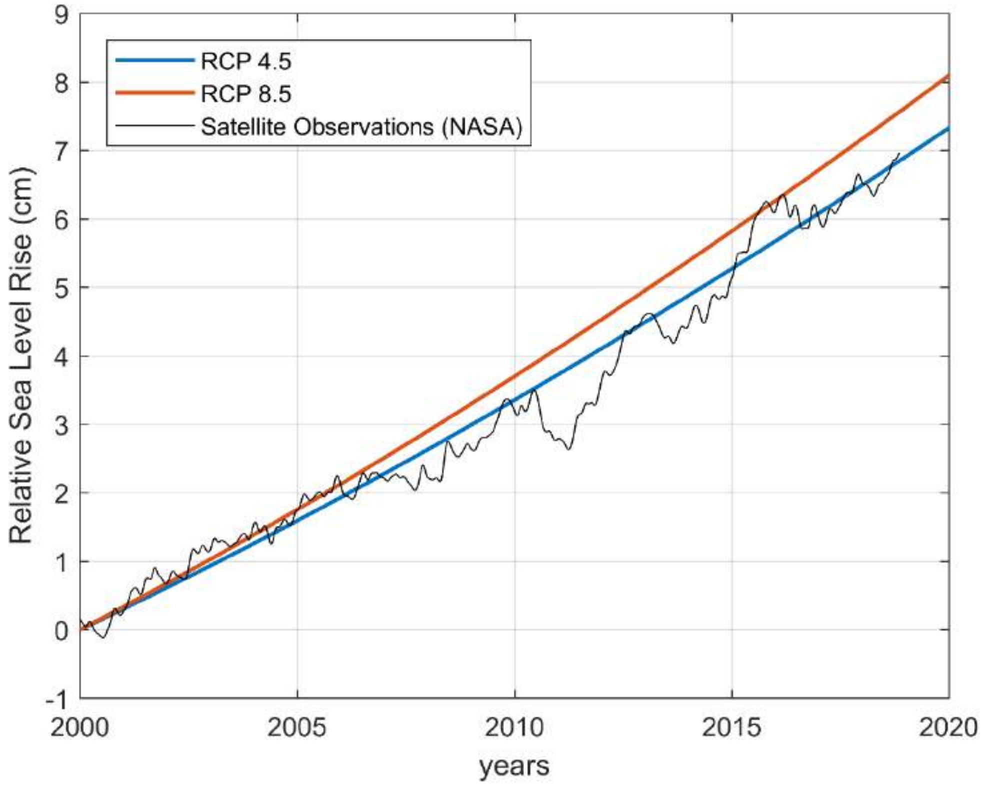


Figure 4-6: Observed and projected relative sea level rise for RCP 4.5 and RCP 8.5

4.3.2 Climate change impact on waves

The coast of Liberia is subjected to persistent long period swell waves. Swell waves are, in contrary to wind waves (which are generated by the immediate local wind), generated by distant weather systems (storms) in the South Atlantic Ocean. These waves travel over a very long distance (thousands of kilometres) and disperse into uniform wave groups with long wave periods (which can be more than 20 seconds). The local wave climate can therefore be described as fairly uniform in both direction (SSW) and wave period. These swells are highly energetic leading to strong wave breaking onto the relative steep sandy shorelines of Liberia. Seasonal changes can be observed: during the rainy season (May to September) the average significant wave height is 1.75 (with maxima up to 3.5 m) and during the dry season (October to April) the average significant wave height is smaller, approximately 1 m. A detailed description of the wave climate, both offshore and nearshore, can be found in Appendix C.

Based on several sources (global hindcast models, see Appendix C.1) it has become evident that the wave climate has changed during the last decade. Below two figures are shown, which show the difference of the wave height distribution for the periods 1979-2000 and 2000-2018, for the two sources that were used for this assessment (data extracted for offshore location 6°N 11°W). It is clear that both data sets show a similar trend: the higher waves (especially the 10% highest waves) are getting higher and increase up to 3 to 5 %.

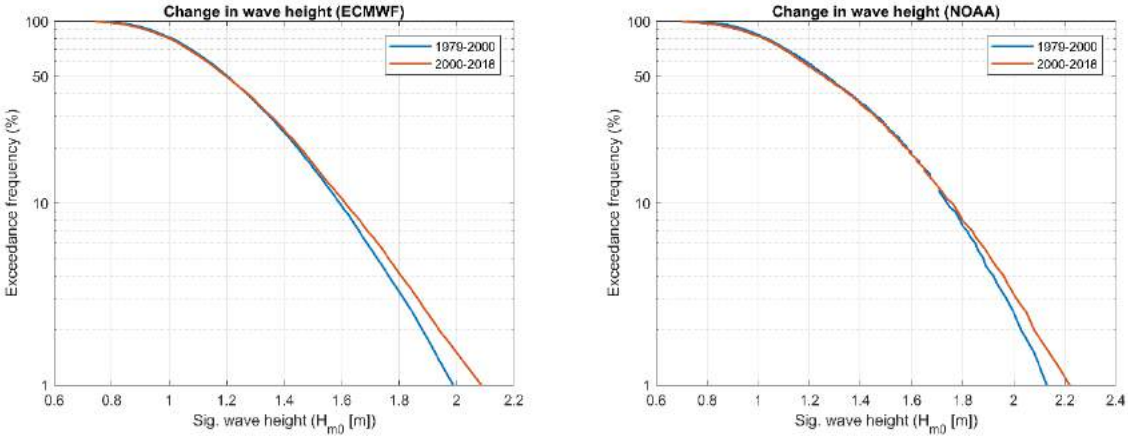


Figure 4-7: Observed impact on wave height last two decades based on ECMWF hindcast data (left) and NOAA hindcast data (right)

This effect on wave height is considered to be caused by climate change which is also found in the future projections of the effects of climate change on the wave climate. To assess the impact of climate change on the local wave conditions the global wind patterns of Global Circulation Models (GCM's) are used. Figure 4-8 shows the work flow how the relative impact of the (offshore) wave conditions have been assessed. A detailed description of the assessment can be found in Appendix C.3.

For both scenarios several ensembles (7 and 4 for resp. RCP 4.5 and RCP 8.5) of the GCM's are used as input for global wave models (e.g. Wave Watch III - Ref [11]). This results in global wave statistics, including significant wave height, wave period and wave direction data up to 2100 for each ensemble member[5]. The resulting wave data has been analysed at a location offshore of the coast of Monrovia (6°N 11°W) to assess the relative impact of climate change on the (offshore) wave conditions.

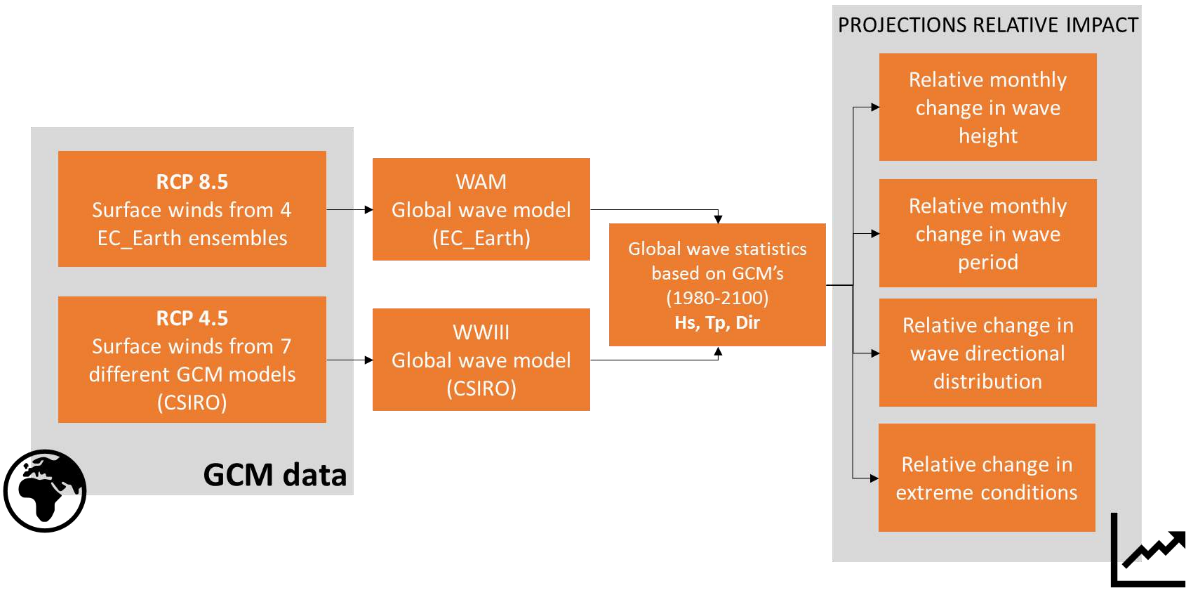


Figure 4-8: Workflow of assessing relative impact of climate change on offshore wave conditions

The relative impact of climate change on the wave conditions is shown in Figure 4-9 for both RCP scenarios. In the figure the average impact on the offshore wave conditions is shown, it is however noted that in the assessment the impact on the complete distribution has been taken into account. For example the deviation in the wave direction of the higher wave angles (more westerly) is more

[5] Not part of this project

compared to the more southerly directions, which is subsequently taken into account in the assessment.

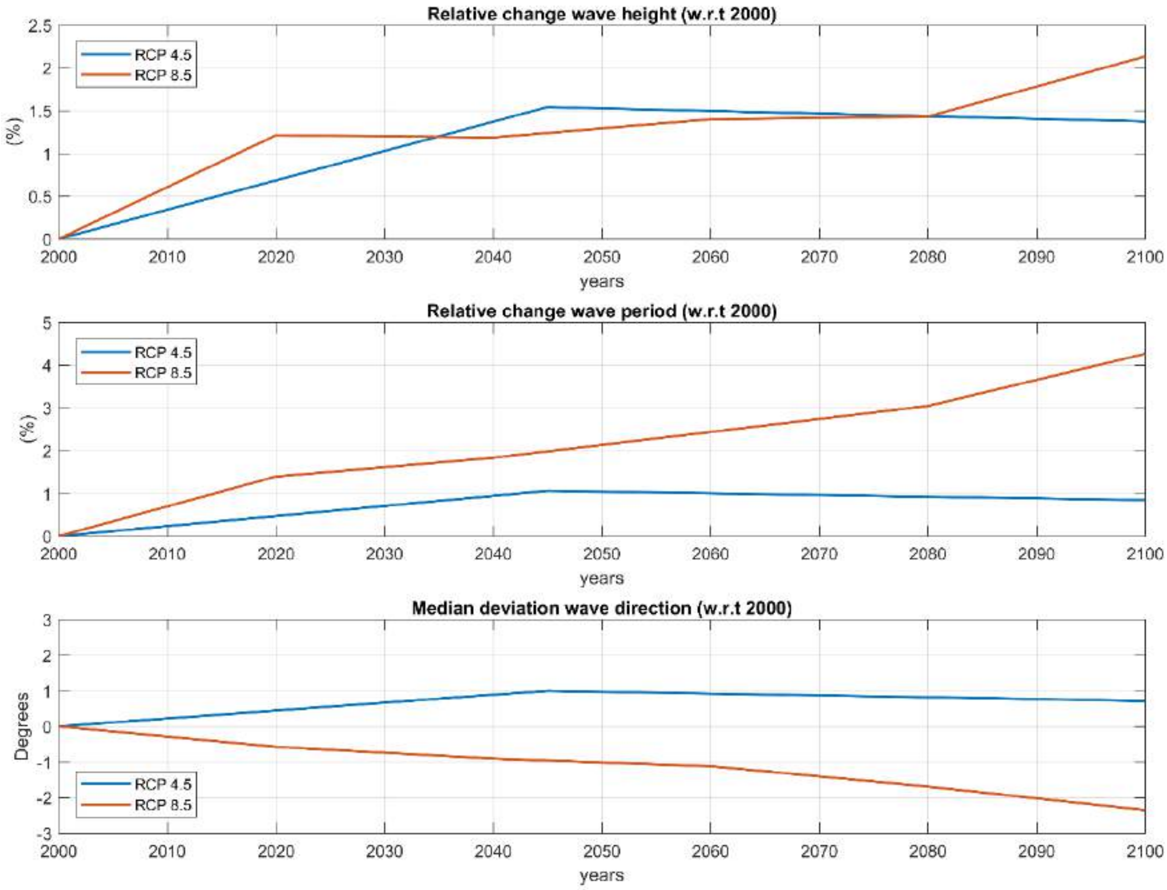


Figure 4-9: Changes in wave conditions, upper panel: relative increase in wave height (%), middle panel: relative increase in mean wave period (%), lower panel: median deviation of wave direction in degrees (positive values means clockwise, negative means anti-clockwise – nautical convention of wave direction: coming from with 0 degrees is North)

From the impact assessment it has become apparent that:

- For both scenarios the wave heights increase, with the highest increase with RCP 8.5. Note that the highest waves increase more compared to the lower waves (see Appendix C.3)
- For both scenarios the wave periods increase, with significant more increase for scenario RCP 8.5.
- For scenario RCP 4.5 the wave direction deviates to more westerly waves (clockwise turn), while for RCP 8.5 the wave direction becomes more southerly/easterly (anti-clockwise turn). Note that for both scenarios the higher wave angles (westerly) shows a larger deviation (compared to the median) than the southerly waves.

Based on these found relative impacts on the wave conditions, two sets of synthetic time series of offshore wave conditions have been constructed for each RCP scenario which includes projected climate change. See Figure 4-10 for the workflow in the generation of synthetic timeseries. Since the generated wave conditions with the use of the GCM surface wind fields are not accurate in the absolute sense (non-calibrated), the determined relative impact needed to be projected on synthetic hindcast wave data. The hindcast wave data were obtained from two sources: NOAA and ECMWF (ERA-Interim). Detailed description is found in Appendix C.

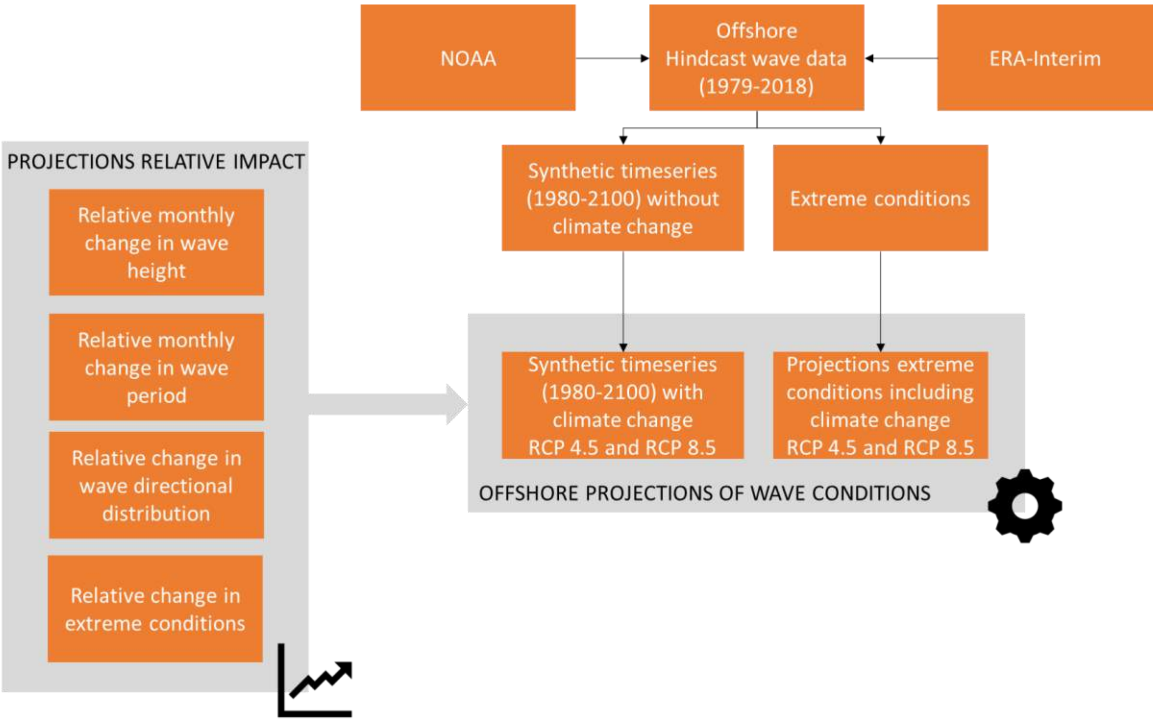


Figure 4-10: Work flow for the generation of synthetic time series for the use in the assessment

These synthetic time series have in turn been translated to nearshore by means of spectral wave modelling (SWAN – Ref [56]) while taking the projected sea level rise into account. The SWAN model has been validated using the nearshore wave measurements. For details see Appendix C. This leads to local nearshore wave climates for the period 1980 to 2100 at several location along all the sections including the climate change effects.

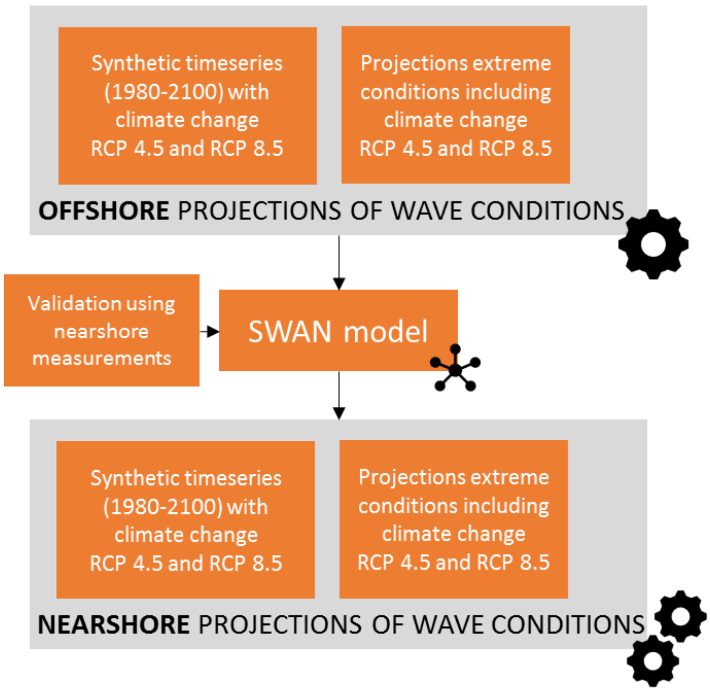


Figure 4-11: From offshore to nearshore wave statistics

4.3.3 Storm conditions

The results from the global wave model ensembles are used to assess the relative increase of storm magnitudes, see Figure 4-8. This is done by evaluating the wave height with a 10-year return period for several time slices of each ensemble. The relative increase has been determined by taking the average of the relative increase of all the ensemble members of each scenario.

Figure 4-12 shows the relative increase of the significant wave height of the extreme wave heights. (10-year RP)

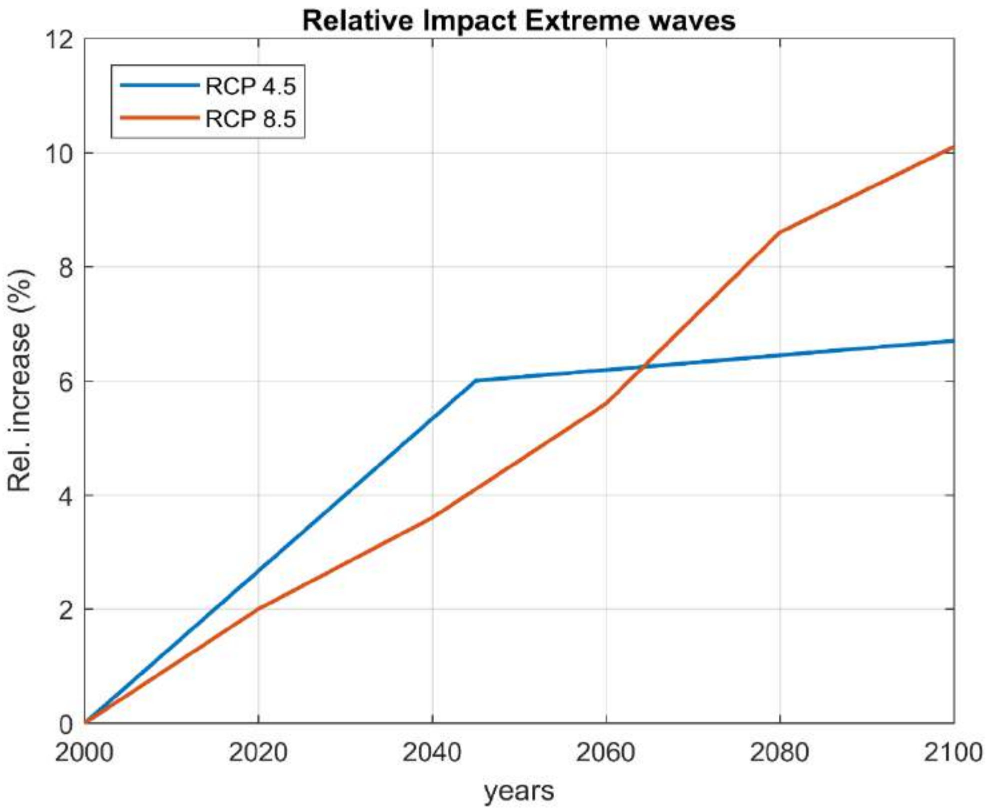


Figure 4-12: Relative impact on storm conditions (wave height) for RCP 4.5 and RCP 8.5

This also means that storms occur more frequently. The storm with a 100-year return period in the year 2000 will have a smaller return period in 2100 due to climate change. The following figure shows the extreme value distributions of the offshore significant wave height for both scenarios in 2100.

From this it can be concluded that due to climate change the 100 year wave height will have a return period of approximately 40 years with RCP 4.5 and 25 years with RCP 8.5 in 2100. Which means that with RCP 4.5 this storm will occur 2.5 times more often and with RCP 8.5 four times more often.

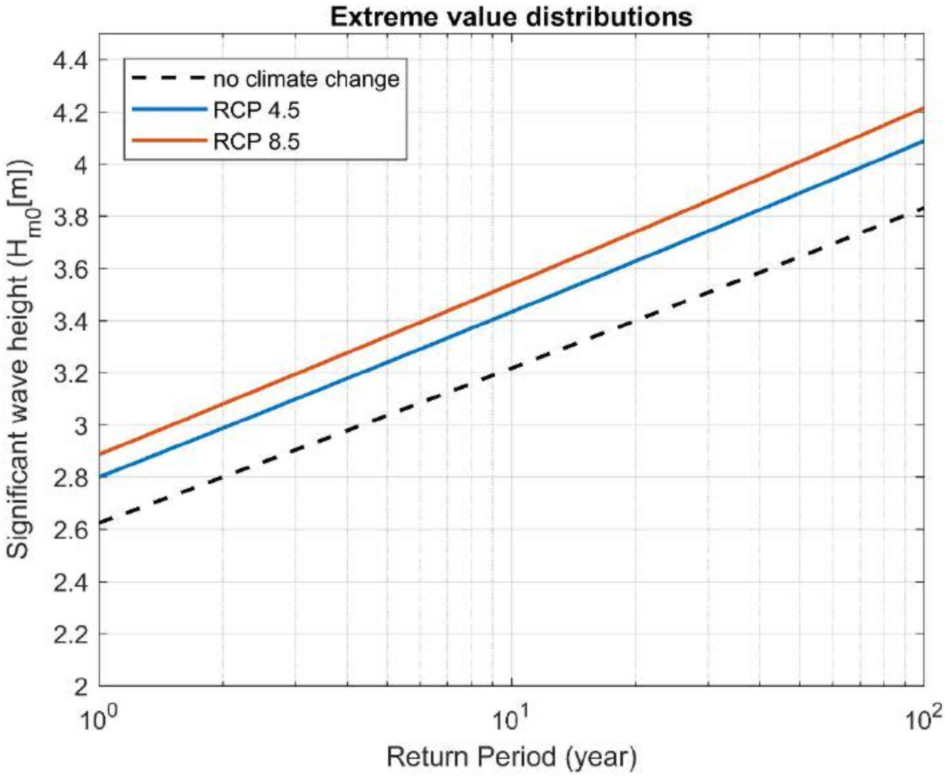


Figure 4-13: Resulting extreme value distributions for RCP 4.5, RCP 8.5 and no climate change for the year 2090-2100

The above has been compared with literature. The study of Mentaschi, L. et al (2017) (Ref [12]) has assessed the global change in the return period of 100 years due to climate change effects for the scenario RCP 8.5. Below a summary of the results can be found (Figure 4-14) for the several ocean basins around the world. It shows the change in the return period for the year 2050 and 2100. Liberia coast is the South Atlantic basin showing that the return period of 100 years decreases. It shows that the change of the return period of 100 years to 25 years is in line with the study of Mentaschi, L. et al (2017).

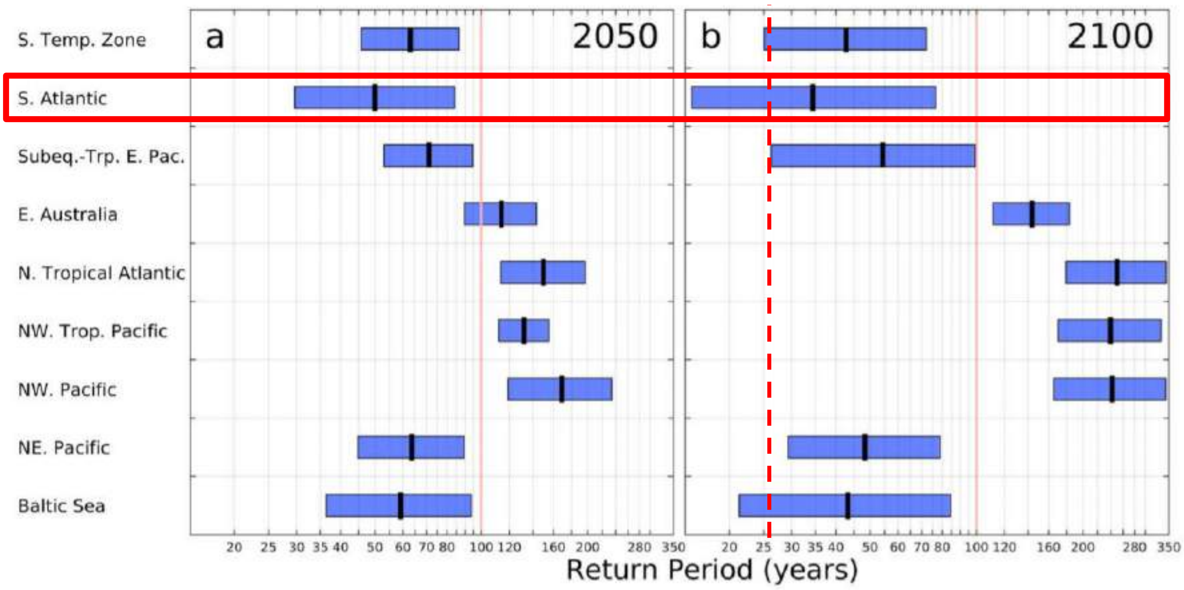


Figure 4-14: Projected return period of the present-day 100 year event (shown as vertical black line) for (a) 2050 and (b) 2100, for RCP 8.5. The rows correspond to different areas, the black lines represent the projected return period, and the blue patches the confidence interval (defined by the intermodel standard deviation). The red dashed line is the estimated return period for 2100 for Monrovia.(source: Ref [12]).

4.3.4 Sediment exchange with rivers and estuaries

The sediment balance of the coastal system of Monrovia is highly dependent on the sediment exchange of the rivers and estuaries in vicinity of the project area. Change in the sediment balance, like a sediment deficit, will result in coastal retreat.

The main sediment sources and sinks in the area are:

- St. Paul river (source)
- Mesurado estuary (sink)
- Farmington and Junk river (source)

In this study we have made use of a state of art model developed by Bamunawala et al., (2018; ref [13]) to estimate the sediment import/export of St. Paul, Mesurado, Farmington and Junk river/estuary systems from 2000 to 2100 including combination of anthropogenic and climate change drivers. A detailed description can be found in Appendix D

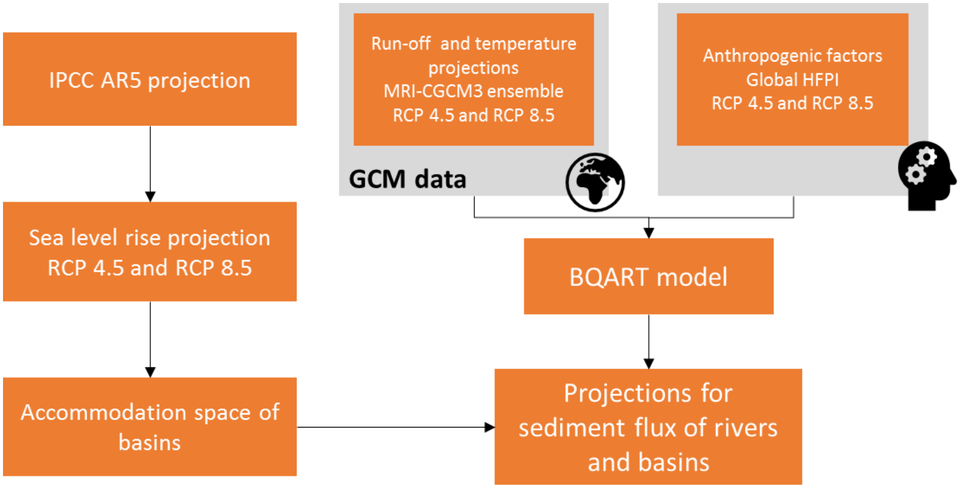


Figure 4-15: Workflow for the assessment of impact of climate change on the sediment exchange of the rivers

The combined effects of climate change and anthropogenic drivers for both RCP scenarios for each river are shown in Figure 4-16, showing the cumulative sediment flux (export positive, import negative) for the different rivers/basins.

It is shown that:

- In both scenarios the sediment import of the St. Paul river increases (12% and 18% in the year 2100 for RCP 4.5 and 8.5 respectively). This is mainly caused by the high contribution of anthropogenic effects, such as expected deforestation and change in land-use.
- In both scenarios the sediment demand of the Mesurado Basin increases significantly due to climate change. This is merely caused by the sediment demand due to the increase of accommodation space, which is linearly affected by Sea Level Rise.
- In both scenarios the sediment import of the Farmington river increases (10% and 12% in the year 2100 for RCP 4.5 and 8.5 respectively). This is mainly caused by the high contribution of anthropogenic effects, such as expected deforestation and change in land-use.

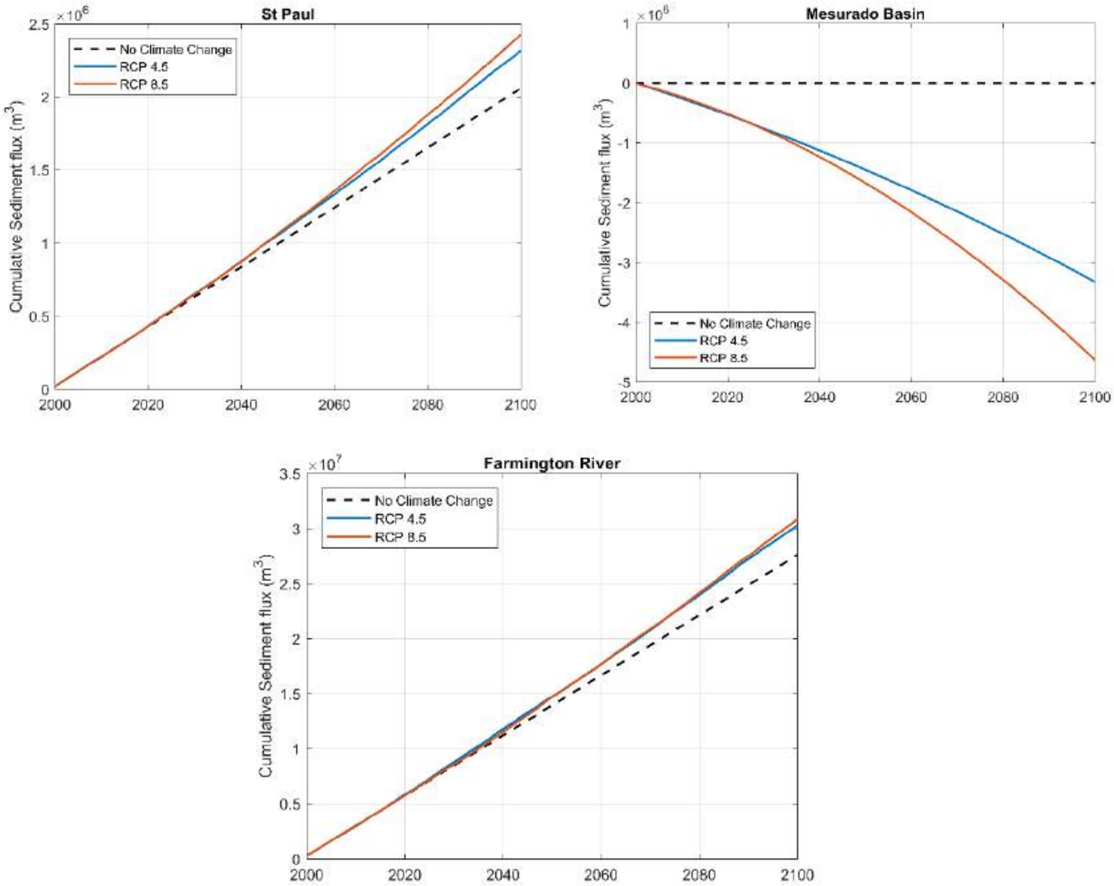


Figure 4-16: Impact on sediment exchange (import/export) of the three main sources and sinks for RCP 4.5 and RCP 8.5 and no climate change

4.4 Impact on coastal processes

Now the forcing agents and the observed and projected impact of climate change has been treated the main processes causing coastal retreat are discussed: the Bruun effect, chronical erosion due to sediment deficit and storm erosion.

4.4.1 Bruun effect

The Bruun effect is the shift of the equilibrium beach profile due to sea level rise, leading to coastal retreat. The below figure shows schematically how the Bruun effect works (Schwartz 1967 – Ref [57]). The resulting coastal retreat is dependent on the sea level rise (linearly), profile slope and depth of closure. The depth of closure (critical depth for which the profile is morphologically active) is in turn dependent on the local wave conditions.

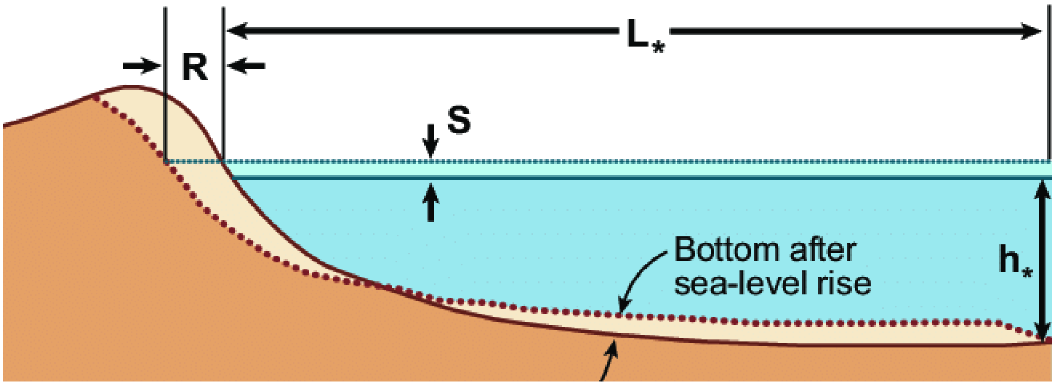


Figure 4-17: Schematic represenation of the Bruun effect

Depth of closure and beach profile slope have been determined to estimate the retreat based on the Bruun for each section and RCP scenario for the coming decades, while including the effect of changing wave conditions, see Table 4-2. It may be evident that without climate change the coastal retreat due to the Bruun effect alone (irrespectively of sediment deficit or storm erosion)will be nil (no sea level rise).

The resulting coastal retreat for each section is shown in Figure 4-18, which show clearly that, as expected, the coastal retreat for RCP 8.5 scenario is more.

Table 4-2: Depth of closure and calculated beach slope for each section and for the year 2000 and 2100 for RCP 8.5

RCP 8.5	Depth of Closure (h*) [m]		Beach slope [-]	
Section	2000	2100	2000	2100
1	4.4	4.8	0.022	0.019
2	4.4	4.8	0.033	0.028
3	3.6	4.0	0.021	0.019
4	5.8	6.2	0.028	0.027
5	5.8	6.4	0.035	0.035

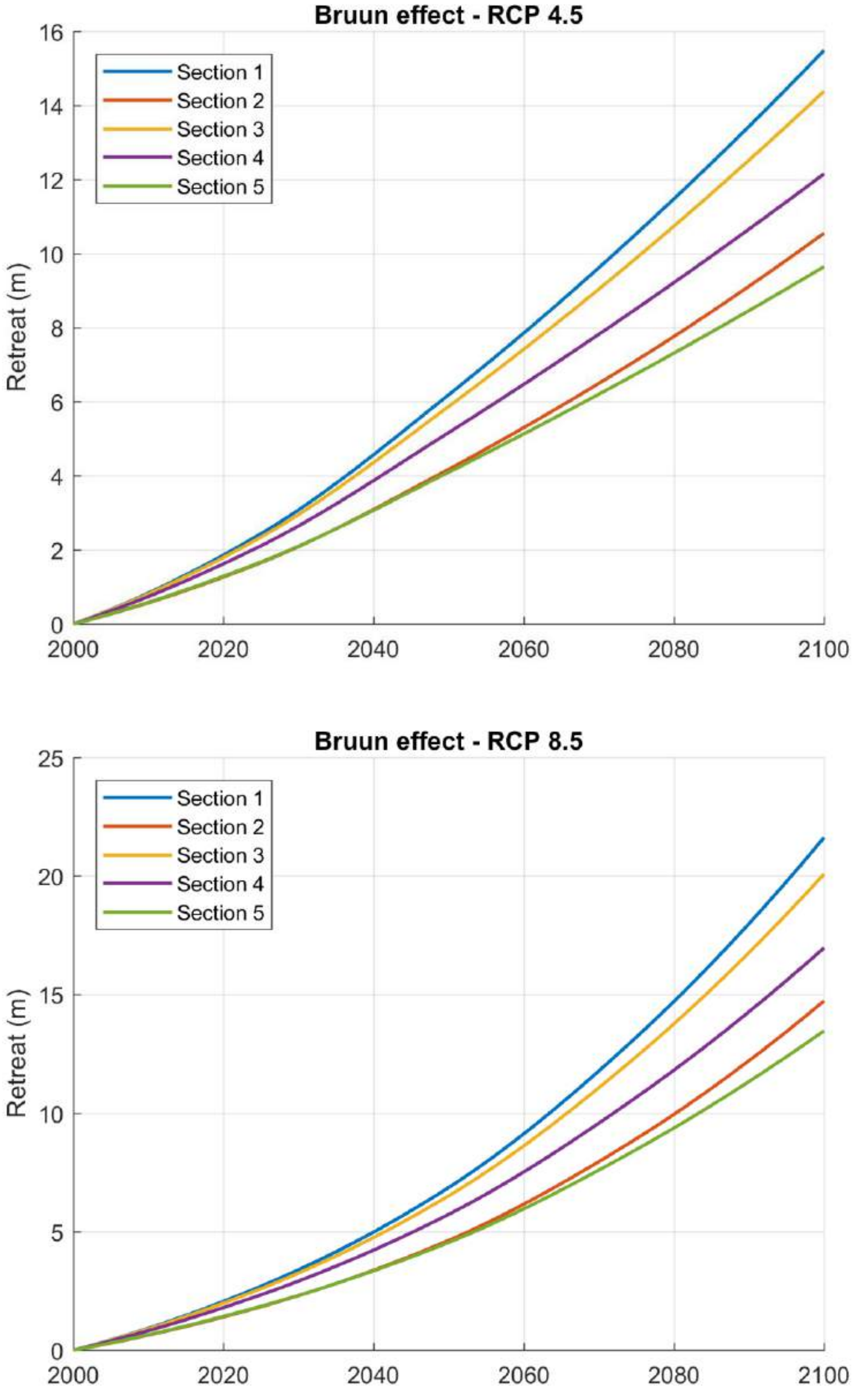


Figure 4-18: Coastal retreat due to the Bruun effect for RCP 4.5 (top panel) and RCP 8.5 (lower panel)

4.4.2 Sediment deficit

The coastal system of Monrovia can be described as a large sediment balance system, which is affected by coastal and riverine processes. A change in this balance may lead to a sediment deficit along certain stretches along the coast. A sediment deficit will ultimately lead to erosion and coastal retreat.

The sediment balance system can schematically be described in Figure 4-19. In the coastal zone of Monrovia a specific coastal cell has import and export of sediment mainly due to a) longshore sediment transport and b) sediment exchange of rivers and estuaries (lagoons), which defines the sediment volume inside the coastal cell (V).

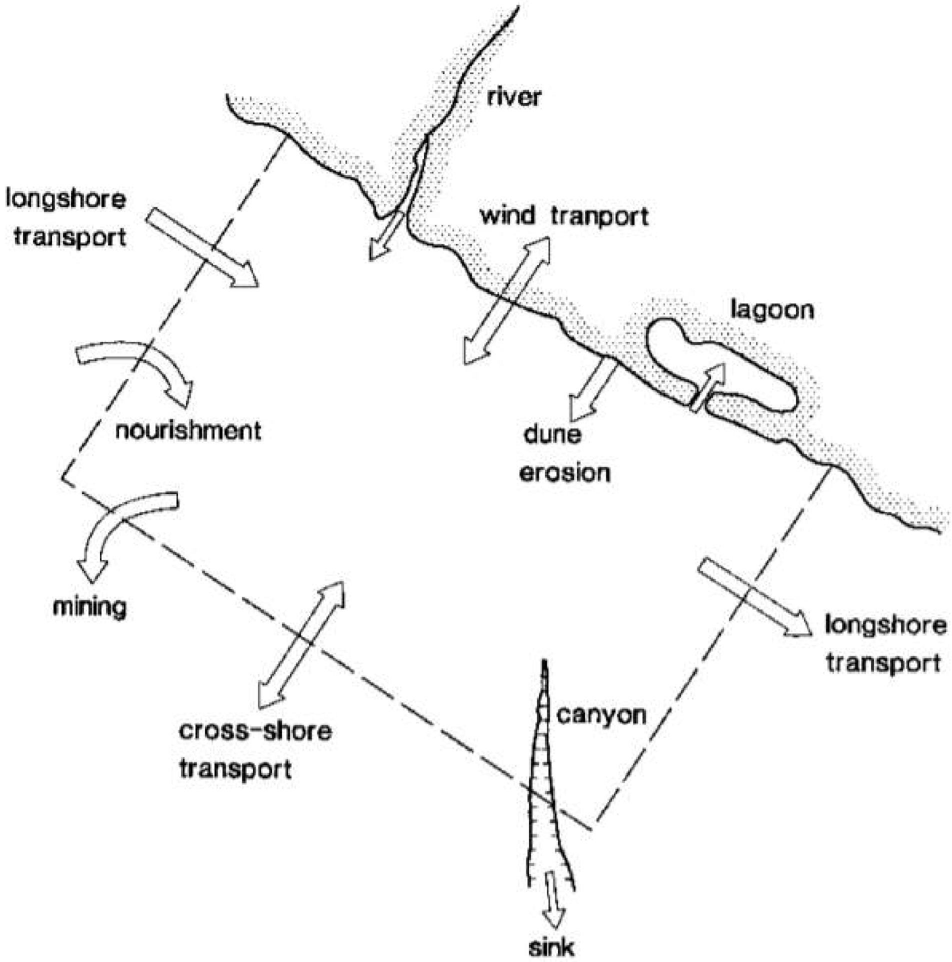


Figure 4-19: Schematic presentation of the coastal sediment budget of a hypotheitcal coastal cell (source: www.simplecoast.com

In case the outgoing longshore sediment transport is increasing the export of sediment will become larger compared to the import leading to a decrease of the sediment volume inside the coastal cell (V). This will lead to erosion and coastal retreat.

The coastal sections of this project are divided into several coastal cells to determine the past, present and future sediment balance along the coastline, based on the climate change scenarios.
Longshore sediment transport is induced by the strong wave breaking of the swell waves arriving oblique to the coastline. A larger wave height, wave period and angle of attack will result in an increase of the longshore sediment transport. Especially the angle of attack is of major importance as this both determines the magnitude and direction of the longshore sediment transport. In case the coastline orientation matches the dominant wave direction closely, the wave direction becomes very sensitive for the longshore sediment transport (if the dominant wave direction is equal to coastline orientation the longshore sediment transport becomes zero and the local coastline is considered in an equilibrium). This is especially the case for section 4 and 5 as these coastline are almost in the equilibrium coastline orientation.
Based on the description above it is important to note that the coastal retreat is not dependent on the longshore sediment transport magnitude itself but on the alongshore variation of longshore sediment transport.
The longshore sediment transports are calculated for each transect of each coastal cell using the nearshore wave climates as derived taking climate change scenarios into account, for the period 1980 to 2100. Appendix E provides the calculated past, present and future longshore sediment transport rates for each coastal cell of each section, for both RCP scenarios.

The figure below shows an example of the net longshore sediment transport annual rates for the three defined transects of section 5 (starting from west to east), see Figure 4-20 and Figure 4-21. Positive transport rates denote westward transport.

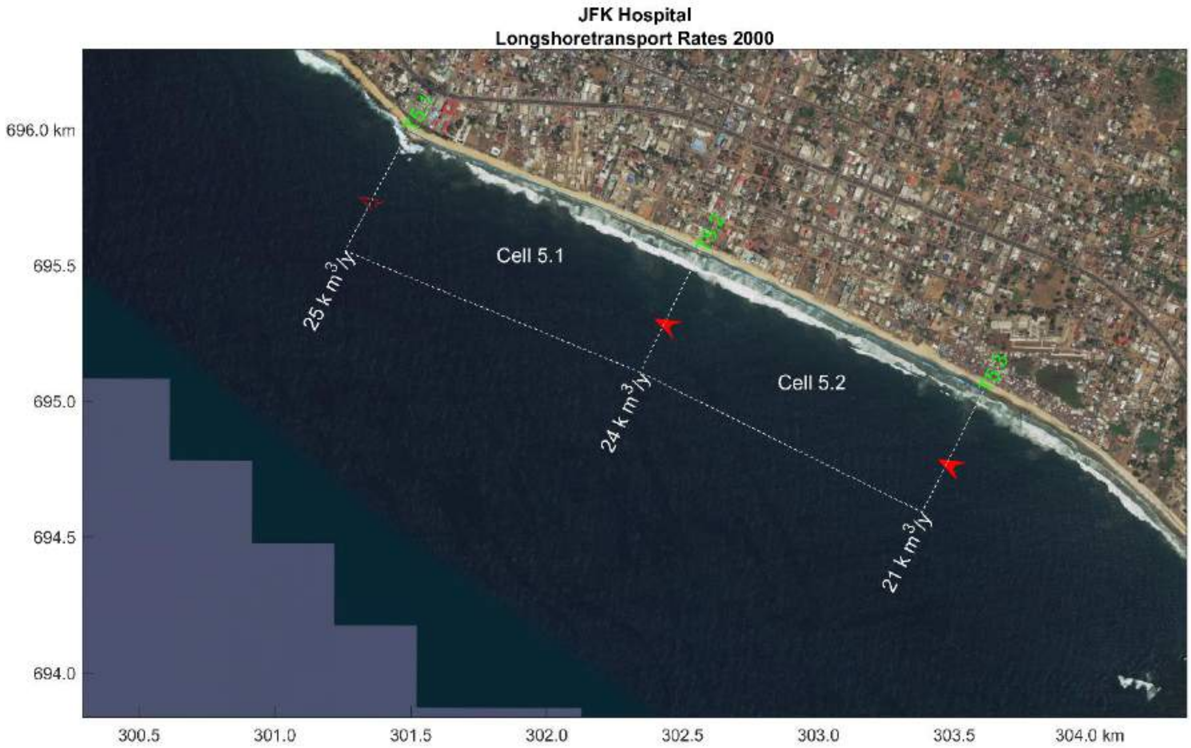


Figure 4-20: The defined coastal cells of section 5 including annual sediment transport rates

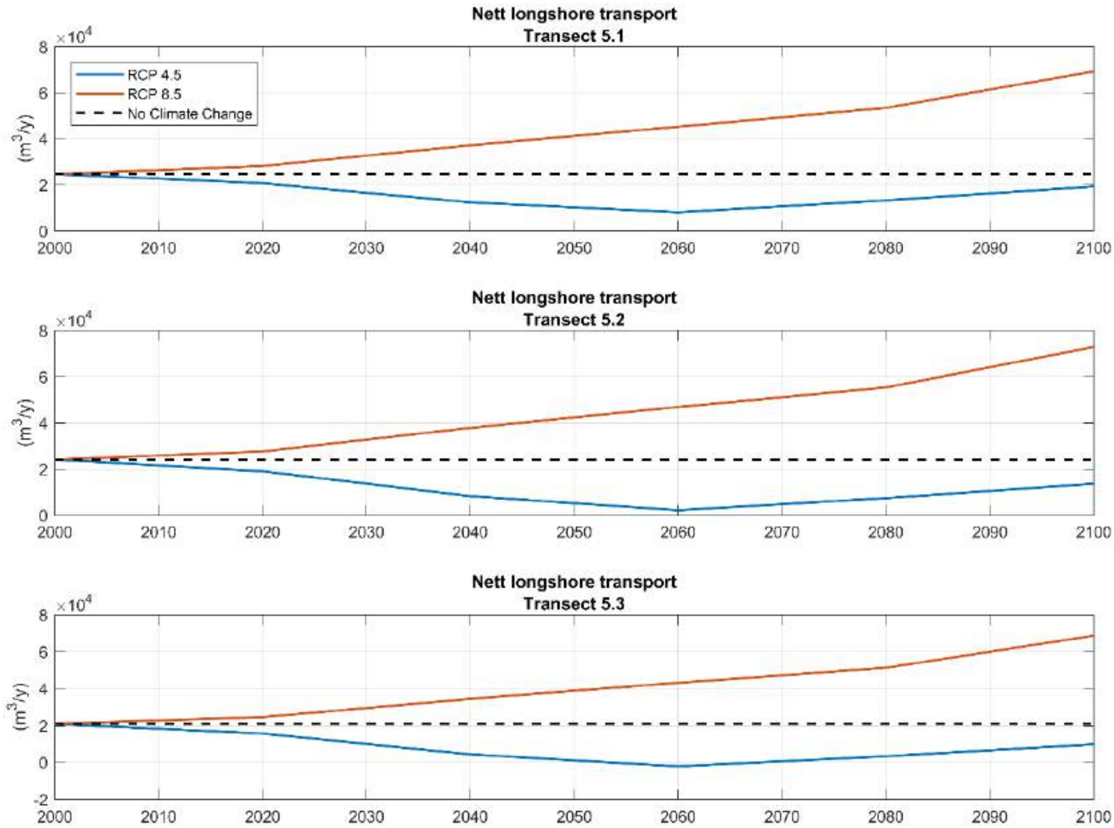


Figure 4-21: Annual transport rates for the three defined transects of coastal section 5 for RCP 4.5, RCP 8.5 and no climate change

From the results it can be seen that the resulting longshore sediment transport rates for each scenario is significantly different. Due to the fact that the projected future wave direction deviation for scenario RCP 8.5 is more southerly/easterly and the wave height increases (see Figure 4-9), the longshore sediment transport rates increase. However, since the wave direction deviation for RCP 4.5 is actually more westerly the longshore sediment transport rates decrease, irrespectively to the fact the wave height increases. This shows the dominant effect of the wave direction to the longshore sediment transport rates and illustrates that variation of all relevant variables need to be taken into account.

These values are used to derive the cumulative sediment transport and hence balance of each coastal cell, including the sediment exchange of the rivers and estuaries. Figure 4-23 shows the cumulative sediment transport at the transects of section 5, based on the values shown in Figure 4-21.

With these values the sediment budget in coastal cell 5.1 and 5.2 can be calculated and is shown in Figure 4-24 below. Note that the longshore sediment transport rates of transect 5.2 is decreasing more rapidly to the year 2060 compared to transect 5.1, for RCP 4.5, leading to an accelerating decrease of the sediment volume and hence accelerating coastal retreat. However, for the RCP 8.5 scenario the increase of longshore sediment transport of transect 5.1 is more compared to transect 5.2 leading to a decrease of sediment budget.

The coastal retreat (or advance) is determined by dividing the change in sediment volume in each cell with the active height of the profile and the length of the cell, assuming the coastal profile shape remains equal. The following expression shows the relationship:

$$\frac{\Delta y}{\Delta t} = \frac{\frac{\Delta V}{\Delta t}}{L * (D_c + h_{beach})}$$

Where *Δy* is the coastline position change in cross-shore direction, *Δt* the time step (in this case years), *ΔV* the volume change in the coastal cell, *L* the length of the coastal cell in alongshore direction, D_c the depth of closure and h_{beach} the beach height (3 m in this case). Figure 4-22 shows schematically the derivation of the coastline change and the definition of the parameters.

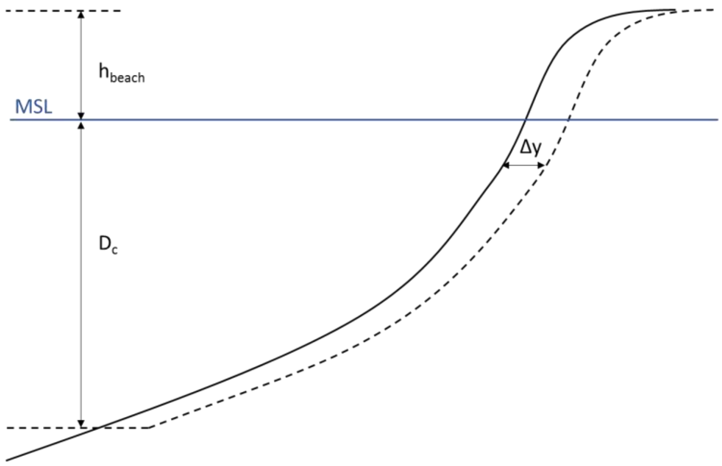


Figure 4-22: Derivation of coastline position change

A decreasing of sediment budget, as seen in coastal cell 5.1, will eventually lead to decelerating coastline retreat as well.

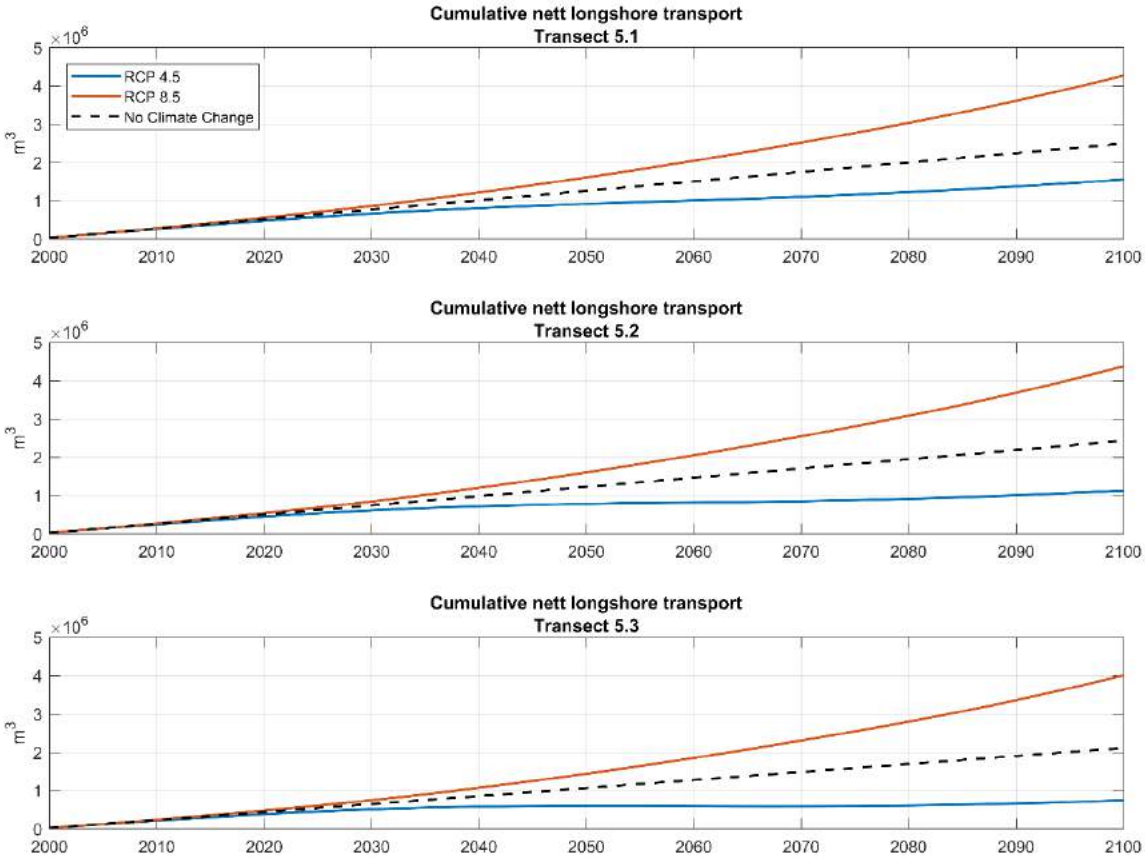


Figure 4-23: Cumulative sediment transport through the transects at coastal section 5 for RCP 4.5 and RCP 8.5

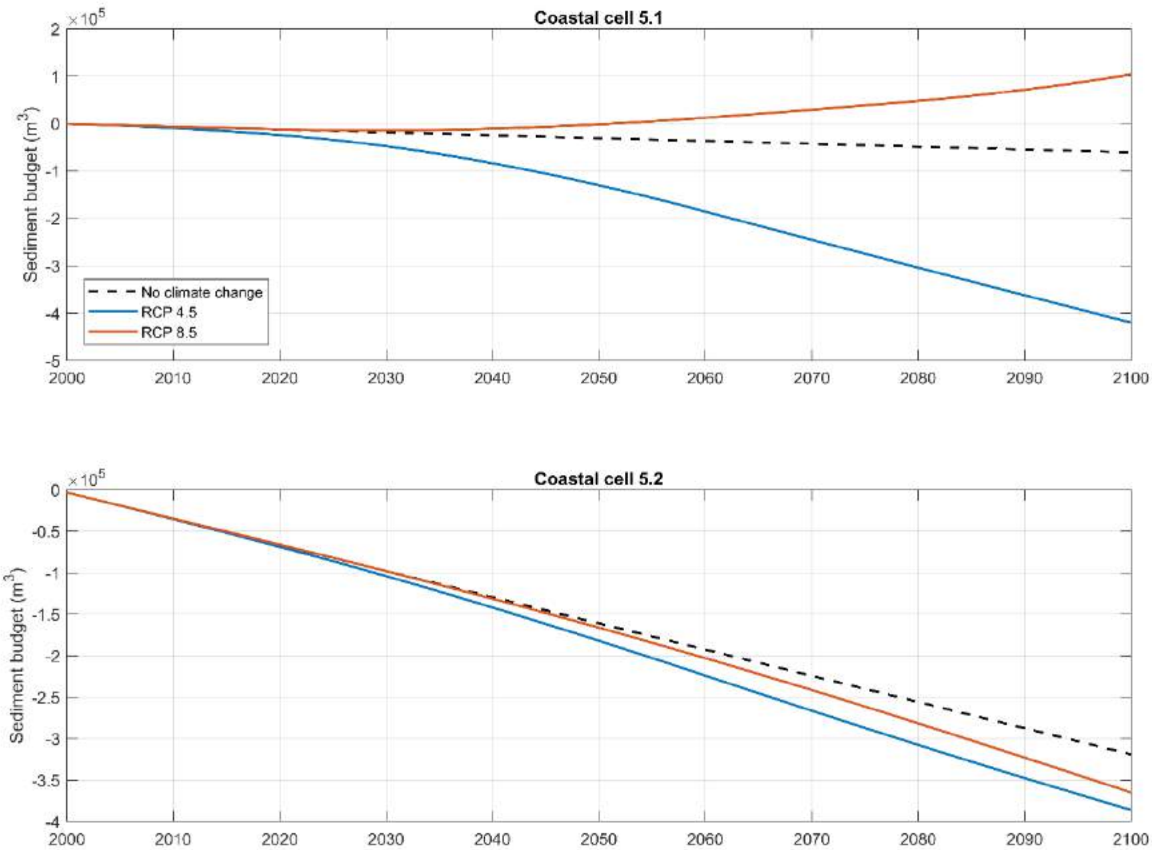


Figure 4-24: Sediment balance for coastal cells of coastal section 5 for RCP 4.5 and RCP 8.5

4.5 Coastal retreat due to sediment deficit and Bruun effect

The above mentioned processes: sediment deficit and the Bruun effect has been combined (added up together) to assess the past, present and future coastal retreat at each section. The *average* coastal retreat of the predefined coastal cells in each section is determined and shown in Figure 4-25.

From the results it is clear that especially section 2 and 3 show relative large coastal retreat, with both significant worsening due to climate change. The resulting coastline for several projection years are shown in the vulnerability section.

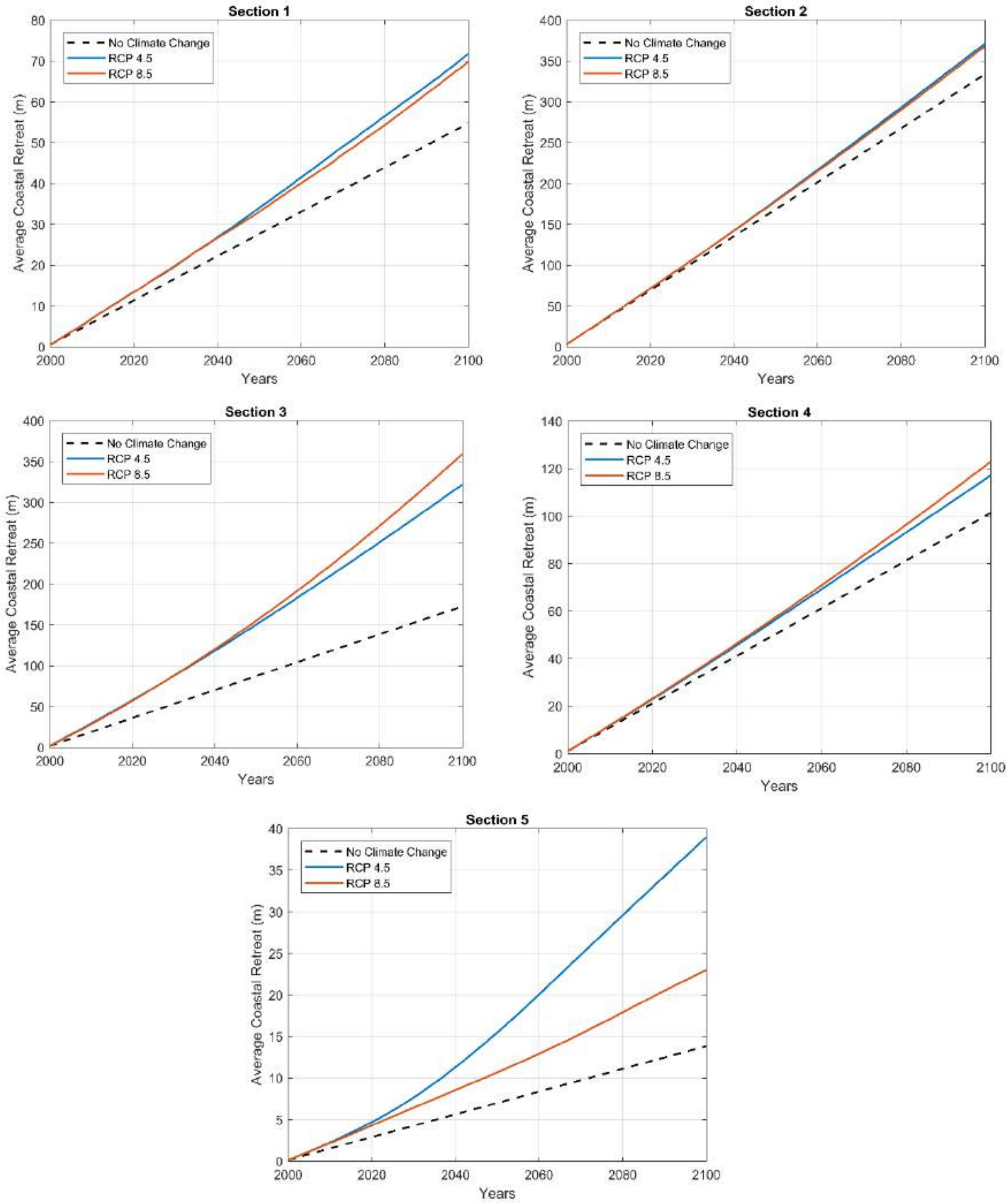


Figure 4-25: Coastal retreat due to sediment deficit and Bruun effect for each section and RCP 4.5, RCP 8.5 and no climate change

The above figures shows the effect of climate change and natural processes on the coastal retreat of each section over the last two decades and future projections. The calculated values are compared to the observed coastal retreat over the last decade with use of satellite images.

Two satellite images of each section are compared one taken on January 30, 2008 and one on March 12, 2018. The average coastal retreat over the sections is calculated by determining the eroded and accreted areas divided by the length of each section. The areas are determined using Google Earth.

Figure 4-26 show an example of West Point (section 3), where the red areas show the eroded areas and the green areas show the accreted areas.

Figure 4-26: Eroded and accreted areas between 2008 (left) and 2018 (right) at coastal section 3

This results in the following observed coastal retreat values between 2008 and 2018 and calculated coastal retreat for both RCP 4.5 and RCP 8.5 and no climate change (no CC). It is clear that the observed coastal retreat is very much in line with the calculated coastal retreat, especially for the calculated values including the effect of climate change and substantiates therefore that the observed coastal retreat is also driven by climate change.

Table 4-3: Observed and projected coastal retreat between 2008 and 2018 for RCP 4.5 and 8.5 and no climate change

	Eroded (m^2)	Accreted (m^2)	Total Eroded (m^2)	Length (m)	Average coastal retreat 2008-2018 (m)			
					Observed	No CC	RCP 4.5	RCP 8.5
Section 1	20000	7250	12750	1950	6.5	5.4	6.6	6.8
Section 2	61500	0	61500	1650	37.3	33.0	34.2	34.3
Section 3	137240	56000	81240	2500	32.5	17.1	28.2	28.2
Section 4	19950	0	19950	2150	9.3	10.0	11.0	11.1
Section 5	10700	0	10700	3750	2.9	1.4	2.4	2.1

4.6 Storm erosion

For each section the storm erosion has been calculated using the extreme wave height statistics as presented earlier in this section by means of the morphological model XBeach (Ref [58]). During storm conditions coastal erosion mostly occurs in the cross-shore direction. The dominance of the processes are different compared to longshore sediment transport, for example the long-wave propagation and under-tow become relevant. The XBeach model is currently the most advanced model for the simulation of these type of processes.

It is expected that after a storm the beach profile is able to recover. Although no structural coastal retreat would occur in such case, damage on property has to be taken into account.

With X-Beach storm erosion profiles has been determined for each section for a representative profile of that section based on the bathymetrical survey that has been conducted. The erosion values are calculated for the years 2020, 2050, 2070 and 2100 and for the return periods 1, 10 and 100 years, based on the scenario RCP 8.5. See Appendix F for a full description of the modelling.

Below the resulting coastal profiles are shown for the return period of 100 years for each section based on the scenario RCP 8.5 for the year 2100. Note that this coastal retreat is merely storm erosion and should be considered as additional retreat with respected probability

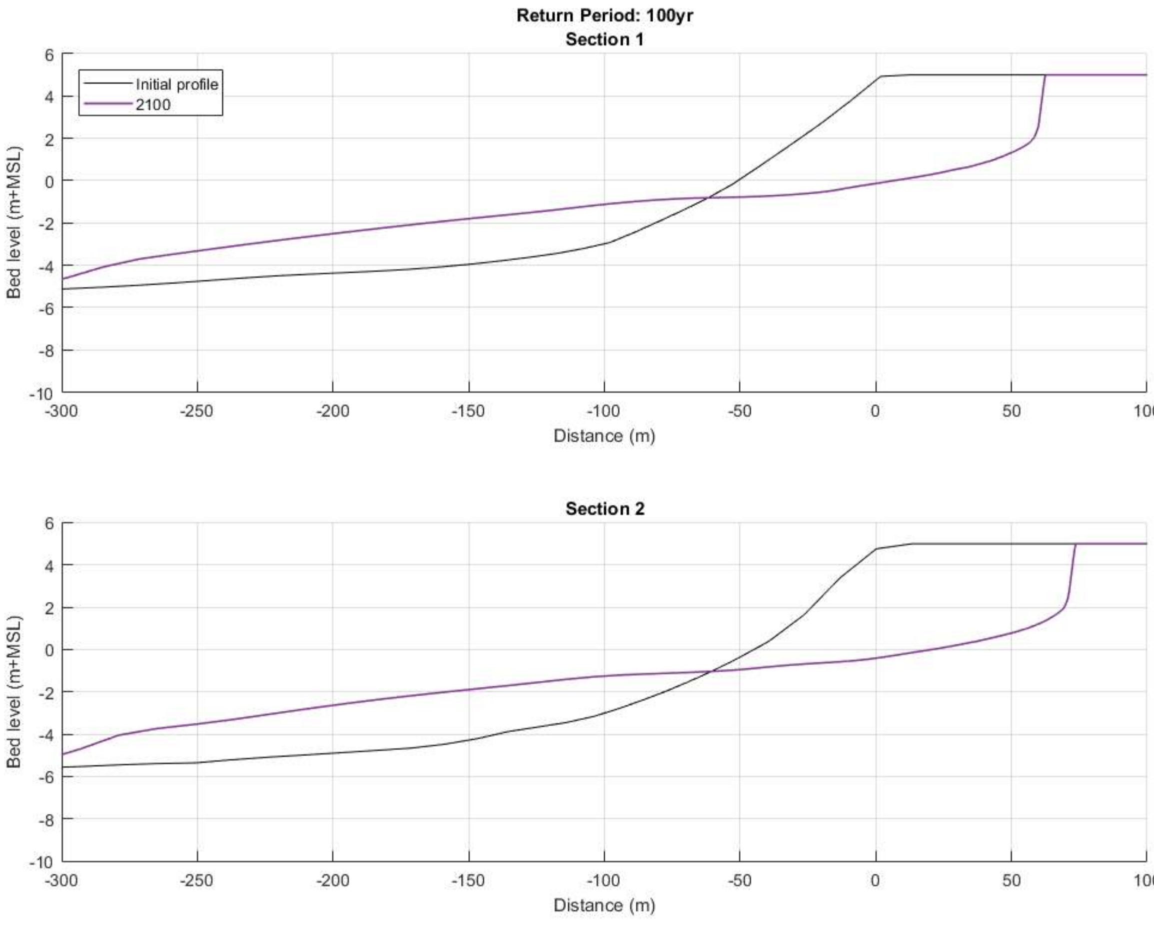


Figure 4-27: Modelled coastal profile for storm with return period of 100 years for RCP 8.5 in 2100 at section 1 and 2

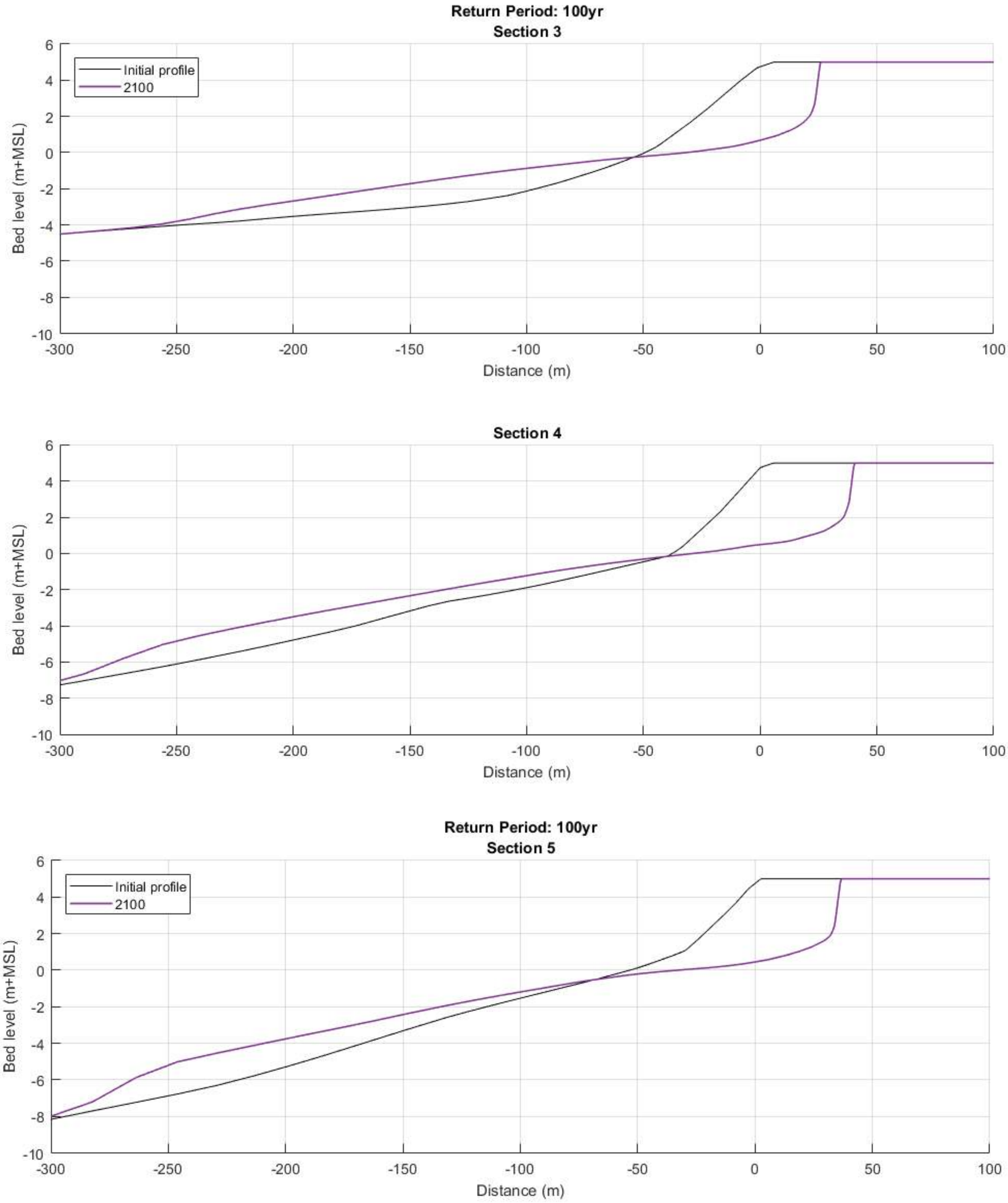


Figure 4-28: Modelled coastal profile for storm with return period of 100 years for RCP 8.5 in 2100 at section 3, 4 and 5

The additional retreat (storm erosion) due to storms are shown in Table 4-4. It is clear that section 1 and 2 suffer the most from storm erosion. This is mainly due to their relative gentle profile in combination with heavy wave attack. It is also evident that the coastal retreat is significantly increased due to climate change.

Table 4-4: Additional coastal retreat (storm erosion) in meters due to storm with return period of 100 year (RCP 8.5).

Section	2020	2050	2070	2100
1	45	49	52	59
2	52	54	59	66
3	21	23	26	28
4	25	28	29	33
5	27	29	30	33

4.7 Climate change attribution

The climate change attribution has been quantified by means of the estimation of the expected coastal retreat with and without climate change effect. The additional coastal retreat due to climate change is determined for the structural coastal retreat (sediment deficit + Bruun rule) and storm erosion separately.

4.7.1 Structural coastal retreat

The figures below show the comparison of the estimated coastal retreat with and without climate change impact for the scenario RCP8.5.

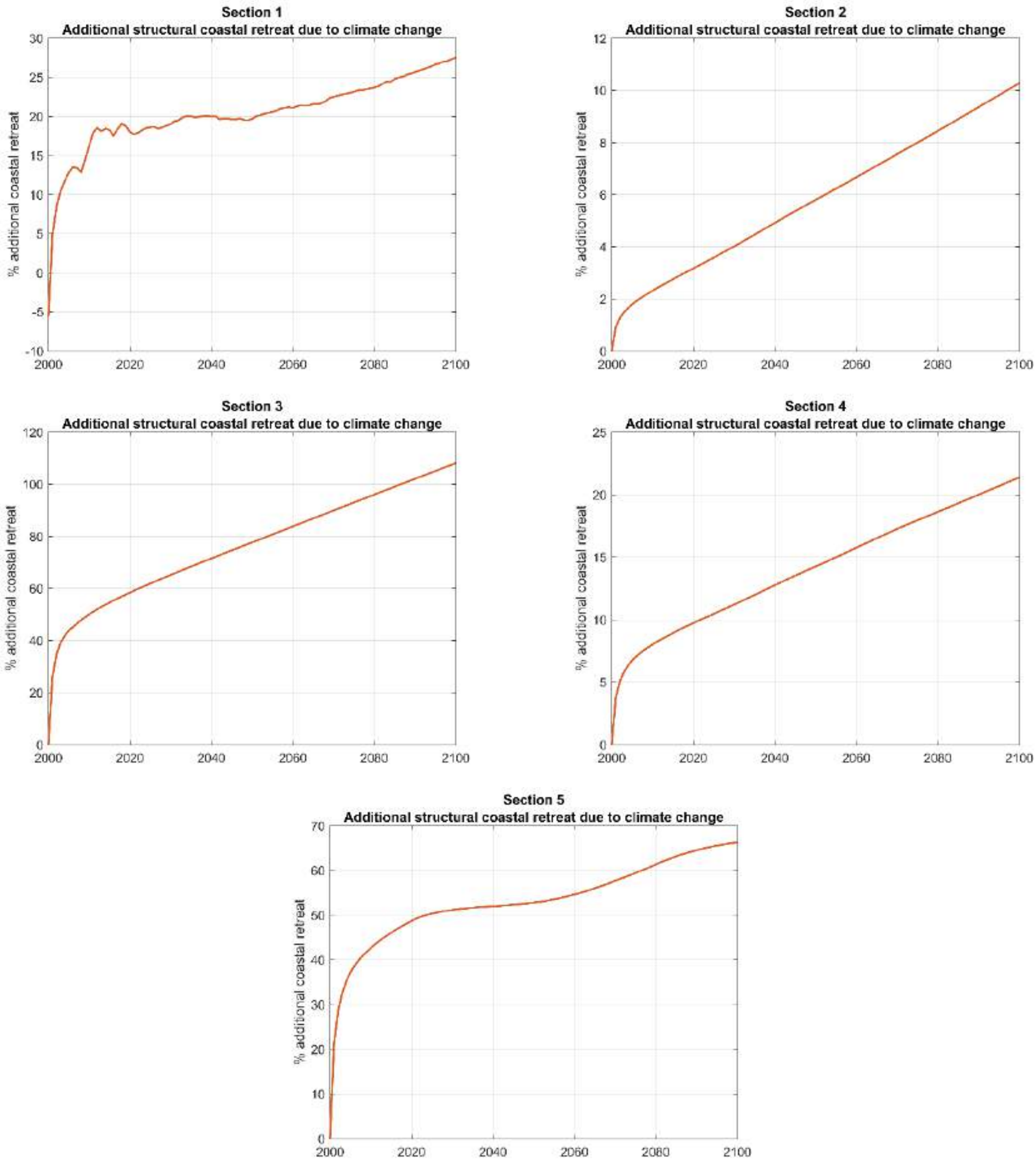


Figure 4-29: Additional structural coastal retreat due to climate change

Table 4-5 shows the additional structural coastal retreat due to climate change for each section for different projection years.

It is clear that the climate change attribution is the highest for section 3 (West Point) where due to climate change the structural coastal retreat since 2000 is increased by 60% in 2020 and will increase by 78% in 2050, 90% in 2070 and 110% in 2100.

Table 4-5: Additional structural coastal retreat due to climate change

	Additional structural coastal retreat due to climate change			
Section	**2020**	**2050**	**2070**	**2100**
1	18.0%	19.7%	22.5%	27.5%
2	3.2%	5.8%	7.5%	10.3%
3	58.4%	77.6%	89.9%	108.0%
4	9.7%	14.2%	17.2%	21.4%
5	48.7%	52.8%	57.7%	66.3%

4.7.2 Storm erosion

The increase of storm erosion due to climate change has been quantified by means of numerical modelling, see section 4.6. Without climate change it is assumed the storm erosion with a return period of 100 years remains equal. The additional storm erosion due to climate change for a return period of 100 years is shown in the figures below.

Figure 4-30 and Table 4-6 show the additional storm erosion due to climate change. Also for the storm erosion the climate change attribution is the highest for section 3 (West Point): it is estimated the storm erosion will increase with 11% in 2050, 20% in 2070 and 26% in 2100.

Table 4-6: Additional storm erosion due to climate change

	Additional storm erosion due to climate change		
Section	**2050**	**2070**	**2100**
1	9.0%	13.6%	23.8%
2	4.0%	10.7%	20.7%
3	10.9%	19.5%	26.1%
4	9.6%	12.2%	22.7%
5	7.1%	8.6%	18.7%

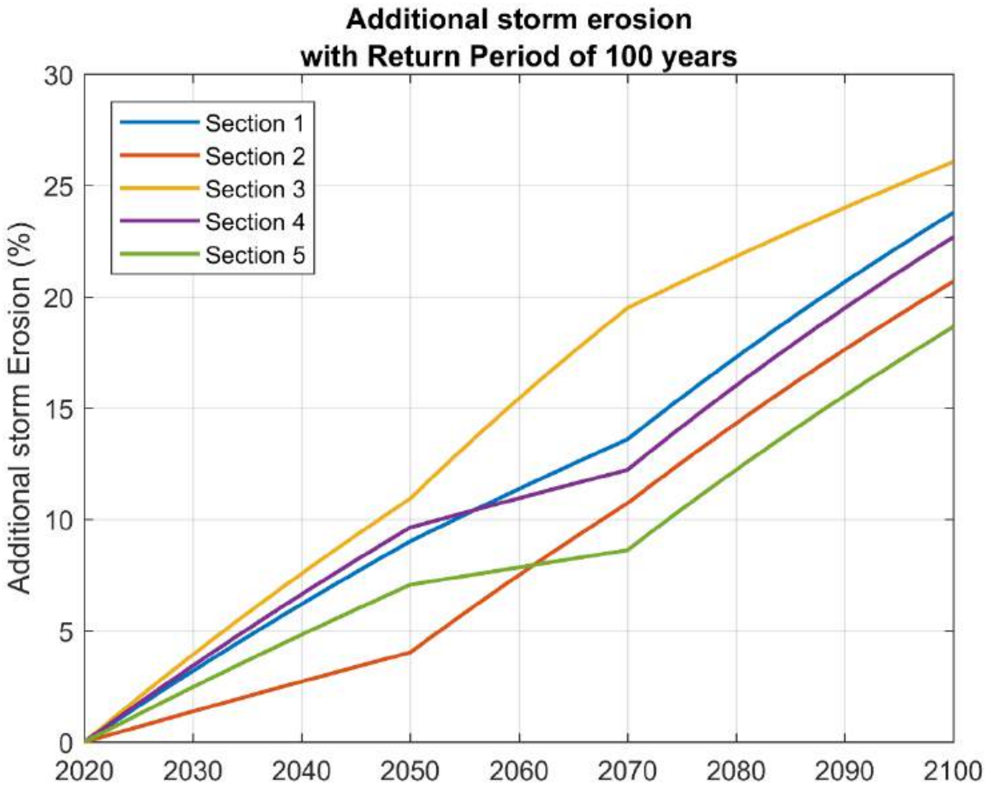


Figure 4-30: Additional storm erosion due to climate change

5. VULNERABILITY

This chapter discusses the vulnerability of the coastal sections in the baseline scenario (i.e., without taking active climate adaptation measures).

5.1 Concept of Vulnerability

Vulnerability mapping allows to identify the areas of highest need for measures and subsequently defines the focus areas or "hotspots". Vulnerability is defined as the intersection between hazards and exposure. Figure 3-2 shows the concept of vulnerability which is the combination of maps of hazard (coastal retreat) and exposure.

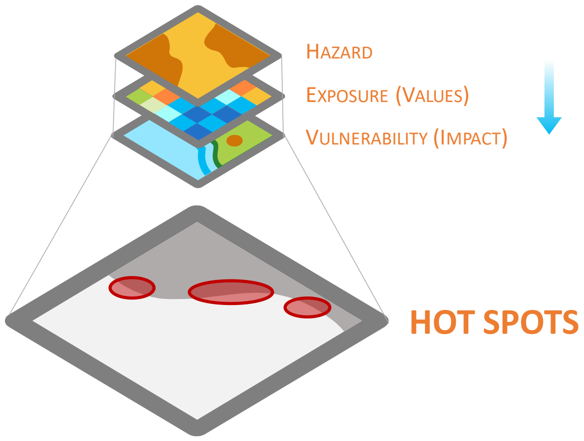


Figure 3-2 Visualization of the methodology of vulnerability assessment

In this study we have three main categories of exposure:

- Population and assets
- Critical infrastructure
- Livelihoods and coastal communities.

The vulnerability is assessed for these aspects separately and treated below. In the first following section the vulnerability maps are shown which provides an overview of the affected areas and the magnitude of the hazard (coastal retreat). The following sections assesses the vulnerability of each aspect separately.

5.2 Affected areas and coastal retreat

In this section the impacts of the hazards on coastal retreat due to coastal retreat and for storm erosion are shown, based on the determined values in the previous section. We show the impacts for the high climate change scenario (IPCC RCP 8.5), given the current map and assets in Monrovia for:

- Coastline at year 2020 (now) with an additional storm erosion due to a storm with return period of 100 years (in 2020);
- Expected coastline at year 2050 due to coastal retreat;
- Expected coastline at year 2050 due to coastal retreat including additional storm erosion due to a storm with return period of 100 years (in 2050);

The coastal retreat and additional storm erosion values for the sections (w.r.t 2020) are as follows, based on the Climate Change analysis study:

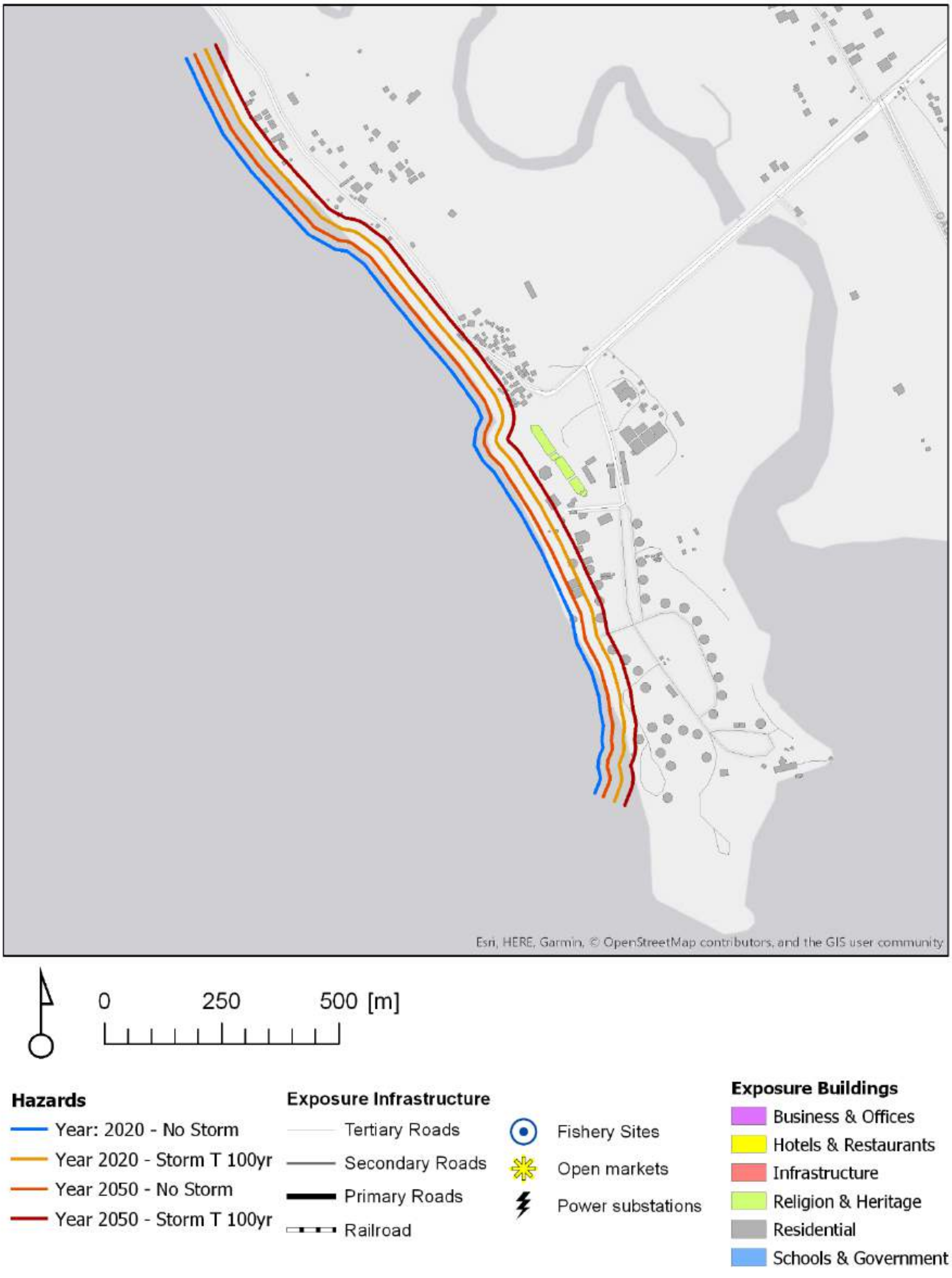
Table 5-1: Coastal retreat and additional storm erosion used for the Vulnerability analysis for RCP 8.5 in meters w.r.t 2020 coastline position.

Section	2020 + Storm 100 y	2050	2050 + Storm 100 y
1	45	20	69
2	52	107	161
3	21	229[6]	252
4	25	35	63
5	27	6	35

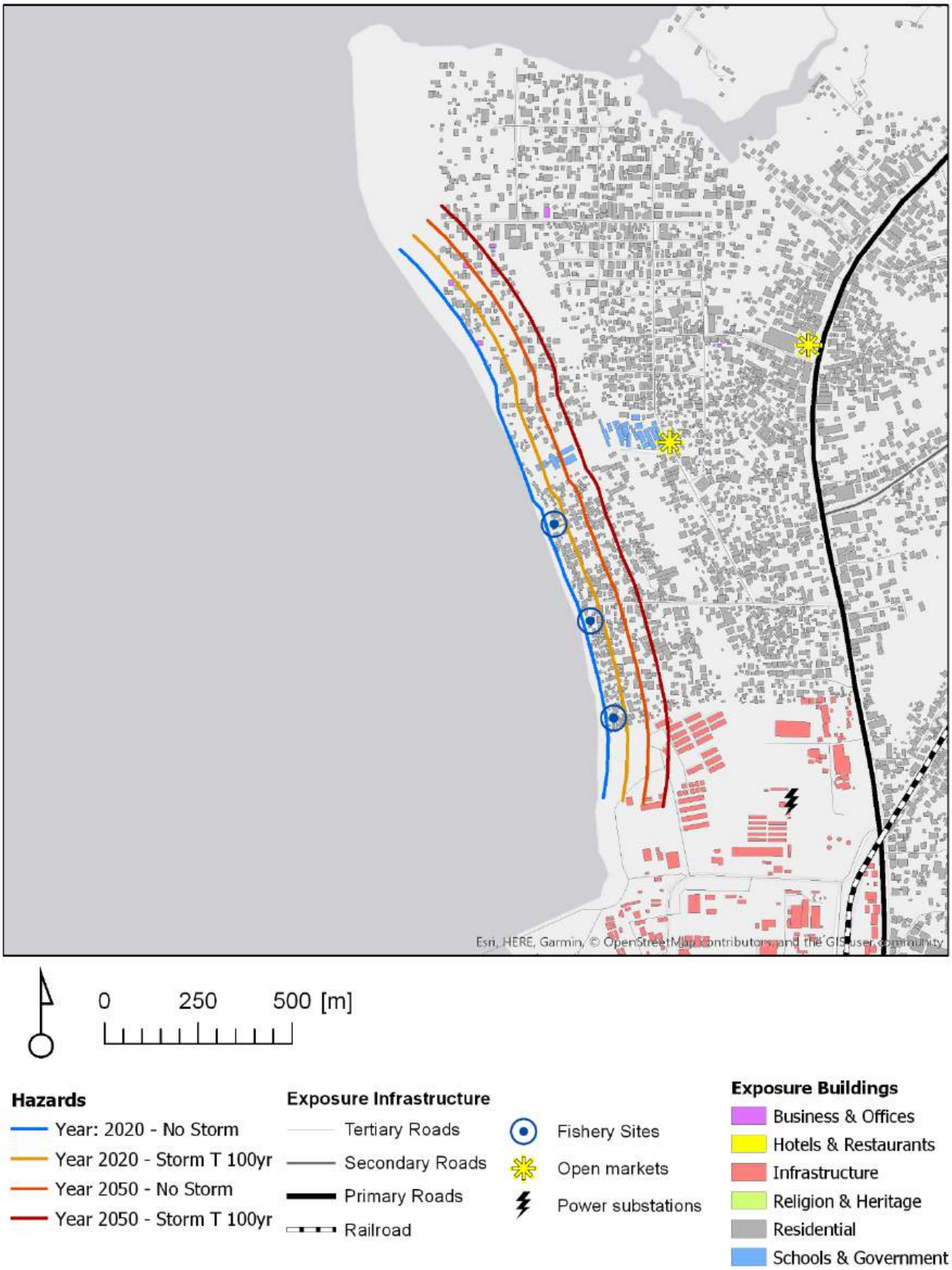
The next pages show the vulnerability maps for each section separately.

[6] It is noted that this value is larger than the earlier presented *average* coastal retreat of section 3 as only the value of the coastal cell 3.2 along West Point has been used for the vulnerability, as using the average over the complete section (from Mamba Point up to the Breakwater) would be too optimistic.

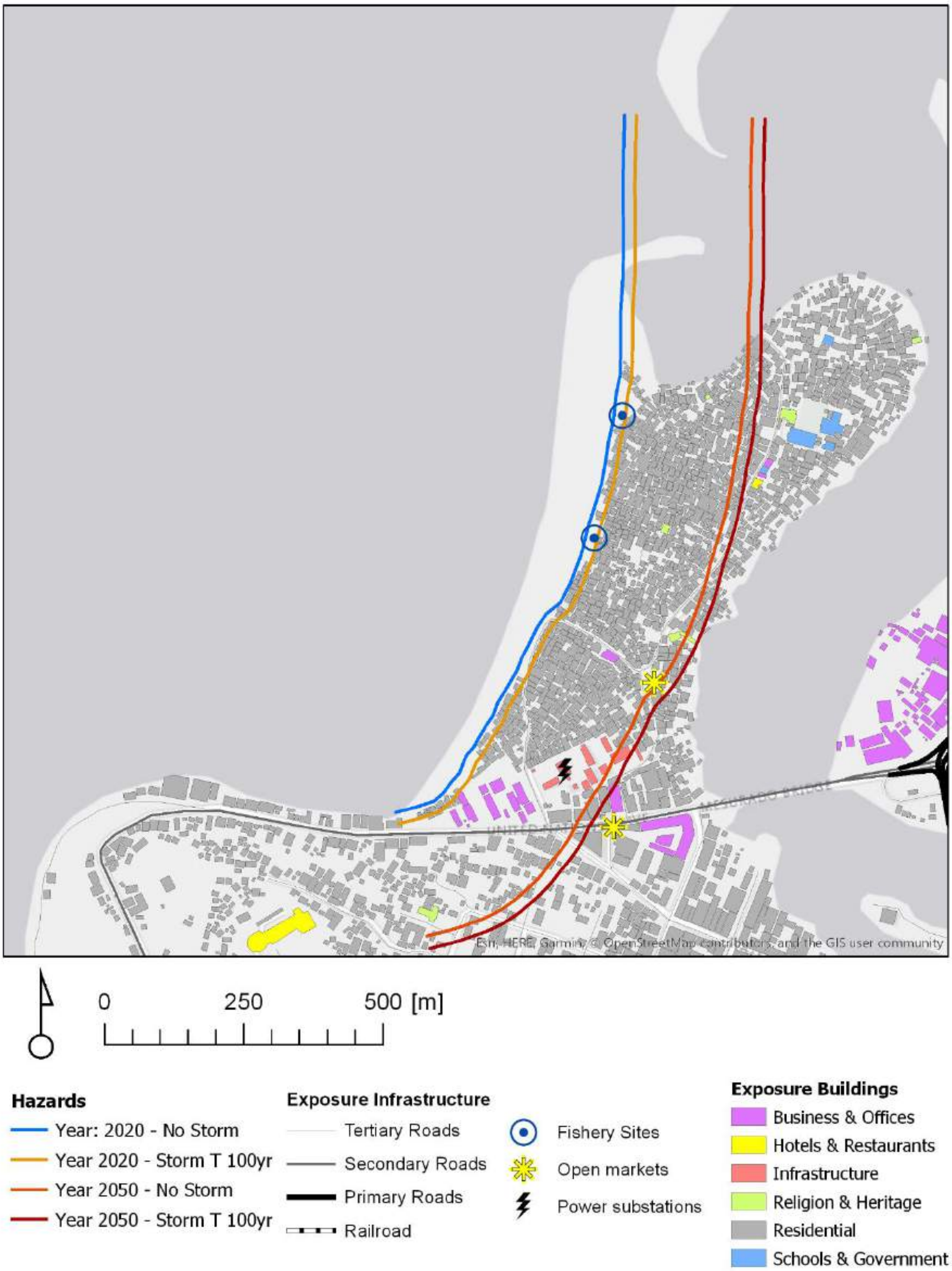
Coastal Section 1



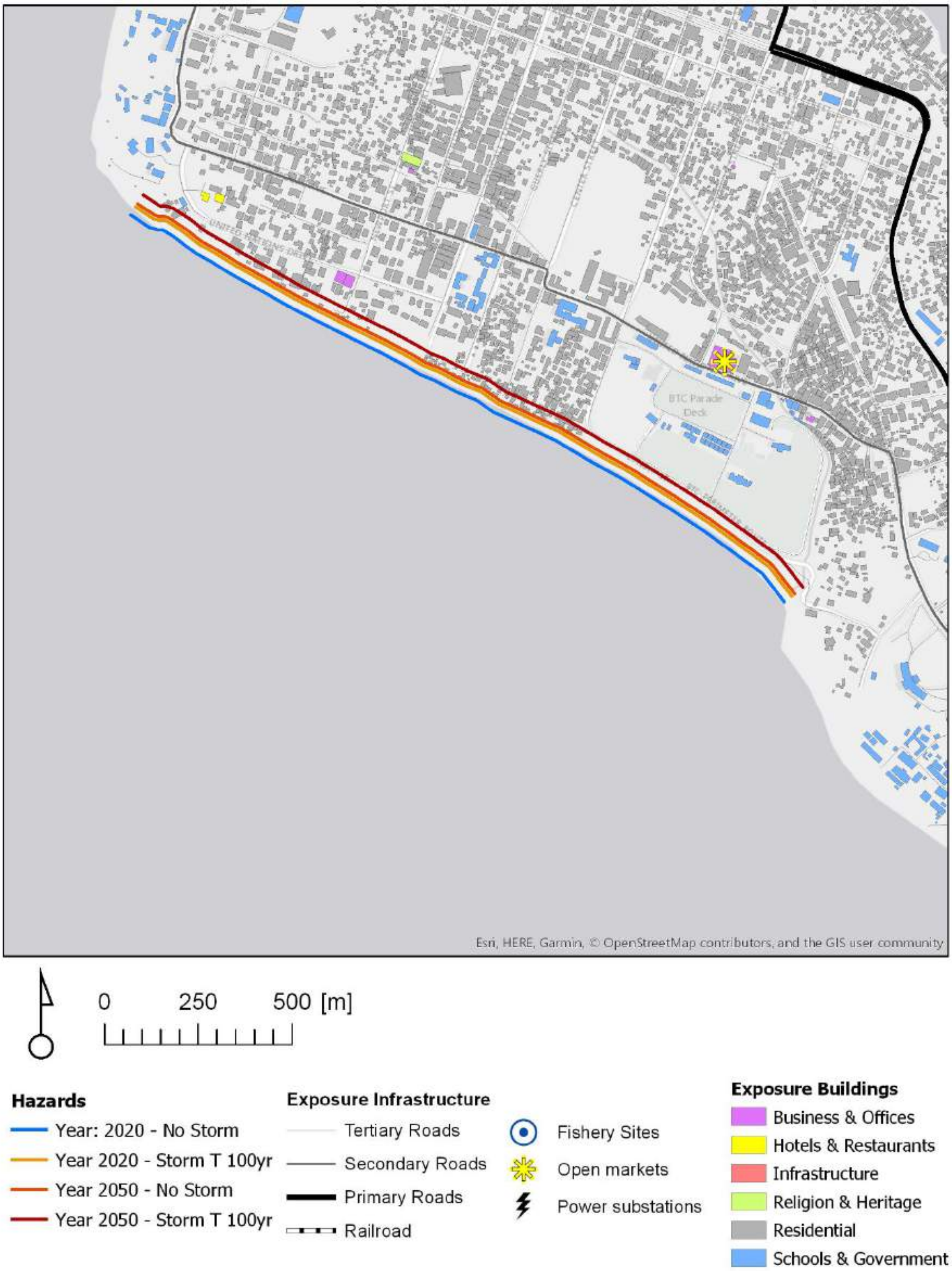
Coastal Section 2



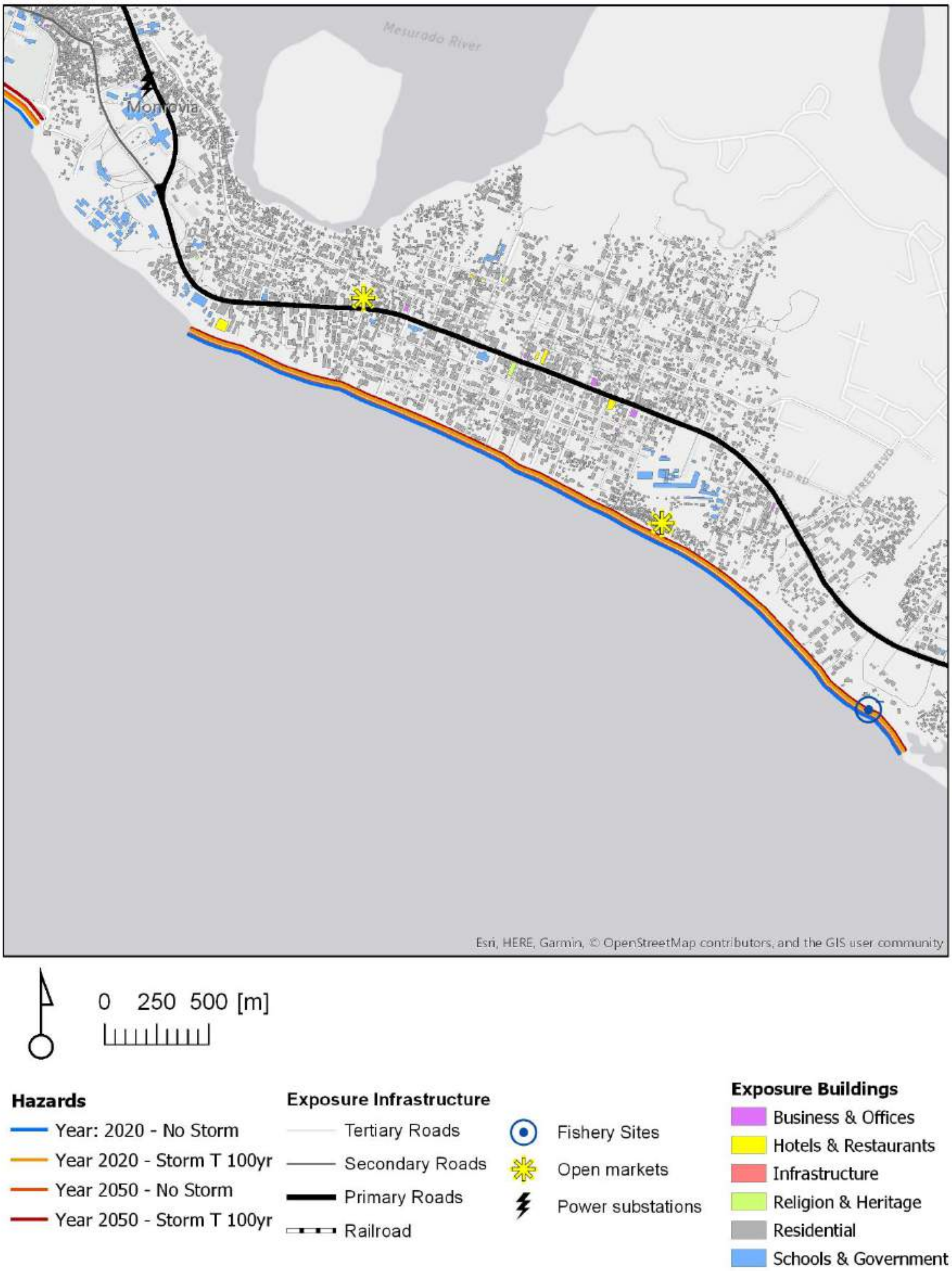
Coastal Section 3



Coastal Section 4



Coastal Section 5



Overview coastal sections

Table 5-2: Assessment of climate vulnerability prone coastal areas 2020-2050, high climate change scenario, RCP 8.5

	Section 1	Section 2	Section 3	Section 4	Section 5
Hazards 2020					
Coastal retreat					
Additional Storm T=100 yr					
Hazards 2050					
Coastal retreat					
Additional Storm T=100 yr					
Hazards Total					

Note: Orange implies small to moderate coastal retreat (in m.) due to coastal erosion and small to moderate number of assets affected by storm erosion. Red = large coastal retreat in m and large number of assets affected by storm erosion.

As can be concluded, the coastal retreat (in meters) due to erosion is to be expected largest in 2050 in the coastal sections 2 (New Kru town) and 3 (West Point). Storm erosion affects the coastal sections 2, 3 and 4 most heavily. Especially, the sections 2, 3 and 4 can be regarded as the hotspots in terms of vulnerability in terms of all hazards.

5.3 Direct and indirect damage of assets.

Scope, exposure and vulnerability of assets

In this study we have identified the following asset categories based upon google earth, open street maps and other GIS information:

- Business & offices buildings (formal commercial assets);
- Religious & cultural buildings;
- Infrastructure (port buildings, utility buildings, etc.);
- Government & education buildings (administration buildings, schools etc.)
- Residential buildings (formal & informal housing);
- Fishery sites (landing sites for canoes);
- Power stations.

For each of these asset classes impacts of the hazards has been identified and estimated.

The total exposure of all the assets, population and infrastructure is shown in the table below, which show the total number of buildings, assets and populations of the coastal sections of Monrovia. See also the map in Figure 3-5, showing the map of all the exposed assets.

Table 5-3: Exposed assets, population and infrastructure (until Trunk Road – baseline)

Section	1	2	3	4	5
Buildings					
Business and Offices	3	7	186	6	3
Hotels and Restaurants	-	-	1	2	2
Infrastructure	-	71	14	-	-
Religion and Cultural Heritage	5	-	6	2	1
Residential	1052	2670	1812	3372	1353
Schools and Government	-	30	5	62	44
Power substations	1	1	1	-	-
Fishery sites	-	3	2	-	1
Open markets	-	2	2	1	1
Population[7]	4208	16020	10872	13488	5412
Area in ha	379.5	137.2	136	235	174
Road length in km	22.15	10.5	7.80	28.4	19.2

Figure 5-1 below shows the potential affected buildings of each section, showing the total number of buildings affected based on a certain amount of coastal retreat (this includes all buildings shown in the table above). Figure 5-2 shows the potential affected buildings of each section, showing the affected number of buildings per type (excluding residential) based on a certain amount of coastal retreat.

[7] Assumed 4 person per res. building in section 1,4 and 5; 6 persons in section 2 &3

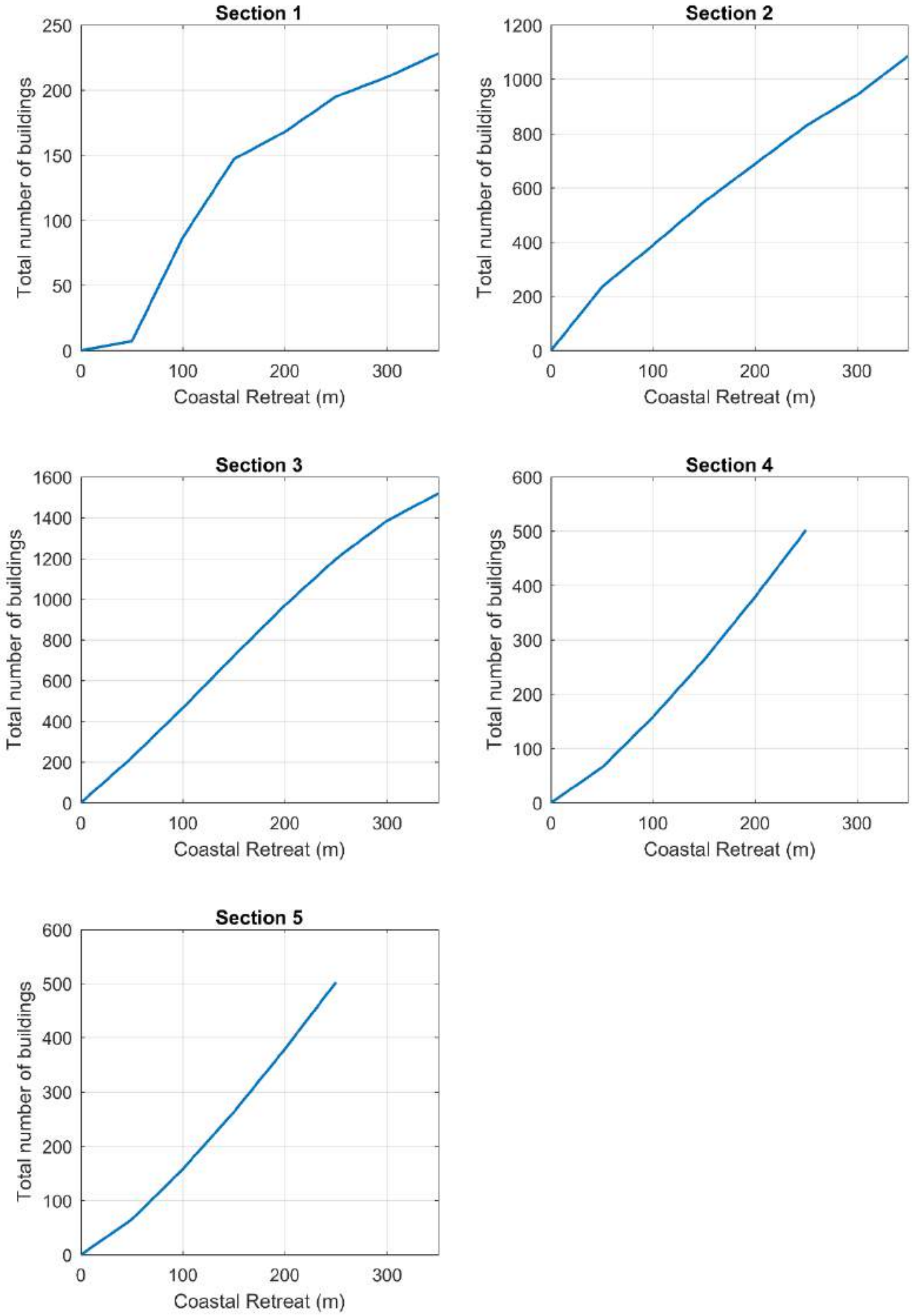


Figure 5-1: Total number of buildings affected with certain amount of coastal retreat

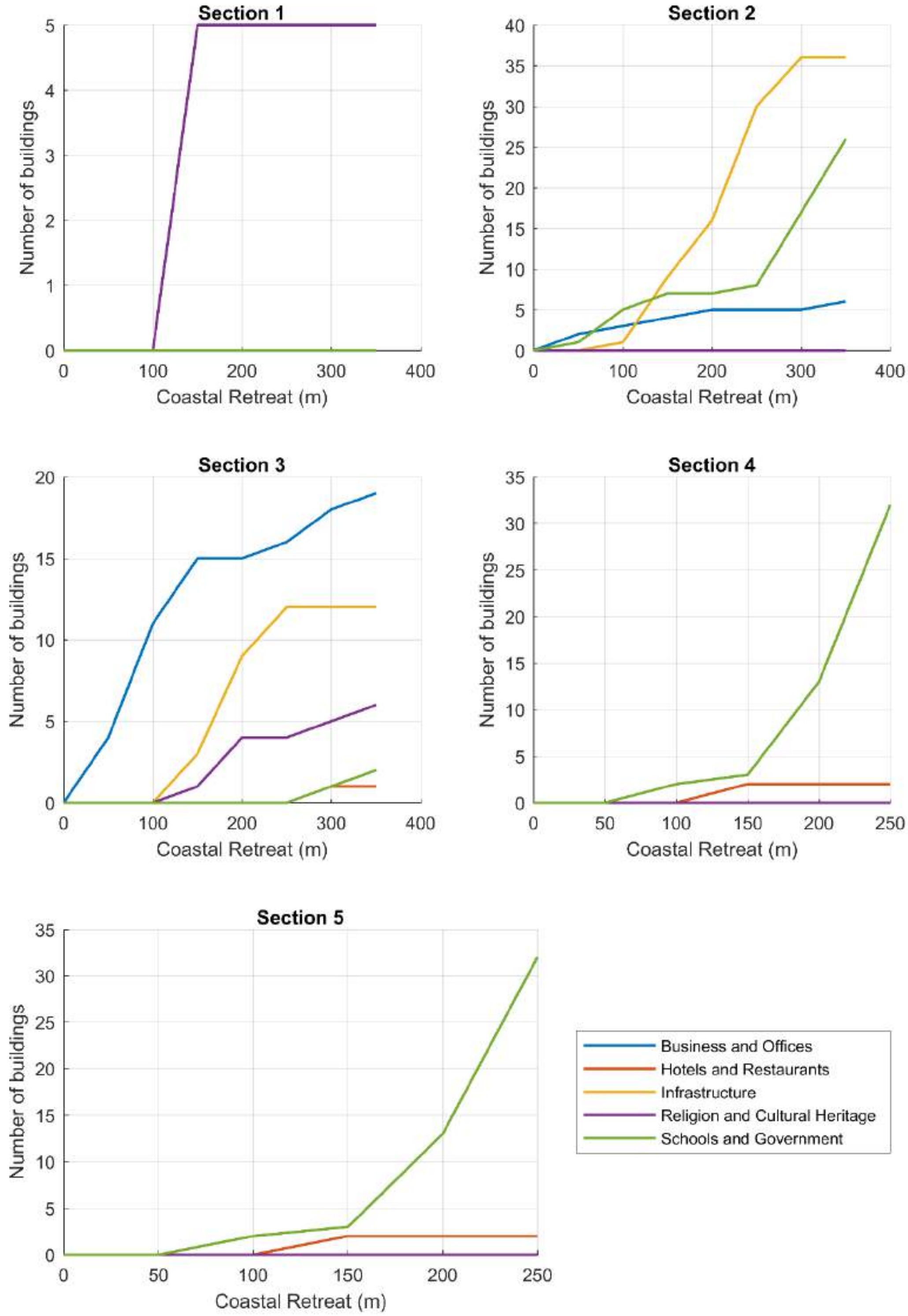


Figure 5-2: Number of buildings (per type, excluding residential) affected with certain amount of coastal retreat

Socio-economic development

The population and economy will continue to develop in Monrovia. Therefore, the assets (buildings, other) might change in volume and in quality over time in the coastal sections. For this reason, we have developed two socio-economic scenarios in this study: a pessimistic socio-economic scenario and an optimistic socio-economic scenario. In Appendix G more details are provided regarding the scenario's and historical trends. In below table the key assumptions for population and GDP growth are summarized for the optimistic scenario.

Table 5-4 Socio-economic scenario assumptions for damage baseline model and Cost-Benefit Analysis (CBA)

Optimistic scenario	**2019-2030**	**2030-2050**	**2050-2070**	**2070-2100**
Economic growth (GDP)	4,8%	4,0%	3,5%	3,0%
Income per capita growth	1,8%	1,5%	1,5%	1,5%
Population growth Liberia	3,0%	2,5%	2,0%	1,5%
Population growth Monrovia	3,9%	3,4%	2,5%	2,0%

Vulnerability of population and assets

The figures below show the affected buildings due to hazards in the coming years, based on the coastal retreat calculated in the section about Climate Change. The first figures provides the total affected buildings (incl. residential) for each section based on the expected coastal retreat for RCP 8.5 (excluding additional storm erosion). The second figure shows the affected buildings per type (excl residential) for each section based on the expected coastal retreat for RCP 8.5.

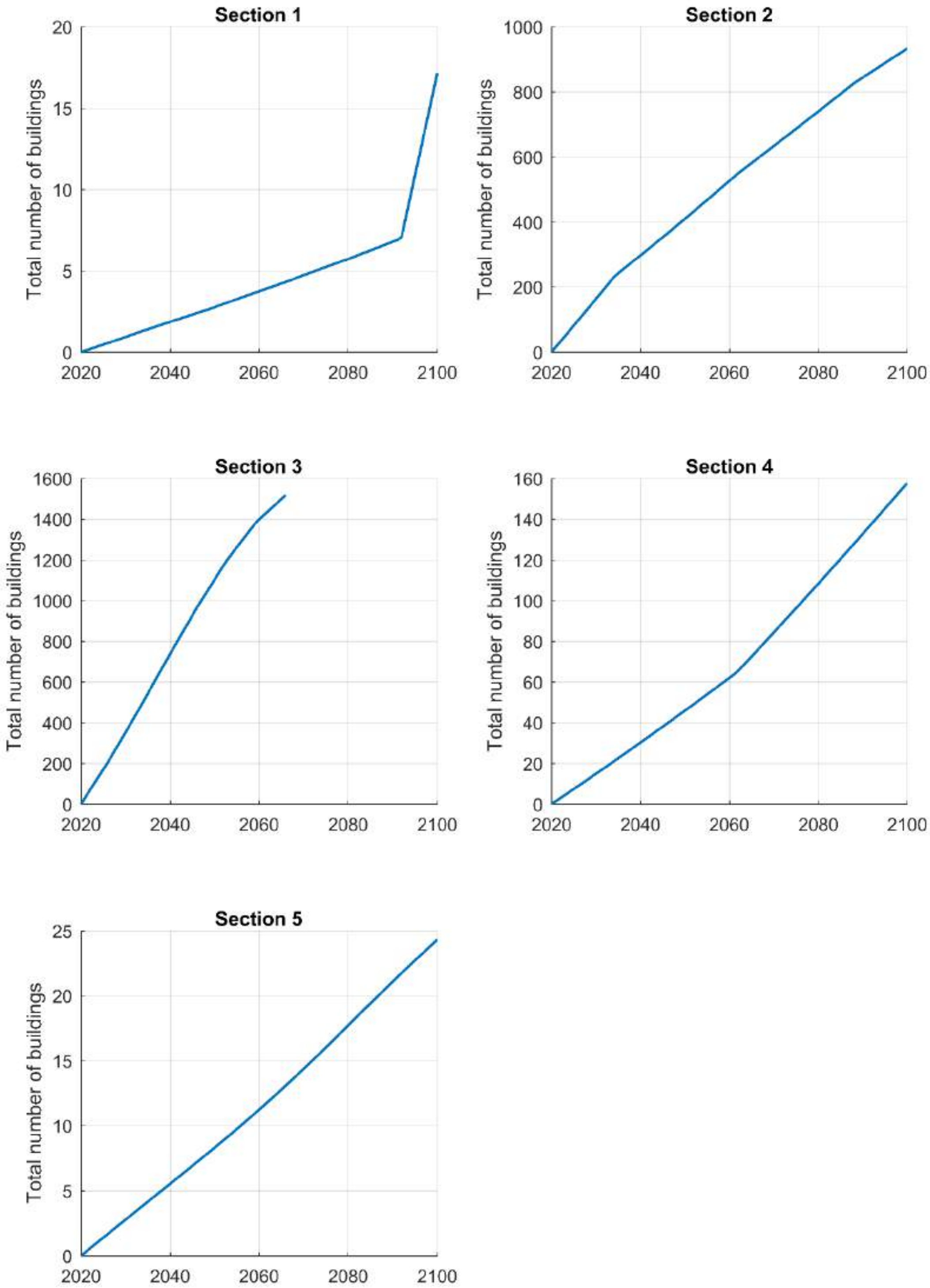


Figure 5-3: Total number of buildings affected due to hazards (coastal retreat) for RCP 8.5

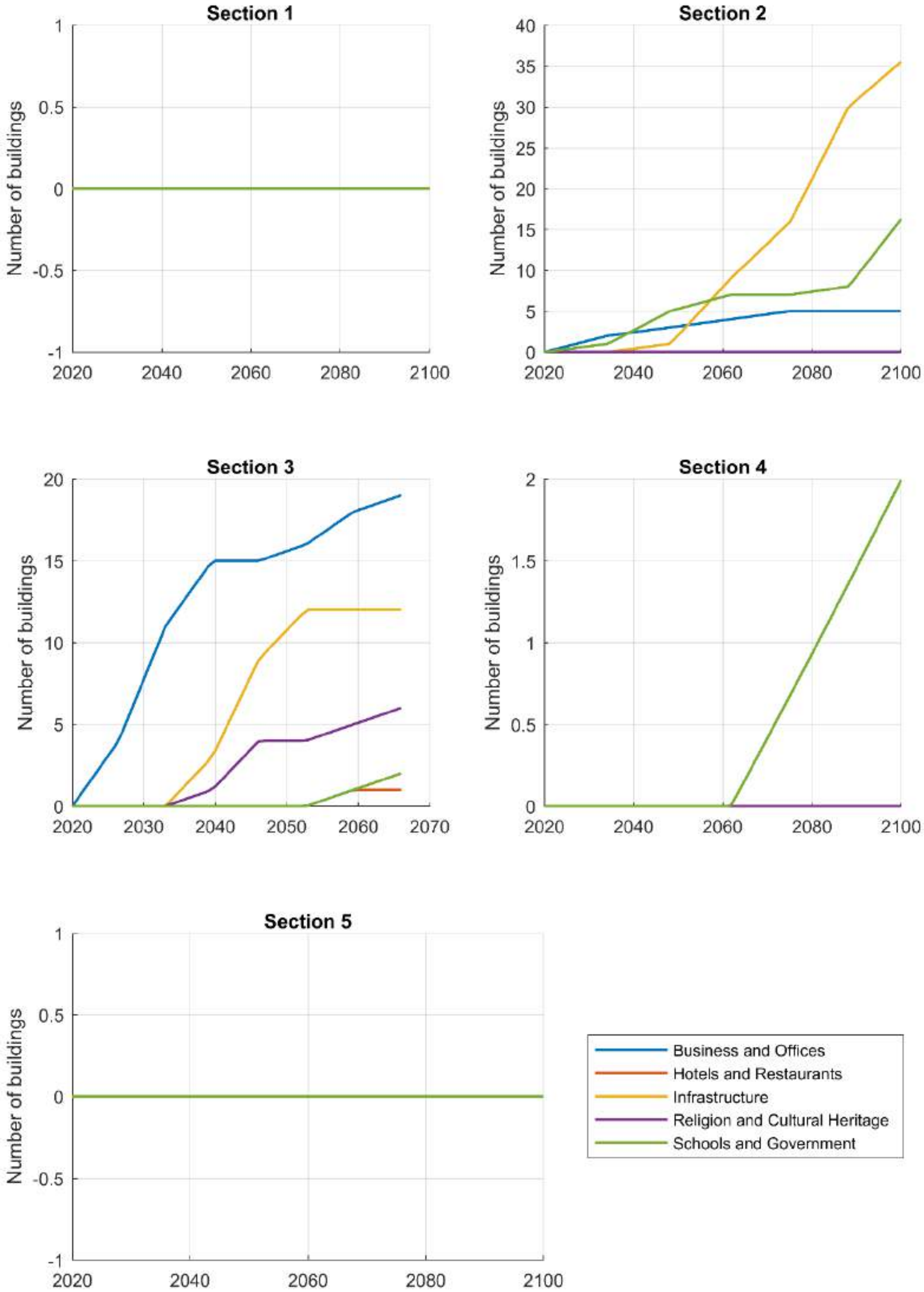


Figure 5-4: Affected buildings due to hazard (coastal retreat) per type (excluding Residential) for RCP 8.5

Below tables provide the population and assets (residential buildings, roads) vulnerable for the hazards for each of the sections. As can be seen in sections 2 and 3 thousands of residents are vulnerable in 2050 for coastal erosion. For an extreme storm erosion event (t=100) sections 2,3 and 4 are seriously vulnerable (more than 50 residential buildings are exposed). In West Point more than 1000 buildings and more than 6000 people could be affected in case of a storm event in 2050.

Table 5-5: Vulnerability of population and assets of the coastal sections for hazards in 2050

	Section					
2020 + Storm T 100y	1	2	3	4	5	**TOTAL**
Population	20	1428	516	0	0	1964
Ha of land	8.58	8.45	2.95	5.11	10.9	36
Residential buildings	5	238	86	-	-	329
Km of road	-	0.04	0.13	-	-	0

2050	1	2	3	4	5	**TOTAL**
Population	4	2394	6480	80	0	8958
Ha of land	3.79	17.68	35.24	7.16	2.42	66
Residential buildings	1	399	1080	20	-	1500
Km of road	-	0.2	1.993	-	-	2

2050+ Storm T 100y	1	2	3	4	5	**TOTAL**
Population	104	3342	7038	396	36	10916
Ha of land	13.22	27.01	39.15	12.9	14.14	106.42
Residential buildings	26	557	1173	99	3	1858
Km of road	0.01	0.55	2.29	0.33	0.003	3

Expected direct & indirect damage

Based upon the volumes of vulnerable assets in each of the sections a damage model has been developed for the baseline (do nothing scenario).

> **Hazard risk modelling - how the Damage model computes expected damages**
>
> The key principle of risk modelling is shown in the following formula:
>
> Risk = Probability * Damage= Annual Expected Damage (AED)
>
> This can be illustrated with the example of a single hazard event, say a storm which occurs on average every 100 years and creates as damage of Tk. 500 million. The risk of this single hazard event occurring in any one year is then (probability = 1 / 100) * (damage = 500 million USD) = 5 million USD. This figure is called the annual expected damage (AED).
>
> In natural disasters, more complexity is introduced because there are obviously different intensities and probabilities of weather events. These intensities lead to different damages (moderate storms with limited wave heights and limited damage versus extreme storms with higher waves and high damage). The total risk is defined as the sum of the expected damage under the different hazard intensities:
>
> Total risk =
> Probability of intensity 1 * resulting damage of intensity 1 +
> Probability of intensity 2 * resulting damage of intensity 2 +
> (…)
> Probability of intensity 10 * resulting damage of intensity 10

The developed damage model estimates for the five coastal sections for each of the hazards the direct (tangible) damage and the indirect (tangible) damage.

The ***direct tangible damage*** is defined as the damage in terms of loss of (physical) assets (buildings, roads, other) due to the identified relevant hazards. For coastal retreat the complete assets (buildings, roads etc.) will be lost once these assets are in the ocean (at the pace of the coastal retreat). This damage occurs at the pace of the coastal retreat and therefore builds up over time. Storms surges (high waves and swells) come additional to the coastal retreat and will damage especially those buildings in the first row (closest to the ocean). For the storm erosion Annual Expected Damage (AED) is estimated based upon the return period of the storms (see box above).

The losses caused by the hazards are estimated in US $ loss of asset values for each asset category. For each asset category asset values (in US $) have been assumed based upon available price or (reconstruction) costs information for Liberia. Data on real estate prices, land values are scarce and historical coastal retreat damages are absent in Monrovia[8]. Nevertheless, some sources and studies have been found for real estate values such as for road (re)construction costs and for rental values (per room) and housing values[9]. Moreover, based upon the damage literature also the % of inventory (content of buildings) have been estimated per category[10]. In Appendix H the assumed asset values and building content fractions are presented.

[8] A search for data of historical damage in Monrovia due to coastal retreat did not result in any documents or data found. Therefore, it has not been possible to verify any estimates from the damage model with past data.
[9] See for example Liberia Housing Profile, 2013.
[10] See for example Scawthorne et al. 2006 – Ref [68]

Apart from loss of assets, *opportunities for urban and recreational development* (beach clubs, restaurants, real estate) could be reduced in some of the coastal areas with current space for development (sections 1, 4 and 5). Basically, this implies lower investment opportunities for these areas due to the hazards.

In below table the direct and indirect tangible damage is estimated for the years 2030, 2050, 2070 and 2100 in the do-nothing scenario (RCP 8.5, optimistic socio-economic scenario). The storm damage should be regarded as additional damage to the coastal retreat damage (in case of a storm event). In section 3 (West Point) the coastal retreat reaches such a distance in 2065 that no additional storm damage is possible anymore after 2065.

Table 5-6: Direct and indirect tangible damage in USD, 2030-2100 (do nothing scenario, RCP 8.5, optimistic socio-economic scenario)

Section 1	2030	2050	2070	2100
Cumulative erosion damage	**18.902**	**94.213**	**269.144**	**2.103.634**
Expected annual storm damage	**67.404**	**128.443**	**1.195.243**	**5.644.610**
Section 2				
Cumulative erosion damage	**5.088.195**	**22.466.653**	**60.495.550**	**204.521.381**
Expected annual storm damage	**1.214.525**	**1.513.759**	**1.874.403**	**3.474.056**
Section 3				
Cumulative erosion damage	**19.641.704**	**85.095.280**	**154.939.075**	**154.939.075**
Expected annual storm damage	**751.537**	**1.740.455**	**-**	**-**
Section 4				
Cumulative erosion damage	**1.106.710**	**1.675.326**	**18.793.620**	**80.070.501**
Expected annual storm damage	**1.272.495**	**2.828.236**	**5.990.126**	**23.675.460**
Section 5				
Cumulative erosion damage	**206.258**	**2.137.388**	**3.203.413**	**12.387.876**
Expected annual storm damage	**6.617**	**12.869**	**23.889**	**69.298**
Total cumulative erosion damage	**26.061.769**	**111.468.860**	**237.700.802**	**454.022.468**
Total AED storm damage	**3.312.579**	**6.223.762**	**9.083.662**	**32.863.425**

Note: In Appendix H damage impacts are presented for the low climate change (RCP 4.5), pessimistic socio-economic scenario.

As can be seen the total (all sections) cumulative damage caused by coastal retreat is substantial and grows from almost 30 million USD in 2030 towards more than 450 million USD in 2100 (a growth by a factor 17 in 70 years). This is caused by several variables. Firstly, the coastal retreat in meters rapidly increases in the next 80 years (i.e. section 3 from almost 8 meters in 2021 to 450 meters retreat in 2067, after 2067 no further retreat). Secondly, the volumes of assets are likely to grow over time in the sections with expansion space (1, 2, 4 and 5). Thirdly, the quality of the stock of assets will increase over time due to income per capita and economic growth. It can also be concluded that action is urgent, especially for sections 2 and 3: damages are within the next 10 years quite substantial (over 5 million USD in section 2 and over 20 million in section 3) in 2030 (in the do-nothing scenario).

Direct intangible damage is defined as loss of life or health or psychological or recreational impacts due to the hazard events. For erosion no loss of life is expected. For storm erosion life lost or injuries could be relevant for extreme storms. Moreover, coastal erosion and coastal retreat will reduce beaches and beachfronts in most of the coastal sections. Currently, these beaches are often used for recreation (football, playing, swimming, restaurants/beach clubs etc.) Therefore, the *recreational value of beach life* for the local residents will be seriously affected by the hazards. However, it was not yet possible to quantify these intangible direct impacts due to lack of data on numbers of visitors (use) and recreational values.

Indirect damage is defined as loss of income due to event induced business interruption and costs of disaster response. Loss of income due to the hazards will be especially relevant for the communities depending on the shore such as fisheries and informal local shops & markets (especially around New Kru town, West point and Bernards beach).

5.4 Vulnerability of livelihoods of coastal communities

From the previous analysis it becomes clear that communities in coastal sections 2 (New Kru town) and 3 (West Point) will be most heavily affected by the hazards. The communities in these sections are also the poorer parts of Monrovia and rely for their existence on fisheries and informal economic activities such as shops & markets. These activities are to a large extent depending on the availability of the coastal shore (beaches as landing sites for canoes). Moreover, the fishing sector results in backward and forward linkages to suppliers (fishing boats, materials) and distribution & sales. In the latter activity a large number of women are active. In section 4.4 it was shown that the landing sites for fisheries will be lost in the do-nothing scenario. This can have serious repercussion on livelihoods if these completely disappear or it implies that these landing sites need to be relocated to the inland part of the West Point peninsula or to more safe other coastal areas in Monrovia. The latter will result in additional costs to the fisheries, which will also negatively affect the livelihood of the community.

A survey (held in February 2019) under this project (as part of the ESAR) shed some more light on data regarding the livelihoods of the communities (fisheries, other) in these most vulnerable coastal sections (see section 5.4). The survey was based upon focus group discussions with groups of fishermen and separately fishmongers – women who process and sell the fish.

Fishing communities report in the survey that they require immediate access to gently sloping beaches. This can allow the beaching of the loaded canoes for selling the fish, repairing nets and other equipment and canoe and net storage when the sea is too rough to go out. Access to beaches is vital for storage and associated works as without such spaces fishing cannot be undertaken. In below table (indicative) data from the survey are presented regarding reported indicative catch values of the fishermen community at the locations.

Table 5-7: Livelihood fisheries communities according to ESAR survey (February 2019).

Community	Hours/ Days per fishing trip	Seasonal variation	Catch values per day (200-290 days per year)	Indicative total values (USD per year, per community)
Banjor Beach	Around 6 hours usually, if go out for 24 hours then am-am	High season catches October to April Low season catches May to September Rely on petty trading in low season	Motorised canoe: 1,500 to 20,000 LD per day Paddling Kru canoe 150 to 1,000 LD per day	30.000-315.000 USD
Popoh Beach/ New Kru Town	1-9 hours depending on catch	High season October to March	Motorised canoe 4000-6000 LD per day	300.000— 450.000 USD

Community	Hours/ Days per fishing trip	Seasonal variation	Catch values per day (200-290 days per year)	Indicative total values (USD per year, per community)
		Low season April to September		
Kru Beach, West Point	Up to one day, go out in morning and come back when ready	For nets – high season for nets October to January and March to May June to September is low season for nets but high season for line and hooks	Kru canoe 500-1000 LD per day	7500-15.000 USD
Fanti town, West Point	1-4 days at sea	High season October to May, low season June to September	Kru canoe 500-1000 LD per day per fisherman, For around 200 days per year. Fanti motorised canoe per fishermen 1000-2000 LD	22.500-45.000 USD

When the reported values and estimated about the number of boats are used to derive total catches per community, the indicative catch values per year vary around 300.000-450.000 USD for New Kru town and around 30.000-60.000 USD for West Point. Processing and sales of the fish add more value in the chain, therefore total values could be 3-5 times higher. Part of these revenues could be lost if the fishery communities are forced to stop their activities due to the hazards of coastal retreat and storm erosion. However, some communities might be able to relocate to other (safer) areas and preserve these catch values, but at higher costs (due to higher distances to the catch areas and relocation costs). If the relocation costs turn out to be passing certain thresholds, fishing activities might become unprofitable and complete loss of livelihood for all communities might occur. All in all, the hazards can have serious negative impacts on the livelihoods of the fishing communities.

Apart from impacts of the hazards on fishing communities, also other economic activities (formal and informal) will be affected in the vulnerable areas. Examples are the shops and kiosks in New Kru town and West Point. However, data on these activities were not available. For this reason, we had to revert to the literature for the estimation of the indirect damage. Based upon the literature a mark-up on the direct damage for indirect damage has been assumed of 18%[11].

In below table the expected cumulative damage due to coastal erosion and the Annual Expected Damage (AED) due to storm erosion are shown for each of the five sections.

[11] See for example Kates, 1965, Briene et al 2002, Ecorys, 2016.

Table 5-8: Direct and indirect damage of hazards, do nothing scenario 2020-2100 (high climate change RCP 8.5, optimistic socio-economic scenario)

	Section 1	Section 2	Section 3	Section 4	Section 5
Direct & indirect tangible damage					
Coastal erosion (Present Value of damages 2020-2100 in mln USD 2019)	0,1	12,4	33,4	3,7	0,6
AED Storm erosion (Present Value 2020-2100 in 2019 in mln USD)	3,1	18,2	14,2	24,3	15,9
Lost opportunities / investments for leisure & urban development	--	-		--	--
Intangible damage					
Life lost & injuries (heavy storm erosion)	-	- -	--	-	-
Loss of recreational value / beach life	-	--	--	-	-
Loss of fishery landing sites		--	--		-

Note: Damage costs have been discounted at 6% real discount rate.

In conclusion, the expected tangible estimated (direct and indirect) damage is highest in sections 2, 3 and 4 (years 2030-2100). The present value of future damages (2020-2100) is in total USD about 30 million USD in section 2, 50 million in section 3 and around 30 million in section 4. The population is relatively poor in sections 2 and 3, therefore the relative expected damage compared to the income of the inhabitants is most substantial for New Kru town and West Point. The damages are already quite substantial in 2030 making a case for urgent action. Moreover, in sections 1, 4 and 5 there might be significant lost opportunities for urban & leisure development.

5.5 Vulnerability of critical infrastructure

Critical infrastructure will be affected by erosion and storm erosion. Depending on the section and hazards, critical infrastructure such as fishery landing sites, roads, churches and a power substation will be damaged in 2050 by the hazards. Below table provides an overview of the fishery sites, m2 roads, churches and schools and power stations affected in 2050 for each of the sections.

Table 5-9: Vulnerable critical infrastructure (m2, roads, number of assets) by hazard, 2050

	Section					
2020 Storm T 100y	1	2	3	4	5	TOTAL
Roads	-	0.04	0.13	-	-	0.17
Fishery Sites	-	3	2	-	-	5
Churches	-	-	-	-	-	0
Schools & Government	-	1	-	-	-	1
Power Substations	-	-	-	-	-	0

2050	1	2	3	4	5	TOTAL
Roads	-	0.2	1.99	-	-	2.19
Fishery Sites	-	3	2	-	-	5
Churches	-	-	4	-	-	4
Schools & Government	-	7	-	-	-	7
Power Substations	-	-	1	-	-	1

2050+ Storm T 100y	1	2	3	4	5	TOTAL
Roads	0.01	0.55	2.29	0.33	0.003	3.18
Fishery Sites	-	3	2	-	1	6
Churches	-	-	4	-	-	4
Schools & Government	-	7	-	-	-	7
Power Substations	-	-	1	-	-	1

Based upon information from LEC the current value of the power station is estimated around 2,3 million USD. The power station will be affected (RCP 8.5 scenario) around 2035. It has been assumed that the depreciated value of the power station (in section 3 West Point) is 1,15 million in 2035. Loss of roads has been valued in the damage model at a loss of 425 USD per m lane. Loss of roads due to coastal retreat is most substantial in the sections New Kru town and West Point (see above table). The estimated damage (present value over the whole period 2020-2100) is estimated at 2,7 million USD in New Kru town and about 4,4 million USD in West Point.

Concluding overview

In below table the vulnerability is presented for the five coastal sections. In terms of damage, damage costs of the hazards are highest in the sections 2,3 and 4. The livelihoods of communities (fisheries, others) are especially at risk in West Point and New Kru town. Regarding tangible damage costs due to coastal retreat and storm erosion the results are presented in terms of present values of damage (2020-2100) discounted to the year 2019.

Table 5-10: Vulnerability and damage intensity assessment coastal sections, Present value 2020-2100 in million USD (high climate change IPPC 8.5, optimistic socio-economic scenario)

Damage	Section 1	Section 2	Section 3	Section 4	Section 5
Tangible direct & indirect damage (assets, economic) Present Value 2020-2100 in million USD in 2019	*3,1*	*30,6*	*47,6*	*28,0*	*16,6*
Intangible damage (health, recreation)					
Livelihood coastal communities (fisheries, etc)					
Opportunities leisure & real estate					
Total damage					

Note: Orange implies small damage to assets and communities from coastal erosion and storms. blue = moderate damage by erosion or storm erosion. Red = large damage of assets and communities affected by erosion & storm erosion.

6. POTENTIAL CLIMATE RESILIENT STRATEGIES

In the previous chapters the socio-economic and environmental systems around the coastal area of Monrovia are analyzed. At this moment, these systems are already under pressure due to a mixture of anthropologic and climate change induced factors. From our vulnerability analysis it appears that future threats to the coastal sections will be increased significantly as a result of climate change.

In this chapter potential solutions are presented which might decrease the vulnerability for climate change of coastal communities along the five coastal sections of Monrovia. Selection of the potential solutions has been based on several studies and literature see Ref [14] to [26]. Furthermore, reference is made to Appendices H, J, K and 0 for a more detailed description of potential measures.

The chapter starts with a description of the overall objectives and requirements for defining climate resilient strategies (in section 4.1). Secondly, general risk mitigation strategies are explained in section 4.2. Based on these a longlist of potential measures is developed in section 4.3. This longlist is assessed on its pros and cons and only those measures are pre-selected which are technically feasible and serve as sustainable protection of the local communities for the identified hazards. From the shortlist of measures providing sustainable protection several alternatives are further developed into potential resilient strategies (options) in section 4.4. These options have been discussed with key stakeholders in a workshop in Monrovia 30 January. The stakeholders have presented their feedback regarding a number of criteria on these options. Based on their feedback we propose several preferred strategies for the most vulnerable coastal sections (the hotspots).

The overall process regarding development and selection of measures and strategies is shown Figure 6-1.

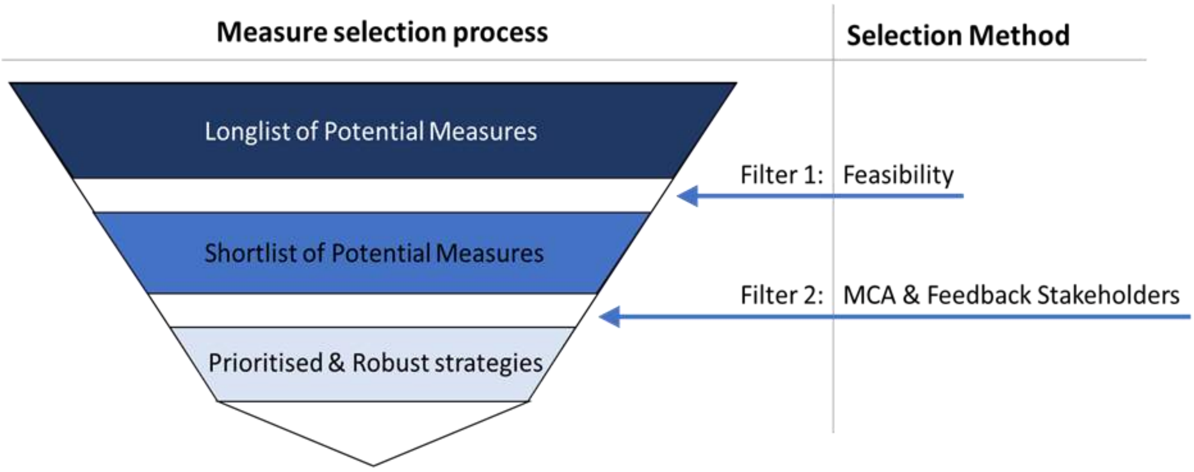


Figure 6-1: Measure and strategy selection process

6.1 Objectives and requirements for climate resilient strategies

Climate resilient strategies for coastal communities in Monrovia could contribute to the following key objectives:

1. **Reduce vulnerability and make society climate resilient**

This implies that the strategy should reduce the vulnerability for the identified hazards of the local communities in the coastal sections. In chapter 2 the key hazards identified were erosion and storm erosion. Due to the energetic wave conditions this implies that protection measures need to be identified which serve to protect the coastal communities from any damage on livelihood and assets (fishery sites, beaches, buildings etc.). This protection needs to be sustainable, protecting the communities for a long period (up until 2100) also for more extreme storm events (i.e. once in 100 years storm events/ t=100). This objective aligns with UN Sustainable Development Goal (SDG) 13 (take urgent action to combat climate change and its impacts).

2. **Protect and enhance livelihoods**

The coastal communities are depending for their livelihood on the coastal shore. This is especially true for the Kru and Shanti fishermen, but also for other communities (such as shop, beach club and restaurant workers, etc.) and women active in the fisheries sector. Measure will be identified which do not only protect these livelihoods, but also enhance livelihoods by community development. This objective contributes to UN SDG 1 (no poverty) and SDG 15 (achieve gender equality and empower all women and girls).

3. **Safeguard food security**

The ocean and mangroves serve as important sources for the fisheries. Fish products have a share of about 15% in protein consumption in Liberia. Measures improving the ecosystem and supporting the fisheries can therefore contribute to food security in Liberia. This objective is strongly rerated to SDG 2 (end hunger, achieve food security and improved nutrition and promote sustainable agriculture) and SDG 13 (life under water).

4. **Enhance ecosystems**

Finally, a resilient strategy should enhance ecosystems. Measures will be identified promoting ecosystems, but also protecting or developing recreational assets. This is both affecting nature, fisheries and recreation in a positive way and contributes to UN SDG 15 (protect, restore and promote sustainable use of terrestrial ecosystems….).

Requirements UNDP, Environmental Protection Agency (EPA) and Green Climate Fund

Next to the overall objectives, the strategy should be aligned to the requirements (and objectives) of UNDP, the Government of Liberia and the Green Climate Fund (as potential funding partner).

UNDP and Government of Liberia

The strategies defined in this chapter should be aligned with the objectives of UNDP. Before, we have showed the overall objectives of the strategies and how these are aligned with the UN Sustainable Development Goals (SDGs). Moreover, the objectives are closely related to UNDP's Strategic Plan (2018-2021) which aims at eradicating poverty; structural transformations; and building resilience to shocks and crises. UNDP Liberia aims as well to contribute to the country’s national development priorities set out in the National Vision 2030 (Liberia Rising) and the Government’s newest Pro-Poor Agenda (PPA). The focus in the resilient strategy is clearly on safeguarding and supporting the poor communities in the most vulnerable coastal sections (fisheries, other), which is precisely in line with the Government of Liberia’s *Pro-Poor Agenda*.

Green Climate Fund

The preferred strategy will serve as the basis of an application (for funding) for the Green Climate Fund (GCF). In this respect the approval process and selection criteria of the Green Climate Fund (GCF) are important to consider. In the GCF document "Initial investment framework: activity specific sub-criteria and indicative assessment factors"[12] some important assessment criteria are described. We highlight a selection of the key criteria relevant for adaptation projects in that GCF document:

- *Adaptation impact*: contribution to increased climate-resilient sustainable development. The number of vulnerable beneficiaries and expected reduction in vulnerability by enhancing adaptive capacity and resilience for populations affected by the proposed activity, focusing particularly on the most vulnerable population groups and applying a gender-sensitive approach are mentioned as important sub-indicators.
- *Paradigm shift potential.* Degree to which the proposed activity can catalyse impact beyond a one-off project or programme investment. Next to the innovative character and scale-up potential of the project, the potential for knowledge and learning (capacity building) is mentioned.
- *Sustainable development*. The potential for wider benefits and priorities such as environmental co-benefits is mentioned.
- *National ownership*. Also, the alignment with national plans and strategies is important.
- *Efficiency and effectiveness*. Economic and, if appropriate, financial soundness of the programme/project. Cost-effectiveness and efficiency regarding financial and non-financial aspects. Positive outcomes of the societal cost-benefit analysis (CBA) are important. Next to this a level of *co-finance from national authorities in Liberia* is required of about 20% of investment costs.
- *Environmental and social safeguards*; GCF applies the regular environmental and social safeguards (consistent with the requirements of the accredited agencies (such as UNDP) who function as the intermediate applying and financing agencies of the GCF.

An important consideration is also the accreditation status of UNDP as GCF accredited entity. Because of the status of UNDP GCF will set limits to the share of "hard" (engineering and works or infrastructural) interventions in the overall strategy. This implies a significant share of the proposed strategies need to consist of soft interventions such as "soft engineering", eco-based solutions, institution & capacity building and community development

[12] See https://www.greenclimate.fund/documents/20182/239759/Initial_investment_framework__activity-specific_sub-criteria_and_indicative_assessment_factors.pdf/771ca88e-6cf2-469d-98e8-78be2b980940

6.2 Integrated Coastal Zone Management

Coastal zone management strategies

Coastal erosion and coastal retreat are the main hazards that are already have caused damages and loss of land, infrastructure, houses and other buildings. Climate change will severally increase the impact of these hazards on the coastal communities of the MMA. Three basic management strategies can be distinguished to decrease the vulnerability of the affected coastal communities:

1. *Retreat* – Accept (changing) natural coastal system and retreat from vulnerable coastal zones
2. *Adapt* – Accept (changing) natural coastal system and adapt the current coastal functions to reduce its vulnerability to coastal hazards
3. *Defend (Protect)* – Intervene in natural coastal system to maintain and safeguard current functions behind the coastline

The main idea behind each strategy is explained visually by Figure 6-2.

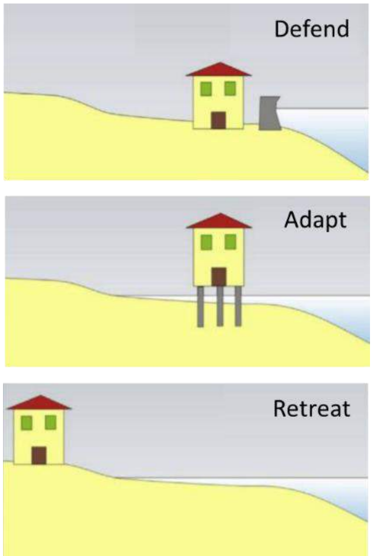


Figure 6-2: Three basic management strategies for coastal flooding

As a system-approach is applied, the final proposed alternatives to decrease the vulnerability of the coastal communities might be a mixture of these three strategies.

Retreat

Accept (changing) natural coastal system and retreat from vulnerable coastal zones.

This strategy simply implies that people move out of the area that is prone to coastal hazards. In reality this strategy is sometimes hard to comply, especially in highly urbanised coastal areas. Monrovia is close to the water because the ocean is an important source for food, transport and all other kinds of livelihood. Retreat therefore is a complex trade-off strategy between benefits and threats.

Adapt

Accept (changing) natural coastal system and adapt the current coastal functions to reduce its vulnerability to coastal hazards.

This strategy means adapting the environment and society such that people and the coastal hazards can be together at the same location. In this report, adaptation measures not only focus on reducing the impact of a coastal hazard, but on strategies that enhance the livelihood of the coastal communities on the long run. Adaptation strategies therefore are often not stand-alone solutions, but add-ons to other measures.

Defend

Intervene in natural coastal system to maintain and safeguard current functions behind the coastline.

This strategy means physically protecting a certain area against coastal hazards, to create or maintain safe living conditions behind the line of defence. From an environmental point of view, this strategy is less favourable than retreat or adapt. However, for urban areas defending is quite often the most feasible option due to the number of buildings on a relatively small piece of land.

Building with Nature

In this chapter we elaborate on possible strategies to make the coastal communities of Monrovia, and the ecosystems on which their livelihoods depend, resilient against the analyzed hazards that are aggravated by climate change. An integrated design approach is used in which hard and soft coastal measures are combined to achieve an overall enhancement of the living environment of the affected communities. The Dutch concept called "Building with Nature" merges Engineering, Nature and Society into one system-approach to develop sustainable mitigation and adaptation measures for the coast around the Monrovian Metropolitan Area.

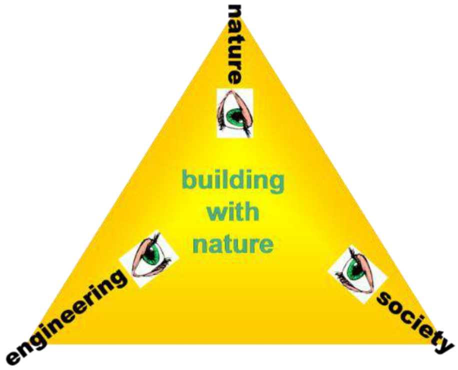


Figure 6-3: The "Building with Nature"-principle. A system approach in which engineering, nature and society are merged into sustainable mitigation and adaptation measures

The considered mitigation measures to make the coastal communities climate resilient are based on this "Building with Nature"-principle. This system approach naturally results in a combination of the management strategies mentioned in the previous paragraph.

6.3 Potential mitigation measures

The sections above explain the general setting and strategy within which feasible mitigation measures have been identified as having potential for use in the project. In Table 6-1they are given an initial evaluation for each of the retreat, adapt and defend strategies. This relates to Filter 1 in Figure 6-1.

In defining the mitigation measures, there are essentially six categories of intervention approach, shown schematically in Figure ZZ. These can be summarised as follows.

No intervention:	Do nothing – just let nature take its course.
Management option:	Use only management measures to address the problem – no physical works.
Working with natural processes:	Use natural processes, modified as necessary, to control physical effects.
Green:	Use only vegetation-based measures to control physical effects.
Green - Grey:	Use a combination of vegetation and rigid engineering structures.
Grey:	Use only hard engineering measures (i.e. rock, concrete and steel).

Overall, the key aim is usually to find the most easily implemented solution to a problem, followed by an economic analysis to ensure that it is affordable. Part of the paradigm shift proposed for this project is to place social and environmental measures as the key priority, with sustainability and economic status as the additional criteria.

Figure 6-4: From (Implementing nature-based flood protection - Guideline)

Table 6-1: Retreat, Adapt and defend strategies

Retreat strategy	Measure	Pros	Cons
Leave vulnerable area	• Do nothing • Set-back line (safety zoning) • Realignment	• No interference in nature • No maintenance • Relatively cheap	• Additional land will be lost • Difficult to implement

Adapt strategy	Measure	Pros	Cons
Adaptation actions	• Sustainable fisheries management • Protected marine and mangrove areas • Effective pollution control and waste management • Sustainable sand extraction	• Improved management of nature and natural resources • High ecological benefits • Improved food security and livelihood diversity	• No direct protection against coastal hazards
Governance	• Development and capacity building of national and metropolitan regulatory institutions (skills, regulations and enforcement) • Development of land use allocations and plans • Update land tenure system • Strengthen community-level management to control land use and illegal settlement • Public awareness campaigns to increase understanding of vulnerability	• Improved management of nature and natural resources • Better and more sustainable management of coastal areas and communities • Increased resilience of coastal societies	• No direct protection against coastal hazards
Adaptation of assets / buildings	• Buildings on piles • Reinforce coastal buildings • Strengthened shoreline roads	• No additional interference in nature	• Very difficult to achieve in highly urbanised areas with dense buildings • Very expensive to retro-fit adapted structural measures

Defend strategy	Measures	Pros	Cons
Add sediment	• Beach nourishment • Sand engine • (Perched beach) • (Sand groynes)	• No downdrift erosion • Flexible solution • Costs spread over long period of time	• Long-term maintenance required
Block longshore sediment transport	• Timber groynes • Rubble mound groynes	• Increase lifetime of a nourishment, less maintenance • Low costs compared to breakwater	• Causes downdrift erosion • Does not mitigate cross-shore erosion
Dissipate wave energy (Ecosystem-based)	• Mangrove forest • Coral reef • Oyster reef • Salt marshes • Seagrass beds	• High ecological benefits • Benefits regarding food security and livelihood diversity	• Require continuous protection and/ or maintenance • Require a lot of space • Reliability highly dependent on environmental conditions and anthropological impacts
Force wave breaking	• Emerged breakwater • Reef breakwater	• Reduces long- and cross-shore transport • Increase lifetime of a nourishment, less maintenance • Can have ecological benefits	• Causes downdrift erosion • High costs
Fixing the shoreline	• Revetment • Vertical seawall	• Minimum long-term maintenance	• Causes downdrift erosion • Causes additional erosion in front of the structure, beach will disappear

6.3.1 Feasibility measures retreat strategy

In this section the feasibility measures for the retreat strategy are treated. Appendix I provides a detailed overview of the measures related to the retreat strategy.

Do nothing

This measure means no action is taken to decrease the vulnerability of the affected coastal communities. The vulnerability analysis shows predictions of the future threats the coastal communities of the MMA will face if no measures are taken. This scenario will also be elaborated in the cost-benefit analysis for each coastal section. This will result in a clear comparative overview between doing nothing and the choice for a certain strategy to increase the climate resilience of the coastal communities.

Strategy	Measure	Requirements	Feasible
Leave vulnerable area	Do nothing	-	Yes
	Set-back line	Prediction of erosion rates	Yes
	Realignment	Former sea defence with relatively low-lying area compared to Mean High Tide	No, requirements not available

Set-back line

Applying a set-back line means that people need to retreat out of the area that is expected to be affected by the coastal hazards. New development are not allowed inside this identified 'buffer zone'. People and businesses that are already present inside this area need to be relocated. For this relocation to be successful, it is essential that the original livelihood and socio-economic dependencies on the environment are not disturbed. Therefore this measure is hard to implement in a highly urbanised area. Implementation of a set-back line should be realised by means of permits, laws, law enforcement and political policies.

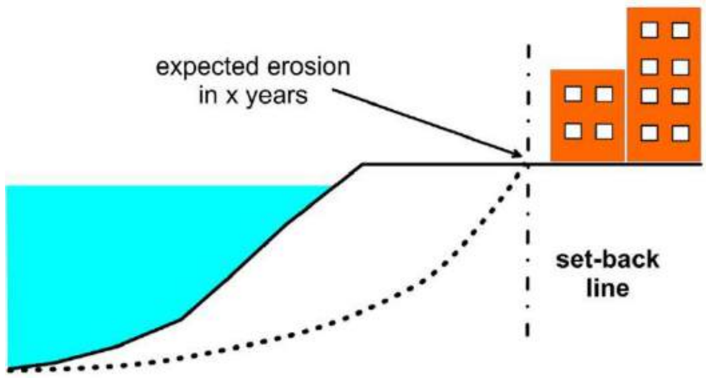


Figure 6-5: Example set-back line regarding coastal erosion

6.3.2 Feasibility measures adapt strategy

The table below provides an overview of the potential adaptation measures including an assessment on its feasibility related to the requirements.

Strategy	Measure	Requirements	Feasible
Adaptation actions	Sustainable fisheries management	Protected artisanal fishing zone; regulated catch volumes of different species; improved fish handling techniques; enhanced storage and conservation methods	Yes
	Protected marine and mangrove areas	Define protected areas that are of importance for the ecosystems around Monrovia; undertake the necessary research to support gazetting as protected areas	Yes, but mangroves near Monrovia are already under serious threat
	Effective pollution control and waste management	Gather and process household waste; design and construct a sewage system for coastal areas; regulate chemicals in industrial and other run-off	Yes
	Sustainable sand extraction	Prevent illegal sand extraction on beaches; identify safe sand extraction pits, taking care that sufficient sand is easily available for the whole Monrovia market	Yes
Governance	Capacity building of national and metropolitan regulatory institutions	Development of skills, regulations and enforcement; increased understanding of coastal issues among public sector staff	Yes, but enforcement requires political will and support
	Development of land use allocations and plans	Support Monrovia City Corporation and Paynesville City Corporation to develop detailed criteria for land use zoning; develop skills, regulations and enforcement	Yes, but may require a new urban planning law and enforcement requires political will and support
	Update land tenure system	Support Monrovia City Corporation to register land plots according to the Land Act 2008 and the Land Rights Act 2018; develop skills, regulations and enforcement	Yes, but enforcement requires political will and support
	Strengthen community-level management	Develop the capacities of community chiefs, community groups and local civil society organisations to manage fringe land areas responsibly (i.e. to control land use and illegal settlement)	Yes, but requires control measures to ensure it remains equitable
	Public awareness campaigns	Devise public messages to promote the awareness and understanding of vulnerability in coastal areas and the optimal adaptation strategies	Yes
Adaptation of assets / buildings	Buildings on piles	Rebuild structures on stilts or higher platforms; put long strong pile foundations under each building	No, technically not feasible

	Reinforce coastal buildings	Integrate first line of buildings into a strong seawall shoreline protection	No, technically not feasible
	Strengthened shoreline roads	Integrate shoreline roads into a protection structure	May be feasible in conjunction with defence measures

Sustainable fisheries management

The coastal fishery sector provides the livelihood basis for large ethnic communities and the broader society in which they are situated. It also provides food for a large part of the population of Monrovia. Management of a sustainable fishery means that the sector is organised and controlled in such a way that it attains an optimal balance between all ecological, economic, social and cultural aspects. Examples of approaches to ensure a sustainable fishery-sector are:

- A protected artisanal fishing zone;
- Regulated catch volumes of the different species;
- Regulated fishing areas, numbers of boats and times;
- Enhanced handling, storage, marketing and conservation methods of the caught fish; this should include more healthy and environmentally sound alternatives for fish smoking.

Protected marine and mangrove areas

In support of fisheries management, protected areas contribute significantly to the sustainability of a fishery, and therefore to the climate resilience of coastal communities. Protecting, maintaining and enhancing the important ecosystems around Monrovia will ensure livelihoods and food supply for the coastal communities in the long run. For example by protecting the mangrove area of the Mesurado basin, important nursery grounds for a large diversity of fish species will be conserved. Marine reserves are also needed to ensure that, if fish populations ever become unbalanced, there are areas of sea where they are not being exploited. Key approaches in this area are:

- Identify areas that are of importance for marine ecosystems around Monrovia, and which might benefit from protection;
- Undertake the necessary research to support gazetting as protected areas;
- Involve the fishermen in the process so that their awareness is raised of the importance of protecting part of their resource base in the interests of safeguarding sustainability.

Effective pollution control and waste management

Household waste, raw sewage, and industrial and other run-off water are currently causing degradation of the ecosystems around Monrovia. Investing in proper waste management will decrease the pressure on this environment. This is an important factor in ensuring resilience of coastal communities, as pollution affects the marine and estuarine resource bases; and this in turn influences livelihoods and food security. Actions required in this respect are:

- Improvement in the gathering and processing of household and industrial waste;
- Design and construct sewage system for coastal areas;
- Regulation of chemicals in industrial and other run-off, along with monitoring of outfall water quality and enforcement of quality standards;
- Control of marine pollution in territorial waters.

Sustainable sand extraction

Sand extraction from beaches is a contributory factor to coastal erosion. Although the quantities are low compared to the natural sediment transport along the Monrovian shoreline, over time the contribution to the vulnerability of the coastal communities is not negligible. Sand is one of the most important construction materials, so abundant sources need to be available for the development of a country. Implementing a sustainable sand mining management plan will therefore contribute to Liberia's climate resilience. Activities in this respect are:

- Identification of safe sand extraction areas, taking care that sufficient sand is easily available for the whole Monrovia market. These should ideally be from raised former beaches on the coastal plain, and not from rivers or active beaches.
- Development of sustainable sand mining management guidelines: an example is the Sustainable Sand Mining Management Guidelines 2016, prepared by the Ministry of Environment, Forest and Climate Change of India.
- Allow developers to apply for permits to exploit sand resources in the designated areas, encouraging the use of low emission transport arrangements.
- Enforce the prevention of illegal sand extraction from active beaches.

Capacity building of national and metropolitan regulatory institutions

The management of the coastal zone requires collaboration among a number of institutions. These include national-level regulatory organisations such as the EPA, National Port Authority (NPA) and the National Fisheries and Aquaculture Authority (NAFAA), and local organisations like the Monrovia City Corporation (MCC) and the Freeport of Monrovia (part of the NPA). It also requires the capacities of these organisations to be enhanced. The main areas of support required here are:

- Development of regulations and quality standards for all aspects of coastal zone management;
- Increased understanding of climate-related coastal issues among public sector staff;
- Improved skills for monitoring and enforcement of environmental conditions and development activities in coastal zones.

Development of land use allocations and plans

Land utilisation must be managed better, both in the shoreside settlements where poor people with few alternatives tend to settle in the most vulnerable locations, and in the fringes of the mangroves (particularly around the Mesurado estuary). Responsibilities for land use management in urban areas lie with the city corporations; most of the project area is under the MCC, but parts are covered by the Paynesville City Corporation (PCC) and the New Kru Town Borough. All of these institutions need to establish land use planning systems for the coastal and mangrove areas, that include formalised zoning. In the context of this project, it is particularly important to ensure that developments can be prevented on vulnerable land. The main activities to be undertaken are:

- Support the development of detailed criteria for land use zoning in the areas that will be affected by the impacts of climate change, particularly the inland incursion of the sea;
- Develop land zoning regulations and the supporting legislation with adequate provision for enforcement (probably using an act of law for the control of development in the tidal fringes of the MMA);
- Improve skills for monitoring and enforcement of land utilisation by the officers of the MCC and the PCC.

Update land tenure system

Reducing the vulnerability of the coastal communities depends in part on improving the status of land ownership, since this in turn affects people's responsibilities towards both their own property and the nearby communal resources. Many vulnerable areas in Liberia are not covered by the issuing of formal title, but instead rely on either the traditional customary land tenure or on squatters' rights. The Land Rights Act 2018 does not deal with the definition and allocation of urban plots, so this remains a gap in the urban planning framework, making the process more difficult to achieve. To improve this situation and ensure that land tenure is strengthened to improve the resilience of poor communities, the following actions are necessary:

- Develop regulations and the supporting legal instruments to allow the allocation and issuance of title on urban plots in appropriate vulnerable zones of the MMA (i.e. excluding those that are allocated for clearance in the land zoning described above);

- Support the MCC, the PCC and the New Kru Town Borough to register land plots according to the Land Act 2008;
- Develop the skills in the implementing institutions for the effective determination of rights and the completion of the formal land registration processes.

Strengthen community-level management

Many of the changes that are required to achieve the outcomes of the project are dependent on appropriate reactions by the communities. Although the intention is that the poor coastal communities should be the main beneficiaries, the historical context of these settlements has been informal, with no proper planning; inappropriate actions by some members of the local populations could largely negate the benefits intended for all. Despite this societal weakness, a system of civil organisation exists. This needs to be strengthened to increase the discipline within the communities for compliance with the safeguard actions being supported by the project. Activities in this area include:

- Development of the capacities of community chiefs, community groups and local civil society organisations to manage fringe land areas responsibly and support the project's initiatives;
- Involvement of community representatives in project planning and implementation, and encouragement to feed information on these matters back to the people;
- Monitoring of activities within the communities and requirement of the chiefs and representatives to resolve any community actions that mitigate against the achievement of project objectives.

Public awareness campaigns

The majority of people in the Monrovia coastal communities are aware of the potential vulnerability from the sea, but not of the increasing effects this will have as a result of sea level rise and greater storm wave damage due to the changing climate. Consequently, at present they do not understand the need to take action to reduce their vulnerability as the situation worsens. Awareness raising among the communities is therefore necessary to increase the public understanding of vulnerability, of the reasons behind the interventions to be implemented by the project, and of the parts that they must play in order to gain the intended benefits. Actions to be undertaken are:

- Devising of public messages to promote the awareness and understanding of vulnerability in coastal areas, and the optimal adaptation strategies supported by the project;
- Delivery of the awareness campaigns to all stakeholders at appropriate times and intervals;
- Monitoring of the effectiveness of the campaign in terms of increases in awareness, and modification and repeating of messages as necessary.

Strengthened shoreline roads

Under the category of adaptation, the only measure identified and considered to be feasible in the project concept, is the strengthening of roads along the shoreline. These are important items of infrastructure and are particularly valuable on the periphery of the low-lying settlements that have been established without any proper planning or system of roads. In areas where the occupation of land is haphazard due to a weak institutional setting (though due to be upgraded by the project), they also form an immovable physical barrier that prevents encroachment into areas that are too vulnerable for occupation to be sustainable. Activities in this respect include:

- Integrate shoreline roads into a protection structure such as a revetment as part of the design;
- Incorporate vegetated surfaces on either side of the roads as part of the overall coastal protection adaptation, providing high wave and spray protection, and also recreational space;
- Ensure that the road reserve areas are safeguarded from encroachment by occupiers.

6.3.3 Feasibility measures defend strategy

The table below provides an overview for the potential defend strategy measures for this project and provides the feasibility of each type of measure based on the main requirements and the local conditions.

A detailed description of the potential measures for defend strategy are provided in the Appendices:

- Ecosystem-based Solutions - Appendix J
- Soft Solutions - Appendix K
- Traditional Measures - Appendix L

Defend strategy	Measures	Main requirements	Feasible
Add sediment	Beach nourishment	• Sand pit with similar or coarser grading as present at the beach	Yes
	Sand engine	• Sand pit with similar or coarser grading as present at the beach • Moderate longshore sediment transport	No, hydraulic condition too harsh
	Perched beach	• Sand pit with similar or coarser grading as present at the beach • Large amount of quarry rock	Yes
	Sand groynes	• Sand pit with similar or coarser grading as present at the beach • Smooth longshore sediment transport that naturally redistributed sediments over large coastal stretch	No, hydraulic condition too harsh
Block longshore sediment transport	Timber groynes	• Long timber piles (with timber sheets) • Gentle slope with large longshore sediment transport or steep slope with coarse sediments	Maybe
	Rubble mound groynes	• Quarry rock • Significant longshore sediment transport	Yes
Dissipate wave energy (Ecosystem-based)	Mangrove forest	• Gently sloping foreshore • Fine nutrient rich sediments • About 500m space in horizontal direction at the shore • Mild wave environment	No, hydraulic condition too harsh + not enough space

Defend strategy	Measures	Main requirements	Feasible
	Coral reef	• Clear water (no suspended sediments) • Hard substratum	No, too much turbidity
	Oyster reef	• Fine (suspended) sediments • Intertidal area at the shore • Mild wave environment	No, hydraulic condition too harsh
	Salt marshes	• Fine (suspended) sediments • Intertidal area at the shore	No, hydraulic condition too harsh + not enough space
	Seagrass beds	• Mild hydraulic conditions (currents and waves)	No, hydraulic condition too harsh
Force wave breaking	Emerged breakwater	• Large amount of quarry rock	Yes
	Reef breakwater	• Large amount of quarry rock	Yes
Fixing the shoreline	Revetment	• Quarry rock • Geotextile	Yes
	Vertical seawall	• Concrete or sheet piles	Yes

Below a description is provided of the potential measures that are considered potentially feasible to apply for this project, based on the results of the table above.

Beach nourishment

A beach nourishment means that the sand that is eroded earlier is artificially brought back to shore. It is often referred to as a soft solution, as a beach nourishment does not interfere with the natural longshore and cross-shore transport processes.

This measure therefore does not cause downdrift erosion like hard measures do. However, it also means that a beach nourishment does not stop erosion. A beach nourishment therefore has to be repeated over time. An explanatory sketch is given in Figure 6-6. This requires long-term planning and management of funds, contracts and implementation of the works. At locations suffering from structural erosion, beach nourishments are often combined with hard measures to lengthen the maintenance interval.

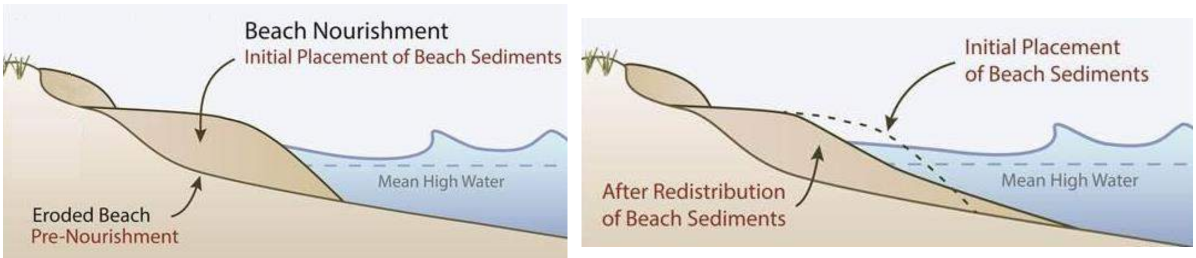


Figure 6-6: Principle of a beach nourishment

Perched beach

A perched beach is an underwater sill that supports the beach at the seaward side. In this way a new equilibrium profile can be created artificially with a relatively short distance to the shore, as shown in Figure 6-7.

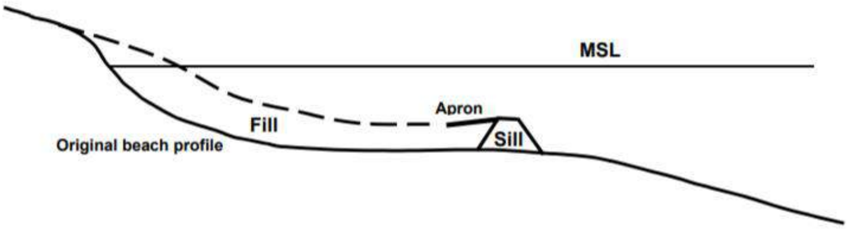


Figure 6-7: Principle of a perched beach

Especially for steep beach profiles, a perched beach can safe a significant volume of sand that needs to be nourished to obtain and maintain a (wider) beach. Different from a submerged breakwater, the sill of a perched beach is deeply submerged and therefore does not force wave breaking. Earlier experiences show that generally the best result are obtained if the deeply submerged sill is attached to partly submerged groynes, creating a closed sediment cell. A good example can be found at Pellestrina beach in Italy, shown in Figure 6-8. A disadvantage is that the submerged sill also blocks the onshore sediment transport during mild hydraulic conditions. On the long run, maintenance nourishments will be required.

Figure 6-8: Pellestrina beach (Italy)

Groynes (Timber / Rubble mound)

Groynes are shore-normal structures that can be applied to reduce the longshore sediment transport for a certain coastal stretch. Long impermeable groynes fully block the longshore sediment transport, which can cause high downdrift erosion rates (example left of Figure 6-9). Shorter and/or permeable groyne allow for some bypassing of sediments, thereby decreasing the amount of lee-side erosion (example right Figure 6-9). Often a series of groynes is applied to stabilize a coastal stretch.

Figure 6-9: Groyne structures (Left long impermeable groyne, Right series of short permeable groynes)

For structural eroding shorelines, groynes are often applied to increase the interval between (maintenance) nourishments. The most important aspects to consider for the design of a groyne solution are schematised in Figure 6-10.

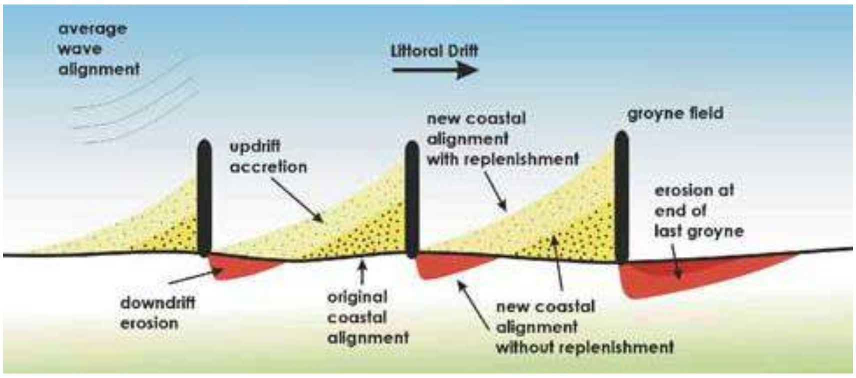


Figure 6-10: Principle of a groyne solution

Detached breakwater (Emerged / Submerged)

A detached breakwater is a shore-parallel structure intended to force wave-breaking, thereby decreasing the wave energy that reaches a sandy shoreline (Figure 6-11).

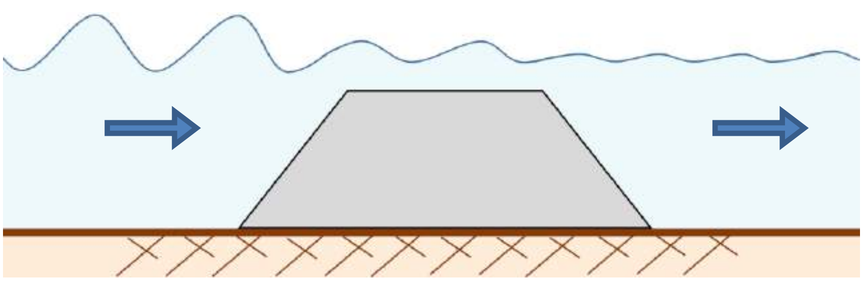


Figure 6-11: Principle of a breakwater

If designed well, this should lead to a local decrease of longshore and cross-shore erosion. However, a breakwater does cause downdrift erosion. A line of multiple detached breakwaters can be used to mitigate structural erosion problems of a large coastal stretch. If required, they can be combined with beach nourishments.

The most conventional type of detached breakwater is the rubble mound breakwater shown at the left side part of Figure 6-12. Other structures one can think of are caissons, geotubes and artificial reefs. Not much is known yet about submerged breakwaters in the form of an artificial reef. Fact is that this type of wave-breaking structures are gaining popularity due to the ecological advantages they might come along with. An example of a reef breakwater made of Reef Balls is shown at the right side of Figure 6-12. Note that it is a wide and continuous breakwater.

Figure 6-12: Left series of emerged detached breakwaters, Right a continuous reef breakwater

Revetment

The aim of a revetment is to fix the shoreline by applying a slope protection that can resist the local hydraulic forces. It can be a fast and effective solution to locally stop further land loss. Most commonly a revetment is constructed of quarry rock (rip-rap), combined with a some rock filters layers and / or a synthetic geotextile to prevent sand transport through the structure. Example of rip-rap revetment are depicted in Figure 6-13.

Figure 6-13: Examples of rip-rap revetments

Fixing the shoreline by a revetment causes downdrift erosion. Moreover, additional erosion (scour) will occur in front of the structure, which will cause lowering of the beach as shown in Figure 6-14. Over time the beach in front of a revetment is expected disappear. For this reason, it is very important to construct a revetment to the expected scouring depth and to include a resilient toe structure and / or a falling apron in the design. The absence of a beach can induce some inconveniences for local fishermen. If desired, landing sites can be included in the revetment design.

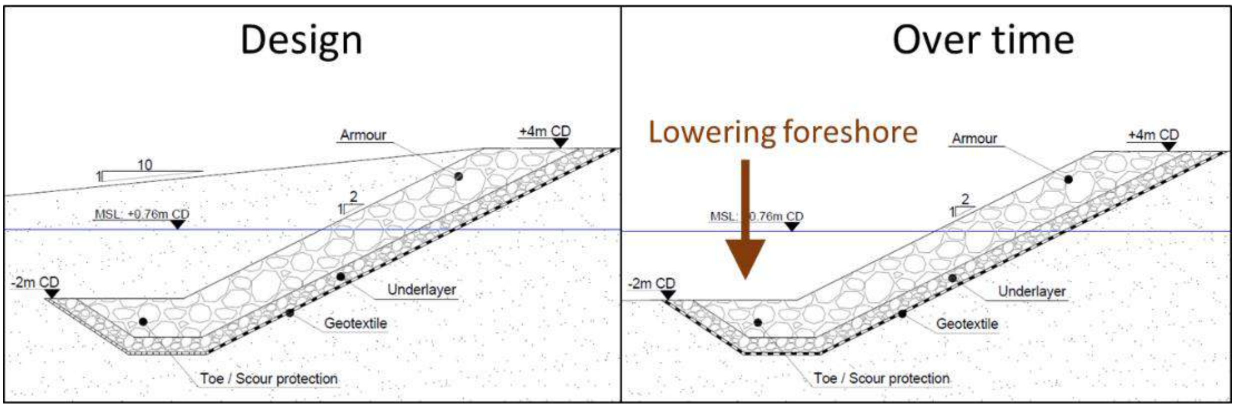


Figure 6-14: Over time the beach in front of a revetment will disappear

Vertical seawall

The principle of a seawall is similar to that of a revetment. The main difference is that the boundary between ocean and land is fixed by a (nearly) vertical structure. Examples are concrete (cantilever) walls, sheet pile walls or gravity block structures.

This intervention can be very effective to locally protect the shoreline against erosion, but has similar disadvantages as discussed for the coastal revetment (Figure 6-15, lowering of the foreshore). A further disadvantage is that incoming waves are almost fully reflected by the vertical face of the structure. This induces even more erosion in front of the wall and can result in dangerous near-shore wave conditions for fishermen. In contradiction to damages to a revetment, damages to a seawall generally do not evolve over time. Failure of a seawall is often characterised by a sudden (partly) collapse of the structure. This increases the risk that severe damages occur without a warning or earlier observed degradation of the seawall.

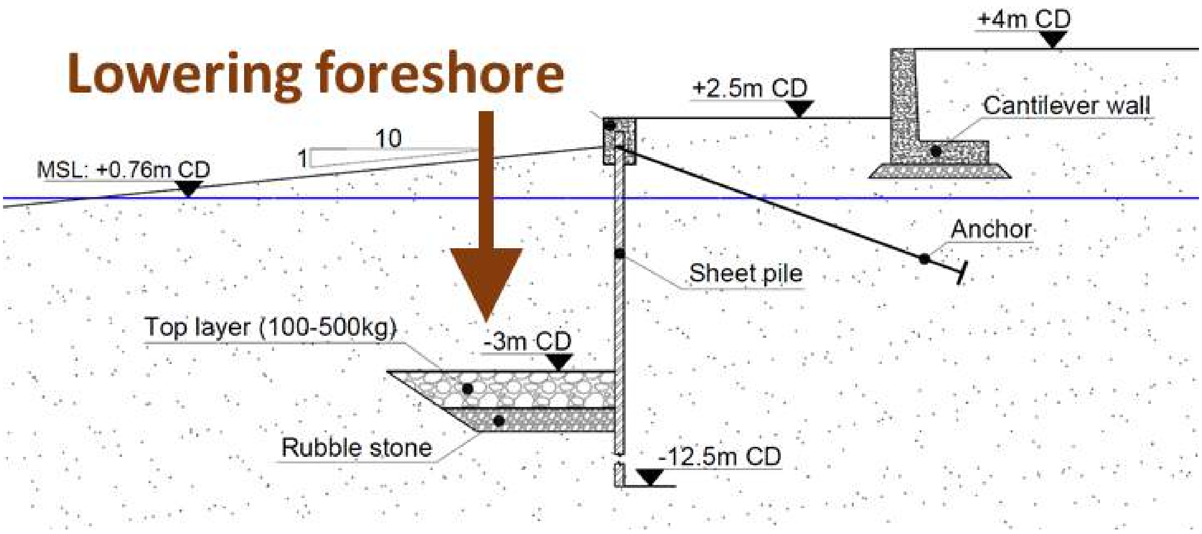


Figure 6-15: Vertical seawall causes lowering of the foreshore

7. PROPOSED CLIMATE RESILIENT STRATEGIES FOR THE HOTSPOTS

Based upon the outcomes of the stakeholder consultation organized 30 January 2019 in Monrovia a first pre-selection of potentially feasible and sustainable strategies is presented in this paragraph. Due to sustainability considerations it became clear from the workshop in January that most stakeholders do not favour beach nourishment only due to the continued maintenance needed and potential risks regarding funding and implementation of regular maintenance. Moreover, set-back lines (safety zones) were not regarded as feasible and sustainable due to enforcement problems and lessons from the past (people came back to the zones).

From the vulnerability analysis it became clear that the hotspots in terms of number of vulnerable assets and people and damage are the coastal sections 2, 3 and 4. For this reason a preliminary selection of strategies (combinations of measures) is presented for these three hotspots.

Results of stakeholder meeting (30 January 2019)
30 January a workshop in Monrovia was organized for stakeholders. In the workshop stakeholders were informed on the climate change, hazards, vulnerability of the coastal sections. Potential safeguarding types of measures (alternatives) per coastal section were presented. In the workshop stakeholders were asked to assess, score and discuss the potential alternative presented measures (options) regarding a subset of criteria:

- Social acceptance: the extend of acceptance by community people based on potential social impacts;
- Economic impacts: the potential for fisheries, urban development etc.
- Sustainability: the long-term effectiveness of the solution in relation to institutional sustainability and financial sustainability (regarding maintenance etc.);
- Political acceptance: the acceptance of potential alternative solutions by political leaders and community leaders.

Important feedback from the stakeholders was that there is a clear preference for sustainable solutions. Participants scored set-back lines (safety zones) and beach nourishment only as not sustainable solutions. The reasons are that beach nourishment requires regular maintenance, which most stakeholders assessed as not very likely to happen. Moreover, the experience from the past with set-back lines has not been good (encroachment happened again, no enforcement, people want to live at the shore because fishing is their livelihood). The local community representatives from West Point and New Kru town clearly had a preference for more solid solutions such as revetments combined with a promenade and landing sites for fishermen and some beach nourishment for the canoes. Combinations of beach nourishment with groynes or revetments were assessed as more positive in terms of economic impacts (fisheries, recreational facilities) compared to set-back lines or revetments only.

In conclusion, this implies that preferred strategies should be based upon combinations of revetments or groynes combined with beach nourishment and eco-based measures.


It is clear from the section above that the consensus is for the project to address the impacts of climate change using a strategy that combines measures of adaptation and defence. These two categories are discussed separately in the following sections, but need to be implemented together to obtain the climate resilient solutions needed for the vulnerable coastal communities and the Monrovia Metropolitan Area as a whole.

Because of the nature of the environment, both measures need to be strong. The interface between ocean and continental fringe can be summarised as follows:

- Land-side: a densely populated urban area significantly dependent for its livelihoods on proximity to the sea; and
- Sea-side: an energetic marine environment with a huge open-ocean reach against a low-lying shore.

To a large extent, adaptation is a societal reaction, whereas protection is more a matter of appropriate and sensitive engineering. The measures of adaptation, involving many individuals of differing stakeholder perspectives, and a number of agencies from local civil society, through local government and including national-level agencies, will necessarily involve changes in thinking and approach. This will take time to achieve and will require more of the project's resources than the relatively straightforward management of most of the protection measures.

Figure 7-1 summarises how adaptation and defence need to go hand in hand: a strong shake by each hand.

Figure 7-1: Adaptation and defence need to go hand in hand

7.1 Adaptation measures

The adaptation measures to be adopted by the project are almost all "soft" in nature and revolve around improvements in capacity and management. Unlike the next section on protection measures, which addresses the issues on a site-by-site basis along the coast, these rely on a more generalised approach. Underlying them is the basic fact that vulnerability to a society is as much a human construct as a physical one. This is where the paradigm of the project's logic has changed from the business-as-usual approach of an engineering-only response to one of a human response supplemented by engineering measures in certain areas. This is because it is clear that the engineering-only response would not itself deliver a society that is resilient to climate change.

The project will make the coastal communities resilient by addressing two main areas of fundamental security: these are the security of settlement and the security of food supply. Once these are assured for any society, it is able to work on its other capitals – such as health and well-being. At present the coastal communities are in a marginal position under the prevailing oceanic conditions of the current climate. Change in the climate and its effects on the oceans have been shown elsewhere in this report to push the situation beyond a point of marginal stability, into one of certain unsustainability. In their current informal state, the coastal communities are not resilient to the massive changes that will occur as a result of climate change, as the area of land they live on will be eaten away by increasingly high tides and strong waves. They have shown resilience through the civil wars and the 2014 Ebola epidemic, but this is a very different threat. To be able to adapt, the society needs to be more aware, more organised, more formal; and to have the basis of its livelihood protected – the inshore fisheries.

The approaches proposed below are made at this interim reporting stage. Further consultation is required, along with a greater degree of engagement with the various institutions that must be involved, before the final project reports are delivered.

Adaptation measures will focus on resource management and governance. Considered most important in this respect is the protection of the fisheries, since these have been sustainable up to now and represent an appropriate low-carbon industry that contributes hugely to the food security of a large part of Monrovia's population, as well as to the livelihoods of the fishermen, fish mongers and the informal service sector in their midst. The project will therefore work with a number of agencies to ensure that the fisheries are safeguarded, through a range of initiatives.

- Awareness of the coastal environment and how it will change needs to be increased on a factual basis among the communities on one hand, and relevant national and local government staff on the other hand. The project will therefore undertake a series of engagement and awareness-raising activities appropriate to the different target groups, to ensure that all of the stakeholders understand the seriousness of the challenges facing Monrovia, and the solutions that are needed to ensure that the city will not be affected by climate change where it can be averted.
- The protection of the artisanal fishing limit of six nautical miles and the regulation of the catch volumes are to be enhanced through improved capacity in the National Fisheries and Aquaculture Authority. The catch volumes will need to be based on a better understanding of the biological resource, which in turn must be established using primary research into species' life cycles and fecundity using statistically valid sampling procedures. This activity would therefore be linked to the action below.
- The Environmental Protection Agency's current project under Global Environment Facility funding, "Improving Sustainability of Mangrove Forests and Coastal Mangrove Areas in Liberia", will be engaged and expanded as necessary to undertake in-depth research on the ecology that underlies Monrovia's fisheries. This is currently being implemented by Conservation International. If areas of key biodiversity importance are identified, a process of consultation with fishermen and other stakeholders would be undertaken to see if it is appropriate for them to be defined and gazetted as protected areas.

- Fish landings and onshore processing and storage facilities will be enhanced in collaboration with the Liberian Artisanal Fishermen's Association, though using best practice community engagement to ensure that the women who dominate the fish mongering businesses are fully involved in the design, implementation and management of these facilities. In this respect it might prove important to support the establishment of fish mongers' and processors' associations.
- Improved methods for fish preservation – traditionally undertaken using an inefficient and unhealthy smoking process – will be developed. This will need to be led locally by fish handling community groups, but would probably be supported by a contracted company or non-governmental organisation with experience of improved smoking technologies elsewhere in West Africa. The aim would be to make this aspect of the fisheries as carbon-neutral as possible.
- The Environmental Protection Agency will be supported to increase enforcement of pollution controls in the creeks, estuaries and inshore waters, mainly through compelling the urban and industrial authorities to meet their obligations. To ensure that this is achieved, capacity building will be necessary in the environmental health and pollution control divisions of the Monrovia City Council, the Paynesville City Council, the New Kru Town Borough (and possibly in other boroughs) and the Freeport of Monrovia. Particular emphasis will be given to the mangroves close to the greater Monrovia urban area, and especially to those in the Mesurado estuary.
- The Ministry of Lands, Mines and Energy will be engaged to lead the stopping of sand extraction from beaches and rivers supplying sediment into the Monrovia inshore marine environment. It will be supported in prospecting alternative sources of sand inland that do not have such big environmental consequences, such as from the raised ancient beaches on the coastal plain. A system of designated supply zones and permits will be established jointly between this ministry and the Environmental Protection Agency to ensure that Monrovia and the neighbouring cities and development areas have ready access to adequate sand for construction. This will allow beach and river sand extraction to be banned, with enforcement totally effective.

Land has long been weakly administered in Liberia, particularly in vulnerable and low value areas. However, the Liberia Land Authority (LLA) was established in October 2016 with the passing of a dedicated act of law and now has the legal mandate for land administration in Liberia. It is to subsume a number of agencies from different ministries: the Department of Lands, Surveys and Cartography under the Ministry of Lands, Mines and Energy; the Deeds Registry within the Center for National Documents and Records Agency; and relevant functions from the Ministry of Internal Affairs (e.g. the County Land Commissioners). The project will therefore work with the LLA and other relevant agencies to resolve a number of key aspects of vulnerability of land use and tenure to the impacts of climate change.

- Land utilisation planning will be supported under the joint perspectives of the Environmental Protection Agency, the Ministry of Lands, Mines and Energy, and the various city corporations and boroughs covering the ocean and tidal inlet shores. The purpose of this action will be to determine appropriate land use zoning to define areas where no development is permitted (to accommodate sea level rise, raised mangroves or protection facilities), and where developments of different categories are permitted (e.g. residential, agricultural, commercial industrial, recreation, etc.); and with what obligatory pollution control and waste management systems. Capacity development of the agencies will be a key part of this, to ensure that the skills are in place to undertake the zoning in a rational, scientifically based manner, to devise the necessary regulations (and supporting legislation if necessary), and then to enforce compliance thereafter.
- Land tenure will be addressed by working with both the Liberia Land Authority and the city corporations and boroughs to define and register land plots under the formal system (i.e.

moving beyond the current squatters' rights and customary tenure systems). In addressing this, the project will support the development of the skills needed by the local government staff to manage this task, and to liaise with the LLA to help create any necessary regulatory and legal instruments to ensure that it can be implemented effectively. Capacity for dispute resolution and enforcement will be particular issues to be addressed here, with specific measures put in place to ensure that disadvantaged groups are equitably represented and that no one loses out due to gender, ethnicity or disability.

- Enforcement of both land utilisation and tenure will require the collaboration of the local communities if it is to be sustainable beyond the relatively short period of project implementation. Capacity building among community representatives will therefore be an essential part of the land security aspect.

Many of the adaptation actions will require political support to ensure that the project's impacts are effective. The project has already engaged with the President's Office at the Executive Mansion and obtained affirmations of support in principle. The administration, with its pro-poor agenda, gives a high importance to the possibility of increased resilience among the coastal communities. With this strong, high level backing, maintained through the implementation phase with an appropriate level of dialogue, it is likely that the project's activities will receive the support that is required to achieve the intended outcomes.

There is a single feasible adaptation option that involves physical infrastructure. This is the strengthening of shoreline roads. It is proposed that this be done in a "soft" way, integrating them with the "hard" infrastructure required for coastal protection but with vegetation screens that both mitigate the effects of high waves and also provide recreational benefits, giving the effect of a traditional sheltered promenade. The vegetation will also act to counter the drivers of climate change, though in a very limited way. These strengthened roads are incorporated where appropriate into the protection options in the next section.

7.2 Protective measures

Different from the table presented in section 6.3.3 is that most measures are now combined with a nourishment. Required for shore of Monrovia as currently there is structural sand deficit. Furthermore it is an appropriate measure to counteract cross-shore erosion by sea level rise.

None of the known ecosystem-based solutions appeared to be applicable as a direct defence strategy and therefore they are not included in Table 7-1. However, just like the feasible adaptation strategies, ecosystem-based solution might be added to the chosen measures to create additional value and increase the climate resilience of the coastal communities. Proposed strategies meet the GCF requirements and are expected to fit in the intended budget.

Table 7-1: Short-list of protective measures

Defend strategy	Measures	Pros	Cons
Add sediment	Perched beach + Nourishment	• Reduces the amount of sediment required for a nourishment	• Very expensive • Sill blocks onshore sediment transport • Relatively poor scientific knowledge
Block longshore sediment transport	Timber groynes + Nourishment	• Downdrift erosion minimized • Relatively low cost solution	• Relatively poor scientific knowledge • Does not mitigate cross-shore erosion
	Rubble mound groynes + Nourishment	• Relatively low cost solution	• Does not mitigate cross-shore erosion
Force wave breaking	Emerged breakwater + Nourishment	• Mild nearshore hydraulic conditions (ecosystem & tourism)	• Very expensive • Return currents between gaps
	Reef breakwater + Nourishment	• Mild nearshore hydraulic conditions (ecosystem & tourism) • Reef itself can attribute to the marine ecosystem	• Very expensive • Can create inconveniences for fishermen
Fixing the shoreline	Revetment	• Relatively low cost solution • Fixed shoreline	• No beach
	Vertical seawall	• Fixed shoreline	• No beach • Wave reflection • Relatively high risk of failure without warning • Expensive

7.3 Section 2: New Kru Town

7.3.1 Site characteristics

The district behind coastal section 2 is a densely populated area and a school is present very near the shoreline. Currently a rip-rap revetment is under construction to protect this region against further erosion (Figure 7-2). Based on the observations of (the construction of) this revetment, the consultant is of the opinion that improvements must be made to increase the lifetime of this structure. Fishing communities are living in this area, which should be considered regarding access to the ocean.

Figure 7-2: School at the shoreline, being protected by a rip-rap revetment (Oct 2018)

The sediment supply to coastal stretch 2 is currently nihil and is not expected to change significantly over time. A possible future increase of sediment supply from the St. Paul river will be mainly transported northwards to coastal section 1. The alongshore sediment drift to the north-west therefore causes erosion of the area. Based on the relative steep cross-shore profile in the breaker zone it can be concluded that also cross-shore erosion (re-distribution of sand) is occurring. Erosion of the shoreline of section 2 will therefore continue, with increasing rates in the future due to climate change. (Refer to section 5.2)

7.3.2 Potential protection measures coastal section 2

Given the erosive drivers and ongoing works in this area, the most viable measure to increase the climate resilient by upgrading the revetment that is currently being build and to expand it over the entire coastal stretch. Attention should be paid to the placement of the geotextile and the construction of a proper toe. Significant lowering of the shorefront due to ongoing alongshore and cross-shore sediment transport must be considered in the design.

When opting to upgrade and extend the current revetment, it is advised to monitor the northern part of section 2 regularly. If necessary, the revetment can be extended along the St. Paul River mouth. However, it would be better to not interfere in this part of section 2 as a river mouth is a highly dynamic area and therefore difficult to fix by a shoreline protection.

It is possible to alternate, or maybe replace, the rip-rap revetment with other types of revetment or a vertical seawall. The choice should depend on the available space and additional functions of the shoreline protection. With the last, especially reference is made to the accessibility of the sea for the fishermen living in this district. E.g. local right angled groynes or local harbour openings can be applied along the coast to provide local shelter for fishery boats. In all cases a sloping revetment is preferred over a vertical seawall for the areas where both of these technical interventions are feasible.

A groyne or breakwater are considered less effective for coastal stretch 2 as cross-shore erosive processes are significant here and due to the presence of the dynamic river outlet. A set-back line would result in a very high displacement of population, loss of assets and living space and therefore not considered feasible.

A beach nourishment can be applied here as both short-term or longer-term solution, depending on the nourishment volume and final erosion rates. Due to the combination of longshore and cross-shore sand losses, regular maintenance is expected. When opting for a beach nourishment, the lifetime should be increased by the construction of (permeable) groynes or a perched beach. This will increase the sustainability if this soft solution.

7.3.3 Proposed protection measures for coastal section 2

Rip-rap revetment with a green coastal promenade and landing sites

This solution includes an upgrade of the revetment that is currently being built to a climate resilient structure that meets the international standards. The lifetime of the present revetment is expected to be relatively low. A well-designed and constructed revetment will minimize the vulnerability to the current and future coastal hazards of the local communities. An artist impression of the proposed solution is shown in Figure 7-3.

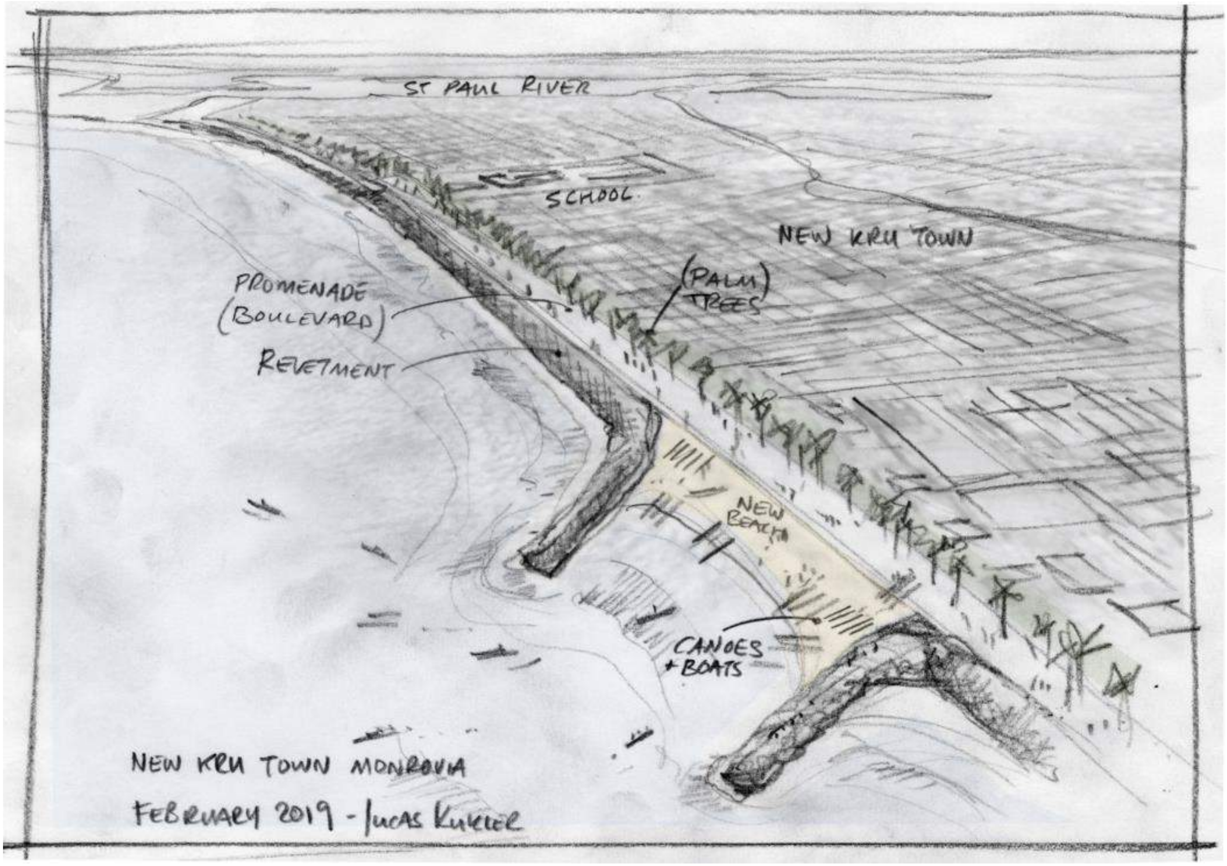


Figure 7-3: Revetment with promenade (by Lucas Kukler)

A green promenade is included in the design to improve the accessibility of New Kru Town and to create space for recreation. By aiming at a safe and highly attractive shoreline, the future perspectives of these coastal communities will be greatly improved. Businesses will be more willing to house in the area and investments made to enhance livelihoods of the local people will increase in value as the protentional risks are decreased significantly.

Moreover, the artist impression of Figure 7-4 includes two groyne-like structures attached to the revetment. In this way a small bay is created in which a beach is present. This beach can be used for recreation and as a landing site for the canoes of local fishermen, thereby safeguarding the livelihood of the coastal communities. An alternative for this small bay is to attach a L-shaped groyne to the revetment. If required, this can be added to a uninterrupted revetment design in a later stadium.

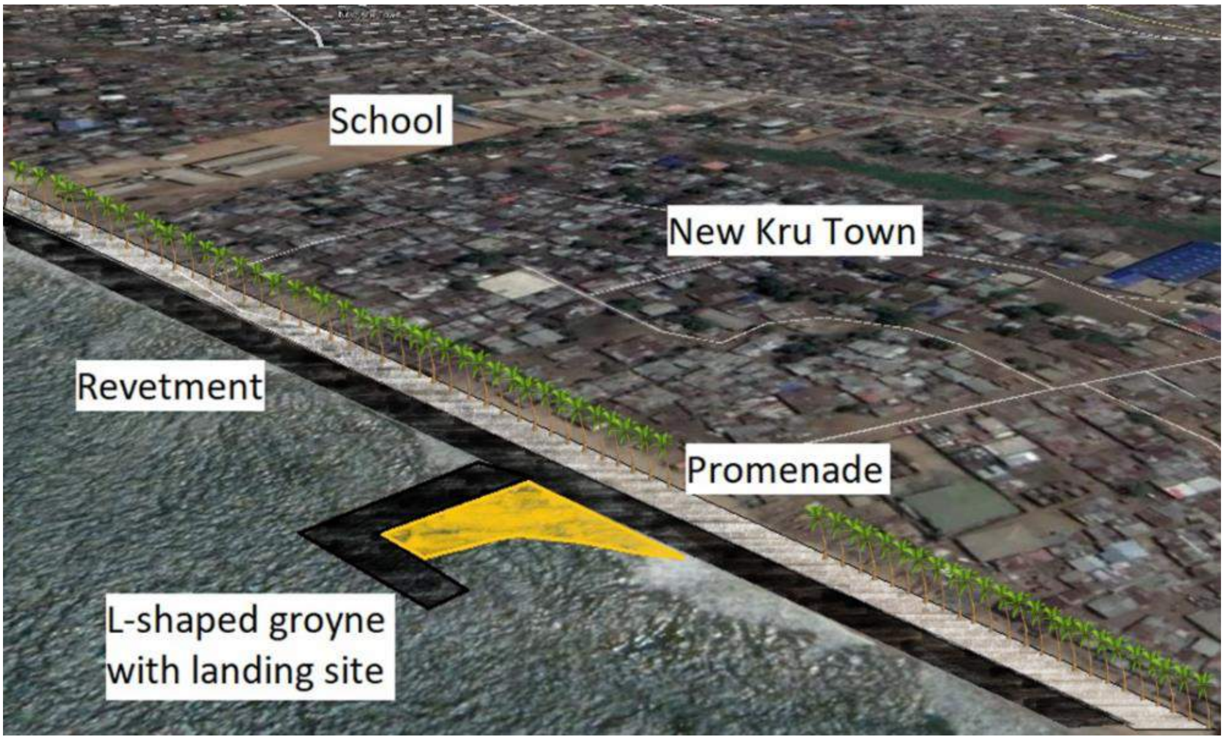


Figure 7-4: Revetment with a L-shaped groyne to create a landing site for fishermen

Including a nourished beach

A disadvantage of the proposed measure is that the beach in front of the revetment will disappear. Currently the people living at coastal section 2 make extensive use of the beach for recreation and fishing purposes. It therefore may be desirable to construct an artificial beach in front of the revetment as sketched in Figure 7-5.

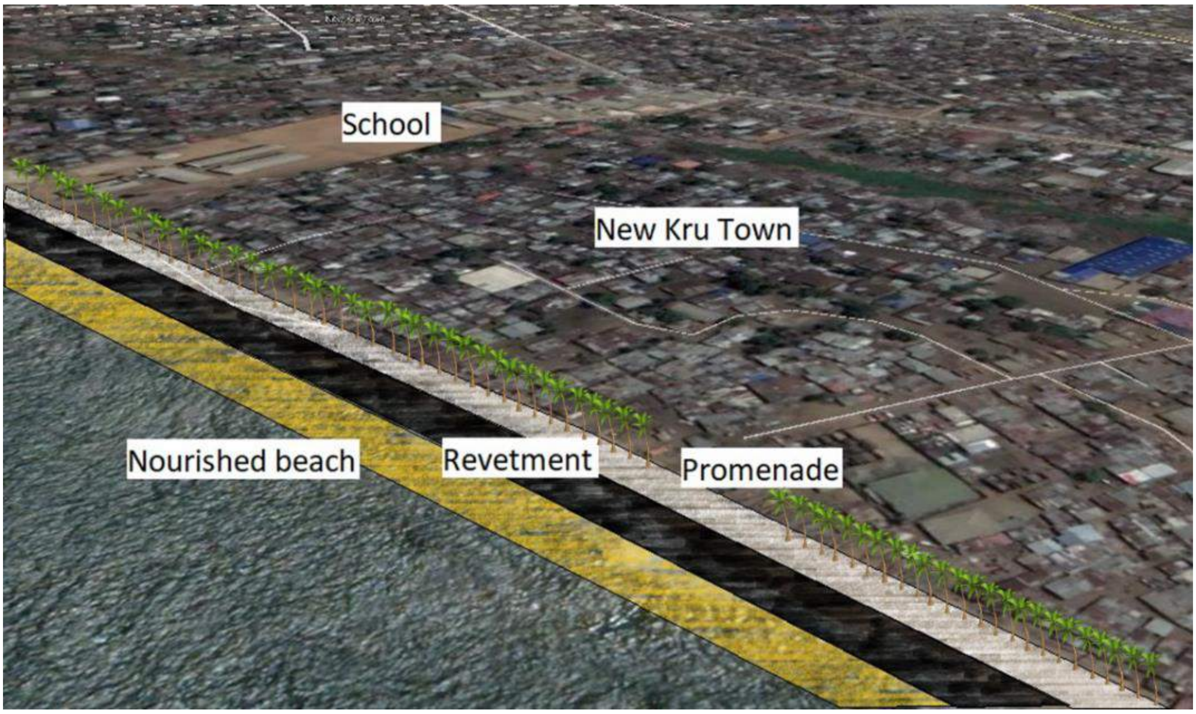


Figure 7-5: Revetment with a nourished beach

Including a beach in the final design of section 2 will be beneficial for the living conditions and livelihood of the coastal communities. However, nourishments are required to construct and maintain the beach. Erosion in front of the revetment is expected to occur relatively fast, thereby increasing the efforts and costs required to maintain the beach. Optionally, relatively short (timber) groynes can be applied to increase the lifetime of the beach nourishments.

7.4 Section 3: West Point


7.4.1 Site characteristics

Coastal section 3 is located in front one of the most densely populated areas of Monrovia, which consist mostly of informal (temporarily) houses. Most inhabitants are fishermen or small market traders. An electricity station is located near the southern end of this coastal stretch.

This district is built on a dynamic sand spit between the ocean and the Mesurado basin. The land has a low elevation and the beach is subjected to serious erosion because of the sand hunger of the Mesurado basin and the northward directed longshore sediment transport. Future projections show that this sand hunger, and thereby the erosion rates, are expected to increase due to sea level rise. The dynamics of the basin mouth and high erosion rates in front of the developed land are clearly visible in Google Earth (reference is made to the Inception report).

7.4.2 Potential protection measures coastal section 3

Due to the dynamic nature of the sand spit and the Mesurado basin, coastal stretch 3 is relatively difficult to protect. Relocation of this district seems to be an appropriate solution, but earlier attempts to realise this failed. During the stakeholder meeting of the 30th of January 2019 it was stressed that implementation of a set-back line will not be accepted by the people of West Point.

The construction of a groyne at the northern end of the sand spit in combination with a beach nourishment is a viable alternative. Because the Mesurado basin will keep its sand hunger, the part of the sand spit above the groyne is expected to erode soon after construction. To prevent erosion behind the landward part of the groyne, the structure has to be extended over a significant length inside the tidal inlet. The groyne can continue as a rip-rap revetment around the northern part of West Point.

It is noted that also the current opening of the basin can be fixed, i.e. at the northern tip of the current sand spit. This in combination with flow guidance structures just northeast of West Point gives the opportunity to easily reclaim and develop the area North of West Point for relatively limited additional costs. This option could be considered by the government if developable land is desired at this location.

Constructing an offshore breakwater will have a very limited effect at coastal stretch 3 and is therefore not considered viable.

Fixing the shoreline by a revetment is technically feasible, however the construction will be more complex and costly than the revetment in of section 2. As the beach will disappear, landing sites should be included in the design to safeguard the accessibility of the sea for the numerous fishermen living in West Point. Alternative recreation areas should be created as well.

7.4.3 Proposed protection measures for coastal section 3

For coastal section 3, two feasible alternatives have been selected which have different pricing and different pros and cons. Both alternatives will be included in the cost-benefit analysis to determine which design is preferred.

Alternative A: A long groyne with a wide sustainable beach

This alternative includes a long groyne that blocks the longshore sediment transport towards the north and inside the Mesurado basin. This groyne will fix the beach that will be constructed by means of a beach nourishment. An artist impression of this alternative is shown in Figure 7-6.

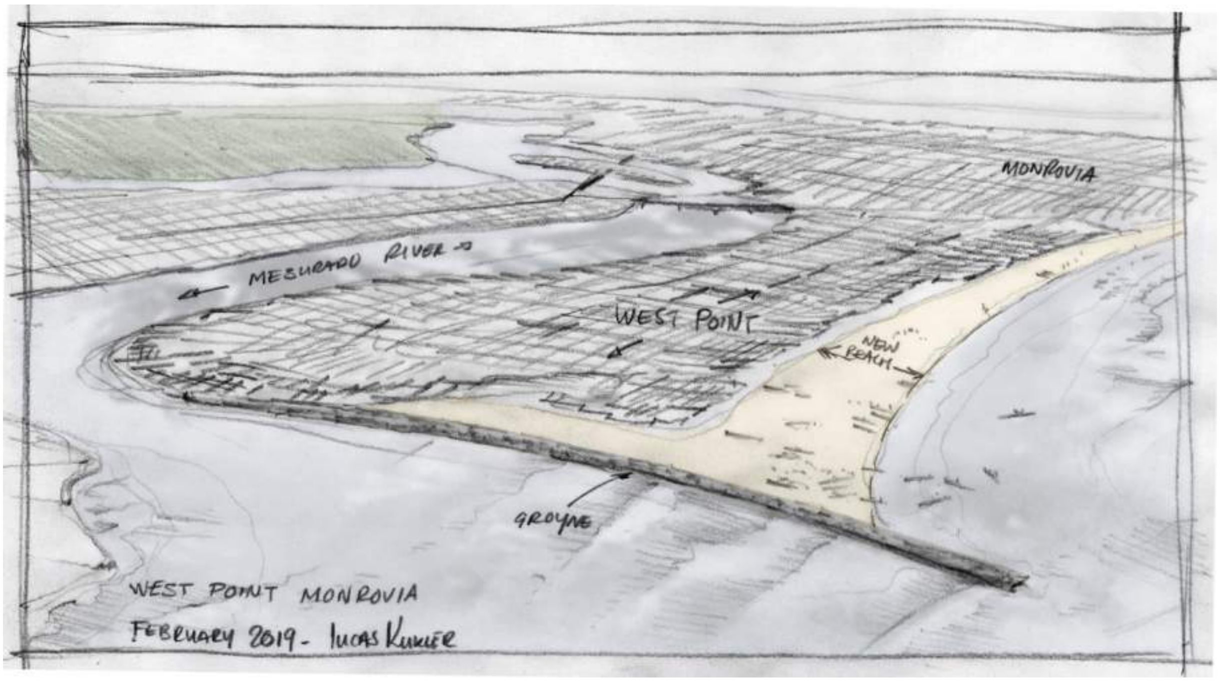


Figure 7-6: Long groyne with a sustainable beach (by Lucas Kukler)

With these protective measures, a beach will be present between West Point and the Atlantic Ocean. Currently the beach of West Point is used extensively for recreation and fishery. By the Consultant the beach is interpreted as a very important area in the daily life of many inhabitants of West Point.

Figure 7-7: Kids playing on the beach at West Point (site visit 31-01-2019)

Having (and preserving) a beach will have a positive impact on the living conditions and livelihood of this coastal community. However, it is stressed that the beach nourishment should be used as a beach and not as reclaimed land that can be used for living. Laws, permits and community awareness programs can be used as a tool to prevent that new (informal) housing will appear on the nourished beach.

Despite the presence of the groyne, the beach nourishment is expected to disappear over time. Therefore maintenance nourishments are required on the long run if opted for this protection strategy.

Alternative B: Revetment with a green promenade (landing site optional)
This alternative looks more like the proposed measure for coastal section 2. It includes a long revetment with a green coastal promenade. To give a first impression, a sketch of this solution is shown in Figure 7-8.

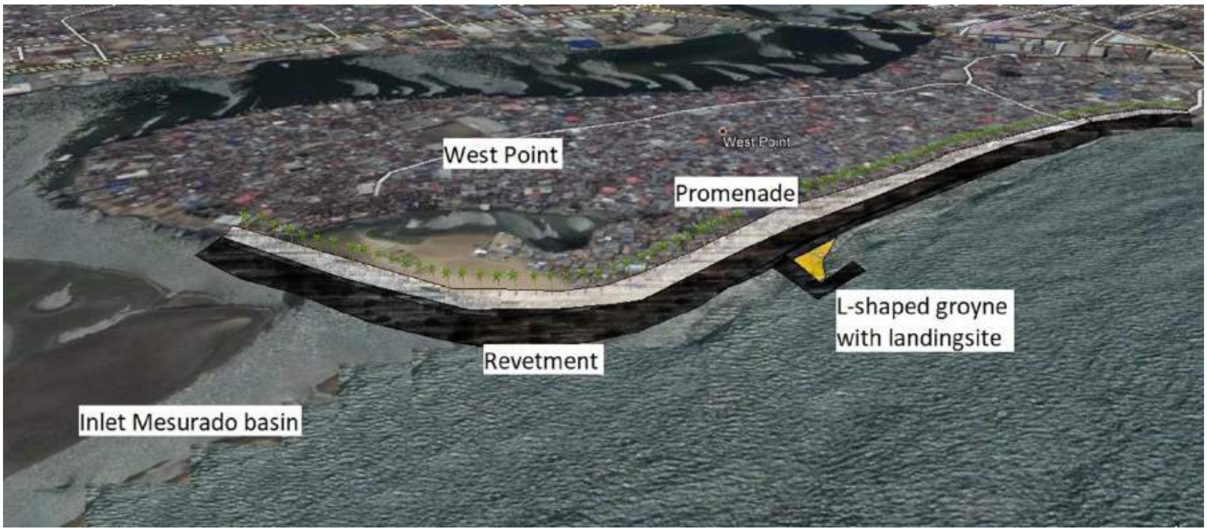


Figure 7-8: Alternative B: Revetment with green promenade at West Point

During the stakeholder meeting of the 30th of January 2019, quite some people appeared to be in favour of this solution, as the solid protection gives people a safe feeling and it seems more sustainable (less maintenance) than for example the solution of Alternative A. The beach in front of the revetment will disappear over time, which means also landing sites for the local fishermen and space for recreation will be lost. New landing sites can be created at the Mesurado side of West Point or by adding a L-shaped groyne to the revetment design as indicated in Figure 7-8.

The green coastal promenade can be used for recreation and serve as a new access road for West Point. As currently only one road is leading into West Point (former second road disappeared in the ocean due to the high erosion rates), a new access road will have a highly positive impact on the living conditions and livelihood of this coastal community.

The initial costs for the revetment will be significantly higher than those for Alternative A. Moreover, especially at the inlet of the Mesurado basin the design and construction of a sustainable revetment will be challenging due to highly dynamic character of this area.

7.5 Section 4: American embassy to Barclay training center

7.5.1 Site characteristics

Coastal stretch 4 is located at the south of an important economic district of Monrovia. Some valuable assets like part of the American Embassy, a road and the Barclay training center are located near the shoreline. Moreover, permanent housing, hotels and some informal (temporarily) housing can be found along this coastal stretch.

The beaches and shoreface of section 4 are (very) steep, because highly energetic waves approach this stretch nearly perpendicular. The net alongshore sediment transport is relatively limited but still problematic as the sandy material transported west of the Cape of Monrovia (rock outcrop) will settle outside the active zone of the beach. At this moment coastline retreat is therefore limited but it will continue and increase in the future due to sea level rise. Compared to section 2 and 3, the vulnerability of section 4 is relatively low. Still the benefits of protecting this shoreline are expected to be higher than the costs of some potential measures. Therefore coastal section 4 is included in the list of hotspots and elaborated in this chapter. (Refer to section 4.7)

7.5.2 Potential protection measures coastal section 4

The construction of groynes combined with beach nourishments is a viable technical solution for coastal section 4. As waves approach the shore nearly perpendicular, short groynes with large spacings can be applied to keep the available sand within the coastal sediment system. The groynes block the west-going sediment drift, making the beach nourishment a cost-efficient operation. The groyne at the most western part of this stretch should be designed such that it fully blocks the remaining longshore sediment transport. The sand nourishment is required to assure resilience against future sea level rise and cross-shore sand loss.

From a technical point of view, offshore (reef) breakwaters combined with beach nourishments are also feasible. Because of the steepness of the shoreface, large structures are required which will make this a very expensive solution. At this stage of the project, the possible aesthetical and ecological benefits of an offshore reef are not sufficient to surmount the high construction costs.

Only applying beach nourishment without constructing groynes is a feasible solution as well, this however requires regular maintenance nourishments. Based on the stakeholder meeting of the 30th of January 2019 this option is considered to be not sustainable and therefore not desirable.

Because of the highly energetic wave attack, a revetment is not a feasible measure for section 4.

7.5.3 Proposed protection measures for coastal section 4

Long groyne with a wide sustainable beach

Taking the costs into account, a beach nourishment fixed by a long groyne is considered to be the most feasible solution for coastal section 4. A sketch of the proposed measure is shown in Figure 7-9.

Figure 7-9: Long groyne with a wide beach

The long impermeable groyne will block the west-going sediment drift, thereby reducing the amount of sediments lost offshore west of the Cape of Monrovia. This will increase the lifetime of the beach nourishment in front of section 4. The beach nourishment is required to counteract further cross-shore erosion due to sea level rise.

Besides that the beach nourishment will prevent further land losses, it is an attractive place for tourism and recreation. Coastal section 4 is located in front of the centre of Monrovia, which is the perfect place to have a well-maintained beach to attract people to the Capitol of Liberia. In this way it can increase the living conditions and livelihood diversity of the coastal communities behind this section.

As this coastal stretch is rather long, the sustainability of the beach nourishment can be increased by applying short (permeable) groynes at regular intervals over the length of the beach, as shown in Figure 7-10.

Figure 7-10: Long groyne with a wide sustainable beach including short (permeable) groynes

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A. BASELINE ENVIRONMENT

This Appendix treats the general environmental conditions that are considered relevant in relation to coastal vulnerability:

1) Geology
2) Bathymetry and topography
3) Tides
4) Surge
5) Grain sizes of beach material
6) Precipitation
7) Seismic Conditions
8) Cyclones and storms

The wave climate and morphological conditions are treated separately in Appendix C, 0 and E.

A.1 Geology

The geology of the Monrovia's coastal areas is characterised by a combination of rock formations, rock outcrops, fluvial, deltaic and beach deposits. Figure 8-1 shows a map of the composition of the geology units for the project area (Ref [32]).

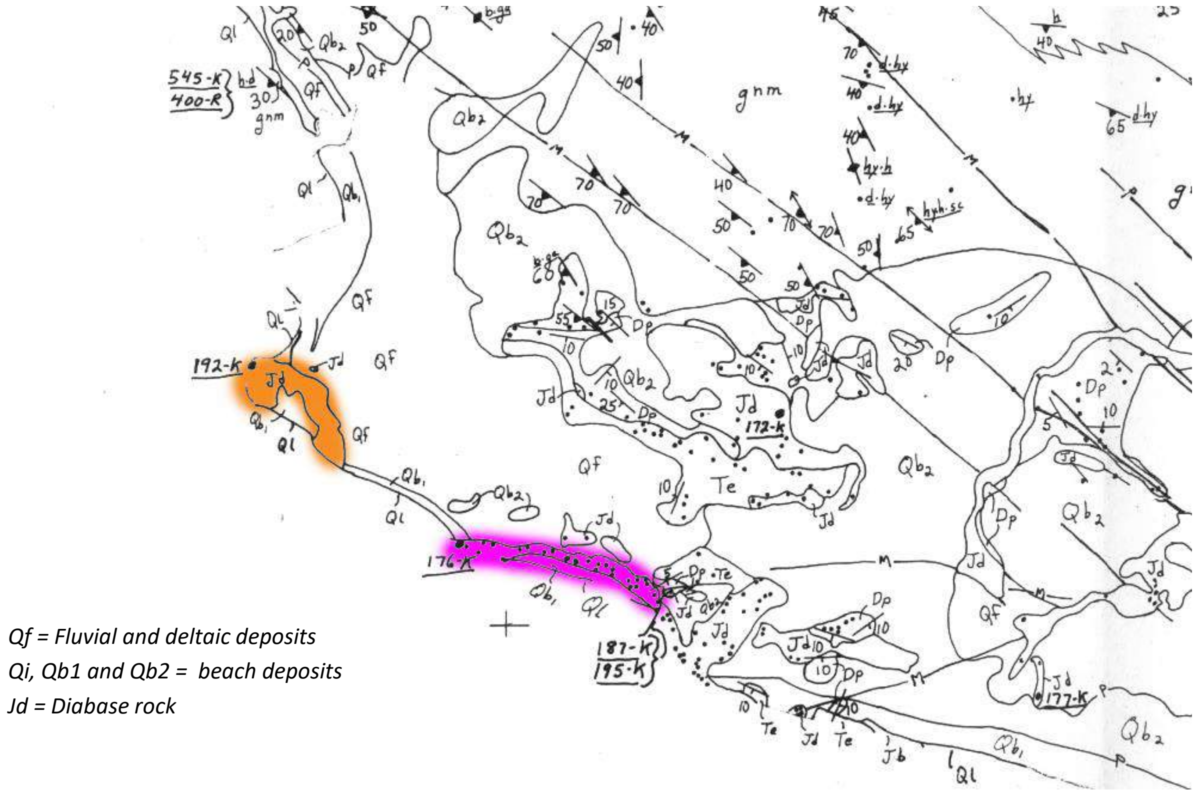

Figure 8-1: Geology map for Monrovia (Ref [32]); orange showing diabase rock at Central Monrovia and purple showing rock outcrops just south east of the coastal sections of this study

The diabase rock formation at Central Monrovia, the Cape of Monrovia, largely explains the coastline orientations and land formations of Monrovia (Figure 8-1). The dominant southerly wave directions induce net longshore sediment transport rates to north western direction. Less erodible geological formations like the Cape of Monrovia, then affect the coastline orientation with typical accretion sections (section 4 and 5) and leeside cape sections (section 1, 2 and 3).

A.2 Bathymetry and Topography

The bathymetry - water side bottom levels - and topography - land side terrain levels - are important determining parameters of this study. The bathymetry (offshore and nearshore) is the main environmental condition affecting offshore to nearshore wave propagation, which in turn determines the magnitude of the forcing behind the main coastal hazard affecting Monrovia, coastal erosion.

For the assessments of this study a combined topographic and bathymetric digital map has been generated (Figure 8-2). This map is composed with several data sources;

- SRTM terrain elevation data (Ref [33])
- Navionics bathymetric charts (Ref [34])
- Monrovia coastal waters bathymetric survey Oct 2018 by SHORE monitoring (ref [35] and Appendix N)

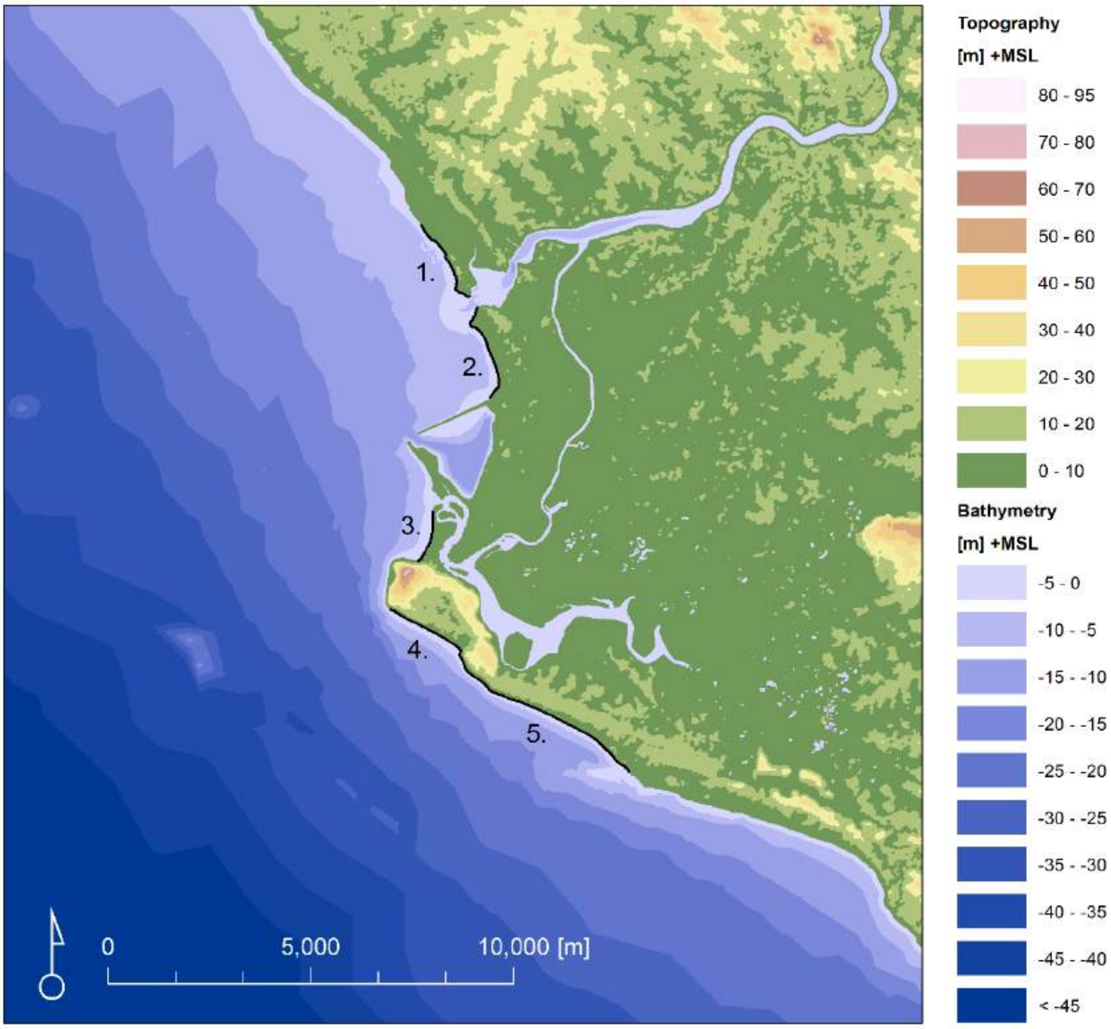

Figure 8-2: Combined bathymetry and topography for Monrovia coastal area

The following observations are made from the topo- and bathymetric map of the Monrovia area:

- Cape of Monrovia is clearly visible with an peak in terrain elevation of approximately 80m +MSL. The topview shape of this hill corresponds to the topview shape of the diabase rock formation at this location.

- As explained in the Geology sub-chapter this cape has affected how the Monrovia coastline has developed over time. At the leeside of the cape the coastline bends to the north backing low lying land with an average terrain elevation of 0 to 10m +MSL.
- The coastal profile is characterised by relatively gentle slopes. Coastal section 4 and 5 have a slightly steeper slope in the range of 1V:200H to 1V:250H, whereas coastal section 1, 2 and 3 (located at the leeside of Cape of Monrovia) have a more gentle slope of approximately 1V:350H to 1V:400H.

Appendix 0 shows a map series with coastal profiles for every 100m, for every coastal section.

A.3 Tides

At Monrovia coastal waters there is semi-diurnal tide, which means there are two high waters and two low waters each day.

The periodic tidal variation has been determined by means of an analysis of astronomic tidal constituents obtained from a local tide station. The tidal constituents have been obtained at Monrovia from the International Hydrographic Organization (IHO) data bank. Based on these tidal constituents time series of more than 20 years have been constructed, from which in turn the tidal levels are estimated. This period is considered to give representative tidal levels since the duration of measurements exceed one lunar nodal cycle (18.61 year). Table 8-1 shows the resulting tidal levels with respect to MSL and LAT. Please note that these values are considered to be with respect to the sea levels in the year 2000.

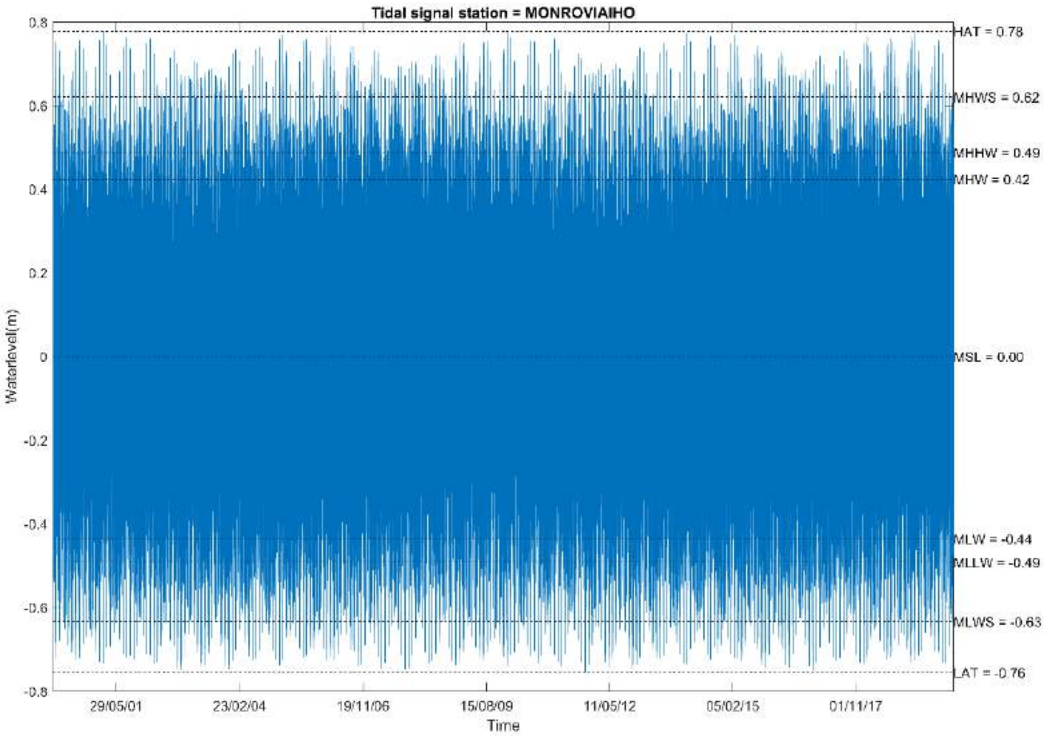

Figure 8-3: Tidal signal of more than 20 years at the tidal gauge of Monrovia (source: IHO)

Table 8-1: Tidal datums at the project area (with respect to MSL and LAT in the year 2000

Datum	m +MSL	m +LAT
HAT	0.78	1.54
MHWS	0.62	1.38
MHHW	0.49	1.25
MHW	0.42	1.18
MSL	0.00	0.76
MLW	- 0.44	0.32
MLLW	- 0.49	0.27
MLWS	- 0.63	0.13
LAT	- 0.76	0.00

A.4 Storm surge

Surge is a temporal and local rise in sea level which can be caused by (a combination of) several effects. Along the West African coast storms (i.e. a violent disturbance of the atmosphere accompanied with strong winds, low depression and high waves) like experienced in Europe for example are virtually absent. Also any tropical cyclonic activity has never been observed in this region, see section A.8.

(Storm) surges in this region are therefore mainly affected by

- Wind (wind setup)
- Changes in atmospheric pressure.

The surges in this area are assessed using the open source data from the global reanalysis of storm surges and extreme sea levels (GTSR – Ref [36]). This global model includes the relevant effects described above and provides daily maxima at the 16,395 locations along the worlds coastline of the total sea level (tide and surge combined).

The daily maxima of the total sea level are extracted at the coastline of Monrovia to assess the extreme total sea levels. The annual maxima have been used to fit a Generalized Extreme Value (GEV) distribution as shown in Figure 8-4 and the resulting extreme total sea levels in Table 8-2. These levels can be considered to be referenced to Mean Sea Level (MSL), and thus includes tide but excludes the effect of Sea Level Rise, which should be considered separately. It is clear from the results that the additional surge is relatively low: e.g. the total extreme sea level with return period of 100 years is 0.23 m above Mean High Water Spring (0.62 m+MSL).

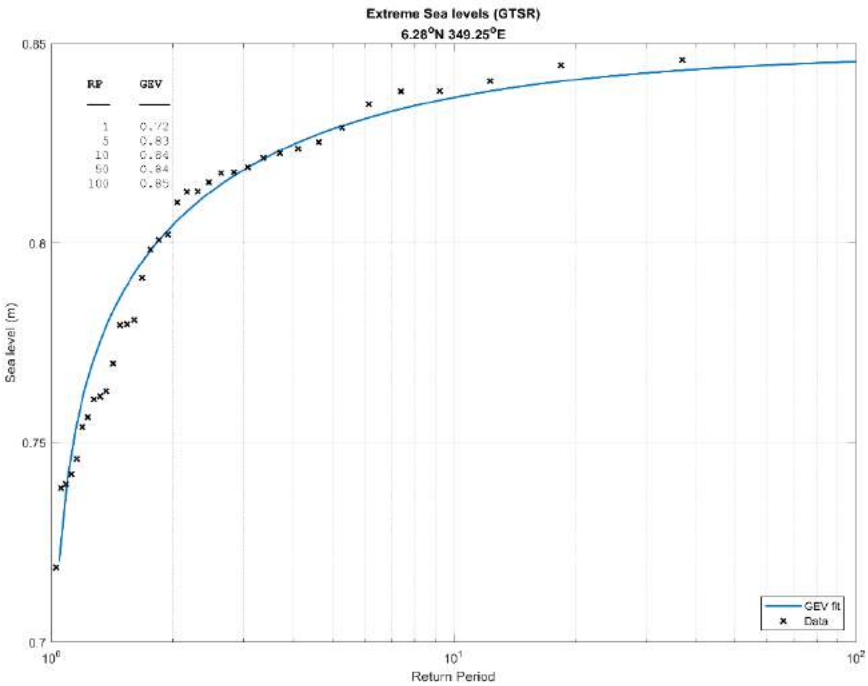

Figure 8-4: Extreme value distribution of Extreme Sea Levels based on GSTSR data

Table 8-2: Extreme total sea levels (including tide), based on GSTSR data

Return period (years)	Total extreme sea level (incl. tide, excl. SLR) [m+MSL]
1	0.72
10	0.84
100	0.85

A.5 Particle size distribution of beach material

To determine the particle size distribution of the beach sediments soil samples were taken and analysed for different coastal stretches onshore and offshore, at various locations along the beach profile. Onshore samples were taken at the highest end of the beach and at the lower part to the swash zone.

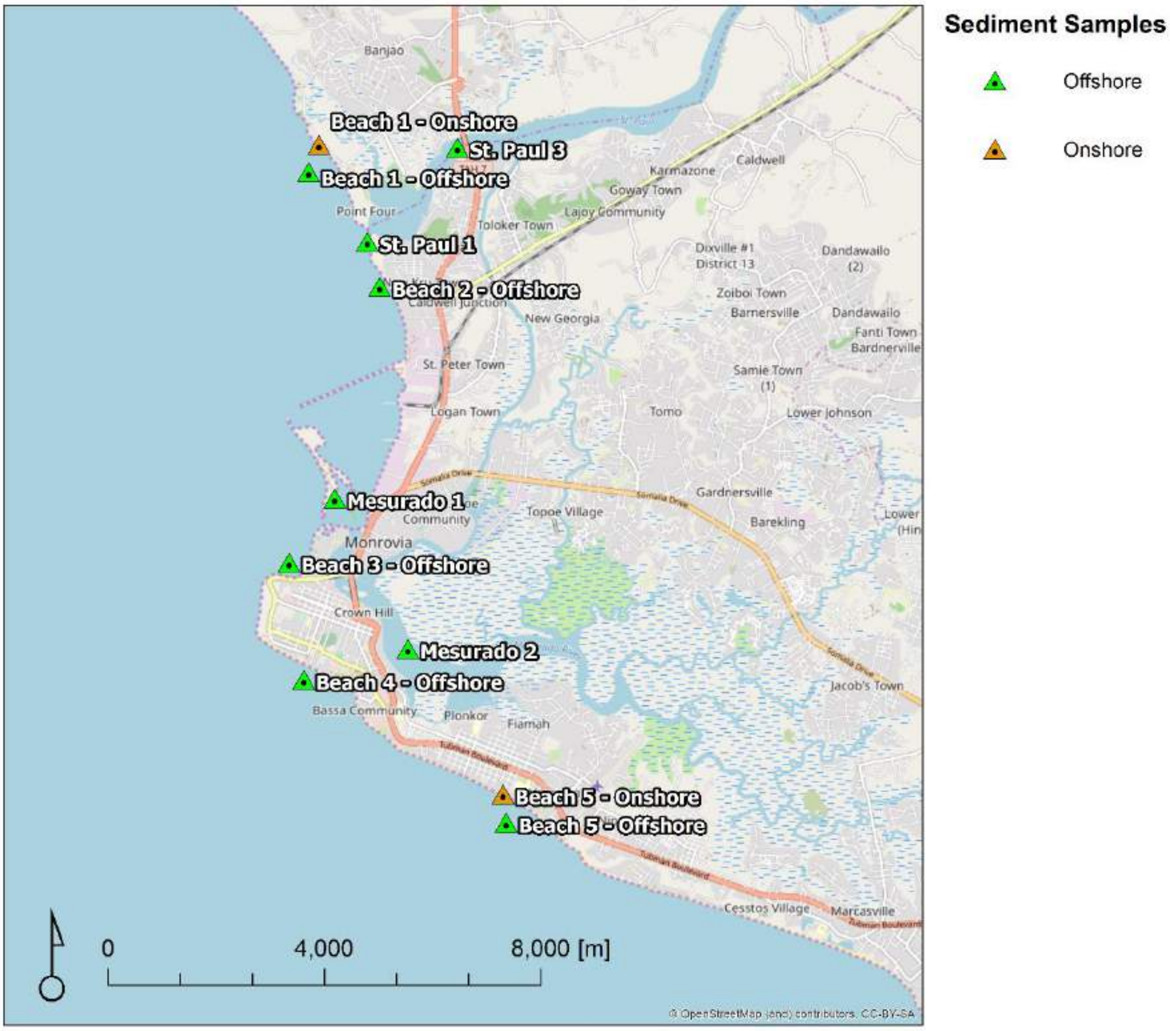

Figure 8-5: Offshore and onshore sediment sample locations

Figure 8-5 shows the various sediment sample locations in the project area, which corresponds with Table 8-3 and Table 8-4 presenting D50 of the particle size distribution. D50 stands for the diameter of the particle of which 50% of the sample's mass is smaller and 50% of the sample's mass is larger than that diameter, and this is the most important sediment characteristic for assessing longshore and cross shore sediment transport as well as an important parameter for designing the interventions. Appendix M shows the complete results of the laboratory results.

Table 8-3: D50 onshore sediment samples

Onshore samples	D50 [mm]
Beach 1 - Onshore - High	0.55
Beach 1 - Onshore - Low	0.46
Beach 5 - Onshore - High	0.52
Beach 5 - Onshore - Low	0.43

Table 8-4: D50 offshore sediment samples

Offshore samples	D50 [mm]
Beach 1 - Offshore	0.14
Beach 2 - Offshore	0.19
Beach 3 - Offshore	0.1
Beach 4 - Offshore	0.08
Beach 5 - Offshore	0.08
St. Paul 1	0.85
St. Paul 3	0.82
Mesurado 1	0.31
Mesurado 2	0.16

Based on these quantitative data and visual inspection the following observations are made:

- Course sand is found in the upper part of the beach. Medium course sand is located at the lower part of the beach.
- Fine sediments are found offshore.
- In the river mouth very course sediments are present.
- In the Mesurado Lagoon there is mainly fine sediments

Figure 8-6: Sieving to assess particle size distribution

A.6 Precipitation

In Monrovia rainfall is on average about 5,100 mm per year. Liberia has a wet season which runs from May to October with two peaks, and a dry season from November to April. The monthly averages of rainfall in Monrovia are given in Figure 8-7.

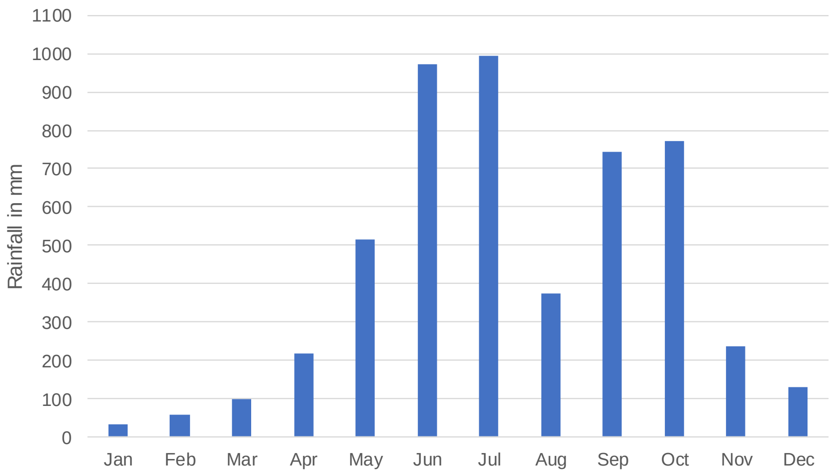

Figure 8-7: Monthly rainfall in Monrovia (Ref [37])

Precipitation in Monrovia typically is intense and of short duration, called convective rainfall. Based on measured rainfall for LEC in 2015 and 2016[13] (period of one year) it can be observed that once in per year the daily rainfall had exceeded 200 mm. Exceedance of 100 mm rainfall per day occurs more often, in the order of a couple of days per month from June until October.

[13] Study conducted by Earthtime for LEC in 2016

A.7 Seismic conditions

According to the map of Figure 8-8, obtained from the Global Seismic Hazard Assessment Program, Monrovia is located in a low risk area of earthquakes/ seismic activity.

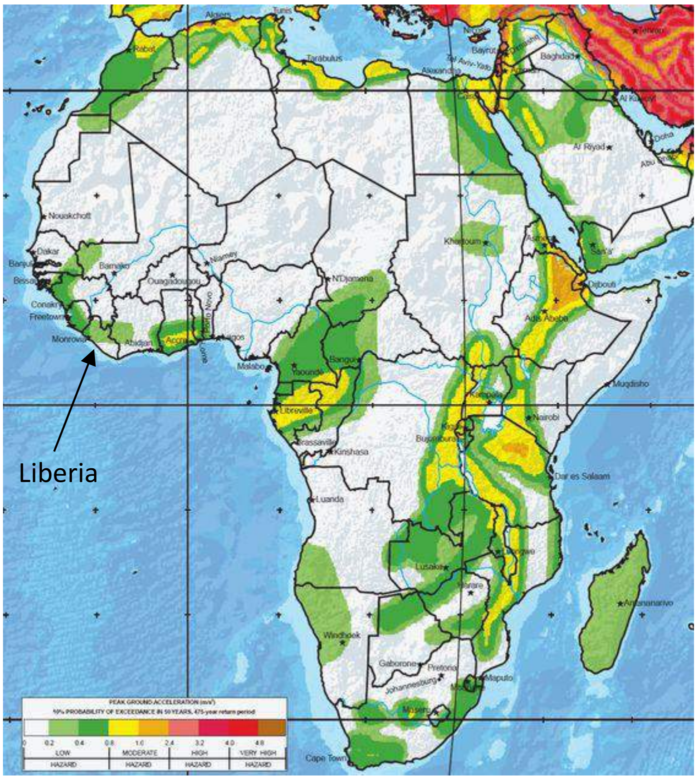

Figure 8-8: Seismic risk map of Africa obtained by the Global Seismic Hazard Assessment Program (Ref [38])

Liberian news feeds are found about an earthquake in Guinee of which some shocks were felt in parts of Liberia (1983). More recent articles describe an earthquake with a magnitude of 7.1 on the Richter scale, 1050km off of the coast of Monrovia, at a depth of 10km in the Atlantic Ocean (2017) (Ref [39]). This earthquake also did not form a threat for the Liberian society or neighbouring countries.

Based on this information, the probability of an earthquake hazard is considered very low and if there is an event it is very likely the magnitude will be also very low (Ref [40]). Hence, seismic activity is negligible for this project. It will therefore not be included in the vulnerability assessment or the designs of the coastal protection.

A.8 Cyclones

Based on the history of cyclones near West-Africa, this hazard is not considered in the vulnerability analysis. Never before a cyclone is reported that affected Monrovia. Reported cyclones closest to the project region are probably those near the islands of Cape Verde. In general, even these cyclones do not cause a lot of damage, as they originate around Cape Verde but then move away from the African Continent while still building up wind speed.

Climate change might cause an increase in the number and severity of the cyclones near the islands of Cape Verde. However, it is very unlikely that in the future the direction of these cyclones will change such that its pathway will cross Liberia. Also, the probability of the formation of a new cyclone region in the vicinity of Liberia is considered to be negligible.

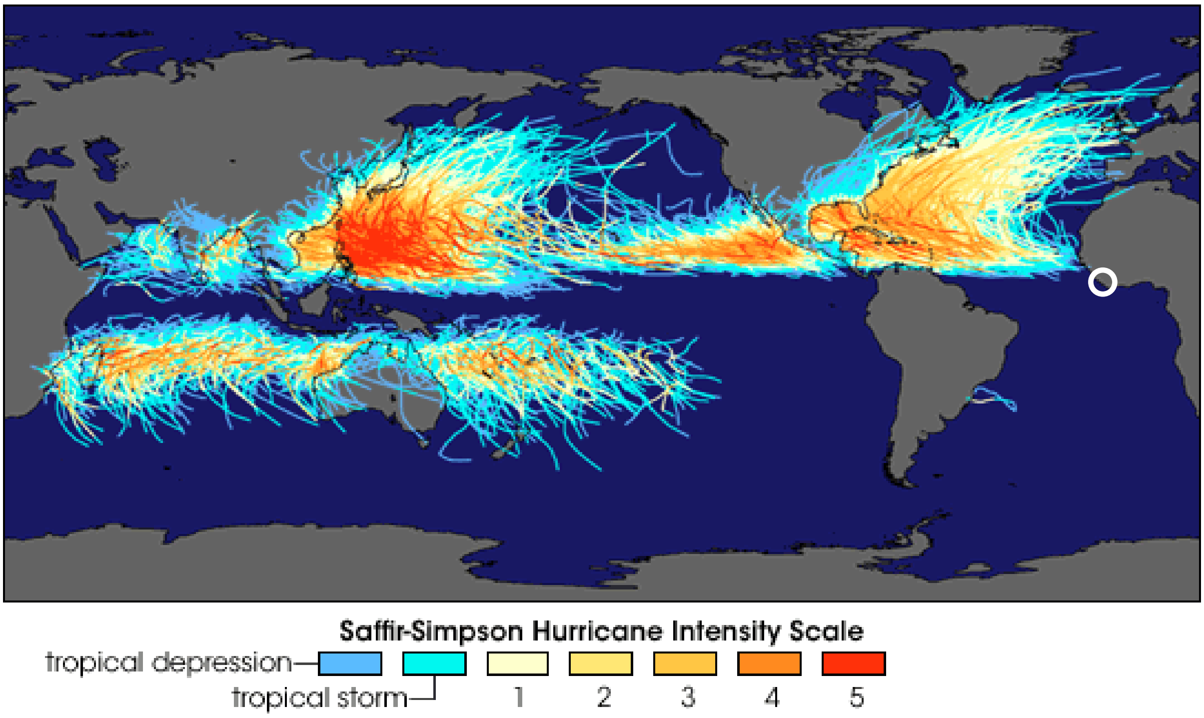

Figure 8-9: Historic tropical cyclone tracks for past 150 years[14]. White circle shows location of Liberia.

[14] https://earthobservatory.nasa.gov/images/7079/historic-tropical-cyclone-tracks

B. RELATIVE SEA LEVEL RISE

B.1 Background

The Synthesis report of IPCC (2014) reported that over the period 1901–2010, global mean sea level rose by 0.19 [0.17 to 0.21] m with an average rate of 1.7 mm/year in the 20th Century (Bindoff et al., 2007 – Ref [41]). The fifth assessment report of the International Panel on Climate Change IPCC 2014 indicated a transition in the late 19th century to the early 20th century from relatively low mean rates of rise over the previous two millennia to higher rates of rise (high confidence). From 1961 to 2003 the average rate of SLR was 1.8 ± 0.5 mm/year, while between 1993 and 2010 the rate was very likely higher at 3.2 [2.8 to 3.6] mm/year; similarly high rates likely occurred between 1920 and 1950. IPCC also reported that ocean thermal expansion and glacier melting have been the dominant contributors to 20th century global mean sea level rise.

Relative sea level rise (RSLR) over the next 30-100 year period is the sum of two major components: global-mean sea-level change and regional (local) spatial variations in sea-level change.

B.2 Global-mean sea-level change (ΔSLG)

The Global mean sea level change results from the change in the volume of the global ocean. This is mainly due to:

- thermal expansion of the ocean as it warms;
- melting of glaciers and ice caps due to global warming (Bindoff et al., 2007 (Ref [41]); Meehl et al., 2007 (Ref [42])); and,
- changes in the mass balance of the Greenland and Antarctic ice sheets, which is less certain (Shepherd and Wingham, 2007 – Ref [43]).

In this study, different scenarios for global-mean sea-level rise were determined based on climate change scenarios developed by IPCC (2014). Based on these projections, for the period 2081–2100, compared to 1986–2005, global mean sea level rise is likely (medium confidence) to be in the 5 to 95% range of projections from process-based models, which give 0.26 to 0.55 m for RCP2.6, 0.32 to 0.63 m for RCP4.5, 0.33 to 0.63 m for RCP6.0, and 0.45 to 0.82 m for RCP8.5. For RCP8.5, the rise by 2100 is 0.52 to 0.98 m with a rate during 2081–2100 of 8 to 16 mm/yr. Figure 8-10 shows the projected Global mean sea level change.

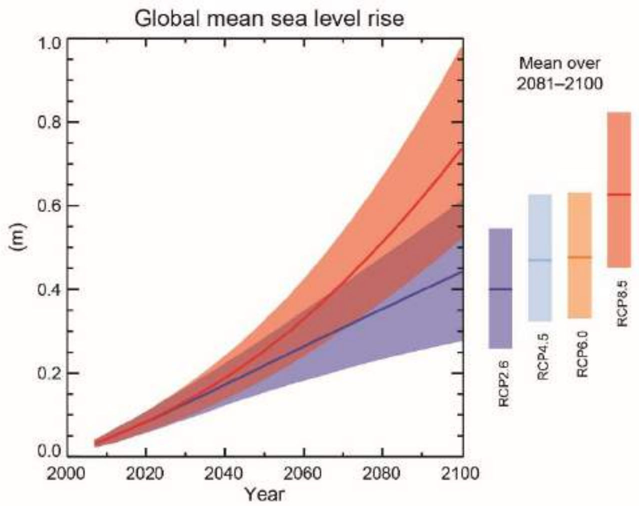

Figure 8-10: Projected Global mean sea level change from IPCC (2014)

New studies (e.g. DeConto and Pollard, 2016 - Ref[49]) estimates maximum of around 2.0 m due to potential for break-up of Antarctic ice shelves (AIS).

B.3 Regional (local) spatial variations in sea-level change

These local variations are mainly due to:

a. Meteo-oceanographic factors (ΔSL_{RM}), including differences in the rates of oceanic thermal expansion, changes in long-term wind and atmospheric pressure, and changes in ocean circulation (such as the Gulf Stream - e.g. Lowe and Gregory, 2006 and in the Indian Ocean - Han et al., 2010). The contributions from these phenomena could be significant, causing large regional departures of up to 50-100% from the global average value of SLR. However, coupled atmosphere-ocean climate models of these effects under global warming are inconsistent on the location of such larger-than-average changes (Meehl et al., 2007 (Ref [42]; Pardaens et al., 2011 (Ref [44]).

b. Changes in the regional gravity field of the Earth (ΔSL_{RG}) due to ice melting (caused by redistribution of mass away from Greenland, Antarctica as well as glaciers). The global sea-level rise caused by the melting of an ice sheet will not be evenly distributed as a single "global eustatic" or global mean value (see Section 5.5.4.4 in Bindoff et al., 2007 (Ref [41]). If a polar ice sheet melts, then the volume of water in the oceans increases, but at the same time, the gravitational pull from the ice sheet on the oceans close to the ice sheet falls. The net effect of these processes is that sea level rise occurs faster in areas farther away from the source of the melting. For example, in the case of melting Greenland ice, there would be less sea level rise than the global average in the North Atlantic, near Greenland, while an enhanced sea level rise (compared to the global eustatic value) will occur at low latitudes and in the southern oceans. Each potential mass source or sink (Greenland ice <sheet, Antarctic ice sheet, glaciers, water storage on land) will produce its own pattern or "fingerprint" of sea level change measured at the coast (e.g. Mitrovica et al., 2001 (Ref [45])).

c. Vertical land movements (uplift and subsidence) (ΔSL_{VLM}) due to various natural and human-induced geological processes (Christensen et al., 2007 (Ref [46]), Box 11.5). Apart from land subsidence phenomena which could significantly affect local relative sea level rise, vertical land movement may be also caused by other natural factors including: i) neotectonics, ii) glacio-isostatic adjustment (GIA), and iii) sediment compaction/consolidation. These changes can be regional, slow and steady, as in the case of GIA, but can also be localized, large and abrupt, for example due to earthquakes.

In this study, the two main components causing vertical land movement are separately considered as ''tectonic uplift'' and ''land subsidence''. Other components causing vertical movement such as GIA are already included in the regional RSLR projected by IPCC (2014).

The inclusion of regional components of relative sea-level rise is important when developing scenarios for impact and adaptation assessment as they provide a critical link between global climate change and regional/ local coastal management strategies (Christensen et al., 2007 (Ref [46]; Nicholls et al., 2007 (Ref [29])).

Relative sea level rise projections for a specific location should take into account the different contributions from the components at the global, regional and local scales described above, as relevant to the study area. These can be integrated for a given site using following equation:

$$\Delta \mathrm{RSL} = \Delta \mathrm{SL_G} + \Delta \mathrm{SL_{RM}} + \Delta \mathrm{SL_{RG}} + \Delta \mathrm{SL_{VLM}} \qquad \text{(B.1)}$$

Where:

- ΔRSL is the change in relative sea level
- ΔSL_G is the change in global mean sea level
- ΔSL_{RM} is the regional variation in sea level to the global mean due to meteo-oceanographic factors
- ΔSL_{RG} is the regional variation in sea level due to changes in the earth's gravitational field
- ΔSL_{VLM} is the change in sea level due to vertical land movement

IPCC guidelines to determine local RSLR by 2100 has been prescribed by Nicholls et al. (2011) (Ref [29]) where 3 different options are given based on data availability. Here, we used the 'intermediate' option together with IPCC AR5 projections of global mean SLR and regional variations in SLR. The 'intermediate' assessment methodology suggested by Nicholls et al. (2011) (Ref [29]) was adopted to derive RSLR scenarios linked to the four IPCC RCP scenarios (RCP2.6, RCP4.5, RCP6.0, RCP8.5). In this approach, RSLR projections for a specific location are calculated while taking into account the different contributions from the components at the global, regional and local scales. These components are then added together using the equation B.1.

Global mean SLR projections are obtained here using the projections given in IPCC AR5 together with the 'intermediate' option. Following the graphs of SLR given in AR5, the SLR estimates presented here are from 2008 to 2100, with a global mean SLR of 40mm by 2008 relative to 1986-2005. To represent the time variation of the global mean SLR, the curves presented in AR5 (Figure 13.11 in Church et al., 2013 – Ref [28]) for the 4 RCP scenarios are reproduced here by deriving the coefficients of Nicholls's (2011 – Ref [29]) method as follows:

$$\Delta SL_G = a_1 t + a_2 t^2 \qquad \text{(B.2)}$$

Where:

- ΔSLG is the change in global mean sea level
- t is number of years starting from 2000
- a_1 is rate of sea level change (per year)
- a_2 is change in the rate (acceleration) of sea level change (per year)

B.4 Regional spatial variations in Relative Sea Level Rise

Over the next decades, regional relative sea level rise over most parts of the world are likely to be dominated by dynamical changes resulting from natural variability, although exceptions are possible near rapidly melting ice sheets where static effects could become large (Church et al., 2013 – Ref [28]). Figure B-3 shows ensemble mean regional relative sea level change between 1986-2005 and 2081-2100 for RCPs 2.6, 4.5, 6.0 and 8.5 (these values include the global mean sea level change as well as regional variations thereof). It is very likely that in about 95% of the World Oceans, regional relative sea level rise will be positive, while most regions with estimated sea level fall are located near contemporary and former glaciers and ice sheets.

It should be noted that the effect of vertical land movement consisting of 'tectonic uplift' (except GIA factor) and 'land subsidence' is not included in estimates of relative regional sea level rise shown in the Figure 8-11.

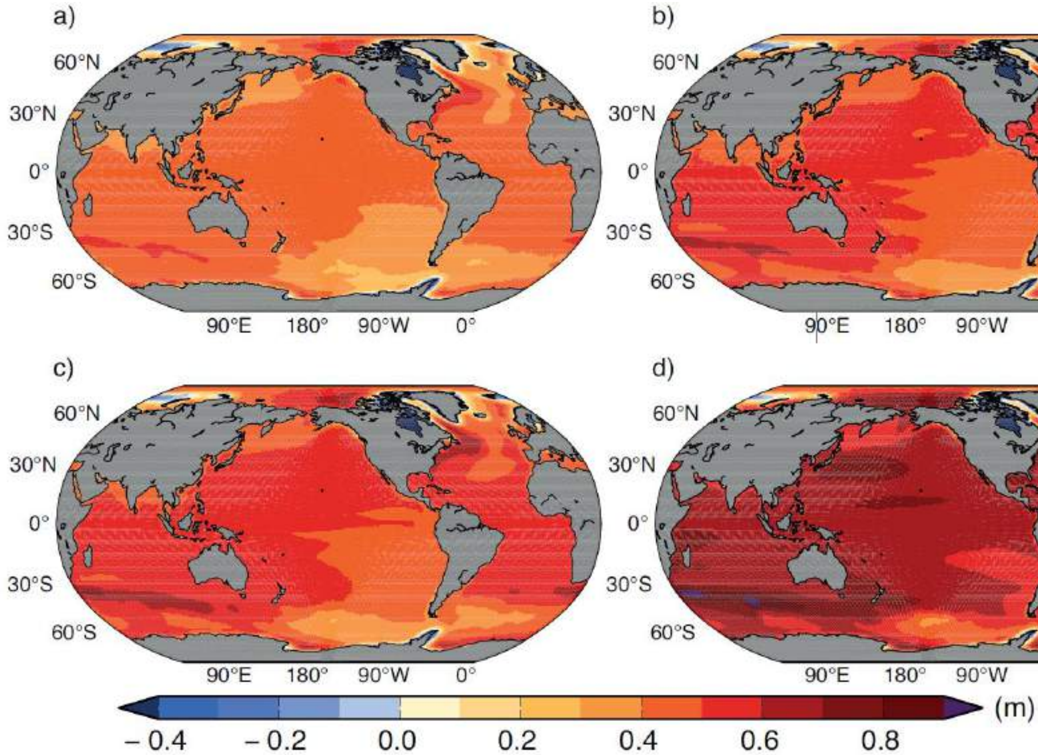

Figure 8-11: Ensemble mean regional relative sea level change (m) evaluated from 21 CMIP5 models for the RCP scenarios (a) 2.6, (b) 4.5, (c) 6.0 and (d) 8.5 between 1986-2005 and 2081-2100. Each map includes effects of atmospheric loading, land ice, glacial isostatic adjustment (GIA) and terrestrial water sources. (Source: Church et al., 2013 – Ref [28]).

To develop local RSLR scenarios, the regional variations in RSLR need to be estimated for the study area. Following Nicholls et al. (2007 – Ref [47]), the different regional RSLR contributions described in Section B.3.1 are computed as follows:

B.5 Regional variation in sea level due to meteo-oceanographic factors (ΔSLRM)

In previous IPCC reports, this component was presented as a separate map (Figure 10.32 in Meehl et al., 2007 – Ref [42]), while AR5 presents maps that combine the global mean sea level rise and the ΔSLRM component, as shown in Figure 8-11. Therefore ΔSLRM at 2100 was computed by estimating the difference between the values shown in Figure 8-11 and the 2100 global mean SLR values for each RCP (see Table 8-5), and assuming that the temporal variation in ΔSLRM is linear from 2008 to 2100.

Table 8-5: Difference between Regional Relative Sea level rise (m) and Global mean Sea level rise (m) due to meteo-oceanographic factors in 2100

	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Regional RSLR	0.4	0.49	0.5	0.65
Global mean SLR	0.38	0.46	0.47	0.62
Regional Variation (ΔSLRM)	0.02	0.03	0.03	0.03

B.6 Changes in the regional gravity field of the Earth (ΔSL_{RG})

This factor is significant under deglaciation of Greenland or Antarctica. A few studies are now starting to develop scenarios of future sea level that recognize changes in the global and regional gravity field associated with mass exchange with the ocean. This is particularly important for future scenarios with a large ice melt component, but less for those dominated by thermal expansion. However, due to the unavailability of reliable projections of the potential RSLR contribution due to this phenomenon at present, this effect is not taken into account in this study.

B.7 Vertical land movements ($\Delta \mathbf{SL_{VLM}}$)

Vertical land movement consists of earth tectonic movements and land subsidence namely $\Delta SL_{VLM\ 1}$ and $\Delta SL_{VLM\ 2}$. For this study we do not have information about the land subsidence which can vary locally and only used the tectonic uplift noting that all RCP scenarios consider the same uplift movement rates. Prof. Richard Peltier at the University of Toronto, using the ICE-5G (VM2 L90) model, estimated that the mean uplift at the west Africa is 0.35 mm/year and consequently 0.032 m in 2100. (https://www.physics.utoronto.ca/research/eapp).

B.8 The regional variations in sea level change at Monrovia

Combining the above values, the regional variations in sea level change (including tectonic uplift, but excluding land subsidence) were estimated for 2100 at Monrovia. Table 8-6 shows the results reflecting the influence of tectonic uplift on the regional variations of sea level rise. Figure 8-12 shows the RSLR values taking into account the global mean SLR and regional variations of SLR due to the effects of tectonic uplift and s meteo-oceanographic factors ($\Delta SL_{RM} + \Delta SL_{VLM1}$) projected from 2008 to 2100. The same data is shown for different years in Table 8-7.

Table 8-6: Effects of tectonic uplift factor on regional variation of RSLR (m) in 2100.

	RCP2.6	RCP4.5	RCP6.0	RCP8.5
Regional variation (ΔSLRM)	0.02	0.03	0.03	0.03
Tectonic uplift (ΔSL_{VLM1})	-0.032	-0.032	-0.032	-0.032
$\Delta SL_{RM} + \Delta SL_{VLM1}$	-0.012	-0.002	-0.002	-0.002

Table 8-7:The ranges of RSLR (m) for the four RCP scenarios at different times (Excluding land subsidence) relative to 2008.

Year	Bound	Climate Change Scenarios			
		RCP2.6	RCP4.5	RCP6.0	RCP8.5
2025	lower	0.07	0.07	0.08	0.08
	upper	0.12	0.12	0.12	0.13
2050	lower	0.14	0.17	0.17	0.19
	upper	0.26	0.29	0.30	0.32
2075	lower	0.21	0.27	0.26	0.34
	upper	0.42	0.48	0.49	0.60
2100	lower	0.26	0.36	0.37	0.52
	upper	0.59	0.70	0.72	0.96

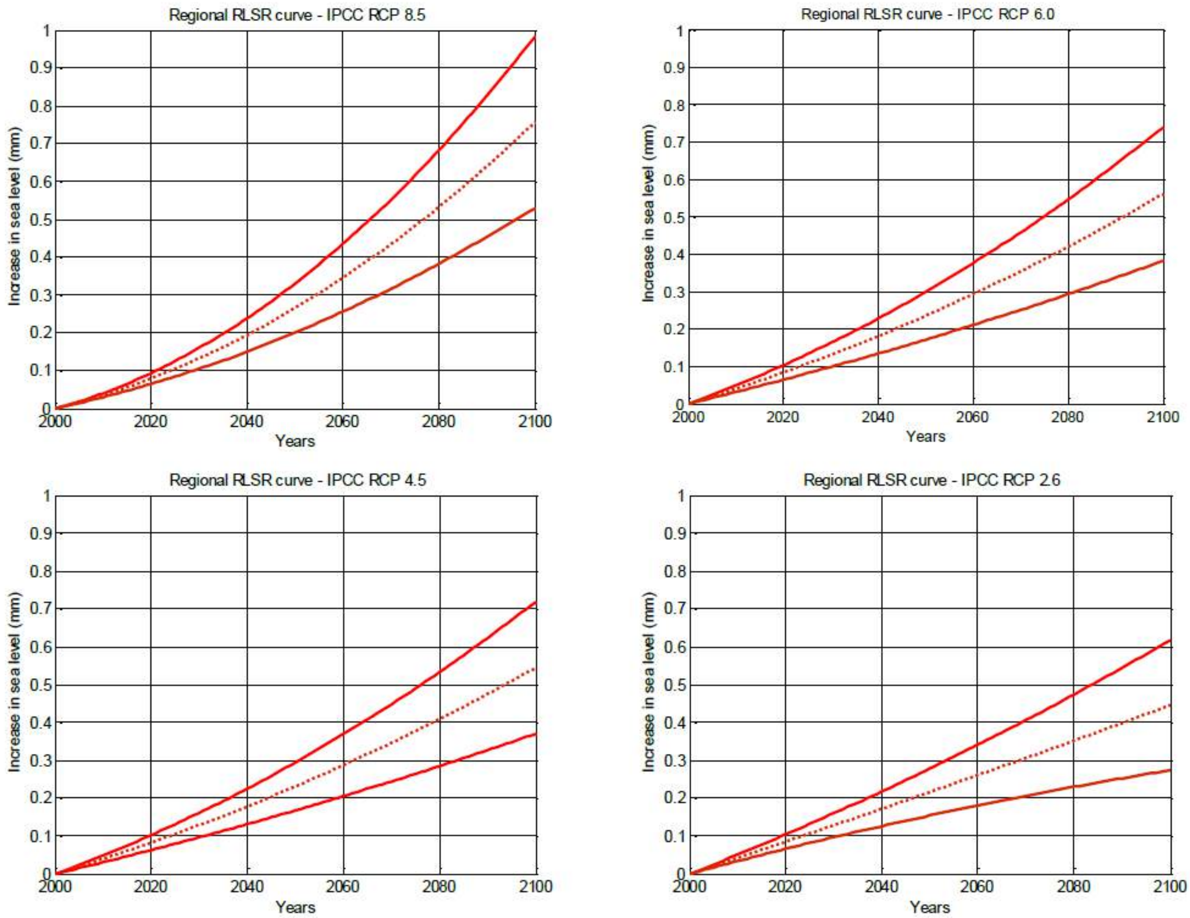

Figure 8-12: Regional RSLR – Excluding land subsidence for the four RCP scenarios by 2100 (relative to 2008).

C. WAVE CLIMATE

C.1 Present offshore wave climate

The present offshore wave conditions are obtained from open source global hindcast data sets.
Two different sources have been used in this study:

- ERA Interim reanalysis (Jan 1979- Nov 2018) data from an operational global atmospheric reanalysis from 1979, continuously updated in real time operated by the European Centre for Medium-Range Weather Forecasts (ECMWF);
- National Centers for Environmental Prediction (NCEP) from National Oceanic and Atmospheric Administration:
    - NCEP Climate Forecast System Reanalysis and Reforecast (CFSRR) (1979-2009)
    - Production hindcast (Feb 2005- Nov 2018)

For both hindcast datasets timeseries of wave and wind data has been extracted for the location : 6°N 11°W (approx. 40 km southwest of Monrovia, see Figure 8-13). Extensive data analysis reports for both data sets separately are attached as reports.

Figure 8-13: Location extraction point hindcast wave data

Normal wave climate

From both data sets it became clear that the wave climate of Liberia's coastline is largely dominated by persistent long period swell waves and relatively uniform, both in direction and height in nature. Swell waves are, in contrary to wind waves (which are generated by the immediate local wind), generated by distant weather systems (storms) in the South Atlantic Ocean. These waves travel over a very long distance (thousands of kilometres) and disperse into uniform wave groups with long wave periods (more than 20 seconds). The local wave climate can therefore be described as fairly uniform in both direction (SSW) and wave period. These swells are highly energetic leading to strong wave breaking onto the relative steep sandy shorelines of Liberia.
Below a short description of the wave climate is provided, with use of figures of the analysis of the NOAA/NCEP hindcast data set.

Figure 8-14 shows the offshore significant wave height and peak period wave rose offshore. The direction of the roses show the peak wave direction. The uniformity of the wave direction is clearly visible in the roses. Two distinct systems can be observed: the dominant swell system from SSW (approx. 200°N) and one from SSE (approx. 160°N). It is noted that both system may occur simultaneously, here the peak wave direction is shown, which show the direction of the peak of the energy spectrum.

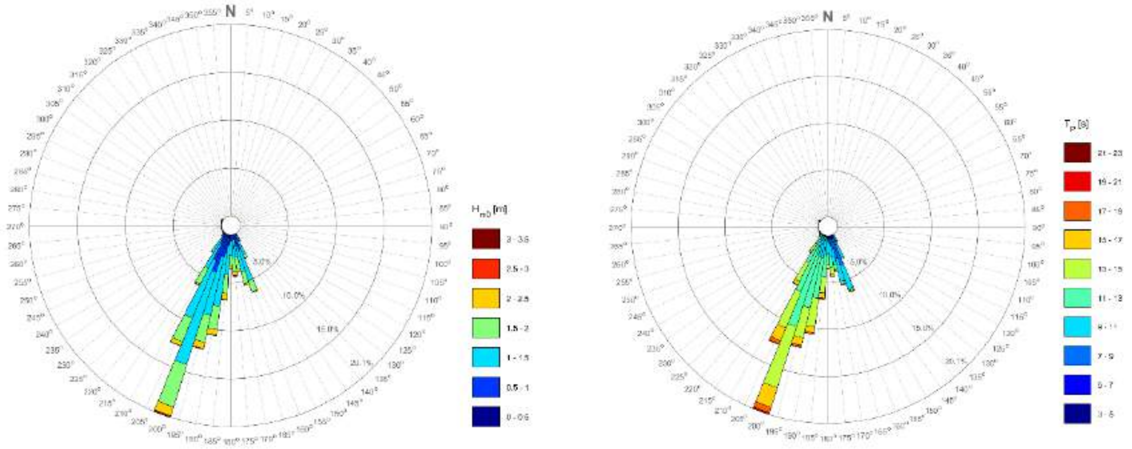

Figure 8-14: Wave height and peak period rose of the NOAA hindcast data set at 6°N 11°W

Figure 8-15 show a scatterplot of the significant wave height and peak period. The colours indicate the wave direction. It shows that there is no clear relationship between the wave period and significant wave height for the majority of the waves, which indicate the waves are mostly swell waves. A small part of the waves can be considered locally generated sea waves (steepness lower than 0.02). The average peak wave period is approximately 12 seconds.

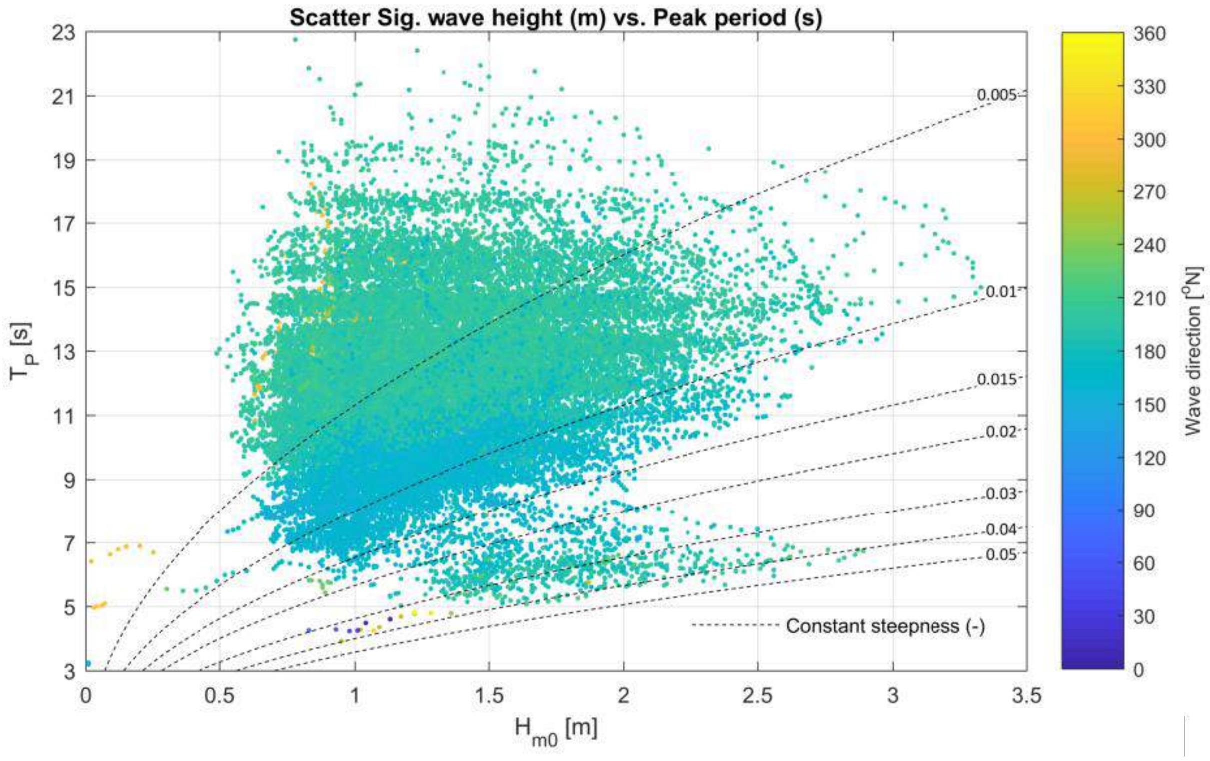

Figure 8-15: Scatterplot offshore wave height and peak period

Figure 8-16 show the monthly distribution of the offshore significant wave height. It is clear that there is some seasonal variation. During the months from April to September the significant waves are higher, on average 1.75 m, compared to the other months, on average 1 m. The significant wave height in the calm months is quite uniform, i.e. the distribution is relatively small. In the stronger season the distribution widens and the most extreme waves can be expected. The extreme wave heights are treated separately in the next paragraph.

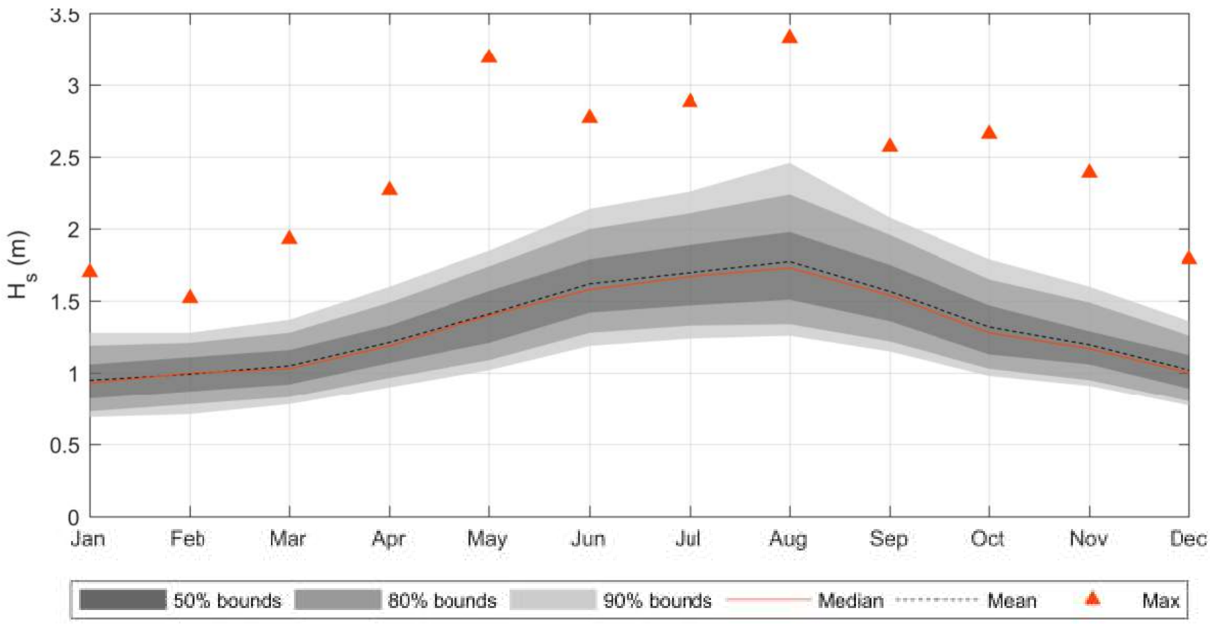

Figure 8-16: Monthly distribution of the offshore significant wave height. (Note: the shown bounds do ***not*** *show the uncertainty of the significant wave heights, but only the variability during those months)*

Figure 8-17 shows the offshore wind rose. The wind climate at Monrovia is considered calm to moderate with respect to windspeed, with dominant wind headings from the South-West to Southerly directions being onshore winds.

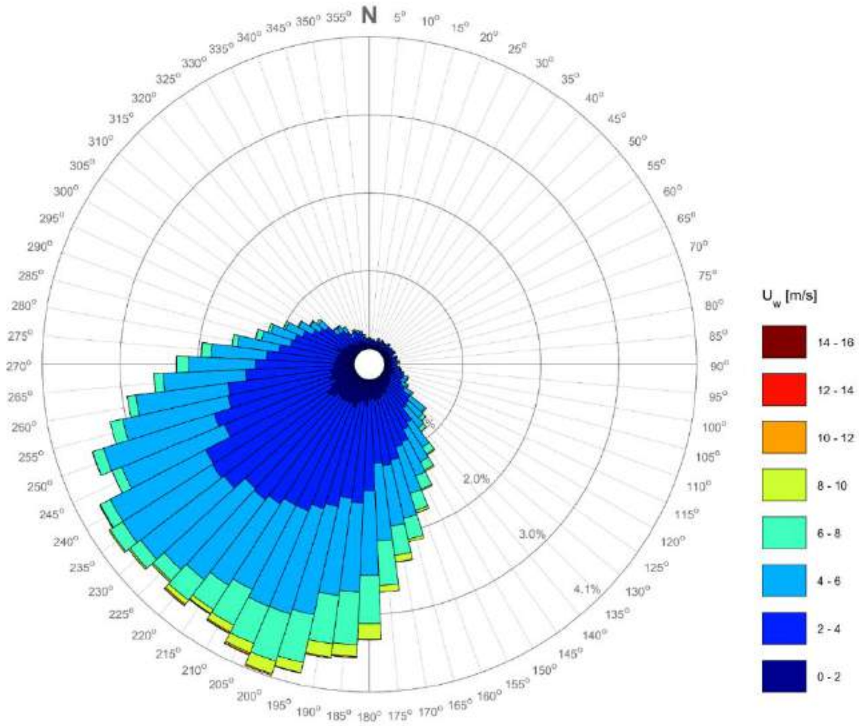

Figure 8-17: Offshore wind rose

Extreme wave conditions

The extreme wave conditions are determined for the offshore data point by means of an Extreme Value Analysis (EVA) and then translated to nearshore using the spectral wave model. The extreme value analysis has only performed using the NOAA data, since the temporal resolution is higher for the NOAA hindcast data set (3hrs) compared to the ERA-Interim data set (6hrs) and hence more extreme values are included.

The EVA has been done primarily on the swell waves of the offshore wave climate, to ensure homogeneity in the data set. The figure below shows the deviation between the wind and swell waves based on the a constant (deep water) wave steepness of 0.017 (higher steepness indicates wind waves (red) and lower steepness indicates swell (blue)). It is clear from this figure that swell highly dominates the wind waves, which justifies that the latter is neglected in further reporting.

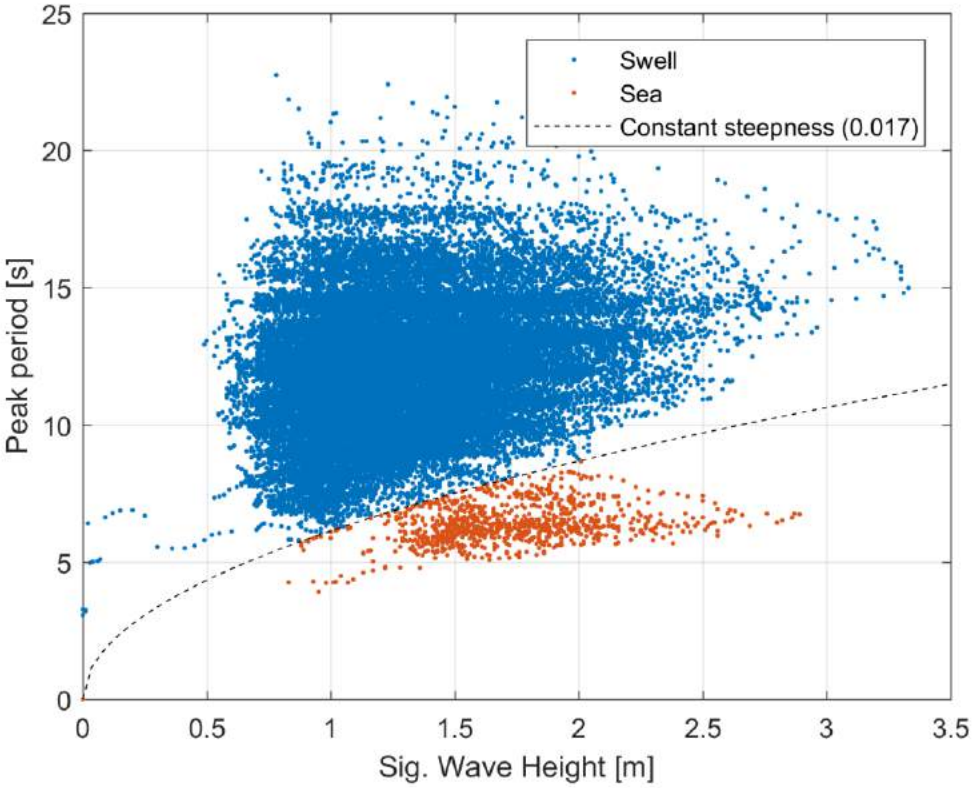

Figure 8-18: Deviation swell (blue) and wind waves (red) based on a constant steepness of 0.017 (black dashed line)

Using the Peak over Threshold (PoT) method the extreme wave heights are derived from the data sets for which an extreme value distribution is fitted. PoT data is theoretically distributed by a Generalized Pareto Distribution (GPD) which is therefore used to fit and extrapolate the extreme wave heights.

The resulting extreme value distribution fit is shown in Figure 8-19, including the estimates for the extreme wave heights with for several return periods.

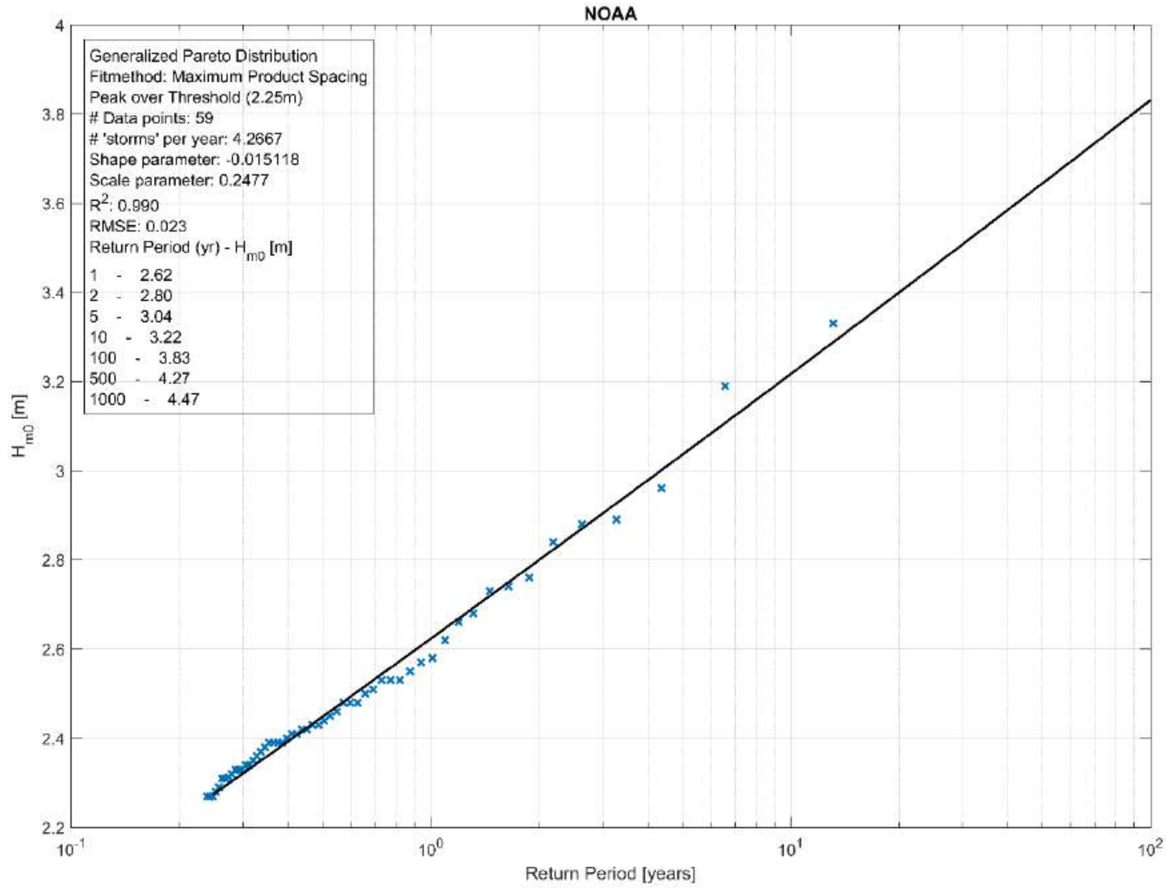

Figure 8-19: Extreme value distribution swell waves based on NOAA data at 6°N 11°W

The corresponding wave period and wind conditions have been derived based on the derived extreme wave heights. With use of quantile regression technique the median and 5th and 95th percentile regression was fitted to obtain the corresponding peak wave period in relation to the extreme significant wave height. In this project the median fit has been used, see Figure 8-20. The same methodology has been used for the derivation of the corresponding wind speed, see Figure 8-21. It would be too conservative to apply extreme wind speeds in combination with extreme wave heights (e.g. 100 year return period wind speed in combination with 100 year return period wave height), since the waves are not wind driven (swell). Their (statistical) dependency is therefore low.

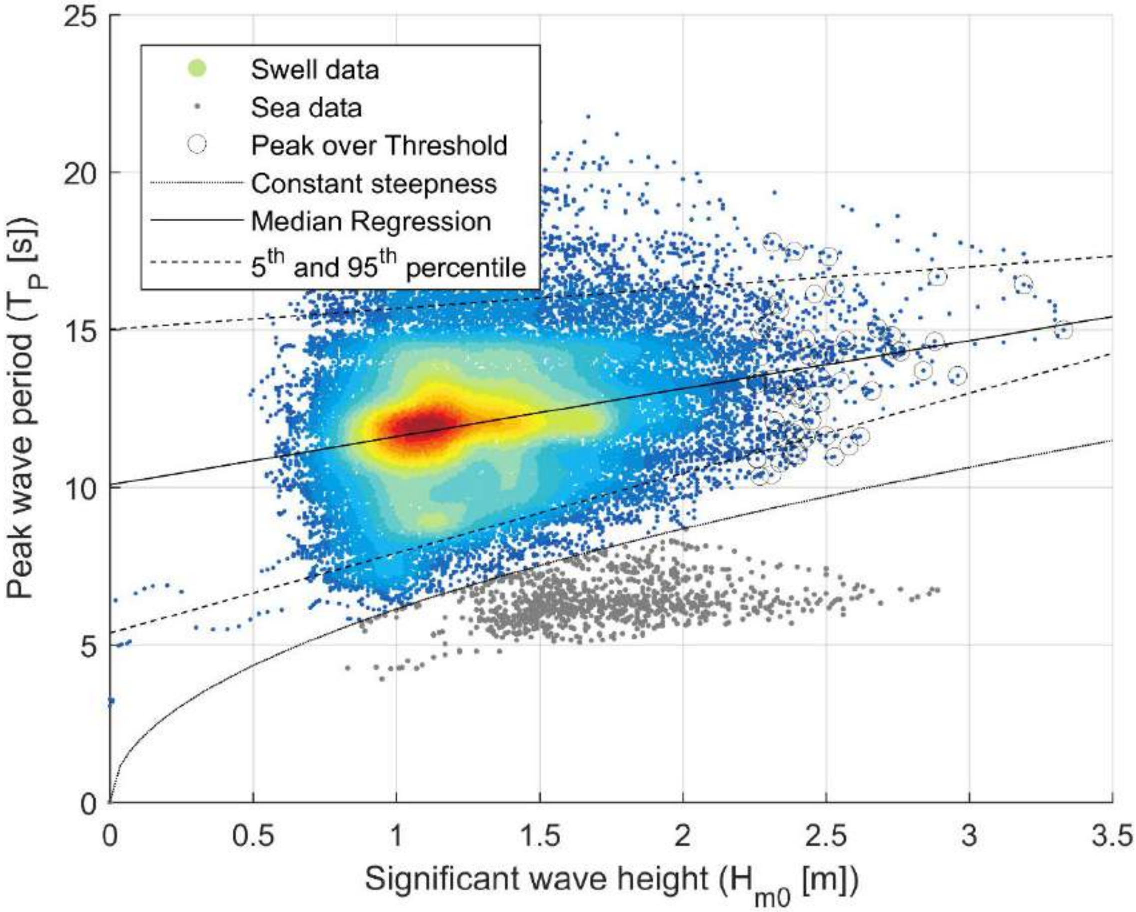

Figure 8-20: Derivation of corresponding wave periods

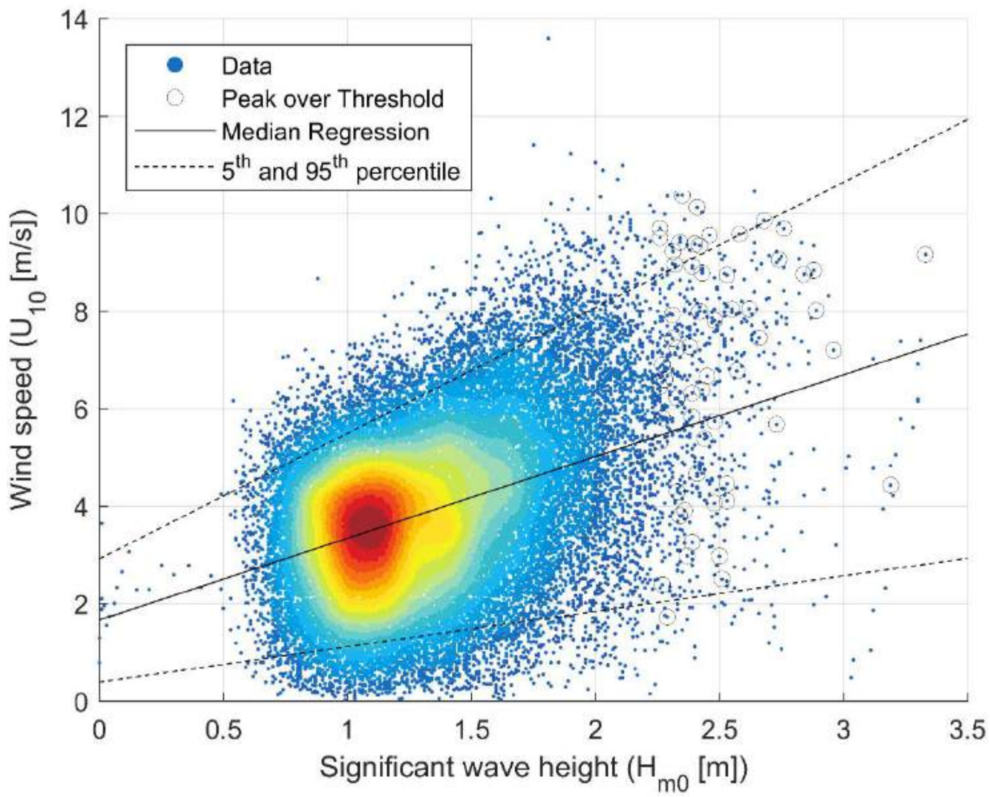

Figure 8-21: Derivation of corresponding wind speeds

As mentioned, the wave direction of the wave climate is fairly uniform. The associated wave direction has been based on the median of all the data and PoT data of the wave directions as shown in and 200 degrees North was chosen to be the representative wave direction for all the extreme values. Conservatively the wind direction has been assumed equal to the wave direction, to include the maximum possible wind growth nearshore for the simulation of the nearshore extremes.

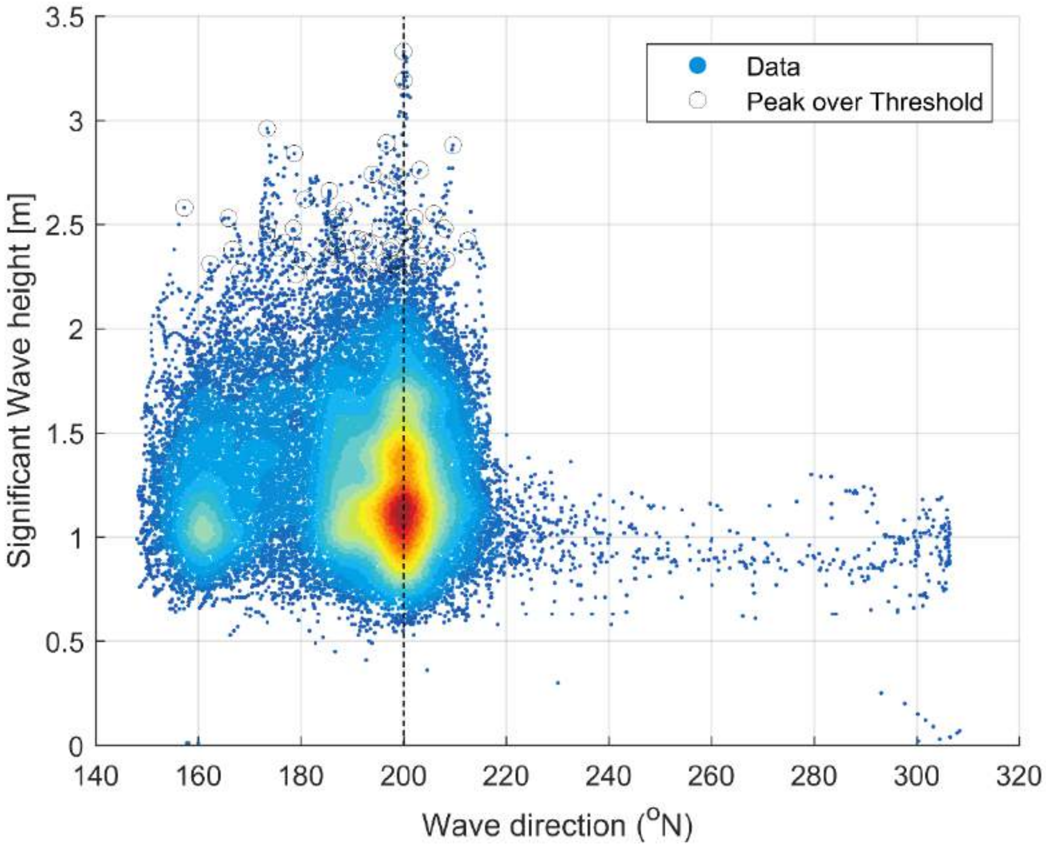

Figure 8-22: Derivation corresponding wave direction

Table 8-8 shows the resulting extreme conditions which are used as baseline extreme conditions for further assessment.

Table 8-8: Extreme offshore conditions for return periods 1, 10 and 100 year

RP	Hs [m]	Tp [s]	Dir [°N]	Uw [m/s]	Udir[°N]
1	2.62	14.1	200	6.1	200
10	3.22	15.0	200	7.1	200
100	3.83	15.9	200	8.1	200

C.2 Wave modelling

The nearshore wave climate has been determined by numerical wave modelling. The offshore wave conditions have been translated from the offshore data point to nearshore using the state-of-the-art spectral wave model SWAN (Simulating WAves Nearshore).

SWAN is a third-generation wave model for obtaining realistic estimates of wave parameters in coastal areas, lakes and estuaries from given wind, bottom and current conditions. It is the most widely used model and the world-wide standard for this type of wave simulations.

Model setup

The model has been set-up using standard parameter settings as much as possible typical for swell climates as found in this region. Reference for standard practice of this model can be found in the user manual of SWAN (Ref [50]).

A triangular grid has been created which allows for flexible varying grid resolution (from 1500 m offshore to 40 m nearshore), see Figure 8-23 and Figure 8-24.

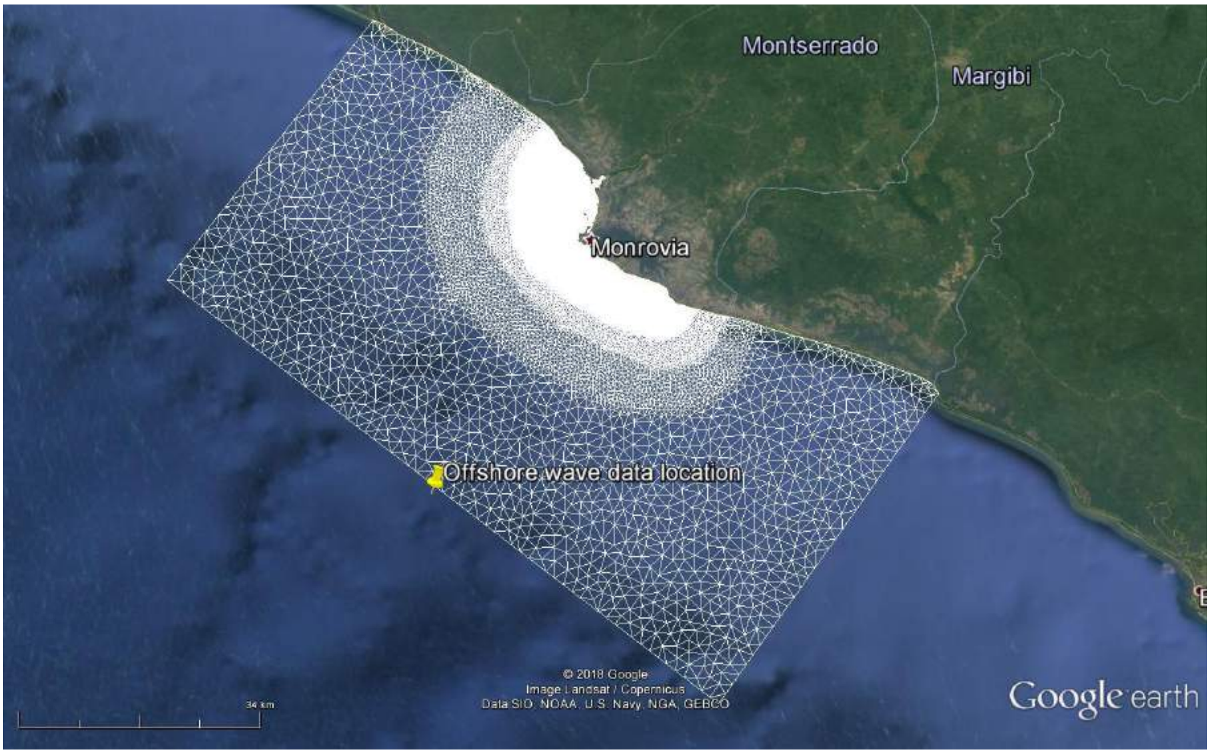

Figure 8-23: Flexible mesh created for SWAN modelling

Figure 8-24: Zoom of flexible mesh created for SWAN modelling

The constructed bathymetry and topography as described under section A.2 has been interpolated onto the grid and imposed in the SWAN model. Figure 8-25 shows the nearshore constructed bathymetry as used in the SWAN model.

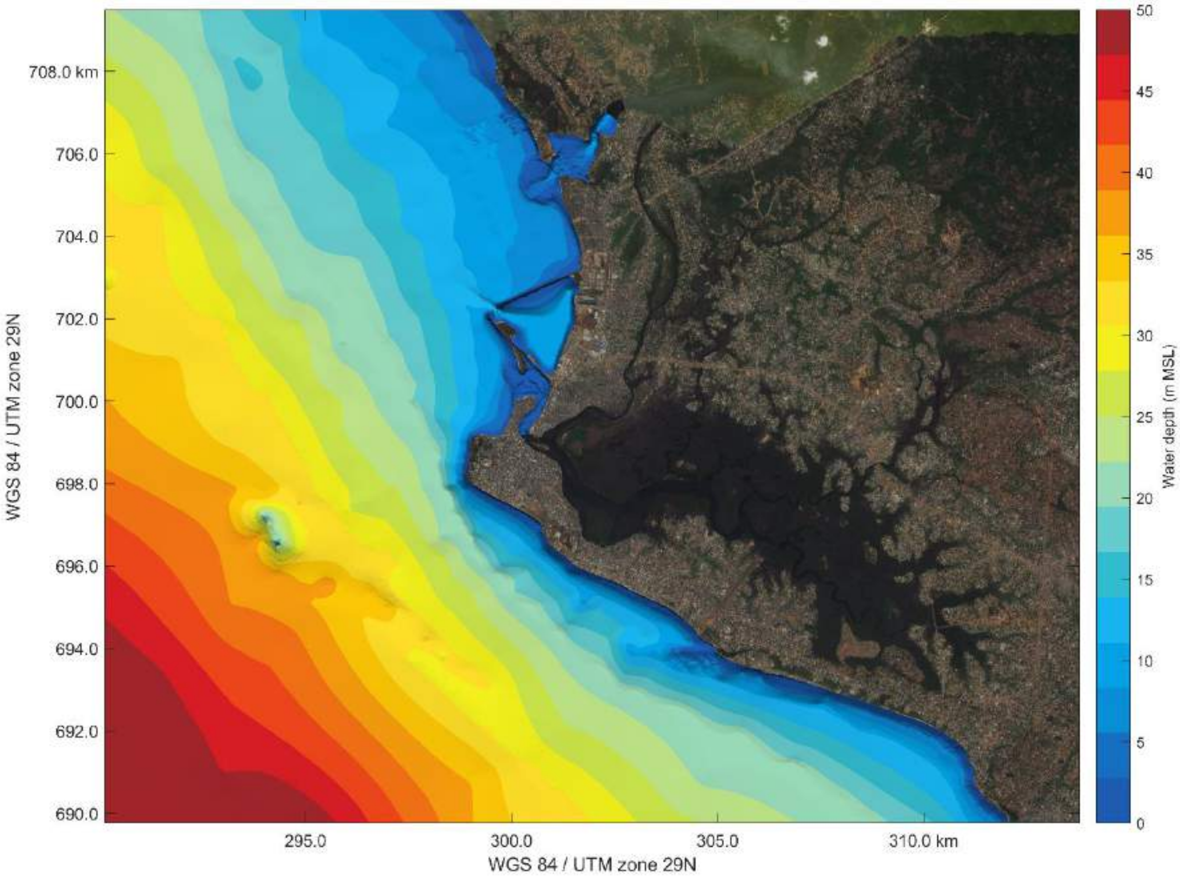

Figure 8-25: Imposed bathymetry as used for SWAN wave modelling

An example of the SWAN output is shown in Figure 8-26, where the simulated nearshore wave field for an average offshore wave condition in the storm season (H_s=1.5 m, T_P = 12 s, Dir = 200°N) is shown. The colours indicate the significant wave height, the arrows show the mean wave direction and the contour lines show the imposed bathymetry.

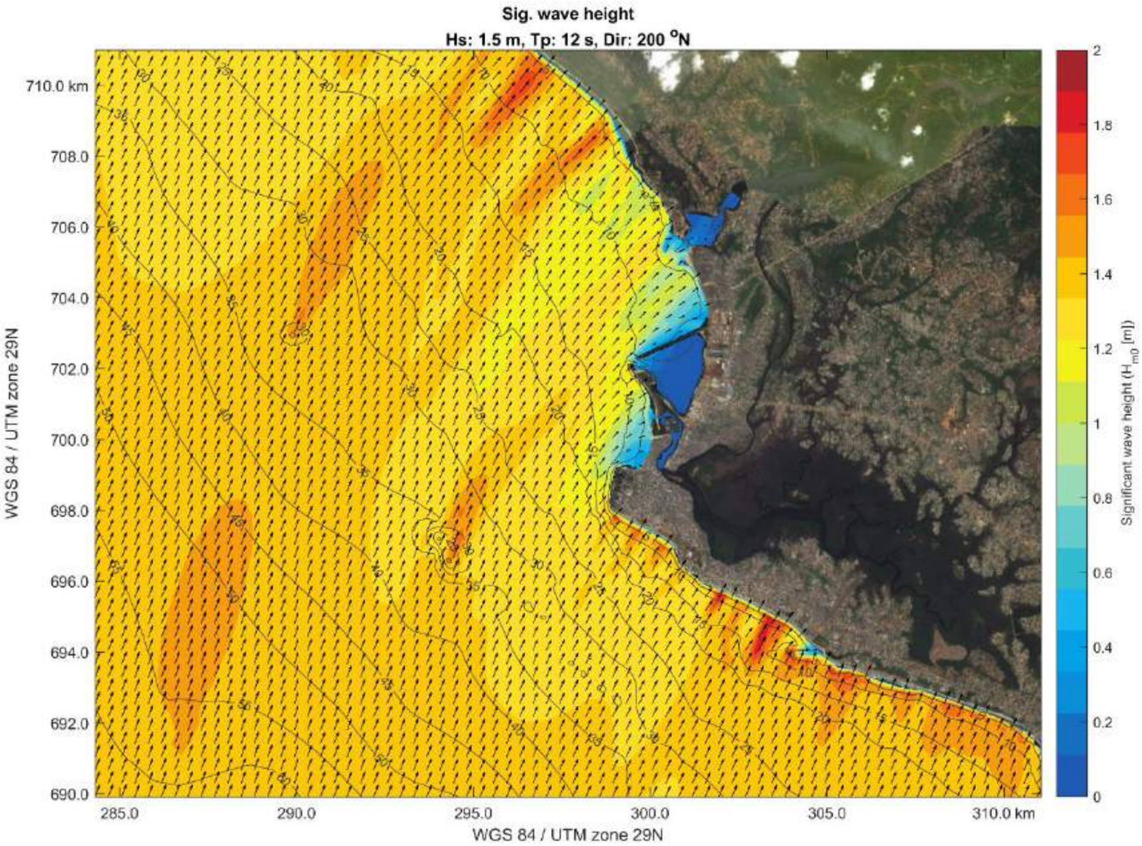

Figure 8-26: Wave field with average offshore wave conditions

Model validation

The wave model has been validated using the wave measurements of the WaveDriods, which were deployed for approx. one week in October 2018.

No local historical wave measurements were available for this project. Hence deploying a WaveDroid for a limited amount of time was the best possible solution that could be done in relation to the validation of nearshore wave modelling.

Figure 8-27 shows the locations of the deployed WaveDroids. It is noted that WD3037 had to relocated at noon 16/10, since it was drifting. It could possibly be that the currents of the St. Paul river were too strong at that location (WD3037_1 from Figure 8-27). Therefore the buoy has been relocated to WD3037_2, where there was no drifting observed. It is therefore questionable if the measured wave conditions before 16/10 are accurate for WD3037. Due to drifting of the buoy the anchor line might have been tightened at some occasions and tilting of the buoy. The measurements are therefore less accurate and reliable during that time and is shown as red squares in the plots below.

Figure 8-28 and Figure 8-29 show the comparison of the observed and modelled wave conditions (based on NOAA) for both WaveDroids separately. It is clear that the wave modelling results is very reasonably able to simulate the wave conditions. The main observed deviation is when there is a sudden shift in the peak wave period, indicating the arrival of a new swell wave train travelled over a long distance from the South Atlantic Ocean. The sudden shift is due to the fact that the new arrived wave train is just 'winning' in terms of peak energy from the other wave condition from the hindcast model. In the measurements this shift seems to be slightly later in time, mainly due to the fact during that time both swell trains are similar in magnitude. From Figure 8-28 it is clear that still the total wave energy (wave height) is still very much comparable with the modelled wave height, although the wave direction is slightly off, mainly due to the fact that the modelled wave data shows the wave direction of the peak direction instead of the total mean direction, as visualized by the measurements and therefore shows a smoother transition to the new wave train.

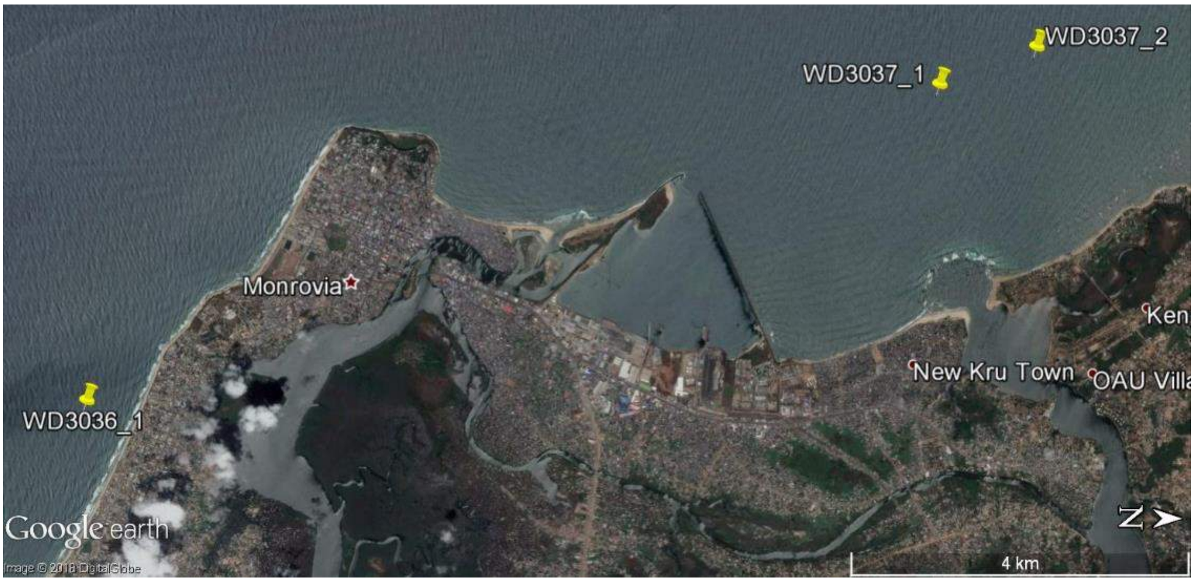

Figure 8-27: Locations of WaveDroid 3036 and 3037 (the locations WD3037_1 and WD3037_2 are the two different location of before and after the relocation of the buoy respectively).

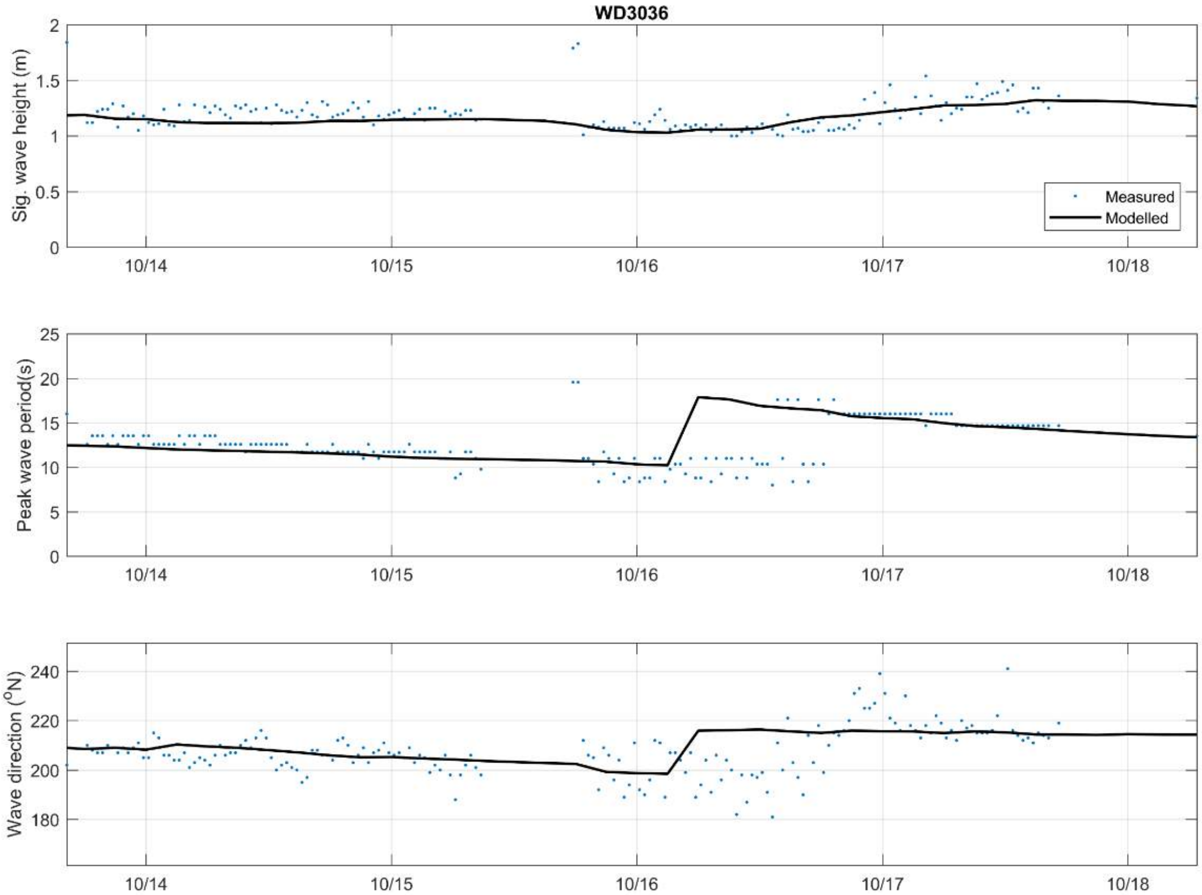

Figure 8-28: Validation of the wave model for WaveDroid 3036

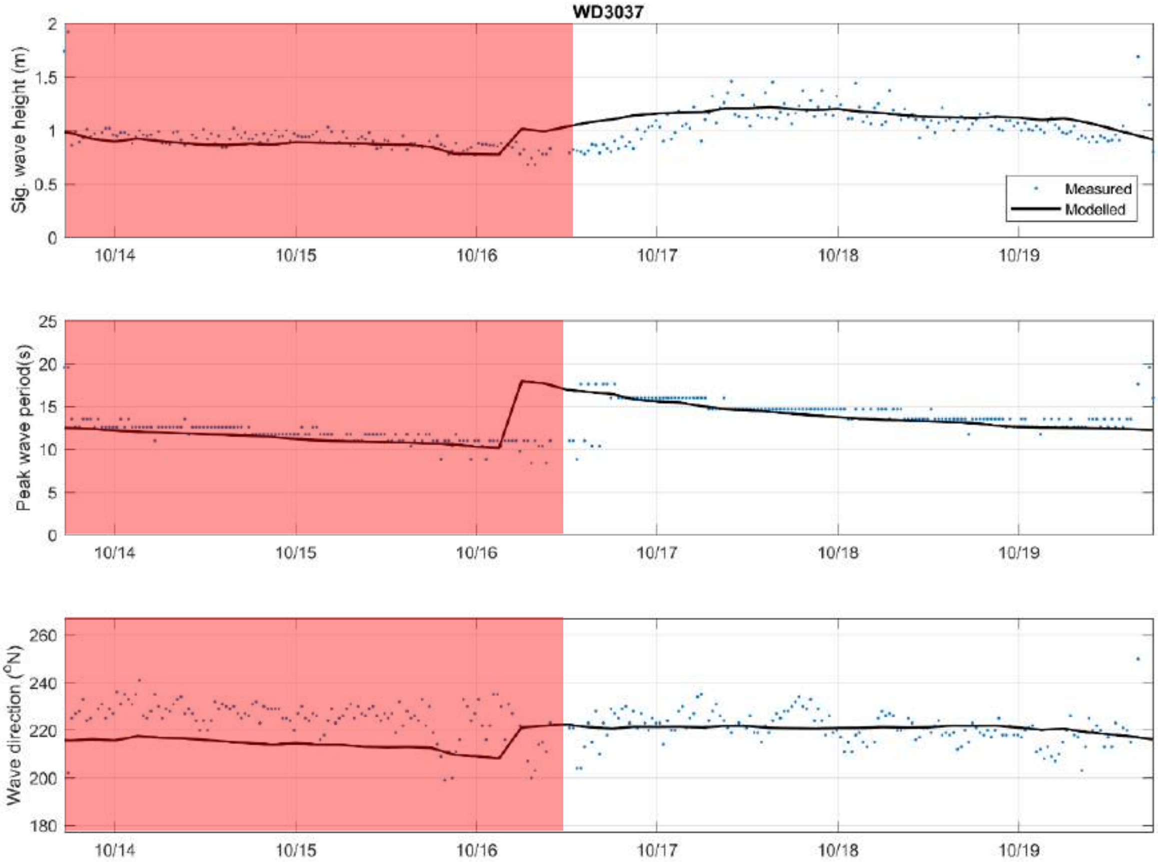

Figure 8-29: Validation of wave modelling for WaveDroid 3037

Generation of nearshore wave climates

The wave model is used for the simulation of both the present and future projections of the wave climates for multiple climate scenarios. This involves very long timeseries and hence a significant amount of data. Simulating all these timeseries for each timestep with the wave model would be computationally too expensive. Therefore a so-called transformation matrix has been used to determine the nearshore wave climates.

A large number of wave transformation simulations have been performed that represent the overall wave climate, from which the nearshore time series are derived using linear interpolation. All combinations of a range of in total 6 variables are simulated with the wave model. For several output locations nearshore this leads to a large matrix with all the nearshore wave conditions, based on the offshore combinations of variables. The range and combinations of the applied transformation matrix is shown in Table 8-9. This has led to a total of (5*5*6*4*5*4=) 12,000 simulations and entries of the multi-dimensional transformation matrix. This matrix can be used to calculate all nearshore wave climates for all scenarios, projection years, sources etc., including the effect of Sea Level Rise. The extreme conditions are calculated separately.

Table 8-9: Combinations and range of offshore variables for transformation matrix

Parameter	Unit	Range						#
H_{m0}	[m]	0.49	1	1.5	2.25	3.35		**5**
T_p	[s]	6	9	12	16	23		**5**
Dir	[deg N]	150	170	190	200	220	300	**6**
U_w	[m/s]	0.1	3.5	8	15			**4**
U_{dir}	[deg N]	50	180	225	270	330		**5**
WL	[m+MSL]	0	0.25	0.5	0.75			**4**

Figure 8-30 shows the resulting nearshore wave roses on te -10m+MSL contour, based on the simulated nearshore timeseries.

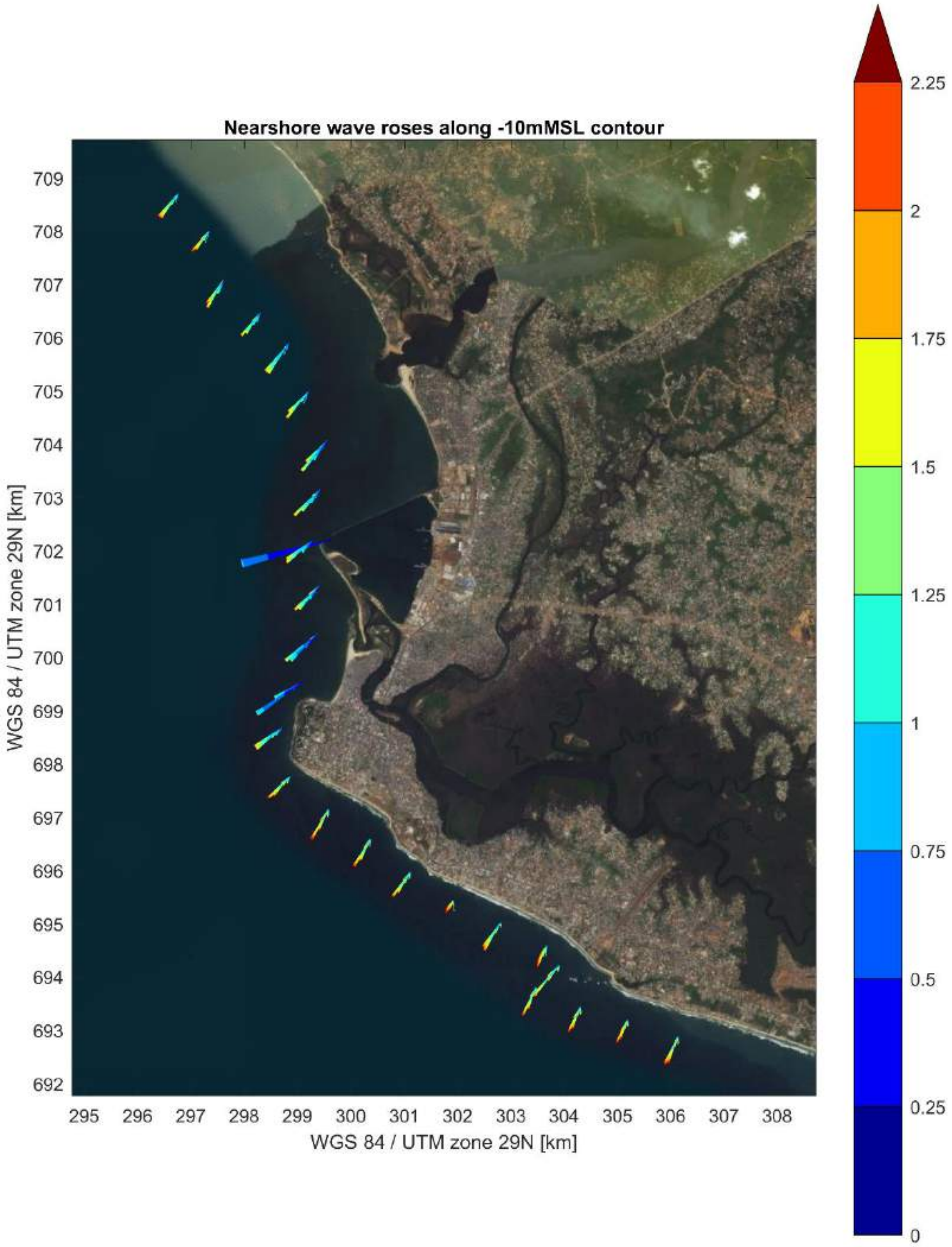

Figure 8-30: Nearshore wave roses

C.3 Climate change impact on wave climate

The effect of climate change on the waves is assessed using climate simulations. Two types of data sources have been used to assess the offshore wave and wind conditions and expected future conditions:

- Hindcast data set as described under section C.1:
  - ERA Interim reanalysis climate (Jan 1979- Nov 2018)
  - NOAA/NCEP
    - NCEP Climate Forecast System Reanalysis and Reforecast (CFSRR) (1979-2009)
    - Production hindcast (Feb 2005- Nov 2018)
- Climate model data set:
  - **RCP 8.5:**
    Modelled wave conditions using WAM wave model using surface winds from 4 EC-Earth ensemble runs prepared for CMIP5 (Ref [30] and [31]).
  - **RCP 4.5:**
    Modelled wave conditions using WaveWatch III (CSIRO) using surface winds from 7 different GCM's:
    - ACCESS10 (CSIRO, Australia),
    - BCC-CSM11 (Beijing Climate Center, China Meteorological Administration, China),
    - CNRM-CM5 (Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique, France),
    - GFDL-CM3 (Geophysical Fluid Dynamics Laboratory, USA),
    - INMCM4 (Institute for Numerical Mathematics, Russia),
    - MIROC5 (Atmosphere and Ocean Research Institute , The University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology),
    - MRI-CGCM3 (Meteorological Research Institute, Tsukuba, Japan).

    From these models the wave model forced by MRI–CGCM3 performs the best for the region. (Hemer and Trenham, 2015 – Ref [11]).

All data sets are from the offshore location: 6°N 11°W (approx. 40 km southwest of Monrovia, see Figure 8-13). The relative climate change impact is assessed by comparing the wave climates of the several projection years, by assessing the representative time-slices chosen from the period 2000 to 2100 of the climate model data. For RCP 4.5 only specific time-slices of data are available: (1971-2005, 2026-2045, 2081-2100). For RCP 8.5 full timeseries are available (1979-2100). The relative impact of the wave data has been assessed for significant wave height, wave period and wave direction.

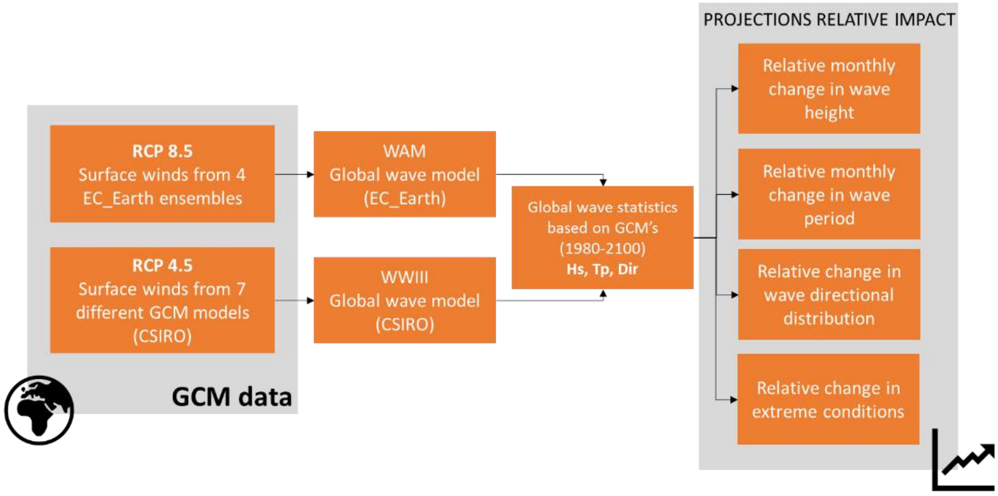

Figure 8-31: Workflow assessment of climate change impact of wave conditions

The relative impact of climate change is assessed for the normal wave climate and extreme wave conditions separately. The found relative climate change impact is in turn projected onto the hindcast wave climate represented by the ERA Interim and NOAA data sets to obtain realistic future projections of the wave climate. The climate data is itself is not accurate in absolute terms near the project location and hence the hindcast data is used as basis for the assessment and the climate data is only used to assess the relative effect. First synthetic timeseries of the NOAA and ERA Interim data sets are created from 2018 to 2100, by copying each month wave conditions from a random year between 1979-2018

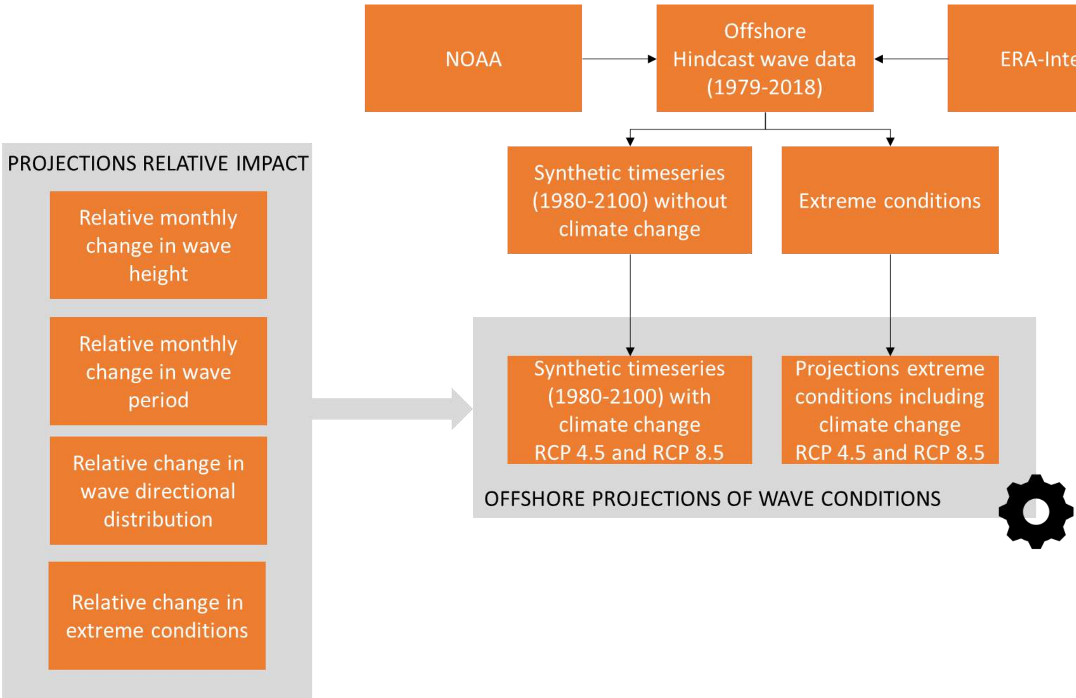

Figure 8-32: Workflow of generation of synthetic timeseries including climate change

Marginal effect of climate change on the offshore wind conditions has been observed in the climate simulations. It is therefore assumed no climate change effect on the wind conditions (both extreme and average normal climate) will take place till 2100.

Normal wave climate

The relative impact of the wave conditions have been assessed for the parameters: wave height, wave period and wave direction. The (running) average of the output of the 4 ensemble members were used for the RCP 8.5 scenario and the (running) average of the output of the 7 runs from the different GCM models.

Significant wave height

Figure 8-33 and Figure 8-34 show the yearly significant wave height distribution for different time-slices for RCP 8.5 and RCP 4.5 respectively. On average for both scenarios the wave height increases up to year 2100, although the impact is not significant: approx. 2 % increase of the average wave height till 2100 compared to 2000 for RCP 8.5 and approx. 1.5% increase for RCP 4.5.
It however became apparent that there is seasonal variation in the relative impact of the wave conditions. Therefore the relative change of the significant wave height has been assessed on a monthly basis for the different time-slices and is shown in Table 8-10 and Table 8-11, for climate scenario RCP 8.5 and RCP 4.5 respectively. From this it is clear that for RCP 8.5 there is a higher increase for the months September till November, while during the months February, March and May there is even a decrease. For RCP 4.5 the distribution over the months is slightly different, but comparable: the highest increase is found in the month July.

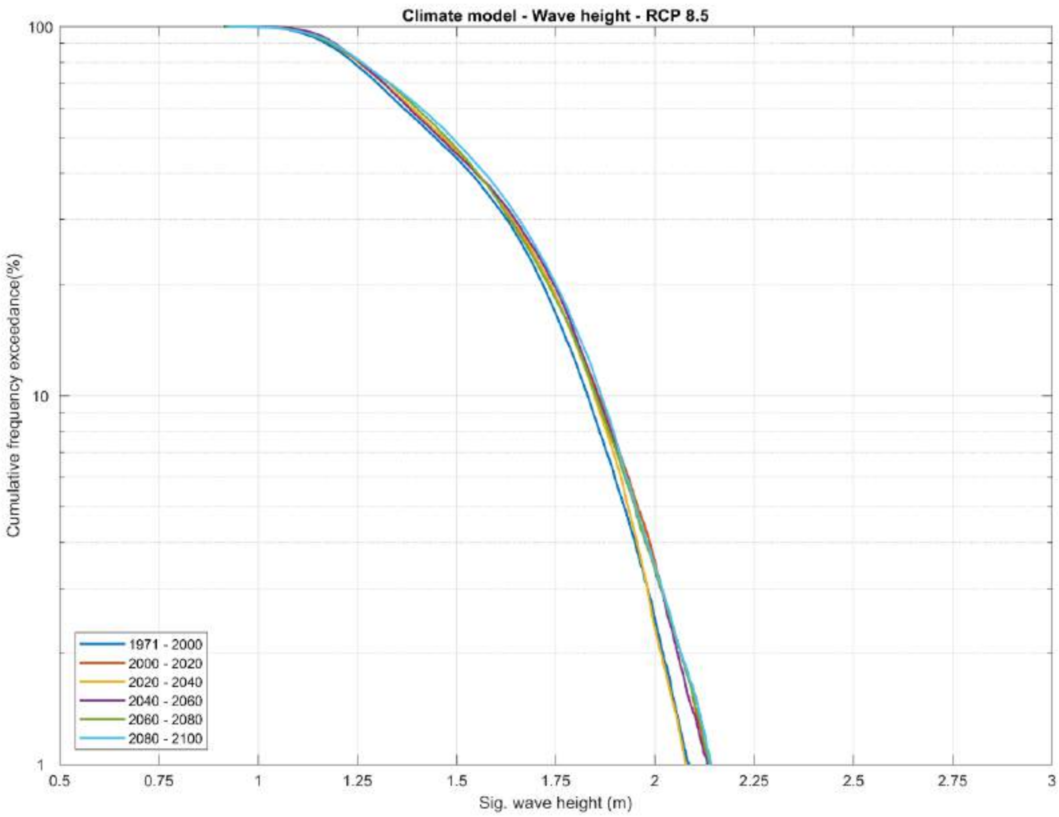

Figure 8-33: Yearly significant wave height distribution for projection periods, based on climate simulations for RCP 8.5 (N.B. absolute values might not be realistic)

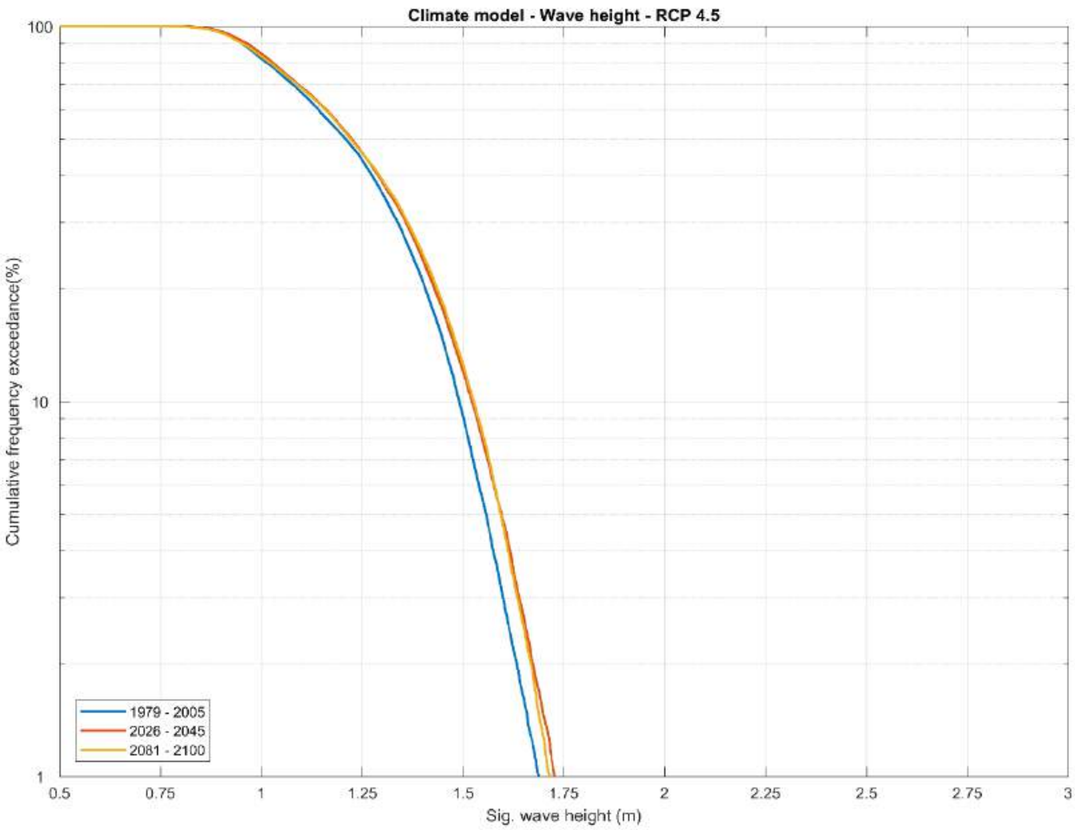

Figure 8-34: Yearly significant wave height distribution for projection periods, based on climate simulations for RCP 4.5 (N.B. absolute values might not be realistic)

Table 8-10: Relative monthly change in significant wave height compared to 2000 for RCP 8.5

from	till	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All year
1971	2000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
2000	2020	1.7%	0.3%	0.1%	0.9%	-0.1%	1.8%	1.2%	2.1%	2.2%	1.1%	2.0%	1.1%	1.2%
2020	2040	2.7%	-0.2%	0.2%	1.5%	0.0%	-0.1%	0.5%	2.0%	1.7%	2.0%	2.2%	2.4%	1.2%
2040	2060	3.2%	0.6%	-0.6%	0.2%	-0.1%	1.8%	0.6%	1.7%	3.5%	1.4%	2.4%	2.6%	1.4%
2060	2080	2.1%	-1.0%	-1.1%	2.2%	-0.3%	-1.2%	0.3%	1.7%	4.1%	4.2%	4.2%	2.6%	1.4%
2080	2100	1.7%	-0.9%	-0.4%	2.3%	-2.5%	1.4%	1.5%	2.8%	5.6%	5.1%	6.3%	3.0%	2.1%

Table 8-11: Relative monthly change in significant wave height compared to 2000 for RCP 4.5

from	till	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All year
1979	2005	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
2026	2045	1.1%	1.5%	0.1%	1.2%	1.9%	1.2%	3.6%	0.9%	1.1%	2.3%	2.0%	1.2%	1.5%
2081	2100	-0.2%	-0.1%	1.1%	1.4%	1.5%	0.8%	3.4%	2.8%	0.7%	1.4%	2.5%	0.0%	1.4%

Wave period

Figure 8-33 and Figure 8-34 show the yearly wave period distribution for different time-slices for RCP 8.5 and RCP 4.5 respectively. On average for both scenarios the wave height increases up to year 2100,: approx. 5 % increase of the average wave height till 2100 compared to 2000 for RCP 8.5 and approx. 1 % increase for RCP 4.5.

It however became apparent that there is seasonal variation in the relative impact of the wave conditions. Therefore the relative change of the wave period has been assessed on a monthly basis for the different time-slices and is shown in Table 8-12 and Table 8-13, for climate scenario RCP 8.5 and RCP 4.5 respectively. The relative increase of the wave period is in general higher compared to the wave height.

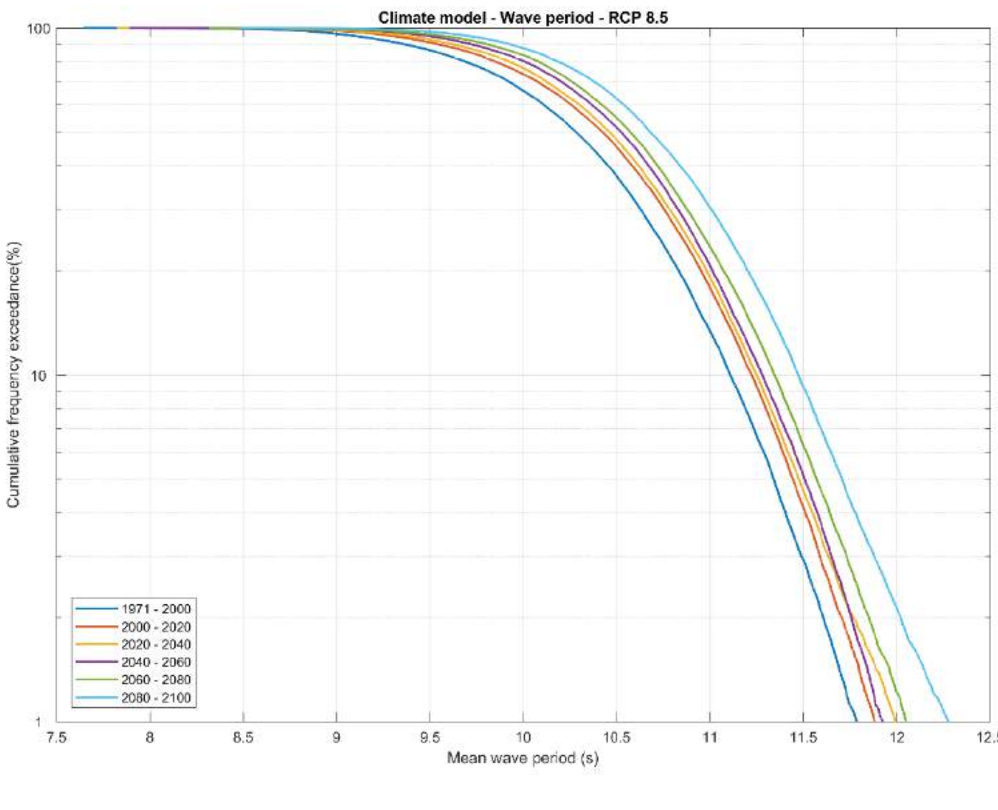

Figure 8-35: Yearly distribution of wave period for different time-slices for RCP 8.5

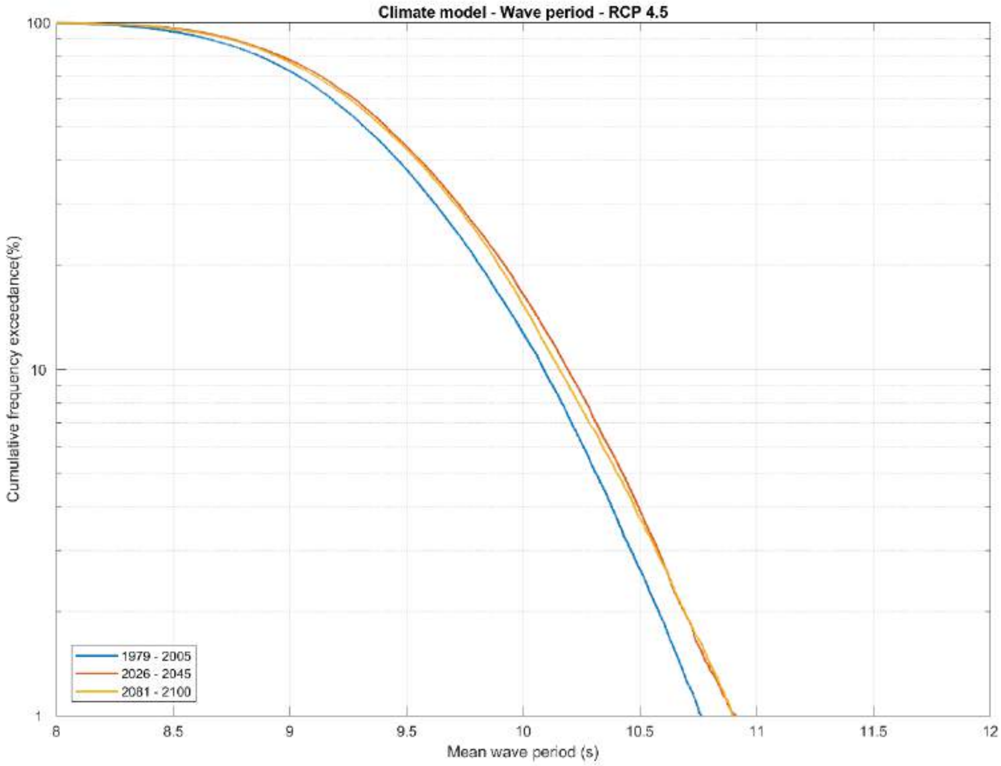

Figure 8-36: Yearly distribution of wave period for different time-slices for RCP 4.5

Table 8-12: Relative monthly change of mean wave period for RCP 8.5

from	till	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All year
1971	2000	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
2000	2020	1.4%	1.4%	0.7%	0.7%	2.0%	2.3%	1.2%	2.7%	3.0%	0.9%	2.1%	1.8%	1.7%
2020	2040	0.8%	0.9%	0.9%	1.5%	3.3%	1.8%	3.3%	4.3%	2.3%	1.3%	3.5%	2.7%	2.2%
2040	2060	1.8%	1.5%	0.8%	1.8%	3.6%	3.1%	3.0%	5.3%	4.2%	1.5%	3.8%	2.6%	2.8%
2060	2080	1.8%	1.1%	0.2%	2.0%	5.3%	3.7%	3.9%	5.9%	5.2%	3.4%	4.4%	2.0%	3.2%
2080	2100	3.2%	1.2%	1.4%	3.5%	5.6%	4.3%	6.9%	6.9%	7.5%	5.4%	6.1%	3.4%	4.6%

Table 8-13: Relative monthly change of mean wave period for RCP 4.5

from	till	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All year
1979	2005	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
2026	2045	1.1%	0.5%	-0.1%	1.2%	0.7%	1.5%	2.0%	1.3%	0.5%	1.4%	1.8%	0.8%	1.1%
2081	2100	0.0%	-0.3%	0.3%	0.6%	0.9%	1.0%	1.3%	1.5%	0.7%	1.4%	1.8%	0.9%	0.8%

Wave direction

Figure 8-37 and Figure 8-38 show the yearly wave direction distribution for different time-slices for RCP 8.5 and RCP 4.5 respectively. The relative impact on the wave direction is for both scenarios very different: for RCP 8.5 the distribution seems to get more narrow and on average the wave direction changes anti-clockwise (smaller wave angle), while for RCP 4.5 the wave angles increase and thus change clockwise on average. This change in distribution (e.g. higher wave angles change more compared to lower wave angles for RCP 8.5) has been assessed by deriving the change in degrees for each 5th percentile of the distribution which has been applied to the synthetic timeseries, see Table 8-14 and Table 8-15 for RCP 8.5 and RCP 4.5 respectively.

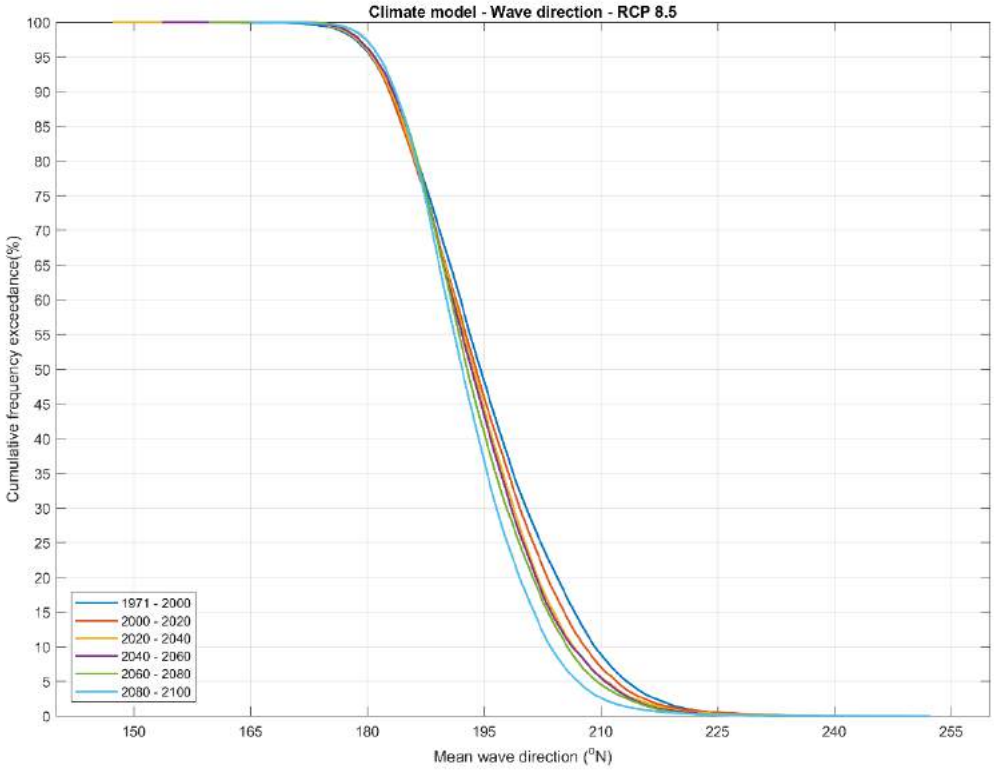

Figure 8-37: Yearly distribution wave direction - RCP 8.5

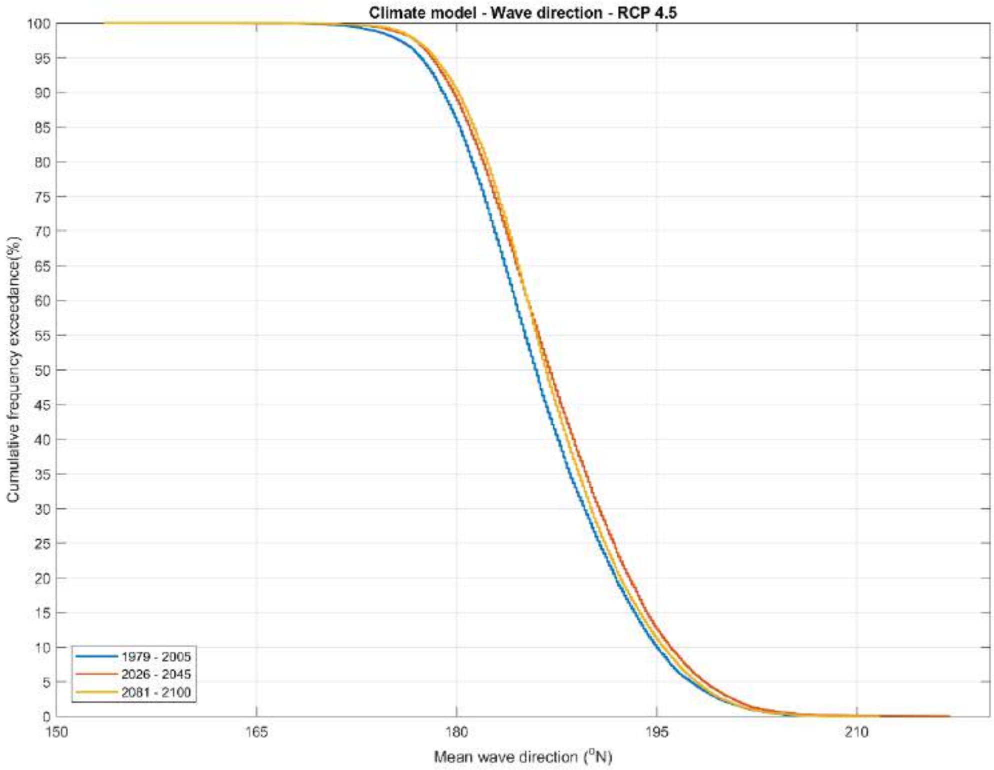

Figure 8-38: Yearly distribution wave direction – RCP 4.5

Table 8-14: Change in wave direction in degrees clockwise, RCP 8.5 per percentile

Percentile (%)	2000	2020	2040	2060	2080	2100
5	0.0	0.1	0.2	0.4	1.0	1.0
10	0.0	0.0	0.2	0.4	0.7	0.7
15	0.0	-0.3	0.0	0.3	0.4	0.3
20	0.0	-0.5	-0.3	0.0	0.0	-0.2
25	0.0	-0.4	-0.3	-0.3	-0.3	-0.5
30	0.0	-0.5	-0.5	-0.5	-0.6	-1.0
35	0.0	-0.6	-0.7	-0.8	-0.9	-1.4
40	0.0	-0.6	-0.8	-1.0	-1.2	-1.8
45	0.0	-0.5	-0.8	-1.0	-1.4	-2.0
50	0.0	-0.6	-0.9	-1.1	-1.7	-2.4
55	0.0	-0.7	-1.1	-1.3	-1.9	-2.7
60	0.0	-0.6	-1.2	-1.4	-2.1	-3.0
65	0.0	-0.6	-1.3	-1.6	-2.2	-3.3
70	0.0	-0.8	-1.6	-1.9	-2.6	-3.8
75	0.0	-1.0	-2.0	-2.3	-2.8	-4.3
80	0.0	-1.3	-2.5	-2.7	-3.1	-4.8
85	0.0	-1.4	-2.7	-3.0	-3.4	-5.2
90	0.0	-1.3	-2.7	-2.9	-3.6	-5.7
95	0.0	-1.3	-2.6	-2.8	-3.8	-6.2

Table 8-15: Change in wave direction in degrees clockwise, RCP 4.5 per percentile

Percentile	2000	2045	2100
5	0.0	0.9	1.0
10	0.0	0.7	1.1
15	0.0	0.7	1.0
20	0.0	0.9	1.1
25	0.0	0.7	1.0
30	0.0	0.9	1.1
35	0.0	1.0	1.1
40	0.0	0.9	0.9
45	0.0	1.0	0.9
50	0.0	1.0	0.7
55	0.0	1.1	0.7
60	0.0	1.1	0.7
65	0.0	1.1	0.6
70	0.0	1.1	0.6
75	0.0	1.0	0.4
80	0.0	1.1	0.4
85	0.0	1.0	0.4
90	0.0	1.0	0.6
95	0.0	1.0	0.4

Synthetic timeseries

Based on the observed relative impacts (figures and tables sections above) offshore synthetic timeseries are created based on the hindcast data. These offshore timeseries in turn describe the relative climate change impact on the wave conditions for both RCP 4.5 and RCP 8.5 separately. These offshore timeseries in turn are used as input for the wave modelling as described in section C.2 to generate the nearshore timeseries of wave conditions for RCP 4.5 and RCP 8.5 separately.

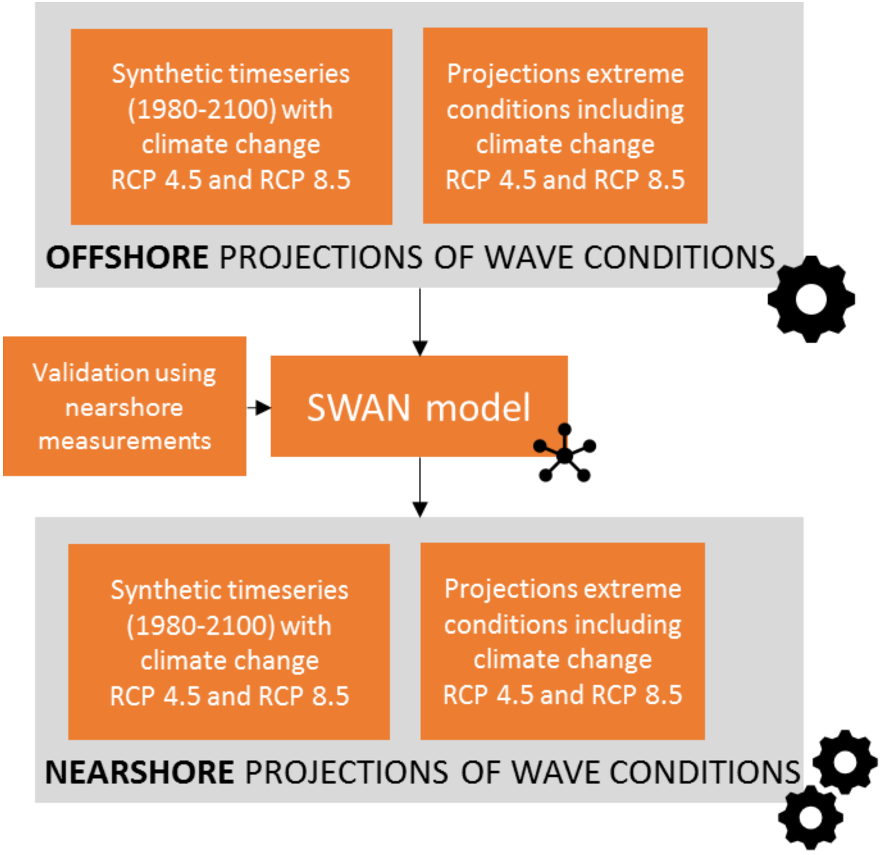

Figure 8-39: Workflow of generation of nearshore timeseries including the effect of climate change

Extreme waves

The relative climate change impact is more severe for the extreme waves compared to the average yearly climate. The relative impact of climate change to the extreme waves has been assessed by obtaining the extreme wave height with a Return Period of 10 years for different projection periods, by means of interpolation of the Peak over Threshold values (see also section C.1). The extreme waves have been determined for the wave model output for the surface winds from each ensemble run (RCP 8.5) and GCM model (RCP 4.5) separately to ensure homogeneity in the data set. The relative impact of these extreme wave heights have been averaged over the 4 ensembles (RCP 8.5) and 7 model outputs (RCP 4.5). Figure 8-40 shows the obtained relative impact of climate change on the extreme wave heights. The extreme wave heights are approximately linearly increased with 10 % and 6.5 % till 2100 for RCP 8.5 and RCP 4.5 respectively.

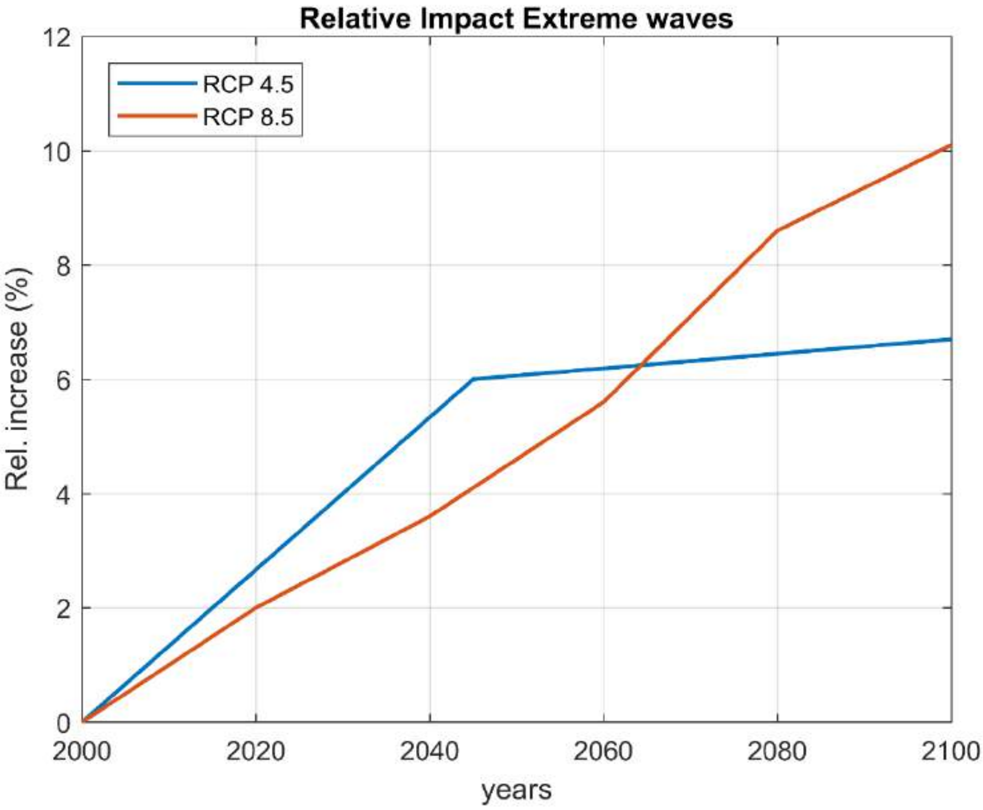

Figure 8-40: Relative impact on extreme wave significant height

The obtained relative impact of climate change on the extreme wave heights has been projected on to the extreme value distributions based on the NOAA hindcast data set, see section C.1. The relative impact as obtained from the Climate Model is in turn projected onto this extreme value distribution which results in different extreme value distributions of the wave heights for several projection years. Figure 8-41 shows the extreme value distribution for the year 2100 for RCP 4.5 and RCP 8.5.

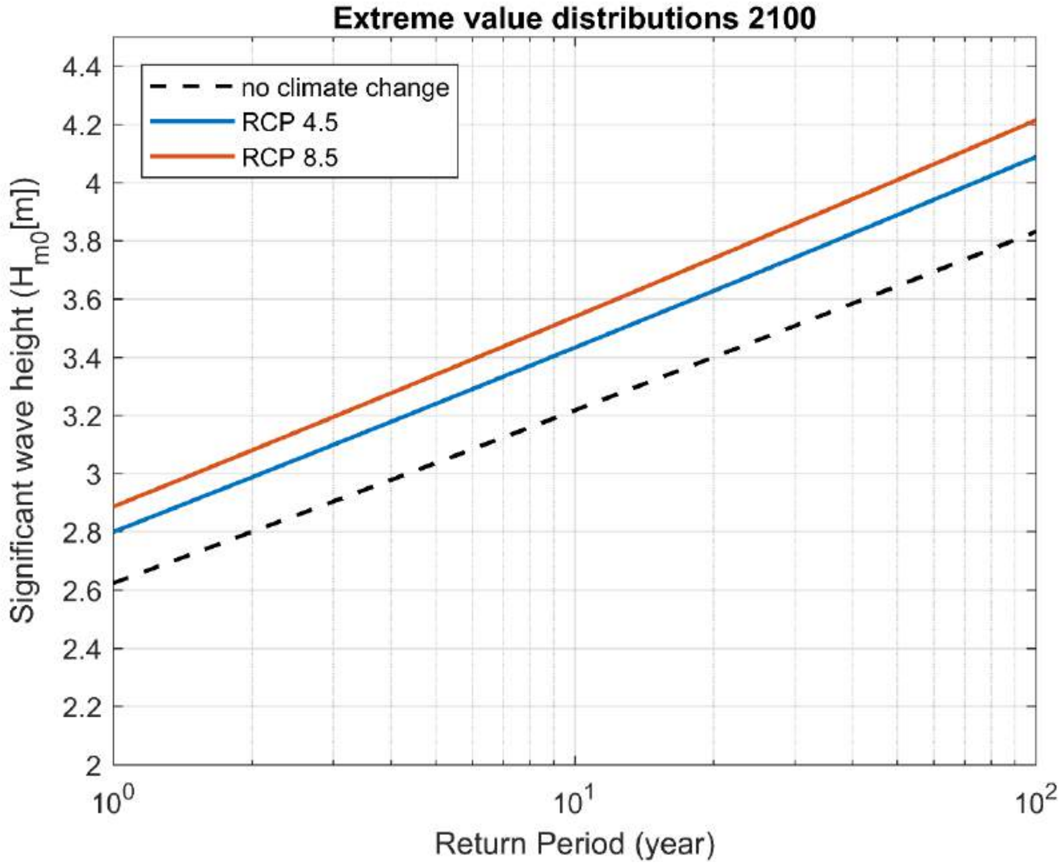

Figure 8-41: Extreme value distributions for the year 2100 for RCP 4.5 and RCP 8.5

This relative impact has been used to derive the offshore extreme wave conditions. The corresponding wave period, wave direction and wind conditions are derived using the same relationships as described in section C.2. This results in the following tables (Table 8-16

Table 8-16 : Offshore extreme wave conditions for relevant projection years for RCP 4.5

	Return period (yrs)	H_{m0} (m)	T_P (s)	Dir (°N)	Uw (m/s)	Udir (°N)
2000	1	2.62	14.1	200	6.1	200
	10	3.22	15.0	200	7.1	200
	100	3.83	15.9	200	8.1	200
2020	1	2.69	14.2	200	6.2	200
	10	3.30	15.1	200	7.2	200
	100	3.93	16.1	200	8.3	200
2050	1	2.78	14.3	200	6.3	200
	10	3.41	15.3	200	7.4	200
	100	4.06	16.3	200	8.5	200
2070	1	2.79	14.3	200	6.3	200
	10	3.42	15.3	200	7.4	200
	100	4.07	16.3	200	8.5	200
2100	1	2.80	14.3	200	6.4	200
	10	3.43	15.3	200	7.4	200
	100	4.09	16.3	200	8.5	200

Table 8-17: Offshore extreme wave conditions for relevant projection years for RCP 8.5

	Return period (yrs)	H_{m0} (m)	T_P (s)	Dir (°N)	Uw (m/s)	Udir (°N)
2000	1	2.62	14.1	200	6.1	200
	10	3.22	15.0	200	7.1	200
	100	3.83	15.9	200	8.1	200
2020	1	2.68	14.2	200	6.1	200
	10	3.28	15.1	200	7.2	200
	100	3.91	16.0	200	8.2	200
2050	1	2.74	14.3	200	6.3	200
	10	3.36	15.2	200	7.3	200
	100	4.01	16.2	200	8.4	200
2070	1	2.81	14.4	200	6.4	200
	10	3.44	15.3	200	7.4	200
	100	4.10	16.3	200	8.5	200
2100	1	2.89	14.5	200	6.5	200
	10	3.54	15.5	200	7.6	200
	100	4.22	16.5	200	8.7	200

These offshore extreme wave conditions are used as input for the wave modelling to determine the nearshore extreme condition, see section C.2. Sea level rise has been included in the simulations and conservatively the extreme water levels as derived under section A.4 are included. This leads to the following applied water levels in the extreme wave model simulations. Here it is assumed that surge will remain the same for over the coming decades.

Table 8-18: Applied water levels in extreme wave model simulations

	Return period (yrs)	Tide+surge (m+MSL2000)	SLR (m)	Total Sea level (m+MSL2000)
2000	1	0.72	0	0.72
	10	0.84	0	0.84
	100	0.85	0	0.85
2020	1	0.72	0.08	0.80
	10	0.84	0.08	0.92
	100	0.85	0.08	0.93
2050	1	0.72	0.26	0.98
	10	0.84	0.26	1.10
	100	0.85	0.26	1.11
2070	1	0.72	0.42	1.14
	10	0.84	0.42	1.26
	100	0.85	0.42	1.27
2100	1	0.72	0.74	1.46
	10	0.84	0.74	1.58
	100	0.85	0.74	1.59

The results of the wave modelling leads to the extreme wave conditions for the relevant return periods, projection periods and climate scenarios at all relevant locations around the project area. These are subsequently used as input for the hazard assessment and design of the coastal structures. Figure 8-42 show the wave field of the extreme wave height with a return period of 100 years for the year 2100 and scenario RCP 8.5.

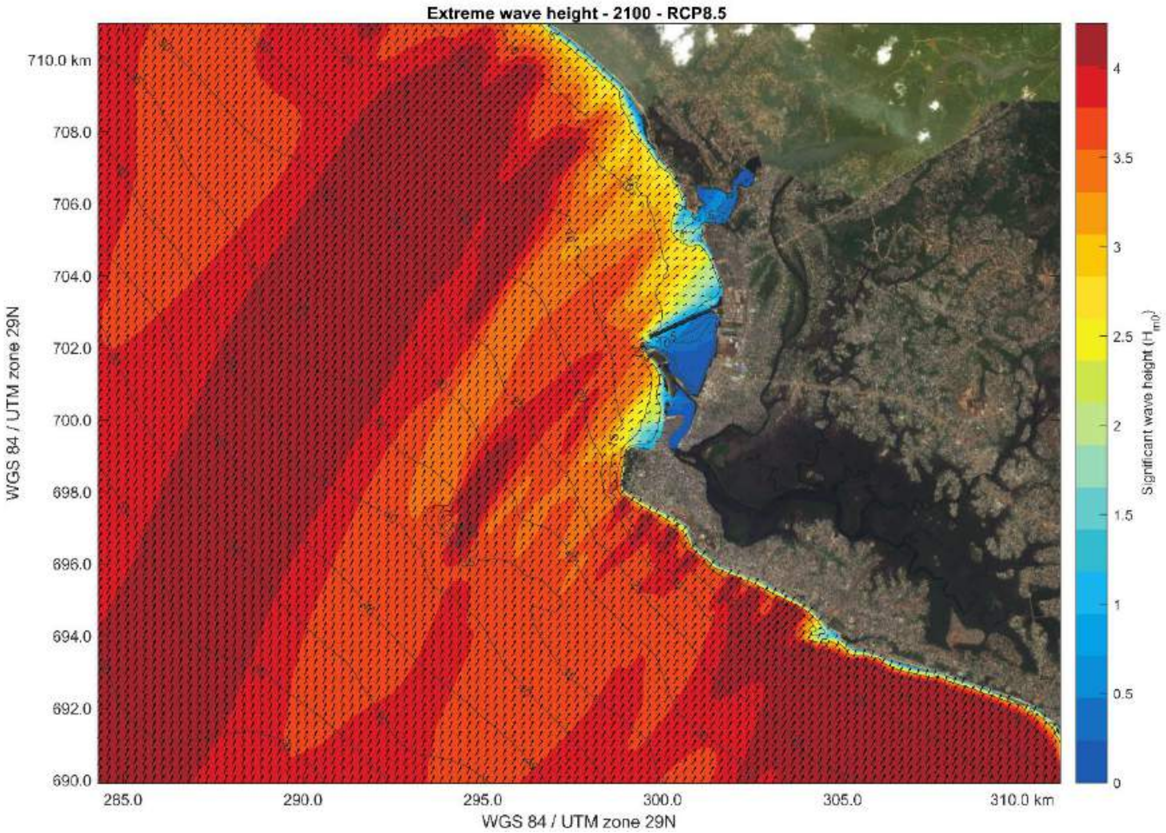

Figure 8-42: Extreme significant wave height field with return period of RP=100 yrs for the year 2100. (Offshore conditions: H_s = 4.22m, T_P=16.5s, Dir=200°N, U_w= 8.7m/s. U_{dir}=200°N, Waterlevel=1.59m+MSL_{2000})

D. SEDIMENT EXCHANGE WITH RIVERS AND BASINS

Coastlines in the vicinity of tidal inlets, river mouths and estuaries, such as the study area of this project, are shaped and affected not only by oceanic processes like tides, waves and mean sea level changes, but also by terrestrial processes, such as river flow, fluvial sediment supply, land use pattern changes, and land management.

Continuous sediment sources and sinks in the coastal system are for example tidal inlets, estuaries, river mouths and canyons etc. They are continuously either feeding the coast with sediment or demanding sediment from the coastline. Temporary or discontinuous sources and sinks are for example occasional sand mining and artificial nourishments.

In this project the major sources and sinks influencing the sediment budget that are considered are:

- St. Paul river;
- Mesurado Tidal inlet;
- Farmington river;

The catchments of these three sources/sinks are shown in Figure 8-43. The river catchment of the St. Paul river has been split in two parts, upstream and downstream of the Mt. Coffee dam.

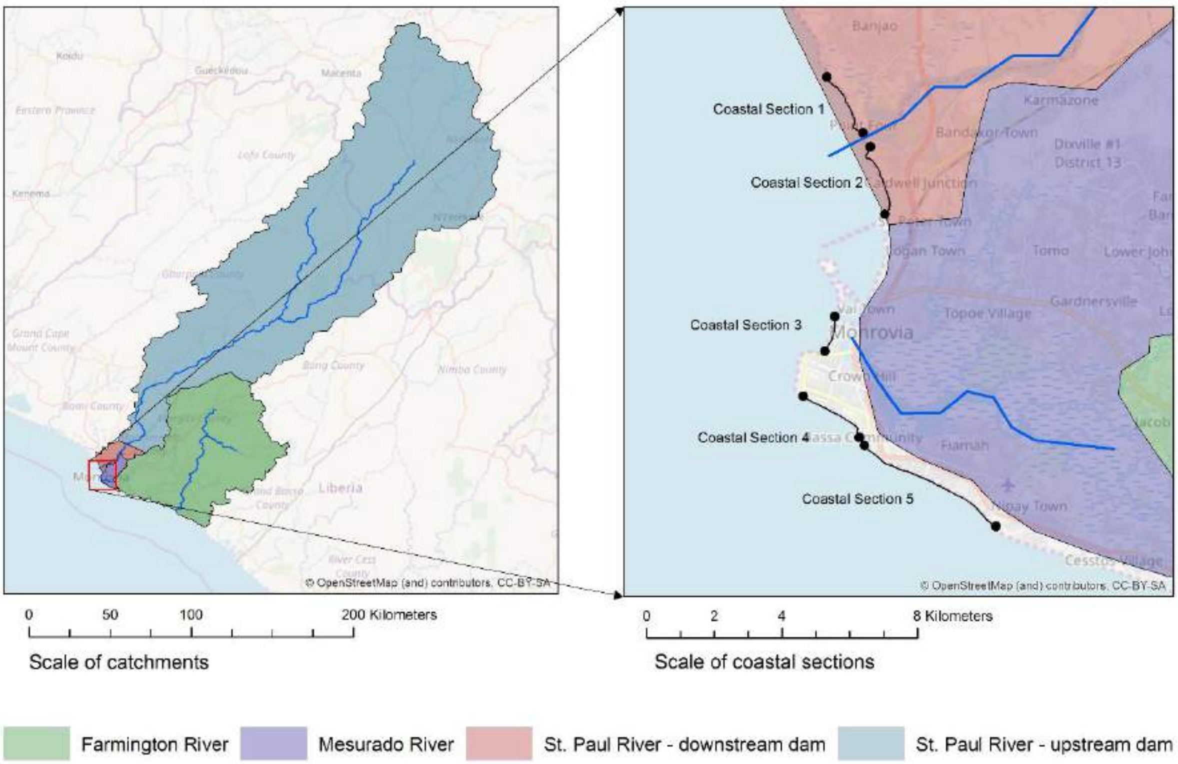

Figure 8-43: Catchments of the three main basins affecting the coast of Monrovia.

Both the St. Paul river and Farmington river are mainly river dominated and hence mainly feed the coastline with sediment. The present sediment flux is estimated using the discharge measurements of the St. Paul river (obtained from the website of Liberian Hydrological Services), precipitation rates, the catchment areas, temperatures and relief of the catchments. The Mt. Coffee dam in the St. Paul river has been included in the analysis, by using the ratio between the upstream and downstream river basin area. This has led to a huge decrease of the sediment supply in the present situation.

The Mesurado Tidal inlet is very tide dominated with a relatively large tidal basin. The 'accommodation space' of the Mesurado estuary is increasing due to sea level rise, which means the 'sand hunger' increases and hence the Mesurado estuary is considered as sink.

D.1 Climate Change impact on sediment exchange

The climate change impact on the sediment exchange of three identified sources and sinks above has been done using the state of the art model developed by Bamunawala et al (2018 – Ref [13]) to estimate the sediment import/export of St. Paul, Mesurado, Junk and Farmington river/estuary systems from 2000 to 2100 including combination of anthropogenic and climate change drivers.

In this study two components affecting the sources and sinks are assessed:

- Increase in accommodation space, leading to sediment demand;
- Change in fluvial sediment supply due to climate and non-climate drivers;

The workflow for the derivation of these two components is shown in Figure 8-44

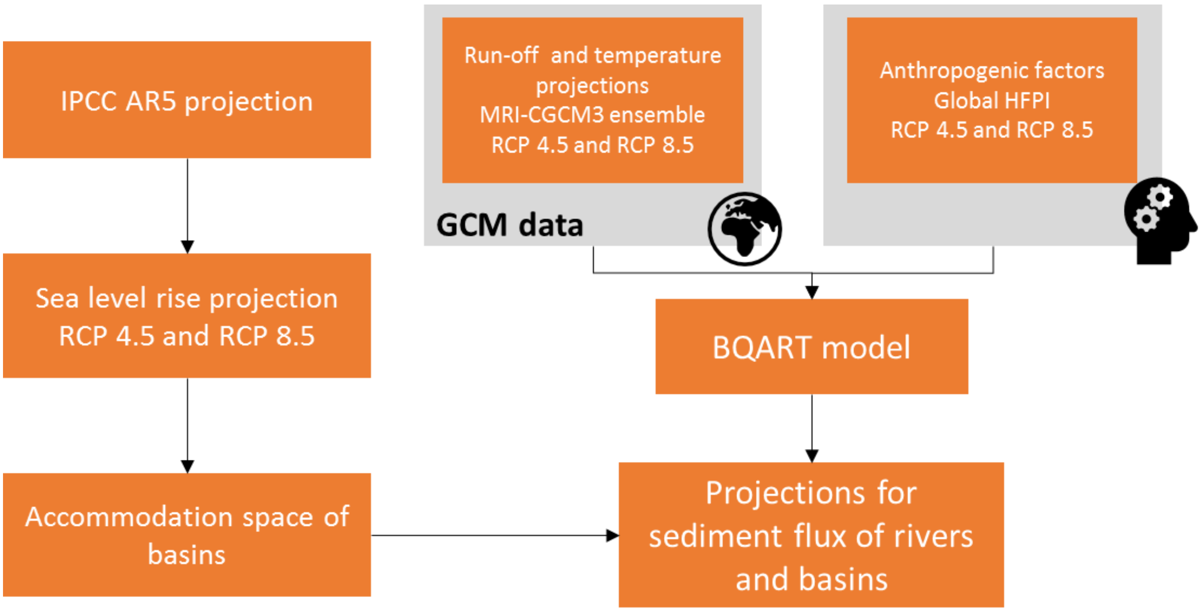

Figure 8-44: Workflow for the derivation of the climate change impact on the sediment exchange

Accommodation space is the additional volume created within the basin due to a given increment in mean sea-level. Sea level rise therefore the main climate driver to this component. The additional volume results in a sediment demand into the estuary and is therefore proportional to the SLR.

The annual fluvial sediment supply to the coast and its changes in the future has been estimated with use of the BQART model. This model includes the relevant climate and anthropogenic factors, such as: temperature, catchment area, precipitation, glacial erosion, catchment lithology, that accounts for its soil type and erodibility, reservoir trapping efficiency factor and human-induced erosion factors.

Fluvial sediment supply (Source)

The amount of soil eroded from catchments is increasing due to the combined effects of climate change and anthropogenic impacts. Climatic factors such as temperature, mean and extreme rainfall, and river flow are the main factors that affect fluvial sedimentation. Increased anthropogenic activities (e.g. agricultural developments in combination with deforestation) increase the rate of soil erosion (both chemical and mechanical) and storage and the release of water from the Earth's lithosphere. The combined effect of reduced rainfall and increased temperature results in water stresses to plants, resulting in diminished growths and, hence, amplified soil erosion that results in a larger sediment yield from catchments. Contrariwise, high rainfall and low temperatures facilitate favourable conditions for plant growth, and hence reduce soil erosion, which in turn diminishes the sediment yield from catchments.

Anthropogenic impacts on fluvial sediment supply are for example: land-use management practices (e.g., urbanization, changes in land use, land management and agricultural practices), changes in water management practices (e.g., dam constructions or demolition, streamflow regulation, introduction of flood control mechanisms), and river sand mining are the most prominent human-induced drivers that affect fluvial sediment supply. In general human activities will increase catchment sediment yield via accelerated soil erosion, yet, may also significantly reduce the amount of sediment received by the coasts due to retention within reservoirs.

To account for the anthropological effects on the fluvial sediment supply and hence on the sediment budget the human footprint index (HFPI) published by Wildlife Conservation Society - WCS and Center for International Earth Science Information Network - CIESIN - Columbia University (2005) is used in the model (Ref [51]). HFPI has been developed by using several global datasets such as population distribution, urban areas, roads, navigable rivers (dredging), electrical infrastructures and agricultural land use. This dataset is available at a spatial resolution of 30 arc-seconds, and is regionally normalized to account for the interaction between the natural environment and human influences. Global and continental scales raster files of HFPI data are available at https://doi.org/10.7927/H4M61H5F.
Most recent version of this datasets is from 2005, and it is assumed that its index will increase linearly through time by 50% in 2100.

The annual fluvial sediment supply to the coast and its changes in the future has been estimated with use of the BQART model. This model includes the relevant climate and anthropogenic factors, such as: temperature, catchment area, precipitation, glacial erosion, catchment lithology, that accounts for its soil type and erodibility, reservoir trapping efficiency factor and human-induced erosion factors. Changes in temperature, rain fall and run-off for which we have relied on the output of the model with maximum output point in the three catchments of alluvial systems affecting the Monrovia coastal zone and shows the trend similar to the projected trend for the region: MRI-CGCM3 (Yukimoto, et al. 2012 – Ref [52]). A sensitivity analysis has been conducted based on the changes in temperature, rain fall and run-off model stem from the models: GFDL, GISS and NorESM.

Bamunawala et al. (2018 - Ref [13]) have illustrated that the empirical BQART model presented by Syvitski and Milliman (2007 - Ref [53]) can be used to assess the annual fluvial sediment supply to the coasts. This empirical model is based on 488 globally-distributed datasets. For catchments with a mean annual temperature greater than or equal to 2°C, the BQART model estimates annual sediment volume supplied to the coast by the following equation:

$$Q_S = \omega \times B \times Q^{0.31} \times A^{0.5} \times R \times T$$

where ω is 0.02 or 0.0006 for the sediment volume (Q_S), expressed in kg/s or MT/year, respectively, Q is the annual river discharge from the catchment considered ($\mathrm{km}^3/\mathrm{yr}$), A is the catchment area (km^2), R is the relief of the catchment (km) and T is the catchment-wide mean annual temperature (°C).
Term 'B' in the above equation represents the catchment sediment production and comprises glacial erosion (I), catchment lithology (L) that accounts for its soil type and erodibility, a reservoir trapping efficiency factor (T_E), and human-induced erosion factor (E_h), which is expressed as follows:

$$B = IL(1 - T_E)E_h$$

Glacial erosion (I) in above equation is expressed as following:

$$I = 1 + (0.09 \times A_g)$$

where A_g is the percentage of ice cover of the catchment area.
According to Syvitski and Milliman (2007 - Ref [53]), human-induced erosion factor (E_h; anthropogenic factor) of the above equation depends on land-use practices, socio-economic conditions and population density. They have estimated this human disturbance potential based on Gross National Product (per capita) and population density and have also suggested its optimum rage to between 0.3 and 2.0.
Instead of using countrywide estimates of GNP/capita and population density to estimate the human-induced soil erosion factor (E_h), high-resolution spatial information in the form of a human footprint index (HFPI) can be used, as described above.

The existence of the Mt. Coffee dam in the St. Paul River has been incorporated in presented calculations.

Accommodation space (Sink)
Accommodation space is the additional volume created within the basin due to a given increment in mean sea-level. Sea level rise therefore the main climate driver to this component. The additional volume results in a sediment demand into the estuary and is therefore proportional to the SLR.

The major impact of this phenomena is on the Mesurado river basin, however the other 2 river mouths do have a (smaller) basin as well leading to an increase of accommodation space.

Total sediment exchange (Sources + Sinks)
The total sediment exchange is the sum of the above two components (fluvial sediment supply and accommodation space). Figure 8-47 shows the cumulative total sediment exchange for the three river basins. The dashed black line indicates the scenario without climate change and impact. For the Mesurado basin the accommodation space would remain the same without sea level rise and therefore the sediment demand remains 0. It is clear that due to climate change and anthropogenic factors both the St. Paul and Farmington river have an increased sediment supply, which in general benefits the coastal system in terms of coastal retreat.

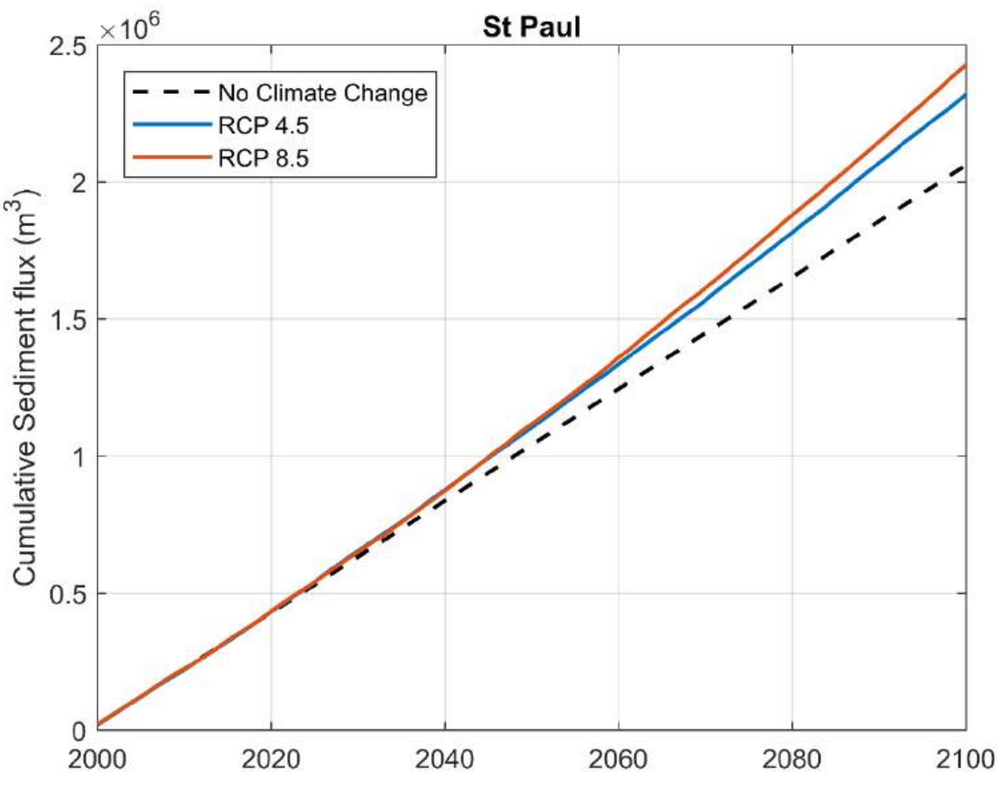

Figure 8-45: Cumulative sediment exchange of the St.Paul river for RCP 4.5, RCP 8.5 and no climate change

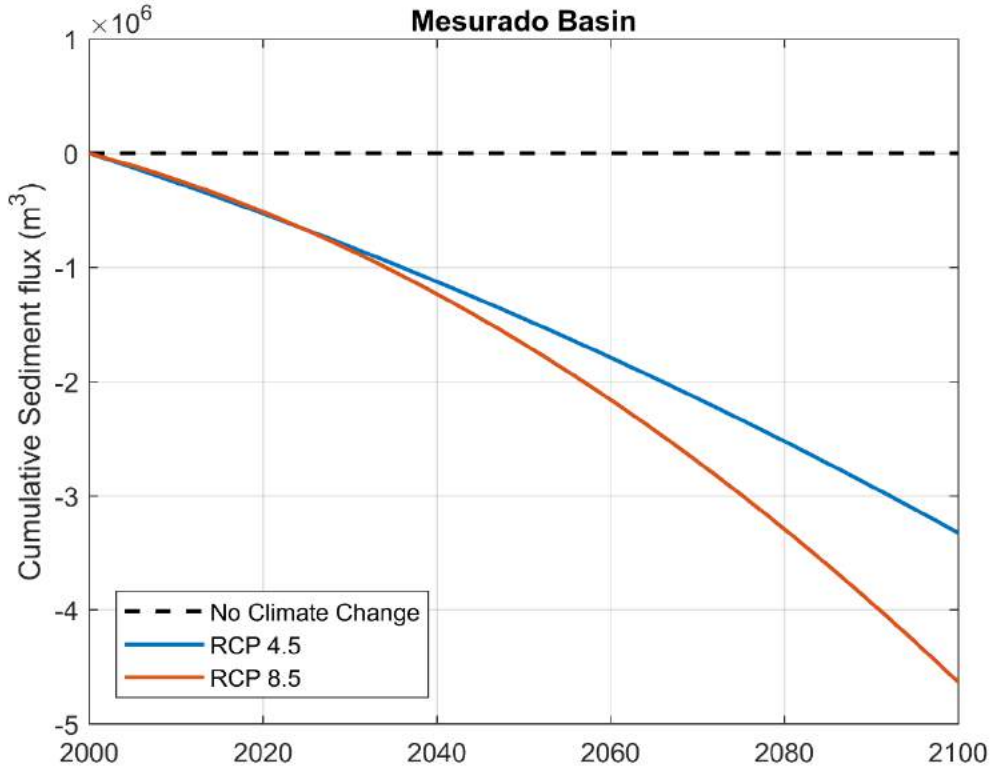

Figure 8-46: Cumulative sediment exchange of the Mesurado Basin for RCP 4.5, RCP 8.5 and no climate change

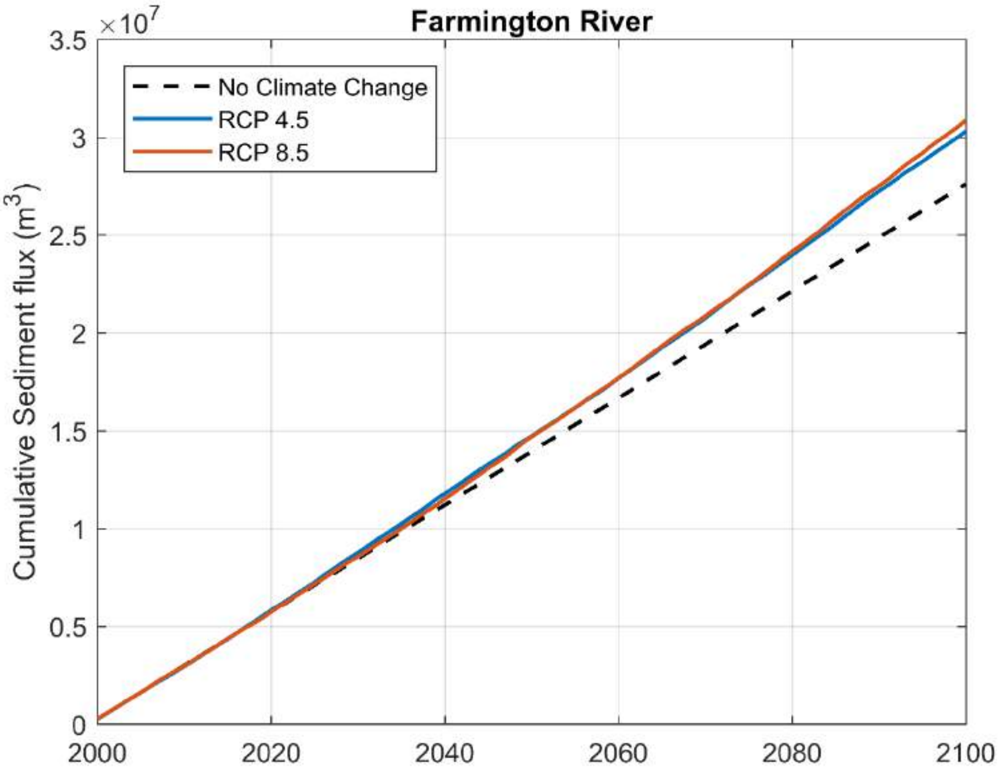

Figure 8-47: Cumulative sediment exchange of the Farmington River for RCP 4.5, RCP 8.5 and no climate change

Sensitivity analysis

Using the changes in temperature, rainfall and run-off of three other GCM model outputs the sensitivity of the determined (change in) sediment flux due to climate change has been assessed for the St. Paul river and Farmington river. The Mesurardo basin is completely dominated by the increase of accommodation space due to Sea Level Rise and is therefore only estimated using the sea level rise projections.

Figure 8-48 and Figure 8-49 show the bandwidth of both RCP scenarios for the St. Paul river and Farmington river based on different model output data of all the four GCM models. It is clear that the bandwidth is relatively small. The difference is less than 3% for St. Paul in 2100 and less than 1 % for Farmington river in 2100 compared the figures above. This will have a very small effect on the total sediment balance.

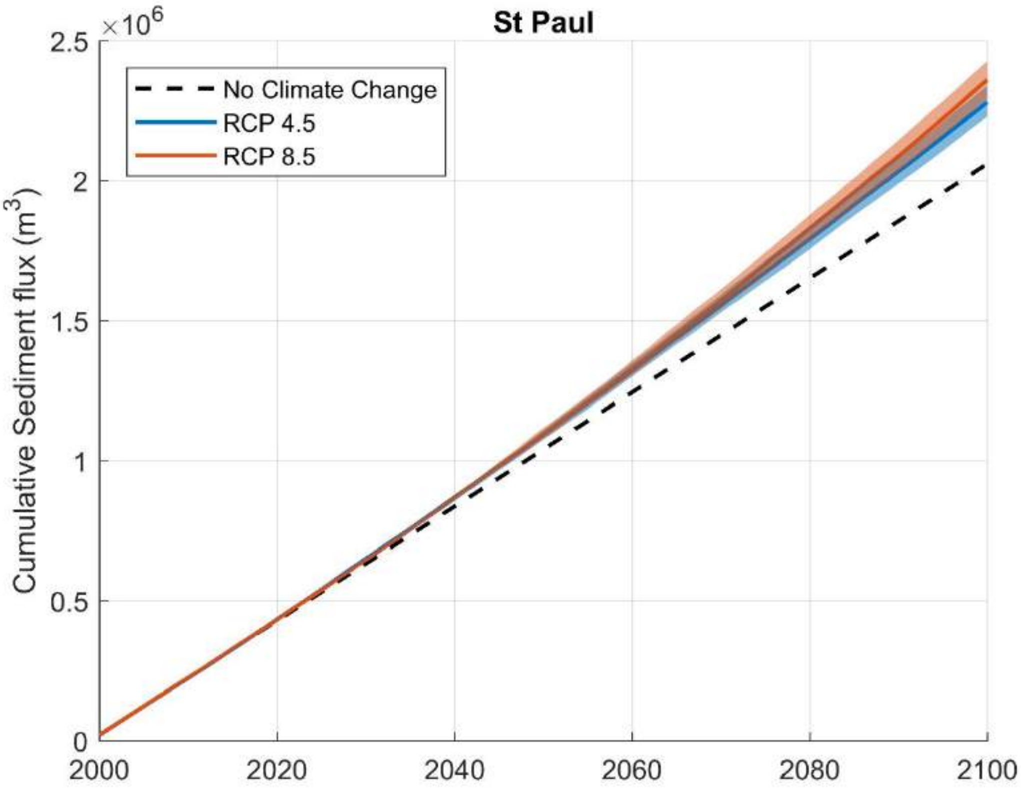

Figure 8-48: Sensitivity (bandwidth) of cumulative sediment exchange based on multiple GCM output data of St. Paul river

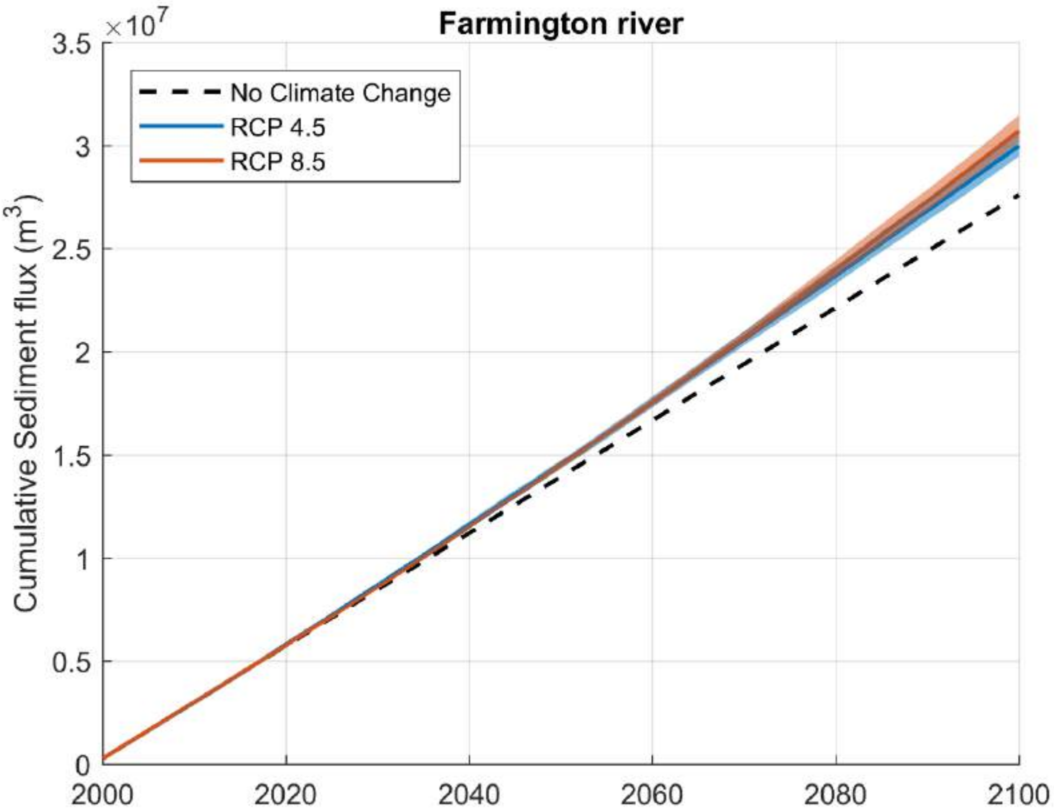

Figure 8-49: Sensitivity (bandwidth) of cumulative sediment exchange based on multiple GCM output data of Farmington river

E. LONGSHORE SEDIMENT TRANSPORT

Wave driven currents that generate longshore sediment transport along the coastlines of Monrovia is an important condition for identifying and designing coastal protection options. The most important factors determining the direction and magnitude of longshore sediment transport are i) the angle of the incoming waves to the coastline, ii) the wave height and wave period and iii) sediment characteristics of the beach:

- The higher the angle between the incoming waves and the shore normal the higher the longshore sediment rate; with a maximum rate at about 45 degrees: $S \sim \sin(2*\Theta)$. No longshore sand transport will occur when the incoming wave direction is exactly perpendicular to the coastline (90 degrees).
- In general the longshore sediment transport rate is proportional to the wave height to the power of 2.5 to 3: $S \sim Hs^{2.5}$.
- The coarser the particle sizes of the beach, the lower the longshore sediment transport rates.

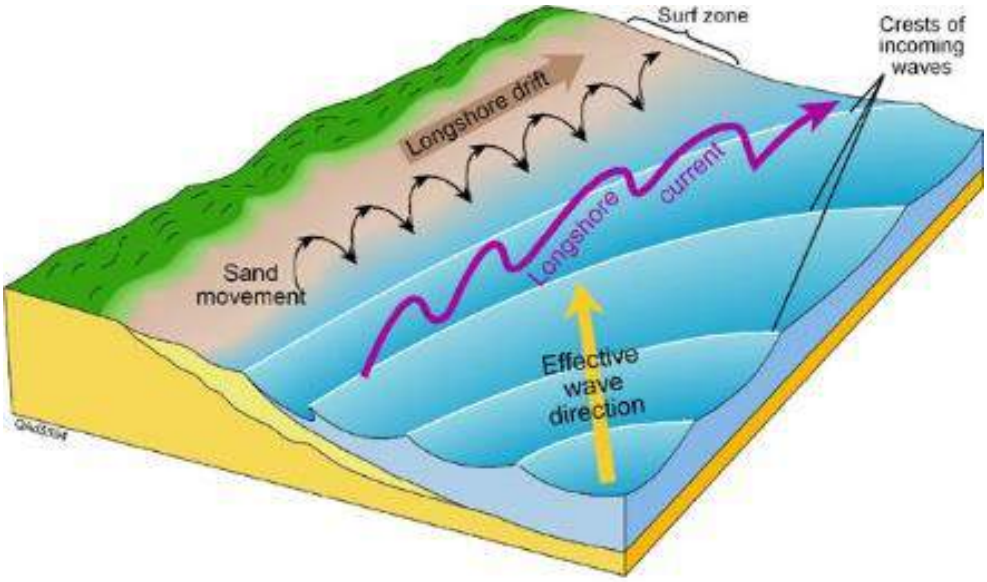

Figure 8-50: Processes affecting longshore sediment transport (source: http://www.beg.utexas.edu)

It is important to note that only an alongshore gradient (change) of the longshore sediment transport rates will lead to a coastal response. A coast with a uniform alongshore sediment transport rate, irrespective of the magnitude, will remain stable. A negative gradient will lead to accretion, while a positive gradient will lead to coastal retreat.

The present longshore sediment transport rates are determined using the nearshore wave climates as determined by means of wave modelling, see section C.2. At several transects along the coastline of the project area the longshore sediment transport capacities are determined with the van Rijn longshore transport formula (Ref [48]).

This bulk sediment transport formula takes all the relevant processes into account and reads:

$$Q_{t,mass} = 0.00018\, K_{swell}\, \rho_s\, g^{0.5} (\tan\beta)^{0.4} (d_{50})^{-0.6} (H_{s,br})^{3.1} \sin(2\theta_{br})$$

Where $H_{s,br}$ is the significant wave height at the breakerline and Θ_{br} is the angle of incidence of the waves at the breaker line, which are determined using appropriate formulae to account for refraction. Other parameters include the particle size (d_{50}), bed slope (β) and a correction factor for the amount of presence of swell (K_{swell}) and is calculated as follows:

$$K_{swell}=1.5(p_{swell}/100) + 1\ (1-p_{swell}/100) = 0.015p_{swell} + (1-0.01p_{swell})$$

Where p_{swell} is the percentage swell of the sea state, which can be considered 100% in this case.

The wave height and wave angle at the breaker line can be calculated as follows.

The breaker depth can be calculated with (and hence the wave height at the breaker line):

$$h_{br}= [(H_{s,o}^2\, c_o \cos\theta_o)/(\alpha\, \gamma^2\, g^{0.5})]^{0.4}$$

Where $H_{s,0}$ is the wave height at deep(er) water, c_0 the wave celerity at deep(er) water ($=L_0/T_P$), Θ_0 the wave angle at deep(er) water, α a calibration coefficient (1.8 most cases), γ the breaker parameter (0.6-0.8, which is the factor between wave height and the breaker depth).

The wave angle at the breaker line can be calculated with the Snells law:

$$\sin\theta_{br}=(c_{br}/c_o)\sin\theta_o$$

For several transects the nearshore wave climate at a depth of 10 m (Section 4 and 5) and 5 m (Section 1, 2 and 3) has been extracted and used as input for the longshore sediment transport calculations. To limit the computational effort, i.e. very long timeseries (1980-2100) simulating over multiple transects, the nearshore wave climate has been schematised in a set of limiting number of conditions for several time-slices, while taking the climate change impact of both scenarios into account as described in section C.3. Along multiple locations of the 10 m and 5 m contour line the wave climate has been schematized in 50 wave conditions (25 direction bins and 2 wave height bins) using the 'equal energy flux' method (Ref [54]). See an example of this binning method in the figure below.

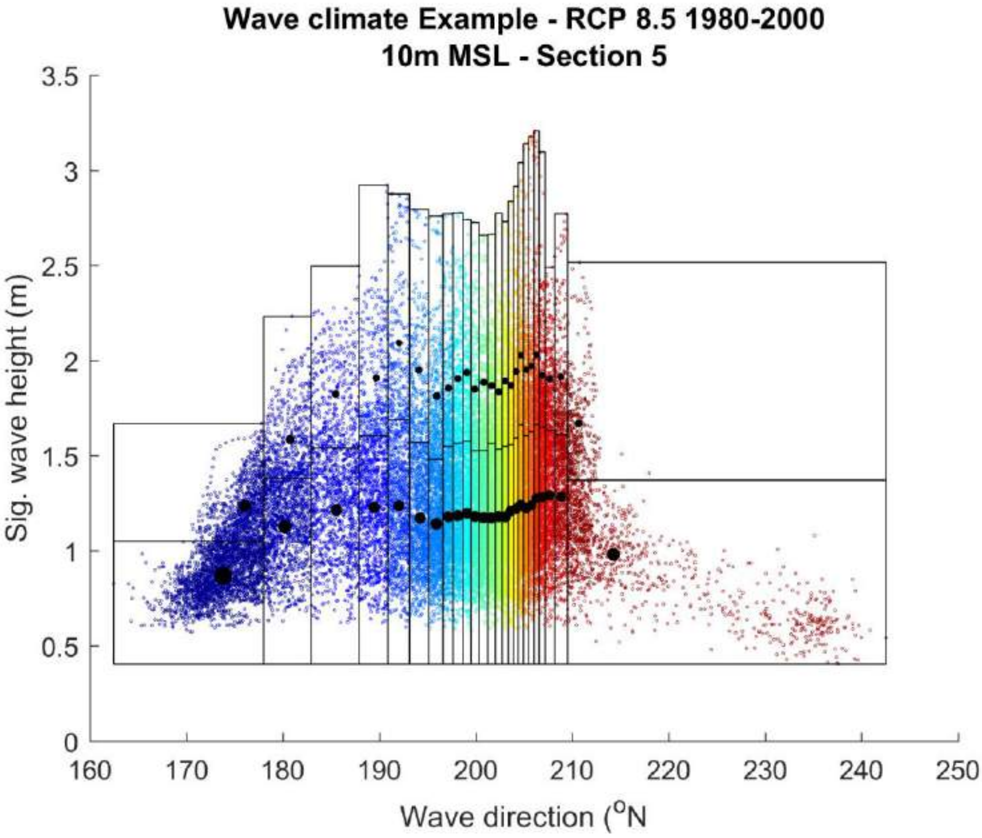

Figure 8-51: Example of morphological wave climate, using energy flux binning method. The boxes show the bins with equal energy flux and the black dots represent the representative conditions, where the size of the dots show the associated probability.

These wave climates have in turn used to calculate the longshore sediment transport rates along the coastline, this results in yearly gross and net longshore sediment transport rates. It is noted that the sediment transport *capacity* is computed by the formula, where the actual sediment transport depends on the availability of sand. On a fully sandy coast the transport capacity is equal to the actual transport, if rock outcrops are present within the breaker zone the actual sediment transport reduces. In this case, in section 1 and between sections 4 and 5 some rock outcrops are present and the actual sediment transport may be lower than computed.

The grain size that has been applied for each section is D_{50} = 450 μm, corresponding to the sediment samples that were taken during the survey (section A.5). The slopes for each transect were based on the bathymetrical survey that was undertaken for this project (Ref [35]).

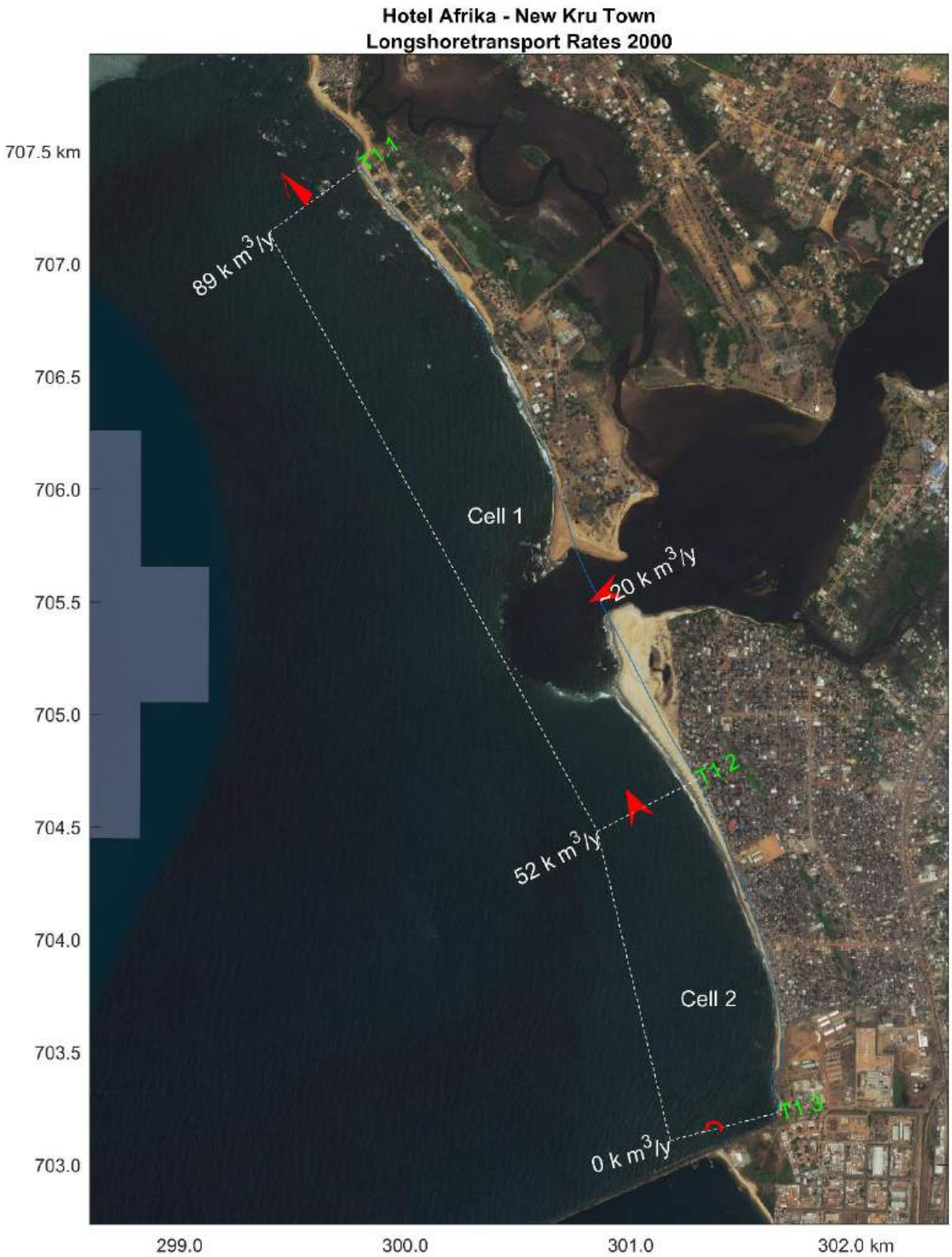

Figure 8-52: Longshore sediment transport rates in 2000 at Section 1 and 2

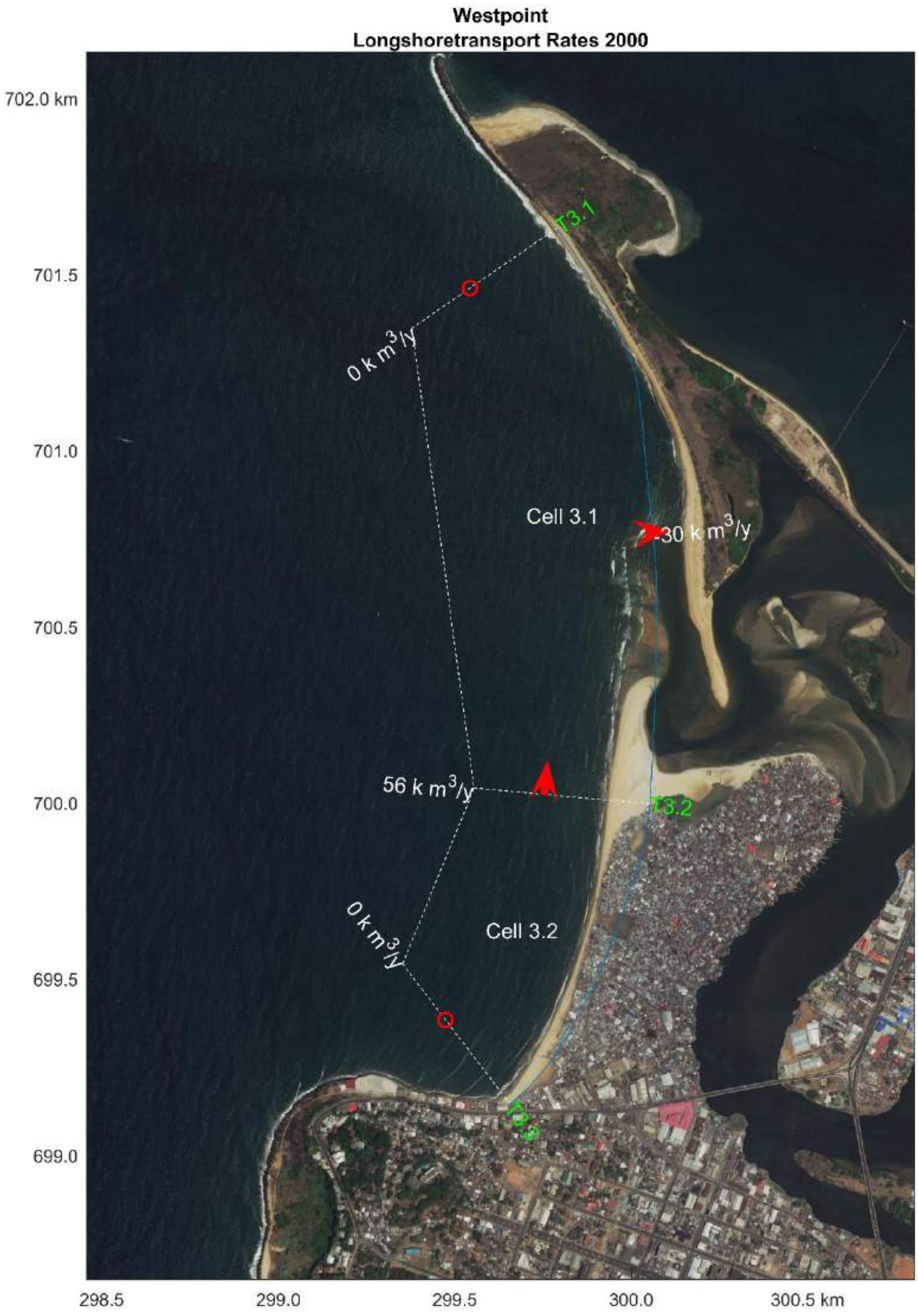

Figure 8-53: Longshore sediment transport rates in 2000 at Section 3

Figure 8-54: Longshore sediment transport rates in 2000 at Section 4

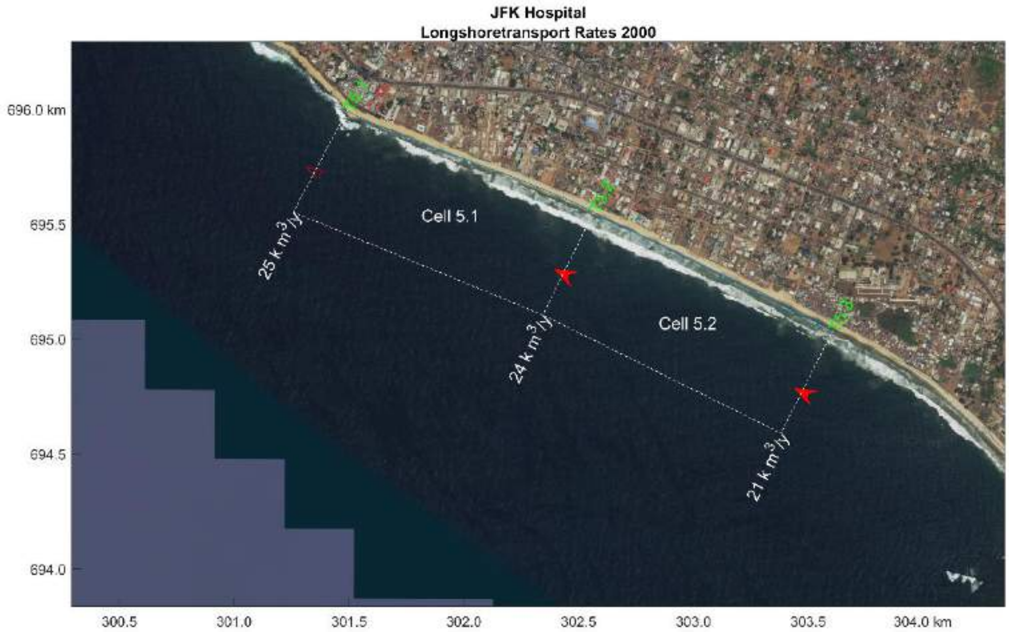

Figure 8-55: Longshore sediment transport rates in 2000 at Section 5

The longshore sediment transport rates are calculated along the transects of each cell defined in the figures above for the (changing) wave conditions based on the projections of the climate scenarios RCP 4.5 and RCP 8.5. The changing wave conditions and impact of climate change of the nearshore wave conditions have been described in section C.3.

The figures below (Figure 8-56 to Figure 8-59) show the net yearly averaged longshore sediment transport rates of each transect shown in the figures above, over the coming decades (2000-2100), based on the nearshore wave climates projected for RCP 4.5 and RCP 8.5. Also the effect of sea level rise has been taken into account. The scenario without climate change is also shown, where it is assumed that longshore sediment transport rates do not change over time, since in that case the wave conditions won't change.

From the figures it is remarkable to see that the changing wave conditions can have major impact on the net longshore sediment transport rates. Especially the difference between climate scenario RCP 4.5 and RCP 8.5 is remarkable. This is mainly due to the deviation in wave direction and the difference in the distributions of the wave directions of both projections for the different scenarios.

Figure 8-60 to Figure 8-63 show the resulting cumulative longshore sediment transport through the transects for the different climate scenarios. Due to the differences in the net longshore sediment transport rates over time, the cumulative rates can be significantly different comparing both scenarios. These cumulative transport rates are used to calculate the sediment balance in each defined coastal cell as shown in the figures above. The changing sediment balance over time will result in the expected coastal retreat for each coastal cell as described in section 4.5.

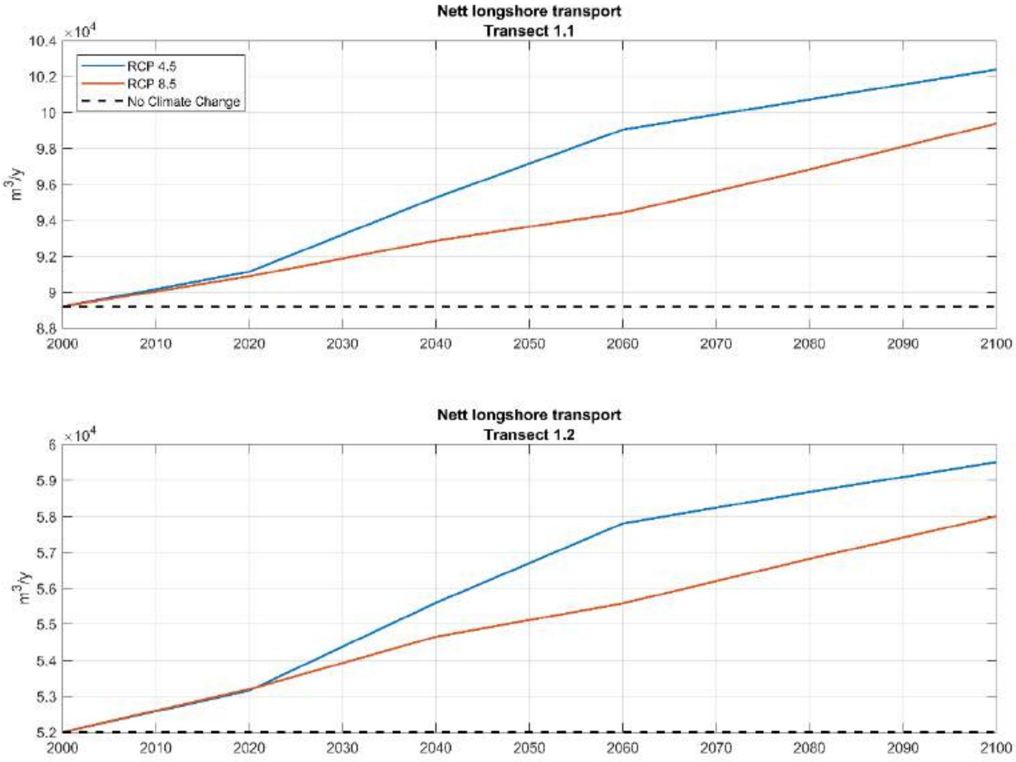

Figure 8-56: Yearly net longshore sediment transport rates for transect 1.1 and 1.2

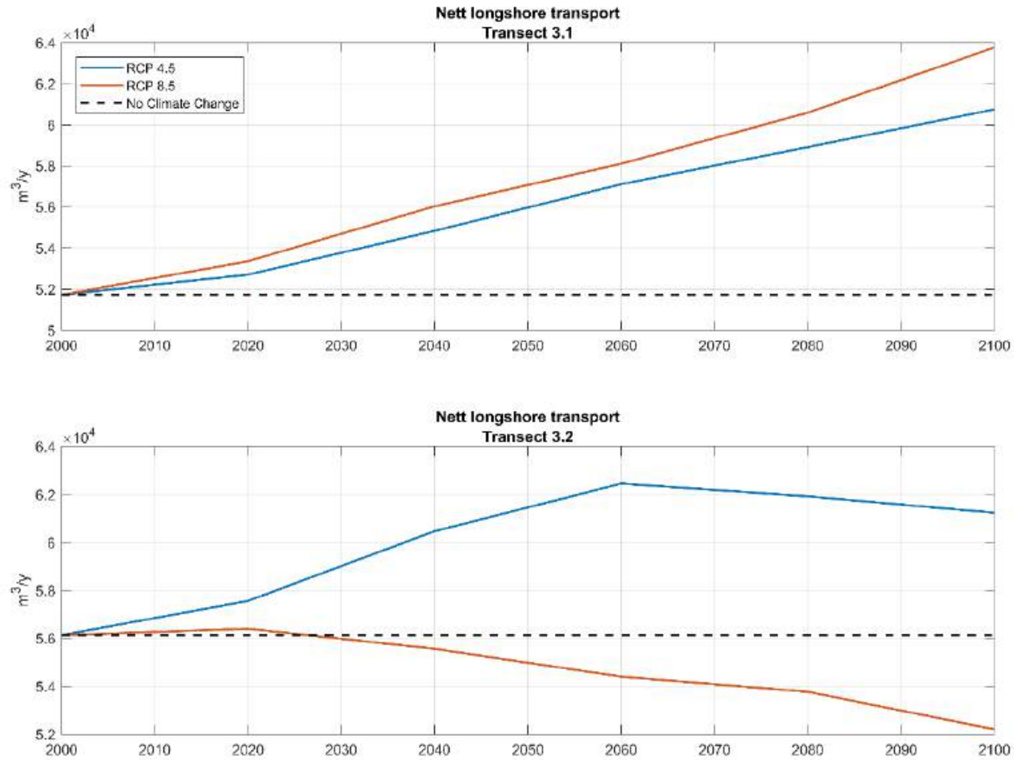

Figure 8-57: Yearly net longshore sediment transport rates for transect 3.1 and 3.2

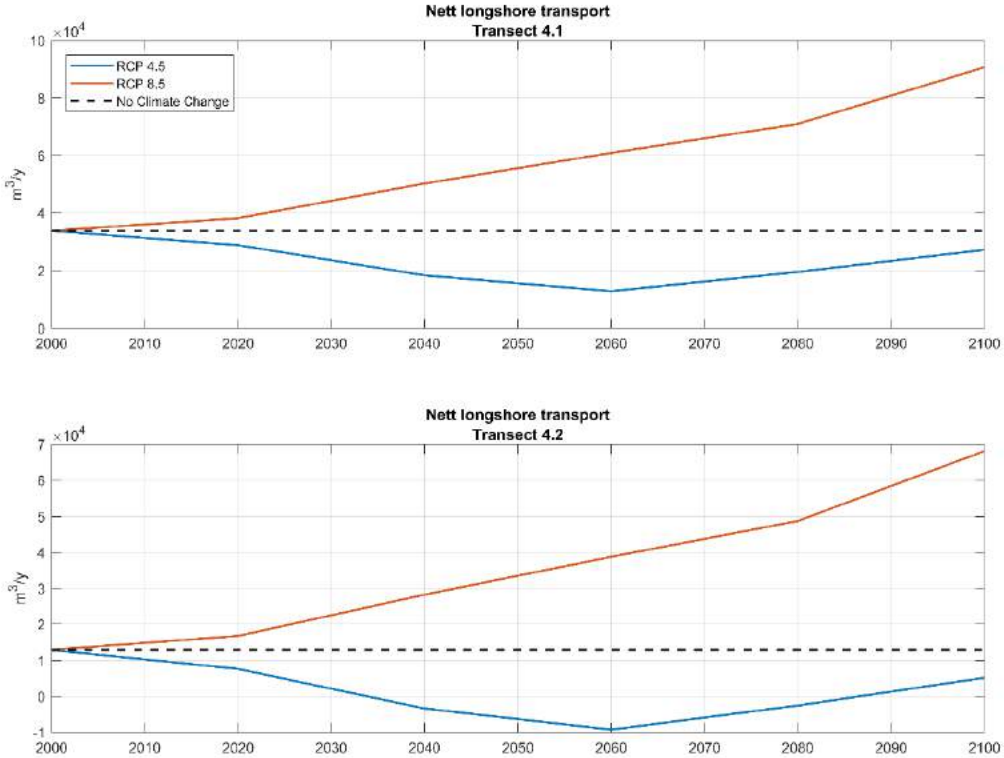

Figure 8-58: Yearly net longshore sediment transport rates for transect 4.1 and 4.2

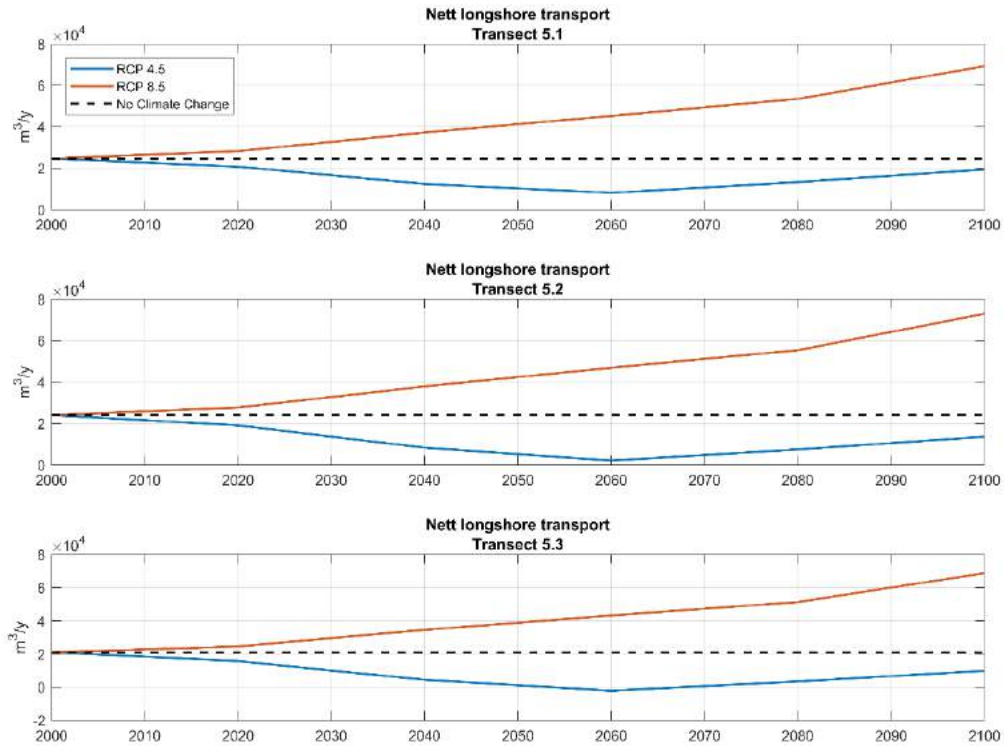

Figure 8-59: Yearly net longshore sediment transport rates for transect 5.1, 5.2 and 5.3

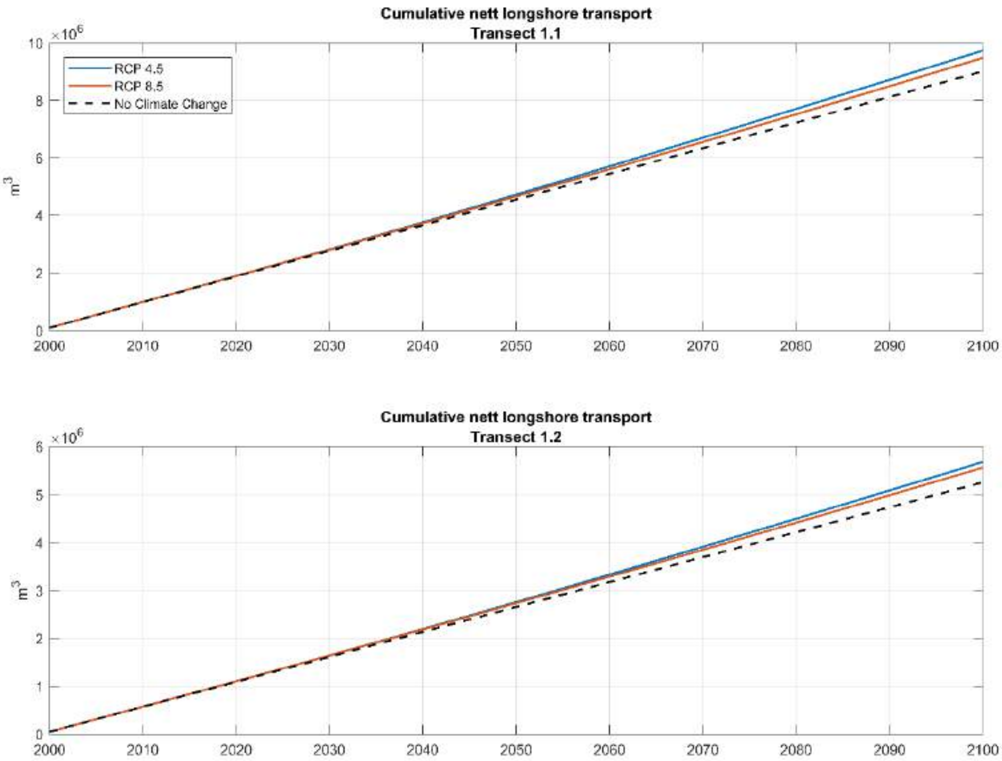

Figure 8-60: Cumulative net longshore sediment transport rates for transect 1.1 and 1.2

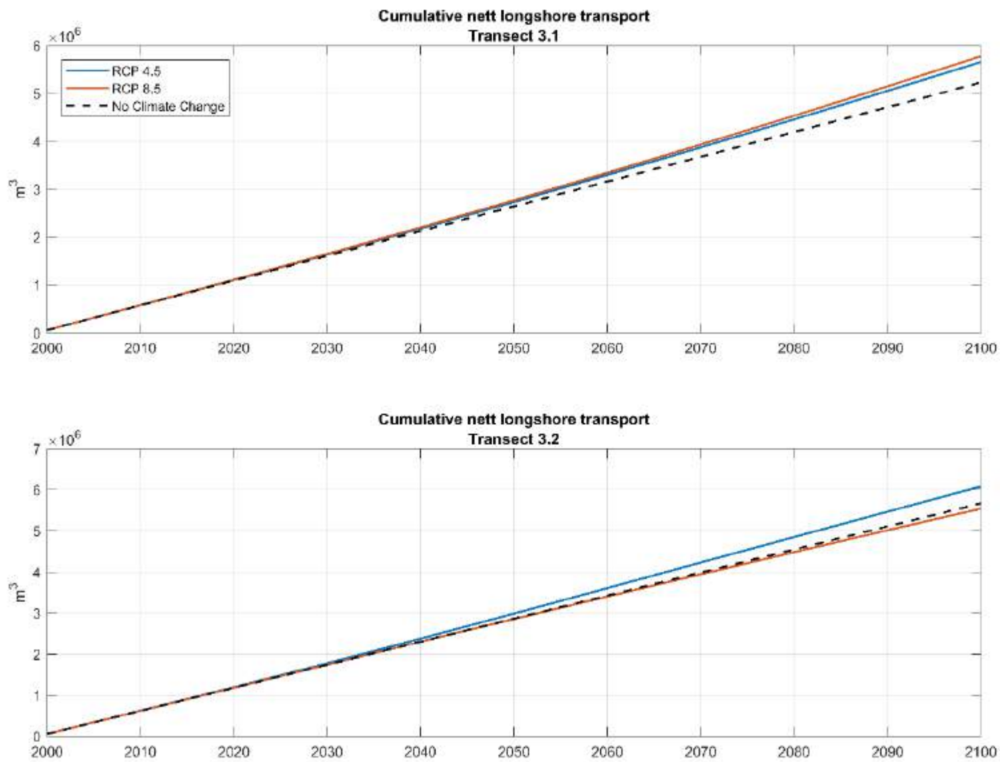

Figure 8-61: Cumulative net longshore sediment transport rates for transect 3.1 and 3.2

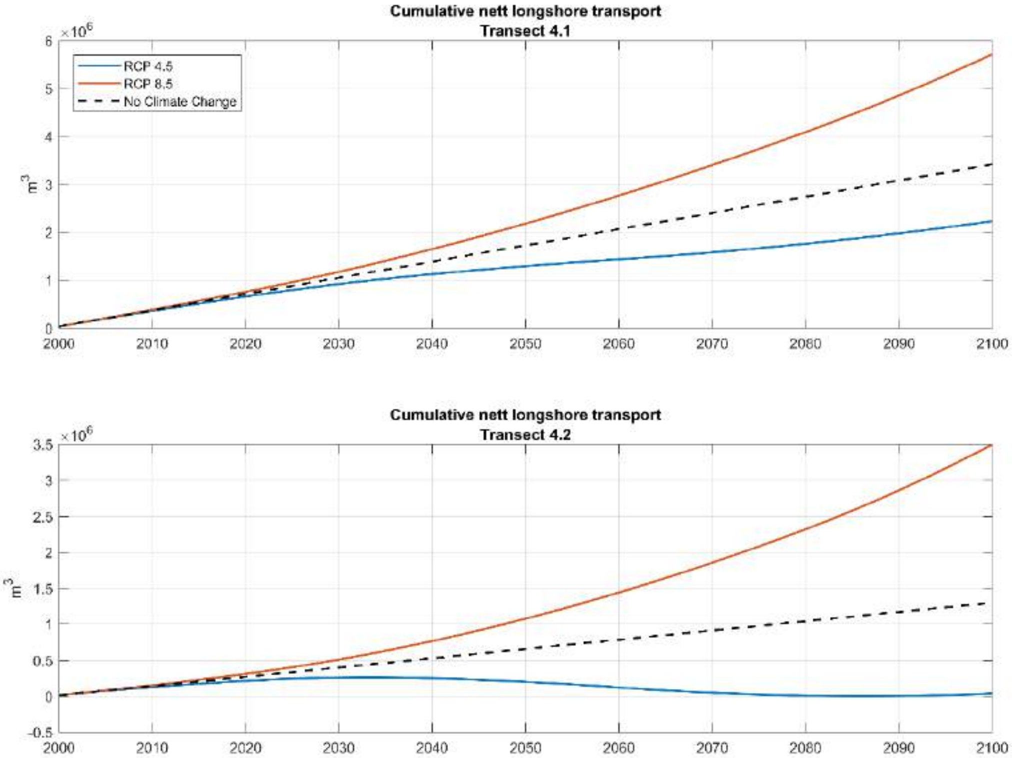

Figure 8-62: Cumulative net longshore sediment transport rates for transect 4.1 and 4.2

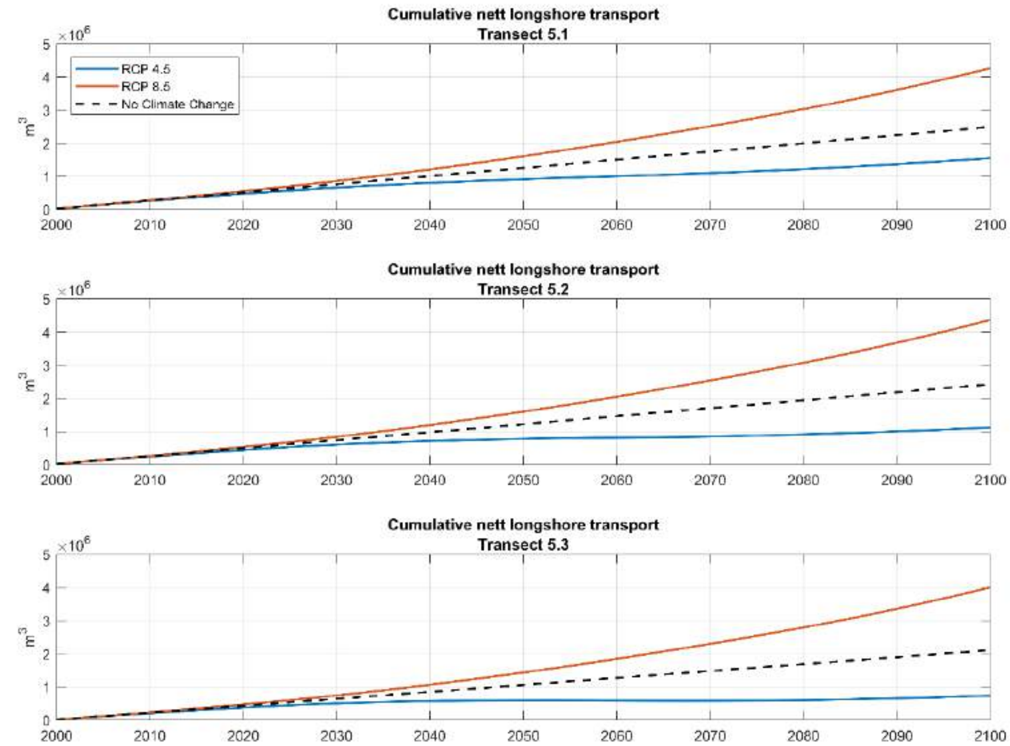

Figure 8-63: Cumulative net longshore sediment transport rates for transect 5.1, 5.2 and 5.3

F. STORM EROSION

The storm erosion has been calculated with use of the morphological model XBeach (Ref [58]). During storm conditions coastal erosion mostly occurs in the cross-shore direction. The dominance of the processes are different, for example the long-wave propagation and under-tow become relevant. The X-Beach model is currently the most advanced model for the simulation of these type of processes.

XBeach is an open-source numerical model which originally was developed to simulate hydrodynamic and morpho-dynamic processes and impacts on sandy coasts with a domain size of kilometres and on the time scale of storms. Since then, the model has been applied to other types of coasts and purposes. The model includes the hydrodynamic processes of short wave transformation (refraction, shoaling and breaking), long wave (infra-gravity wave) transformation (generation, propagation and dissipation), wave-induced setup and unsteady currents, as well as overwash and inundation. The morpho-dynamic processes include bed load and suspended sediment transport, dune face avalanching, bed update and breaching. The model can be used in both 1D and 2DH and is able to simulate the propagation of waves in both stationary, surfbeat mode and non-hydrostatic mode (phase-resolving). Surfbeat waves (long waves) are an important process for dune erosion. In this project the model has been used in 1D as the goal of this assessment is to determine the expected coastal retreat after a storm (heavy swell) has hit the coast.

For each section a representative cross-shore profile has been extracted/created based on the bathymetrical survey that has been performed (Ref [35]) and subsequently used as input for the model.

The boundary conditions stem from the nearshore results of the wave simulations of the extreme conditions for output locations at 10 m water depth (see section C.3). The average wave conditions of several output locations in vicinity of the representative profile have been used as input for the XBeach model.

A very important aspect of the storm erosion modelling is the storm duration. A longer storm will lead to significantly more erosion. The storm duration in relation to the storm intensity is assessed by looking at the peak over threshold data (see section C.1) and derive a relationship between storm duration and the storm peak wave height. Some correlation is observed between the storm duration and storm peak wave height, see Figure 8-64. The relationship has been derived by applying quantile regression. The median regression line is used to derive an associated storm duration with the extreme wave conditions. It is clear the storms are relatively long in duration, which shows the dominance of the swell waves: (extreme) swell trains can persist for days.

The storm sequencing is then created by using the nearshore extreme wave height, associated peak wave period, the storm duration, the extreme sea level (see section 4)A.4), the tide (the M2 and S2 component, see section A.3) and sea level rise. An example of the storm sequencing is shown in Figure 8-65. Such sequence has been created for 3 return periods (1, 10 and 100 years), 5 sections and 4 projection years (2020, 2050, 2070 and 2100). The climate scenario RCP 8.5 has been adopted.

Since any validation/calibration data for storm erosion lacks (e.g. consecutive profiles before and after specific storms) the model has been run with default parameters as much as possible (see Ref [58]). The only parameters that were adapted are the *facua* (0.15) and the *wetslp* parameter (0.3). Both parameters are based on the work of Vousdoukas et al (2011 – Ref [55]) where the XBeach was used for reflective beaches as in this case. A *morfac* of 10 has been applied to limit the computational effort. Also here a grain size of 450 μm has been adopted, based on the sediment samples that were taken on the beach (section A.5).

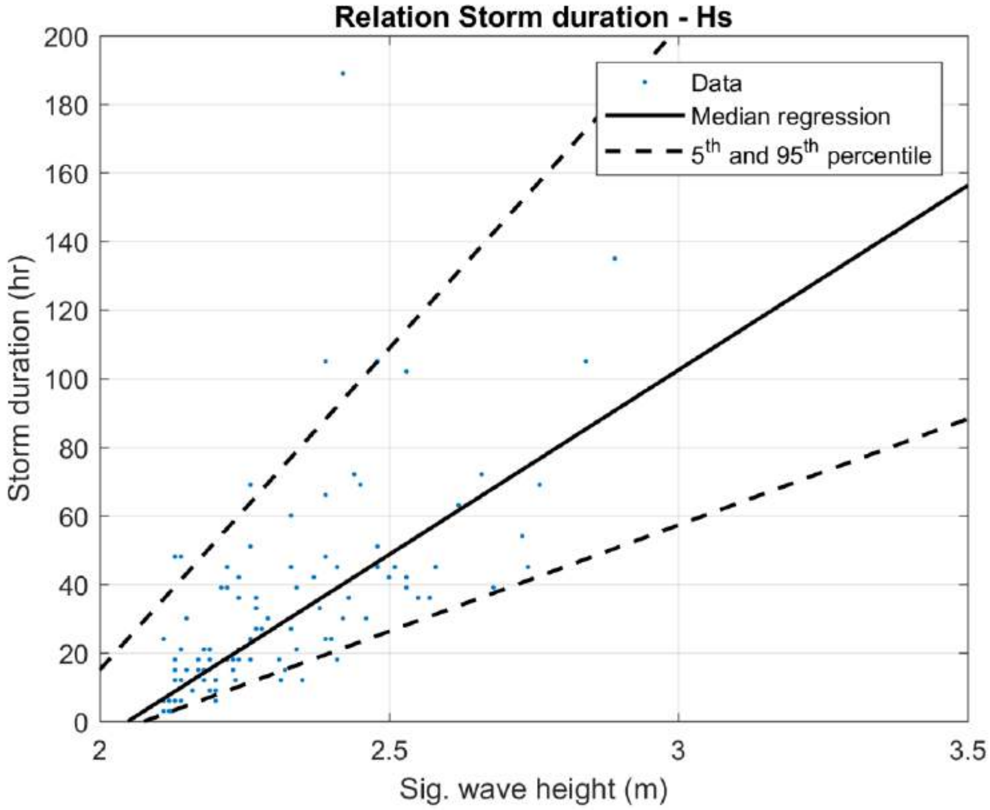

Figure 8-64: Relation between storm duration and the significant wave height

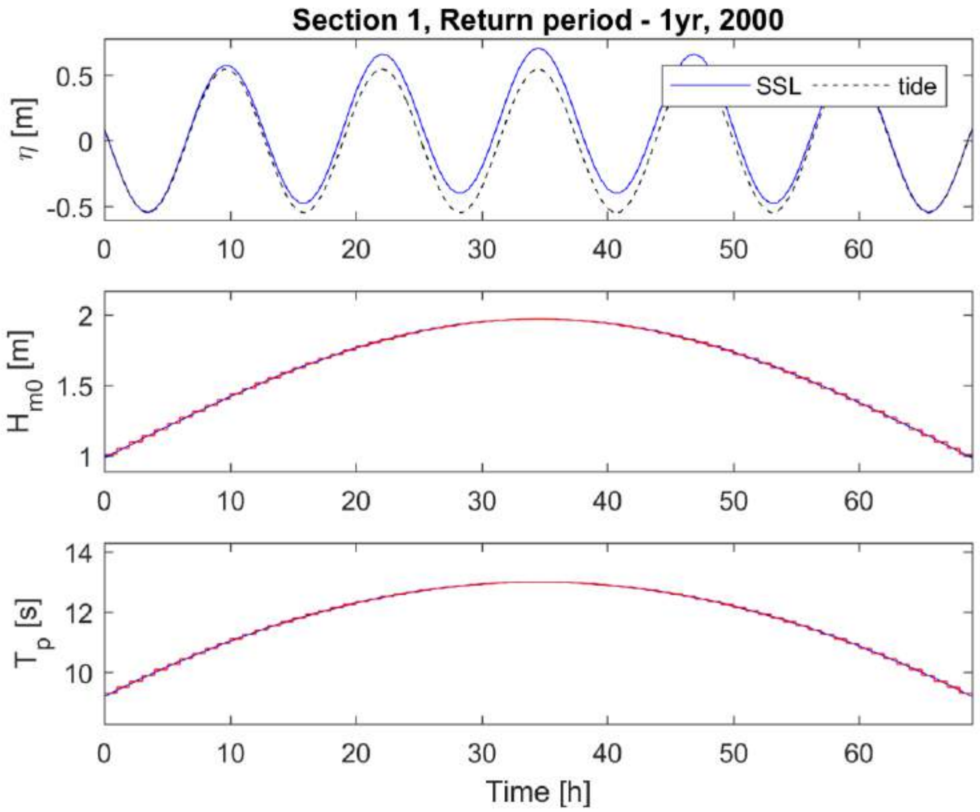

Figure 8-65: Example storm sequence time series as applied as boundary conditions for X-Beach model

An example of the resulting storm profiles is shown in section 4.6. The resulting coastal retreat is dependent on the vertical level. For example the coastal retreat at MSL is in general more than the coastal retreat at +2 mMSL. Hence the erosion volume has been used to estimate the coastal retreat. Dividing the calculated erosion volume by the active profile height a general coastal retreat parameter is determined. In this case the active profile height is estimated to be 7 m.

Table 8-19 shows the resulting erosion volumes and coastal retreat for all simulated cases by XBeach. These are subsequently used in the further assessment.

Table 8-19: Resulting erosion volume and coastal retreat for all simulated cases (RCP 8.5)

Section #	Return Period (years)	Projection year	Erosion Volume (m^3)	Coastal retreat (m)
1	1	2020	155	22
1	10	2020	250	36
1	100	2020	313	45
1	1	2050	171	24
1	10	2050	264	38
1	100	2050	344	49
1	1	2070	194	28
1	10	2070	282	40
1	100	2070	362	52
1	1	2100	200	29
1	10	2100	307	44
1	100	2100	410	59
2	1	2020	175	25
2	10	2020	278	40
2	100	2020	366	52
2	1	2050	194	28
2	10	2050	303	43
2	100	2050	381	54
2	1	2070	211	30
2	10	2070	325	46
2	100	2070	410	59
2	1	2100	223	32
2	10	2100	358	51
2	100	2100	461	66
3	1	2020	69	10
3	10	2020	110	16
3	100	2020	144	21
3	1	2050	78	11
3	10	2050	126	18
3	100	2050	162	23
3	1	2070	84	12
3	10	2070	135	19
3	100	2070	179	26
3	1	2100	99	14
3	10	2100	157	22

Section #	Return Period (years)	Projection year	Erosion Volume (m^3)	Coastal retreat (m)
3	100	2100	195	28
4	1	2020	69	10
4	10	2020	135	19
4	100	2020	177	25
4	1	2050	85	12
4	10	2050	146	21
4	100	2050	196	28
4	1	2070	94	13
4	10	2070	153	22
4	100	2070	201	29
4	1	2100	111	16
4	10	2100	181	26
4	100	2100	229	33
5	1	2020	76	11
5	10	2020	140	20
5	100	2020	189	27
5	1	2050	84	12
5	10	2050	150	21
5	100	2050	203	29
5	1	2070	95	14
5	10	2070	156	22
5	100	2070	207	30
5	1	2100	108	15
5	10	2100	179	26
5	100	2100	232	33

G. SOCIO-ECONOMIC SCENARIOS

This Appendix provides the key figures of the socio-economic scenarios used for the vulnerability analysis (damage estimations in do nothing scenario) and Cost Benefit Analysis (CBA). The study is assessing climate change scenarios for the period 2020-2100. This is a long-time horizon with uncertainty regarding the climate change and future development of population, households, dwellings and economic activities in the study area. Given this uncertainty two scenarios for the social-economic development of Liberia, Monrovia and the coastal sections have been developed. Scenarios are basically plausible and consistent stories regarding the possible future developments relevant for the topic under consideration. In this case scenarios are developed relevant for assessing the impacts of climate change on the coastal sections of Monrovia and the consequences for potential measures regarding climate adaptation. The aim is to develop realistic development paths for population and assets in the coastal sections and asset values affected by climate change.

Moreover, the so-called baseline scenario (do nothing scenario without implementing measures) will serve (in the feasibility study) to assess the prioritized measures: cost-effectiveness (by comparing costs of measures and benefits, for example averted damage). Hence, the scenarios need to be quantitative regarding key functions at risk and should include a spatial footprint. In this study we use different scenarios for the key (uncertain) determinants of future exposed and vulnerable population and assets: the extent of climate change (by IPPC scenarios) and the magnitude of demographic and economic development. The combinations of extreme climate change scenario (IPPC 8.5) and high socio-economic development shows the upper side of the bandwidth of damage due to the hazards, while a limited climate change scenario (IPPC 4.5) combined with a lower socio-economic scenario shows the lower side of the bandwidth of risks due to climate change.

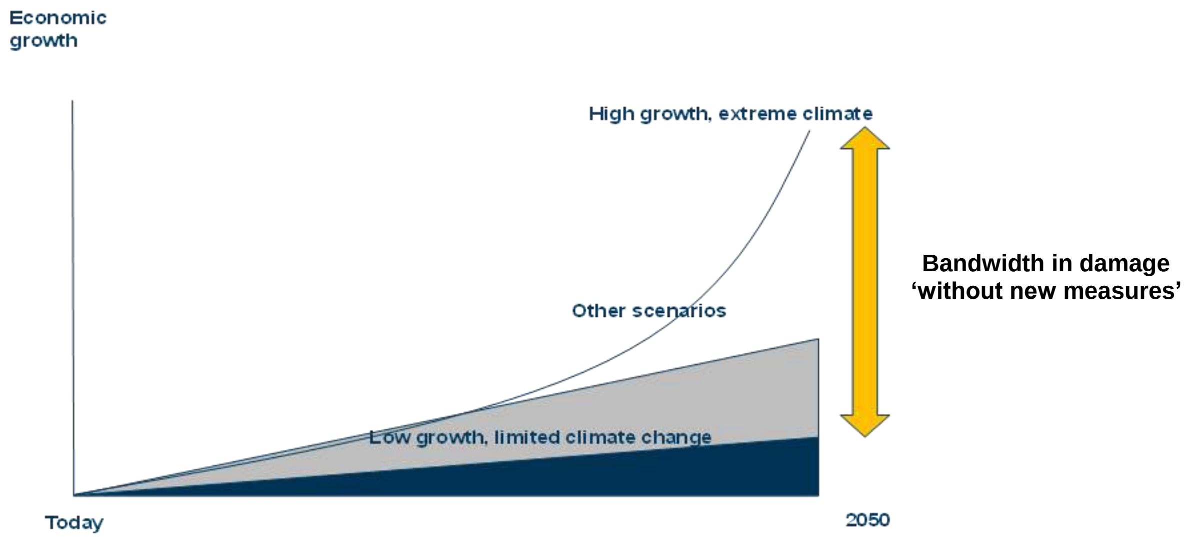

Figure 8-66: Climate and socio-economic scenarios illustrating the bandwidth of vulnerability (damage in time)

In order to estimate the future vulnerability and damage due to the hazards in the five coastal sections two socio-economic scenarios have been developed. The figures have been based on extrapolations of trend data from the period 1990-2017 (see below).

Table 8-20: Socio-economic data 1990-2017

Social-economic data	1990-2017	2009-2017	2017
Economic growth (GDP annual in %)	5,03%	2,32%	2,50%
Income per capita (GNI) growth (annual)		1,45%	1,64%
Population growth Liberia (annual)	3,06%	2,00%	2,55%
Population growth urban	2,30%	3,66%	3,40%

Source: World Bank Development Report, Indicators Liberia

As can be seen the volume of GDP growth has varied considerably in the past, also due to the civil war period and the Ebola crisis. The average for the period 1990-2017 was about 5% per year. More recently, real GDP growth was around 2,5% per year, while average annual population growth varied between 2,5% and 3% per year for Liberia.

Optimistic socio-economic scenario

Regarding future GDP developments rates of almost 5% per year are foreseen for the period until 2020. In an optimistic scenario it might be plausible such growth rates will continue for some time, but due to an expected decreasing in the growth of population, growth figures could flatten out over time. The slowdown of population growth is assumed in both scenarios due to declining birth rates, but in a different extent. Below the assumptions for the optimistic socio-economic scenario are presented.

Table 8-21: Key assumptions optimistic socio-economic scenario for Liberia, 2019-2100

Optimistic scenario	2019-2030	2030-2050	2050-2070	2070-2100
Economic growth (GDP)	4,8%	4,0%	3,5%	3,0%
Income per capita growth	1,8%	1,5%	1,5%	1,5%
Population growth Liberia	3,0%	2,5%	2,0%	1,5%
Population growth Monrovia	3,9%	3,4%	2,5%	2,0%

In line with the growth of urban population and economic growth, the number of buildings and economic activities is assumed to grow in coastal sections where there is still some space for growth (basically sections 1,2, 4 and 5). Moreover, the quality of the buildings might increase over time with income increases. This will result in higher real estate values (corrected for normal inflation).

Pessimistic socio-economic scenario

In a more pessimistic scenario, we assume that GDP growth will be closer to the recent average of 2,5%, declining over time consistent with the decreasing population growth. Below table provides these assumptions for this scenario.

Table 8-22: Key assumptions pessimistic socio-economic scenario for Liberia, 2019-2100

Pessimistic scenario	2019-2030	2030-2050	2050-2070	2070-2100
Economic growth (GDP)	3,5%	3,0%	2,5%	2,0%
Income per capita growth	1,0%	1,0%	1,0%	1,0%
Population growth Liberia	2,5%	2,0%	1,5%	1,0%
Population growth Monrovia	3,4%	2,9%	2,0%	1,5%

H. DAMAGE ESTIMATION

Damage estimation do-nothing scenario

In the do-nothing scenario (or baseline), damage due to the identified hazards – coastal erosion and storm erosion- will increase over time. Direct physical damage will occur to the assets in the coastal sections due to the loss of land (beaches and other urban land) due to the process of erosion and storm erosion events. The damage will increase over time due to two determinants;

- ***Climate change***: climate change will result in sea level rise. Sea level rise increases the effects or erosion and storm erosion in the sense that more meters of land will be lost to the ocean. The extent depends on the climate change scenario. Two scenarios have been used in the damage and CBA model: the RCP 4.5 moderate climate change and RCP 8.5 high climate change IPPC scenarios. In the Chapter Vulnerability Analysis, maps with the areas of lost land and assets were presented.
- ***Socio-economic developments***. Increasing population and economic activities will result in higher exposure of people and assets in the coastal sections over time. The socio-economic scenarios as described in Appendix E have been used to estimate the number of people and assets in the future years (2050, 2070, 2100) in the coastal sections. For West Point no growth has been assumed due to lack of space in this section for expansion.

In this study we have identified the following vulnerable asset categories based upon google earth, open street maps and other GIS information and the vulnerability analysis:

- Business & offices buildings (formal commercial assets);
- Religious & cultural buildings;
- Roads;
- Government & education buildings (administration buildings, schools etc.)
- Residential buildings (formal & informal housing);
- Fishery sites (landing sites for canoes);
- Power stations.

In below tables the number of lost assets for the years 2030, 2050, 2070 and 2100 are presented for sections 2 (New Kru town) and 3 (West Point) for the high climate change, optimistic socio-economic development scenario). The number of assets lost are based on the coastal retreat in meters from RCP 8.5 scenario. The storm events cause additional assets (mainly residential buildings) lost in the first row (30 meters) of the area behind the line of coastal retreat. In the tables below only the additional lost assets due to storm events are presented.

Table 8-23: Lost assets due to hazards 2030-2100 sections 2 and 3, high climate change – optimistic socio-economic scenario

Section 2	2030	2050	2070	2100
Assets CDR High climate change, optimistic socio-economic scenario				
Coastal retreat due to erosion (no storms)				
Business and Offices	1,79	6,34	14,71	31,54
Hotels & restaurants	-	-	-	-
Infrastructure	-	2,06	13,28	35,54
Religion and Cultural Heritage	-	-	-	-
Residential	185,41	590,97	1.158,99	2.437,03
Schools and Government	0,80	7,79	13,33	45,37
Fishery sites	3,00	3,00	3,00	3,00
Power station	-	-	-	-
Roads total m	5,96	233,39	1.506,49	4.031,28

Section 2	2030	2050	2070	2100
Assets CDR High climate change, optimistic socio-economic scenario				
Storm t=1				
Business and Offices	0,84	0,57	0,40	0,57
Hotels & restaurants	-	-	-	-
Infrastructure	0,22	4,54	5,85	0,47
Religion and Cultural Heritage	-	-	-	-
Residential	41,23	33,22	31,61	33,29
Schools and Government	1,18	1,12	0,22	5,81
Fishery sites	-	3,00	-	-
Power station	-	-	-	-
Roads total m	17,85	366,73	473,04	37,71

Section 2	2030	2050	2070	2100
Assets CDR High climate change, optimistic socio-economic scenario				
Storm t=100				
Business and Offices	1,39	1,11	0,40	-
Hotels & restaurants	-	-	-	-
Infrastructure	0,78	8,68	13,98	-
Religion and Cultural Heritage	-	-	-	-
Residential	92,42	79,77	75,43	-
Schools and Government	3,37	1,76	0,79	-
Fishery sites	-	3,00	-	-
Power station	-	3,00	-	-
Roads total m	14,32	160,36	258,19	-

Section 3	2030	2050	2070	2100
Assets CDR High climate change, optimistic socio-economic scenario				
Coastal retreat due to erosion (no storms)				
Business and Offices	9,95	31,54	55,32	55,32
Hotels & restaurants	-	-	2,91	2,91
Infrastructure	-	10,75	12,00	12,00
Religion and Cultural Heritage	-	4,00	6,00	6,00
Residential	344,83	1.071,78	1.477,96	1.477,96
Schools and Government	-	-	2,00	2,00
Fishery sites	1,00	2,00	2,00	2,00
Power station	-	1,00	1,00	1,00
Roads total m	34,51	1.350,71	1.507,55	1.507,55

Section 3	2030	2050	2070	2100
Assets CDR High climate change, optimistic socio-economic scenario				
Storm t=1				
Business and Offices	1,44	0,22	-	-
Hotels & restaurants	-	-	-	-
Infrastructure	-	0,67	-	-
Religion and Cultural Heritage	-	-	-	-
Residential	12,22	12,49	-	-
Schools and Government	-	-	-	-
Fishery sites	-	-	-	-
Power station	-	-	-	-
Roads total m	-	1.517,79	-	-

Section 3	2030	2050	2070	2100
Assets CDR High climate change, optimistic socio-economic scenario				
Storm t=100				
Business and Offices	3,00	0,51	-	-
Hotels & restaurants	-	0,05	-	-
Infrastructure	-	1,25	-	-
Religion and Cultural Heritage	-	0,05	-	-
Residential	50,75	50,80	-	-
Schools and Government	-	0,05	-	-
Fishery sites	-	-	-	-
Power station	-	-	-	-
Roads total m	-	-	-	-

Data regarding the value of assets (real estate, schools, churches, roads) are limited available in Liberia. Nevertheless, in order to estimate the value of the assets a number of sources and more informal information from site visits have been used. For example, for residential buildings data are based upon interview with a real estate company. For West Point rental prices are based upon data from the Commissioner and Liberia Housing Profile 2013 and these rental prices per room have been transformed to real estate values. In below table the assumed values for the assets are presented.

Table 8-24: Estimated value of assets in 2019 (in US$ per building or asset)

Asset category	Section 1	Section 2	Section 3	Section 4	Section 5
Business and Offices	10.000	10.000	10.000	50.000	50.000
Hotels and restaurants	40.000	40.000	40.000	40.000	40.000
Infrastructure	-	-	-	-	-
Religion & cultural heritage	10.000	10.000	10.000	15.000	15.000
Residential	8.500	12.500	31.200	30.000	30.000
Schools and Government	20.000	20.000	20.000	20.000	20.000
Fishery sites					
Power station	-	-	1.115.000	-	-
Road costs in USD per m lane	425	425	425	425	425

Over time the value of assets will increase, because of two reasons. Firstly, construction costs inflation will cause prices to go up. However, all damage costs are presented in current prices, so we did not inflate the values based upon cost inflation. But secondly, it is to be expected that the quality of the buildings will increase over time. With increasing income and economic growth people and firms will demand higher quality of buildings (in terms of construction materials, space etc.). This trend is taken into account in the damage model by increasing real values of all real estate with the income per capita growth in the relevant socio-economic scenario.

Content value of buildings

Apart from the physical value of building structures, the contents of buildings will be lost due to the hazards. Based upon Scawthorne et al. (2006 – Ref [68]) the following fractions have been used for the content values (as % of structural value).

Table 8-25: Fractions used for content value of buildings

Content damage of residential buildings	50%
Content damage of commercial buildings	100%
Content damage of government & other buildings	75%

Indirect tangible damage

Indirect damage is defined as loss of income due to event induced business interruption and costs of disaster response. Loss of income due to the hazards will be especially relevant for the communities depending on the shore such as fisheries and informal local shops & markets (especially around New Kru town, West point and Bernards beach). The conducted survey under the fisheries communities for ESAR included very indicative catch values for fisheries. However, these reported figures are very indicative and other economic activities were not included in the survey. Therefore, the survey could not be used due to lack of completeness regarding the economc activities in the areas.Thus, the damage model could not be based upon the ESAR survey. Instead indirect damage percentages from the literature had to be used (as second-best option). The literature a mark-up on the direct damage for indirect damage has been assumed (for now) of 18%[15].

[15] See for example Kates, 1965, Briene et al 2002, Ecorys, 2016.

Table 8-26: Overview damage per section, 2030-2100 (US$) high climate change (RCP 8.5) and optimistic socio-economic scenario

Section 1	2030	2050	2070	2100
Cumulative erosion damage	**18.902**	**94.213**	**269.144**	**2.103.634**
Expected annual storm damage	**67.404**	**128.443**	**1.195.243**	**5.644.610**
Section 2				
Cumulative erosion damage	**5.088.195**	**22.466.653**	**60.495.550**	**204.521.381**
Expected annual storm damage	**1.214.525**	**1.513.759**	**1.874.403**	**3.474.056**
Section 3				
Cumulative erosion damage	**19.641.704**	**85.095.280**	**154.939.075**	**154.939.075**
Expected annual storm damage	**751.537**	**1.740.455**	**-**	**-**
Section 4				
Cumulative erosion damage	**1.106.710**	**1.675.326**	**18.793.620**	**80.070.501**
Expected annual storm damage	**1.272.495**	**2.828.236**	**5.990.126**	**23.675.460**
Section 5				
Cumulative erosion damage	**206.258**	**2.137.388**	**3.203.413**	**12.387.876**
Expected annual storm damage	**6.617**	**12.869**	**23.889**	**69.298**
Total cumulative erosion damage	**26.061.769**	**111.468.860**	**237.700.802**	**454.022.468**
Total AED storm damage	**3.312.579**	**6.223.762**	**9.083.662**	**32.863.425**

Table 8-27: Overview damage per section, 2030-2100 (US$) low climate change (RCP 4.5) and pessimistic socio-economic scenario

Section 1	2030	2050	2070	2100
Cumulative erosion damage	**18.132**	**79.242**	**198.493**	**1.273.804**
Expected annual storm damage	**64.658**	**102.239**	**881.489**	**3.208.774**
Section 2				
Cumulative erosion damage	**4.478.684**	**16.663.282**	**38.016.569**	**100.810.486**
Expected annual storm damage	**1.109.039**	**1.282.742**	**1.466.541**	**2.302.908**
Section 3				
Cumulative erosion damage	**17.979.478**	**70.651.424**	**115.744.387**	**115.744.387**
Expected annual storm damage	**686.981**	**1.572.699**	**-**	**-**
Section 4				
Cumulative erosion damage	**974.829**	**1.242.902**	**11.743.326**	**38.673.881**
Expected annual storm damage	**1.120.858**	**2.098.231**	**3.742.972**	**11.827.154**
Section 5				
Cumulative erosion damage	**35.873**	**1.417.771**	**139.048**	**321.119**
Expected annual storm damage	**1.219.044**	**1.900.861**	**3.120.183**	**6.301.752**
Total erosion damage	**23.486.995**	**90.054.622**	**165.841.822**	**256.823.677**
Total AED storm damage	**4.200.581**	**6.956.772**	**9.211.185**	**23.640.588**

Table 8-28: Overview discounted damage costs 2020-2100 (in million US$ 2019, high climate change (RCP 8.5) and optimistic socio-economic scenario

Present value Damages overview (RCP 8.5, Opt) mln USD	**Section 1**	**Section 2**	**Section 3**	**Section 4**	**Section 5**
Coastal retreat	0,1	12,4	33,4	3,7	0,6
Storms AED	3,1	18,2	14,2	24,3	15,9
Total PV	***3,1***	***30,6***	***47,6***	***28,0***	***16,6***

Note: Damage costs have been discounted at 6% real discount rate

Table 8-29: Overview discounted damage costs 2020-2100 (in million US$ 2019, low climate change (RCP 4.5) and pessimistic socio-economic scenario

Present value Damages overview (RCP 8.5, Opt) mln USD	**Section 1**	**Section 2**	**Section 3**	**Section 4**	**Section 5**
Coastal retreat	0,0	8,4	27,6	2,4	0,7
Storms AED	2,3	16,2	13,2	18,0	38,0
Total PV	***2,4***	***24,6***	***40,8***	***20,4***	***38,7***

Note: Damage costs have been discounted at 6% real discount rate

I. MEASURES RETREAT STRATEGY

I.1 Do nothing

This measure means no action is taken to decrease the vulnerability of the affected coastal communities. The vulnerability analysis shows predictions of the future threats the coastal communities of the MMA will face if no measures are taken. This scenario will also be elaborated in the cost-benefit analysis for each coastal section. This will result in a clear comparative overview between doing nothing and the choice for a certain strategy to increase the climate resilience of the coastal communities.

I.2 Set-back line

Applying a set-back line means that people need to retreat out of the area that is expected to be affected by the coastal hazards. New development are not allowed inside this identified 'buffer zone'. People and businesses that are already present inside this area need to be relocated. For this relocation to be successful, it is essential that the original livelihood and socio-economic dependencies on the environment are not disturbed. Therefore this measure is hard to implement in a highly urbanised area. Implementation of a set-back line should be realised by means of permits, laws, law enforcement and political policies.

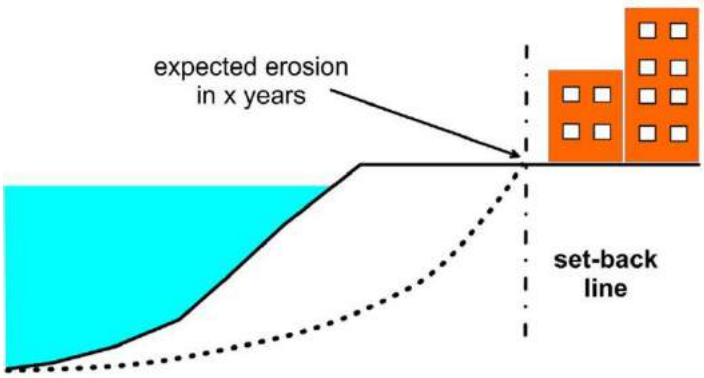

Figure 8-67: Example set-back line regarding coastal erosion

I.3 Realignment

Realignment also is a form of retreat; not based on a set-back line for developments but on creating new intertidal habitats behind the former line of defence. The former defence system is deliberately not maintained, allowing for flooding of the area it originally defended. In this way, new wetlands are created that become part of the new sea defence. If required, a new line of technical measures is constructed to defend the hinterland. The sea defence thereby moves more land inwards, even as the coastal communities, giving more space to the development of valuable ecosystems.

J. ECOSYSTEM-BASED SOLUTIONS

J.1 Coastal mangrove system

As mangroves can survive in highly saline areas, they can protect coasts against hazards like erosion, flooding and storm surges. They can capture sediments with their roots, thereby building up and consolidating silty intertidal areas (Lee et al. 2014 – Ref [59]). By pushing themselves up into the peat layer they create, mangroves can even keep up with sea level rise to a certain extent (McIvor et al. (2013) – Ref [20]). Moreover, if waves pass through the aerial roots of the trees (or canopies for larger water depths), the wave height and energy that reaches the shoreline can be reduced significantly (Hashim and Catherine, 2013 – Ref [14]).

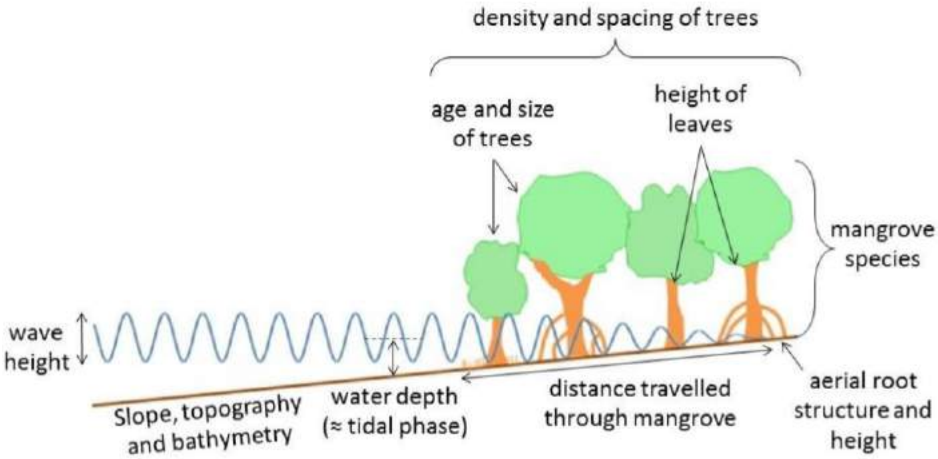

Figure 8-68: Factors affecting wave attenuation in mangroves (McIvor et al. (2012) – Ref [19])

Besides these physical qualities to reduce the hydrodynamic attack on the shoreline, mangroves are amongst the most productive and biologically most important ecosystems of the world (Shrikanth et al. (2015) – Ref [18]). By providing additional sources of income and nutrition for the coastal communities, mangroves reduce the vulnerability to coastal hazards even more. For example, mangrove forests form a natural nursery for (commercially) important marine life, thereby increasing the livelihood and food security of fishing communities and the surrounding services sector.

Although mangroves can grow on a lot of different subsoils, they are mostly found in (sub-)tropical swampy areas with fine silty sediments. Generally the wave conditions are very mild in these coastal environments, giving the mangrove forest time to grow and strengthen. Their ability to reduce wave impact on the shorelines they protect is most notable during tropical storms. Depending on the species and the density of the forest, a mangrove belt of about 100m to 500m is required to reduce the wave height by 50%. This implicitly means that a coastal mangrove system can only exist at flat foreshores that have a large intertidal area.

J.2 Dune and beach system

A dune and beach system can be seen as a wide sandy buffer between land and sea. Especially dunes can play a vital role to protect coastal communities against flooding and storm erosion. The wider and higher these systems are, the more the vulnerability of the hinterland is decreased.

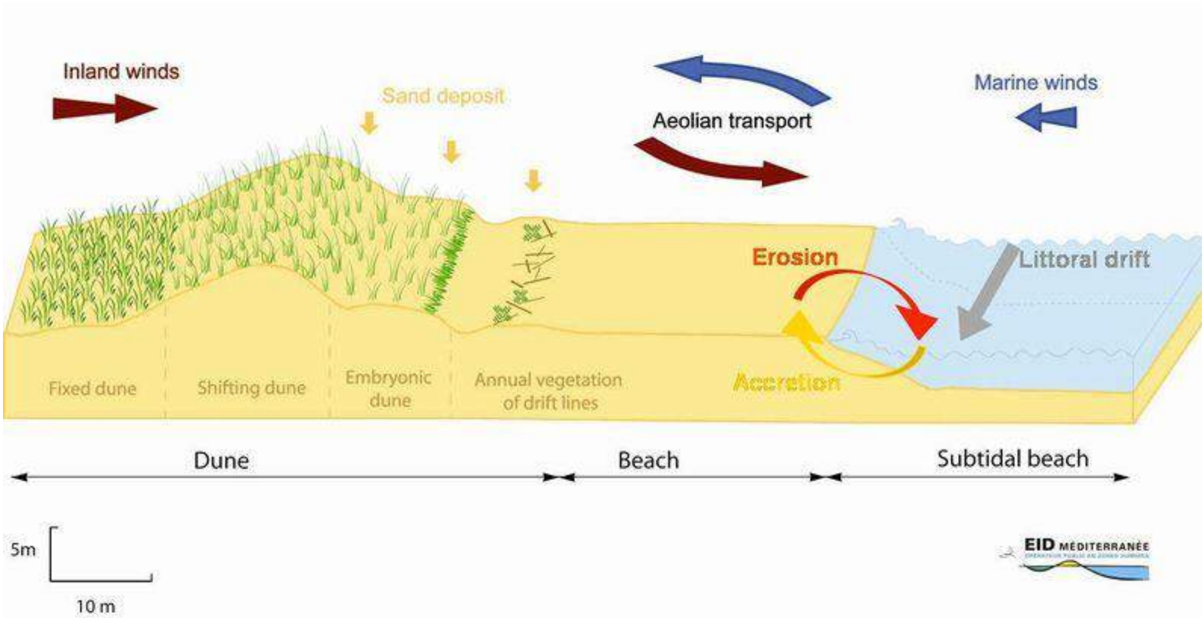

Figure 8-69: A schematised view on a wide dune and beach system (Ref [60])

Sandy dunes can also be used as natural purification system of water. For example in the Netherlands, the aquifers below the dunes are an important source of fresh water. Additionally beach and dune systems are attractive for tourism, which can be an important source of income. Creating more diverse livelihoods by implementation of a tourism sector can increase the climate resilience of coastal communities. However, it should be noted that the development should be controlled well by governmental policies and community engagement to prevent that the tourism creates an excessive pressure on the ecosystem.

Naturally, beach and dune systems only occur at locations where the prevailing winds are strong enough to transport sand particles. An abundance of sand should feed this dynamic environment which is constantly changing due to wind, waves and tides. If required, additional sand quantities can be supplied in the form of by beach nourishments. Vegetation or soft physical structures can be used to increase sand deposition and stabilize the sandy system to a certain extend. In urbanised areas especially the lack of space often conflicts with the restoration of beach and dune systems.

J.3 Coral reef breakwater

Coral reefs can be found in shallow coastal zones of (sub-)tropical areas. They can form a natural shoreline protection, as wave will break especially over the highest end of a reef i.e. the rough 'reef crest'(Ref [61]). Acting as a breakwater, this ecosystem can decrease the vulnerability of coastal communities against coastal erosion and storm and flood protection. The growth of a healthy coral ecosystem can even keep up with a certain rate of sea level rise.

Additionally coral reefs are a very valuable ecosystems for coastal communities, as they provide food, shelter and nursery grounds for a large variety of organisms. Although only a small percentage of the oceans is occupied by coral reef, almost one-third of the world's marine fish species are found in and around reef areas (Moberg and Folke (1999) – Ref [16]). Furthermore, a well-conserved coral reef attracts diving and snorkelling tourism, thereby increasing the diversity of the livelihood of the coastal communities.

Strict regulations and governmental policies are required to maintain a healthy coral reef, together with committed communities that are aware of the fragility and importance of this ecosystem. Coral reefs are very sensitive to pollution and other anthropological impacts. Moreover, reefs should not be exposed to (a high degree of) sedimentation. They do require a certain amount of sunlight, a bare hard substratum, a salinity rate between 15 and 36ppt, a large inundation time and a water temperature between 28 and 34°C (Ref [62]).

J.4 Oyster (shellfish) reefs

Up to now, only some experience is gained with the use of (Pacific) oyster reefs as part of a building with nature solution but in certain situations other shellfish might be applicable as well. The advantage of oysters is that they use a strong cement-like glue by which they stay attached to the subsoil after dying. In this way oysters can build a sustainable reef, that causes high bed friction values for shallow (intertidal) coastal zones. An oysters reef thereby can reduce the wave energy that reaches the shoreline and trap sediments to mitigate erosion.

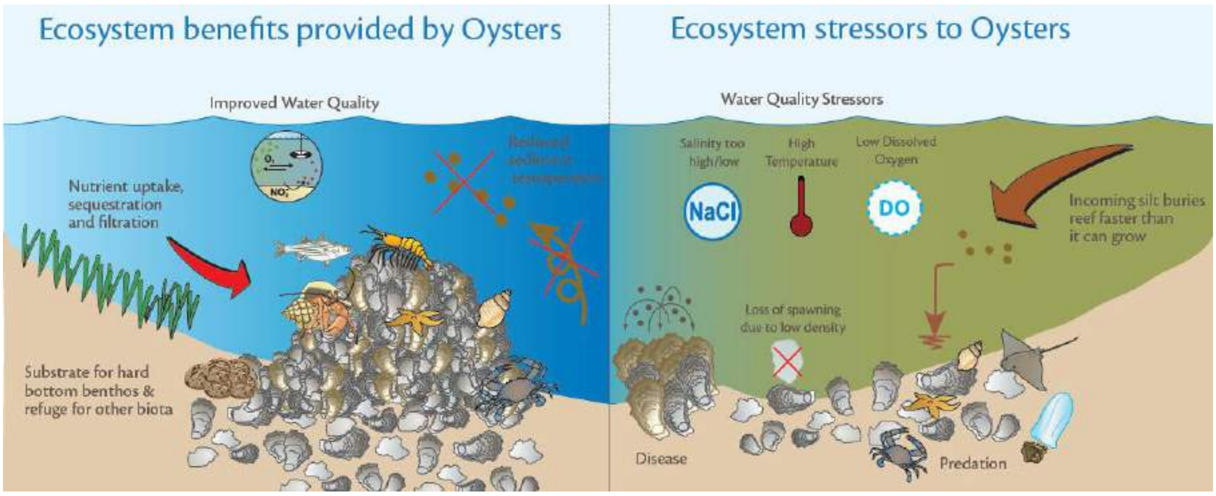

Figure 8-70: Schematic overview of the benefits and stressors to an Oyster-ecosystem (Ref [63])

Furthermore, oyster reefs can enhance biodiversity, creating additional benefits in the form of food security and a diversity of livelihoods. As they filter out nutrients, organic materials and fine sediments, oyster reefs can even cause an improve of the local water quality. A proper assessment should be done to check if the intended oyster (shellfish) species does not cause a degradation of the native ecosystem. In environments contaminated by faecal matter or heavy metals, the oysters should be checked on viruses before human consumption.

They Pacific Oyster grows at intertidal areas, on a soft-sediment substratum with temperate wave conditions. Compared to coral reefs, oysters can withstand a large range of temperatures (about -1 to 35°C) and water depths (less dependent on sunlight). The salinity requirements are similar those of a coral reefs.

J.5 Seagrass field

Similar to oyster reefs, seagrass fields can increase the bed friction in shallow coastal waters. This contributes to the resilience of coastal communities by mitigating erosion and decreasing the wave height that reaches the shore.

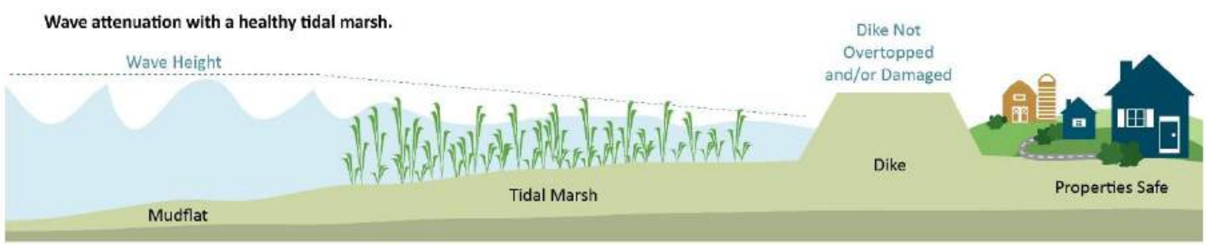

Figure 8-71: Principle of wave attenuation by seagrass fields (Ref [64])

Additionally seagrass fields can provide food and habitat for all forms of marine life, thereby increasing biodiversity and food security for the coastal communities. They also improve the water quality by filtering nutrients and contaminants, and turn carbon dioxide into oxygen by means of photosynthesis. However, seagrasses are highly sensitive to pollution, physical damage and other anthropological factors.

Seagrass ecosystems require low-energy hydraulic conditions, i.e. low waves and low current velocities. They need a considerable amount of sunlight and should be inundation at least 75% of the time. Although the reliability of seagrass beds as a direct coastal protection diminished fast with an increasing water depth, their contribution to the full ecosystem and its biodiversity can significantly increase the resilience of coastal communities against climate change.

J.6 Salt marshes

Salt marshes are upper-tidal coastal zones that are flooded regularly by sediment-rich seawater. They form a natural buffer zone between developed land and the sea during high water levels. Wave energy is dissipated when flowing over the vegetated salt marshes by which (storm) erosion rates and the risk of flooding can be decreased. Moreover, the vegetation can trap the suspended sediments of the seawater, thereby building up land and adapting to sea level rise to a certain extend.

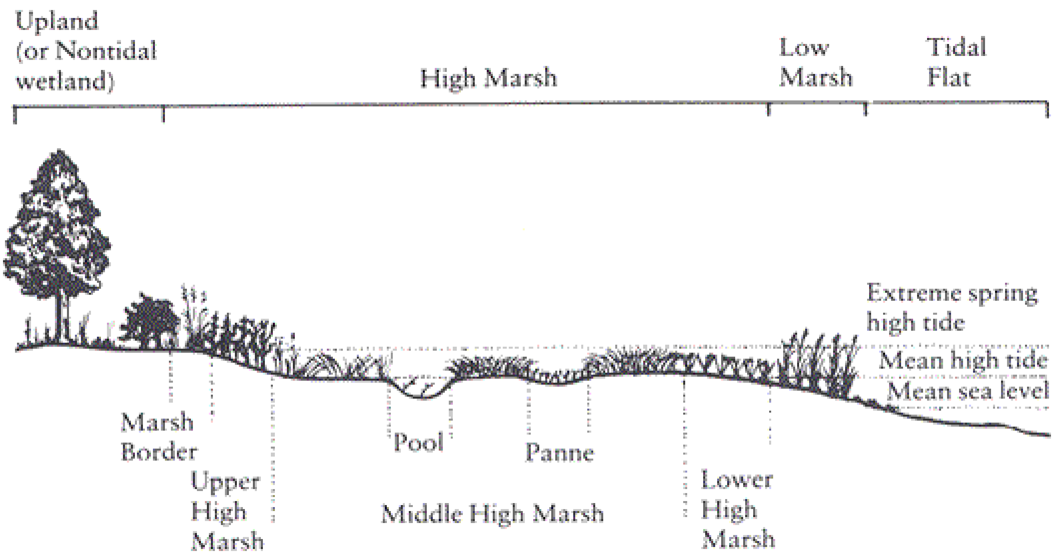

Figure 8-72: Schematic overview of a salt marsh (Ref [65])

Besides this direct impact on the safety of the coastal communities, salt marshes also increase the resilience against climate change impacts. They can enhance the water quality and provide food and nursery grounds for birds and specific forms of (sub-)marine life thereby increasing biodiversity. Beside this, salt marshes add natural carbon storage capacity and form an attractive landscape for recreational purposes.

Vertically, salt marshes generally extend from the Mean High Tide towards the yearly maximum water level. The adjacent sea should be energetic enough to bring in fine-grained suspended sediments, but not too energetic for the pioneer vegetation species to grow. Accretion rates should be equal or preferably higher than that the sea level rises. Sufficient suspended sediment should be available to ensure a sustainable salt marsh ecosystem.

K. SOFT SOLUTIONS

K.1 Beach nourishment

A beach nourishment can be applied to counteract coastal erosion by replenishing the eroded sand. This is often referred to as a soft solution, as a beach nourishment does not interfere with the natural longshore and cross-shore transport processes. A big advantage of this solution therefore is that it does not cause downdrift erosion or significant change in the coastal processes, which always occurs when hard solutions are applied.

The disadvantage is that if the shore is already subjected to structural erosion, this process will continue. Therefore, nourishments have to be repeated over time if they are not combined with 'hard' solutions. This requires long-term planning and management of funds, contracts and implementation of the works.

A nourishment can be applied on the beach or on the shoreface, as long as it is placed in the active zone of a coastal stretch. In both cases the replenished sand should have the approximate same grading of the sand that is originally present. It can be supplied from land by trucks or by dredging from an offshore borrow pit.

Regarding the coastal stretches of this project, beach nourishments are required to impose a direct stop to further land loss, to directly increase the safety against coastal flooding and to counteract sea level rise. However, without complementary 'hard interventions' the beach nourishments might disappear relatively fast, as highly energetic waves will keep attacking the Monrovian shoreline and a longshore sediment transport gradient will still be present. The magnitude of the erosion rates should determine if the nourishments need to be combined with hard structures.

Ecological landscaping

Often the sand for a beach nourishment is extracted from the seabed. During this process the local ecosystem will be disturbed. Several techniques are developed to minimize the environmental impact of this sand extraction. For example depth limitations can be prescribed, sand suctions systems are improved and specific extraction locations can be pointed out by the local authorities. A relative new technique called “ecological landscaping” is presented below.

For the traditional sand extraction methodology, the seabed is lowered over a certain area after which a relatively flat seabed remains. Generally this is bad for the local biodiversity (left picture of Figure 8-73). If sand is extracted according to the newly developed ecological landscaping principles, a seabed with small sand banks remains after the project is finished. These sandbanks enhance the local biodiversity and will induce a faster recovery of the local marine and benthic life (right picture of Figure 8-73).

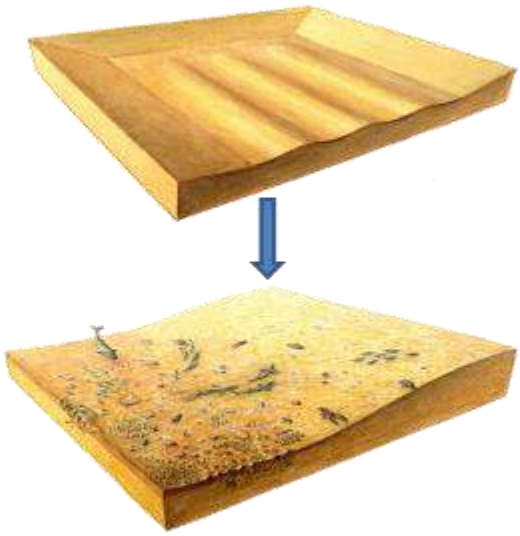

Figure 8-73: Traditional sand extraction method. Right: Ecological landscaping enhancing the local biodiversity

K.2 Sand engine

As stated earlier, a nourishment has to be repeated over time as it does not prevent erosion. Often long stretches of shore have to be nourished repeatedly within several years. The sand engine is developed in an attempt to optimise this nourishment process. Instead of nourishing a long coastal stretch, a very big nourishment is constructed at one location. The idea is that this sand will be distributed naturally towards the “upstream” beaches by the longshore current. In this way, nature itself will nourish the “upstream” beaches over time with the sand from the sand engine.

The first sand engine is constructed in 2011 near Kijkduin in the Netherlands. The development of the sand engine and the neighbouring shorelines are monitored frequently over the years. All information about this project can be found on the project website (Ref [66]).

Figure 8-74: Sand Engine near Kijkduin, the Netherlands (Ref [66])

K.3 Perched beach

A perched beach is an underwater sill that supports the beach at the seaward side. In this way a new equilibrium profile can be created artificially with a relatively short distance to the shore. Especially for steep beach profiles, a perched beach can safe a significant volume of sand that needs to be nourished to obtain and maintain a wide beach. The principle of the perched beach solution is visualised in Figure 8-75.

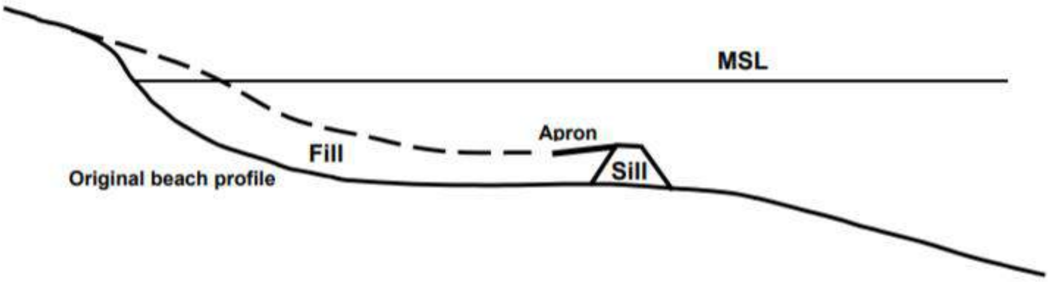

Figure 8-75: A new equilibrium beach profile can be created between the shoreline and the submerged sill, without nourishing the entire foreshore

Different from a submerged breakwater, the sill of a perched beach is deeply submerged and therefore does not force wave breaking. Earlier experiences show that generally the best result are obtained if the deeply submerged sill is attached to partly submerged groynes, creating a closed sediment cell. A disadvantage is that the submerged sill also blocks the natural onshore sediment transport during mild hydraulic conditions. On the long run, maintenance nourishments will be required.

An example where the perched beach solution is applied successfully is Pellestrina beach, in Italy, show in Figure 8-76.

Figure 8-76: Perched beach at Pellestrina beach (Italy)

K.4 Sand groynes

The basic idea is that a series of multiple groynes of sand (or sandy headlands) are build that function partly as a small sand engine and partly as a temporarily groyne. Over time the sand of the artificial headlands will be naturally distributed over the neighbouring coastal areas. The sand is kept longer inside the groyne system because the sandy structures (partly) block the longshore sediment transport. Not much is known yet about the efficiency of this experimental erosion mitigation measure. In 2009 a pilot project has been executed at the Delfland coast in the Netherlands. The findings of this project are described in Hoekstra et al. (2012 – Ref [67])

Figure 8-77: Sand groyne at Delfland, the Netherlands(Ref [67])

L. TRADITIONAL MEASURES

L.1 Groynes

Groynes are shore-normal structures that are commonly applied to reduce the longshore sediment transport. Depending on their length and design, groynes often allow for bypassing of the sand to reduce the downstream erosion caused by the structure. In that case, series of multiple groynes are needed to stabilize a coastal stretch. Nevertheless, it is also possible to opt for a long groyne that fully blocks the longshore sediment transport at a certain location. One should bear in mind that long impermeable groynes can cause very high downstream erosion rates.

Depending on the available and desirable sediment transport rate, the choice can be made between impermeable, high crested groynes or permeable, low crested structures. An example of an impermeable groyne is a linear structure of quarry stone, where a permeable groyne can be made of narrow spaced wooden piles.

Groynes are often applied to protect structural eroding shorelines against further erosion and to extend the lifetime of beach nourishments by fixating the replenished sand. Groynes are often combined with beach nourishments to increase the sediment quantity in a coastal system, and to assure a certain beach width for resilience against future sea level rise. Combined with beach nourishments, this type of structures is considered to be very suitable to reduce the exposure of Monrovia to sea level rise, structural land loss, and flooding events.

L.2 Detached (shore-parallel) breakwaters

A detached breakwater is a shore-parallel structure intended to force wave-breaking, thereby decreasing the wave energy that reaches a sandy shoreline. If designed well, this should lead to a decrease of the longshore sediment transport rate. A line of multiple detached breakwaters can therefore be used to mitigate structural erosion problems of a large coastal stretch.

There are several types of offshore breakwaters, which generally can be subdivided into emerged and submerged structures. The design of an emerged breakwater is more predictable than that of a submerged one, but also more expensive (larger structure) and has more impact on the aesthetics of a shoreline. The effectivity of a breakwater is depending on the structural height, tidal range, occurrence of storm surges, gap distance between breakwaters, distance to the shoreline, the availability of sediments etc. and therefore not straightforward. A badly designed breakwater can even cause increased erosion rates.

The most conventional type of detached breakwater is the rubble mound breakwater shown in the upper right picture. Other structures one can think of are caissons, geotubes and artificial reefs.

Not much is known yet about submerged breakwaters in the form of an artificial reef. Fact is that this type of wave-breaking structures are gaining popularity due to the ecological advantages they might come along with. An example of a reef breakwater made of Reef Balls is shown in the picture at the right. Note that it is a wide and continuous breakwater.

Breakwaters are interesting structures for all coastal sections of this project, as they can reduce both storm erosion and erosion due to a longshore transport gradient. Nevertheless, the water depth close to the shoreline increases rather fast, which is disadvantageous regarding the costs of effective wave-breaking structures. It might be possible to create additional benefits by opting for a submerged breakwater in the form of an artificial reef.

L.3 Revetment

Most commonly a revetment is constructed of quarry rock (rip-rap) or prefabricated concrete blocks to directly protect a sloping shoreline against cross-shore erosion. It can be a fast and effective solution to locally stop further land loss. Therefore, this hard intervention is especially suitable to (temporarily) protect important assets that are directly threatened by coastal erosion. Local revetments do cause increased erosion rates for the neighbouring unprotected land, which is an undesired side-effect. To stabilize a whole coastal stretch, a revetment has to be constructed over the full length of the shoreline. This will locally affect the cross-shore and alongshore transports; therefore increased erosion should be considered in the design. A revetment can further induce some inconveniences, for example it reduces the accessibility of the ocean for local fishermen.

In the design of a revetment long-term sea level rise can already be accounted for by simply heightening the protection. However, a revetment does not intervene with the longshore sediment transport, therefore lowering of the shoreface in front of the revetment can be expected if no additional interventions are taken. If present, a beach in front of a revetment is expected to disappear. For this reason, it is very important to place the revetment until a sufficient depth and include a falling toe apron or scour protection.

For this project, applying a revetment is considered an interesting intervention to locally protect important assets that are directly threatened by erosion. Furthermore, in front of Coastal stretch 2 currently already a rock revetment is being build. In this section a revetment could be considered functional, the revetment should then be continued along the whole stretch here.

L.4 Vertical Seawall

The principle of a seawall is similar to that of a revetment. The main difference is that the boundary between ocean and land is fixed by a (nearly) vertical structure. Examples are concrete (cantilever) walls, sheet pile walls or gravity block structures. This intervention can be very effective to locally protect the shoreline against erosion, but also has similar disadvantages as discussed for the coastal revetment. A further disadvantage is that incoming waves are almost fully reflected by the vertical face of the structure, locally increasing the wave disturbance and increasing scour depths.

Compared to a sloping revetment, the erosion in front of a seawall is larger as reflecting waves increase the local scour. In contradiction to damages to a revetment, damages to a seawall generally do not evolve over time. Failure of a seawall is often characterised by a sudden (partly) collapse of the structure. This increases the risk that severe damages occur without a warning or earlier observed degradation of the seawall. Especially regarding the structural erosion issues this can be dangerous, as the erosion will cause (invisible) lowering of the shoreface in front of the seawall. Wave reflection against the vertical wall might initiate even more scour, of which the total amount is hard to predict.

For this project, it is expected that only in Section 2 a seawall might be applied. However, a sloping revetment is currently considered more appropriate as cross-shore scour is expected to continue. In such situations a rubble mound structure is more resilient. Nonetheless, it is being kept as an option to be investigated further.

M. LABORATORY TESTS SEDIMENT SAMPLES

RPS

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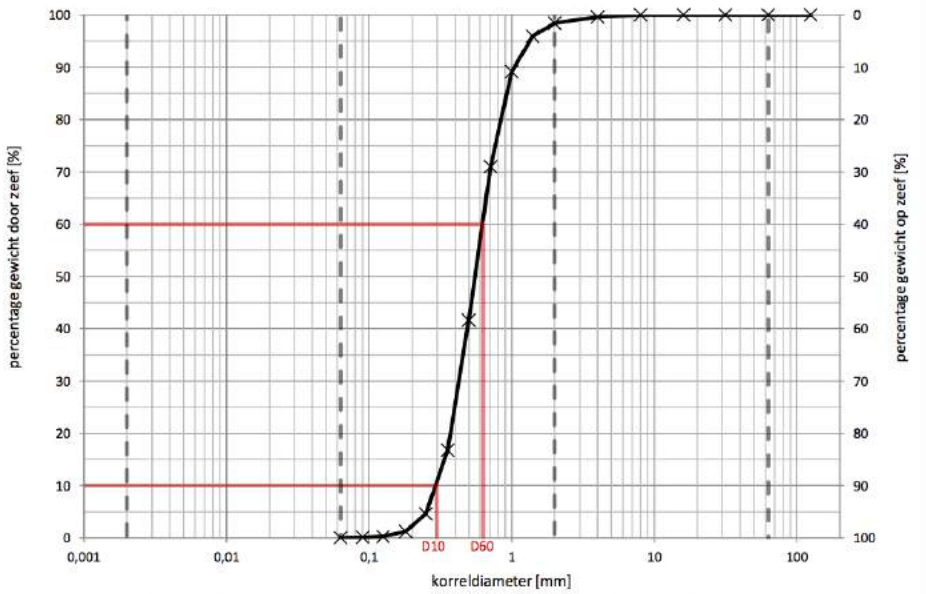
KORRELGROOTTEVERDELINGSDIAGRAM

inclusief humus, CaCO3 en Fe2O3

Project: B1804-07-LBR
Boring: -; monster: Beach 1 (HA) Hoog

boring	-	maaiveld NAP 0 m
monster	Beach 1 (HA) Hoog	
kleur	oranje	
bijzonderheden	-	
diepte	-	m tov mv



aereometerproef	
<0,063	-
<0,020	-
<0,002	-

zeefproef - percentage gewicht op zeef [%]			
2,0	1,6	C125	0,0
1,4	4,1	C63	0,0
1,0	10,8	C31,5	0,0
0,71	29,0	C16	0,0
0,5	58,4	C8	0,0
0,355	83,3	C4	0,4
0,25	95,4		
0,18	98,8		
0,125	99,7		
0,09	99,9		
0,063	100,0		

fracties	
grind (>2mm)	1,6%
zand (0,063 - 2 mm)	98,4%
silt (0,002 - 0,063 mm)	-
lutum (<0,002 mm)	-

kentallen	
D60/D10	2,13
D10	0,297
D60	0,632
M50 0,063 - 2 mm	0,55
D60/D10 0,063 - 2 mm	2,12

Geotechnische laboratoriumproeven
Project: B1804-07-LBR
Boring: -; monster: Beach 1 (HA) Hoog

Korrelgrootteverdelingsdiagram conform RAW 2015

datum	paraaf
7-12-2018	mr
project	versie
B1804-07-LBR	1.1.2
project-analyse	pagina
1811-3899	1

RPS analyse bv KvK 20059540, btw NL0089.00.620.B.01

Nederland | Engeland | Ierland | Rusland | Verenigde Staten | Canada | Australië | Zuidoost-Azië | Brazilië | Midden-Oosten | Afrika

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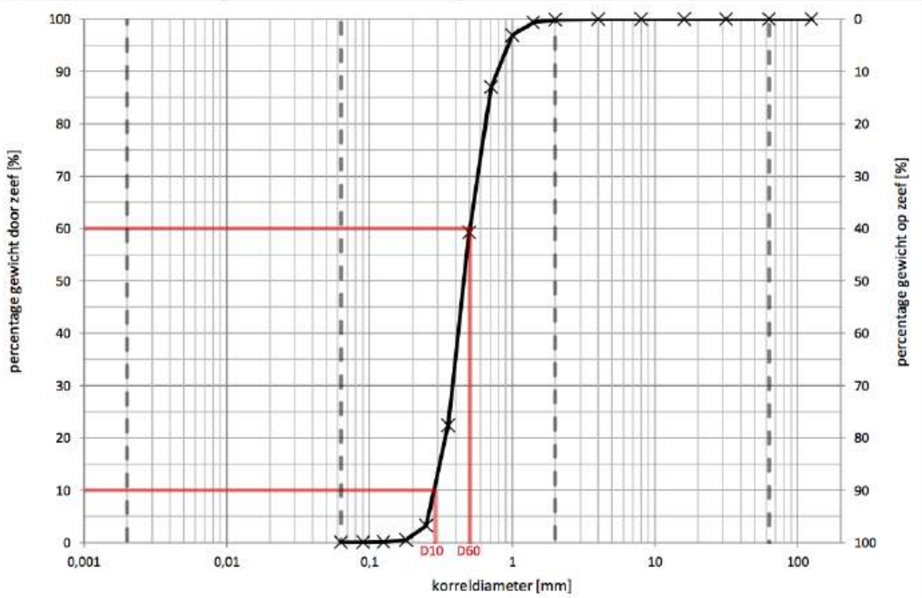
KORRELGROOTTEVERDELINGSDIAGRAM

inclusief humus, CaCO3 en Fe2O3

Project: B1804-07-LBR

Boring: -; monster: Beach 1 (HA) Branding (laag)

boring	-	maaiveld NAP 0 m
monster	Beach 1 (HA) Branding (laag)	
kleur	-	
bijzonderheden	oranje	
diepte	-	m tov mv



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<0,020	-
<0,002	-

zeefproef - percentage gewicht op zeef [%]			
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0,71	13,0	C16	0,0
0,5	40,8	C8	0,0
0,355	77,6	C4	0,0
0,25	96,8		
0,18	99,5		
0,125	99,9		
0,09	99,9		
0,063	100,0		

fracties	
grind (>2mm)	0,1%
zand (0,063 - 2 mm)	99,9%
silt (0,002 - 0,063 mm)	-
lutum (<0,002 mm)	-

kentallen	
D60/D10	1,76
D10	0,287
D60	0,506
M50 0,063 - 2 mm	0,46
D60/D10 0,063 - 2 mm	1,76

Geotechnische laboratoriumproeven
Project: B1804-07-LBR
Boring: -; monster: Beach 1 (HA) Branding (laag)

Korrelgrootteverdelingsdiagram conform RAW 2015

datum	paraaf
7-12-2018	mr
project	versie
B1804-07-LBR	1.1.2
project-analyse	pagina
1811-3899	1

RPS analyse bv KvK 20059540, btw NL0089.00.620.B.01

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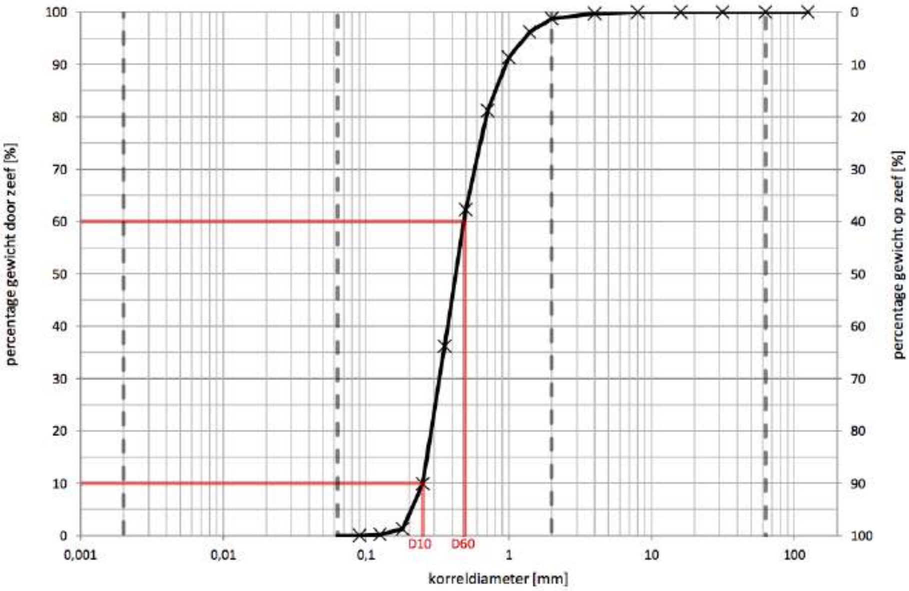
KORRELGROOTTEVERDELINGSDIAGRAM

inclusief humus, CaCO3 en Fe2O3

Project: B1804-07-LBR

Boring: -; monster: Beach 5 (JFK) Branding (laag)

boring	-	maaiveld NAP 0 m
monster	Beach 5 (JFK) Branding (laag)	
kleur	oranje	
bijzonderheden	-	
diepte	-	m tov mv



aereometerproef	
<0,063	-
<0,020	-
<0,002	-

zeefproef - percentage gewicht op zeef [%]			
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1,4	3,8	C63	0,0
1,0	8,7	C31,5	0,0
0,71	18,8	C16	0,0
0,5	37,8	C8	0,0
0,355	63,8	C4	0,3
0,25	90,1		
0,18	98,7		
0,125	99,8		
0,09	100,0		
0,063	100,0		

fracties	
grind (>2mm)	1,2%
zand (0,063 - 2 mm)	98,8%
silt (0,002 - 0,063 mm)	-
lutum (<0,002 mm)	-

kentallen	
D60/D10	1,95
D10	0,250
D60	0,488
M50 0,063 - 2 mm	0,43
D60/D10 0,063 - 2 mm	1,94

Geotechnische laboratoriumproeven
Project: B1804-07-LBR
Boring: -; monster: Beach 5 (JFK) Branding (laag)

Korrelgrootteverdelingsdiagram conform RAW 2015

datum	paraaf
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RPS analyse bv KvK 20059540, btw NL0089.00.620.B.01

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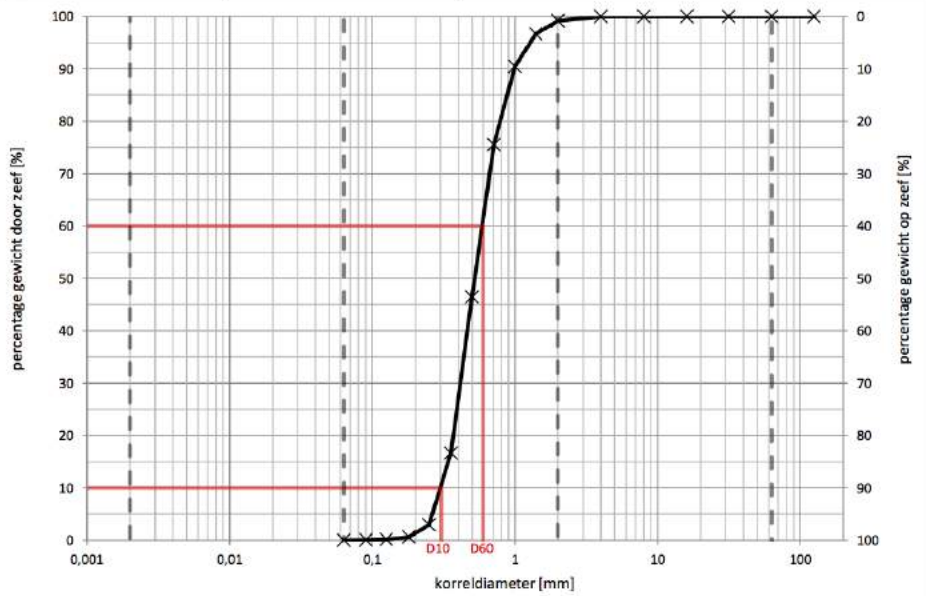
KORRELGROOTTEVERDELINGSDIAGRAM

inclusief humus, $CaCO_3$ en Fe_2O_3

Project: B1804-07-LBR
Boring: -; monster: Beach 5 (JFK) Hoog

boring	-	maaiveld NAP 0 m
monster	Beach 5 (JFK) Hoog	
kleur	oranje	
bijzonderheden	-	
diepte	-	m tov mv



aereometerproef	
<0,063	-
<0,020	-
<0,002	-

zeefproef - percentage gewicht op zeef [%]			
2,0	0,8	C125	0,0
1,4	3,3	C63	0,0
1,0	9,6	C31,5	0,0
0,71	24,5	C16	0,0
0,5	53,6	C8	0,0
0,355	83,4	C4	0,0
0,25	97,1		
0,18	99,4		
0,125	99,8		
0,09	99,9		
0,063	100,0		

fracties	
grind (>2mm)	0,8%
zand (0,063 - 2 mm)	99,2%
silt (0,002 - 0,063 mm)	-
lutum (<0,002 mm)	-

kentallen	
D60/D10	1,97
D10	0,304
D60	0,598
M50 0,063 - 2 mm	0,52
D60/D10 0,063 - 2 mm	1,96

Geotechnische laboratoriumproeven
Project: B1804-07-LBR
Boring: -; monster: Beach 5 (JFK) Hoog

Korrelgrootteverdelingsdiagram conform RAW 2015

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RPS analyse bv KvK 20059540, btw NL0089.00.620.B.01

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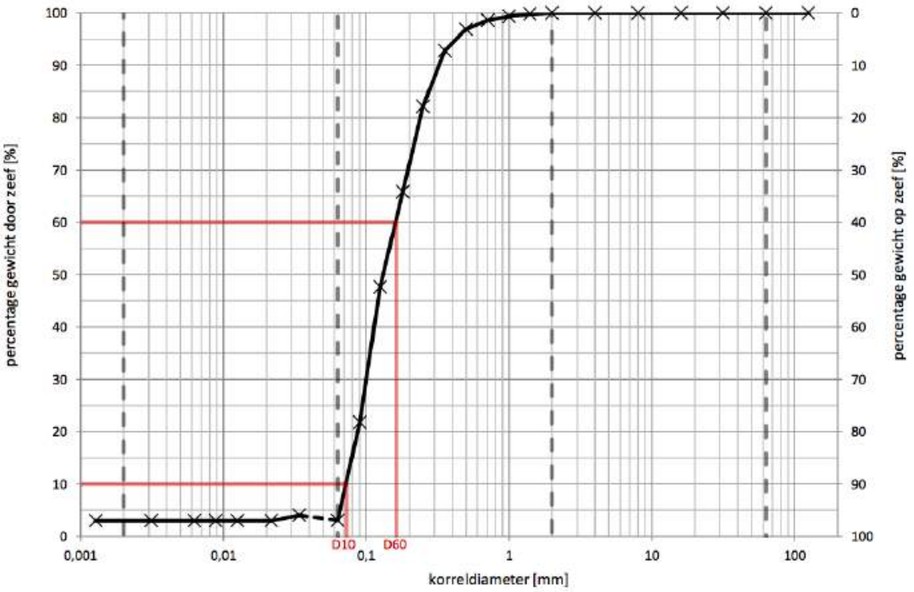
KORRELGROOTTEVERDELINGSDIAGRAM

inclusief humus, $CaCO_3$ en Fe_2O_3

Project: B1804-07-LBR
Boring: -; monster: Sample B1B (Offshore)

boring	-	maaiveld NAP 0 m
monster	Sample B1B (Offshore)	
kleur	grijs	
bijzonderheden	-	
diepte	-	m tov mv



aereometerproef	
<0,063	3,1
<0,020	3,0
<0,002	3,0

zeefproef - percentage gewicht op zeef [%]			
2,0	0,0	C125	0,0
1,4	0,2	C63	0,0
1,0	0,7	C31,5	0,0
0,71	1,4	C16	0,0
0,5	3,1	C8	0,0
0,355	7,2	C4	0,0
0,25	17,8		
0,18	34,2		
0,125	52,4		
0,09	78,2		
0,063	96,9		

fracties	
grind (>2mm)	0,0%
zand (0,063 - 2 mm)	96,9%
silt (0,002 - 0,063 mm)	0,1%
lutum (<0,002 mm)	3,0%

kentallen	
D60/D10	2,22
D10	0,073
D60	0,162
M50 0,063 - 2 mm	0,14
D60/D10 0,063 - 2 mm	2,16

Geotechnische laboratoriumproeven
Project: B1804-07-LBR
Boring: -; monster: Sample B1B (Offshore)

Korrelgrootteverdelingsdiagram conform RAW 2015

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RPS analyse bv KvK 20059540, btw NL0089.00.620.B.01

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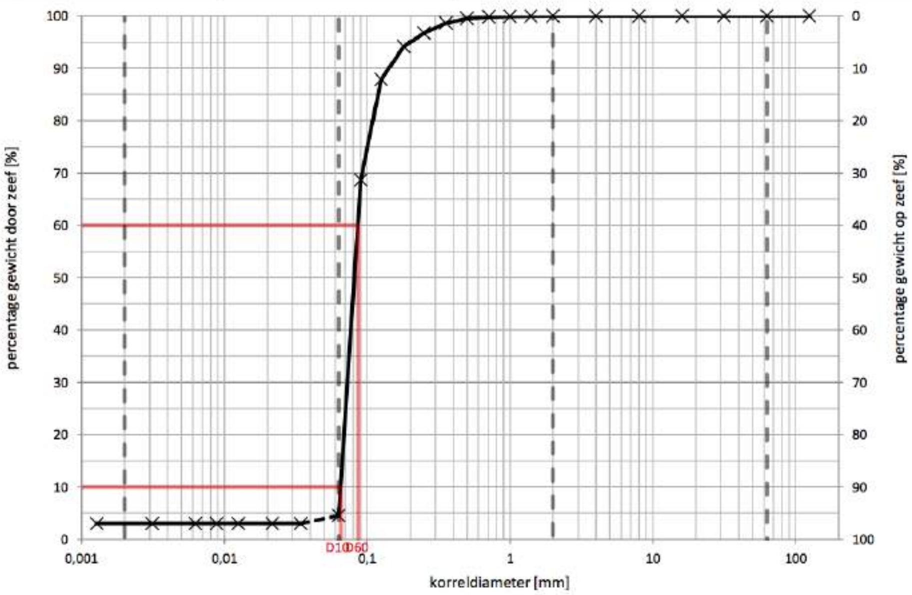
KORRELGROOTTEVERDELINGSDIAGRAM

inclusief humus, CaCO3 en Fe2O3

Project: B1804-07-LBR
Boring: -; monster: Sample B5B (Offshore)

boring	-	maaiveld NAP 0 m
monster	Sample B5B (Offshore)	
kleur	grijs	
bijzonderheden	-	
diepte	-	m tov mv



aereometerproef	
<0,063	4,5
<0,020	3,0
<0,002	3,0

zeefproef - percentage gewicht op zeef [%]			
2,0	0,0	C125	0,0
1,4	0,0	C63	0,0
1,0	0,1	C31,5	0,0
0,71	0,2	C16	0,0
0,5	0,5	C8	0,0
0,355	1,4	C4	0,0
0,25	3,3		
0,18	5,8		
0,125	12,1		
0,09	31,4		
0,063	95,5		

fracties	
grind (>2mm)	0,0%
zand (0,063 - 2 mm)	95,5%
silt (0,002 - 0,063 mm)	1,5%
lutum (<0,002 mm)	3,0%

kentallen	
D60/D10	1,32
D10	0,065
D60	0,086
M50 0,063 - 2 mm	0,08
D60/D10 0,063 - 2 mm	1,30

Geotechnische laboratoriumproeven
Project: B1804-07-LBR
Boring: -; monster: Sample B5B (Offshore)

Korrelgrootteverdelingsdiagram conform RAW 2015

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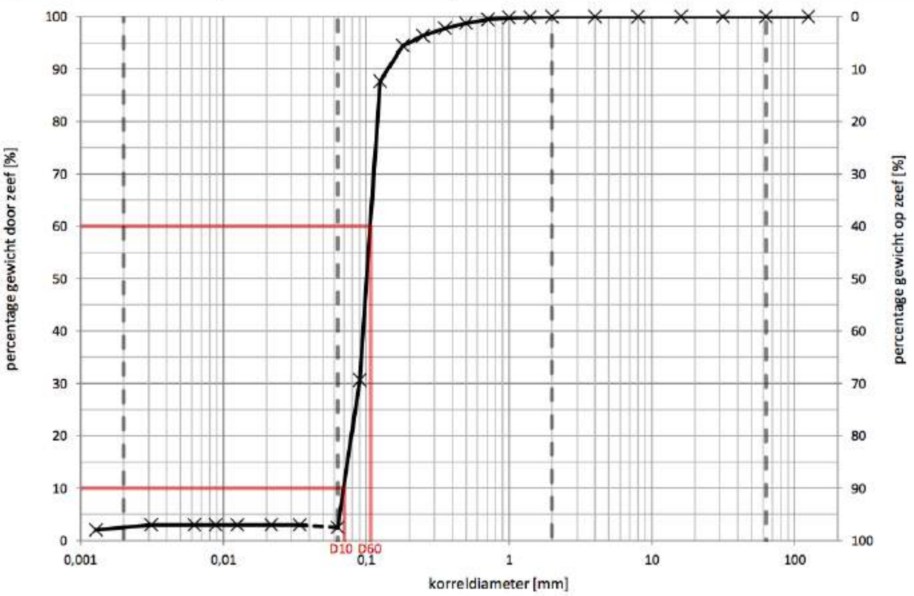
KORRELGROOTTEVERDELINGSDIAGRAM

inclusief humus, CaCO3 en Fe2O3

Project: B1804-07-LBR

Boring: -; monster: Sample B3A (Offshore)

boring	-	maaiveld NAP 0 m
monster	Sample B3A (Offshore)	
kleur	grijs	
bijzonderheden	-	
diepte	-	m tov mv



aereometerproef	
<0,063	2,5
<0,020	3,0
<0,002	2,4

zeefproef - percentage gewicht op zeef [%]			
2,0	0,0	C125	0,0
1,4	0,1	C63	0,0
1,0	0,2	C31,5	0,0
0,71	0,5	C16	0,0
0,5	1,2	C8	0,0
0,355	2,2	C4	0,0
0,25	3,6		
0,18	5,5		
0,125	12,3		
0,09	69,4		
0,063	97,5		

fracties	
grind (>2mm)	0,0%
zand (0,063 - 2 mm)	97,5%
silt (0,002 - 0,063 mm)	0,1%
lutum (<0,002 mm)	2,4%

kentallen	
D60/D10	1,54
D10	0,070
D60	0,108
M50 0,063 - 2 mm	0,10
D60/D10 0,063 - 2 mm	1,50

Geotechnische laboratoriumproeven
Project: B1804-07-LBR
Boring: -; monster: Sample B3A (Offshore)

Korrelgrootteverdelingsdiagram conform RAW 2015

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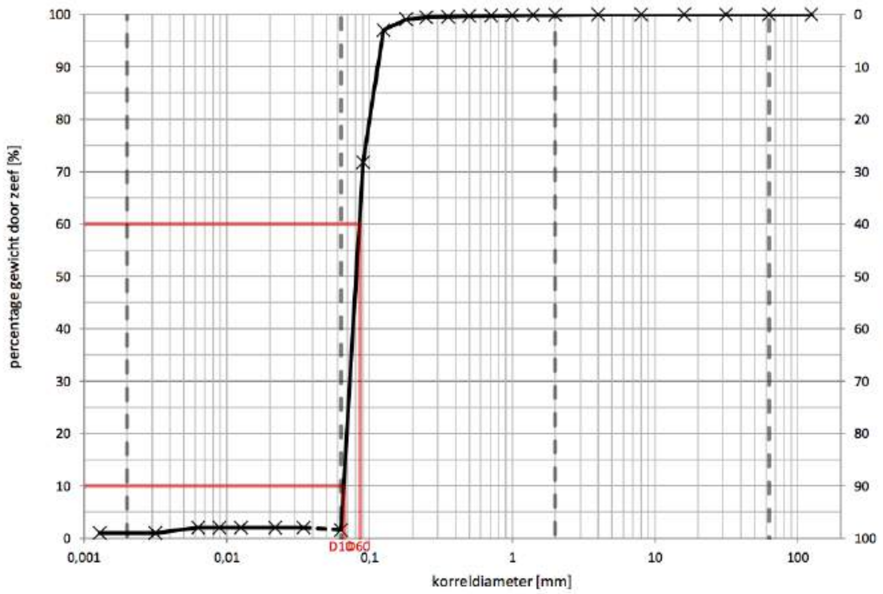
KORRELGROOTTEVERDELINGSDIAGRAM

inclusief humus, CaCO3 en Fe2O3

Project: B1804-07-LBR

Boring: -; monster: Sample B4B (Offshore)

boring	-	maaiveld NAP 0 m
monster	Sample B4B (Offshore)	
kleur	grijs	
bijzonderheden	-	
diepte	-	m tov mv



aereometerproef	
<0,063	1,6
<0,020	2,0
<0,002	1,0

zeefproef - percentage gewicht op zeef [%]			
2,0	0,1	C125	0,0
1,4	0,1	C63	0,0
1,0	0,1	C31,5	0,0
0,71	0,2	C16	0,0
0,5	0,3	C8	0,0
0,355	0,4	C4	0,0
0,25	0,5		
0,18	0,9		
0,125	3,0		
0,09	28,2		
0,063	96,4		

fracties	
grind (>2mm)	0,1%
zand (0,063 - 2 mm)	98,4%
silt (0,002 - 0,063 mm)	0,6%
lutum (<0,002 mm)	1,0%

kentallen		
D60/D10		1,29
D10		0,066
D60		0,085
M50	0,063 - 2 mm	0,08
D60/D10	0,063 - 2 mm	1,28

Geotechnische laboratoriumproeven
Project: B1804-07-LBR
Boring: -; monster: Sample B4B (Offshore)

Korrelgrootteverdelingsdiagram conform RAW 2015

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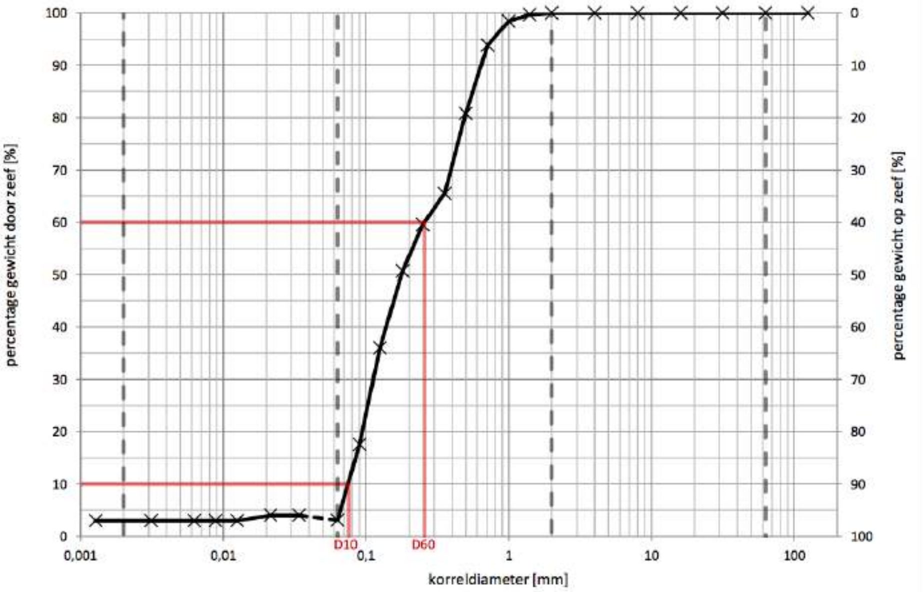
KORRELGROOTTEVERDELINGSDIAGRAM

inclusief humus, CaCO3 en Fe2O3

Project: B1804-07-LBR
Boring: -; monster: Sample B2C (Offshore)

boring	-	maaiveld NAP 0 m
monster	Sample B2C (Offshore)	
kleur	grijs	
bijzonderheden	-	
diepte	-	m tov mv



aereometerproef	
<0,063	3,1
<0,020	3,8
<0,002	3,0

zeefproef - percentage gewicht op zeef [%]			
2,0	0,0	C125	0,0
1,4	0,3	C63	0,0
1,0	1,6	C31,5	0,0
0,71	6,2	C16	0,0
0,5	19,2	C8	0,0
0,355	34,5	C4	0,0
0,25	40,4		
0,18	49,3		
0,125	64,0		
0,09	82,4		
0,063	96,9		

fracties	
grind (>2mm)	0,0%
zand (0,063 - 2 mm)	96,9%
silt (0,002 - 0,063 mm)	0,1%
lutum (<0,002 mm)	3,0%

kentallen		
D60/D10		3,39
D10		0,076
D60		0,258
M50	0,063 - 2 mm	0,19
D60/D10	0,063 - 2 mm	3,45

Geotechnische laboratoriumproeven
Project: B1804-07-LBR
Boring: -; monster: Sample B2C (Offshore)

Korrelgrootteverdelingsdiagram conform RAW 2015

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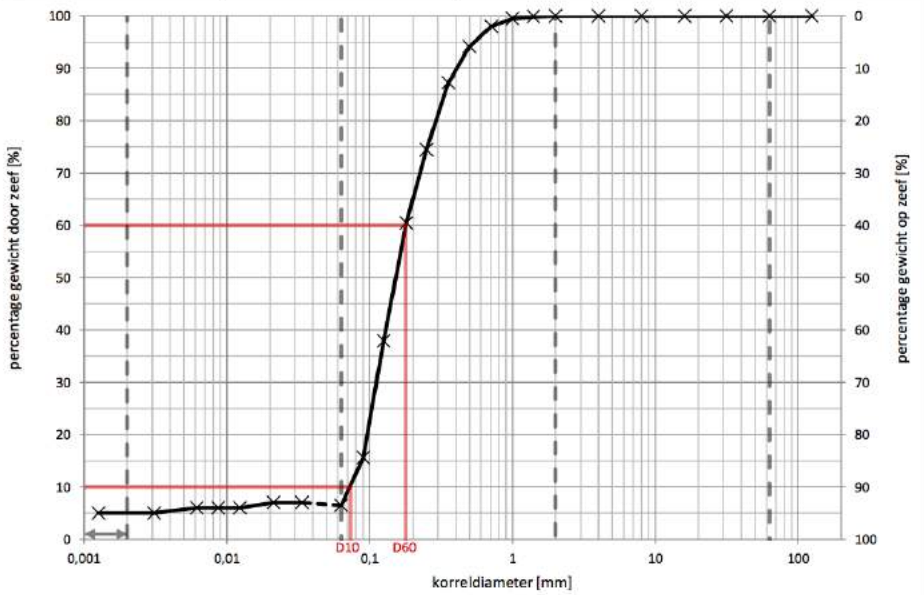
KORRELGROOTTEVERDELINGSDIAGRAM

inclusief humus, CaCO3 en Fe2O3

Project: B1804-07-LBR
Boring: -; monster: Sample LGN 2 (Mesurado river)

boring	-	maaiveld NAP 0 m
monster	Sample LGN 2 (Mesurado river)	
kleur	-	
bijzonderheden	-	
diepte	-	m tov mv



aereometerproef	
<0,063	6,5
<0,020	6,9
<0,002	5,0

zeefproef - percentage gewicht op zeef [%]			
2,0	0,0	C125	0,0
1,4	0,1	C63	0,0
1,0	0,5	C31,5	0,0
0,71	2,0	C16	0,0
0,5	5,8	C8	0,0
0,355	12,8	C4	0,0
0,25	25,5		
0,18	39,5		
0,125	62,1		
0,09	84,4		
0,063	93,5		

fracties	
grind (>2mm)	0,0%
zand (0,063 - 2 mm)	93,5%
silt (0,002 - 0,063 mm)	1,5%
lutum (<0,002 mm)	5,0%

kentallen		
D60/D10		2,44
D10		0,073
D60		0,179
M50	0,063 - 2 mm	0,16
D60/D10	0,063 - 2 mm	2,11

Geotechnische laboratoriumproeven
Project: B1804-07-LBR
Boring: -; monster: Sample LGN 2 (Mesurado river)

Korrelgrootteverdelingsdiagram conform RAW 2015

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RPS analyse bv KvK 20059540, btw NL0089.00.620.B.01

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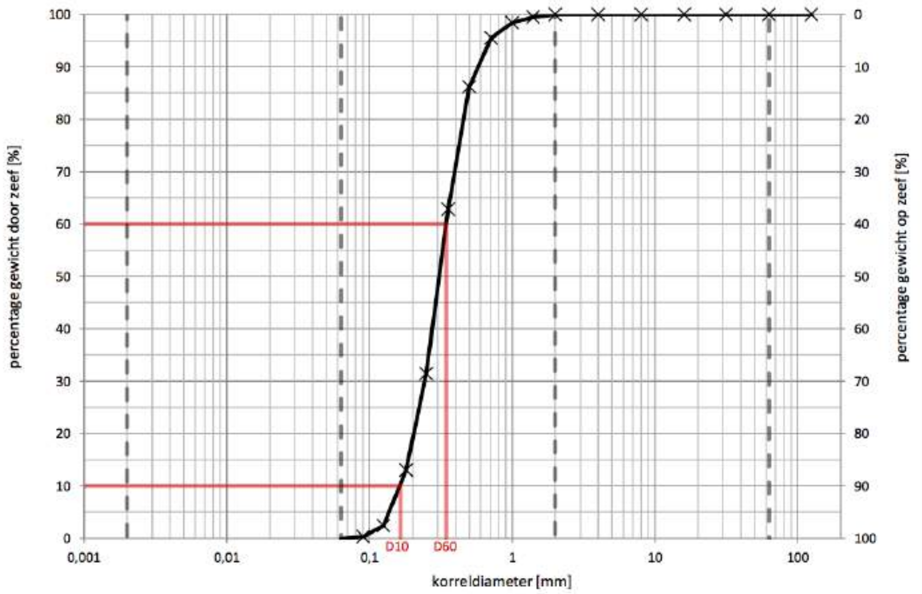
KORRELGROOTTEVERDELINGSDIAGRAM
inclusief humus, CaCO3 en Fe2O3

Project: B1804-07-LBR
Boring: -; monster: Sample LGN 1 (Mesurado river)

boring	-	maaiveld NAP 0 m
monster	Sample LGN 1 (Mesurado river)	
kleur	oranje	
bijzonderheden	-	
diepte	-	m tov mv



aereometerproef	
<0,063	-
<0,020	-
<0,002	-

zeefproef - percentage gewicht op zeef [%]			
2,0	0,0	C125	0,0
1,4	0,5	C63	0,0
1,0	1,6	C31,5	0,0
0,71	4,5	C16	0,0
0,5	13,8	C8	0,0
0,355	37,2	C4	0,0
0,25	68,6		
0,18	87,0		
0,125	97,6		
0,09	99,7		
0,063	100,0		

fracties	
grind (>2mm)	0,0%
zand (0,063 - 2 mm)	100,0%
silt (0,002 - 0,063 mm)	-
lutum (<0,002 mm)	-

kentallen		
D60/D10		2,10
D10		0,165
D60		0,346
M50	0,063 - 2 mm	0,31
D60/D10	0,063 - 2 mm	2,10

Geotechnische laboratoriumproeven Project: B1804-07-LBR Boring: -; monster: Sample LGN 1 (Mesurado river)	datum 7-12-2018	paraaf mr
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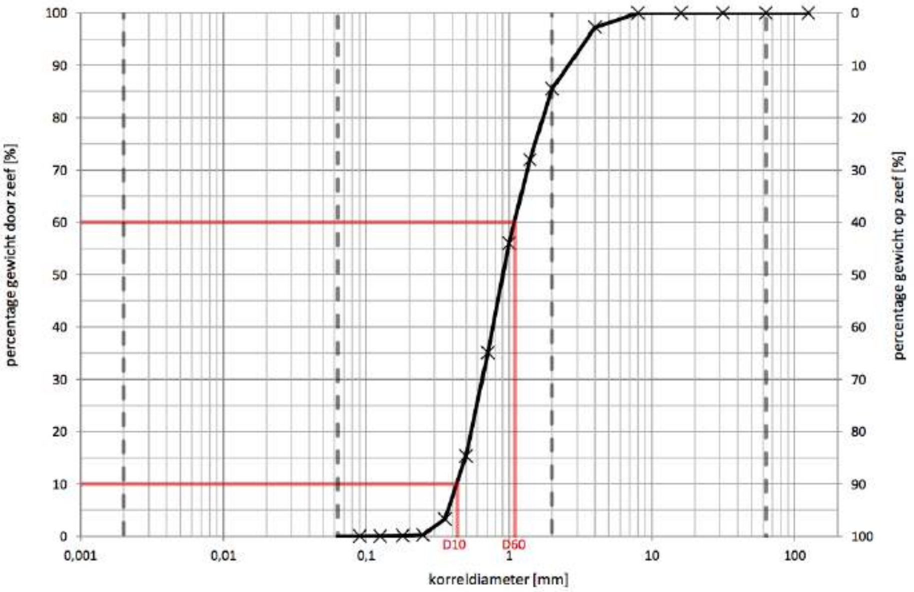
KORRELGROOTTEVERDELINGSDIAGRAM

inclusief humus, CaCO3 en Fe2O3

Project: B1804-07-LBR
Boring: -; monster: Sample River 3 (St. Paul river)

boring	-	maaiveld NAP 0 m
monster	Sample River 3 (St. Paul river)	
kleur	-	
bijzonderheden	oranje	
diepte	-	m tov mv



aereometerproef	
<0,063	-
<0,020	-
<0,002	-

zeefproef - percentage gewicht op zeef [%]			
2,0	14,5	C125	0,0
1,4	28,0	C63	0,0
1,0	44,0	C31,5	0,0
0,71	64,9	C16	0,0
0,5	84,7	C8	0,0
0,355	96,7	C4	2,8
0,25	99,7		
0,18	99,9		
0,125	100,0		
0,09	100,0		
0,063	100,0		

fracties	
grind (>2mm)	14,5%
zand (0,063 - 2 mm)	85,5%
silt (0,002 - 0,063 mm)	-
lutum (<0,002 mm)	-

kentallen		
D60/D10		2,52
D10		0,436
D60		1,100
M50	0,063 - 2 mm	0,82
D60/D10	0,063 - 2 mm	2,23

Geotechnische laboratoriumproeven Project: B1804-07-LBR Boring: -; monster: Sample River 3 (St. Paul river)	datum 7-12-2018	paraaf mr
	project B1804-07-LBR	versie 1.1.2
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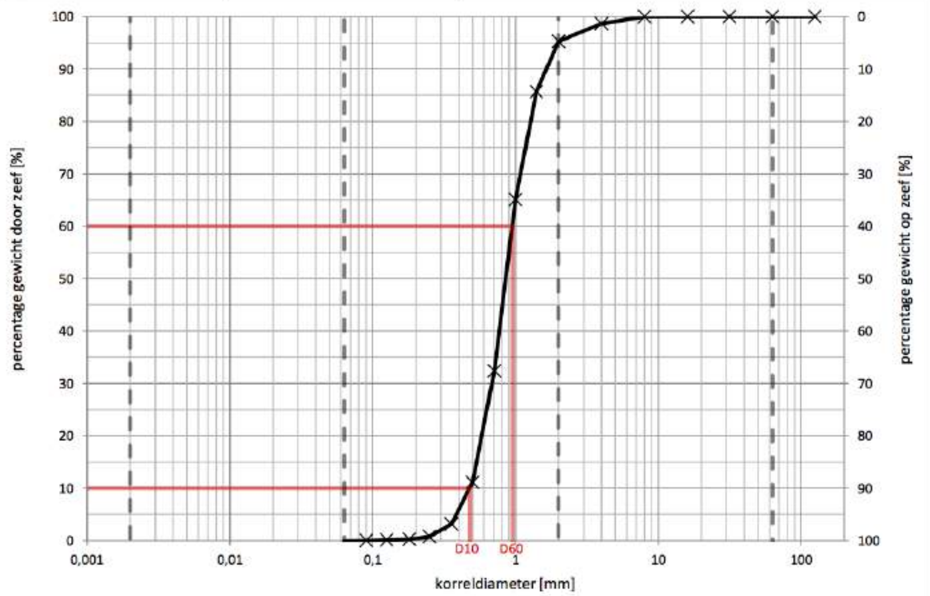
KORRELGROOTTEVERDELINGSDIAGRAM

inclusief humus, CaCO3 en Fe2O3

Project: B1804-07-LBR
Boring: -; monster: Sample river 1A (St. Paul river)

boring	-	maaiveld NAP 0 m
monster	Sample river 1A (St. Paul river)	
kleur	oranje	
bijzonderheden	-	
diepte	-	m tov mv



aereometerproef	
<0,063	-
<0,020	-
<0,002	-

zeefproef - percentage gewicht op zeef [%]			
2,0	4,7	C125	0,0
1,4	14,3	C63	0,0
1,0	34,9	C31,5	0,0
0,71	67,6	C16	0,0
0,5	88,9	C8	0,0
0,355	96,9	C4	1,3
0,25	99,2		
0,18	99,7		
0,125	99,9		
0,09	100,0		
0,063	100,0		

fracties	
grind (>2mm)	4,7%
zand (0,063 - 2 mm)	95,3%
silt (0,002 - 0,063 mm)	-
lutum (<0,002 mm)	-

kentallen	
D60/D10	1,99
D10	0,480
D60	0,955
M50 0,063 - 2 mm	0,85
D60/D10 0,063 - 2 mm	1,97

Geotechnische laboratoriumproeven
Project: B1804-07-LBR
Boring: -; monster: Sample river 1A (St. Paul river)

Korrelgrootteverdelingsdiagram conform RAW 2015

datum	paraaf
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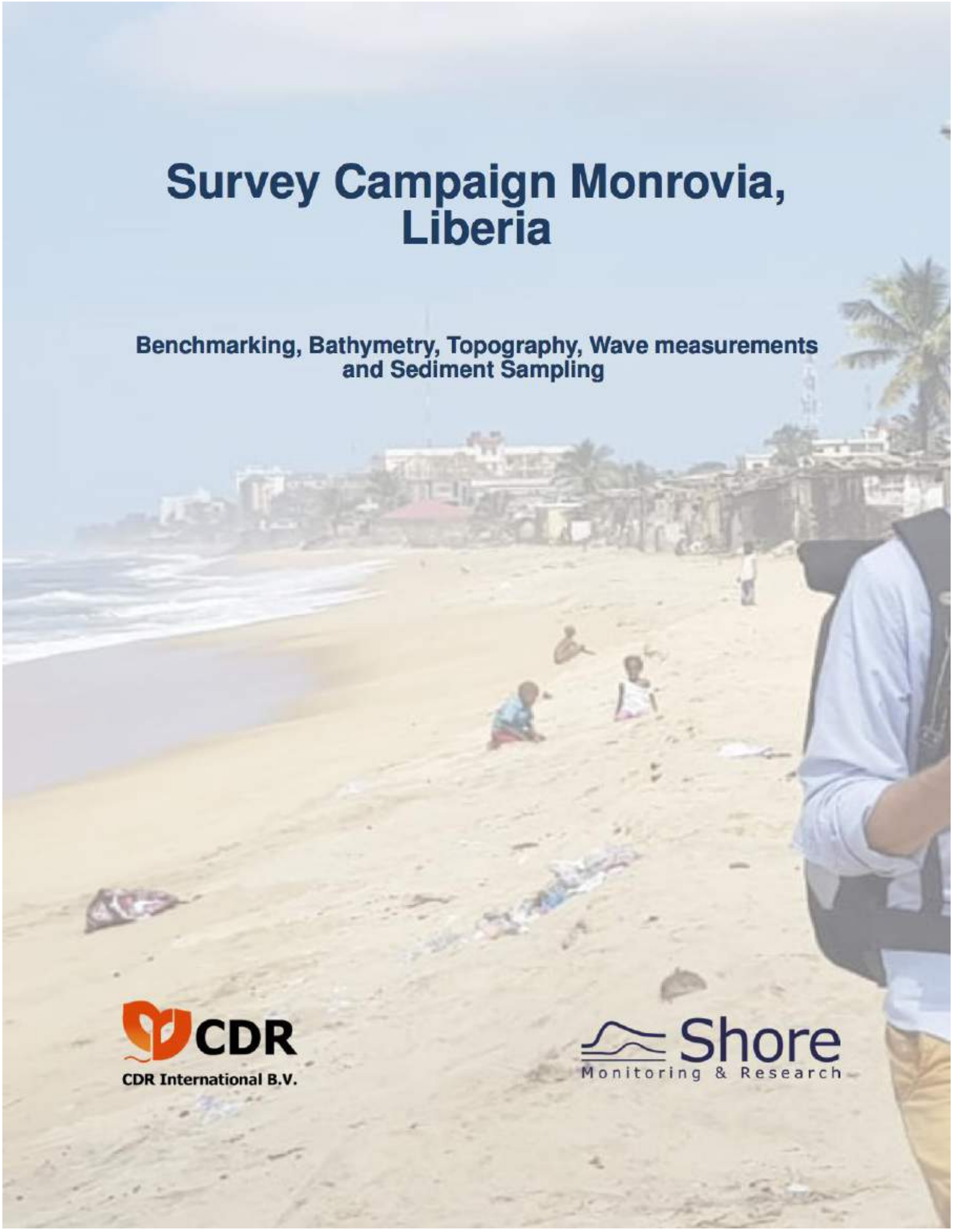
N. SURVEY REPORT – SHORE MONITORING



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Field Report

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Project: Survey Campaign Monrovia, Liberia
Subject: Field Report
Field campaign: 12 - 26 October 2018
Author: F.J.H. Gulden MSc
Internal reviewer: R.C. de Zeeuw MSc
Reference: W201809-03
Version: November 1, 2018

Contents

1 Introduction

1.1 Background

In the beginning of October, 2018, Shore Monitoring & Research BV (herafter: SHORE), has been commissioned by CDR-International (hereafter: CDR), for a comprehensive survey campaign around Monrovia, Liberia. After a short preparation period SHORE mobilised a team of 2 surveyors and the necessary equipment on October 12th and started with the first measurment on October 12th. After a campaign of two weeks the survey team arrived back in the Netherlands on October 27th.

The initial scope involved the following survey activities:

- Creation of RTK-GNSS benchmark.
- Bathymetric survey in front of 5 beaches (sea).
- Topographic survey of 5 beaches.
- Bathymetric survey of a lagoon.
- Wave buoy deployment, measurements and retrieval.
- Sediment sampling (grab samples with Van Veen grabber), from a vessel on the sea.

During the course of the field campaign, this scope was extended with:

- Measuring existing benchmarks in the harbour created by Bam International BV, during a previous project.
- Determining the vertical clearance height of bridges on the river.
- Determining typical elevation of Balli island.

The 'outside' acquired data (i.e. bathymetry & topography of 5 beaches, wave buoy and sediment sampling) will be used for further hydraulic modelling and ultimately design of possible interventions of the 5 beaches. The bathymetric survey of the lagoon, determination of vertical clearance height of bridges and determination of the elevation of Balli island have been carried out in the context of inland navigability. The creation of a new benchmark and measuring of existing benchmarks is to respectively ensure the quality of referencing of the SHORE survey and subsequently be able to relate the SHORE survey data to previously executed works.

1.2 Project location and survey area

The survey campaign has been performed on several locations in and around the city of Monrovia in Liberia (Fig. 1.1). The names introduced in Fig. 1.1 will be used to indicate the geographical locations corresponding to the results presented in chapter 3.

Figure 1.1: Indication of survey area. The red lines correspond to the bathymetric/topographic beach surveys. The green line corresponds to the lagoon/river survey, whereas also the locations of bridges and Balli island are shown. The wave buoy and sediment sample locations will be indicated in the designated sections in chapter 2.

The next chapters of this report treat the following aspects:

- Description survey equipment and followed methodology (chapter 2)
- Results of carried out survey activities (chapter 3)
- Relevant observations done by the surveyors during the field activities (chapter 4

2 Methodology

2.1 Introduction

This section will elaborate on the followed methodology during the field activities and subsequent processing. First, the used coordinate system will be introduced and explained (2.2). Next, the detailed survey and processing methodology will be treated (2.3).

2.2 Coordinate system

Details of the coordinate system used for this survey and delivered results are listed in Tab. 2.1

Table 2.1: Coordinate System

Parameter:	Value:
Horizontal Datum:	WGS84 UTM 29 N
EPSG code:	32629
SPHEROID:	WGS84
PROJECTION:	UTM
Unit:	metre
Vertical Datum:	CD

2.3 Details of methodology

The field campaign included the following survey activities:

- Creation of RTK-GNSS benchmark
- Bathymetric survey
- Topographic survey
- WaveDroid deployment
- Sediment samples
- Determination of vertical clearance height bridges

The details of these activities will be treated separately in subsections 2.3.1 - 2.3.6.

2.3.1 Creation of RTK-GNSS benchmark

Clear documentation of the horizontal and vertical reference system of field measurements is very important to obtain generically useful data for any party that might be using it. Most often, (some) local data is available, though without a clear and reliable description of the referencing to horizontal and vertical reference systems. Hence, SHORE created a new benchmark.

The benchmark has been created on the first day of the campaign on the roof of the office of Earthtime centrally located in the survey area (Fig. 2.1 left panel). The benchmark was created using a Leica GNSS receiver on a tripod, positioned above a survey bolt that was drilled and marked into the concrete roof (Fig. 2.1 right panel).

Figure 2.1: Creation of new benchmark. Left panel: Location of benchmark. Right panel: survey bolt drilled into concrete (annotation 1). Tripod with RTK-GNSS positioned above the bolt (annotation 2). Extended radio antenna to increase the area where RTK-GNSS corrections can be received (annotation 3). Leica RTK-GNSS; logging raw observations during creation of benchmark, lateron used as basestation (annotation 4).

The Leica GNSS receiver has been logging raw observations for at least 12 hours. Raw observations were processed using AUSPOS GPS data processing. The final coordinates of the created benchmark are shown in Tab. 2.2 below:

Table 2.2: Coordinates created benchmark at roof of Earthtime in WGS84 UTM 29 N projection

Point ID:	Easting (m)	Northing (m)	WGS84 ellipsoid (m)
Benchmark Earthtime	300863.3939	699941.8623	50.196

During subsequent days, a base station has been set up above the benchmark, sending RTK corrections to the rovers in the field. Next to the newly created benchmark, the existing benchmarks of BAM International BV have been measured with a similar procedure although the GNSS receiver has been logging raw observations for 10 minutes instead of 12 hours.

2.3.2 Bathymetric survey

The used bathymetric survey system is a combination of multiple instruments that together form a modular survey kit that can be used on a variety of vessels. The modular character of the system increases the flexibility as the type of vessel can be selected based on specific local conditions and is not restricted to fixed setups.

During the field campaign the survey system has been used in combination with a jetski (Fig. 2.2) to be able to enter the shallow near shore and have increased manoeuvrability in between waves to survey the bathymetry in front of the beaches. The lagoon/river survey has been performed with the system and a local wooden boat. First the details of the survey system will be explained. The set up of the survey system on the local jetski and boat will be presented thereafter.

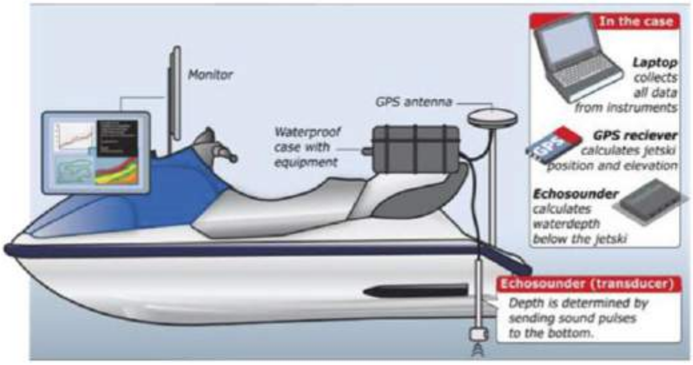

Figure 2.2: The instrument setup for a bathymetric survey. Example of deployment on a jetski

Details survey system

The water depth under the jetski is measured with a Hydrobox Single Beam Echo Sounder (SBES, frequency 10 Hz). The SBES sends sound pulses towards the bottom which reflect and are received back by the SBES sounder. From the time between sending and receiving a pulse and the speed of sound through water, the water depth under the echo sounder can be determined.

The speed of sound through water varies based on differences in water temperature and salinity. Therefore, CTD-measurements are performed multiple times during a survey to collect the necessary information. Locations of CTD-measurements are carefully selected, based on expected spatial gradients in the speed of sound among the surveyed area.

The survey system is equipped with a motion sensor to log movement (pitch / roll) of the jetski. The logged movements are used to correct/reject the depth measurements for pitch and roll. For further details reference is made to Appendix A.2.1.

A dual frequency (L1/L2) RTK GPS and GLONASS (GNSS) receiver with real time radio/GPRS/3G connection with a GNSS base station has been used. Its antenna is placed in one vertical axis with the SBES transducer of which the offset is measured carefully before deployment of the survey system on a 'new' vessel. The GNSS receiver logs the X,Y,Z position of the jetski at 2 Hz. RTK technique is used to obtain centimetre positional accuracy.

The latency between the instruments is calculated from the correlation between the time series of the jetski's GPS elevation and the sounding depths below the jetski. The presence of waves results in vertical movement (heave) in the jetski elevation, which is reflected in an equal variation in the depth measured below the jetski. The time shift to correlate maxima of both signals is the resulting latency, with which the sounding depths are corrected. For further details reference is made to Appendix A.2.2.

The final measurement of the elevation of the bed level is then obtained from the elevation of the GNSS (z_{GNSS}) subtracted with the vertical offset between the GNSS antenna and SBES (z_{offset}) and the depth measured by the SBES (d):

$$z_{bedlevel} = z_{GNSS} - z_{offset} - d \tag{2.1}$$

The above is illustrated in Fig. 2.3 below.

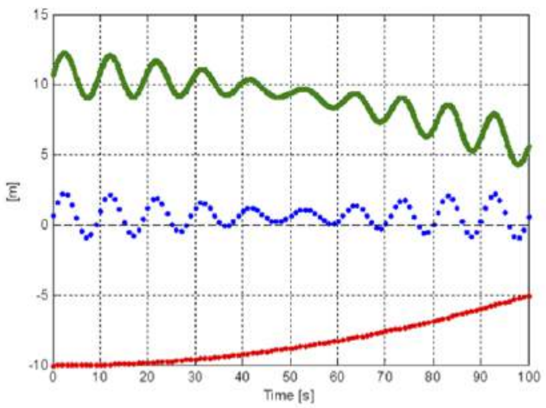

Figure 2.3: Calculation of the bed level. The green line shows the 10 Hz measurements of depth under the SBES. The blue points correspond to the 2 Hz RTK-GPS elevation of the jetski *at the bottom of the SBES* ($z_{GNSS} - z_{offset}$). The resulting bottom level (2 Hz) is obtained by subtracting both signals and is shown in red.

Details of the instruments of the survey system are summarized in Tab. 2.3 below:

Table 2.3: Overview of instruments and corresponding accuracy used for bathymetric survey. The accuracy is based on the manufacturer's declaration.

Instrument:	Brand and type:	Accuracy:
SBES	Syqwest Hydrobox 210kHz	$\pm$ 0.01 m +/- 1% depth
RTK-GNSS	Leica GX1230GG	$\pm$ 2 cm + 1 mm/km
Speed of sound sensor	YSI Castaway CTD	$\pm$ 0.15m/s
Motion sensor	Xsens MTi 300 AHRS	Gyro bias stability 10°/h, Roll/Pitch 0.2°, Yaw 1.0°

The survey system is completed with a wireless monitor kit and waterproof case containing hardware and a rugged laptop which collects and visualises the survey data real-time. The monitor shows the operator all data needed for a safe, accurate and effective survey: real-time sensor status, speed, position, depth, GNSS statistics, survey tracks, sailed tracks, background drawings etc.

Local setup and execution of survey

The survey system has been used in combination with a locally rented jetski and a locally rented wooden boat. Both setups are treated separately below:

Setup in combination with jetski

For surveying the beach locations, the survey system was mounted on a locally rented jetski (Fig. 2.4). With this setup it was possible to survey the cross-shore transects to relatively shallow area's compared to regular survey setups with for instance a boat. The jetski offers the manoeuvrability to survey in the shallow surf zone, whereas the skilled surveyors of SHORE are trained on reading the waves and identifying critical situations in time.

Figure 2.4: Instrument setup modular SBES system on local jetski. RTK-GNSS antenna (annotation A), SBES (annotation B) and survey kit (annotation C).

The jetski survey plan contained cross shore transects with an approximate spacing of 50 meters and offshore extension till the -10m water depth contour. In case the surveyors observed interesting featurs (e.g. gullies), additional data has been acquired.

Setup in combination with local boat

During the lagoon/river survey, the system was mounted a locally rented boat (Fig. 2.5, right). The SBES transducer and GNSS antenna were mounted on the side of the vessel as shown in Fig. 2.5 (left and middle).

Figure 2.5: Instrument setup modular SBES system on local boat.

Fig. 1.1 indicates the centre line of the surveyed lagoon/river sections. Perpendicular to this line, cross shore transects have been surveyed with an approximate spacing of 100 meters.

For both the jetski and the boat survey, the GNSS and SBES data has been post-processed on a daily basis to monitor quality and progress of the survey. Data processing follows a strict procedure:

1. Automatic filtering and cleaning of sounding depths
2. Manual inspection of the filtered sounding depths
3. Latency inspection and correction
4. Correcting sounding depths with measured speed of sound
5. Rejecting sounding depths based on motion sensor data
6. Correcting vertical offset GNSS and SBES
7. Post processing of vessel GNSS positions with local base station data
8. Filtering/rejection of non-RTK fixed positions
9. Combining only RTK fixed positions with cleaned echosounder signal
10. Converting WGS84 Lat, Lon to UTM Easting and Northing coordinates (site specific)
11. Inspection of bed level elevation at crossings of the survey paths
12. Visualization of survey points in GIS or Google Earth
13. Writing ascii file containing all points that passed the post processing and quality control procedure (X/Easting (m); Y/Northing (m); Z/elevation (m) w.r.t. a generic reference level (WGS84 ellipsoid, CD, etc.)

Reference is made to Appendix A for more details on the above steps.

2.3.3 Topographic survey

Next to the bathymetric survey, the topography of the beach areas has been surveyed with RTK-GNSS. Hereto, the surveyor was equipped with a RTK-GNSS in a back pack after which he walked cross shore transects with an approximate spacing of 50 meters over the beaches of interest (Fig. 2.6 right panel). The vertical offset between GPS-antenna and the ground has been measured before and after every survey (Fig. 2.6 left panel) and has been taken into account during processing.

Figure 2.6: Topographic survey. Left panel: measuring vertical offset between GPS antenna reference point and ground. Right panel: surveyor walking on the beach.

The topographic survey has been carried out with Leica GS10 and 1200 RTK-GNSS devices. The specifications of these instruments are presented in Tab. 2.4 below:

Table 2.4: Overview of instruments and corresponding accuracy used for topographic survey. The accuracy is based on the manufacturer's declaration.

Instrument:	Brand and type:	Accuracy:
RTK-GNSS	Leica GX1230GG	$\pm$ 2 cm + 1 mm/km
RTK-GNSS	Leica GS10	$\pm$ 2 cm + 1 mm/km

As for the bathymetric data, the topographic data has been evaluated everyday to ensure data quality and progress. Data processing of the topographic data involves the following steps:

1. Correcting vertical offset GNSS antenna reference point and ground
2. Post processing of GNSS positions with local base station data
3. Filtering/rejection of non-RTK fixed positions
4. Converting WGS84 Lat, Lon to UTM Easting and Northing coordinates (site specific)
5. Visualization of survey points in GIS or Google Earth
6. Writing ascii file containing all points that passed the post processing and quality control procedure (X/Easting (m); Y/Northing (m); Z/elevation (m) w.r.t. a generic reference level (WGS84 ellipsoid, CD, etc.)

The elevation of Balli island has also been determined by a surveyor who walked over the island with a RTK-GNSS on his back.

2.3.4 WaveDroid deployment and retrieval

WaveDroids have been deployed on the two locations indicated in Fig. 2.7 below.

Figure 2.7: WaveDroid deployment. Left panel: Indication of WaveDroids. WaveDroid1 in front of the JFK Hospital beach and WaveDroid2 in the vicinity of the Hotel Africa and New Kru Town beaches. Right panel: Deployed WaveDroid1.

Before installation, the electronic compass of the WaveDroids has been calibrated according to the manual provided by the manufacturer[1]. Hereto, the buoy has been taken outside in an area that is free of magnetic disturbances (i.e. away of large metal objects). Subsequently, a 30 minute WaveDroid measurement has been started and the buoy has been rotated gently around its vertical axis for at least 2 minutes.

After the 30 minutes have passed, the raw data files have been loaded from the SD-card and uploaded to the WaveDroid Data Portal. Here, the compass calibration parameters are determined automatically and the results have been downloaded. To verify that the calibration was successful, it has been checked if the fitted circle matches the data points which is clearly the case (Fig. 2.8).

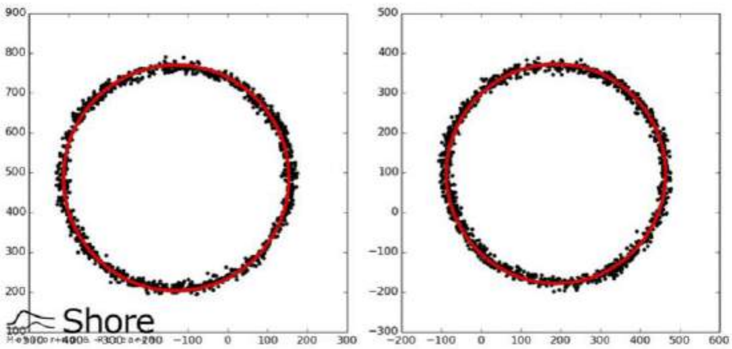

Figure 2.8: WaveDroid calibration. Left panel: Calibration WaveDroid1. Right panel: Calibration WaveDroid2.

Although the above calibration figures look alright, the calibration has been re-done after the survey

[1]Document: *'WaveDroid_Manual_Block3_v5.pdf'* section: *'6. Calibrating the electronic compass'*

based on the data collected during the time the buoy was deployed. This additional calibration step was strongly advised by the manufacturer and is therefore adopted by SHORE.

The WaveDroids have been moored following the Mooring design guidelines of the manufacturer[2]. The lines (rope) and in-line floats have been prepared in the Netherlands, whereas the chains and anchors have been arranged locally. The specifications of the WaveDroids are presented in Tab. 2.5 below:

Table 2.5: Overview of WaveDroid accuracy. The accuracy is based on the manufacturer's declaration.

Instrument:	Brand and type:	Accuracy:
Wave buoy	WaveDroid	H_s: 7-10cm T_{m01}: 0.25-0.5s Dir_p: 5-10°

2.3.5 Sediment sampling

During the field campaign, sediment samples have been collected on 21 locations spread over the river, lagoon and the sea, determined by CDR. At each location, three samples have been taken with a 0.5 L Van Veen grabber (Fig. 2.9 left panel) which were subsequently put together in one plastic zip-lock bag (Fig. 2.9 right panel). At each location the GPS coordinates in UTM 29 N were measured.

Figure 2.9: Sediment samples. Left panel: Van Veen Grabber. Right panel: sediment sample secured in plastic zip-lock bag.

2.3.6 Determination of vertical clearance height between bridges and river

The vertical clearance height of the Somalia Drive bridge, Bong Mine Rail bridge, Bing mine Road and Bing Mine Pipe bridge has been determined. Hereto, the wooden boat was sailed close to the bridge. Subsequently, the distance between the bottom of the bridge and top of the GNSS-antenna has been measured with measuring tape (Annotation A, Fig. 2.10). Next, the distance between the top of the antenna and the antenna reference point is taken into account (Annotation B, Fig. 2.10) as well as the distance from the antenna reference point to the water line (Annotation C, Fig. 2.10).

[2]Document: *'WaveDroid_Manual_Block3_v5.pdf'* section: *'8. Mooring design guideline'*

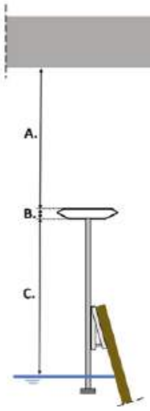

Figure 2.10: Schematic determination vertical clearance height bridges and river. Annotation A: distance between bottom bridge to top of antenna. Annotation B: distance between top antenna and antenna reference point. Annotation C: distance between antenna reference point and water level.

3 Results and Deliverables

This chapter is structured by the following subsections:

1. Results of benchmark surveys
2. Results of bathymetric and topographic survey of beaches
3. Results of lagoon and river survey
4. Results of wave measurements
5. Results of sediment sampling
6. Results of measuring vertical clearance height of bridges

3.1 Results of Benchmark surveys

The benchmark created at Earthtime (sec. 2.3.1) has been processed using AUSPOS GPS post processing and resulted in a clearly marked point with X,Y coordinates in UTM 29 N Easting/Northing and Z in WGS84 ellipsoidal height (Tab. 3.1).

Table 3.1: Coordinates created benchmark at roof of Earthtime in WGS84 UTM 29 N projection

Point ID:	Easting (m)	Northing (m)	WGS84 ellipsoid (m)
Benchmark Earthtime	300863.3939	699941.8623	50.196

For modelling, design and construction purposes the elevation data is requested to be referenced to Chart Datum instead of WGS84 elevation, as determined in 2013 by BAM, in relation to the construction of a terminal in the Freeport of Monrovia. The report[3] mentions the creation of three (3) benchmarks in the coping beam of the quay and the terminal terrain (Fig. 3.1) of which the horizontal coordinates are expressed in UTM 29 N and the vertical reference is CD. What CD actually means (physically) is still unclear, but it is assumed to be either MSL or LAT.

[3] L-BIS-RHS-0797_benchmark.pdf

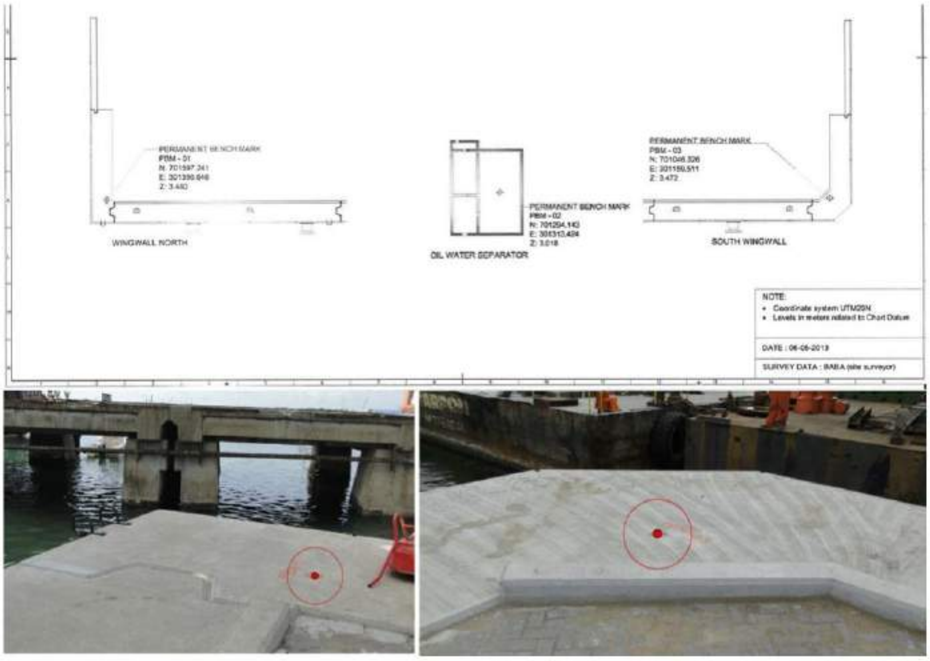

Figure 3.1: Overview of BAM benchmarks in coping beam of quay (top). Benchmark PBM-01 (left) and PBM-03 (right)

To connect all measurements of the SHORE survey to Chart Datum, the BAM benchmarks were surveyed. Benchmarks PBM-01 and PBM-03 were still recognisable. PBM-02 was covered by a container and consequently not surveyed by SHORE. Each benchmark was surveyed three (3) times, by means of 10 minute measurements with RTK-GNSS set up over the marker of the benchmark. The final coordinates of the benchmark were obtained through averaging the three (3) measurements per benchmark and are listed in Tab. 3.2.

Table 3.2: BAM benchmarks with original coordinates (UTM 29 N and CD) and coordinates as surveyed by SHORE, referenced to the Earthtime Benchmark (UTM 29 N and WGS84)

Point ID:	Easting (m)	Northing (m)	CD (m)	WGS84 ellipsoid (m)	dZ CD - WGS84
BAM PBM-01	301390.646	701597.241	3.460	-	-
SHORE PBM-01	301417.025	701683.132	-	32.784	29.324
BAM PBM-03	301159.511	701046.326	3.472	-	-
SHORE PBM-03	301185.970	701132.124	-	32.802	29.330

The coordinates show a shift in Easting (-26.379 m & -26.459 m) and Northing (-85.891 m & -85.798 m) between BAM and SHORE measurements and a vertical offset between CD and WGS84 of 29.324 m & 29.330 m. SHORE has checked the coordinates by plotting the BAM and SHORE benchmark coordinates as well as SHORE benchmark at EarthTime in Google Earth (GIS). This shows that the SHORE measurements actually correspond with the locations of the physical benchmark locations and that the BAM coordinates do not correspond with the right physical locations of the benchmarks in UTM 29 N (Fig. 3.2).

Figure 3.2: BAM and SHORE coordinates plotted in Google Earth for check on physical location of BAM benchmarks and EarthTime benchmark)

It is therefore concluded that SHORE's horizontal coordinates are more accurate and physically sound to adhere to in the future and will **not** be shifted to BAM horizontal coordinates.

In vertical sense, the SHORE survey data will be corrected to CD by subtracting 29.327 m of the WGS84 elevation data. However, SHORE expresses it's doubts towards the physical meaning of this CD. Judging by the pictures of the BAM report it might be MSL, but LAT doesn't seem plausible due to the estimated height of the coping beam (3.42 m CD) and the recognisable water level in the pictures (Fig. 3.1).

Final benchmark coordinates established through the abovementioned methodology are listed in Tab 3.3.

Table 3.3: Final Benchmark coordinates (UTM 29 N and CD)

Point ID:	Easting (m)	Northing (m)	CD (m)	WGS84 ellipsoid (m)
SHORE PBM-01	301417.025	701683.132	3.457	32.784
SHORE PBM-03	301185.970	701132.124	3.475	32.802
EarthTime	300863.394	699941.862	20.869	50.196

3.2 Bathymetric and topograhpic survey of beaches

Results are presented by Google Earth screen shots containing the final survey data, which passed SHORE quality control procedures (App. A.3). After the processing procedures, a crossings analysis of multiple randomly selected crossings showed a standard deviation in bottom level elevation of 0.076 m of the evaluated crossings (Fig. 3.3).

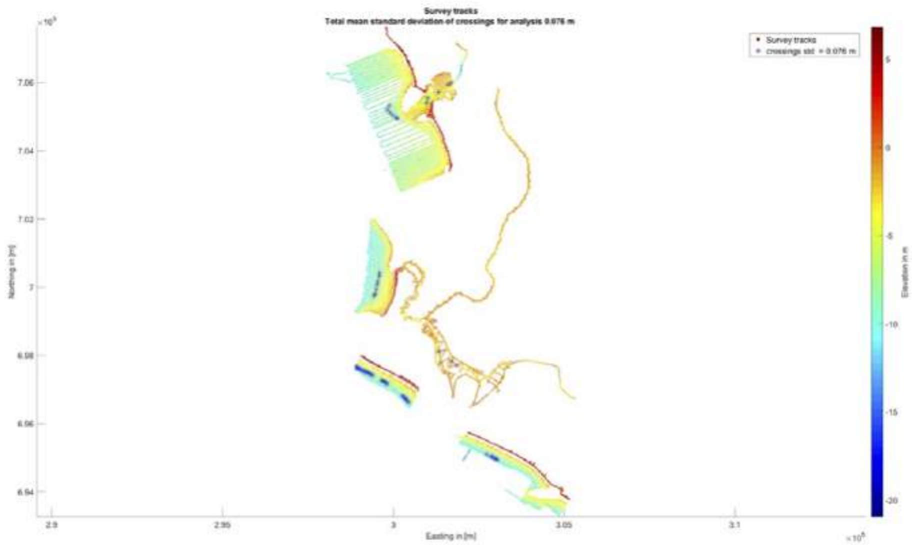

Figure 3.3: Overview of the crossings analysis. Warm (cold) colours correspond to high (low) bottom level elevation. Colour bar on the left corresponds with CD.

For presentation purposes only, the survey points are thinned by showing only every 10th point along the survey paths. The ascii files delivered to CDR contain all survey data along the sailed and walked paths.

Results are presented by area referring to the names introduced in Fig. 1.1:

1. Overview of all survey data
2. Hotel Africa & New Kru Town & Northern river part
3. West Point & Southwestern river part
4. Center Street & JFK Hospital & lagoon

Deliverables are:

1. Ascii file containing all points that passed post processing and quality control procedure (X/Easting UTM 29N (m); Y/Northing UTM 29N (m); Z/elevation (m) w.r.t. CD)
2. Google Earth file containing every 10th point that passed post processing and quality control procedure (X/Easting UTM 29N (m); Y/Northing UTM 29N (m); Z/elevation (m) w.r.t. CD)
   - SHORE_Monrovia_SurveyData_CD_october2018.txt
   - SHORE_Monrovia_SurveyData_CD_october2018.kmz

3.2.1 Overview of all survey data

The results corresponding to the total bathymetric and topographic survey in front of/ on the beaches is presented in Fig. 3.4. The survey points are plotted in Google Earth. Warm colours in the figure correspond to higher bottom level elevation, blue colours to lower elevations.

Figure 3.4: Overview of the total bathymetric and topographic survey in front/ on the beaches. Warm (cold) colours correspond to high (low) bottom level elevation. Colour bar on the left corresponds with CD.

3.2.2 Results Hotel Africa & New Kru Town & Northern river part

Zooming towards the rivermouth and beaches of Hotel Africa and New Kru town, some more detail is visible. Rocks were encountered in the nearshore at Hotel Africa, which is visible in the surveydata by alternating colours along the surveypaths, indicating bottom level elevation (Fig. 3.5). Results of the river survey (northern part) are also visible in the figure.

Figure 3.5: Overview of the bathymetric and topographic survey in front of/ on the Hotel Africa beach and New Kru Town beaches and rivermouth. Warm (cold) colours correspond to high (low) bottom level elevation. Colour bar on the left corresponds with CD.

3.2.3 Results West Point & Southwestern river part

Survey results of the beach near Westpoint, the small rivermouth channels and river survey are presented in (Fig. 3.6). Also Balli Islands typical height was mapped by surveying a contour on the relatively dry part of the island.

Figure 3.6: Overview of the bathymetric and topographic survey in front of/ on the on the Westpoint beaches and rivermouth. Warm (cold) colours correspond to high (low) bottom level elevation. Colour bar on the left corresponds with CD.

3.2.4 Results Center Street & JFK Hospital & lagoon

Results of beaches at Center Street and JFK Hospital and the lagoon are presented in (Fig. 3.7). A large rock outcrop in the east of JFK beach, made surveying impossible. The area around it was surveyed.

Figure 3.7: Overview of the bathymetric and topographic survey in front of/ on Center Street, JFK and the lagoon. Warm (cold) colours correspond to high (low) bottom level elevation. Colour bar on the left corresponds with CD.

3.3 Wave measurements

Deploying the WaveDroids was of a high priority due to the increase of wave data that would be collected as a result of an early deployment. Therefore, the WaveDroids have been deployed on 13 October, the first day of field activities.

Unfortunately, the WaveDroids have been fished out of the water by local fisherman multiple times. Thanks to the local support, the WaveDroids could be obtained from the fisherman and deployed again. Tab. 3.4 shows an indication of the period that the WaveDroids have been operational.

Table 3.4: Indication of operational time WaveDroids. Time in UTC.

	WaveDroid1	WaveDroid2
Deployment	13/10/2018 17:00	13/10/2018 17:30
Out of position	15/10/2018 11:00	16/10/2018 10:00
Back in position	15/10/2018 19:00	16/10/18 12:00 (new position)
Out of position	17/10/2018 21:00	-
Back in position	18/10/2018 10:00	-
Retrieval	19/10/2018 09:00	19/10/2018 15:15

The delivered WaveDroid data originates from the SD-card (so not from the WaveDroid data portal) and has been post-processed based on a re-done calibration. The data is delivered in numerous .txt-files corresponding to the format it was stored on the WaveDroids SD-card.

3.4 Sediment samples

During the field campaign, sediment samples have been collected on 21 locations spread over the river, lagoon and the sea, determined by CDR. At each location, three samples have been taken with a 0.5 L Van Veen grabber, which were subsequently put together in one plastic zip-lock bag. At each location the GPS coordinates were measured (UTM 29 N). The depth at that location is obtained through interpolation from the bathymetric survey results w.r.t. m CD (Fig. 3.8). The samples were delivered to CDR, for analysis of the grain size characteristics. Locations of the samples are delivered to CDR by an ascii .txt and .kml file:

- Sediment Samples van meting October 2018 tov CD.txt
- Sediment Samples van meting October 2018 tov CD.kmz
- Sediment Samples van meting October 2018 tov CD markers.kml

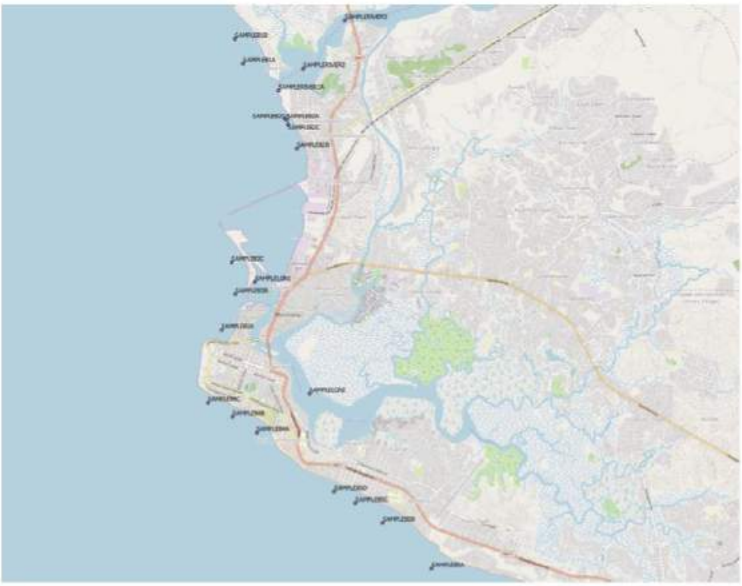

Figure 3.8: Sediment sample Locations.

3.5 Determination of vertical clearance height

In total 4 bridges have been visited to determine the vertical clearance between the bridge and the water level. Recall from section 2.3.6 and especially Fig. 2.10 that the vertical clearance height has been determined by summing:

A Distance between bottom of bridge to top of GNSS-antenna
B Distance from top of GNSS-antenna to antenna reference point
C Distance from antenna reference point to water level

Numbers B and C are the same for all bridges as the former is a characteristic of the used GNSS-antenna, whereas the latter has been determined during installation of the survey kit on the local wooden boat. The surveyors observed a significant lowering of the bottom level near all bridges. The obtained results are treated separately for each bridge in the coming sections.

3.5.1 Somalia Drive Bridge

The Somalia Drive Bridge has a straight bottom and was low enough to be reached by the survey team from the boat (Fig. 3.9 left panel). The total vertical clearance height of the Somalia Drive Bridge is **213.5cm** (Fig. 3.9 right panel).

Figure 3.9: Vertical clearance height Somalia Drive bridge. Left panel: photo of bridge. Right panel: schematic of determined distances. Total vertical clearance height: 213.5cm

3.5.2 Bong Mine Road Bridge

The bottom of the Bong Mine Road bridge is slightly curved and the clearance height decreases towards the middle pillar. The clearance height has been determined at the point with the highest bridge bottom (Fig. 3.10 left panel). The total vertical clearance height of the Bong Mine Road Bridge is **271.5cm** (Fig. 3.10).

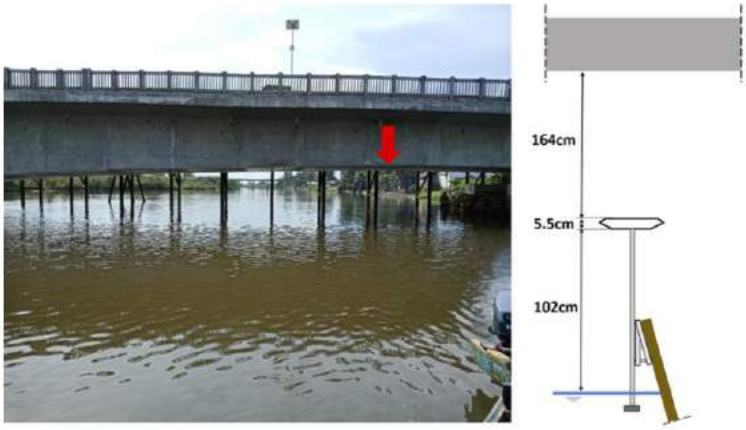

Figure 3.10: Vertical clearance height Bong Mine Road bridge. Left panel: photo of bridge with red arrow indicating which point at the bridge bottom has been used. Note: the steel pillars in the back correspond to the Bong Mine Pipe Bridge which is treated in the next section. Right panel: schematic of determined distances. Total vertical clearance height: 271.5cm

3.5.3 Bong Mine Pipe Bridge

The Bong Mine Pipe Bridge is a steel construction located parallel to the Bong Mine Road bridge (Fig. 3.11). Unfortunately, the vertical clearance of the Bong Mine Pipe Bridge was too large to be measured from a boat on the water. Therefore, no clearance height has been determined.

Figure 3.11: Bong Mine Pipe bridge. This bridge is the steel construction in front of the concrete structure which is the Bong Mine Road bridge.

3.5.4 Bong Mine Rail Bridge

Unfortunately, the vertical clearance of the Bong Mine Rail Bridge (Fig. 3.12) was to large to be measured from a boat on the water. Therefore, no clearance height has been determined.

Figure 3.12: Bong Mine Rail bridge.

4 Observations during field campaign

During the field campaign, the surveyors made notes of remarkable features observed during the survey activities. These notes will be elaborated and illustrated in this chapter. This chapter is structured as follows:

1. Observations Hotel Africa
2. Observations St. Paul River mouth
3. Observations New Kru Town
4. Observations West Point
5. Observations Center Street
6. Observations JFK Hospital

This structure largely corresponds to the previously introduced beaches (Section 1, Fig 1.1), although the St. Paul River mouth is not named before. This area is located in between the Hotel Africa an New Kru Town beaches. Moreover, during discussion of the the observations, West Point also includes the river mouth near this area where previously West Point only referred to the beach.

4.1 Observations Hotel Africa

At the Hotel Africa location the following aspects have been observed:

1. Shallow rocks above the surface
2. Shallow rocks under the surface
3. Man-made coastal defence
4. Eroded bungalows

Figure 4.1: Observations Hotel Africa area. The numbers correspond to the above this figure listed observations.

On the north side of this area, rocks are located close to the beach (Fig. 4.1 annotation 1). Surveying between these rocks was not possible. In front of the former 'Hotel Africa' there are stones on the beach. These stones protrude seaward look like having been placed by people to protect the hotel (Fig. 4.1 annotation 3).

Offshore in front of Hotel Africa is a rock below the water surface (Fig. 4.1 annotation 2). It was not possible to sail over this rock with the jet ski. South of hotel Africa there are bungalows at the sea side (Fig. 4.1 annotation 4). The foundation of some of these bungalows has been eroded.

4.2 Observations St. Paul River mouth

At the St. Paul River mouth location the following aspects have been observed:

1. Sand spit
2. Rocks under the surface
3. Rocks above the surface

Figure 4.2: Observations St. Paul River mouth area. The numbers correspond to the above this figure listed observations.

North of the estuary are two sandbars located that run into the sea from the beach (Fig. 4.2 annotation 1). On the south side there is a sandbank with a flat dry part (Fig. 4.2 annotation 1). This area is used to play football.

Rocks are present under water on the north side of the narrowest part of the estuary (Fig. 4.2 annotation 2). The estuary is relatively deep around here. Further upstream there are several stones above water (Fig. 4.2 annotation 3). According to the captain (i.e captain Flash), the river mouth is very dynamic. In the dry season, when the flow is low, the mouth is twice as narrow as observed during the survey campaign.

4.3 Observations New Kru Town

At the New Kru Town location the following aspects have been observed:

1. Eroding houses
2. Breakwater
3. Scarp
4. Shipwreck

Figure 4.3: Observations New Kru Town. The numbers correspond to the above this figure listed observations.

In the north the beach profile decreases relatively gentle. Here, several houses have been damaged by the sea (Fig. 4.3 annotation 1). In the middle of this area a breakwater is currently being made along the coast (Fig. 4.3 annotation 2). At this location it was difficult to connect the topography to the bathymetry as it was not possible to measure in the toe of the breakwater.

To the south of the breakwater, the beach profile becomes steeper. On the south side a large scarp has been observed (Fig. 4.3 annotation 3). This scarp is most likely caused by one of the drainage rivers near this locations. Offshore at sea, different shipwrecks have been observed (Fig. 4.3 annotation 4). At one location two mats protrude from the water whereas the other wrecks are located below the water surface.

4.4 Observations West Point

At the West Point location the following aspects have been observed:

1. River mouth
2. Deepest point of river mouth
3. Rocks in the surfzone
4. Refracting waves at the cape

5. Rock under the surface

Figure 4.4: Observations West Point area. The numbers correspond to the above this figure listed observations.

The beach on the north side of the estuary has a relatively steep profile. Moreover, the highest waves have been observed on this part of the beach. In front of the river mouth (Fig. 4.4 annotation 1), the waves break further offshore. In the outer bend of the estuary the water flows the fastest. The lowest bottom elevation has also been observed here (Fig. 4.4 annotation 2).

In front of West point there are a few stones in the surf zone (Fig. 4.4 annotation 3). Going south, the waves become smaller and the beach profile is also getting smoother. At the rocks on the south side the waves refract towards the beach (Fig. 4.4 annotation 4). Offshore, at a depth of 9m a big rock has been observed (Fig. 4.4 annotation 5).

4.5 Observations Center Street

At the Center Street location the following aspects have been observed:

1. American Embassy
2. Township
3. Beach road

Figure 4.5: Observations Hotel Africa area. The numbers correspond to the above this figure listed observations.

Surveying in front of the American embassy (Fig. 4.5 annotation 1) was not possible as several armed soldiers did not know exactly what was going on. It was decided to not take any risk and therefore this section has not been surveyed. The Sand grains on the beach were considerably larger compared to the northerly beaches. Moreover, the beach profile was steep over the entire beach and continued steep under the water surface. The waves broke 100 meters offshore from the beach on a shallow sand bank. A deeper section between the sandbank and the beach has been observed.

A township is located close to the sea (Fig. 4.5 annotation 2). Some houses use car tires to stop the water (Fig. 4.6).

Figure 4.6: Car tires on the beach to protect houses

On the south side of the beach there is a main road: the beach road (Fig. 4.5 annotation 3). This road is on the same level as the beach and is sensitive to flooding from the sea.

4.6 Observations JFK Hospital

At the JFK Hospital location the following aspects have been observed:

1. Reef

Figure 4.7: Observations Hotel Africa area. The numbers correspond to the above this figure listed observations.

In terms of profile, waves and sand grains the JFK Hospital locations looks like the Center Street location. On the south side of this area an offshore reef has been observed (Fig. 4.7 annotation 1). The waves break on this reef and therefore surveying on and around the reef was not possible. The beach profile behind the reef is smoother. This location is used as a natural harbour by the fishermen. At the southern end of the beach, past the river mouth, the height of the beach increases considerably.

Appendix A Bathymetric Survey System

A.1 Introduction

The bathymetric survey system is a combination of multiple instruments that together form a modular survey kit that can be used on a variety of vessels. The modular character of the system increases the flexibility as the type of vessel can be selected based on specific local conditions and is not restricted to fixed setups. In this introduction the survey system with corresponding instruments is introduced based on deployment on a PWC (Fig. A.1).

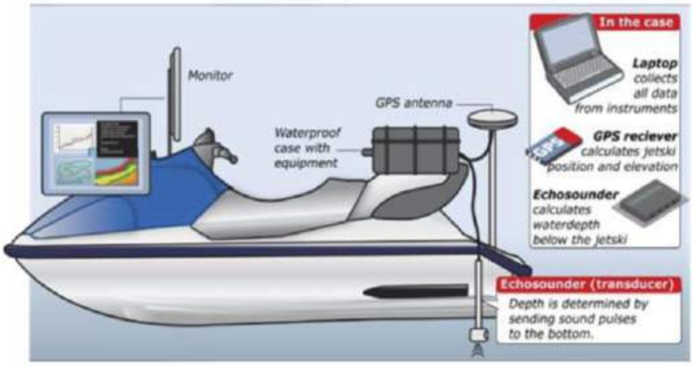

Figure A.1: The instrument setup for a bathymetric survey. Example of deployment on a PWC

The water depth under the vessel is measured with a Hydrobox Single Beam Echo Sounder (SBES, frequency 10 Hz). The SBES sends sound pulses towards the bottom which reflect and are received back by the SBES sounder. From the time between sending and receiving a pulse and the speed of sound through water, the water depth under the echo sounder can be determined.

The speed of sound through water varies based on differences in water temperature and salinity. Therefore, CTD-measurements are performed multiple times during a survey to collect the necessary information. Locations of CTD-measurements are carefully selected, based on expected spatial gradients in the speed of sound among the surveyed area.

The survey system is equipped with a motion sensor to log movement (pitch / roll) of the vessel. The logged movements are used to correct/reject the depth measurements for pitch and roll.

A dual frequency (L1/L2) RTK GPS and GLONASS (GNSS) receiver with real time radio/GPRS/3G connection with a GNSS base station or reference network is used. Its antenna is placed in one vertical axis with the SBES transducer of which the offset is measured carefully before deployment of the survey system on a 'new' vessel. The GNSS receiver logs the X,Y,Z position of the vessel at 2 Hz. RTK technique is used to obtain centimeter positional accuracy.

The latency between the instruments is calculated from the correlation between the time series of the vessel's GNSS elevation and the sounding depths below the vessel. The presence of waves results in vertical movement (heave) in the vessel elevation, which is reflected in an equal variation in the depth measured below the vessel. The time shift to correlate maxima of both signals is the resulting latency, with which the sounding depths are corrected.

The final measurement of the elevation of the bed level is then obtained from the elevation of the GNSS (z_{GNSS}) subtracted with the vertical offset between the GNSS antenna and SBES (z_{offset}) and the depth measured by the SBES (d):

$$z_{bedlevel} = z_{GNSS} - z_{offset} - d \tag{A.1}$$

The above is illustrated in Figure A.2 below.

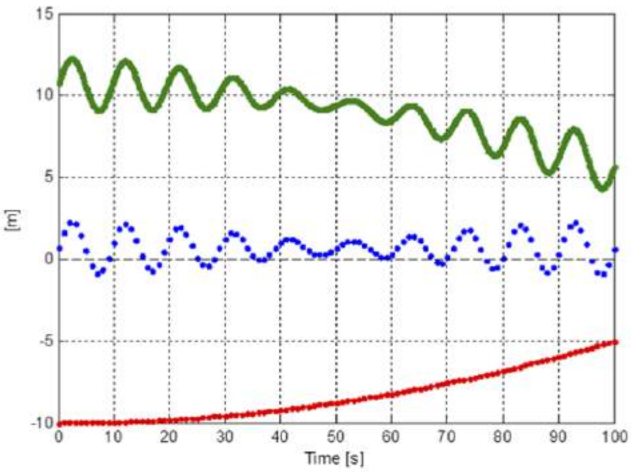

Figure A.2: Calculation of the bed level. The green line shows the 10 Hz measurements of depth under the SBES. The blue points correspond to the 2 Hz RTK-GPS elevation of the vessel *at the bottom of the SBES* ($z_{GNSS} - z_{offset}$). The resulting bottom level (2 Hz) is obtained by subtracting both signals and is shown in red.

Details of the instruments of the survey system are summarized in Table A.1 below:

Table A.1: Overview of used instruments and corresponding accuracy. The accuracy is based on the manufacturer's declaration

Instrument:	**Brand and type:**	**Accuracy:**
SBES	Syqwest Hydrobox 210kHz	± 0.01 m +/- 1% depth
RTK-GNSS	Leica GX1230GG	± 2 cm + 1 mm/km
Speed of sound sensor	YSI Castaway CTD	± 0.15m/s
Motion sensor	Xsens MTi 300 AHRS	Gyro bias stability 10°/h, Roll/Pitch 0.2°, Yaw 1.0°

The survey system is completed with a wireless monitor kit and waterproof case containing hardware and a rugged laptop are used to collect and display the survey data real-time. The monitor shows the operator all data needed for a safe, accurate and effective survey: real-time sensor status, speed, position, depth, GNSS statistics, survey tracks, sailed tracks, background drawings etc.

A.2 Details motion correction and latency

A.2.1 Motion correction (heave, pitch and roll)

Heave

The heave motion of the vessel is not compensated for with a heave compensator due to the high accuracy of the GNSS positioning. A heave sensor will record (and compensate for) the changes in vertical positioning of the vessel, which is done in the bathymetric surveys by using the elevation data from the GNSS. The vertical accuracy of the GNSS is smaller than 3 cm due to the close proximity of the GNSS base station that was used to compute the positions.

As the GNSS antenna and the transducer are in one fixed vertical line, no separate compensation is needed for the dynamic draft of the vessel as function of the vessel speed.

Pitch and roll

Two sources of vertical error can be distinguished when the vessel pitches or rolls. Firstly there is a small change in the vertical distance of the GNSS antenna to the transducer (dz in Fig. A.3). As the distance between these instruments is small, this effect is limited.

The second source of error is due to the angle of the transducer. The transducer of the SBES transmits 210kHz pulses in a cone-like beam of which the central lobe has a beam angle of 8 degrees. Within this cone the bottom is recognized as reflection point of the signal. Under conditions with small rotation angles, the smallest distance within this beam (d in Fig. A.3) corresponds to the actual depth and no compensation is needed for the roll of the vessel. For large angles of roll (Fig. A.3, right panel), the smallest distance within the cone, d, deviates from the actual depth d.

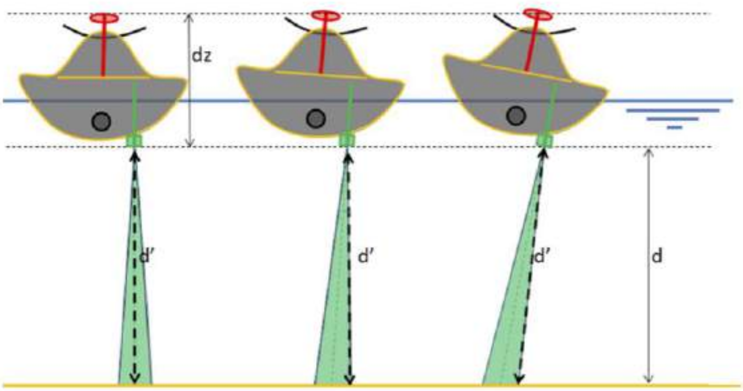

Figure A.3: Schematic of the PWC with GNSS and SBES for different angles of roll. From left to right: upright position, small angles of roll (within the SBES beam angle) and large angles of roll

The rotational motions of the vessel are logged by a motion sensor. When the logged rotational motions result in the situation shown in the right panel of Fig. A.3, the corresponding depth measurements are rejected.

A.2.2 Latency correction

The heave motion is on the timescale of individual waves and is used to resolve the relative latency of the GNSS device with respect to the echo sounder. Hereto, small fragments of both time series are analysed. If these fragments are inspected closely, a small shift between the peaks in both signals can be observed due to the latency (Fig A.4). The timing of the echosounder signal is slightly adjusted by increments of 0.1 s, after which the correlation between the GNSS elevation and shifted echosounder signal is calculated as:

$$R_{x(t_0)y(t_0+\tau)} = \frac{\overline{xy}(t_0;\tau)}{[\overline{x^2}(t_0)\overline{y^2}(t_0+\tau)]^{0.5}} \tag{A.2}$$

Where R_{xy} represents the correlation function, $x(t)$ is the elevation signal of the GNSS and $y(t+\tau)$ is the signal of the echosounder (shifted by time offset τ). The time shift that gives the largest value of the correlation function, i.e. the best alignment of both signals, is taken as the value for the relative latency between both instruments (Fig. A.4, right panel).

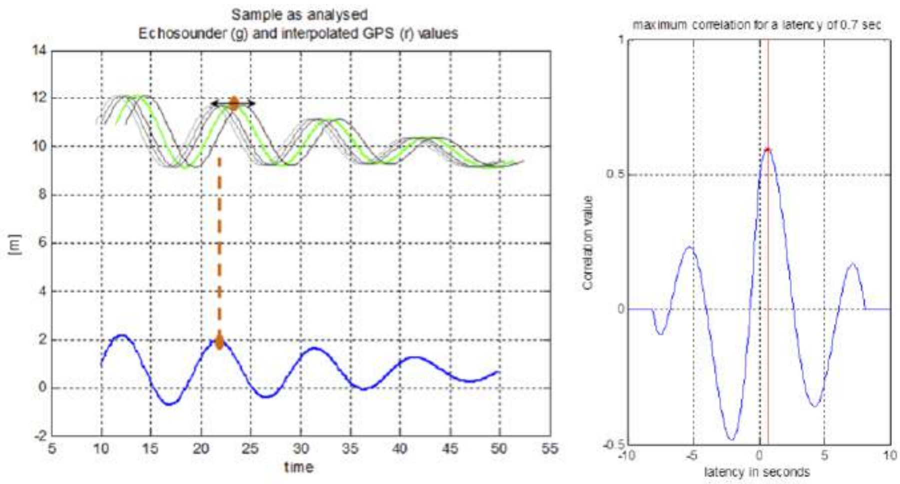

Figure A.4: Left panel: The calculation of the latency. The timing of the echo sounder signal (green) is adjusted slightly (light gray realisations) to obtain the best alignment with the GNSS elevation signal (in blue). Right panel: The correlation function of the GNSS elevation signal and the echosounder signal as function of different time lags (latency). Maximum correlation in this example is found for a latency of 0.7 s.

The latency value is checked for several subsets of the entire survey, but is generally not varying as it is mostly determined by the hardware configuration. Nevertheless, the latency test is done for each of the recordings, as part of the standard quality control.

A.3 Quality control

A.3.1 Control of SBES signal

The measured SBES signal is checked on outliers and other sources of noise. If present, outliers and noise are removed from the signal.

A.3.2 Control of quality GNSS-signal

The GNSS signal is checked on the availability of a RTK solution. Points that are aqcuired without a RTK fix are removed from the dataset.

A.3.3 Crossing analysis

The crossings of the cross-shore and alongshore survey tracks are analyzed, with the purpose to show the accuracy/robustness of the survey method. The analysis is based on the bottom level elevation of the survey points of the alongshore and cross shore tracks in the vicinity of the crossing location.

The methodology contains the following steps:

1. Identification of the locations of crossings between alongshore and cross-shore tracks.
2. Listing of all survey points in an area of 10 by 10 meter centered around the crossing. This area is chosen to be rather small (10x 10 m) to minimize large variations in bottom level within the area investigated. Taking a larger area will result in larger standard deviations, which are not the result of the accuracy of the survey system, but resulting from the actual gradients in the bed level, even on mildly sloping beaches.
3. Calculating the statistics of the points per crossing. Three main statistics are calculated:
   A The number of points n in the 10x10 meter area around the crossing
   B The mean bed level μ at the crossing obtained by using $\mu = \Sigma z_i/n$
   C The standard deviation σ in bed level values at each crossing, obtained using $\sigma^2 = \Sigma(z_i\mu)^2/(n-1)$

The methodology is illustrated using an arbitrary crossing from a bathymetric survey in Ghana performed in 2015 (Fig. A.5). The crossing contains data of two cross shore tracks (one from the beach to intermediate water depth, and one from intermediate water to deep water) and the alongshore track.

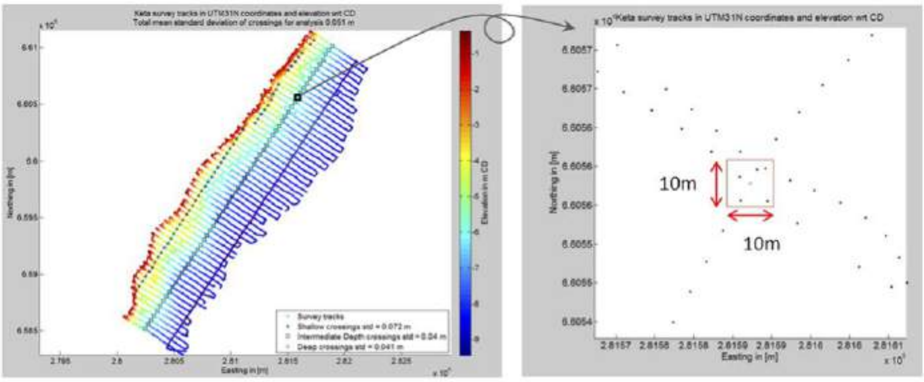

Figure A.5: Left: Survey tracks with crossings of alongshore and cross shore survey tracks. Right: Detailed view of crossing of an alongshore and cross shore track in intermediate water. Red square indicates the 10x10m area surrounding the crossing that has been investigated, black dots are the individual bed level measurements.

The survey point data in the vicinity (10x10m area) of the crossing are given in Tab. A.2. The mean water depth at the evaluated location is -5.84 m and the 5 points have a standard deviation of 3 cm.

Table A.2: Example crossings analysis values

Point nr.	Elevation bed in point in CD
1	-5.8302 m
2	-5.8124 m
3	-5.8901 m
4	-5.8444 m
5	-5.8251 m
	Mean μ = -5.8405 m, Standard deviation σ = 0.0300 m

Next, the results of all crossings are averaged per alongshore track to obtain bulk values per depth zone. The following results were obtained for the example survey (Tab. A.3).

Table A.3: Example crossings analysis values per depth zone

Alongshore transect	Number of crossings	Average bed level at crossings	Average standard deviation of bed level in survey points at crossings
Near the beach	51	-4.09 m CD	0.072 m
At intermediate water depth	61	-6.53 m CD	0.040 m
Near deep water boundary of survey	59	-8.19 m CD	0.041 m

O. COASTAL PROFILES

Link to all Coastal Profiles