THE LAGOS COAST

Investigation of the long-term morphological impact of the Eko Atlantic City project

MSc Thesis

K.M. van Bentum

January 2012

TU Delft Delft University of Technology

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Deltares Enabling Delta Life

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MSc Thesis

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A thesis submitted in partial fulfilment of the requirements for the degree of
Master of Science in Civil Engineering at the Delft University of Technology

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PREFACE

Barely one week after my first acquaintance with the Royal Haskoning department of River and Coastal Management, I found myself on a plane towards Lagos, Nigeria together with four Royal Haskoning employees. This was about the best start of a MSc study a graduate can think of. There I was, right in the middle of the immense city Lagos, the subject of my thesis.

This thesis concludes my Master of Science program in Civil Engineering, specialization in Hydraulic Engineering at the Delft University of Technology. The study is initiated by Royal Haskoning, to complement its previous studies on the Lagos coast. Deltares is involved in the modelling part of the study.

I would like to express my gratitude to my graduation committee for guiding me through the Master study. I would like to thank prof. dr. ir. M.J.F. Stive for his interest, enthusiasm and motivating discussions; dr. ir. M. van Ledden for his very constructive feedback and for taking a lot of time to aid me during my thesis work; dr. J.E.A. Storms for sharing his knowledge in the geological part of this thesis; ir. A.P. Luijendijk for always triggering me to get the most out of my study and making me reflect critically on the findings and ir. C. Hoyng for her enthusiasm for my study and for all the advices and information she provided me with.

I would like to thank Royal Haskoning, and especially, D. Heijboer, M. van Ledden and C. Hoyng, for providing the interesting and challenging thesis subject combined with the opportunity to take part on the trip to Lagos and to make such a great start with my study. Also, the Nedeco fund is thanked for the financial contribution to the trip. Besides the fact that staying two weeks in Lagos was very educational and instructive, it was also a great possibility to get to know the Royal Haskoning employees and the on-going projects in Lagos.

Moreover, I owe many thanks to ir. B. Huisman and ir. H. de Vroeg for all their help during the modelling phase and for providing me with lots of useful information and enthusiasm regarding the Unibest software.

Finally, especially, I would like to thank my family and close friends for their unconditional support, love and care and of course, for the fantastic years I had during my study. Most of all, I would like to thank Luuk for his never-ending support, encouragement and help when I needed it the most.

Karen van Bentum - Delft, January 2012

ABSTRACT

This study is performed to assess the long-term morphological impact of the Eko Atlantic City project on the adjacent Lagos coast. Lagos is situated at the western part of the Nigerian coast around a tidal inlet which leads to the Lagos Lagoon. In 1908 man started to interfere with the natural coastal situation by the construction of three stone moles at the tidal inlet. These moles are the West Mole, the Training Mole and the East Mole. Nowadays, the tidal inlet is called the Commodore Channel and it constitutes the seaside entrance to the Lagos Harbour.

As of the completion of the moles, the Lighthouse Beach, situated updrift of the inlet, expanded about 800 m over circa hundred years due to sediment trapping at the West Mole. Consequently, the Bar Beach, located downdrift of the inlet, suffered enormous rates of erosion. Over roughly hundred years the total retreat of the coast has reached values of more than one km. To counteract the large loss of beach width due to the erosion, man started to apply nourishments around 1960. Enormous volumes of sediment have been supplied to the Bar Beach, but the beach kept on eroding anyhow. An additional problem at Lagos is the growing population, entailing large space demands for residential, commercial and recreational activities.

To cope with this space deficit and the land loss due to the erosion of the Bar Beach, the private project developer South Energyx Nigeria Ltd. has initiated the Eko Atlantic City project. This project comprises a land reclamation of 9 km² in front of the Bar Beach, directly east of the East Mole. The newly reclaimed land is protected against erosion by a revetment, which has a length of roughly 6.5 km.

Royal Haskoning provides, among others, the consulting services for the marine works of Eko Atlantic City. One of its main studies concerning the Eko Atlantic City project has been into the short-term impact of the project on the adjacent coast. Preliminary conclusions on the impact of the project are drawn and locations where erosion is expected are pointed out. To provide for a comprehensive approach, the long-term effects of the project on the adjacent coastline should be investigated as well. Therefore, Royal Haskoning initiated this study.

The main objective of the study performed in this thesis is:

Investigate the long-term morphological behaviour of the coastal stretch around Lagos with the presence of Eko Atlantic City in a qualitative and quantitative way.

To achieve the objective, several research questions need to be answered:

1) *What are the governing processes and mechanisms determining the long-term and large-scale morphological behaviour of the Lagos coast?*

2) *What was the influence of the construction of the Lagos Harbour Moles and other human interferences on the historical coastline development?*

3) *How does the construction of Eko Atlantic City change the present morphological processes?*

In the study into these questions, two clear parts can be indicated. In the first part the Lagos coast is analysed by a theoretical approach, which results in a conceptual model of the Lagos coast. And thereafter, the numerical simulation model Unibest is applied to complete the analysis and to assess the impact of Eko Atlantic City.

So, the first part of the analysis of the Lagos coast starts with a literature study into the historical development and into the governing processes and mechanisms at the Lagos coast. Using the results of the literature study, preliminary conclusions on the governing processes and mechanisms can be drawn and a conceptual model regarding the long-term and large-scale morphological development of the Lagos coast is constructed. In the conceptual model, the governing sediment fluxes, sources and sinks in the Lagos coastal system are quantified via consideration of the sediment balance at the coast of Lagos. Thereby, the first research question can be answered.

Persistent high-energy swell waves, reaching Lagos with a mean direction of 188°, induce a mean eastward longshore sediment transport. In general, the whole Lagos coast suffers erosion due to high rates of relative sea level rise. This high relative sea level rise is induced by the natural dewatering and compaction of the soil, combined with large volumes of water extraction by men and the Eustatic sea level rise.

The high rates of erosion downdrift the inlet are not induced by sea level rise alone however. The governing factors are the accumulation of sediment by the West Mole and the import of sediment into the Commodore Channel and the Lagos Lagoon. The sediment import occurs due to sea level rise, dredging of the channel and dredging of the lagoon. These processes disturb the morphodynamic equilibrium of the inlet and the lagoon as they create additional sediment accumulation space. This leads to a so-called sediment demand in the lagoon and the tidal inlet.

The result of the sediment trapping at the West Mole and the sediment import into the tidal inlet and the lagoon is that almost no sediment is able to bypass the East Mole. Thereby, a sediment deficit in the longshore current downdrift of the tidal inlet arises. Subsequently, the Bar Beach starts to erode, to provide for a sediment source to the longshore sediment transport.

The first part of the second research question is hereby answered. The construction of the moles led to expansion of the Lighthouse Beach, via sediment accumulation at the West Mole. And, together with the other processes occurring in the tidal inlet and in the lagoon, the construction of the moles resulted in significant erosion of the Bar Beach.

To answer the second part of the second research question, the effect of the nourishments performed on the Bar Beach since 1960 is investigated. Although erosion of the Bar Beach was not prevented by the artificial sediment supply, the nourishments clearly have had an alleviating effect on the erosion. If the nourishments had not been conducted, the erosion of the Bar Beach would have been even worse.

Subsequently, the conceptual model is used to formulate hypotheses regarding the future morphological behaviour of the Lagos coast with the presence of the Eko Atlantic City project.

The second part of the study into the long-term influence of the Eko Atlantic City project on the adjacent coast is the construction of a model using the numerical simulation model Unibest. With this model, the analysis of the Lagos coast is continued. And thereafter, the model is applied to answer the third research question by testing the hypotheses.

According to the output of the Unibest model, the total volume of erosion occurring downstream of the tidal inlet is not altered by the presence of the Eko Atlantic City project. But, since the revetment fixes the coast of the newly reclaimed land, the erosion of the Bar Beach is shifted eastward by the construction of the project. As concluded in the conceptual model, the volume of erosion and the corresponding rate of beach retrogression are determined by the volume of sediment bypassing along the East Mole.

The erosion that would occur at the Bar Beach, without the construction of Eko Atlantic City, is spread quite equally over the beach. The erosion that occurs downstream the Eko Atlantic City project, on the contrary, reaches much higher values locally. So, although the total erosion volumes are equal, the erosion rates directly downstream of the project are increased significantly. But, because the erosion volume downstream of the project is spread out over a larger distance than the distance over which the erosion is spread out if the project is not constructed, the erosion rates downstream Eko Atlantic City diminish rapidly.

If the development of the erosion downstream of Eko Atlantic City is considered until 2060, it can be concluded that the erosion rates downstream of the project are highest just after the construction. Over the years, the erosion rates and the erosion volumes decrease somewhat, but the length of the erosion wave increases.

Keeping the longer-term effects of Eko Atlantic City in mind, and investigating the hinterland of the coast downdrift of Eko Atlantic City, it becomes clear that mitigation measures are required.

Directly downstream of the project the inland Kuramo Waters East are situated. Erosion of the narrow beach in front of these waters can lead to a breakthrough, which can have devastating effects since the hinterland is built very densely.

To prevent a breakthrough to the inland waters, it is investigated what volume of nourishment is required to provide for a stable coast downstream of the project, in the scenario where zero bypassing along the East Mole occurs. Annually, a volume in the order of the longshore sediment transport must be nourished to prevent a breakthrough to the inland waters.

Circa 6 km downstream of Eko Atlantic City the Alpha Beach is located, where a large indigenous fishing community lives directly next to the coast. Erosion of this beach must, therefore, be prevented by e.g. a groyne scheme or a revetment. If the effects of this potential mitigation measure at Alpha Beach are studied, the presence of Eko Atlantic City must be taken into account.

Similar to the effects of Eko Atlantic City, the protection of Alpha Beach shifts erosion further downstream. The erosion of the coastal stretch in between Eko Atlantic City and Alpha Beach is alleviated somewhat by the presence of the second revetment. This is explained by the fact that if the coast obtains an orientation equal to its equilibrium orientation (relative to the mean angle of the dominant waves), the sediment transport diminishes. Due to the presence of the protection at the Alpha Beach, the erosion is shifted eastward once the coastal stretch between both structures has acquired its equilibrium orientation.

However, erosion of the coastal stretch in between the two structures must be prevented from erosion completely, to protect the valuable hinterland. Application of a nourishment volume in the order of the annual sediment transport can prevent erosion at this part of the coast. Thereby some erosion occurs downdrift of Alpha Beach, but the execution of the nourishments has an alleviating effect there as well.

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1 INTRODUCTION

In this thesis, the long-term impact of the Eko Atlantic City project on the coast of Lagos, Nigeria is investigated. This chapter serves as an introduction to the performed study.

First, a general description of Nigeria and Lagos is presented in section 1.1. Then, in section 1.2 some background information on the erosion problem occurring at the Lagos coast is discussed where the causes and effects of the erosion are pointed out. Hereafter the Eko Atlantic City project is introduced. Among others the motives for the construction of the project and the layout of the land reclamation are presented.

In section 1.3 the objective of this thesis is posed and explained. The research questions required to accomplish the objective are discussed in section 1.4. The chapter ends with the outline of this thesis report presented in section 1.5.

1.1 CONTEXT

Nigeria is a country in West Africa, bordered by the Republic of Benin at the West, by the Republic of Niger in the North, by Chad in the North-East and by Cameroon in the East. At the South of the country, the 853 km long coastline borders on the Gulf of Guinea (in the South Atlantic Ocean), see Figure 1-1 and Figure 1-2.

Figure 1-1: Location of Nigeria in Africa [after Google (2010)]

Figure 1-2: Nigeria and its surrounding countries [after Google (2010)]

The Nigerian coast forms the social and economic nerve centre for the whole country where over 70 per cent of the national income is generated. The Niger Delta, positioned in the centre part of the Nigerian coast, contributes the main part (about 80 per cent) of the foreign exchange earnings by oil and gas exploitation (Okude and Ademiluyi, 2006). The nation's largest city Lagos, the former Federal Capital City and the present capital of the Lagos State, is situated at the western part of the coastline. This city is of great economic, commercial and industrial importance for the country. Besides, the city functions as the home to about 15 million people (Okude and Taiwo, 2006) making it even one of the biggest cities in Africa.

Lagos, and more specific its coast, is the subject of this study. The city is built around a tidal inlet, which connects the Lagos Lagoon to the South Atlantic Ocean, see Figure 1-3. Nowadays the inlet facilitates the entrance to the Lagos Harbour via the Commodore Channel. Since 1912 the position of this entrance channel is ensured by three moles; being the West Mole, the Training Mole and the East Mole. At the western side of the inlet, the Lighthouse Beach is situated and at the eastern side of the channel the Bar Beach is located, on Victoria Island. Victoria Island is at present the commercial, economical and business centre of the city.

Figure 1-3: Overview of the Lagos Harbour Moles, the Commodore Channel, the beaches and the Lagos Lagoon [after Google (2010)]

1.2 PROBLEM DESCRIPTION

1.2.1 EROSION AT BAR BEACH

The Victoria Island is a popular, extensively used and densely built area. But the six kilometres long Bar Beach is also the area where the highest erosion rates of the whole country are observed. The erosion at the Bar Beach section, of which maximum values of 20 m to 30 m per year have been measured in the past (Awosika *et al.*, 1994; Ibe and Antia, 1983), caused severe losses of land over the past hundred years. This resulted in structural coastline retreat, which became a serious threat to the buildings and infrastructure close to the beach.

Just as at many other coasts around the world, the erosion of the Lagos coast is not the result of just one single cause. The high erosion rates at the Victoria Island can be attributed to both natural and anthropogenic causes (Ibe and Antia, 1983; Okude and Ademiluyi, 2006; Okude and Taiwo, 2006). However, the human act that had the most significant impact on the Lagos coast is the construction of the three stone moles at the tidal inlet to the Lagos Lagoon, between 1908 and 1912. These moles were put in place to protect and stabilize the deeply dredged Commodore Channel; the entrance channel of the Lagos Port.

Before the construction of the moles, the two beaches were part of the same barrier-beach system with in front an underwater sandbar, formed by the littoral eastward drift. After construction, the moles constituted an obstruction to the west – east directed longshore sediment transport. At the West Mole the sediment became trapped, leading to a seaward expansion of the Lighthouse Beach. The Bar Beach started to erode, because of the sediment deficit in the longshore current.

An impression of the enormous rates of coastal retreat can be obtained by comparing the sketch presented in Figure 1-4 to the sketch of Figure 1-5.

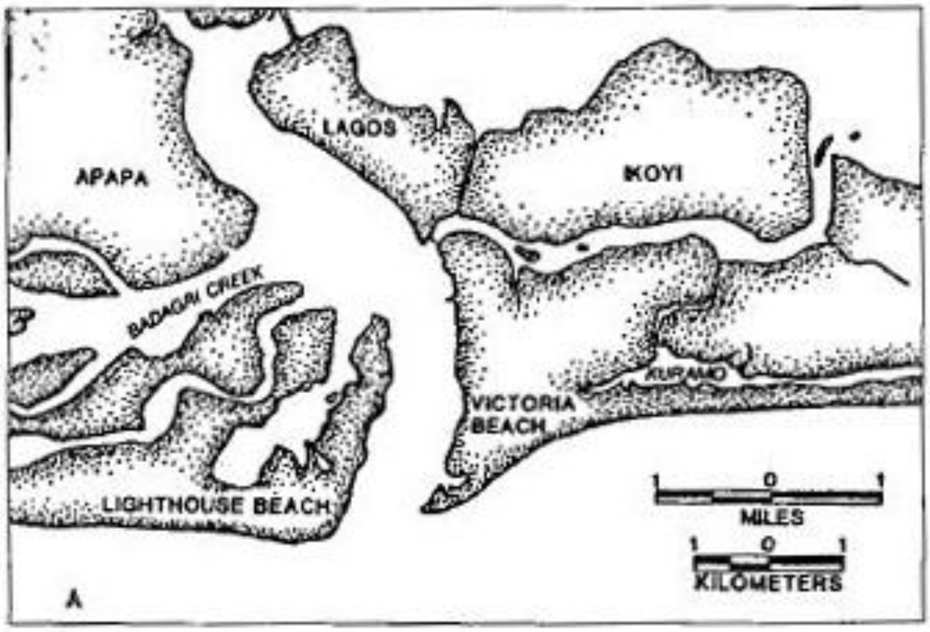

Figure 1-4: Lagos coast before construction of the Harbour Moles, in 1900 [after figure 1 Onolaja (1988)]

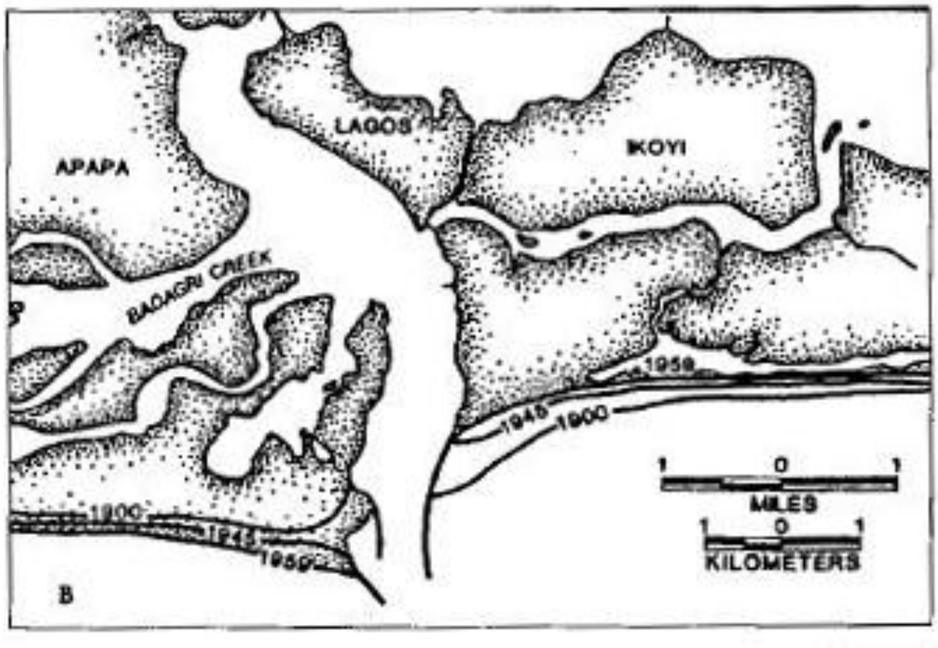

Figure 1-5: Lagos coast with the harbour moles, in 1959 [after figure 1 Onolaja (1988)]

Some authors state that the erosion got amplified by the angle of construction of the East Mole relative to the wave angle of incidence, which caused notable eddy formation and thereby an intensification of the wave impact (Ibe and Antia, 1983; Ibe *et al.*, 1991; Onolaja, 1988). Ibe (1988) estimates that the shoreline at Bar Beach has receded more than one km in the first seventy years after construction of the moles.

In the past fifty years already a lot of measures have been taken to counteract the erosion, of which the most frequently applied one is sand nourishment on the beach. However, none of them proved completely successful, as the coastline kept on regressing. The construction of a one kilometre long Xbloc revetment on the Bar Beach in December 2006 resulted in the absence of significant erosion at that specific coastal stretch. It must be kept in mind, however, that this structure not only influences the coast locally but the coastal stretch downdrift as well. A solution that would result in significant effect on both a greater spatial and time scale was, therefore, still required.

1.2.2 THE EKO ATLANTIC CITY PROJECT

The great national importance of Lagos has shortly been pointed out in the previous section. At present the city experiences an enormous pressure on the exhausted infrastructure, accompanied by almost permanent traffic jams and chaos on the roads. Also, shortage of land and resources is a serious problem in the Lagos area. The commercial centre of Lagos, Victoria Island, is overpopulated and extensively built. Moreover, nowadays, it has become very hard to develop more infrastructure or residential, commercial or business areas.

To provide for a permanent erosion mitigation solution at the Bar Beach and to deal with the still growing population and the adjoining demand for space and development area, the private project developer South Energyx Nigeria Limited (SENL) has initiated the development of the Eko Atlantic City project. This project comprises the reclamation of 9 km^2 of land directly east of the East Mole, in front of the Bar Beach. It is estimated that the project is able to provide residential area for about 250,000 people and area for work activities for another 150,000 people (SENL, 2011). The length of Eko Atlantic City is around 6.5 km and the average width is approximately 1.3 km (Prince A. Oniru, 2011). In Figure 1-6 an overview of the project is depicted and in appendix A.3 two artist’s impressions of the project can be found.

Figure 1-6: Layout of Eko Atlantic City; the colours indicate the different phases in the construction [after Royal Haskoning [4], (2011)]

Royal Haskoning provides the consulting services for the marine works of Eko Atlantic City. This comprises among others the designs of both the sea defence and the inland waterway and an overview of all sand reclamation works executed by the dredger (an international contractor). The sea defence of the project (to be built by a local contractor) consists of a revetment, which provides a protection against the severe wave climate and prevents erosion of the newly reclaimed land. The sand for the land reclamation is dredged at a location offshore of Lagos. Royal Haskoning supervises both the land reclamation and the construction of the revetment (Royal Haskoning [1], 2011, Part 0).

The current status of the project is that a start has been made with the dredging and pumping of sediment to the project area and the first part of the sea defence has been constructed. The dark grey part in Figure 1-6 represents the completed work.

1.3 OBJECTIVE

As stated before, Victoria Island is the coastal zone suffering the highest erosion rates in Nigeria. Because of its enormous economic, commercial and industrial importance for the nation, many studies on the Nigerian and Lagos coastal area have been performed over the years. Among others, the Nigerian Institute of Oceanography and Marine Research (NIOMR), Royal Haskoning and Deltares conducted several studies.

In January 2011 Royal Haskoning completed a “Coastal Analysis Report” for its client SENL. In the report an extensive study on the expected short-term impact of the presence of Eko Atlantic City on the adjacent coast is presented. In appendix A the results of the study of Royal Haskoning are summarized.

This study builds on the results of the “Coastal Analysis Report”. Royal Haskoning came up with the first conclusions about the short-term coastal response to the project. Morphological simulations were done to investigate the initial morphological changes.

This study goes more into detail on the expected long-term impact of the presence of Eko Atlantic City on the Lagos coast. The study aims to provide a detailed qualitative and quantitative analysis of the long-term morphological behaviour of the coastal stretch up to 10 km immediately downdrift of the project, as the study done by Royal Haskoning showed that this coastal section would probably suffer the most erosion. More insight is provided into the locations at which retreat (or advance) is expected to occur, into the sediment transport volumes and into the extent and volumes of expected beach erosion.

Especially the long-term morphological response of the coast to the presence of Eko Atlantic City is interesting, since the construction of such artificial land reclamation could be an innovative solution to similar erosion problems occurring worldwide. Nowadays, usually structures like groynes, breakwaters or revetments are used to mitigate the (generally negative) side-effects of the construction of harbour moles and jetties. Possibly, an artificial land expansion like Eko Atlantic City could result in a less severe impact on the coast downdrift. Besides the erosion mitigation function, this project also provides additional land, which can be of great value in the densely populated coastal areas.

To draw any conclusions concerning the long-term impact of Eko Atlantic City, it is of importance to understand the large-scale and long-term morphological behaviour of the Lagos coastal system. Therefore, the processes and mechanisms inducing and influencing the large-scale and long-term coastal morphology at the Lagos coast should be investigated.

To put the above in short, the main objective of this thesis is:

Investigate the long-term morphological behaviour of the coastal stretch around Lagos with the presence of Eko Atlantic City in a qualitative and quantitative way

In order to be able to achieve this objective, the following sub-objectives are set:

- *Develop a conceptual model that provides insight in the long-term and large-scale behaviour of the coastal system*
- *Quantify the processes and impacts described in the conceptual model*
- *Investigate what impacts the historical human actions along the coast and the natural boundary conditions had on the system*
- *Assess the impact of the construction of the Eko Atlantic City project on the adjacent coast*

1.4 RESEARCH QUESTIONS

To accomplish the objectives posed above, the following research questions have to be answered:

- *What are the governing processes and mechanisms determining the long-term and large-scale morphological behaviour of the Lagos coast?*
- *What was the influence of the construction of the Lagos Harbour Moles and other human interferences on the historical coastline development?*
- *How does the construction of Eko Atlantic City change the present morphological processes?*

1.5 OUTLINE

This thesis starts in chapter 2 with a general discussion of the Lagos coast, based on a literature study. First, the greater West African coastal system the Lagos coast is part of, is analysed and the relevant large-scale processes are discussed. Then, the historical development of the coast of Lagos is investigated and the governing long-term morphological mechanisms are presented. Thereby, the first research question is answered.

Using the results of the literature study, the conceptual model is constructed and discussed in chapter 3. The relevant processes and mechanisms determining the Lagos coastal morphology are elaborated on and quantified. Hereafter, hypotheses regarding the impact of the Eko Atlantic City project on the long-term morphological behaviour of the Lagos coast are formulated.

In chapter 4 the investigation of the Lagos coast is continued using the numerical simulation model Unibest. After the model setup and calibration the output is compared to the conceptual model. This chapter concludes with the assessment of the impact of several historical human interferences at the Lagos coast, to answer the second research question.

The hypotheses on the long-term development of the coast of Lagos are investigated using the Unibest software in section 5. Thereby, the third research question is answered. Also, the longer-term morphological behaviour with the presence of Eko Atlantic City is investigated. And subsequently, some potential mitigation measures, to cope with the effects induced by the presence of Eko Atlantic City, are discussed.

Chapter 6 concludes this thesis; the conclusions of the performed study into the Lagos coast and the assessment of the long-term morphological impact of Eko Atlantic City are presented and recommendations for further research are given.

2 THE LAGOS COAST

This chapter provides an overview of the Lagos coastal system, obtained by a literature study. Firstly, the greater West African coastal system is analysed. The main characteristics of the large-scale coastal system and the processes acting on this scale are presented.

Then the study zooms in on the Nigerian continental shelf and the Nigerian coast. Among others the general features and coastal types are discussed. Subsequently, the Lagos coast is analysed. A description of the city Lagos and the Lagos Lagoon is provided. Thus, via the bigger, cross-border coastal system, it is investigated which large-scale factors are of relevance for the morphological behaviour of the Lagos coastal system. This analysis is presented in section 2.1

Besides the analysis of the spatial scale, a study on the development over time of the coast of Lagos is done as well. This is presented in section 2.2. Based on the human interventions at the Lagos coast, the timescale is classified into four significant periods. Per period the governing coastal processes and mechanisms at the Lagos coast are discussed. Simultaneously, other human interferences along the West African coast and their influences on the coastal morphology are discussed per period.

2.1 AREA DESCRIPTION

2.1.1 COAST OF WEST AFRICA

The part of the West African coast that is considered in the commencement of this study stretches over approximately 1,300 km, from the eastern part of Liberia until West Nigeria. Allersma and Tilmans (1993) state that this part of the West African coast constitutes one coastal system. As a first approach, this conception is followed in this study and the analysis of the relevant coastal area is limited likewise. Figure 2-1 depicts the considered part of the West African coast.

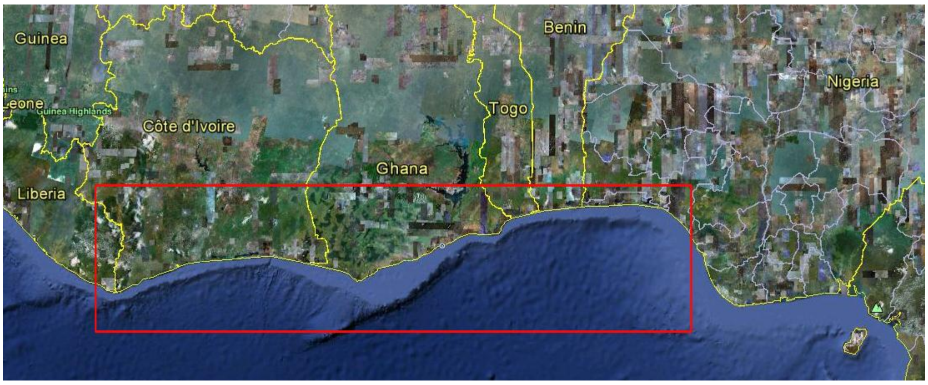

Figure 2-1: West African area of interest [after Google (2011)]

TRAILING-EDGE COAST

In geomorphological terms the coast of West Africa can be defined as a trailing-edge coast. Trailing-edge coasts are generally tectonically stable and often possess coastal features like barrier islands and deltas. More specific, the West African coast can be classified as an Afro-trailing-edge coast. Africa is located in the middle of a crustal plate and, because of the tectonic stability, no significant mountain ranges are present. Therefore, compared to other continents, small sediment volumes are brought to the coastal zone from inland (Bosboom and Stive, 2010).

SWELL CLIMATE

The West African coast borders on the South Atlantic Ocean. It can be characterized as a 'West coast swell climate' (Bosboom and Stive, 2010). The wave climate at the coast is dominated by swell waves. These waves originate in distant storms, which are generated by western winds (the so-called 'Westerlies') in the Earth's Southern storm wave belt.

Via frequency and directional dispersion[1], several wave fields consisting of waves approximately uniform in direction, period and height are developed. At bigger distances from the storm only longer waves are present, as the shorter waves are quicker affected by dissipation processes, like white capping (Bosboom and Stive, 2010). Therefore, at the West African coast high-energetic swell waves mostly arrive from a south – southwest direction, which have a very narrow frequency and direction spectrum. The general direction for the significant wave angle of incidence used in this study is 188°, with respect to the geographic North (see appendix D.2).

GUINEA CURRENT

The ocean current occurring in front of the West African coast is the Guinea Current. The Guinea Current flows at approximately 3°N eastward in front of the West African coast. The current is generally warm and has a low salinity, due to heavy rainfall (UNEP, 2004). It originates from the North Equatorial Counter Current and the Canary Current, see Figure 2-2. The seasonal variations in the Guinea Current are therefore induced by the seasonal instability of those two currents. In summer, from May to September, the Guinea Current is at its strongest, as it can reach velocities of about 1 m/s at 5°W (and 3°N). It has a minimum velocity of approximately 0.5 m/s during winter, from November to February (Gyory *et al.*, 2008).

The Guinea Current is a superficial flow. It flows in the upper 15 m of the water column near the coast and more offshore the current extends from the surface to 25 m deeper (Ajao *et al.*, 1996; Binet and Marchal, 1993). Its width is about 370 km offshore (UNEP, 2004). The current is in geostrophic balance[2]. The gradient of the isotherms is upwards to the northern coast. When the current becomes more intensified, the slope becomes steeper and the thermocline moves closer to the surface. This leads to seasonal coastal upwelling between July and late September (Gyory *et al.*, 2008; UNEP, 2004). The upwelling mostly occurs in front of the coast of Ghana, Togo and Benin. In front of the West Nigerian coast, the upwelling is assumed to be negligible.

The steep topography of the Gulf of Guinea causes the current to bend back towards the West in front of the Cameroon coast. Eventually the current joins the South Equatorial Current (UNEP, 2004), which is also depicted in Figure 2-2.

Under the Guinea Current flows the Guinea Under Current, which flows westward as a return branch of the Equatorial Under Current (Binet and Marchal, 1993).

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[1] In deep water, the propagation velocity of the wave energy depends on the frequency of the wave component. Therefore, longer waves travel at higher phase speeds than shorter waves. This is called the frequency dispersion. Direction dispersion is the phenomenon of waves changing from short-crested to long-crested. This happens because the waves in the storm travel in a range of directions, in which the initial wave field will disintegrate eventually. (Holthuijsen, 2007)

[2] The pressure gradient force in the flow is balanced by the Coriolis force.

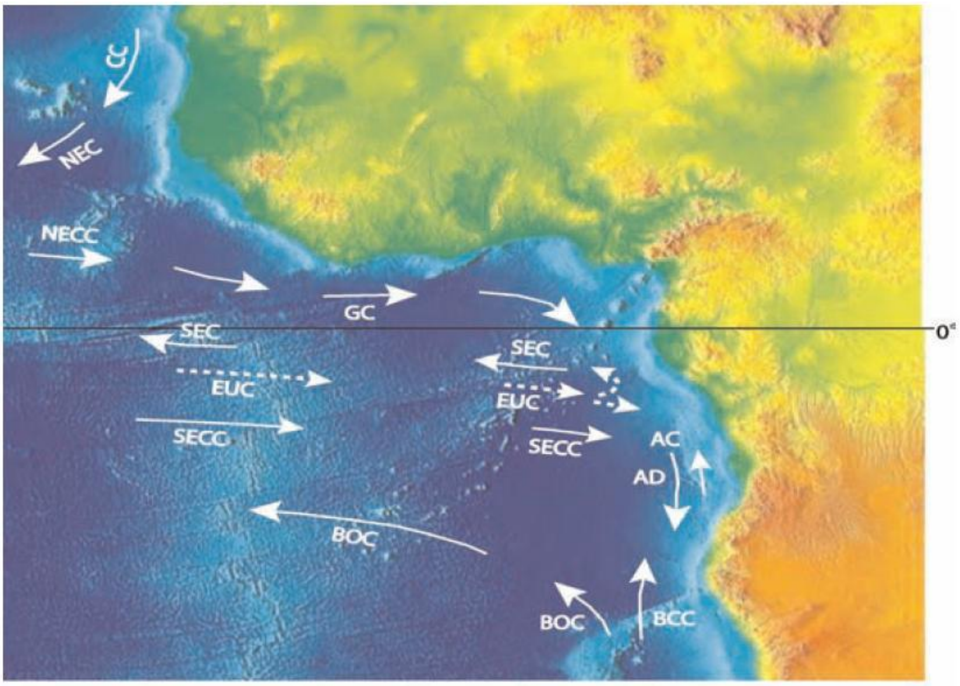

Figure 2-2: The Currents in the South Atlantic in front of the West African coast: Guinea Current (GC), North Equatorial Counter Current (NECC), the Canary Current (CC) and the South Equatorial Current (SEC) [after figure 2-3, GCLME Regional Coordinating Unit (2006)]

INTER-TROPICAL CONVERGENCE ZONE

The Inter-Tropical Convergence Zone (ITCZ) is the area where the Northern and Southern Trade Winds meet. The ITCZ circles around the Earth near the Equator. The zone separates the dry, continental, heavy air masses from the wet, maritime, lighter southern winds. The zone is unstable and rain-generating. The northern and southern migration of the ITCZ induces the seasons at the tropical Atlantic Ocean and at the West African coast (Binet and Marchal, 1993; UNEP, 2004). Generally, the ITCZ starts moving northward in June, and thereby it crosses the shoreline of the West African coasts. This causes the first rains to occur and therefore, the rivers on the West African land masses subsequently obtain high water levels. From September to November, the ITCZ migrates to the South, entailing the second and most important flooding season (Binet and Marchal, 1993).

TIDE

The tide at the West African coast is semi-diurnal. It occurs nearly simultaneously along the coast with an average tidal range of approximately 1 m, which increases eastward a little. The currents the tide induces in longshore direction are quite weak, but near inlets and estuaries the tidal currents are of importance (Allersma and Tilmans, 1993).

EUSTATIC SEA LEVEL RISE

As the West African coast is generally low-lying and comprises among others marshes, lagoons, swamps, estuaries and barrier beaches, increase of the sea level has considerable negative effects. For instance, the best-known negative result is coastal recession, due to a redistribution of the sediment as reaction to the sea level rise (SLR). Among others, Allersma and Tilmans (1993) and Ibe (1990) state this increase of the sea level is an important cause for coastal erosion at Nigeria. If the sea level rises, flooding happens more frequently and its effects are more devastating. A higher sea level also leads to more severe storm surges, accompanied by powerful waves. In section 3.4.2 and in appendix C.7 the effect of SLR on the coastal morphology is discussed further.

2.1.2 NIGERIAN CONTINENTAL SHELF

The Nigerian continental shelf, together with the basin of the Gulf of Guinea in the South Atlantic Ocean, originates from the beginning of the Cretaceous, with the separation of South America and West Africa, about 180 million years ago. The separation of the two continental land masses resulted in a deep ocean basin and in the rise of the continental margins (Awosika, 1990).

Unlike the other parts of the coast of West Africa, the Nigerian continental shelf is in general very narrow, which is rather unusual for trailing-edge coasts. The western part of the Nigerian shelf is relatively gently sloping with a mean gradient of 1:150 to 1:165. A width of 25 km to 30 km makes it the narrowest part of the shelf. The continental shelf width increases up to about 63 km at the Niger Delta (in Cape Formoso) and further eastwards it extends even more, up to 75 km at Calabar (close to the border with Cameroon) (Awosika, 1990). Consistently along the whole coast, the Nigerian continental shelf breaks abruptly to the continental slope at a depth of 110 m to 120 m (Awosika and Folorunsho, 2010; Ihenyen, 2003).

The Nigerian coastal regions are formed of Tertiary and Quaternary deposits, see Figure 2-3. The recent coastal plain is formed by Pleistocene and Holocene (both Quaternary) deposits, which comprise sands nearshore, silts in moderate depths and clays in deep water (CEDA, 1997). They form, among others, the coastal barrier-islands, beaches and lagoons with heights up to a couple of metres above present sea level. In small bays, the coastal plain has a width of only a few metres while in the broader, sandy coastal parts the plain obtains a width of several kilometres (e.g. up to 35 km in the Niger Delta). Behind and beneath the Quaternary deposits lie the Tertiary deposits, consisting mostly of sandy clays (Allersma and Tilmans, 1993).

In Figure 2-3 the Quaternary deposits are indicated by the yellow surface. The location of Lagos is defined by the green ellipse.

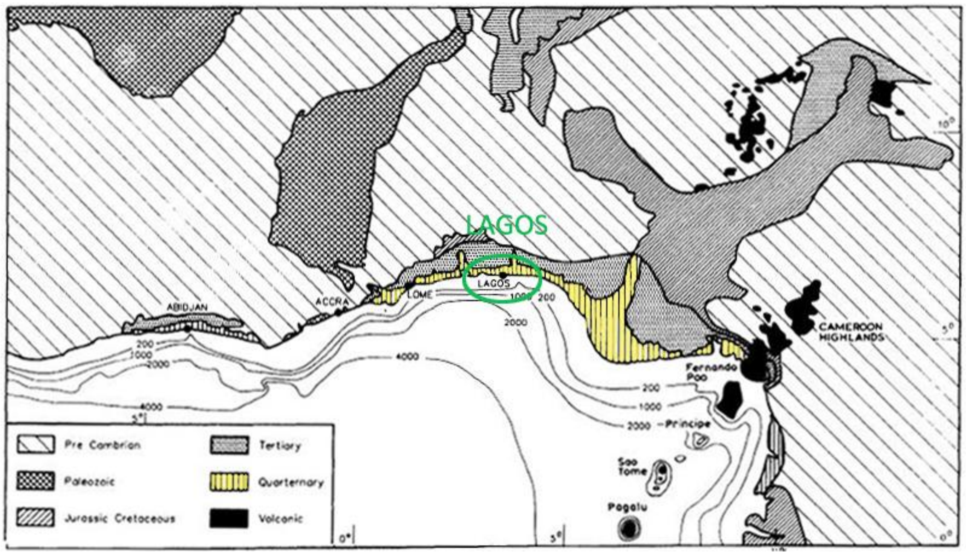

Figure 2-3: Regional geology of the Nigerian Coast, including main bathymetric lines [after figure 2, Allersma and Tilmans (1993)]

Considering Figure 2-3, it can be seen that the coast at Lagos is composed completely of Quaternary deposits, which are the youngest sediments. Therefore the coast at Lagos experiences high rates of subsidence, due to natural compaction and natural dewatering of the soil.

2.1.3 COAST OF NIGERIA

Nigeria is positioned between latitudes 4°N to 14°N and between longitudes 2°E to 15°E. Based on morphology, vegetation and beach type, the Nigerian coast can be divided into four main zones. From east to west, these regions are: the Barrier-Lagoon Complex, the Mahin Transgressive Mud Coast, the Niger Delta and the Strand Coast (Ajao *et al.*, 1996; Awosika, 1990; CEDA, 1997; Okude and Ademiluyi, 2006). In Figure 2-4 the location of the four coastal zones is depicted.

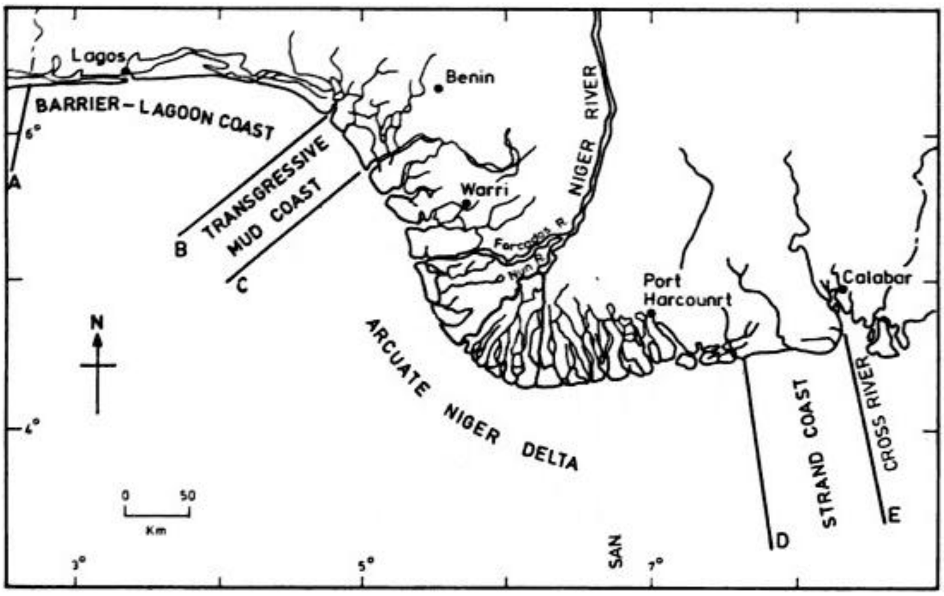

Figure 2-4: The four main zones of the Nigerian coast [after figure 3.1, Ibe (1988)]

In Figure 2-4 it can be seen that Lagos is located on the Barrier-Lagoon coast. A description of, among others, this coastal type is presented in the next section.

NIGERIAN COASTAL ZONES

The Barrier-Lagoon Complex is a continuation of a system of barriers and lagoons covering the West African coast between Cote d'Ivoire and West Nigeria. The coastal stretch comprises low lying islands and narrow beach ridges aligned parallel to the coast, which are backed by several creeks and lagoons. In Nigeria, the Barrier-Lagoon Complex reaches from the western border with Benin to 200 km further eastward, at the western limit of the Transgressive Mud Coast, approximately 100 km east of Lagos. Between the Volta Delta (in Ghana) and Lagos, the outer barrier beach ridges stretch over about 320 km, with only two natural inlets and one artificial inlet intersecting the coast. The outer barrier ridges in the remaining part of the Nigerian Barrier-Lagoon Complex comprise much shorter barrier segments, as many tidal inlets intersect the coast (Blivi *et al.*, 2002). The high energy wave climate induced steep beach profiles at the coastline. The sediments are generally medium to coarse and moderately well sorted, with a fining sequence in grain size eastwards.

The Mahin Transgressive Mud Coast consists of a gentle sloping mud beach that is backed by freshwater swamps and creeks. This coastal stretch has a length of about 75 km, running from east of the Lekki Lagoon to the mouth of the Benin River (i.e. the most western river of the Niger Delta, see also Figure 2-4). This part of the Nigerian coast is very low-lying and does barely contain any sand. The absence of sand is sometimes explained by the presence of the Avon and Mahin canyons, in which sand would be caught and brought offshore. However, as discussed in section C.3, contradicting opinions regarding the role of the canyons exist in literature.

The Niger Delta reaches from the mouth of the Benin River to about 450 km eastward. It forms a major geomorphic feature in the Nigerian coastal zone by occupying about sixty per cent of the entire coast (Oyegun, 1993). The delta contains several ecological zones like fresh water swamps, mangroves, barrier islands, creeks and estuaries. In total 21 tidal inlets and river inlets are connected to the sea through the delta.

The Strand Coast forms an 85 km long coastal stretch between the Niger Delta and the Cameroon border. The coast consists of flat beaches and beach ridge plains, which are backed by mangrove swamps.

OFFSHORE CANYONS

In front of the Nigerian coast three offshore canyons are present, being the Avon, the Mahin and the Calabar canyon, which deeply groove the Nigerian continental shelf and slope. In Figure 2-5 their location is depicted in red and the location of Lagos is shown by the green ellipse.

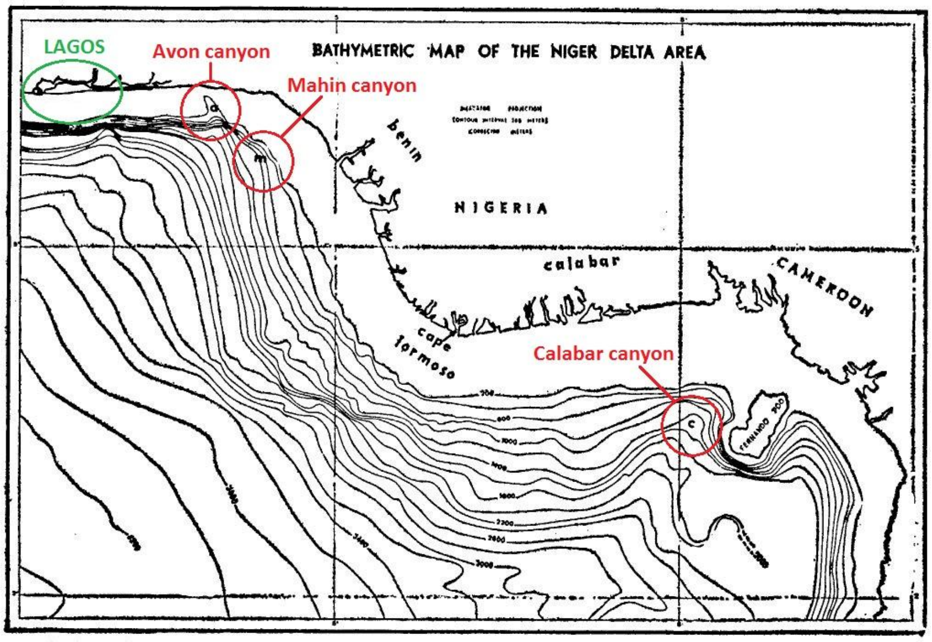

Figure 2-5: Bathymetry of the Nigerian coast, including the locations of the Avon, the Mahin and the Calabar canyon [after figure 3, Mascle (1976)]

In the western part of the Nigerian continental shelf lies the Avon canyon, with a V-shaped profile. It is located at latitude 6˚10’N and longitude 3˚55’E. Its head lies relatively close to the shore, about three to five kilometres away from the coastline, see Figure 2-5. The canyon head has about the same depth as the area surrounding it, which is approximately 18 m. The depth of the canyon increases quickly to more than 340 m, while water depths of the surrounding area are only around 80 m. The width of the canyon is about fifteen kilometres, with the deepest parts located at a depth of 730 m.

The Mahin canyon is located offshore of the Mahin Mud Coast, at latitude 6˚00’N and longitude 4˚25’E. This canyon is U-shaped and double branched. The head lies deeper than the head of the Avon canyon, in a depth of roughly 55 metres. The canyon is relatively short but, with a depth varying between 180 m to 900 m, it is quite deep. It deepens abruptly into the outer continental shelf. The canyon’s width is approximately 1.6 km.

Eastwards offshore of Calabar, at latitude 3˚55’N and longitude 8˚15’E, lies the Calabar canyon. It has a width of approximately 3 km and a depth varying in between 180 to 450 metres (Awosika, 1990; Ibe, 1988; Ihenyen, 2003).

Considering Figure 2-5, it can also be concluded that bathymetric lines are positioned more or less parallel to the coastline, except at the locations of incision by the canyons. In front of Lagos, the coast is quite steep compared to the milder slope in front of the Niger Delta. This can be explained by the many rivers in the Niger Delta, transporting sediment to the coast.

The significance of the canyons to the Lagos coastal system for this study is elaborated in appendix C.3. It is concluded that for the analysis of the Lagos coastal behaviour the canyons do not have a relevant role. Therefore, the canyons are not taken into account in this study.

2.1.4 COAST OF LAGOS

The Lagos coast is part of the earlier described Barrier-Lagoon Complex. This coastal stretch consists of a lot of interconnected lagoons, creeks, lakes, rivers, channels etcetera. The city Lagos is located partly at several densely built islands and partly at the mainland of Nigeria.

THE CITY LAGOS

Lagos is positioned around 6˚27’N and longitude 3˚23’E. In Figure 1-3 an overview of the location of among others the Lagos Harbour Moles, the Commodore Channel, Bar Beach and Lighthouse Beach is already provided. In Figure 2-6 the different parts of the City of Lagos, discussed below, are depicted.

Figure 2-6: Different parts of the City of Lagos [after Google (2011)]

Victoria Island, as mentioned before, is the most commercial part of the city. It houses most of the business buildings of the city. Ikoyi is the area where the most effluent inhabitants and most expats live. This used to be a distinct island; the McGregor Channel, dug by the British, separated it from Lagos Island. When the channel was landfilled, leading to the connection of Ikoyi and Lagos Island into one island, is not known exactly. Banana Island at the eastern side of Ikoyi was created by artificial land reclamation with sand dredged from the Lagos Lagoon. The Lagos Mainland houses most of the inhabitants of Lagos.

The main part of the Port of Lagos is located at Apapa. At Tin Can Island also a part of the harbour is located. At the eastern tip of Snake Island several harbour and shipping activities take place. There are plans for future development of other parts of Snake Island for harbour activities as well. The Badagry Creek connects the harbour to the Commodore Channel. The Five Cowries Creek is a water connection between the Lagos Lagoon and the Commodore Channel. Just behind the Bar Beach the Kuramo Waters are located, connected to the Five Cowries Creek via a small channel.

LAGOS LAGOON

The Lagos Lagoon has a surface area of approximately 200 km^2, which makes it one of the bigger lagoons of the West African coast. The largest river debouching in the lagoon is the Ogun River. In the dry season (from October to May) the river discharge is not of importance, but in the wet season (from June to September) the river can have a significant discharge. Unfortunately, not much is known about the sediment discharge. In Jakobsen *et al*. (1989), an estimation is made for the sediment discharge of the Ogun River. An assumption for the sediment load and for the catchment area provided a maximum sediment discharge of 0.1 million m^3/year into the Lagos Lagoon. However, the sediment input by the Ogun River is not taken into account in this study, because the assumptions used in their approach are very crude and no further information on the sediment discharge could be found.

The Commodore Channel, which is a coastal inlet, is the only significant connection between the Lagos Lagoon and the Atlantic Ocean. The large difference in precipitation between the wet and the dry season causes a significant seasonality in the discharge through the channel. Hence, especially during the wet season the discharge through the Commodore Channel can be large. Subsequently, during the wet season, the water level gradient over the Commodore Channel can become about 0.5 m. Measurements conducted by Royal Haskoning (2011) during the wet season revealed a maximum discharge of almost 10,000 m^3/s.

A characteristic aspect of tidal inlets is the reversal of the flow during transition of the tide into ebb or flood. During flood the water flows from the sea into the channel, directed to the lagoon and during ebb the water flows out to the sea again. As the sea water is more saline than the fresh water in the lagoon, the flow reversal phenomenon is accompanied by density currents in the channel, because the saline sea water is heavier than the fresh water.

However, since this study investigates the long-term morphological development of the Lagos coast, it is assumed that (relatively) short-term phenomena and effects, like the density currents in the inlet and the seasonality in the river discharge, are averaged out on the long-term. Therefore, these effects are not taken into account in this study. Moreover, other short-term phenomena as sea waves and storm surges are also not explicitly accounted for in this study. It is assumed that they are averaged out over the representative yearly wave climate.

In section 3.4 more attention is paid to the characteristics of the Commodore Channel and the Lagos Lagoon and especially to their influence on the morphological behaviour of the Lagos coast.

2.2 HISTORICAL COASTAL DEVELOPMENT

After a first glimpse at the literature considering the historical coastal development of Lagos, a couple of interventions at the scale of the Lagos coast clearly stand out:

- The construction of the Lagos Harbour Moles between 1908 and 1912
- The start of beach nourishments at Bar Beach and the start of dredging in both the Commodore Channel and Lagos Lagoon, around 1958
- The commencement of the construction of Eko Atlantic City in 2009

In the study these actions are used to classify the historical development of the Lagos coast. The history is divided into four periods; each having its specific characteristics. The (schematised) periods that are investigated are the following:

❖ Before 1910	*No structures present*
❖ Between 1910 and 1960	*Influence of moles only*
❖ Between 1960 and 2010	*Moles, beach nourishments and dredging*
❖ After 2010	*Moles, beach nourishments and Eko Atlantic City*

Not only at Lagos, but also at other parts of the West African coast several human constructions can be found, which have their own particular impact on the coastal morphology. The impact could be only local but it is investigated whether there are human factors that have a greater, border crossing influence.

Before the human constructions in the other West African countries are studied, the area of interest for this study is redefined. In order to do this, it must be kept in mind that the spatial scale and the time scale are coupled. If the spatial scale of a certain feature becomes larger, also the time scale increases and vice versa. The time scale defines how long it takes a coastal system to adjust to its (new) equilibrium, for instance after a distortion.

If one studies human interferences at the coast, usually this occurs at the so-called 'engineering scales'. This comes down to a spatial scale of one to hundred kilometres and a time scale of years to decennia (Bosboom and Stive, 2010).

Taking this into account, it can be concluded that a great part of the earlier described West African coast can be left out of a more detailed study. If engineering scales are considered, Cote d'Ivoire and Ghana are located too far from Lagos.

In setting the western boundary of the preliminary study area, it is referred to for instance Allersma and Tilmans (1993), who concluded that the sediments of the coast of West Nigeria come from as far as the Volta Delta (i.e. positioned in the most eastern part of Ghana, about 320 km west of Lagos). Whether the Volta Delta does supply sediment to the West Nigerian coast or not, is subject to discussion in literature however.

So, on account of these uncertainties regarding the role of the Volta Delta as a sediment source, it is decided as a first approach for this study to include the Volta Delta in the study area. In doing this, it is presumed that after more time, for instance in a modelling study, more insight in the extent of relevant coastal stretch and e.g. the role of the Volta Delta can be acquired.

In setting the eastern boundary of the study area, the difference in coastal types of Nigeria is taken into account. The Mahin Transgressive Mud Coast is a completely different type of coast than the Barrier-Lagoon Complex Lagos is part of, as it barely contains any sand.

The eastern boundary of the area of interest is therefore taken at the transition from Barrier-Lagoon Complex to Mahin Transgressive Mud Coast, roughly 100 km eastward of Lagos. In Figure 2-7 the preliminary study area is depicted.

Figure 2-7: Preliminary area of interest [after Google (2011)]

2.2.1 BEFORE 1910

NIGERIA – LAGOS

Before the Lagos Harbour moles were constructed, the tidal inlet and its adjacent beaches constituted a very dynamic coastal system, of which the natural coastline remained approximately in a dynamic equilibrium. The persistent swell waves propagating to the shore from a south – southwest direction induced a longshore sediment transport to the East. This facilitated the existence of an underwater sandbar in front of the tidal inlet, which was a serious hindrance for ships wishing to enter the Lagos Harbour. Besides the small drought permitted to pass this sandbar also the heavy breaking of incoming waves on the shallow area caused the Lagos Harbour being hard to reach. And because the position and the depth of the sandbar kept on changing[3], such that bathymetric charts were not very reliable, it became an even bigger venture to sail to the Lagos Harbour (Smith, 1979). If one studies Figure 2-8 and Figure 2-9, which are both charts of Lagos in a natural condition (i.e. without human interferences), the different positions of the shallow bar and ebb-tidal shoals can be noticed. This emphasizes the dynamic character of the system.

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[3] In (Coode and Son, 1898) it is stated that: ”The soundings near the Bar alter sometimes as much as three feet in one week and the position of the Channel is constantly changing”.

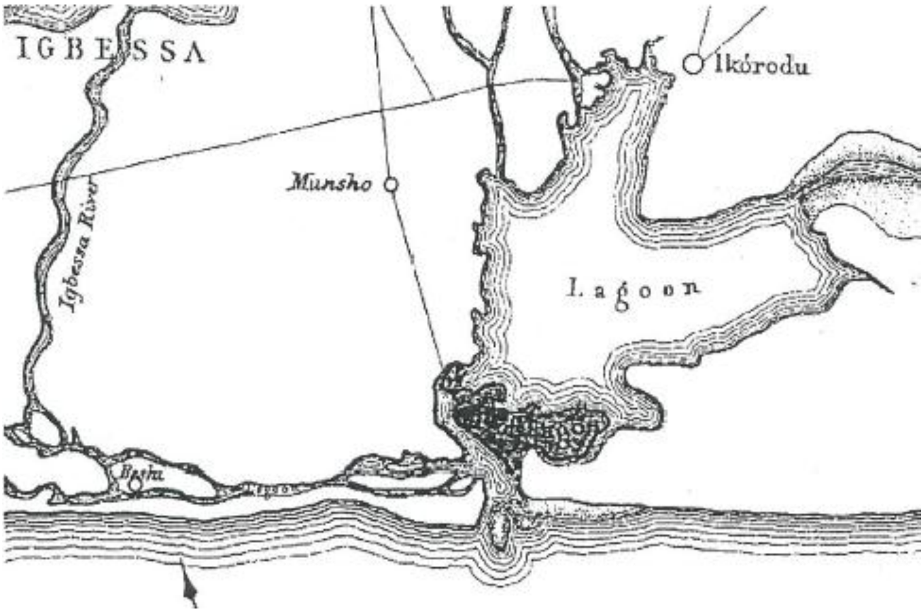

Figure 2-8: Map of Lagos in 1865 [after Ord (1865)[4]]

The Lighthouse Beach is positioned on the eastern end of a long and narrow spit, as can be seen in Figure 2-8. The spit has its origin roughly 100 km eastward, near Cotonou, Benin. The spit formation is facilitated by the great amount of sediment transported by the wave-induced littoral drift. Its existence indicates the predominance of waves over tides, as spit formation requires waves and wave-induced currents to arrange the accumulation of sediments (Bosboom and Stive, 2010). It has been mentioned above that in literature, various authors do not agree on the source of the sediment in the West African coastal system. Some assume the main source is the sediment supplied by the Volta Delta. But, for instance, Ibe (1988) states that sediment is also supplied to the littoral drift by other fluvial input from, among others, the small river Ogun (discharging in the Lagos Lagoon). According to Blivi *et al*. (2002), both the Ouémé River (discharging in the lagoon near Cotonou) and the Mono River (in Benin, near the border with Togo) are also sediment suppliers of importance[5].

The spit ends at the interruption of the coast by the inlet to the Lagos Lagoon, which is kept open by tidal forces and, in the wet season, also by river discharge. At the inlet the longshore sediment transport is interrupted by the cross-shore tidal (and river) current. The tidal current induces the velocity of the longshore drift to decrease and therefore the drift loses its transport capacity.

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[4] This is the original source. However, figure was found in: (Shanghai Waterway Engineering Design and Consulting Co. Ltd., 2007)

[5] In section 3.1.2 and in appendix C.1 more attention is paid to the relevant coastal stretch for the analysis of the Lagos coast.

Subsequently, sediment becomes deposited on a sandbar updrift of the tidal inlet, elongating the spit. Once a bar has been developed, it enhances further sand accumulation at that location, as the bar by itself also forms an obstruction for the longshore sediment transport. In Figure 2-9 the sand bar formation and the sediment accumulation in front of the tidal inlet can be distinguished.

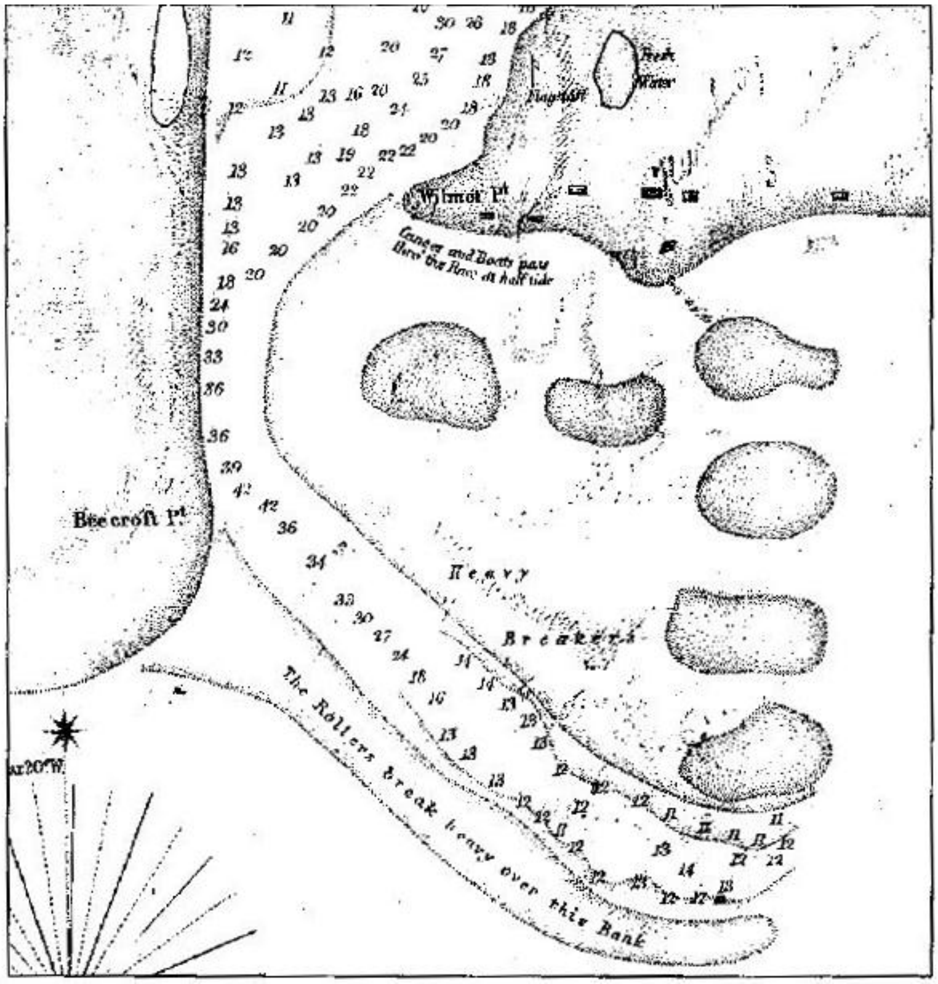

Figure 2-9: Shallow areas near Lagos Harbour entrance in 1858 [after figure 2, (Royal Haskoning [2], 2001)[6]]

If one looks at Figure 2-8 and Figure 2-9, the more northerly position of the Bar Beach in relation to Lighthouse Beach is clearly visible. This could be explained by a couple of coastal processes.

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[6] This figure is used in the report of Royal Haskoning (2001), without reference to the original source. It is presumed that the original source is the report 'Lagos Harbour Report' by M. Coode & Son, dated 1898.

First, due to the updrift sediment accumulation (at the spit), the sediment supply at the shadow zone of the bar, at the downdrift side, is a decreased somewhat. And a little more east of the inlet the littoral drift regains its former transport capacity. Therefore, the gradient in longshore sediment transport along Victoria Island is positive, which induces some erosion of Victoria Island. This is a general phenomenon at tidal inlets, as described by Costas and FitzGerald (2011).

However, this phenomenon would, most probably, cause a local effect only. Therefore, there must be a greater, more dominant cause for the erosion. Hence, it is assumed here that, in order to explain the great extent of the erosion, the lagoon must have a significant influence on the morphology. Most likely, it was expanding, for instance due to a rise in sea level, due to abundant rain input or by erosion of its banks, and therefore the lagoon was demanding sand to restore its equilibrium. The sediment was supplied to the lagoon by the flood tidal currents and consequently, a part of the sediment transported into the tidal inlet did not return to the longshore sediment transport.

Looking at Figure 2-9, the shallow areas of the ebb-tidal delta near the harbour entrance are visible. Using the classification of ebb-tidal deltas by Oertel (1985)[7], the former conclusion about the Lagos inlet being characterized by a prevailing, wave-induced easterly longshore current, which constitutes a greater force than the tidal forces, can be supported. The south-easterly orientation of the channel margin bar indicates the large influence of the west – east directed longshore sediment transport. It can also be concluded that bypassing, at least partially, took place via the shallow sand bar and the ebb-tidal delta shoals[8]. These shoals would have migrated from the updrift to the downdrift barrier island.

On the other hand, the shallow areas near the Victoria Island depicted in Figure 2-9, could also be residues of a previous channel margin sand bar. Once the channel flow resistance would have become too high, because the sand bar had become very long, the tidal flow could have breached through the sand bar to shorten its flow path. Subsequently, a new tidal channel would have been formed and a new channel margin sand bar would start to develop. Meanwhile, the parts of the former sand bar would lie in a slightly sheltered area. And during moderate wave conditions they could have become transported onshore.

The former consideration could explain why some authors, for instance Webb (1960) and Ibe (1988), report that the Bar Beach and Lighthouse Beach were positioned more or less in one line, for instance as depicted in Figure 1-4. The difference in coastline position drawn in Figure 1-4 and in Figure 2-8 could also be explained by the potential occurrence of a very severe storm. While striking the coast, such storms can cause all the sediments from the shallow areas to become stirred up and transported away.

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[7] See appendix B.1

[8] See appendix B.3.

A severe storm would than act as some kind of ‘set-back’ event; repositioning the layout of the whole ebb-tidal delta, which could result in a smoothening of the transition between the Bar Beach and the Lighthouse Beach.

Yet another explanation of the difference in coastline position in the two figures mentioned, could be provided by the moment of measurements of the Lagos coast. The shallow ebb-tidal delta shoals could have fallen dry at low water, such that they seemed to be part of the coast. On the contrary, if the coastal measurements would have been performed during high water, the shallow parts of the ebb-tidal delta would have been submerged, such that the difference in coastline position became visible. However, in this study it is assumed that, before 1910, the coastline of the Bar Beach was already positioned more northerly than the Lighthouse Beach coastline.

Summarizing, it can be concluded that the natural coastal system at Lagos was very dynamic. The position of the shallow parts of the ebb-tidal delta kept on changing position. This is certainly supported by the difference in shallow areas as depicted in Figure 2-8 and Figure 2-9. Furthermore, it must be kept in mind that most of the considerations made in this section are based on hypotheses, drawn up with help of the two figures presented.

It is assumed that before men started to interfere with the coast (i.e. before 1910) the Lagos Lagoon was demanding sediment to maintain its morphological equilibrium. Sea level rise is indicated as the main cause for the disturbance of the morphological equilibrium of the lagoon. The sediment would have been provided to the Lagos Lagoon by the flood tidal currents, which imported the sediment transported by the longshore current. Therefore the ‘natural’ location of the Bar Beach was already a little further north than the Lighthouse Beach.

2.2.2 BETWEEN 1910 AND 1960

NIGERIA – LAGOS

Harbour Moles

In order to tackle the navigational problem of the migration and frequent siltation of the inlet providing access to the Lagos Port (Ibe, 1988; Nwilo, 1997), the British[9] decided upon the construction of three stone moles, which had to fix the deep dredged entrance channel. In Figure 2-10 a map showing the planned locations of the moles is depicted. Comparing this map to Figure 2-9, it appears that the West Mole would be located on the former channel margin bar and that the position of the East Mole was chosen such that it would be placed on the shallow parts of the ebb-tidal delta.

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[9] Since 1861 Nigeria was a British Colony (after first being a British Protectorate for ten years).

Figure 2-10: British plan for locations of the three Lagos Harbour Moles [after Coode and Son (1898)]

The construction of the moles was started in 1908 and finished in 1912. The East Mole was the first one that was completed. Immediately after construction, it started to trap sediment, transported by the eastward longshore sediment transport. The several shallow shoals of the ebb-tidal delta (as depicted in Figure 2-9) subsequently merged into one large spit, the 'Eastern Spit', located at the channel side of the East Mole (Royal Haskoning [2], 2001).

After the West Mole was completed, sediment became trapped at its updrift side. Therefore the width of the Lighthouse Beach started to increase. This sediment accumulation also induced the former ebb-tidal delta to start functioning as a sediment source to the longshore current and the lagoon.

Concluding, due to the sand trapping by the West Mole, the ebb-tidal delta would have disappeared over the years. In appendix B.1 the potential equilibrium volume of the delta is computed. Although the 'real' volume of the delta is unknown, it is concluded that the delta could have had an alleviating effect on the erosion downstream.

The main flow in the channel became located at the western side. The flow was deflected towards the Training Mole, which resulted in a deepening of the western part of the Commodore Channel (Royal Haskoning [2], 2001).

As the littoral drift in front of the Bar Beach still had a certain transport capacity, but barely contained any sediment, erosion of the Bar Beach started; in order to provide for a sediment source to the drift. Another factor enhancing local coastal erosion, that has to be added to the sand trapping at the West Mole, was the eddy formation by the East Mole (Ibe and Antia, 1983; Ibe *et al.*, 1991). These eddies caused more sediment to become suspended by generating extra turbulence.

In sections 3.2 and 3.3 and in appendix C.5 more information can be found on the erosion and accretion rates and volumes.

The Tarkwa Bay, which is the 500 m wide coastal stretch between the West Mole and the Training Mole, accreted about 0.5 km in between 1912 and 1980. This was probably the result of sediment transport into the tidal inlet by the flood tides (Royal Haskoning [2], 2001). Because the sediment volume associated to this beach expansion is negligible compared to the volumes of accretion and erosion at the adjacent two beaches (see appendix C.5), it is not taken into account in this study.

Sea level rise

It is assumed that sea level rise (SLR) has an important role in the Lagos coastal system. In section 2.2.1 it is presumed that the SLR was the main cause for the disturbance of the morphodynamic equilibrium of the Lagos Lagoon.

Besides the fact that the Lagos coastal area is composed of relatively young sediments (see section 2.1.3), which are still subject to natural compaction, also the large amount of water extraction from the Lagos coastal area for drinking purposes causes significant land subsidence. Therefore, it is assumed that the relative sea level rise at Lagos is quite big and that it is an important factor in the behaviour of the coastal system.

For instance, SLR induces an increase of depth in the Lagos Lagoon. Thereby, it disturbs the morphodynamic equilibrium of the lagoon, which subsequently starts to import sediment. So, the effects of the SLR add up to the, already present, natural sand-demand of the lagoon, as discussed in section 2.2.1. In section 3.4.2 the effects SLR causes are elaborated more quantitatively.

2.2.3 BETWEEN 1960 AND 2010

The construction of the moles at Lagos was one of the first human interferences in the West African coastal system. And it was up until 1962, that it was even the only significant coastal construction of men. In the earlier defined area of interest, two other harbours and a dam were constructed in the time span 1960 – 2010.

BENIN – COTONOU

Cotonou is located circa 100 km west of Lagos, on a coastal stretch in between the Lake Nokoué and the Gulf of Guinea. This lake is connected to the Lagos Lagoon via the complex systems of creeks and tidal channels backing the coast. Via the Lagune de Cotonou (i.e. a channel dug by the French in 1885), the lake is connected to the Atlantic Ocean. Just east of this channel the Port of Cotonou is located, which was finished in 1962. In Figure 2-11 the location of the Port of Cotonou, the Lagune de Cotonou and Lake Nokoué are depicted.

Figure 2-11: Cotonou Harbour [after Google (2011)]

Similar to the Lagos coastal situation, erosion is an enormous problem in Cotonou. The construction of the breakwater for the seaport meant an obstruction in the longshore sediment transport. Subsequently accretion occurred on the updrift side, while the downdrift side started to erode. Already in the 1960's, two additional groynes were constructed downstream the harbour breakwaters to protect the area east of the harbour. Maximum erosion rates of 10 – 15 m/year have been measured. In total roughly 600 m has eroded downstream of the second breakwater between 1962 and 1993 (Tilmans *et al.*, 1993).

GHANA – VOLTA

The Lake Volta connects to the Gulf of Guinea via the Volta Delta. The mouth of the main river is located about 320 km east of Lagos. The biggest feature of the Volta Delta is the Keta Lagoon. The coast west of the Volta Delta is rocky and at its eastern side beaches are present. Allersma and Tilmans (1993) and Ibe (1988) state that the Volta Delta supplied sediments to the coasts of East Ghana, Togo, Benin and to West Nigeria as well, via the littoral drift. Some authors, e.g. Anthony and Blivi (1998), even state it is the main source of sediment to all the coasts of the Bight of Benin.

Between 1961 and 1965 the Akosombo Dam was built, to provide electricity via hydropower. It is positioned approximately 60 km upstream of the river mouth (Anthony and Blivi, 1998). This dam induced a reduction of sediment in the coastal system in two ways.

The first is that the sediment is getting trapped in the reservoir where it settles, whereas the second influence is the reduction of the transport capacity of the river, as its discharge becomes more regulated (Jakobsen *et al.*, 1989). Allersma and Tilmans (1993) estimate that the Akosombo Dam led to a reduction of the sediment amount supplied to the coast by the Volta River to sixty per cent of its original amount. Among others, the coast at the town Keta suffered severe erosion, entailing almost 1 km of coastal retreat (Anthony and Blivi, 1998).

Whether the Akosombo Dam does also have a significant effect on the sediment supply in West Nigeria is subject to several contradictory views in literature. For instance, Jakobsen *et al.* (1989) state that the impact of the Akosombo Dam is limited to the local coast only, because erosion of the south coast of the Volta Delta (e.g. at the town Keta) would constitute a new sediment source to the longshore drift. In section 3.1.2 the coastal stretch relevant for the Lagos coast is investigated in more detail.

Figure 2-12: Volta Delta [after Google (2011)]

TOGO – LOMÉ

In 1967 the Lomé Harbour in Togo was inaugurated. The city lies about 250 km west of Lagos. The breakwater of this deep water seaport meant a notable disturbance in the littoral drift. West of the structure the coast accreted almost one kilometre, inducing considerable erosion of several hundred metres at the eastern side, see Figure 2-13. To cope with the erosion and to protect the nearby villages, a groyne field was constructed in 1988. The nearby coast was approximately stabilised by this field. The downdrift coast in West Benin, on the contrary, experienced exacerbated erosion rates (Anthony and Blivi, 1998).

Figure 2-13: Harbour of Lomé [after Google (2011)]

NIGERIA – LAGOS

As the breakwaters at the Lagos coast were present for about fifty years already, the erosion of the Bar Beach coast had become tremendous in 1960. Not only had the beach disappeared greatly, also the root of the East Mole was in danger of becoming undermined, because there was hardly any sand present next to it. It can be concluded that at Lagos, the coast reacted just as the coasts around the other West African artificial structures: accretion updrift and considerable erosion downdrift. Especially the effects of the Cotonou Harbour can be compared to the impact of the Lagos Harbour Moles, as similar rates of annual erosion occur.

Nourishments at Bar Beach

As of 1958 the Lagos State and the Federal Government started to apply erosion control measures at Bar Beach. The first action they undertook was the strengthening of the foot of the East Mole by a groyne, to prevent a breakthrough towards the Port of Lagos. After completion of this construction, the most frequently applied erosion control measure has been beach nourishment. If one considers all the measures taken and especially, if one looks at the frequencies and volumes of the artificial sand supplies, it turns out that enormous amounts of sediment have been dumped on the beach over the years. In Table 2-1 the erosion mitigation measures taken at Bar Beach are summarized.

Table 2-1: Erosion control measures applied at Victoria Island since 1958 [after Ibe (1988), van Tonder *et al*. (2002), Okude and Taiwo (2006) and Shanghai Waterway Engineering Design and Consulting Co. Ltd. (2007)]

Year	Action
1958	Construction of a shore-parallel groyne at foot of East Mole, to prevent its undermining due to shoreline erosion.
1958 – 1960	Dumping of sediment dredged from Commodore Channel at the extremity of the East Mole, for dispersal along the beach by waves.
1960 – 1968	Permanent pumping station built on the East Mole, supplying an average of 0.66 million m^3/year of sediment from the Commodore Channel to the beach.
1969 – 1974	Some artificial sand replenishment (however, no reliable records of volumes or frequency available).
1974 – 1975	3 million m^3 of sand dumped and spread on the beach, with a self-discharging Trailing Suction Hopper Dredger (TSHD).
1977	Some sand nourishment by a self-discharging TSHD (volume unknown).
1981	2 million m^3 of sand dumped and spread on the beach.
1985 – 1986	3 million m^3 of sand dumped on the beach, with the use of a TSHD and a Cutter Suction Dredger (CSD). Before the start of the works in April, the culvert to the main boulevard parallel to the shoreline was already being undermined by the waves at some locations.
1990 – 1991	5 million m^3 of sand dumped on the beach, with the use of a TSHD, a CSD and a booster station. Before the work started in August 1990 almost all of the sand of the former nourishment had been washed away.
1994 – 1995	4 million m^3 of sand, dredged 29 km offshore, deposited on the beach, with the use of a TSHD, a CSD and a booster station.
1996 – 1997	Approximately 2 million m^3 of sand deposited on the beach, with the use of a TSHD, a CSD and a booster station. The beach obtained a width of 115 m. In September 1999, however, it was observed that this sediment had been washed away.
1998	Construction of a T-groyne at the back of the Federal School of Fisheries (which is just at the East of the East Mole) as an emergency measure.
1999	2 million m^3 of sand dumped and spread on the beach, with the use of a TSHD, a CSD and a booster station.
2002 – 2003	More than 2 million m^3 of sand dredged and a renovation of the Ahmadu Bello Way (the road along the Bar Beach).
2006	Construction of 1 km long Xbloc revetment.

Referring to Table 2-1, the frequency at which the beach has been nourished gives an indication of the high erosion rates. It can be concluded that none of the nourishments performed over the years had a permanent, positive influence on the beach state. Among others, Shanghai Waterway Engineering Design and Consulting Co. Ltd. (2007) mentions the ad hoc manner that erosion is dealt with. It seems that the erosion control measures (mostly nourishments) were executed only if infrastructure or buildings were in direct, perceptible danger.

Moreover, no additional measures were taken to protect the nourished beach, for instance by fixing the nourishments by structures. Furthermore, it is discussed by, among others Awosika *et al*. (1999) and Ibe *et al.* (1991) that the sand used for nourishment was not suited for the Bar Beach due to the difference in sediment composition between the nourished sediment and the native sediment. Yet another factor influencing the ineffectiveness of the nourishments is the location of dredging. If this occurs too close to the beach (i.e. in the foreshore), the equilibrium between the beach and the inner shelf is disturbed. However, it is unfortunately not known where exactly all nourished sediment was dredged.

Sea level rise

For reasons of simplicity, it is assumed that the SLR in the time span 1960 – 2010 has been the same as in the time span 1910 – 1960. The amount of the SLR and its effects are discussed further in section 3.4.2.

Dredging of Commodore Channel

Since the Commodore Channel is the entrance channel to the Lagos Harbour, it should maintain a minimum navigational depth. Therefore, the channel is dredged often. The dredging of the channel started around 1960 and it is assumed that the dredging will continue in the future. How much sediment is taken from the channel is, unfortunately, not known exactly. In section 3.4.3 more attention is paid to the dredging volumes in the Commodore Channel.

Dredging of Lagos Lagoon

Another problem aggravating the coastal erosion is the phenomenon of sand mining and dredging in the lagoon, both being considered under the umbrella term ‘dredging of the lagoon’. Around 1960 the practise of sand extraction became organised in local, professional organisations (DDH, 2008). However, also a lot of illegal dredging is executed in the Lagos coastal area. Because little information is found on the use of the dredged sediment, it is assumed here that all sediment is used for construction activities and artificial land reclamation in the lagoon.

The exhaustive dredging is a serious erosion amplification, due to two reasons. Firstly, large sediment volumes are extracted from the coastal system, which constitutes a direct sink in the coastal system. Secondly, by withdrawal of the sediment, the morphodynamic equilibrium of the lagoon is disturbed.

Just as the reaction to SLR, it induces the lagoon to start importing sediment in order to restore its equilibrium. Therefore, the dredging can be schematised as a sink in the Lagos coastal system.

Data on dredged volumes are hard to acquire. One exception hereupon is a report written by Awosika and Dublin-Green (1994)[10], which did provide some data on dredging related to a large land reclamation project for Lekki. It is stated that more than 13 million m^3 of sediment was dredged in the lagoon between 1984 and 1989, and they estimate that another 66 million m^3 of sand would be required for completion of the project after 1989. Although it is not mentioned where these data are derived from, the data do serve as an indication of the enormous volumes associated with the dredging. In section 3.4.4 the dredging of the lagoon is further elaborated.

Deforestation

Deforestation of the coastal lagoon system, mainly for the timber industry, induces erosion to increase as well. The removal of trees and other vegetation leads to less protected land, because the roots of the vegetation are no longer able to enforce the soil and to retain the sediments. Together with the sand mining in the creeks and lagoon, deforestation leads to very rapid devastation of the barrier-creek system (e.g. many landslides) at Lagos. This effect is kept in mind in the study, but, because the effects are hard to quantify in terms of sediment volumes, it is not studied in more detail.

2.2.4 AFTER 2010

Eko Atlantic City project

The most prominent man-made construction of this period is the Eko Atlantic City project, in front of Bar Beach. In section 1.2.2 an introduction into this project is provided. The most important aspect of the project regarding this study is the approximately 6.5 km long revetment, which fixes the sediment of the land reclamation. The toe of the revetment reaches to depths of -7 m to -10 m.

Sea level rise

Just as for the time span 1960 – 2010, it is assumed that the SLR in the time span 'After 2010' will be equal to the SLR in the preceding time spans.

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[10] Quoted in (CEDA, 1997) Original source: AWOSIKA, L.F. and C.O. DUBLIN-GREEN (1994), Sand mining in the Lagos and Lekki Lagoons. Journal of Mining and Geology, Vol. 30, No. 1, pp 137-139.

Dredging of Commodore Channel

As mentioned before, it is assumed that the dredging of the Commodore Channel will continue after 2010.

Dredging of Lagos Lagoon

Personal communication provided the information that plans are being made to perform more land reclamation in the Lagos Lagoon (Geldenhuys, 2011), associated with enormous amounts of sediment to be dredged from the lagoon. Although it is yet unknown whether these plans will actually be executed in the first ten years after construction of the Eko Atlantic City project or not, the potential effects of the dredging executed for the land reclamation are taken into account in this study.

3 CONCEPTUAL MODEL

In the previous chapter an analysis of the historical coastal development at Lagos is presented, in which the dominant processes and mechanisms are discussed. The sediment fluxes, sinks and sources in the area of interest have been elaborated qualitatively. In this chapter the conceptual model of the morphological behaviour of the Lagos coast is described. First the setup of the model is discussed in section 3.1.

In order to set-up hypotheses on the future morphological development of the Lagos coast, these sediment fluxes, sinks and sources have to be quantified as well as possible. Therefore, some more assumptions and calculations, regarding the morphological elements in the system, are made in section 3.2, section 3.3 and section 3.4.

Once the calculations are made and subsequently, all processes and mechanisms have been assigned a magnitude, the sediment balance of the coastal system is assessed per time span. In order to do this clearly, all sediment fluxes, sources and sinks are expressed as a percentage of the total volume of longshore sediment transport. In section 3.5 the sediment balance of each period is represented graphically in the summary of the historical coastal development.

Using these balances, it is investigated which factors have the main influence on the (expected) morphological development of the coast of Lagos. From here, hypotheses can be made upon the long-term impact of Eko Atlantic City. In section 3.6 these hypotheses are discussed and the theoretical base for the modelling study is set.

3.1 SETUP OF CONCEPTUAL MODEL

Before the conceptual model is constructed, first the area of interest is further defined. To do so, first the uncertainty regarding one of the most important coastal processes, being the longshore sediment transport, is discussed and assigned a value. Subsequently, the theoretical setup of the sediment balances is presented.

3.1.1 VOLUME OF LONGSHORE SEDIMENT TRANSPORT

In order to set up the sediment balances, thus in order to express all sediment fluxes, sources and sinks as a percentage of the total longshore sediment transport (LST), the volume of LST needs to be specified.

The analysis of the coast of Lagos is an iterative process. The LST volume found using the Unibest software model (see section 4.4) matches quite well to the values of LST found in literature (i.e. 500,000 to 1,000,000 m^3/year). Therefore in this chapter the volume of LST used in the calculations is 600,000 m^3/year.

3.1.2 FURTHER BOUNDING OF PROJECT AREA

Referring to section 1.3, the objective of this thesis is to investigate the long-term behaviour of the coastal stretch around Lagos with the presence of Eko Atlantic City. As explained in section 2.2, on 'engineering scales' years to decennia are considered. The long-term impact of Eko Atlantic City is therefore defined as the impact occurring in the first ten years following construction of the project.

To define the relevant 'coastal stretch' for continuation of this study, the 'single line theory' of Pelnard-Considère (1956)[11] is applied. The basic assumption in the single line theory is that the cross-shore beach profile does not change its shape. This theory can be used to investigate, among others, the influence of structures on the adjacent coastline. The length of the coastal stretch at which accretion and erosion occurs and the value of the coastal expansion respectively retreat can be quickly assessed using this theory (Bosboom and Stive, 2010). In appendix C.1 more information on the single line theory is presented.

The effect of the human-made structures is investigated until 2020. First the impact of the Cotonou Harbour is studied, as this is the construction nearest to the Lagos Harbour. In Tilmans *et al.* (1993) it is stated that the volume of longshore sediment transport at Cotonou is roughly 1.25 million m^3/year and the mean angle of wave incidence relative to coastline orientation at Cotonou is approximately 22°, which equals around 0.38 rad.

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[11] Quoted in Bosboom and Stive (2010)

In appendix C.1 it is concluded that the Cotonou Harbour does not have an effect noticeable in Lagos in 2020. Sixty years after construction (i.e. roughly around 2020), the effect of the Cotonou Harbour reaches a maximum distance of 22 km downstream.

So, in setting the boundaries of the study, it is investigated how far updrift and downdrift the influence of the Lagos Harbour Moles can be distinguished. The volume of longshore sediment transport (LST) at Lagos used is 600,000 m³/year and the relative angle of wave incidence is about 10°. In appendix C.1 the width of the area of interest is found to be approximately 50 km. Figure 3-1 depicts the area of interested for the conceptual model.

Figure 3-1: Area of interest for conceptual model [after Google (2010)]

3.1.3 SETUP OF SEDIMENT BALANCES

The assumption underlying the setup of the sediment balances is that far upstream and far downstream of the inlet, beyond the influence of the moles, the volume of LST is 100 per cent, schematised by 'S'.

Furthermore, in the schematisation of the Lagos coastal system, the balance is formulated such that every sink and source is expressed as a percentage of 'S'. In Figure 3-2 the schematisation of the sediment balances is depicted.

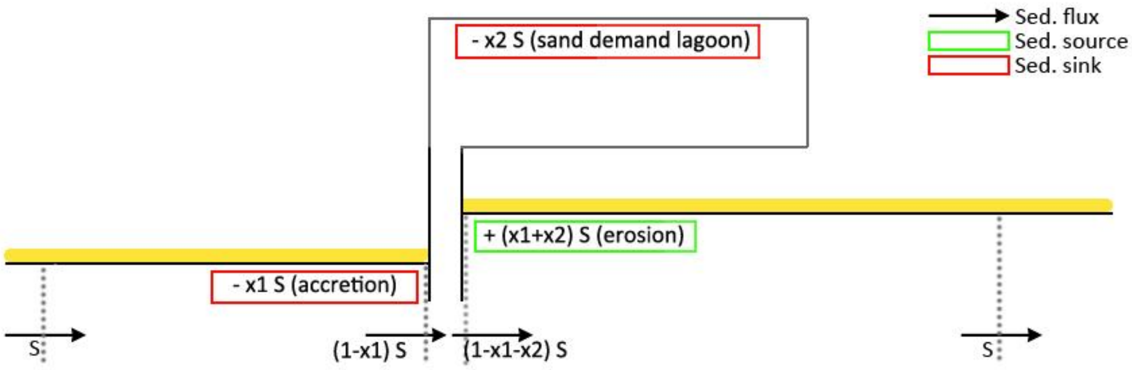

Figure 3-2: Schematised sediment balance

In general, an initial LST volume of 'S' arrives at the Lighthouse Beach, where a certain part (e.g. $x_1 \cdot S$) is blocked by the West Mole. This is schematised as a sink, as the accretion means withdrawal of sediment from the longshore current. Subsequently, a part of the LST volume, defined as $(1 - x_1) \cdot S$, bypasses the West Mole. The sediment volume that bypasses the West Mole is partly transported into the inlet and into the lagoon by the flood tidal currents. Due to a certain sand demand of the lagoon, some percentage of the sediment remains in the inlet or lagoon (e.g. $x_2 \cdot S$). This entails a reduction in the sediment volume that bypasses the East Mole, which is a volume of is $(1 - x_1 - x_2) \cdot S$ (see Figure 3-2).

Therefore, the longshore current east of the East Mole has a deficit of sediment. Hence, erosion of the Bar Beach occurs, to supply the longshore current with sediment. If the coastal system is in balance, the erosion provides an amount of $(x_1 + x_2) \cdot S$ of sediment to the littoral drift. The erosion is thus schematised as a source, while the sediment import into the lagoon and into the Commodore Channel is schematised as a sink.

3.2 COASTAL STRETCH UPSTREAM OF WEST MOLE

In this section the morphological development of the Lighthouse Beach is elaborated per period.

3.2.1 BEFORE 1910

The analysis of the historical development of the Lagos coast (see section 2.2) showed that before 1910 the Lagos coastal system was very dynamic. Sediment transported eastward by the longshore current became deposited on the eastern end of the spit (i.e. the location of the Lighthouse Beach) and in the ebb-tidal delta. It is assumed that the sediment accumulation at the end of the spit did not constitute a sink in the coastal system, because gradually the sediment became transported further downdrift. Partly, the sediment was transported into the inlet and the lagoon by the flood-tidal currents and partly, it bypassed the inlet via the shallow sand bar and ebb-tidal shoals.

3.2.2 BETWEEN 1910 AND 1960

The volumes of accretion of the Lighthouse Beach and erosion of the Bar Beach are computed using the values of accretion respectively erosion obtained using Figure 1-5 and Figure 3-3.

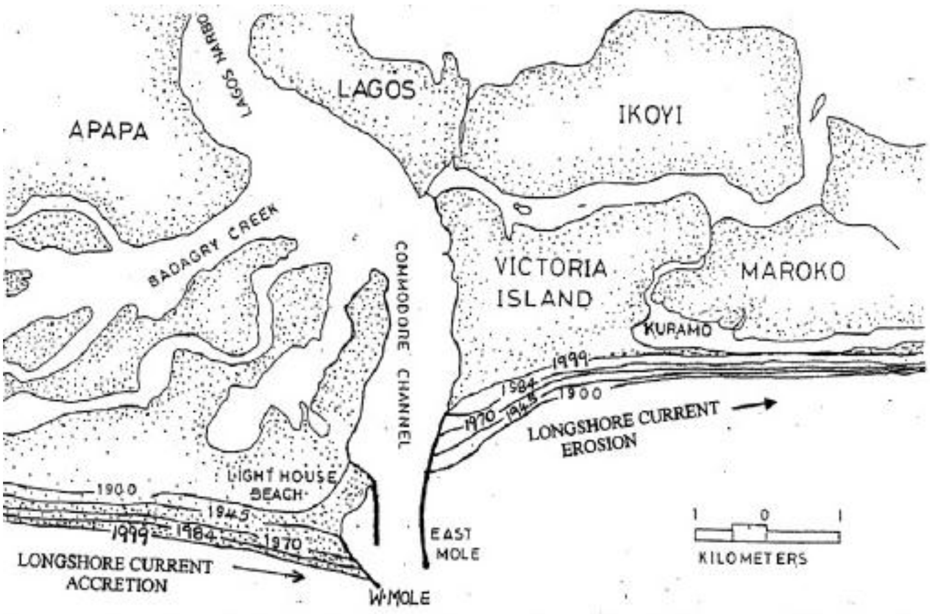

Figure 3-3: Accretion and erosion of the Lagos coast, between 1900 and 1999 [after figure 3-6, (Royal Haskoning [1], 2011, Part I)[12]]

The following rates of accretion of the Lighthouse Beach, between 1910 and 1960, are read from the figures:

- 440 m directly west of the West Mole
- 340 m at 2 km upstream the West Mole
- 280 m at 5 km upstream the West Mole

In appendix C.5 the whole calculation of the accretion volumes can be found. First, the total accreted sediment volume is calculated using the values of beach expansion, mentioned above. Subsequently, a check on this accretion value is done, using the theory of Pelnard-Considère (1956) and hereafter, a final value for the volume of accretion is obtained.

Over 50 years the accreted volume is $20 \cdot 10^6$ m^3, which comes down to an annual accretion volume of approximately 400,000 m^3/year. If S is about 600,000 m^3/year, this sink equals 65 per cent; schematised as $0.65 \cdot S$.

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[12] Original source is unknown.

3.2.3 BETWEEN 1960 AND 2010

In the same manner as done for the previous time span, the accretion volumes of the Lighthouse Beach are computed. The following rates of accretion of the Lighthouse Beach between 1960 and 2010 are taken from Figure 3-3:

- 280 m directly west of the West Mole
- 280 m at 2 km upstream the West Mole
- 240 m at 5 km upstream the West Mole

Concluding, in the 100 years after construction of the moles, the Lighthouse Beach has increased its width in total:

- 720 m directly west of the West Mole
- 620 m at 2 km upstream the West Mole
- 520 m at 5 km upstream the West Mole

In appendix C.5 the total accreted sediment volume is calculated for the time span 1960 – 2010. In the 50 years of this period, the accreted volume is $10.5 \cdot 10^6$ m³, which comes down to a yearly volume of: 210,000 m³/year. The accretion is schematised as a sink of 0.35 · S.

3.3 COASTAL STRETCH DOWNSTREAM OF EAST MOLE

In this section, the development of the coastal morphology of the Bar Beach is presented per period.

3.3.1 BEFORE 1910

The more northern location of Bar Beach, as compared to Lighthouse Beach, is explained in section 2.2.1 by the effects of a natural sediment demand of the Lagos Lagoon, caused by the SLR.

The size of the sink induced by the sediment demand of the lagoon, in the period 'Before 1910', is therefore taken equal to the size of the sink caused by the SLR in the other periods, elaborated in section 3.4.2. Thus, the sink in this period is schematised as 0.1 · S.

As a certain part of the sediment volume transported by the longshore current is imported into the lagoon, erosion of the Bar Beach occurs, to supply sediment to the longshore current.

In this period, the sediment demand of the lagoon and the erosion of the downdrift beach are the only two important morphological processes. Therefore, the source constituted by the erosion of the downdrift beach must be equal to the size of the sink. Hence, the erosion is schematised as a source of 0.1 · S.

3.3.2 BETWEEN 1910 AND 1960

The volume of erosion of the Bar Beach in the first fifty years after construction of the moles is calculated in the same manner as done to obtain the accreted volumes.

By comparison of Figure 1-5 to Figure 3-3, it turns out that the figures match fairly well for the accretion rates of the Lighthouse Beach, but the rates of erosion of the Bar Beach do not match that well. In appendix C.5 the calculation of erosion volumes is made using both figures.

As the erosion volumes obtained by using Figure 1-5 provide more realistic values, the erosion calculation for the period 1910 – 1960 is based on this figure.

The values of retreat of the Bar Beach, as used in the calculation, are:

- 690 m directly east of the East Mole
- 370 m at 2 km downstream the East Mole
- 260 m at 5 km downstream the East Mole

One is referred to appendix C.5 for the elaboration of the calculation. Between 1910 and 1960, a total volume of $22.3 \cdot 10^6$ m^3 is eroded. This equals a yearly erosion volume of approximately 450,000 m^3/year. If the total annual sediment transport is 600,000 m^3/year, the accretion can be schematised as a source (for the longshore current) of $0.75 \cdot S$.

No further investigation is made on the progress of the erosion of the ebb-tidal delta in this time span, as described in section 2.2.2. It is assumed that the erosion of the former ebb-tidal delta alleviated the erosion of the Bar Beach somewhat. Its function as a source for the longshore current is therefore indirectly included in the schematisation under the source term ‘erosion of Bar Beach’.

3.3.3 BETWEEN 1960 AND 2010

EROSION RATES

To obtain the volume of erosion of the Bar Beach in this period, Figure 3-3 is used (because Figure 1-5 does not depict the coastline after 1960). The values of retreat of the Bar Beach in this period are:

- 430 m directly east of the East Mole
- 240 m at 2 km downstream the East Mole
- 190 m at 5 km downstream the East Mole

This means that the total retreat of the Bar Beach, hundred years after construction of the Lagos Harbour Moles is:

- 1120 m directly east of the East Mole
- 610 m at 2 km downstream the East Mole
- 450 m at 5 km downstream the East Mole

The calculations made to obtain the erosion volume can be found in appendix C.5. A total erosion volume of $10.4 \cdot 10^6\ m^3$ is obtained for the time span between 1960 and 2010.

Annually this equals an erosion volume of 200,000 m^3/year, which is schematised as a source of $0.35 \cdot S$.

It has to be noted that the volume of erosion calculated this way can be seen as the 'net erosion' of the Bar Beach. Namely, in this period also several nourishments on the Bar Beach were conducted (see section 2.2.3). So despite the fact that the Bar Beach received a lot of extra sediment, it receded anyhow. For instance, in Onolaja (1988) it is also stated that although the beach nourishments were performed, the Bar Beach still experienced erosion.

The total 'gross' erosion volume of the Bar Beach can therefore be obtained by adding the nourishment volumes to the erosion volume calculated in this section. In section 3.5 this is investigated further.

NOURISHMENTS ON BAR BEACH

The nourishments of the Bar Beach in the period 1960 – 2010 are schematised in the conceptual model as a source. Except for a few nourishments in the beginning of this time span, it is assumed that all sediment for the nourishments is obtained from a borrow area offshore, such that the nourished sediment is added to the coastal system.

The frequency and volumes of sediment supply at the Bar Beach are presented in Table 2-1. In determining the size of the source these nourishments constitute, the total volume of nourishments in this time span is divided over the 50 years. An annual volume of roughly 580,000 m^3/year is supplied to the Bar Beach, which equals a source of the size $0.95 \cdot S$.

3.4 COMMODORE CHANNEL AND LAGOS LAGOON

In this section first the characteristics of the tidal inlet are discussed. Subsequently, the sediment fluxes, sources and sinks around the tidal inlet and into the lagoon are elaborated and quantified in order to set up the conceptual model.

In the consideration of the Lagos coastal system, the Badagry Creek is not taken into account. A study performed by Royal Haskoning (2011) shows that mostly fine sediment transport occurs at this part of the system. It is therefore assumed that no significant transport of sand happens in the Badagry Creek and that this part of the inland waters can be left out of the consideration of the sediment fluxes.

3.4.1 CHARACTERISTICS OF THE TIDAL INLET

The Commodore Channel is a tidal inlet. To investigate whether this inlet is in equilibrium or not, several checks can be applied. Once the equilibrium characteristics of the inlet are known, conclusions can be drawn on aspects as, for instance, the sediment demand of the inlet.

INLET EQUILIBRIUM CROSS-SECTIONAL AREA

The tidal prism and the equilibrium cross-section of an inlet of a lagoon are related via a frequently used, empirical relationship, which was firstly described by LeConte (1905) and further extended by O'Brien (1931, 1969)[13]:

$$A_e = C \cdot P^q$$

Where A_e is the inlet equilibrium cross-sectional area relative to MSL [m^2], P is in general the spring tidal prism [m^3], and C [m^{-1}] and q [-] are empirical parameters.

In literature, there exist numerous papers, reports, etcetera that treat above equation. In this study, the investigations and conclusions of Jarrett (1976)[14] with the additional information provided by a review done by Stive *et al.* (2009) are used. Jarrett (1976) concluded that for inlets with two jetties, at the U.S. Atlantic Coasts, $C = 6.7 \cdot 10^{-4}$ and $q = 0.87$. Although this study concerns another continent, these parameters are used in this study, because considering the coasts Jarrett (1976) studied, the U.S. Atlantic Coasts resemble the Nigerian coast most, i.e. both coasts are trailing edge coasts. Moreover, it is the most detailed study found in literature.

There are two broadly used equations to calculate the tidal prism (Seabergh, 2002).

The first one is via the area of the basin:

$$P = 2a_b \cdot A_b$$

Where a_b equals the mean tidal amplitude [m] and A_b is the surface area of the lagoon [m^2]. Using a value of 200 km^2 for the (horizontal) area of the Lagos Lagoon and a mean tidal range of 1 m, the tidal prism becomes $200 \cdot 10^6$ m^3.

The second option to obtain the tidal prism is via the tidal characteristics:

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[13] Quoted in Bosboom and Stive (2010). Original references: LECONTE, L.J. (1905) Discussion on the paper "Notes on the improvement of river and harbor outlets in the United States" by D.A. Watt, paper no. 1009. Trans. ASCE 55 (December): pp. 306-308. And: O'BRIEN, M.P. (1931) Estuary and Tidal Prisms Related to Entrance Areas, *Civil Eng*. Vol. 1, No. 8, pp.738-739. And: O'BRIEN, M.P. (1969) Equilibrium flow areas of inlets on sandy coasts. *Journal of Waterway Port Ocean Coast Eng* Vol. 95, No. 1, pp. 43-52

[14] Jarrett (1976) wrote his report following a research program under the surveillance of the U.S. Army Coastal Engineering Research Center (CERC).

$$P = \frac{T \cdot Q_{\max}}{\pi}$$

Where T is the tidal period [s] and Q_{max} is the maximum (spring) tidal discharge [m^3/s]. For T = 44700 s and Q = 10,000 m^3/s [15], the tidal prism is computed as $140 \cdot 10^6$ m^3. Via the above mentioned formula to determine the equilibrium cross-sectional inlet area, it is found that A_e lies in between 8,000 – 11,000 m^2.

For its "Coastal Analysis Report" Royal Haskoning (2011) performed a measurement campaign in the Commodore Channel and its surroundings. Using these data, it is estimated that the cross-sectional area of the inlet is about 10,000 m^2. This would indicate that the inlet is in approximate dynamic equilibrium and that therefore about equal volumes of sediment enter and leave the Commodore Channel during the flood respectively ebb tides.

Tung (2011) defines the stability of a cross-section as "*the ability to restore or maintain this equilibrium when acted upon forces tending to disturb it*". Therefore, disturbance of the inlet equilibrium can have a significant effect on the sediment fluxes. For instance, sea level rise and dredging activities could create additional accommodation space for the sediment, by enlarging the cross-section of the inlet. This would cause a demand for sediment in the system. Whether this disturbance occurs within the margins of the dynamic equilibrium of the inlet, or causes a significant sediment demand, is investigated in this section.

INLET EQUILIBRIUM FLOW VELOCITY

The equilibrium flow velocity in the channel, u_e [m/s], can be obtained by:

$$u_e = \frac{\pi P}{A_e T}$$

With the earlier computed tidal prisms and equilibrium cross-sectional areas, u_e is computed to be 1.2 – 1.3 m/s. In Table 3-1 the calculated characteristics of the tidal inlet are summarized.

Table 3-1: Characteristics Commodore Channel

	$P = 140 \cdot 10^6$ m^3	$P = 200 \cdot 10^6$ m^3
A_e [m^2]	8,000	11,000
u_e [m/s]	1.2	1.3

---

[15] Obtained from (Royal Haskoning [1], 2011, Part IV)

Reflecting on above calculations of the characteristics of the Commodore Channel, it is important to keep the basic assumption underlying the theory considering tidal inlets in mind, as is also emphasized by Stive *et al.* (2009) and van de Kreeke (1992). In the tidal inlet theories it is assumed that the bay level fluctuates uniformly. A simple calculation (see appendix C.6) of the time needed for the tidal wave to propagate through the lagoon indicates that the Lagos Lagoon can be defined as a 'short basin'. Hence, it can be assumed that the bay surface remains more or less horizontal and therefore the theories can be applied on the Lagos Lagoon.

SEDIMENT TRANSPORT CAPACITY OF FLOOD TIDAL CURRENT

If the morphodynamic equilibrium of the Lagos Lagoon and the Commodore Channel becomes disturbed, both elements try to restore their equilibrium by importing sediment. This sediment has to be transported into the system by the flood tidal current. In appendix C.8 it is checked whether the flood tide has the capacity to transport the required amounts of sediment. A rough approximation shows that, most likely, it is indeed possible that the flood tidal current has the capacity to transport great amounts of sediment into the lagoon and inlet.

3.4.2 SEA LEVEL RISE

In section 2.2.2 it is already mentioned that the (relative) SLR at the Lagos coast is assumed to be quite large. And it is also mentioned earlier that as a reaction to SLR, the Lagos Lagoon and the Commodore Channel start to import sediment to restore their morphodynamic equilibrium. This causes additional erosion of the shore downdrift of the Lagos Lagoon, because the lagoon acts as a sink.

Stive and Wang (2003) provide an expression for such shoreline recession:

$$c_{pr} = \frac{\delta\zeta}{\delta t}\frac{L_{ac}}{h_{ac}} + \frac{\delta\zeta}{\delta t}\frac{A_b}{h_{ac}\cdot L_{ac}}$$

Where the first term on the right-hand side is equal to the 'Bruun rule' (see appendix C.4) representing the direct coastal retreat due to SLR, and the second term provides the shoreline recession due to sediment import into the lagoon. C_{pr} is the rate of shoreline recession [m], δζ/δt is the SLR [m], L_{ac} is the length of the adjacent coast impacted [m], h_{ac} is the height of the active cross-shore profile [m] and A_b is the basin area [m²].

In appendix C.7 some calculations are made to determine the potential coastal recession, due to both the Bruun rule and sediment import by the lagoon. The uncertainties in the determination of the absolute SLR and, probably even more important at Lagos, in the determination of the land subsidence are kept in mind while investigating the coastal recession. Therefore, two different rates of (relative) SLR are considered: a low SLR of 5 mm/year and a high SLR of 10 mm/year.

With use of the above formula, it turns out that at the coast downdrift of the tidal inlet, the erosion rate due to sediment import into the Lagos Lagoon is about a factor two to three bigger than the coastal recession solely caused by the effect of the Bruun rule, see appendix C.7.

If the SLR would be 5 mm per year, the coastal recession due to the sediment import into the lagoon would be 0.3 m. This means that the total 'erosion' of the coast downstream of the lagoon is around 0.4 m.

The same calculation is made considering a high SLR, see Table 3-2, in which the effects of the different SLR are summarized. It must be mentioned that, as explained in appendix C.3, it is assumed that the eastward longshore transport of sediment relieves the erosion rates at the coast east of the area of interest (i.e. approximately 25 km downdrift the inlet and further downstream). So therefore, the presented rates of erosion are probably overestimating the occurring erosion.

Table 3-2: Amount of sediment import into Lagos Lagoon & Commodore Channel and rate of coastal recession, due to SLR

	Low SLR [5 mm/year]	High SLR [10 mm/year]
Annual sediment import into Lagos Lagoon [m^3/year]	75,000	150,000
Relative to amount of LST	$0.1 \cdot S$	$0.25 \cdot S$
Total coastal recession due to SLR [m/year]	0.4	0.85
• **Bruun rule** • **Sediment import into lagoon**	0.12 0.3	0.24 0.6

3.4.3 DREDGING OF COMMODORE CHANNEL

Another human action in the Lagos coastal system is dredging of the Commodore Channel for navigational purposes. As has been mentioned earlier, the dredging disturbs the dynamic equilibrium of the channel since the dredging enlarges the channel cross-section. Thereby, it creates more sediment accommodation space. Hence, the inlet reacts to the dredging by importing sediment to restore its equilibrium.

Apparently, as dredging occurs a lot in the channel, the equilibrium depth of the channel is less than the optimum depth required for navigation. It is not known exactly how much sediment is dredged at the Commodore Channel, but to obtain an idea about the potential influence of the dredging, an estimation of the dredged volume is made.

The Nigerian Port Authority (NPA) has three dredgers in service (Visser, 2007). To estimate the volume of dredging, the minimum depth required for navigation of 14.5 m (CARES Ltd., 2011), is taken into account.

By inspecting a depth map of the Commodore Channel[16] however, it seems like the whole channel is more or less deep enough. The northern part of the channel, at the Apapa docks of the Lagos Port, is the shallowest part. So in order to obtain an idea about the potential dredged volume, this part of the channel is considered.

The relevant part of the channel has a length of approximately 2 km, while the width of the fairway is around 200 m. To calculate the dredged volume, the dredged depth must be obtained. In appendix C.7 it is concluded, using the characteristics of one of the dredgers of the NPA, that the dredger can dredge a layer of maximum thickness of 0.3 m. It is assumed that this dredged depth is sufficient to remove any settled sediment and to guarantee sufficient navigational depth.

Thus, if the bottom in the relevant channel part is deepened 0.3 m, the amount of sediment dredged is 120,000 m^3. This is around 20 per cent of the annual LST.

As a first approximation, it is assumed dredging occurs once a year. This scenario is referred to as 'little dredging'. However to take into account the uncertainty regarding the dredged volumes, also the possible scenario of dredging more than one layer, referred to as 'much dredging', is considered. It is assumed that dredging the same part of the fairway twice, leads to an increase in depth of 0.6 m. The dredged volume is than 240,000 m^3, schematised as 40 per cent of the annual LST.

The values obtained by the approximation made in this section correspond well to the mean siltation rates of the Commodore Channel as reported by CARES Ltd. (2011). In Table 3-3 a short overview is presented.

Table 3-3: Amount of sediment import into Commodore Channel, due to dredging

	Little dredging	**Much dredging**
Import due to dredging [m^3/year]	120,000	240,000
Relative to volume of LST (S)	0.2 · S	0.4 · S

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[16] In possession of Royal Haskoning.

3.4.4 DREDGING OF LAGOS LAGOON

The Lagos Lagoon has an important role in the Lagos coastal system. Besides the effects caused by SLR, also the dredging and sand mining in the lagoon induce an additional effect on the sediment fluxes. The increase of depth disturbs the morphodynamic equilibrium (just as SLR does), which leads to more sediment import by the lagoon.

As has been discussed in section 2.2.3, almost no data are available on the sand extraction in the lagoon. Therefore, the dredging volumes are obtained by an investigation of the balance in sediment fluxes, sources and sinks, which is presented in section 3.5.3.

3.5 SUMMARY HISTORICAL COASTAL DEVELOPMENT

In this section the sediment balance of the Lagos coastal system is considered for each period. The main processes and mechanisms in each time span are repeated shortly in a table, after which the balance is presented graphically. To complete each overview, in the tables it is also mentioned whether the magnitudes of the fluxes, sources and sinks are acquired by (literature) data, calculations, hypotheses or by estimations.

3.5.1 BEFORE 1910

The most important sediment fluxes, sources and sinks in this time span have been determined in the previous sections. A synopsis is presented in Table 3-4 below.

Table 3-4: Overview sediment fluxes, sources and sinks; Lagos coast before 1910

Phenomenon	*Type of function*	*Magnitude*	*Type of data*
Eastward longshore sediment transport	*Flux*	*S*	
Natural sediment demand of the Lagos Lagoon	*Sink*	$-0.1 \cdot S$	*Hypothesis*
Erosion of Bar Beach	*Source*	$+0.1 \cdot S$	*Hypothesis*

In Figure 3-4 the conceptual sediment balance of the coastal system before 1910 is depicted.

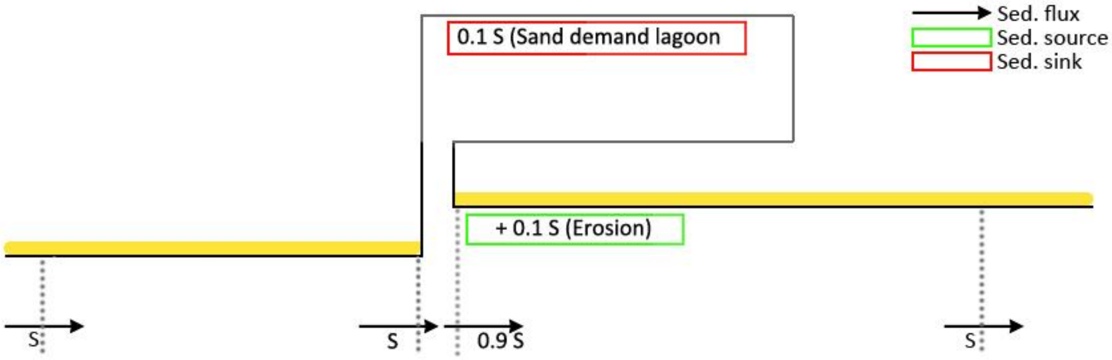

Figure 3-4: Conceptual sediment balance before 1910

3.5.2 BETWEEN 1910 AND 1960

The dominant sediment fluxes, sources and sinks of this time span are summarized in Table 3-5 below.

Consideration of the sizes of the sink constituted by the accretion of the Lighthouse Beach and the source formed by the erosion of the Bar Beach, it can be concluded that the SLR in this time span corresponds to the 'low SLR' of 5 mm/year, leading to a sediment import of 0.1 · S.

Table 3-5: Overview sediment fluxes, sources and sinks; Lagos coast 1910 – 1960

Phenomenon	*Type of function*	*Magnitude*	*Type of data*
Eastward longshore sediment transport	*Flux*	*S*	
Accretion of Lighthouse Beach	*Sink*	*- 0.65 · S*	*Estimated from data*
Erosion of Bar Beach	*Source*	*+ 0.75 · S*	*Estimated from data*
Sediment import due to SLR	*Sink*	*- 0.1 · S*	*Hypothesis*

The conceptual sediment balance of the Lagos coastal system in the period 1910 to 1960 is presented in Figure 3-5.

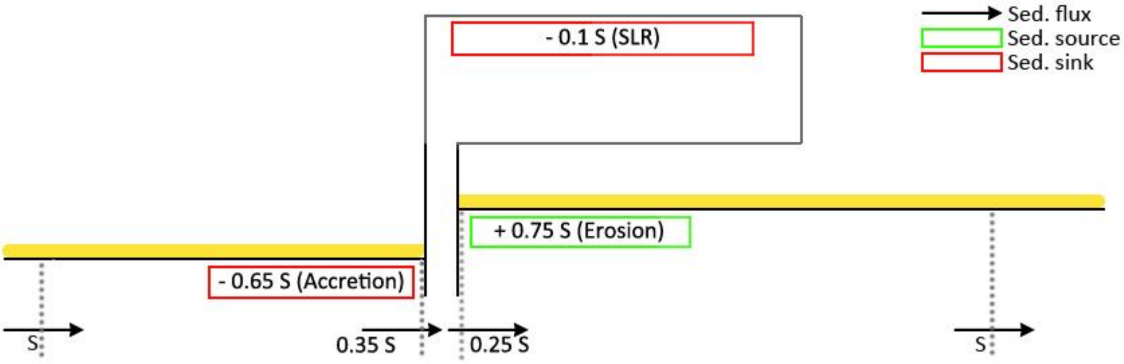

Figure 3-5: Conceptual sediment balance between 1910 and 1960

3.5.3 BETWEEN 1960 AND 2010

As stated in section 2.2.3, it is assumed that the size of the sink induced by SLR in this period is equal to the previous period. So again, the SLR constitutes a sink of 0.1 · S.

Before the summary on the morphological situation in this period can be presented, two processes are explained some more.

EROSION OF BAR BEACH

The erosion and the nourishment of the Bar Beach both constitute a source to the longshore current. The total value of the sink they constitute is 1.30 · S (i.e. 0.35 · S + 0.95 · S). However, it is presumed that in the beginning of this time span, the erosion meant a greater sink than it was at the end of the time span. Concerning the nourishments, in appendix C.9, a figure is presented in which the division of the nourishments over the years can be found. It turns out that the frequency and size of the nourishments have increased significantly in the second half of the time span.

Hence, the total size of the sediment source at Bar Beach stays equal over the years, because the erosion rates extracted from Figure 3-3 signify the 'net erosion' (see section 3.3.3). But the size of the different parts that the total erosion volume comprises does vary during this time span.

To illustrate this, two different sediment balances are made in this time span, one for the period 1960 – 1985 and one for the period 1985 – 2010. In appendix C.9 the sizes of the different parts of the source are elaborated, shown in Figure 3-6 and Figure 3-7.

SEDIMENT IMPORT DUE TO DREDGING OF THE LAGOS LAGOON

The total sediment balance is considered, to determine the size of the sink induced by the dredging in the Lagos Lagoon (e.g. for construction activities and artificial land reclamation within the lagoon).

As depicted in the previous sections, the sediment fluxes in and out the system for the time spans ‘Before 1910’ and 1910 – 1960 are more or less in balance. Regarding the time span 1960 – 2010, most of the uncertainty lies in the volume of dredging in the lagoon. In section 2.2.3 it has already been clarified that only very little data of the dredging volumes and frequencies are available. Therefore, the dredging volume is used as a ‘closure term’, to make the sediment fluxes approximately balance each other.

In Table 3-6 the dominant sediment fluxes, sources and sinks are defined for the period 1960 to 2010.

Table 3-6: Overview sediment fluxes, sources and sinks; Lagos coast 1960 – 2010

Phenomenon	*Type of function*	*Magnitude*	*Type of data*
Eastward longshore sediment transport	*Flux*	*S*	
Accretion of Lighthouse Beach	*Sink*	*- 0.35 · S*	*Estimated from data*
Erosion of Bar Beach	*Source*	*+ 0.35 · S*	*Estimated from data*
Nourishments on the Bar Beach	*Source*	*+ 0.95 · S*	*Data*
Sediment import due to SLR	*Sink*	*- 0.1 · S*	*Hypothesis*
Sediment import due to dredging of the Commodore Channel	*Sink*	*- 0.2 · S*	*Estimation*
Sediment import due to dredging of the lagoon	*Sink*	*- 0.65 · S*	*Closure term*

In Figure 3-6 and Figure 3-7 the sediment balance is represented graphically.

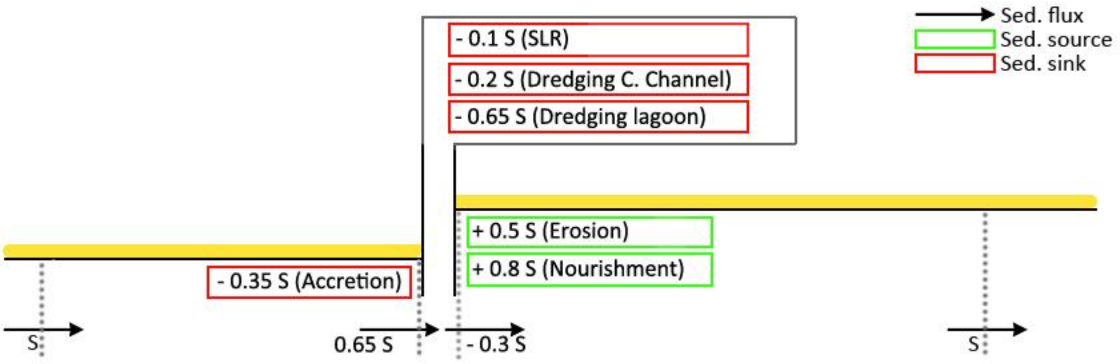

Figure 3-6: Conceptual sediment balance between 1960 and 1985

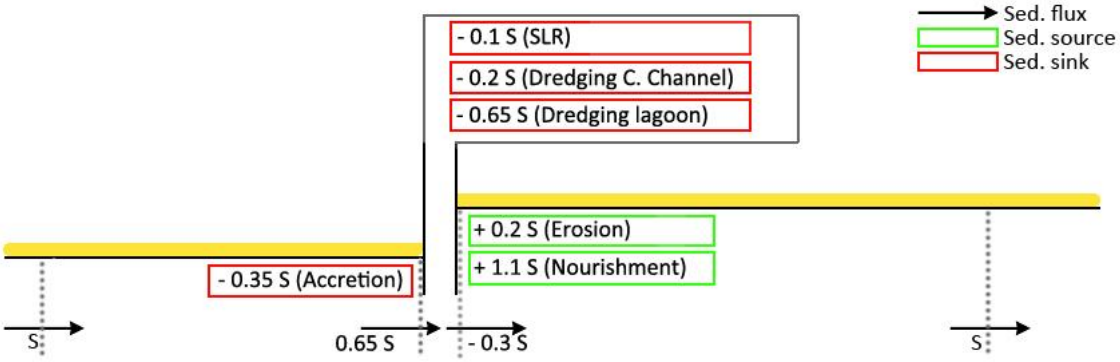

Figure 3-7: Conceptual sediment balance between 1985 and 2010

3.6 HYPOTHESES ON FUTURE COASTAL DEVELOPMENT

In the previous sections the conceptual model of the Lagos coastal system is presented. Using this conceptual model, four potential scenarios regarding the future morphological development of the Lagos coast are set up.

3.6.1 DISCUSSION OF HISTORICAL DEVELOPMENT

The historical coastal development of the Lagos coast is in contrast with what is generally found in literature. For instance, Bosboom and Stive (2010)[17] state that the erosion rates are highest just after construction of the breakwaters, slowing down over the years. Usually, the amount of erosion is therefore not equal to the amount of accretion. Especially after some years, the accreting coast has received more sediment than the eroding coast has lost. Bypassing via a migrating shallow shoal in front of the inlet normally arranges the downdrift coast to receive sediment, such that erosion diminishes.

However, the analysis presented in this chapter shows that at the Lagos coast, the erosion volumes are larger than the accretion volumes, because the sediment accumulation at the West Mole is not the only sink of importance. There are four major factors of importance concerning the erosion downstream the Lagos Harbour Moles:

- Sediment trapping at the West Mole
- Sea level rise
- Dredging in the Commodore Channel
- Dredging of the Lagos Lagoon

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[17] Reference is made to Mangor (2004), see appendix C.10.

3.6.2 DISCUSSION OF FUTURE SCENARIOS

The sediment accumulation at the Lighthouse Beach determines what amount of sediment is able to bypass the West Mole. Using the earlier applied theory of Pelnard-Considère (1956), it is estimated what percentage of the LST is able to bypass the West Mole in the first ten years after construction of the Eko Atlantic City project. In this estimation, it is taken into account that the West Mole is rehabilitated around 2010. The seaward end mole is damaged heavily by the severe wave climate. To restore its function, the mole is heightened till CD +5 m over a length of 100 m, stretching from the tip of the mole towards land (Royal Haskoning [1], 2011, Part I). In appendix C.5 it is calculated that the mean bypassing volume along the West Mole, in the period 2010 – 2020, is $0.85 \cdot S$.

The SLR, dredging of the Commodore Channel and dredging of the lagoon together determine the magnitude of the total sediment sink and thereby they determine the bypassing volume along the East Mole. If the sink is schematised by '$x \cdot S$', the volume of sediment that is able to bypass the East Mole is: $(0.85 - x) \cdot S$.

Therefore, the longshore current downdrift Eko Atlantic City has a sediment deficit of $(1 - 0.85 - x) \cdot S$, which has to be replenished by erosion of the downdrift coast. In Figure 3-8 the conceptual sediment balance for the period 'After 2010' is depicted.

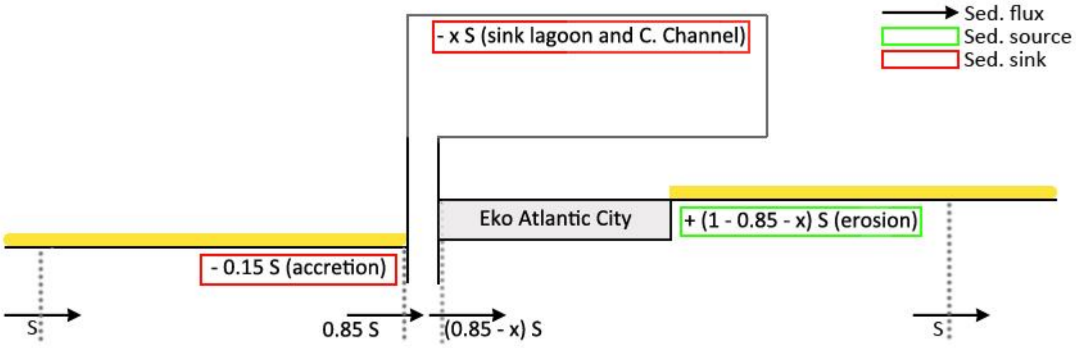

Figure 3-8: Conceptual sediment balance for the period 2010 – 2020

The previous section shows that most of the uncertainty in predicting potential scenarios for the future coastal development at Lagos is included in the rate of SLR respectively in the amount of dredging. The corresponding sink these phenomena constitute, determines what volume of sediment is able to bypass the East Mole.

It is also concluded that the effects of dredging of the Lagos Lagoon are dominant over the effects of SLR and dredging of the Commodore Channel. However, the sinks the dredging of the Commodore Channel and the SLR create, can be quantified a little better than the sink caused by dredging of the lagoon (as almost no data of the last phenomenon are available). Whether the dredging of the Lagos Lagoon will occur in the future is not certain. Therefore, four potential future scenarios are considered in the modelling study.

All four scenarios are run in a software model for two situations: with and without the presence of Eko Atlantic City. The setup of the scenarios is such that much variation between the scenarios is obtained.

1) Low SLR, little dredging of the Comm. Channel, no dredging in lagoon
2) High SLR, much dredging of the Comm. Channel, no dredging in lagoon
3) Low SLR, little dredging of the Comm. Channel, dredging in lagoon
4) High SLR, much dredging of the Comm. Channel, dredging in lagoon

Where low SLR corresponds to 5 mm/year and high SLR is taken as 10 mm/year. The corresponding sink is $0.1 \cdot S$ and $0.2 \cdot S$ respectively. And, summarising, little dredging of the Commodore Channel corresponds to a dredging depth of 0.3 m, and thus to a sink of the size $0.2 \cdot S$. Much dredging signifies a dredging depth of 0.6 m and an accompanying sink of $0.4 \cdot S$. Concerning the dredging of the lagoon, the dimension of the sink it causes is taken equal to the size of this sink in the period 1960 – 2010 (i.e. $0.7 \cdot S$).

A base for the modelling study, including the expected magnitude of the sink (i.e. sediment flux into Lagos Lagoon and Commodore Channel) is presented in Table 3-7.

Table 3-7: Four scenarios concerning the future Lagos coastal situation

Scenario	SLR	Dredging of Comm. Channel	Dredging of lagoon	Expected size of sink	Expected volume bypassing EM
1	Low	Little	No	$0.3 \cdot S$	$0.55 \cdot S$
2	High	Much	No	$0.6 \cdot S$	$0.25 \cdot S$
3	Low	Little	Yes	$1 \cdot S$	$-0.15 \cdot S$
4	High	Much	Yes	$1.3 \cdot S$	$-0.45 \cdot S$

3.6.3 ELABORATION FUTURE SCENARIOS

In general, some assumptions can be made regarding the situation when Eko Atlantic City is present.

- Considering the length of Eko Atlantic City (around 6.5 km), the project lies completely in the area of influence of the Lagos Harbour Moles (more than 20 km). As a first approach, it could be presumed that Eko Atlantic City has a second order effect on the coast, compared to the effect the moles had. However, not only the length of the project is of importance, as described in the next comments.

- The cross-section of the surfzone directly east of the harbour moles is greatly influenced by the presence of Eko Atlantic City. There is no active beach anymore because roughly all the sediment from the beach is fixed by the revetment. The only potential sediment supply to the longshore drift, at the location of Eko Atlantic City, is therefore from the bottom.

  Whether the bottom is eroded or receives sediment depends largely on the water depth at the toe of the revetment. If the depth is large, the flow velocities decrease significantly and the wave-induced longshore current is unable to mobilize sediment. This results in sediment deposition just east of the East Mole. Consequently, no sediment is added to the longshore current and erosion of the coast east of Eko Atlantic City is to be expected, as the longshore current starts to collect sediment there. However, if the water depth at the toe is shallow and if the flow velocities are high enough to stir up the sediment, bottom scour could be expected if the amount of bypassing along the moles is small. Moreover, in case of a small sediment bypassing volume, erosion of the coast east of Eko Atlantic City is also expected, because the bottom scour probably cannot supply sufficient sediment to the longshore current. The erosion problem, caused by the moles and by the additional sediment withdrawal at the inlet respectively by the lagoon, is then shifted to the coast east of Eko Atlantic City.

  The bottom depth at the toe varies between CD -7 m to CD -10 m (Royal Haskoning [3], 2011). In appendix C.1 the depth of closure is found to be CD -6.5 m, which would indicate that the toe of the revetment lies just outside the active zone. Then, no sediment is transported and sediment accumulation in front of the western part of Eko Atlantic City as well as erosion east of the project is expected. It has to be kept in mind, however, that the calculation of the closure depth is a rough approximation. The model runs are expected to give more clarity on this.

- According to the “Coastal Analysis Report”, the presence of Eko Atlantic City induces the longshore current to flow more smoothly along the coast (see appendix A), because the shadow zone east of the East Mole is significantly reduced. Turbulent eddy formation, and the additional erosion it causes, is decreased by the presence of Eko Atlantic City. If the amount of bypassing is large, less erosion is expected downstream of the project, because the sediment is more efficiently transported along the moles.

Scenario 1: Low SLR, little dredging of the Comm. Channel, no dredging in Lagoon

Of the four scenarios considering the future morphological behaviour of the coast of Lagos, this is the one where the least amount of sediment is ‘lost’ to the Lagos Lagoon and the Commodore Channel, as in this scenario the equilibrium of the Commodore Channel and the lagoon is disturbed the least. Since no dredging occurs in the lagoon and both the SLR and the amount of dredging in the Commodore Channel are small, the expected sink is also small. The sediment import is schematised as a sink of 0.3 · S. Consequently, a sediment volume of (0.85 – 0.30) = 0.55 · S is able to bypass the East Mole.

However, if the water depth at the western part of Eko Atlantic City is deep, such that the bypassed sediment starts to accumulate there, erosion at the East of the project area is still expected, despite of the high bypassing volume.

Scenario 2: High SLR, much dredging of the Comm. Channel, no dredging in Lagoon

Although the SLR is high and the dredged volume in the inlet is much, their effects are less severe than the effects caused by potential dredging of the lagoon. The sink is therefore schematised as moderate. The size of the sediment flux into the inlet and the lagoon is estimated as 0.6 · S, such that a sediment volume of (0.85 – 0.6) = 0.25 · S is able to bypass the East Mole. Just as in scenario 1, if the water depth at the toe of the revetment is large, the coast downdrift of Eko Atlantic City still starts to erode, despite the bypass along the East Mole.

Scenario 3: Low SLR, little dredging of the Comm. Channel, dredging in Lagoon

Compared to scenarios 1 and 2, the sink is quite big because the volume of sediment import due to dredging of the Lagos Lagoon has been shown to be higher than the import due to SLR or dredging of the inlet. The amount of bypassing is therefore relatively small. The sink is schematised as 1 · S, such that the sediment volume bypassing the East Mole is a negative flux of size: -0.15 · S. The sediment is withdrawn from the Bar Beach and the shallow areas in the downdrift surf zone e.g. by the turbulent tidal currents around the inlet.

Eko Atlantic City probably shifts the erosion problem, primary caused by the existence of the moles and aggravated by the sinks, eastward. If the current at the western part of the project is unable to transport sediment, due to the large water depth, the erosion rate is increased.

Scenario 4: High SLR, much dredging of the Comm. Channel, dredging in Lagoon

This is the scenario where the severest effects downstream of Eko Atlantic City are expected. Because the morphological equilibriums of both the Commodore Channel and the Lagos Lagoon are greatly disturbed, a lot of sediment has to be imported to restore the equilibriums. The size of the sink is about 1.3 · S. Therefore, a negative bypass is expected along the East Mole, of size -0.45 · S. If next to the big sink, the sediment settles just east of the East Mole, the expected erosion rates east of the project are very high.

4 UNIBEST MODEL

In this chapter the analysis of the Lagos coast is continued using the numerical simulation model Unibest. The conceptual model created in chapter 3, serves as the basis for the setup of the Unibest model.

First, a description of the Unibest software is provided in section 4.1. The configuration of the software and the underlying theory are discussed. Thereafter, the setup of the two different modules of the model is presented in section 4.2 and section 4.3.

In order to provide for a reliable model, the model is calibrated. The data used for the calibration and the way the calibration is performed are discussed in section 4.4.

After the calibration, the Lagos coastal system is investigated further in section 4.5. Using the output of the Unibest model runs, the conceptual model is reviewed. This chapter is subsequently concluded with the assessment of the influence of the harbour moles, the nourishments performed on the Bar Beach and the land reclamation in the Lagos Lagoon on the Bar Beach.

4.1 UNIBEST

The hypotheses made in the previous chapter are tested using the numerical simulation model Unibest (UNIform BEach Sediment Transport)[18]. In short, the model can be used to compute longshore and cross-shore processes and the associated morphodynamics of beach profiles and coastline development. The model is especially suited for wave-dominated coasts.

The Unibest software is used in this study to assess the long-term coastal morphology. The advantage of the use of a 1D model such as the Unibest software is that a large coastal system can be analysed. Also the possibility to simulate the longer-term morphological development is proven very useful in this study. And since the dataset on the Lagos coast is by no means complete, the application of a 1D model is the most logical choice in this study.

The Unibest model consists of two modules, run separate from each other: the LT (Longshore Transport) module and the CL (CoastLine) module. First the LT module is run and thereafter the output of the LT module run is used as input in the CL module.

4.1.1 LT MODULE

In the LT module several profiles can be defined. Under the assumption of an alongshore uniform beach, the longshore sediment transport capacity at every profile is computed via the calculation of wave-induced and tidal-induced longshore currents. Per profile the calculation of the LST capacity is done for several coastline orientations in the range of the initial orientation. In the model, refraction and shoaling are accounted for and also non-linear energy dissipation processes as wave breaking and bottom friction are taken into account.

The output of this module comprises the so-called S-ϕ curves per profile. For a number of coastline orientations (ϕ) the corresponding volume of longshore sediment transport (S) is computed.

4.1.2 CL MODULE

In the CL module the actual coastline is defined. The evolution of the coastline is simulated on the basis of the single line theory, also used in section 3.1.2 and further discussed in appendix C.1.

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[18] All information presented in this section is acquired from Deltares (2011)

In short, the volumes of longshore sediment transport (LST) computed in the LT module provide a certain gradient in the LST between the profiles along the coast. These gradients are used in the CL module to define the accretion or erosion of the coast. Herein it is assumed that the layout of the cross-shore profiles does not change and that behind the (user defined) active depth no sediment transport occurs.

Accretion or erosion of the coast changes its orientation. Subsequently the ‘updated’ volume of LST is defined with help of the S-ϕ curve (created in the LT module). Using these predefined curves in the CL module saves a lot of computation time.

At the model boundaries specific boundary conditions can be imposed. Structures as groynes, revetments and offshore breakwaters can be created in the CL module of the Unibest model.

4.1.3 INPUT DATA

Most of the data used in this study have been acquired by Royal Haskoning, while conducting its former studies on the Lagos coast. Royal Haskoning performed, among others, a 1D modelling study into the sediment transports along the Lagos coast, using the software model Litpack. The input data used for the Litpack study are also used as input for the Unibest model. However, adjustments to the data have to be made in order to acquire the fitting input for Unibest.

4.2 LT MODULE SETUP

To schematise the bathymetry of the Lagos coast, a total of 11 profiles is defined. Seven profiles are distributed along the whole coast and four profiles lie in the shadow zone (i.e. on the eastern side) of the East Mole. Each profile is characterized by a specific initial bathymetry and coastline orientation. In between the defined profiles, the coastal bathymetry is obtained by linear interpolation between the two profiles. All profiles are defined perpendicular to the coast.

4.2.1 PROFILE LOCATIONS

From East to West, the profiles are named East 1, East 2, East 2A, East 3, West 4, West 5 and West 6. The locations of, and the intermediate distances between the seven main profiles are shown in Figure 4-1. In appendix D.1 the characteristics and the S-ϕ curves of the cross-sections can be found. The bathymetry is obtained using data in possession of Royal Haskoning.

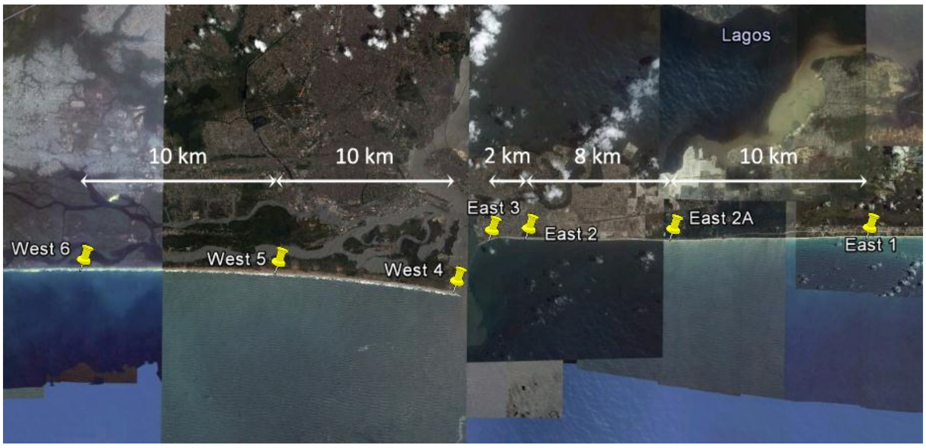

Figure 4-1: Locations and intermediate distances of cross-shore profiles used in Unibest [after Google (2010)]

The four profiles located in the shadow zone are used to correctly simulate the effects of diffraction near the East Mole. The profiles in the shadow zone are referred to as East 3-1, East 3-2, East 3-3 and East 3-4. The locations of these profiles are depicted in Figure 4-2, where also the location of profile East 2 can be seen.

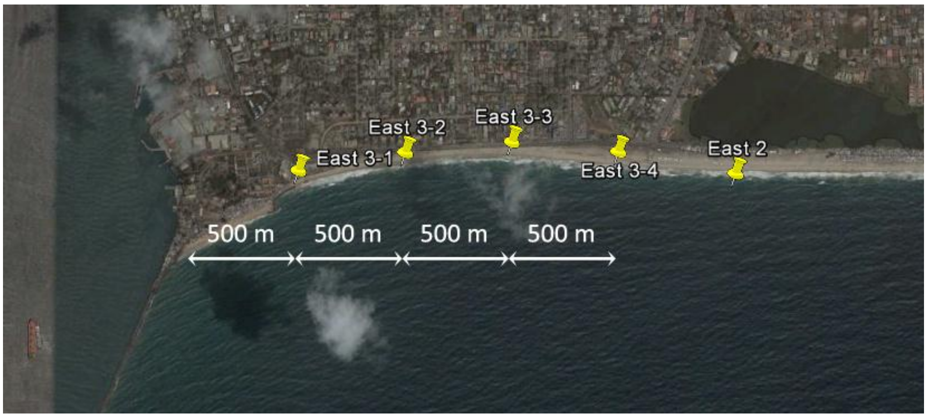

Figure 4-2: Locations of cross-shore profiles in the shadow zone of the East Mole [after Google (2010)]

4.2.2 ACTIVE HEIGHT

The active profile height used in Unibest is equal to the active profile height as used in the conceptual model, which is 10 m (i.e. the depth of closure plus the berm height; see appendix C.1).

4.2.3 INITIAL COASTLINE ORIENTATION

The model starts simulating the coastline development in 1910, when the moles are constructed. The initial coastline position, at 1910, is obtained using Figure 3-3. Because this figure only depicts the coast approximately 5 km upstream and downstream of the inlet, the initial coastline location further upstream and downstream is approximated by consideration of the topography; at some locations along the Lighthouse Beach, its gradual expansion over the years is clearly visible in the beach ridges present. Hence, it is assumed that via these ridges, the location of the 1910 coastline can be found. In Figure 4-3 the 1910 coastline around the tidal inlet is depicted in yellow.

Figure 4-3: Location of 1910 coastline, in yellow [obtained using Figure 3-3 and Google (2011)]

4.2.4 SEDIMENT TRANSPORT PARAMETERS

SEDIMENT CHARACTERISTICS

Not much sediment data are available, but it is known that the sediment on Lighthouse Beach differs from the sediment on the Bar Beach. It is assumed that the sediment characteristics of the upstream side of the inlet can be approximated by the Lighthouse Beach sediment and, likewise, that the sediment of the downdrift coast is similar to the Bar Beach sediment. The sediment data used are similar to the data used by Royal Haskoning.

The sediment at the Bar Beach and further downdrift the moles has a mean diameter d_{50} of 0.56 mm. The d_{90} is about 0.64 mm.

At the Lighthouse Beach, the sediment has a mean grain diameter of d_{50} of 0.20 mm and a d_{90} of 0.26 mm.

LONGSHORE SEDIMENT TRANSPORT FORMULA

In the Unibest model, several formulas are available to calculate the longshore sediment transport capacity. First, the well-known CERC (1984) formula is investigated.

However, probably due to the big mean grain diameter of the sediment, this formula overestimates the LST volumes at Lagos. Therefore, the van Rijn (2004) formula is used, since this formula provides better results for the Lagos coast[19].

4.2.5 WAVE CLIMATE

In the Unibest model, the wave climate is defined per cross-shore profile, at the seaward boundary. An important aspect of the setup of the Unibest model is the (manual) conversion of the wave climate used in the Royal Haskoning model to wave climates at the offshore boundaries of the cross-sections used in Unibest.

The wave climate used by Royal Haskoning is based on a translation of the offshore climate, obtained by the hindcast model NOAA[20], to a location at a depth of 30 m with use of the wave model SWAN[21]. The climate comprises wave height, wave period and wave direction. In order to reduce calculation time, Royal Haskoning converted the original one year climate, containing approximately 32,152 records, to a multiple year climate by classification of wave conditions. Because the wave climate at Lagos has a very narrow directional spreading, this simplification could be executed (Royal Haskoning [1], 2011, Part IV).

WAVE CLIMATE ALONG THE WHOLE PROJECT AREA

As stated in section 4.2.1, the profiles used in the Unibest model are based on the available bathymetric data of the Lagos coast. The seaward end of the profiles lies around a depth of 10 m (this differs per profile). So therefore, as the wave climate used by Royal Haskoning is defined at a depth of 30 m, the waves have to be propagated from 30 m depth to roughly 10 m depth. Hereby, the effects of shoaling and refraction must be taken into account.

Waves approaching the coast have a velocity depending on the water depth. If a long-crested wave (e.g. a swell wave) propagates into shallow water, this leads to lower velocities at the front of the wave and to a shorter wave length. The wave height increases due to this effect. This change of the wave in longitudinal direction is called shoaling.

When a long-crested wave is obliquely incident, the part of the wave crest travelling in shallower water slows down. Thereby, the wave crest turns towards an orientation perpendicular to the depth contours and the coast. This change of the wave in lateral direction is called refraction (Bosboom and Stive, 2010; Holthuijsen, 2007).

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[19] More information on the LST formulas can be found in Deltares (2011)

[20] NOAA stands for National Oceanic and Atmospheric Administration.

[21] SWAN stands for Simulating WAves Nearshore. It is a third-generation wave model that computes random, short-crested wind-generated waves in coastal regions and inland waters The SWAN Team (2011).

Because there is very little information about the bathymetry of the Lagos coast in the regions deeper than roughly 10 m, it is assumed for reasons of simplicity that the bottom contours between depths of 30 m and 10 m can be schematised as parallel. This means that Snell's can be applied to calculate the change of wave direction due to refraction (see appendix D.2). In order to account for effects of shoaling some rules of thumb are available, provided in the linear wave theory. In appendix D.2 the propagation of the wave climate is explained in more detail.

The result of the (manual) propagation of the wave climates is a wave climate at every seaward end of the cross-sectional profiles. Within the Unibest module, the effects of further refraction and shoaling (and energy dissipation due to bottom friction and wave breaking) are taken into account.

LOCAL WAVE CLIMATE IN SHADOW ZONE OF EAST MOLE

When the waves approach the coast around the East Mole, the breakwater forms an obstacle for a part of the wave crest, inducing a variation of wave energy along the crest which leads to energy transfer along the wave crest. So, waves approaching the coast start to diffract when they reach the tip of the East Mole. As a result a shadow zone just east of the East Mole arises, in which the wave height and direction is changed.

To take the diffraction into account, four profiles are defined in the shadow zone, on which an adjusted wave climate is imposed. The original deep-water (30 m depth) wave climate is first propagated to the seaward end of the profiles, such that the effects of refraction and shoaling are accounted for. And hereafter, the climates are adjusted via the guidelines of Kamphuis (1992)[22] for diffraction. In appendix D.2 the conversion of the deep-water wave climate to the diffracted wave climates is discussed further. In Figure 4-4 the locations where the adjusted wave climates are imposed are depicted.

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[22] Quoted in an appendix of WL|Delft Hydraulics (1998). Kamphuis, J.W. (1992) Computation of coastal morphology, ICCE 1992, Venice, Italy

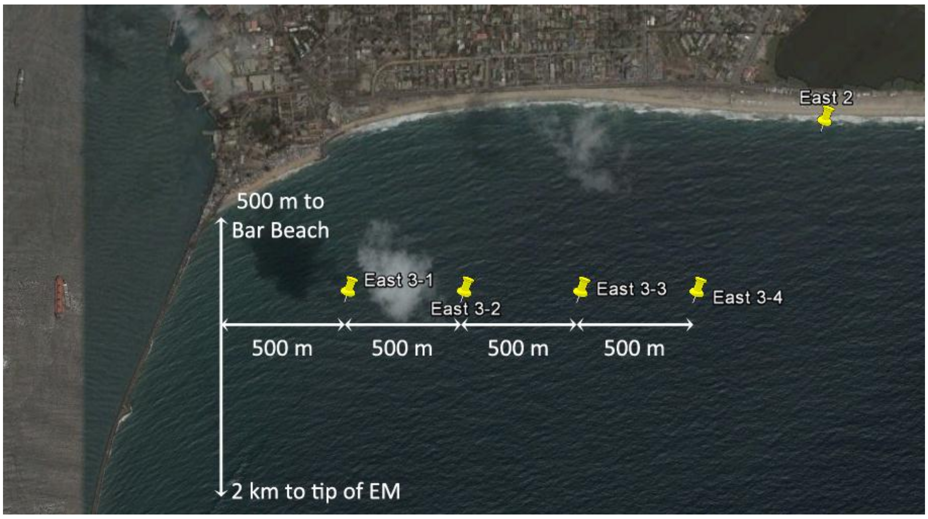

Figure 4-4: Locations where the adjusted waves climates in the shadow zone of the East Mole are imposed [after Google (2010)]

As can be seen in Figure 4-4, the adjusted wave climates are imposed at a distance of around 500 m off the coast. In the Unibest model, the East Mole (abbreviated to EM in Figure 4-4) is schematised at the location of the white vertical line. Hence in the software model, the distance between the adjusted climate at profile East 3-1 and the mole is approximately 500 m. The mole has a length of 2.5 km, thus the climates are defined roughly 2 km landward from its tip.

4.2.6 TIDE

In the Unibest model no tidal currents are included because very little data on the alongshore tidal currents are available. Since the Lagos coast is wave-dominated, it is assumed that this simplification does not induce significant errors.

4.3 CL MODULE SETUP

In Figure 4-1 an overview of the model area is depicted. The modelled coast has a length of 48.9 km.

4.3.1 BOUNDARY CONDITIONS

The boundary conditions at the western and eastern boundary are set as ‘coast angle constant’, which is a quite neutral boundary condition. It ensures that the orientation of the coastline at the boundaries remains approximately stable. The analysis of the length of influence of the Lagos Harbour Moles (see section 3.1.2) shows that at these locations the moles nearly have an impact, so this boundary condition is most suitable.

4.3.2 LAGOS HARBOUR MOLES

The Lagos Harbour Moles are located at both sides of the tidal inlet. In the Unibest model, the Training mole is not taken into account, as the West Mole and the East Mole have the most relevant effects in this study. Running from west to east in the model, the West Mole lies approximately at a longshore distance of 20.6 km and the East Mole is located at a distance of 22 km. The length of the West Mole is circa 1 km and the length of the East Mole is roughly 2.5 km.

4.3.3 COMMODORE CHANNEL

Between the two moles lies the Commodore Channel, which is simulated as a part of the coast in Unibest. It is not possible to create a channel in the model; so therefore a sink is placed at this part of the 'coast'.

The Unibest model does not simulate bypass correctly. At a certain moment in time, when the Lighthouse Beach reaches the tip of the mole, bypass along the West Mole does occur in the model. But once the sediment has bypassed the West Mole, it is trapped in the inlet by the East Mole. So no further bypass occurs. It can happen that the part of 'coast' between the two moles receives abundant sediment volumes, such that the sediment bypasses the East Mole, but this does not represent reality correctly.

Bypassing of the East Mole is therefore simulated by adding of a source (or, in case of negative bypassing, a sink) just east of the mole. The volume of this source (or sink) is provided by the conceptual model. The size the sink between the moles has, does not matter, as long as the 'accretion' between the moles does not reach the tips of the moles (such that bypassing along the East Mole does not occur).

4.3.4 DIFFERENT PERIODS

Similar to the conceptual model, three different periods are defined in the CL module. The first period is 1910 to 1960, the second period is from 1960 to 2010 and the third period is 'After 2010'. The end year of the third period is in general 2020, but in the investigation of the longer-term coastal morphology (see section 5.3), the end year is adjusted.

In all scenarios the Lagos Harbour Moles are present. In the first and second period, the local diffracted wave climate is imposed in the shadow zone of the East Mole. The difference in the first two periods is in the size of the bypass along the East Mole. In the first period, a positive bypass occurs and in the second period, the flux along the East Mole is negative. And in the second period also several nourishments are conducted, which are put in the model as sources varying over time.

In the third period Eko Atlantic City is added to the model as a 6 km long revetment located on the 2010 coastline. The local wave climate near the East Mole is removed, as the land reclamation fills the shadow zone completely. The volume of bypassing along the East Mole in the third period differs between the scenarios.

4.4 CALIBRATION

In order to achieve a correct model, which represents the coastline development as accurate as possible, the model is calibrated. The calibration is done by comparing the model results (e.g. the changes in coastline position) to the literature data, historical coastline positions (as depicted in Figure 1-5 and Figure 3-3) and the current position of the coastline, extracted from Google Earth (2010). Thereafter, the Unibest model is adjusted, such that the most realistic results are obtained.

4.4.1 AVAILABLE DATA

Concerning the historical morphological behaviour, not much data is available to calibrate the model on. One of the most cited references is the work done by Ibe (1988)(Ibe, 1988), so therefore this source is looked at first. However by comparing the data provided by Ibe (1988) to Figure 3-3, it can be concluded that the literature data of Ibe (1988) overestimate the drawn rates of erosion respectively accretion (elaborated in appendix C.5). Therefore, as a first approach, the rates of erosion and accretion obtained from Figure 3-3 are used to calibrate the model.

Because much interference has occurred at the eroding Bar Beach, of which not much data is available, the focus in the calibration lies on the Lighthouse Beach. In principle this beach increased its width due to the sand trapping by the West Mole and no further interventions were conducted at this beach. Therefore the Unibest model should be able to simulate the development of the Lighthouse Beach very accurately.

Regarding the volume of longshore sediment transport, several sources exist. Most of the values discussed in literature lie in between 0.5 and 1 million m³/year. Royal Haskoning generally uses a value of 700,000 m³/year in its models and reports. In this model, the same amount of LST is strived to obtain.

4.4.2 ADJUSTMENTS TO MODEL

Taking into account the possibilities to calibrate the model, certain adjustments are made. The reason for these adjustments, their effects and the results of the adjustments are discussed in this section.

LENGTH OF WEST MOLE

In the coastline calculations in Unibest, the model assumes a certain distribution of the longshore sediment transport over the active zone of the cross-section. By adjusting the length of the West Mole, the expansion of the Lighthouse Beach can be influenced a little. If the length of the mole is shortened, more sediment can bypass the mole into the Commodore Channel and the broadening of the Lighthouse Beach is less. On the contrary, a longer mole retains more sediment and thereby the influence of the mole extends further upstream.

The increase in width of the Lighthouse Beach is obtained using Figure 3-3. It turns out that the initial length of the West Mole of 1 km is sufficient to obtain the required rate of beach expansion.

INITIAL COASTLINE ORIENTATION

The initial coastline orientation put in the LT module influences the initial longshore sediment transport volumes. A difference of 1° can lead to an initial difference in sediment transport of about 100,000 m^3/year. So, in the first years of the model, the influence of the initial coastline orientation can be distinguished most clearly. After a couple of years, the coastline orientation is changed sufficiently, such that the initial coastline orientation does not influence the further coastline development very much. But for instance, the velocity of initial accretion of the Lighthouse Beach is investigated, such that a realistic increase of the accretion over the years is obtained. The initial coastline orientation of the cross-shore profiles can be found in appendix D.1.

EQUILIBRIUM ANGLE

The equilibrium angle is the angle of the coast, relative to the wave angle of incidence, for which the sediment transports are zero. Per cross-section, an equilibrium angle is defined.

After the Unibest model is calibrated to fit approximately to the data on erosion and accretion rates used in the conceptual model (which are obtained from Figure 3-3), the Unibest output is converted to another extension, such that the results can be visualised in Google Earth (2010). In the map of Google Earth (2010) the location of the most recent coastline available, i.e. dated October 2008, is depicted. Once the model results are plotted in Google Earth (2010), it turns out that the 'November 2008' coastline, generated by the Unibest model, is not curved as much as it is in reality. So, the model needs to be calibrated somewhat more.

Therefore, the curvature of the coastline needs to be adjusted somewhat. If one increases the equilibrium angle of the coast by e.g. a couple degrees, the orientation of the modelled coastline, with respect to the dominant wave angle of incidence also increases a couple degrees. Thereby, the occurring amount of LST is changed as well. So in principle, the S-ϕ curve is calibrated.

After some iteration it turns out that if the equilibrium angles increase by one degree, the simulated location of the Lighthouse Beach coastline matches well to the real location. In Figure 4-5 the location of the modelled coastline is plotted, in blue, over the actual coastline.

Figure 4-5: Location of 2010 coastline modelled with Unibest, plotted in the 2008 coast at the Lighthouse Beach

Besides the coastline in 2008, also the locations of the coastline in 2004 and 2006 are indicated by an orange plane in the figure, to take into account the differences in depicted coastline location during e.g. high or low tidal conditions. The coastal stretch enclosed by the plane has a mean width of approximately 50 m.

The adjustment of the equilibrium angle is justified because the wave climate used in the model is quite limited. As the wave climate is rather simplified, consisting of only 23 conditions, it is not accurate on the degree. Therefore, it could be very well possible that the weighted wave energy is a couple of degrees incorrect. The calibration is performed mainly to ensure that a correct wave climate is imposed on the model.

In addition to this, also the assumption of linear depth profiles between depths of 30 m to circa 10 m (see section 4.2.5) must be kept in mind. Only wave shoaling and refraction are taken into account in the propagation of the wave climate, while perhaps other, non-linear, processes can be of importance as well. Therefore, adjusting the equilibrium angle by one degree is permitted in this Unibest model.

ACCRETION VELOCITY

Another aspect regarding the reliability of the model is the velocity of accretion of the Lighthouse Beach. The expansion of the beach due to the accretion happens gradually over the years, although a bit faster in the first decade after the construction of the moles. The Unibest coastline output is plotted for every tenth year between 1910 and 2010, as depicted in Figure 4-6. The colour of the year corresponds to the colour of the accompanying coastline.

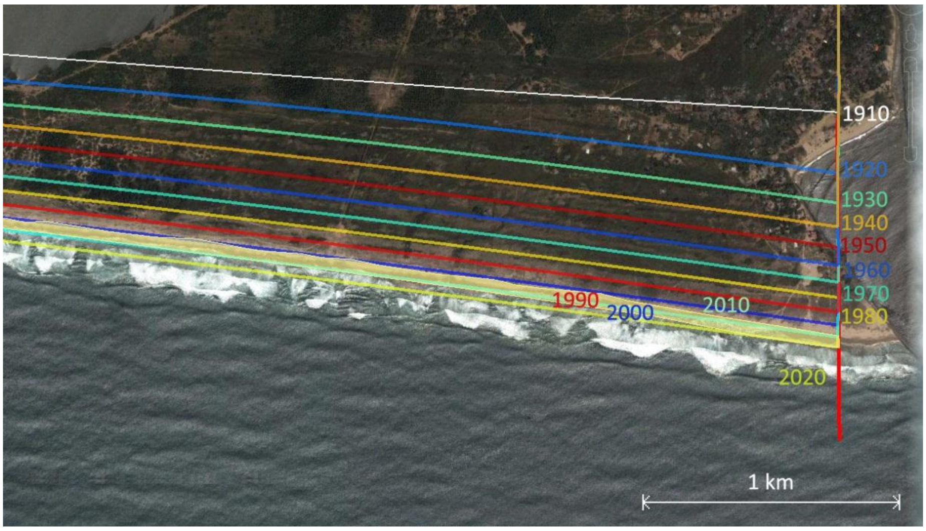

Figure 4-6: Location of coastline at Lighthouse Beach, per decennium between 1910 and 2020 [after Google (2010)]

It can be concluded that the beach accretion simulated by Unibest goes gradually and the accretion velocity decreases somewhat over the years, especially in the last decade. Therefore, it can be stated that the Unibest model is calibrated quite well for the Lighthouse Beach development. If one investigates the coastline orientation of the beach relative to the dominant angle of wave incidence, it can be seen that the beach more or less has reached the equilibrium orientation. The difference between both angles is about 5°.

LONGSHORE SEDIMENT TRANSPORT

The longshore sediment transport capacity differs per location. The volume of LST is mainly determined by the wave climate, which is roughly equal per location. And besides this, also the sediment properties have a significant effect on the potential sediment transport volume and the layout of the cross-sectional beach profile is important as well.

As explained in section 4.2.3, the initial coastline orientation influences the initial longshore sediment transport capacity. Averaged over the model area, the initial volume of LST is about 500,000 m^3/year to 800,000 m^3/year.

In the simulation, the volume of LST differs over the years. A value of 600,000 m^3/year to 700,000 m^3/year is acquired as the average amount of LST per year in the model area. So, this volume matches the target value of LST of 700,000 m^3/year.

4.4.3 REMARKS ON THE UNIBEST MODEL

The Unibest model is a 1D model and therefore it has certain limitations. One of the most important limitations regarding this study is that the sediment fluxes in and out the tidal inlet, which are generally complex phenomena, cannot be simulated by the model itself. As explained, the bypass along the East Mole is therefore put in manually.

Another aspect is the way in which erosion is simulated. In the Unibest model, erosion of the coast downstream a construction can happen quite abrupt, leading to triangular erosion patterns. In the simulation, it is assumed that the longshore current gains its maximum sediment transport capacity directly downstream of a construction. While in reality, the current does not acquire the maximum transport capacity directly downstream of a construction, resulting in a more curved erosion wave.

It has to be kept in mind that, for instance, bottom scouring cannot be modelled by Unibest, while this can be a sediment source of importance at the Lagos coast. If the depth in front of Eko Atlantic City is too deep for the longshore current to transport any sediment, sediment deposition in front of the land reclamation occurs. The sediment deposition continues until the area is shallow enough for the longshore current to further transport the sediment further downstream. This can influence the development of the erosion over time. In the first years after construction of the project, the deposition of sediment can lead to a larger sediment deficit in the longshore current, while a couple of years later, the water depth at the sediment deposition location can become sufficiently small, such that the longshore current is able to transport the sediments again.

4.5 LAGOS COASTAL SYSTEM ANALYSIS

The analysis of the Lagos coast is started in chapter 3. In this section the analysis is continued using the Unibest model. First, an investigation of the simulated volumes of accretion and erosion is presented and thereafter, these results are used to review the conceptual model.

In order to assess the influence of the different human interferences at the Lagos coast, the relative impact of the human actions on the coastal morphology is investigated. First a run is made in the Unibest model in which the specific human action is excluded and secondly the human action is put in the model and another simulation is executed. By comparison of the model outputs concerning the coastal situation, for instance after 50 or 100 years, the relative impact of the human interference can be distinguished. If the coastline position in a certain year is compared to the 1910 coastline, the absolute coastline changes can be obtained.

4.5.1 ACCRETION OF LIGHTHOUSE BEACH

Visually, the Unibest model results match well to the coastline obtained by Google Earth (2010). To check to what extent the Unibest model matches the conceptual model, the accretion volumes between 1910 – 1960 and for the period 1910 – 2010 are obtained from the output of the model:

- 1910 – 1960: 36.1 million m³ ≈ 0.72 million m³/year
- 1910 – 2010: 70.2 million m³ ≈ 0.70 million m³/year

So, therefore:

- 1960 – 2010: 34.1 million m³ ≈ 0.68 million m³/year

If one compares these accretion volumes to the volumes used in the conceptual model, it appears that the volumes simulated by the Unibest model are larger than the volumes in the conceptual model.

The accretion rates simulated by the Unibest model for the period 1910 – 1960, at a distance of 5 km upstream, 2 km upstream and next to the West Mole are presented below, together with the accretion rates in the conceptual model, between brackets:

467 m directly west of the West Mole	(440 m)
440 m at 2 km upstream the West Mole	(340 m)
412 m at 5 km upstream the West Mole	(280 m)

Similar, the rates of accretion for the period 1960 – 2010 are compared:

382 m directly west of the West Mole	(280 m)
275 m at 2 km upstream the West Mole	(280 m)
143 m at 5 km upstream the West Mole	(240 m)

Comparison of these accretion rates to the rates used in the conceptual model, again demonstrates the bigger amount of accretion simulated by the Unibest model. Only at the position 5 km upstream of the West Mole, the accretion is more in the conceptual model than in the Unibest model. Before any conclusions can be drawn on the two models, the simulated development of the Bar Beach is considered first.

4.5.2 EROSION OF BAR BEACH

Although the model is calibrated on the accretion of the updrift coast, it is checked whether the morphological behaviour of the Bar Beach is simulated sufficiently correct. The model should simulate the erosion more or less similar to the real situation. Therefore the simulated coastline is plotted in Google Earth (2010) again, for every decade between 1910 and 2010, see Figure 4-7. The colour of the year is similar to the colour of the corresponding coastline.

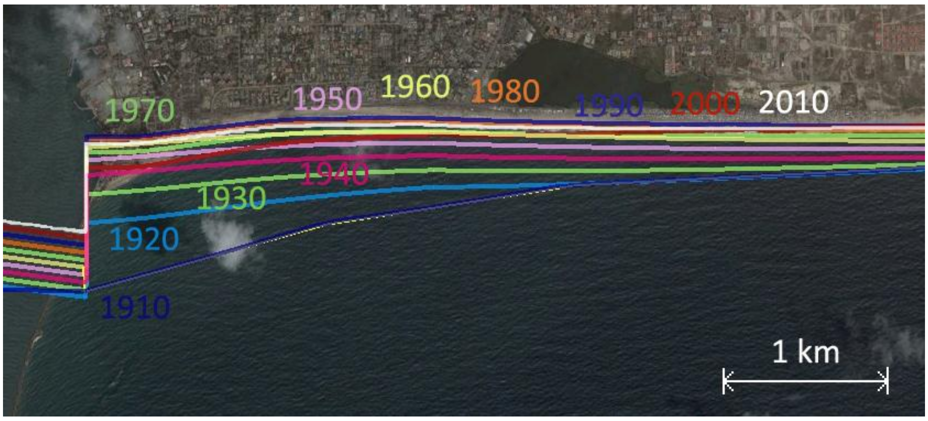

Figure 4-7: Location of coastline at Bar Beach, per decennium between 1910 and 2010 [after Google (2010)]

If one investigates the simulated development of the erosion over the first 100 years after construction of the Lagos Harbour Moles, it can be concluded that the model represents the real situation quite well. In 100 years, the coast receded about 900 m in the shadow zone of the East Mole. This erosion value matches reasonably well to the values used in the conceptual model.

Using Figure 4-7, it can be concluded that in the first 20 to 30 years after construction of the moles the erosion of Bar Beach was very severe. Also the influence of the nourishments can be distinguished, especially, if one considers the difference in coastline position next to the East Mole between 1990 (in dark blue) and in 2000 (in dark red). If subsequently the 2010 coastline position (in white) is taken into account, the high erosion rates become visible.

It can be concluded that the nourishments between 1960 (in yellow) and 1970 (in light green) have been useful as well, as the coastline in 1970 has not receded compared to its position in 1960.

Besides visually, the erosion simulated by the Unibest model is also compared numerically to the conceptual model. First, the erosion volumes are considered:

- 1910 – 1960: 31.5 million $m^3 \approx 0.63$ million m^3/year
- 1910 – 2010: 47.0 million $m^3 \approx 0.47$ million m^3/year

So, therefore:

- 1960 – 2010: 15.5 million $m^3 \approx 0.31$ million m^3/year

The volumes obtained in the conceptual model in the period 1910 – 1960 are, again, smaller than the erosion volumes provided by the Unibest model.

Considering the erosion volumes in the time span 1960 – 2010, the volumes obtained by the Unibest model are, similar to the conceptual mode, the 'net' values of erosion. As stated in 3.3.3, despite of all the nourishments performed, the coast still experienced erosion. Hence, the erosion volumes in this period have to be compared to the 'net' erosion values of the conceptual model.

Subsequently the rates of erosion between 1910 and 1960 obtained by Unibest are compared to the conceptual model rates of erosion (between brackets):

851 m directly east of the East Mole	(690 m)
477 m at 2 km downstream the East Mole	(370 m)
179 m at 5 km downstream the East Mole	(260 m)

For the period 1960 – 2010 the same comparison is presented:

24 m directly east of the East Mole	(430 m)
57 m at 2 km downstream the East Mole	(240 m)
93 m at 5 km downstream the East Mole	(190 m)

Comparison of the erosion rates clearly indicates the difference in results from the conceptual model and the Unibest model. Therefore, a reflection on the conceptual model is presented in the next section

4.5.3 REFLECTION ON CONCEPTUAL MODEL

The output of the Unibest model runs provides values of erosion volume and accretion volume that differ from the values used in the conceptual model. To check in what extent the models match, it is assessed whether the relative amount of sediment sources and sinks (defined as a percentage of the total volume of LST, see section 3.1.3) obtained by the Unibest models matches the percentages as defined in the conceptual model.

Further investigation of the volume of LST in the Unibest runs provides a mean value of 700,000 m^3/year. The sediment fluxes, sinks and sources in the time span 1910 – 1960 obtained via the Unibest model are represented graphically in Figure 4-8.

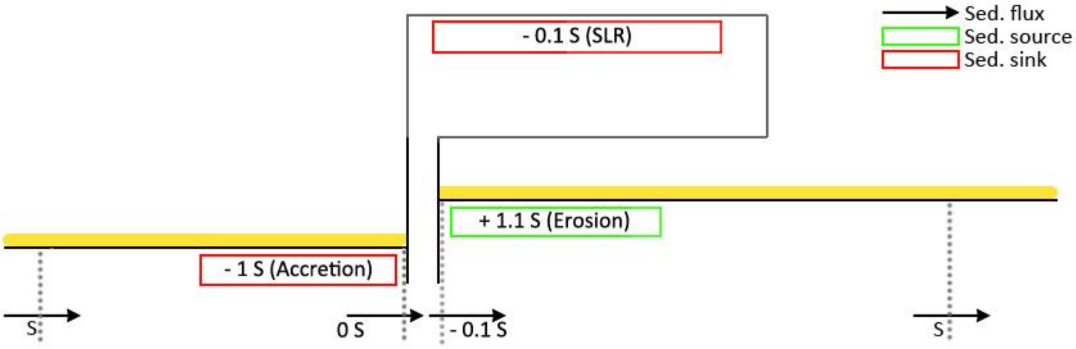

Figure 4-8: Conceptual sediment balance according to Unibest output; 1910 – 1960

Summarizing, according to the Unibest model all sediment transported eastward by the longshore current is trapped at the West Mole between 1910 and 1960. SLR induces sediment import into the lagoon, which leads to negative bypass along the East Mole. The negative bypass can be explained by the tidal currents around the inlet that are able to transport the sediment from the coast downstream and from the shallow parts of the downstream surfzone towards the inlet. Subsequently, high erosion volumes occur at the Bar Beach.

In Figure 4-9 the sediment balance as obtained by the output of the Unibest model is depicted for the period 1960 – 2010.

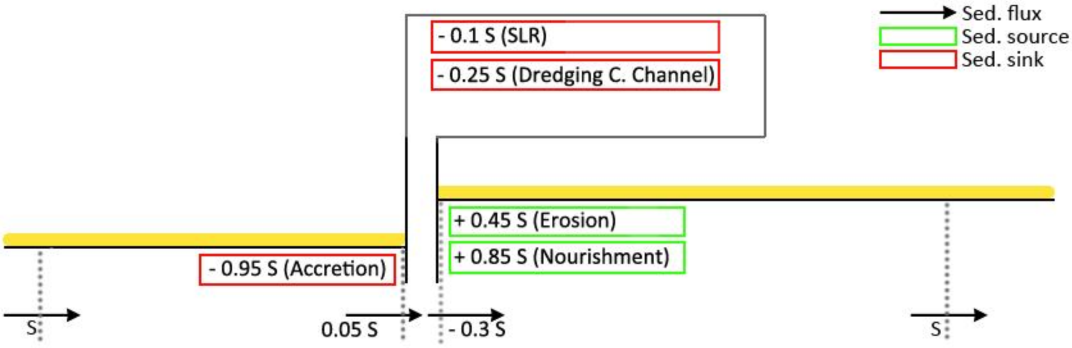

Figure 4-9: Conceptual sediment balance according to Unibest output; 1960 – 2010

It can be concluded that in the Unibest model, in the second period, about 95 per cent of the total volume of sediment transported eastward accumulates at the West Mole. The bypass along the West Mole is therefore very small: 5 per cent. Consideration of the volumes of the erosion downstream (obtained via Unibest) and the nourishments (mean volume of 0.58 million m^3/year) provides the size of the sink at the inlet. According to the Unibest model, the sink is $0.35 \cdot S$; hence much smaller than in the conceptual model. This would suggest that e.g. the dredging in the Lagos Lagoon was performed at a location far from the inlet, such the dredging did not influence the sediment fluxes around the inlet (and the sediment to cope with the sink due to dredging was supplied to the lagoon by other sources as for instance bank erosion). However, the sediment volume bypassing the East Mole does not differ from the original conceptual model.

In the consideration of the different outputs of the conceptual model and the Unibest model, it has to be kept in mind that both models are based on the data acquired from Figure 3-3 and both models make use of the single line theory of Pelnard-Considère (1956). So, the differences are not in the basis of both models.

In appendix E.1 the complete elaboration of the analysis of the differences between the two models can be found. Using the plots of the output of the Unibest models, for instance as depicted in Figure 5-3, the calculation of volumes of accretion and erosion in the conceptual model is examined.

It turns out that the assumptions applied in the calculations for the conceptual model are not completely valid. The volumes of erosion and accretion in the conceptual model seem to be computed too low.

According to the Unibest output, the data provided by Figure 3-3 do not represent as much of the total accretion and erosion volumes as assumed earlier (see appendix C.5). Adjustment of the calculations made in the conceptual model provides values of erosion and accretion that match fairly well to the values obtained via the Unibest model.

CHECK WITH UNIBEST

A final check is made by applying the 'updated' conceptual model in a Unibest run and investigating the output of this model.

So, in this Unibest model the volume of bypassing along the East Mole in the first period (i.e. 1910 – 1960) is -0.1 · S (instead of +0.25 · S). The second period (1960 – 2010) is not adjusted, as the bypassing volume along the East Mole in the 'reviewed' conceptual model is identical to the bypass in the original conceptual model.

In Figure 4-10 the coastline position at Bar Beach in different years is depicted.

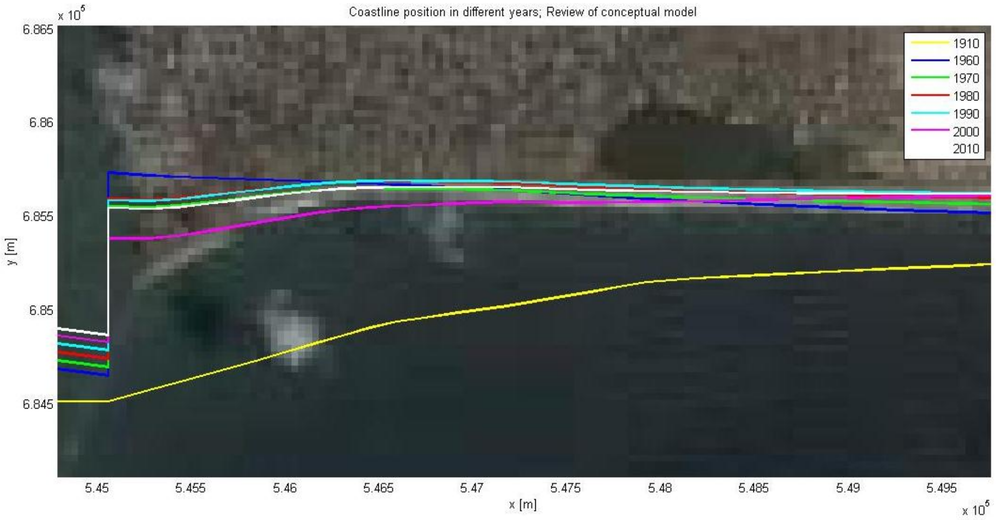

Figure 4-10: Coastline position in different years, obtained by the Unibest model based on the 'reviewed' conceptual model

It can be concluded that the Unibest run based on the 'reviewed' conceptual model does not simulate the development of the coast downstream of the tidal inlet correctly. Instead, the simulation of this part of the coast by the original conceptual provides a far better match to the real situation.

Therefore, it can be concluded that the 'reviewed' conceptual model also does not represent the historical development of the Lagos coastal system correctly. The 'valid' conceptual model is assumed to lie somewhere in between the two conceptual models presented in this thesis.

However, compared to the original conceptual model, the Unibest model is based on additional data like the recent bathymetry and the actual wave climate present at the relevant coast. Besides, the Unibest model results resemble the most accurate data available (i.e. the Google Earth (2010) data) around 2010 quite well. Therefore, it is assumed that the Unibest model provides a fairly good representation of reality and that it can be applied in this study, as long as one keeps the uncertainties in mind.

4.5.4 LAGOS HARBOUR MOLES

The influence on the coastal development of the Lagos Harbour Moles is already quite clear: the Lighthouse Beach accreted and the Bar Beach eroded. To investigate the natural behaviour of the system, a model is made in Unibest in which the moles are not constructed. This model is subsequently run from 1910 until 2010 and the output is compared to the coastal situation as simulated by Unibest for the scenario with the moles present. To investigate the natural behaviour, only the SLR sink is taken into account in this model.

In Figure 4-11 the coastline is plotted for 1910 in yellow, for 1960 in red and for 2010 in green.

Figure 4-11: Coastline position in 1910 in yellow, 1960 in red and 2010 in green in scenario without Lagos Harbour Moles

The coastline positions plotted Figure 4-11 show that the coast is approximately stable under natural conditions. The difference in positions between the Lighthouse Beach and the Bar Beach remains also in 1960 and 2010.

In appendix E.1 plots on the relative differences between the scenarios with the moles and without the moles and plots of the absolute erosion occurring over the years can be found.

Between 1910 and 1960 a volume of 16.5 million m³ is eroded due to the sink induced by SLR. The total accretion volume in the same time span is about 13.8 million m³.

Between 1960 and 2010 the erosion is significantly less: 5.6 million m³ erodes away. Also the volume of accretion is decreased: 3.1 million m³ in this period.

The values on erosion and accretion indicate that the natural behaviour of the coast of Lagos downstream of the inlet is erosive, due to the effects of SLR in the tidal inlet and lagoon. More sediment is eroded than accreted in the system. The coast upstream the tidal inlet accretes slightly. However, it has to be kept in mind that the general behaviour of the Lagos coast is erosive due to the effects of SLR on the coast, as described by the 'Bruun rule', see section 3.4.2. However, this phenomenon is not accounted for in the Unibest model, because the model is mainly created to assess the impact of the Eko Atlantic City project. It is expected that the effects of SLR are very small compared to the effects of the project.

4.5.5 NOURISHMENTS

It has been mentioned earlier that, although many nourishments were conducted, the Bar Beach still kept on eroding. The importance of the nourishments is investigated by comparison of two model simulations: one simulation is done with inclusion of the nourishments, and the second run is made without the nourishments. Then, the alleviating effect of the nourishments can be assessed by looking at the difference in coastline position in 2010 between the two model outputs.

The difference in coastline position in 2010, if no nourishments would have been conducted, can be seen in Figure 4-12. In red is the coastline position without the nourishments and in yellow is the model output if the nourishments are included (which is actually the real situation as can be seen in the figure). It is clearly visible that the nourishments have had a positive effect on the coastline development; if no nourishments would have been performed, a significant part of the Bar Beach would have suffered immense erosion.

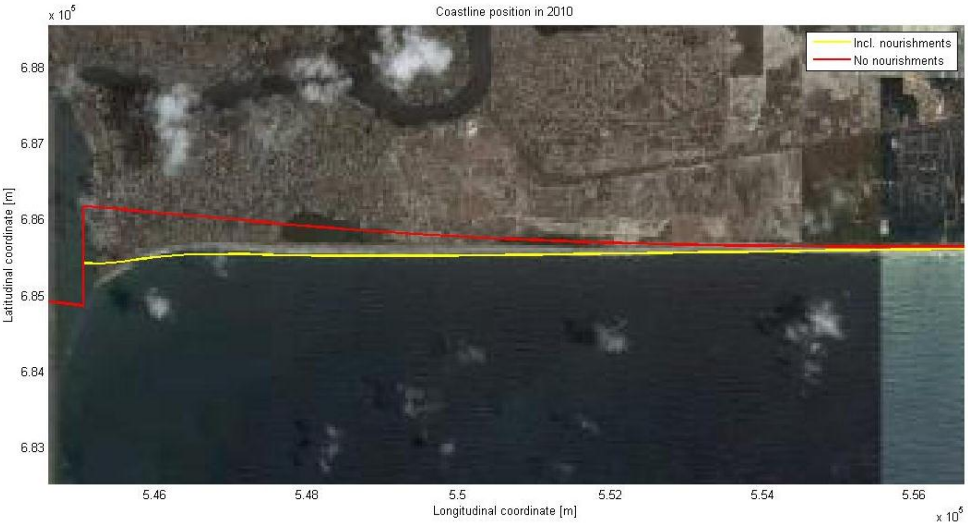

Figure 4-12: Difference in coastline position in 2010 between scenario with nourishment (depicted in yellow) and scenario without nourishment (in red)

The hypothetically eroded part of the Bar Beach in the scenario without nourishments contains the Kuramo Waters (see also Figure 2-6) behind a beach of a width of circa 100 m. If the beach in front of these small lakes would have eroded as much as predicted by the Unibest model, the effects would probably be even worse than depicted in Figure 4-12. A breakthrough of the erosion to the Kuramo Waters would entail much more erosion than modelled. Then, at once a significant part of the coast is flooded (and eroded) also from the landside, instead of from the seaside alone.

The hypothetical erosion volume prevented by the sediment supply is calculated by comparison of the absolute erosion volumes between 1910 and 2010 of the scenario with nourishments and the scenario without nourishments. In appendix E.1 several plots of the coastline changes of both scenarios can be found.

If the nourishments are executed, a total sediment volume of roughly $47 \cdot 10^6$ m³ is lost from Bar Beach, compared to the 1910 coastline. And if no nourishments would be performed, the total erosion volume would be around $75 \cdot 10^6$ m³, from 1910 until 2010. So the total volume of prevented erosion is about $28 \cdot 10^6$ m³.

If the nourishments would not have been performed, the erosion rates just east of the East Mole would have been increased by almost 600 m. Compared to the mean, annual nourishment volume of $0.58 \cdot 10^6$ m³/year, it can be concluded, just as discussed in the conceptual model, that approximately all nourished sediment supplied in the time span of 50 years has been eroded. So, the nourishments have been very useful as roughly 600 m of erosion is prevented by their execution.

4.5.6 LAND RECLAMATION IN LAGOS LAGOON

In the original conceptual model the impact of the land reclamation in the Lagos Lagoon is discussed. The sediment extraction induces a large sediment demand in the lagoon, which subsequently leads to much sediment import into the lagoon. However, according to the 'reviewed' conceptual model, the dredging in the lagoon had no effect on the sediment fluxes around the inlet, and the erosion of the Bar Beach was induced mainly by the sediment trapping of the West Mole instead of by the dredging of the lagoon.

However, to provide for a comprehensive investigation, the original conceptual model assumptions are studied a little more. Using a Unibest model run (based on the original conceptual model), it is investigated what the development of the coast would have been if the land reclamations in the Lagos Lagoon would not have been performed. The coastline positions obtained with the model are depicted in Figure 4-13. In yellow is the 1910 coastline, in red the 1960 coastline and in green the 2010 coastline is depicted.

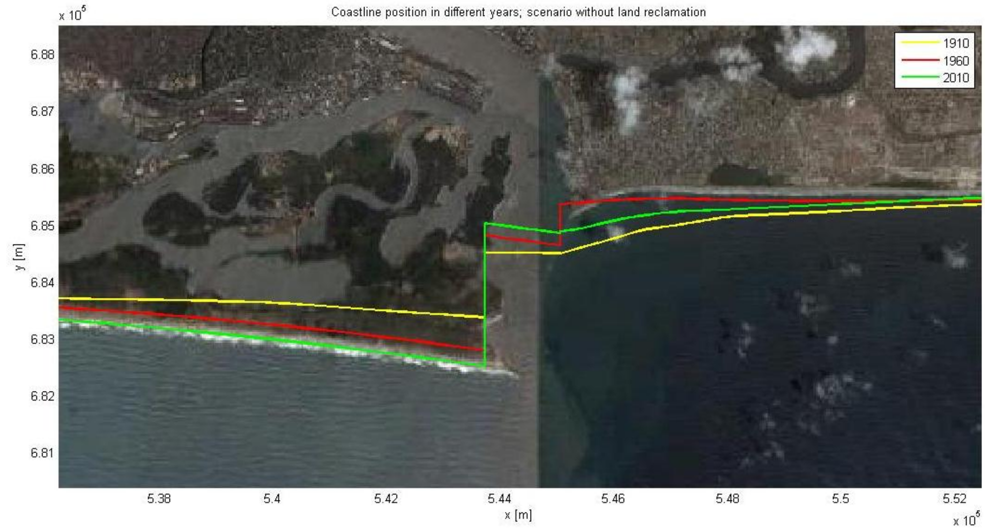

Figure 4-13: Coastline position in 1910 in yellow, 1960 in red and 2010 in green in scenario without the land reclamations performed

Considering the differences in the downstream coastline position between 1960 and 2010, as depicted in Figure 4-13, shows the large impact of the land reclamations. Without the land reclamations in the lagoon a sediment volume of 0.35 · S would have bypassed the East Mole. So, if these reclamations would not have been performed, then the coast at Bar Beach would have eroded significantly less.

The erosion rates directly downstream the East Mole reach a maximum of 400 m extra if the land reclamation is performed. An additional erosion volume of 19.5 million m^3 is induced by the land reclamations compared to the scenario without the reclamations.

Whether the dredging of the lagoon had an impact on the sediment fluxes around the inlet or not, is not certain. As the analysis in section 4.5.3 shows, the 'true' conceptual model is assumed to lie somewhere in between both conceptual models obtained in this thesis. But the investigation presented in this section does show that the large volume of the sink, whether is induced by the dredging of the lagoon or by the sediment trapping at the West Mole, did have a severe effect on the coastal morphology downstream of the inlet. It can be seen in Figure 4-13 that, without the presence of such a large sink (i.e. either the dredging of the lagoon or the sediment trapping at the West Mole) the Bar Beach would not have eroded as much as it did over the last fifty years. So, it can be concluded that there must have been such a large sink in the Lagos coastal system, to induce the enormous erosion volumes at the Bar Beach.

5 FUTURE MORPHOLOGICAL DEVELOPMENT

In this chapter the hypotheses concerning the future morphological development of the Lagos coast, created in chapter 3, are elaborated with help of the Unibest software.

The scenarios for the future development of the Lagos coast are discussed in section 5.1. The impact of the Eko Atlantic City project in 2020 is investigated relative to the 2020 situation without the presence of the project and relative to the coastal situation in 2010. Subsequently, the general conclusions arising from the study performed into the future coastal development are presented in section 5.2

Also the development of the coast up to 2060 is investigated in section 5.3. It is concluded that mitigation measures downstream of Eko Atlantic City are required. Therefore some possible mitigation measures are discussed in section 5.4.

5.1 IMPACT OF EKO ATLANTIC CITY

To investigate the long-term impact of the Eko Atlantic City project, the model is expanded. A third period, running from 2010 to 2020, is added to the Unibest model, in which Eko Atlantic City is schematised as a revetment. At the location of the revetment, the coastline position of 2010 is fixed and no more coastline changes can occur. The length of the revetment is 6 km, running from directly next to the East Mole further to the East.

In chapter 3 four scenarios were constructed, based on the volume of sediment bypassing the East Mole. For all four scenarios a specific Unibest model is constructed. Also a so-called 'zero-bypassing-scenario' is tested in a Unibest model. As the name implies, in the scenario 0, no sediment bypasses the East Mole.

Every model is run twice: first a run is made with Eko Atlantic City present and thereafter, a simulation is done without the revetment in the model.

The 'bypassing volume' along the East Mole is put in the models as a source or, in the case of negative bypass, as a sink. In the model runs without Eko Atlantic City the source or sink term is put directly east of the East Mole. However, if the revetment is present in the models, the source or sink term is put directly east of the revetment because the model gets instable if one puts a source on the revetment itself.

The accretion of the Lighthouse Beach is equal for all model runs, since the difference between the models is the volume of sediment bypassing along the East Mole and the presence or absence of Eko Atlantic City. Therefore, the analysis of the model runs focuses on the coast at the downdrift side of the inlet (i.e. Bar Beach and further eastward).

By comparison of the output of the two model runs per scenario for a certain year, the relative impact of the Eko Atlantic City project can be investigated. For instance, the difference in coastline positions between both model runs is investigated for a specific output year. Hence, it is obtained what changes in erosion are induced by Eko Atlantic City, compared to the scenario without the project constructed.

The absolute changes in coastline position, if Eko Atlantic City is present, are acquired by comparison of the coastline in the specific output year to the 2010 coastline, when the Eko Atlantic City project is not yet constructed. In this way the rates of erosion occurring between the output year and 2010 are obtained.

In the output figures presented in this section and in appendix E, positive coastline changes and accretion are represented by green bars and negative coastline changes and erosion by red bars. The width of the bars is approximately 1.32 km. The Commodore Channel is located at the grey surface, positioned in between longshore distances 20.6 and 22 km. The western boundary of the model lies left in the figures, at longshore distance 0 km, and the eastern boundary is positioned at the right part of the figures, approximately at longshore distance 50 km.

To prevent a repetition of similar looking figures, most of the figures discussed in this section are depicted in appendix E. In the discussion of the scenario 0 results, all relevant figures are depicted as an example but in the analysis of the other four scenarios, one is referred to appendix E for the corresponding figures.

5.1.1 SCENARIO 0

No bypass along the East Mole occurs in scenario 0. The sediment that bypasses the West Mole gets transported into the tidal inlet, for instance due to the sediment demand of the Lagos Lagoon and the Commodore Channel, and does not return to the longshore current.

RELATIVE IMPACT

The coastline positions in 2020 for the model runs of scenario 0 with Eko Atlantic City and without Eko Atlantic City are plotted in Figure 5-1. The coastline in yellow is without the revetment in the model, and the red line is with the presence of Eko Atlantic City.

Figure 5-1: Coastline in 2020, for scenario 0. In yellow is the result of the model run without Eko Atlantic City, and in red with the land reclamation constructed

If Figure 5-1 is considered, it can be seen that the land reclamation changes the location of the erosion. Just east of the East Mole, the project prevents further erosion of the coast, as it retains the sediment there. But this happens at the expense of the coast further downstream, as the longshore current still has a sediment deficit.

It can also be seen in Figure 5-1 that, at the location of the expected erosion, the Kuramo Waters East are present behind the coast. The width of the beach in front of these inland waters is less than 100 m. Hence, with the simulated increase of erosion rates, a breakthrough is likely to happen.

So, just as discussed in the analysis of the influence of the nourishments, once the coast in front of these waters has been eroded and a breakthrough to these inland waters happens, much more erosion as modelled in this run can occur[23]. The Unibest model computes a certain volume of erosion, depending on the gradient in the longshore sediment transport, but a part of the simulated erosion volume of the coast consists of water, instead of sediment. Therefore, it is expected that the final erosion rates are higher and that the erosion reaches further inland. The land adjacent to these inland waters is built densely, which makes flooding very harmful.

The changes in coastline position in 2020, relative to the initial coastline location in 1910, per model run of scenario 0 are presented in Figure 5-2. The first figure represents the coastline changes from 1910 until 2020, if the project is not constructed. The second figure depicts the coastline changes over the same period, if Eko Atlantic City is present. The positive respectively negative values of coastal changes in the third figure represent the difference in the 2020 coastline position, between the output of scenario 0 with Eko Atlantic City and without the project. So, using this Figure 5-2 (depicted on the next page), the relative impact of the project is investigated.

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[23] The small lakes backing the coast cannot be taken into account in the Unibest model.

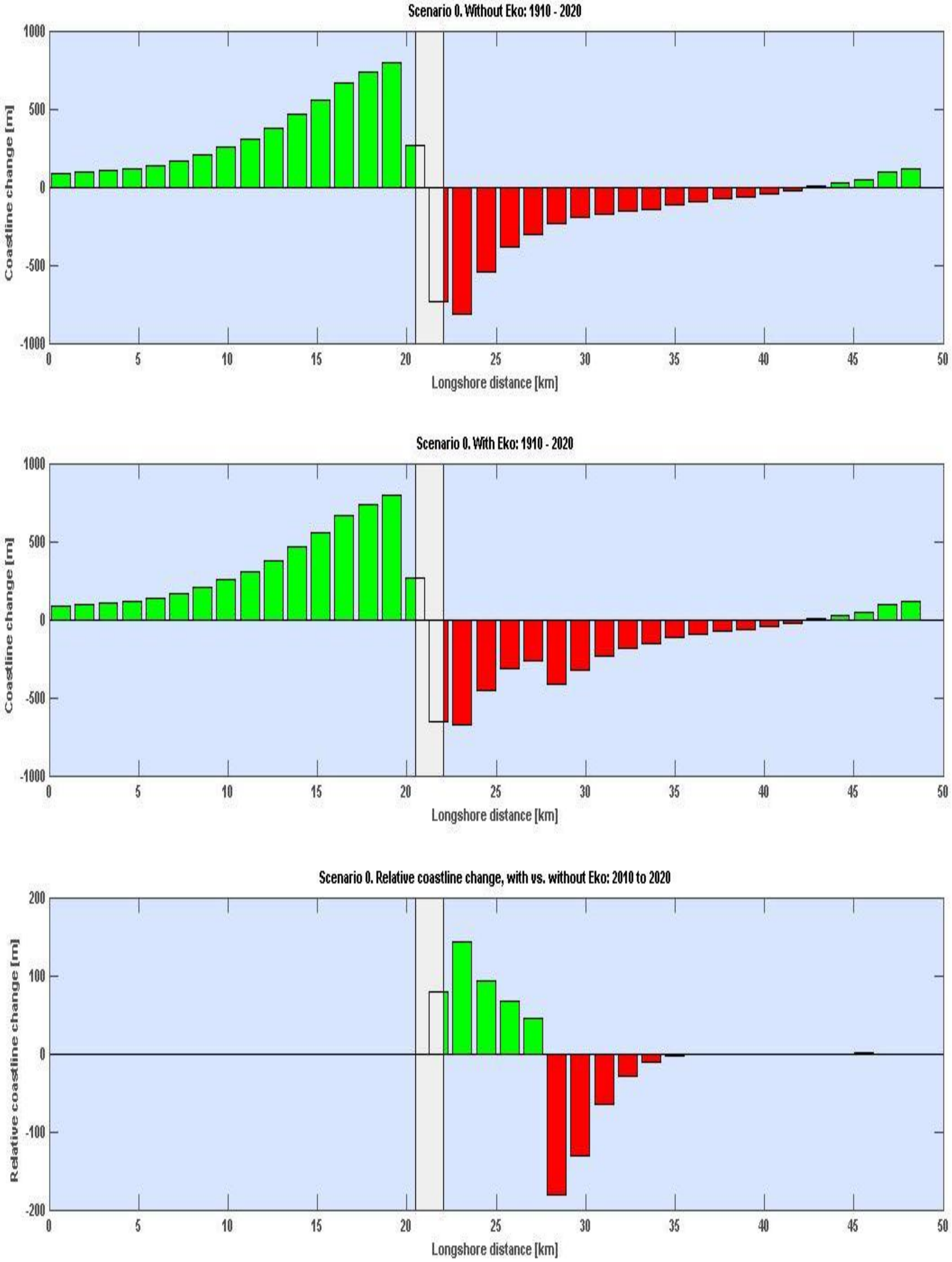

Figure 5-2: Above: absolute coastline change, between 1910 and 2020, for scenario 0 without Eko Atlantic City. Middle: absolute coastline change, between 1910 and 2020, for scenario 0 with Eko Atlantic City. Below: relative coastline change between both scenarios, between 2010 and 2020

The shift of erosion towards the east of Eko Atlantic City is visible in the middle figure of Figure 5-2. The smaller erosion rate just east of the East Mole can be distinguished in the middle figure as well. The lowest figure shows the relative influence of the land reclamation for scenario 0. At the location of the revetment (i.e. the first 6 kilometres next to the East Mole), a positive influence is observed, as the Eko Atlantic City project prevents further erosion by fixation of the coast. The biggest benefit of the project occurs just east of the East Mole, around a longshore distance of 23 km, where circa 140 m of erosion is prevented.

However, the erosion rates just east of Eko Atlantic City in 2020 are roughly 180 m higher compared to the scenario without the revetment. Locally, the coastal erosion is approximately 420 m instead of 240 m. The increase in local erosion east of Eko Atlantic City is noticeable until circa 8 km downstream the project after ten years.

The erosion volume can be obtained by multiplication of the erosion rates by the active profile height and by the grid cell width[24]. The total erosion volume, between 1910 and 2020, in scenario 0 without Eko Atlantic City is around 57 million m³. Considering the total erosion volume in the same time span for the scenario 0 with Eko Atlantic City, it turns out that the total volume of erosion is equal for both scenarios, as the erosion volume in the latter scenario is also about 57 million m³.

Thus, the net effects of Eko Atlantic City in terms of erosion volumes are zero, since the total volume of erosion is the same in both model runs of scenario 0. The gross effects of the project however are of importance, as a translation of the location of erosion occurs. If one compares the coastal situation in 2020 for both scenario 0 alternatives, the volume of the erosion prevented by the project (i.e. the volume of the green bars next to the East Mole) is about 5.6 million m³. And logically, the local additional erosion next to the Eko Atlantic City project, compared to the situation without Eko Atlantic City, is also approximately 5.6 million m³.

ABSOLUTE CHANGES

If one considers potential maintenance schemes for the coast, not the relative but the absolute changes in coastline location are of importance. The absolute local increase of erosion due to the presence of Eko Atlantic City can be obtained by comparison of the 2020 coastline position to the 2010 coastline position.

Using Figure 5-3, the absolute changes are investigated. The upper figure represents the accretion and erosion of the coast in the time span 1910 – 2010 and the middle figure shows the absolute coastal changes in the period 1910 – 2020, when Eko Atlantic City is constructed. Comparison of these two upper figures provides the absolute rates of local additional erosion and accretion in the period 2010 – 2020, with the presence of Eko Atlantic City, depicted in the under most figure.

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[24] The calculations done are executed using Matlab scripts to evaluate the output files of Unibest; written by Deltares. Manually a check is made via the described method.

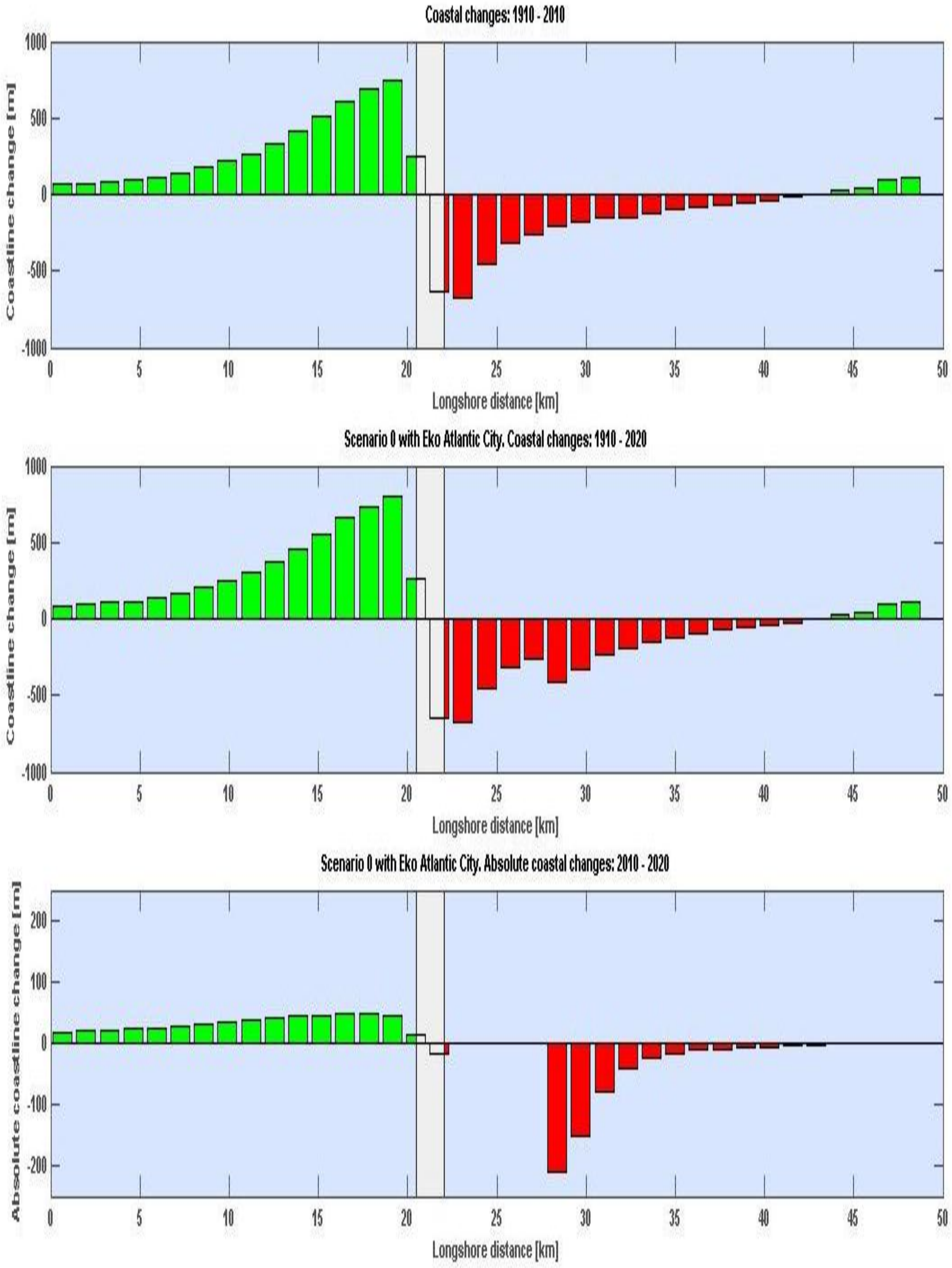

Figure 5-3: Above: absolute coastline change, between 1910 and 2010. Middle: absolute coastline change, between 1910 and 2020, for scenario 0 with Eko Atlantic City. Below: absolute coastline change in scenario 0, between 2010 and 2020, with Eko Atlantic City present

As can be seen in Figure 5-3, just east of the revetment the maximum absolute rate of erosion between 2010 and 2020 is about 210 m. The absolute erosion volume in the 10 years after construction of the project is roughly 7.7 million m³. The alongshore distance that suffers erosion stretches from circa 28 km to 38 km, thus a coastal stretch of 10 km length downstream the project is eroded.

The same analysis is made for the situation without Eko Atlantic City in the period from 2010 to 2020, of which the plots can be found in appendix E.4. If the revetment is not constructed, the maximum erosion rate of circa 140 m occurs next to the East Mole. The total erosion at this location in the time span 1910 – 2020 is about 820 m. Thus, if the revetment is constructed, the total erosion for the same location in the same period is circa 680 m.

The analysis of the relative impact of Eko Atlantic City shows that the total volume of erosion between 1910 and 2020 is independent of the presence of the project. Therefore, the absolute erosion volume in scenario 0 without Eko Atlantic City in the time span 2010 – 2020, is also approximately 7.7 million m³ of erosion. However, compared to the situation with Eko Atlantic City, the length of eroded coast is greater: 16 km instead of 8 km.

SUMMARY SCENARIO 0

Concluding, compared to the situation in 2020 without the presence of Eko Atlantic City, ten years after construction, the impact of the project on the downdrift coast consists of a local increase of erosion volume of 5.6 million m³. This additional erosion volume is spread over a coastal length of roughly 8 km, and it induces a maximum additional retrogression of the coast of approximately 180 m.

In total, between 2010 and 2020, the coast recedes about 210 m east to the revetment. So the erosion at this location is 30 m if the project is not constructed, but due to the shift of erosion induced by the presence of Eko Atlantic City an additional retreat of 180 m occurs.

The absolute erosion volume in the period 2010 – 2020 is about 7.7 million m³. The absolute erosion volume downstream the project is spread out over a coastal stretch of roughly 16 km. So if the project is not constructed, the absolute volume of erosion at this coastal stretch is about 2.1 million m³.

Compared to the scenario without the construction of Eko Atlantic City, the total absolute erosion volume does not increase; however if the land reclamation is present, the erosion volume is shifted eastward and is concentrated at a smaller longshore distance. In Table 5-1 an overview of all data mentioned in this section is presented.

Table 5-1: Overview output scenario 0

SCENARIO 0	With Eko Atlantic City	Without Eko Atlantic City
Location of maximum absolute erosion	Downdrift of the project	Next to the East Mole
Maximum absolute rate of erosion 2010 – 2020 [m]	210	140
Absolute erosion volume 1910 – 2020 [m^3]	54.9 million	54.9 million
Absolute erosion volume 2010 – 2020 [m^3]	7.7 million	7.7 million
Length of eroded coast [km]	10	16
Additional rate of erosion downstream Eko Atlantic City [m]	180	-
Additional local erosion volume downstream of Eko Atlantic City [m^3]	5.6 million	-
Alongshore influence of additional erosion [km]	8	-
Prevented erosion downstream East Mole by Eko Atlantic City, compared to scenario without the project [m]	140	-
Prevented erosion volume downstream East Mole due to Eko Atlantic City, compared to scenario without the project [m^3]	5.6 million	-

5.1.2 SCENARIO 1

In scenario 1 a part of the sediment volume that bypasses the West Mole gets transported into the tidal inlet and further into the lagoon. Another part of the sediment volume is transported back to the longshore current and is able to bypass the East Mole. The bypass volume along the East Mole equals 0.55 · S (i.e. 360,000 m^3/year).

RELATIVE IMPACT

In appendix E.7 the plots depicting the relative coastline changes can be found. The difference in coastline position in 2020 between the scenarios with and without the revetment is less than in the scenario 0. This is as expected since, in this scenario, bypass along the East Mole occurs.

Just as concluded for scenario 0, the scenario 1 model runs indicate a shift of the erosion zone, due to the local fixation of the coast by the Eko Atlantic City project. Also in scenario 1, it can be seen that the inland Kuramo Waters backing the coast have to be taken into account in the analysis of the effects of the project.

The total eroded volume in scenario 1 without Eko Atlantic City from 1910 until 2020 is about 53.4 million m^3. Calculation of the total erosion volume in scenario 1 with the presence of Eko Atlantic City provides the same total volume of erosion. Hence, the total volume of erosion is not altered by the presence of Eko Atlantic City. At the location of the land reclamation the coast is fixed and therefore further erosion is prevented. At the longshore location of 26 km (i.e. next to the East Mole), the positive effect of Eko Atlantic City is most obvious, in the prevention of circa 50 m of erosion.

However, the location where erosion occurs is shifted downdrift by the project. Just east of the land reclamation, the local erosion rates over the period from 1910 to 2020 are almost 300 m, instead of 240 m without the project. So, at this location, the relative erosion rate is 60 m. East of Eko Atlantic City the local additional erosion, compared to the scenario without the project, reaches a volume of circa 2 million m^3 in ten years. The additional erosion is noticeable until a distance of 8 km downstream the land reclamation.

ABSOLUTE CHANGES

The absolute changes in coastline position are investigated via comparison of the 2010 and 2020 coastal situation, if Eko Atlantic City is constructed. The plot is depicted in appendix E.7.

The maximum absolute erosion rate, from 2010 to 2020, with the presence of Eko Atlantic City is approximately 90 m, downdrift of the revetment. The total absolute volume of erosion, downdrift the project, is about 4.1 million m^3, stretched over a longshore distance of approximately 10 km.

The 2020 coastal situation without the presence of the land reclamation is also investigated. In appendix E.7 a similar overview of coastal changes between 1910 and 2020, compared to the coastal changes in the period 1910 – 2010 is presented. If the Eko Atlantic City project is not constructed, the maximum absolute erosion rate of 50 m, between 2010 and 2020, is located downdrift the East Mole. As the total absolute erosion volumes for both cases in the time span 1910 to 2020 are equal, the absolute volume of erosion downdrift the East Mole is also equal to the absolute erosion volume in the scenario 1 with Eko Atlantic City: 4.1 million m^3. In the scenario without the project however, this erosion volume is spread over a greater distance, of roughly 16 km.

SUMMARY SCENARIO 1

The impact of the Eko Atlantic City project is a shift in the location of erosion. If one compares the 2020 output of the scenario 1 model runs to each other, the impact of the revetment is a translation of an absolute erosion volume of 4.1 million m³, from the Bar Beach to downdrift the revetment. Taking into account the relative increase of erosion of 2 million m³, this means that at this location, the erosion is 2.1 million m³ if the revetment is not constructed.

Despite of the equal absolute erosion volumes, downdrift of Eko Atlantic City the absolute erosion rates are higher than the absolute erosion rates downdrift the East Mole, in the scenario without the project. Hence the erosion is translated and more concentrated at one location by the presence of Eko Atlantic City. In Table 5-2 all values of erosion rates and volume discussed in this section are summarized.

Table 5-2: Overview output scenario 1

SCENARIO 1	With Eko Atlantic City	Without Eko Atlantic City
Location of maximum absolute erosion	Downdrift of the project	Next to the East Mole
Maximum absolute rate of erosion 2010 – 2020 [m]	90	50
Absolute erosion volume 1910 – 2020 [m³]	53.4 million	53.4 million
Absolute erosion volume 2010 – 2020 [m³]	4.1 million	4.1 million
Length of eroded coast [km]	10	16
Additional rate of erosion downstream Eko Atlantic City [m]	60	-
Additional local erosion volume downstream of Eko Atlantic City [m³]	2 million	-
Alongshore influence of additional erosion [km]	8	-
Prevented maximum rate of erosion downstream East Mole by to Eko Atlantic City, compared to scenario without the project [m]	50	-
Prevented erosion volume downstream East Mole due to Eko Atlantic City, compared to scenario without the project [m³]	2 million	

An additional conclusion is that the total absolute erosion rate between 1910 and 2020 at a longshore distance of around 28 km (which is directly east of the Eko Atlantic City) is the same (i.e. 240 m) for both scenario 0 without Eko Atlantic City and scenario 1 without Eko Atlantic City. Apparently, the influence of the source in scenario 1 does not extend until this part of the coast, but the source has its main impact at the location closest to the East Mole.

5.1.3 SCENARIO 2

In scenario 2 bypass along the East Mole occurs, though the volume is less than in scenario 1. A sediment volume of 0.25 · S (i.e. 150,000 m^3/year) is able to bypass the East Mole.

RELATIVE IMPACT

A plot of the coastline in 2020 for both model runs made for this scenario is presented in appendix E.8. Just as in scenario 0 and scenario 1, the influence of the land reclamation is observed in the shift of location of erosion. And again, the inland Kuramo Waters just east of Eko Atlantic City have to be kept in mind in the analysis of the model output, as stated in section 5.1.1.

The total volume of erosion for both models runs of scenario 2, with and without the presence of Eko Atlantic City, is equal: about 56 million m^3 in 110 years.

The volume of erosion of Bar Beach prevented by the Eko Atlantic City project, in the ten years after its construction, is approximately 4.6 million m^3. The most positive effect of the project is the prevention of erosion just east of the East mole, around the longshore distance of 23 km. About 110 m of erosion is prevented by the revetment, as the erosion rate with revetment between 1910 and 2020 is circa 680 m instead of a total retreat of 790 m in the same period, if the revetment is not built.

This also means that the local increase of erosion east of Eko Atlantic City is equal to circa 4.6 million m^3, which occurs over 8 km in ten years. Just east of the revetment the erosion rates are increased by 150 m. Instead of 240 m without the project, the coast recedes almost 390 m between 1910 and 2020.

ABSOLUTE CHANGES

The net erosion and accretion values occurring in the period 2010 – 2020 are obtained via the investigation of the absolute changes between the 2010 and the 2020 coastline, depicted in appendix E.8.

If the Eko Atlantic City project is constructed, the translation of the erosion leads to a maximum retrogression of the coast of almost 180 m, east of the revetment. The total volume of erosion, between 2010 and 2020, is about 6.7 million m^3, spread out over a longshore distance of about 10 km.

An analysis of the absolute erosion rates, in the same period, if Eko Atlantic City is not constructed is also presented in appendix E.8.

Without the presence of the revetment, the maximum rate of erosion between 2010 and 2020 occurs downdrift of the East Mole. The coast recedes circa 110 m. The absolute erosion volume is equal to the scenario without the revetment: approximately 6.7 million m³, but the erosion happens over a longer distance: 16 km.

SUMMARY SCENARIO 2

Likewise as in the previous sections, an overview of all erosion rates and volumes discussed in this section is presented in Table 5-3.

Table 5-3: Overview output scenario 2

SCENARIO 2	With Eko Atlantic City	Without Eko Atlantic City
Location of maximum absolute erosion	Downdrift of the project	Next to the East Mole
Maximum absolute rate of erosion 2010 – 2020 [m]	180	110
Absolute erosion volume 1910 – 2020 [m³]	56 million	56 million
Absolute erosion volume 2010 – 2020 [m³]	6.7 million	6.7 million
Length of eroded coast [km]	10	16
Additional rate of erosion downstream Eko Atlantic City [m]	150	-
Additional local erosion volume downstream of Eko Atlantic City [m³]	4.6 million	-
Alongshore influence of additional erosion [km]	8	-
Prevented erosion downstream East Mole due to Eko Atlantic City, compared to scenario without the project [m]	110	-
Prevented erosion volume downstream East Mole due to Eko Atlantic City, compared to scenario without the project [m³]	4.6 million	-

Just as concluded for scenario 1, the influence of the source added east of the East Mole (i.e. the simulated bypass), in the model for scenario 2 without Eko Atlantic City, does not reach the location at a longshore distance of 28 km (i.e. just east of the location of the revetment). The erosion rates at the longshore distance of 28 km are 240 m, with or without the occurrence of the bypass.

5.1.4 SCENARIO 3

Scenario 3 represents the first situation in which a negative bypass along the East Mole exists. Due to the great sediment demand of the Lagos Lagoon, no sediment is able to bypass the East Mole and sediment is even extracted from the downdrift coast (e.g. transported by turbulent tidal currents). The sediment flux along the East Mole is schematised as $-0.15 \cdot S$ (i.e. -90,000 m^3/year).

RELATIVE IMPACT

The coastline position in 2020 obtained by the two model runs made for scenario 3 is presented in appendix E.9.

Equal to the results of the other scenarios, the difference in 2020 coastline position is observed clearly. At the location of Eko Atlantic City, erosion is prevented by the revetment and the coast remains at its position. But in the scenario in which the revetment is constructed, the eastward translation of the erosion is visible. And since in this scenario not a source but a sink (i.e. the negative bypass) is added to the system, the erosion rates are higher compared to the previous scenarios. And again, the presence of the inland waters must be kept in mind as well, while investigating the impact of the land reclamation. The importance of the presence of the inland waters is described in section 5.1.1.

The total erosion volume between 1910 and 2020 is the same for both scenario 3 model runs, about 58 million m^3. Hence the presence of the Eko Atlantic City project does not influence the total volume of erosion.

In scenario 3 with Eko Atlantic City the volume of local additional erosion east of the revetment, compared to the scenario without the revetment, is about 6.6 million m^3. This volume is equal to the preserved volume of erosion just east of the East Mole, if the land reclamation is constructed. Next to the project, the erosion rates are increased the most. The translation of the location of erosion leads to a difference in erosion rates, between the 2020 coastline simulated in the two runs of scenario 3, of almost 210 m. Instead of 240 m erosion without the revetment, values of about 450 m occur. The effect of Eko Atlantic City is perceptible till a distance of 8 km downstream the project.

East of the East Mole, the erosion is reduced most directly next to the mole. If the revetment is not constructed, the coast recedes in total roughly 860 m in the period from 1910 to 2020. The construction of the project prevents some 180 m of erosion, as the total erosion in the same period is then about 680 m.

ABSOLUTE CHANGES

The absolute changes in coastline position between 2010 and 2020 are plotted in appendix E.9. The maximum absolute erosion between 2010 and 2020, if Eko Atlantic City is constructed, reaches a value of 240 m downstream the revetment. In total, the absolute erosion volume downstream the Eko Atlantic City project, from 2010 to 2020, is about 8.7 million m^3, reaching a distance of 10 km downdrift.

If the project is not constructed, the total erosion volume between 2010 and 2020 is the same, but it occurs at the downdrift side of the East Mole then and it is spread out over an alongshore distance of 16 km. The corresponding maximum erosion rate, east of the East Mole is almost 180 m.

SUMMARY SCENARIO 3

In Table 5-4 the discussed values of erosion rates and erosion volume are repeated.

Table 5-4: Overview output scenario 3

SCENARIO 3	With Eko Atlantic City	Without Eko Atlantic City
Location of maximum absolute erosion	Downdrift of the project	Next to the East Mole
Maximum absolute rate of erosion 2010 – 2020 [m]	240	180
Absolute erosion volume 1910 – 2020 [m³]	58 million	58 million
Absolute erosion volume 2010 – 2020 [m³]	8.7 million	8.7 million
Length of eroded coast [km]	10	16
Additional rate of erosion downstream Eko Atlantic City [m]	210	-
Additional local erosion volume downstream of Eko Atlantic City [m³]	6.6 million	-
Alongshore influence of additional erosion [km]	8	-
Prevented erosion downstream East Mole due to Eko Atlantic City, compared to scenario without the project [m]	180	-
Prevented erosion volume downstream East Mole due to Eko Atlantic City, compared to scenario without the project [m³]	6.6 million	-

It can be concluded that the influence of the sink directly east of the East Mole, in the scenario 3 run without Eko Atlantic City, has no influence on the erosion rates at the longshore location of 28 km. Comparison of the output plots of scenario 3 to Figure 5-2 indicates that the sink impacts a coastal stretch of approximately 3 km length (which is from longshore distance 22 km to 25 km).

5.1.5 SCENARIO 4

Of all scenarios, the worst-case-scenario is represented by scenario 4. A negative flux of $-0.45 \cdot S$ passes the East Mole; meaning sediment is extracted from the downdrift side of the inlet to supply the lagoon.

RELATIVE IMPACT

The impact of the land reclamation is similar to the impact as described in the previous scenarios, although due to the presence of a (larger) sink, the erosion rates and erosion volume are bigger.

The prevented volume of erosion and the local increase of erosion due to the construction of the revetment, compared to the situation without the revetment, are studied via the coastlines in 2020, presented in appendix E.10.

A similar accretion and erosion pattern as in Figure 5-2 can be observed for scenario 4. The difference between all figures lies mainly in the erosion rates, which are depending on the size of the source or sink in the model.

The total erosion volume in scenario 4 is equal in both model runs: 60 million m³ in 110 years. The Eko Atlantic City project has the biggest advantage directly east of the East Mole, where the relative changes in coastline position are the greatest. The prevented erosion rate is about 240 m; instead of circa 920 m of erosion between 1910 and 2020, without the revetment, the erosion in the same time span is approximately 680 m if the project is constructed.

The local extra erosion volume east of the revetment is about 8.6 million m³, occurring in 10 years. This volume is bigger than the mean annual volume of longshore sediment transport due to the presence of the sink. The increase in local erosion rates is about 280 m: from circa 240 m erosion to almost 520 m erosion. The influence of the land reclamation, meaning local extra erosion, is observable until a distance of 8 km downstream the project.

ABSOLUTE CHANGES

The absolute values of erosion downstream Eko Atlantic City between 2010 and 2020 in scenario 4 are obtained in the same way as done in the previous scenarios. If the Eko Atlantic City revetment is constructed, the maximum erosion takes place downdrift of the project and reaches a value of about 310 m. In total, a volume of 10.6 million m³ is eroded from the downdrift coast, spread over a length of approximately 10 km.

If the project is not constructed, the maximum erosion is located east of the East Mole. The coast recedes a maximum of 240 m. In total also a volume of 10.6 million m³ is eroded, influencing a longshore distance of 16 km.

SUMMARY SCENARIO 4

Table 5-5 summarizes the data presented in this section.

Table 5-5: Overview output scenario 4

SCENARIO 4	With Eko Atlantic City	Without Eko Atlantic City
Location of maximum absolute erosion	Downdrift of the project	Next to the East Mole
Maximum absolute rate of erosion 2010 – 2020 [m]	310	240
Absolute erosion volume 1910 – 2020 [m³]	60 million	60 million
Absolute erosion volume 2010 – 2020 [m³]	10.6 million	10.6 million
Length of eroded coast [km]	10	16
Additional rate of erosion downstream Eko Atlantic City [m]	280	-
Additional local erosion volume downstream of Eko Atlantic City [m³]	8.5 million	-
Alongshore influence of additional erosion [km]	8	-
Prevented erosion downstream East Mole due to Eko Atlantic City, compared to scenario without the project [m]	240	-
Prevented erosion volume downstream East Mole due to Eko Atlantic City, compared to scenario without the project [m³]	8.5 million	-

If one compares the changes in coastline position depicted in Figure 5-2 to the changes depicted in appendix E.6, it can be concluded that the negative bypass, simulated as a sink downdrift of the East Mole, in the scenario 4 without Eko Atlantic City, has an impact over a distance of circa 4 km. Therefore, the erosion at the alongshore location of 28 km (i.e. just east of the revetment) in scenario 4 without the presence of Eko Atlantic City is equal to the erosion at this location in the other scenarios, despite of the bigger sink in this scenario.

5.2 GENERAL CONCLUSIONS IMPACT EKO ATLANTIC CITY

Now all scenarios are discussed, some general conclusions regarding the impact of Eko Atlantic City can be drawn:

- In all scenarios, the difference between the relative[25] and the absolute[26] volume of erosion downstream Eko Atlantic City is around 2.1 million m³. The difference between the absolute erosion rate and the relative erosion rate is also equal in every scenario; about 30 m. These outputs indicate that the coast downdrift the Commodore Channel is an eroding coast, regardless of the presence of Eko Atlantic City.

- The total absolute volume of erosion between 2010 and 2020 is not altered by the presence or absence of Eko Atlantic City.

- The final volume of erosion and value of the beach retreat at the downdrift coast are dependent on the sediment volume bypassing the East Mole. Thus, the sink induced by the sediment trapping at the West Mole, the sediment withdrawal in the Commodore Channel and in the lagoon and the SLR determines the coastal morphology downstream the tidal inlet.

- Between 2010 and 2020, the length of the coastal stretch suffering erosion does not differ between the five scenarios discussed. Hence the length of the erosion wave seems to be independent of the volume of the source respectively sink.

- The construction of the Eko Atlantic City land reclamation prevents further erosion of the Bar Beach, as it fixes the coast locally.

- Although the total erosion volume is not altered by the presence of Eko Atlantic City and further erosion of the Bar Beach is prevented, there occurs a shift in erosion location due to the project. The translation of erosion induces erosion of the coast downstream Eko Atlantic City.

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[25] I.e. compared to the 2020 scenario without the presence of Eko Atlantic City

[26] I.e. compared to the 2010 coastal situation.

- In every scenario the additional erosion rates, next to Eko Atlantic City, stretch over a distance of roughly 8 km. And the coastal stretch where erosion is prevented has the same length as the revetment, which is about 6 km. Since the volume of additional erosion equals the volume of prevented erosion, one would expect the erosion rates next to Eko Atlantic City to be smaller than the prevented erosion rates.

  However, this does not happen. Instead, the erosion rates directly next to Eko Atlantic City are bigger than the prevented erosion rates. This means that the rates of erosion diminish rapidly further downstream Eko Atlantic City. So the high erosion rates directly downstream the project reported in this section are, most probably, occurring very locally.

- In the discussion of the impact of the land reclamation, one has to take the hinterland of the coast into account. Just east of Eko Atlantic City the inland Kuramo Waters are present very close to the beach. If the narrow beaches in front of these waters start to erode, a breakthrough to the inland waters is very likely to occur. This has to be opposed e.g. by mitigation measures to prevent flooding of the vulnerable hinterland.

As the analysis of the expected impact of Eko Atlantic City shows, anticipation on the effects of the construction of the project is necessary. Therefore a couple of potential mitigation measures are discussed in the next chapter. But before the mitigation measures are elaborated, first an investigation of the erosion downstream the project on the longer term is made.

5.3 FUTURE DEVELOPMENT OF EROSION

In order to investigate the ‘longer-term’ development of the erosion downstream the Eko Atlantic City project, the ‘most-neutral’ scenario 0 is extended and four more runs are made: until 2030, until 2040, until 2050 and until 2060.

In Figure 5-4 the coastline position is depicted per decennium between 2010 and 2060, for the scenario of zero bypassing along the East Mole. The colour of the year is equal to the colour of the corresponding coastline. The initial coastline position in 1910 is shown by the yellow line.

Figure 5-4: Location of coastline downdrift of Eko Atlantic City, per decennium between 2010 and 2060 [after Google (2010)]

Considering Figure 5-4, it can be seen that the erosion rate between 2010 and 2020 is very high compared to the erosion rates in the period from 1910 to 2010. This means that in the ten years after construction of the project, the coast locally recedes about as much as it did in the hundred years before. This conclusion is also drawn from Figure 5-2 (in section 5.1.1), in which the increase in erosion rate of 180 m, between 2010 and 2020, is visible. After 2020, the erosion rates decrease significantly.

In the previous section it is also observed that the length of the erosion wave between 2010 and 2020 does not depend on the size of the sink or source. In each scenario the downstream influence of the additional erosion reaches over a similar distance. This is expected to change if one considers the scenarios on a longer term because, after a while, the coast adjusts itself such that it obtains an orientation more or less perpendicular to the dominant wave angle of incidence (which is roughly 188° at Lagos).

Therefore, it is to be expected that the erosion rates directly next to Eko Atlantic City will decrease over the years. However, also due to the adjustment of the orientation of the coast, the length of the coastal stretch suffering erosion will increase.

5.3.1 RELATIVE IMPACT

Similar to the analysis made for the five scenarios, discussed in section 5.1, first the relative erosion volume is investigated. In section 5.2 it is concluded that the absolute volume of erosion in 2020 does not depend on the presence of Eko Atlantic City. To check whether on the longer term the total erosion volume also does not differ between the scenarios with and without Eko Atlantic City, the relative coastline differences are investigated for the scenarios in 2060. In appendix E.11 the corresponding figures are presented.

Comparison of the output of scenario 0 in 2060 to, for instance, the output of scenario 0 in 2020, depicted in Figure 5-2, shows that the reach of additional local erosion increases.

In this scenario along approximately 18 km downstream, the influence of the shifted erosion can be distinguished. This happens due to the above explained adjustment of the orientation of the coast. Once the coast has an orientation more or less perpendicular to the main angle of wave incidence, the local sediment transport capacity of the longshore current decreases and the erosion at that location slows down. A little further downstream, the longshore current regains its transport capacity, leading to the elongation of the eroding coastal stretch.

The volume of local additional erosion downstream the project between 2010 and 2060 is about 21.7 million m³. This is the same as the volume of erosion that is prevented by the presence of Eko Atlantic City. So, the net effects of the land reclamation on the erosion volumes are zero in 2060 as well.

The maximum rate of erosion, relative to the 2060 scenario without Eko Atlantic City, occurs a little downstream the project and is about 350 m bigger: 690 m instead of 340 m.

If Eko Atlantic City is not constructed, the maximum absolute rate of erosion in 2060 (relative to the 1910 coastline) is about 1150 m, directly east of the East Mole. The revetment prevents roughly 470 m of erosion at this location, as it is 680 m with the revetment constructed.

Thus, it can be concluded that, contrary to the 2020 scenarios, the positive influence of Eko Atlantic City can clearly be seen in this scenario. The increase of local erosion downstream the revetment (350 m) is smaller than the rate of erosion the revetment prevents (470 m) next to the East Mole. This can be attributed to a greater longshore distance over which the downstream additional erosion is spread out.

5.3.2 ABSOLUTE EROSION

In order to obtain an idea about the decrease of erosion rates over the years, the absolute erosion is investigated; meaning the amount of erosion in e.g. 2060 is considered relative to the 2010 coastline.

Using the output plots presented in appendix E.11, the local rate of erosion, downstream the project is obtained. Between 2010 and 2060, the coast recedes almost 530 m downstream the revetment. In total a volume of approximately 34 million m³ is eroded from the coast downstream the project. The longshore distance over which the erosion occurs is about 16 km.

The same analysis is made for the situation without Eko Atlantic City. The highest erosion rates, of approximately 480 m, are located just east of the East Mole.

Between 2010 and 2060, also a volume of 34 million m³ is eroded in this scenario. The length of coast suffering erosion is about 20 km. As the length of coast suffering erosion is longer if the revetment is not constructed, this leads to smaller absolute erosion rates.

5.3.3 SUMMARY FUTURE EROSION

The output of the model runs of scenario 0 until 2030, 2040 and 2050 is elaborated in the same manner. In appendix E.11 the results of these runs are plotted. Both the relative as the absolute changes in coastline position are provided. In

Table 5-6 the output of all the runs for scenario 0 with Eko Atlantic City is presented and Table 5-7 depicts the outputs for all runs without Eko Atlantic City.

Table 5-6: Overview output scenario 0 with Eko Atlantic City: in 2020, 2030, 2040, 2050 and 2060

SCENARIO 0, with Eko Atlantic City	2020	2030	2040	2050	2060
Maximum absolute rate of erosion 2010 – output year [m] (downstream Eko Atlantic City)	210	310	400	470	530
Absolute erosion volume 1910 – output year [million m³]	54.9	61.7	68.4	74.8	81
Absolute erosion volume 2010 – output year [million m³]	7.7	14.7	21.4	27.8	34
Length of eroded coast [km]	10	12	14	14	16
Additional rate of erosion downstream Eko Atlantic City [m]	180	240	280	320	350
Additional local erosion volume downstream Eko Atlantic City [million m³]	5.6	10.2	14.3	18.1	21.7
Alongshore influence of additional erosion [km]	8	12	14	16	18
Prevented erosion downstream East Mole due to Eko Atlantic City, compared to scenario without the project [m]	140	250	330	400	470
Prevented erosion volume downstream East Mole due to Eko Atlantic City, compared to scenario without the project [million m³]	5.6	10.2	14.3	18.1	21.7

Table 5-7: Overview output scenario 0 without Eko Atlantic City: in 2020, 2030, 2040, 2050 and 2060

SCENARIO 0, without Eko Atlantic City	2020	2030	2040	2050	2060
Maximum absolute rate of erosion 2010 – output year [m] (downstream East Mole)	140	240	330	410	480
Absolute erosion volume 1910 – output year [million m³]	54.9	61.7	68.4	74.8	81
Absolute erosion volume 2010 – output year [million m³]	7.7	14.7	21.4	27.8	34
Length of eroded coast [km]	16	20	22	22	24

In appendix E.11 a graph is presented of the erosion rates over the years. It can be seen that, slowly, the growth in erosion rates downstream Eko Atlantic City decreases.

However, the growth of the length of the erosion wave (i.e. the length of eroded coast in

Table 5-6) does not decrease between 2010 and 2060, see appendix E.11. Every ten years the erosion wave gains approximately 2 km in length. This means that per year 200 m of coast further downstream experiences erosion.

If one considers the development of the erosion volume, also plotted in appendix E.11, a slight decrease can be distinguished over the years. Hence on the longer-term, it is expected that the erosion downstream Eko Atlantic City decreases. But as the erosion rates reach significant values, mitigation measures are required anyhow.

5.4 MITIGATION MEASURES

The previous section shows that the erosion of the Bar Beach is shifted eastward by the construction of Eko Atlantic City. Although the total erosion volumes are not affected by the presence of the Eko Atlantic City project, the shift in erosion does induce significant retreat of the coast downstream the project.

5.4.1 NOURISHMENT SCHEME

The analysis of the different scenarios shows that erosion of the beach in front of the Kuramo Waters East, downdrift Eko Atlantic City, can lead to severe problems. One of the possible measures to prevent the erosion of the beach and a breakthrough to the inland waters is the application of a nourishment scheme. This is one of the most applied mitigation measures worldwide. In conducting nourishments, sand is added to the system and no structural interferences are applied.

A trailing suction hopper dredger and a cutter suction dredger are in use by the Nigerian Port Authority, so possibly, once every year a sediment nourishment can be conducted east of Eko Atlantic City. Just as for the Bar Beach nourishments performed in the time span 1960 – 2010, the borrow sediment can be obtained offshore.

The required sediment volume to prevent a breakthrough is investigated in this section. The requirement set is that the beach in from of the Kuramo Waters East must remain approximately stable.

2020

Firstly, an annual sediment volume of 300,000 m³/year is considered. In appendix F.1 the corresponding figures can be found. It turns out that with an annual nourishment volume of 300,000 m³/year, already between 2010 and 2020 the coast recedes too much. Ten years after construction of the Eko Atlantic City project, the beach in front of the Kuramo Waters East shows a retreat of circa 100 m.

Therefore, the influence of a nourishment volume of 600,000 m³/year is investigated. In Figure 5-5 the coastline in 2020 is depicted, both for the scenario without the nourishments performed (in yellow) and for the scenario including the nourishments (in red).

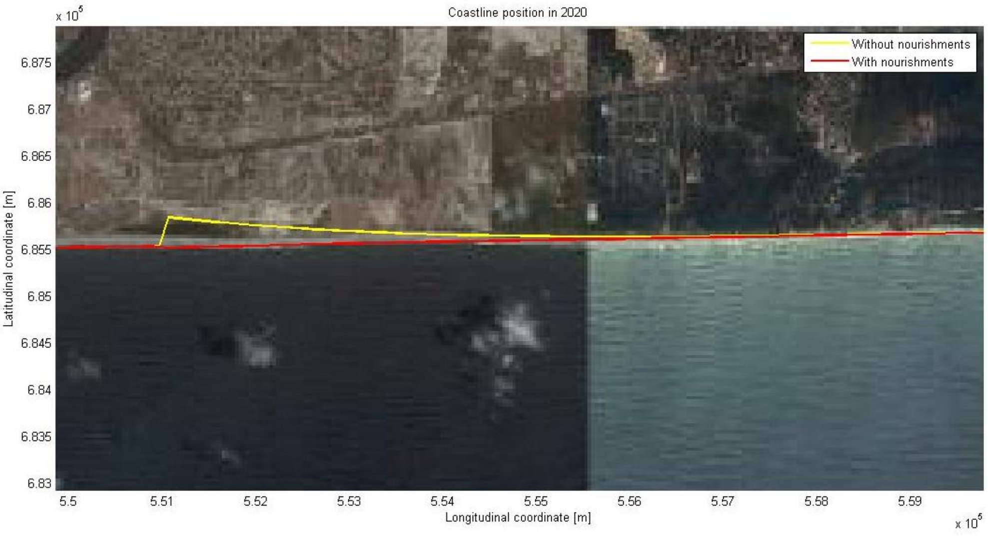

Figure 5-5: Coastline in 2020, for scenario 0 with Eko Atlantic City. In yellow is the result of the model run without the nourishments, and in red the nourishments are included

Considering Figure 5-5, it can be concluded that application of a larger annual nourishment volume provides a roughly stable coastline downstream Eko Atlantic City.

For the other plots of the output, one is referred to appendix F.1. The volume of absolute erosion occurring between 2010 and 2020 is about 1 million m³, accompanied by a maximum rate of erosion of just a little more than 10 m located approximately 7 km downstream Eko Atlantic City. The length of coast that is eroded (very slightly) is about 12 km. In front of the Kuramo Waters, the beach accretes about 10 m.

2030

To check whether on a longer term this nourishment volume is adequate as well, the Unibest model is run until 2030 and until 2060. Again, the plots of the output of these runs are located in appendix F.1.

In the period 2010 – 2030, the maximum rate of erosion is about 20 m, located circa 7 km downstream of the revetment. The total erosion volume of approximately 1.8 million m³ occurs over a length of circa 13 km. The coast in front of the Kuramo Waters East does not erode in this period; instead it still accretes slightly. So, 20 years after construction of Eko Atlantic City, the nourishment volume of 600,000 m³/year is sufficient to provide a stable beach in front of the Kuramo Waters East.

2060

In the fifty years following construction of the revetment, the nourishment of 600,000 m³/year alleviates the erosion rates such that a maximum of 35 m is eroded, located roughly 7 km downstream of Eko Atlantic City. The total volume of erosion in 50 years is around 3.9 million m³, stretched over a distance of 17 km.

After 50 years, the erosion rates directly in front of the Kuramo Waters East reach a value of less than 10 m. Therefore, it is concluded that a nourishment volume of 600,000 m³/year accomplishes the demand of a stable beach in front of the inland waters.

5.4.2 ALPHA BEACH

Roughly 6 km downstream Eko Atlantic City is the circa 3 km long Alpha Beach located, depicted in Figure 5-6. At this part of the coast, an indigenous fishing community of about 7000 inhabitants lives very close to the beach. Over the last decades, they had to move parts of their town further inland as the SLR lead to high rates of coastal retreat (Opia, 2011). A potential solution for the erosion at Alpha Beach is the construction of a revetment or groyne scheme along the coast.

Figure 5-6: Location of Alpha Beach [after Google (2010)]

In designing a potential structure for the Alpha Beach, the effects of Eko Atlantic City on the downdrift coast have to be taken into account. Once the project is constructed, it induces a shift in erosion location. From the analysis made in sections 5.1 and 5.3, it can be concluded that, already in the 10 years following construction of the project, Alpha Beach lies in the influence zone of the Eko Atlantic City project.

By fixation of the coast locally at the Alpha Beach, it is expected that the shift of erosion induced by Eko Atlantic City is translated further eastward. How much erosion the coast downstream Alpha Beach experiences is investigated using a Unibest model.

The scenario 0 model is adjusted a little. Next to the revetment of Eko Atlantic City, now also a 3 km long revetment at Alpha Beach is put in the Unibest model. A total of three runs are made: one until 2020, another one until 2030 and the final run until 2060.

RELATIVE IMPACT

Similar to the analysis presented in sections 5.1 and 5.3, first the relative impact of the Alpha Beach revetment is considered.

2020

In the investigation of the coastal situation in 2020, with the presence of the Alpha Beach revetment, it becomes clear that, ten years after construction, the Alpha Beach revetment does not impact the coast significantly yet. Therefore, the scenario in 2030 is elaborated further. One is referred to appendix F.2 for the discussion of the 2020 situation.

2030

The coastline position in 2030, for both the models runs with and without the Alpha Beach revetment present are depicted in Figure 5-7.

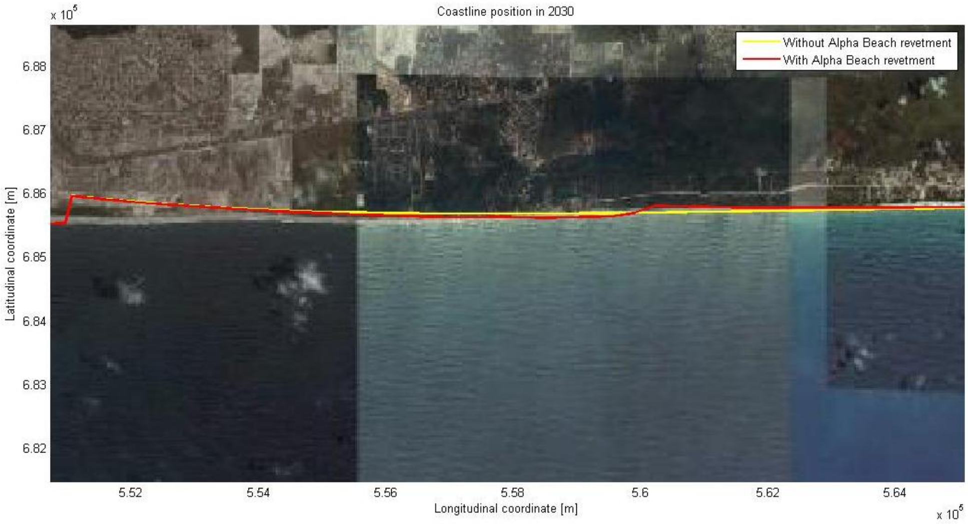

Figure 5-7: Coastline in 2030, for scenario 0 with Eko Atlantic City. In yellow is the result of the model run without the Alpha Beach revetment, and in red the revetment is included

Considering the coastline positions in 2030, it can be seen that the Alpha Beach revetment does shift some erosion downstream, although the erosion next to Eko Atlantic City does not decrease significantly. In appendix F.2 a plot depicting the relative changes can be found.

Downstream the Alpha beach revetment, the erosion increases locally by almost 80 m: from about 90 m to approximately 170 m. The additional erosion volume is roughly 2.7 million m³, spread over circa 6 km downstream the project.

2060

The same analysis is made for the situation in 2060. Presented in Figure 5-8 is the coastline without the Alpha Beach revetment, in yellow, and the coastline with the revetment, in red. Now, the influence of the Alpha Beach revetment can be distinguished clearly[27].

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[27] When comparing Figure 5-8 to the plots in appendix F.2, please note the difference in alongshore distance depicted.

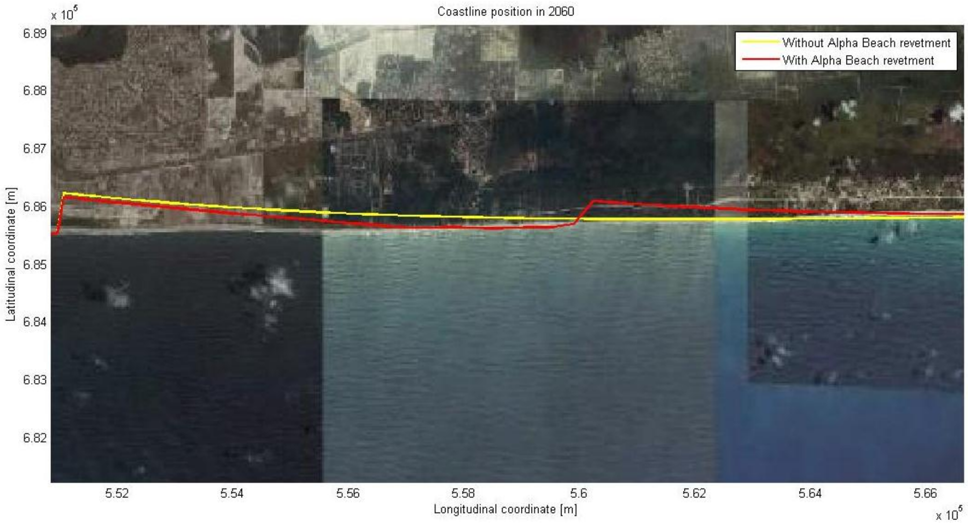

Figure 5-8: Coastline in 2060, for scenario 0 with Eko Atlantic City. In yellow is the result of the model run without the Alpha Beach revetment, and in red the revetment is included

Looking at Figure 5-8, it becomes clear that at the location of the revetment further erosion is prevented. It can also be seen that downstream Eko Atlantic City, the erosion rates are decreased somewhat by the presence of the revetment. So, the Alpha Beach revetment shifts a part of the erosion volume towards downstream.

In appendix F.2 the relative coastline changes are depicted. Compared to the 2060 coastline position without the revetment, the total erosion volumes occurring downdrift the Eko Atlantic City project do not change. However, downstream Alpha Beach, locally the erosion volume increases by 11.8 million m³, inducing the erosion rate next to the project to increase locally by almost 260 m. The additional erosion occurs over a longshore distance of about 12 km.

The most positive effect of the Alpha Beach revetment is the prevention of more than 190 m of erosion at its location. Moreover, directly east of Eko Atlantic City, almost 60 m of erosion is prevented, as it is 680 m with the Alpha Beach revetment and about 740 m without the revetment. At the whole coastal stretch between Eko Atlantic City and Alpha Beach, the erosion is reduced by 11.8 million m³. This can be attributed to the equilibrium coastline orientation, relative to the mean angle of wave incidence, as described in section 5.3. Between the Eko Atlantic City project and the Alpha Beach revetment, the erosion wave can obtain a limited length. Once this part of the coast obtains an orientation equal to the equilibrium orientation, in principle no further erosion occurs. This results in more erosion downstream of Alpha Beach.

ABSOLUTE CHANGES

Likewise as done in sections 5.1 and 5.3, the absolute changes are obtained by comparison of the 2030 (or 2060) coastline to the 2010 coastline. The graphical comparison of the coastlines for both output years is presented in appendix F.2.

2030

Twenty years after construction, in 2030, the absolute erosion rate downstream Alpha Beach is a little more than 100 m. In total an absolute erosion volume of 3.6 million m³ occurs over a length of 6 km.

At the part of the coast between the two revetments, the volume of absolute erosion is approximately 11.1 million m³. Just downstream of Eko Atlantic City the maximum erosion rate, between 2010 and 2030, is almost 310 m. Comparison of this value to the erosion rate if Alpha Beach is not constructed shows that the rate of erosion is not changed by the Alpha Beach revetment in 2030.

2060

In 2060 the absolute erosion volume of 15.6 million m³ is spread out over circa 12 km downstream the revetment, leading to an absolute erosion rate downstream revetment of about 350 m.

At the coastal stretch between Eko Atlantic City and the Alpha Beach revetment, the absolute erosion volume is around 18.4 million m³. The maximum rate of erosion at this part of the coast is about 470 m. Compared to the erosion rate in the situation without the revetment at Alpha Beach, the erosion downstream Eko Atlantic City is about 60 m less (i.e. 470 m instead of 530 m). Thus, in 2060, a positive effect of the Alpha Beach revetment is noticed downstream Eko Atlantic City. The decrease in erosion happens due to the change in orientation of the coast, as explained earlier in this section.

IMPACT OF ALPHA BEACH REVETMENT

The analysis in the previous section shows the shift in erosion volume due to the Alpha Beach revetment. Especially in 2060 the impact of the project is visible in the decrease of erosion rates downstream Eko Atlantic City. However, the erosion rates downstream the land reclamation still reach values that are too high if the Kuramo Waters East, backing the coast there, are considered.

Inspection of the residential and infrastructural areas close to the coast shows that downstream Alpha Beach, not much valuable areas are present. This part of the coast could therefore be allowed to erode. Hence, the shift of erosion induced by the Alpha Beach revetment can be an interesting option to investigate further. But still, a breakthrough to the Kuramo Waters East must be prevented. Therefore, the possible scenario of the presence of a revetment at Alpha Beach combined with a nourishment scheme downstream of Eko Atlantic City is investigated in the next section.

5.4.3 ALPHA BEACH REVETMENT COMBINED WITH NOURISHMENT SCHEME

In section 5.4.1 it is shown that an annual nourishment volume of 600,000 m³/year results in a coastline that is more or less stable. Therefore, the effect of the same nourishment volume on the coastal development, with the presence of the Alpha Beach revetment, is investigated for the years 2030 and 2060.

2030

In Figure 5-9 the coastline position in 2030 is presented. The yellow line depicts the coastline if no nourishments are performed and the red line shows the coastline for the situation including the nourishments.

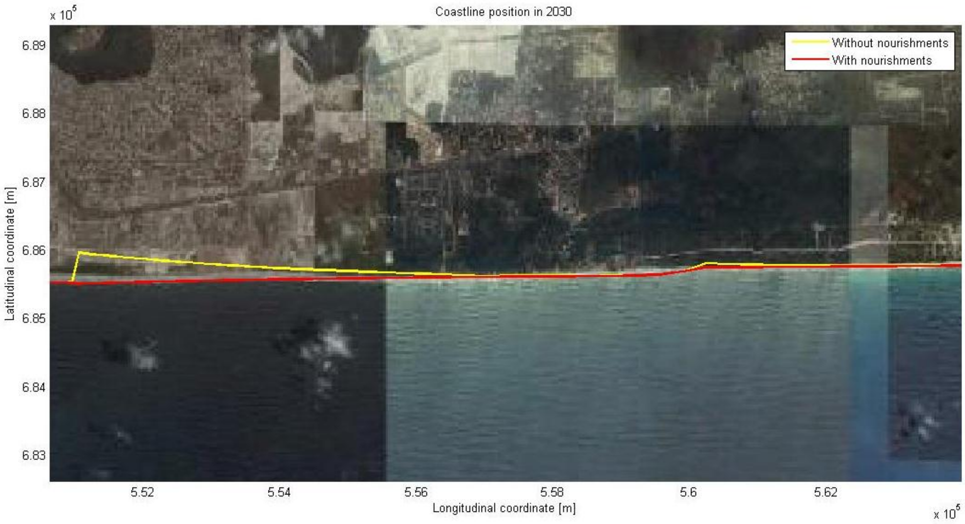

Figure 5-9: Coastline in 2030, for scenario 0 with Eko Atlantic City and Alpha Beach. In yellow is the scenario without the nourishments and in red the nourishments are included

The effects of the nourishments can be seen in the distinct difference in coastline position between the two scenarios. The coastal stretch between the two structures does not retreat in the period 2010 – 2030. Downstream of the Alpha Beach revetment, the nourishments have a slightly positive effect as well, since the red coastline in Figure 5-9 lies a little more seaward than the yellow coastline at this location.

In appendix F.2 the absolute and relative coastline changes between 2010 and 2030 are depicted. The absolute effects of the nourishments are a slight accretion of 0.7 million m³ spread over the coastal stretch between the two structures, which means that the coast downstream Eko Atlantic City is stabilised and a breakthrough to the Kuramo Waters is prevented. Downstream the Alpha Beach revetment, the maximum absolute erosion rate is about 60 m. The absolute erosion volume of 2.5 million m³, occurring between 2010 and 2030, is spread over circa 8 km.

2060

In appendix F.2 the results for the model run until 2060 are depicted. The effects of the nourishments downstream Eko Atlantic City in 2060 can clearly be distinguished. At the coastal stretch between the Alpha Beach revetment and the Eko Atlantic City project, the coast accretes slightly. In total, a volume of 1.4 million m³ is accreted over circa 6 km. Comparison of the 2060 position of the coastline in the scenario with the nourishments to the scenario without the sediment supply shows that the nourishments clearly benefit the coast downstream Alpha Beach as well, although some erosion does occur.

The absolute erosion volume shifted downstream Alpha Beach is around 5.3 million m³, affecting a coastal stretch of 12 km. The maximum erosion rate of roughly 90 m is located directly downstream the revetment. So, compared to the erosion rate without the nourishments, it can be seen that the sediment supply decreases the erosion rate downstream Alpha Beach by 260 m. And the total erosion volume is alleviated by more than 10 million m³.

5.4.4 CONCLUSION MITIGATION MEASURES

The above sections show the positive influence of the nourishment volume of 600,000 m³/year. One thing that is striking is that the coastal stretch between Eko Atlantic City and the Alpha Beach will benefit more from the nourishments if the Alpha Beach revetment is constructed. Then, this 6 km long part of the coast even accretes somewhat. But, logically, then the effects downstream the Alpha Beach revetment are more severe. The maximum erosion rate (i.e. 90 m) is about three times bigger than the maximum erosion rate if the revetment is not constructed (i.e. 35 m).

If the hinterland and the use of the land behind the coast are taken into account, it can be stated that the coastal stretch between Eko Atlantic City and Alpha Beach is not allowed to erode, due to the presence of the Kuramo Waters East and several residential areas behind the coast. Therefore, the translation of the erosion by the construction of the revetment at Alpha Beach and the subsequent protection of the coast between the two structures by nourishments, which also lead to an alleviation of the erosion downstream Alpha Beach, have a clear advantage in this situation.

6 CONCLUSIONS & RECOMMENDATIONS

In this chapter a summary of the main conclusions regarding the long-term morphological behaviour of the Lagos coast with presence of the Eko Atlantic City project are presented. First, the general findings on the Lagos coastal system are presented and the research questions posed in the introduction of this thesis are answered.

It has to be kept in mind that the conclusions presented in this chapter are the results of the study into the Lagos coast using a conceptual model and the 1D numerical simulation model Unibest. In order to create both models, several assumptions have to be made, due to a lack of data and due to the time limit associated with the completion of an MSc thesis. The assumptions are made as good as possible by using well-known coastal theories, reference coastal situations etcetera, but still several uncertainties exist. In the schematisations of the governing coastal processes and mechanisms also several uncertainties and inaccuracies arise. Therefore, recommendations for further research into the Lagos coastal system and into the long-term impact of the construction of Eko Atlantic City are given at the end of this chapter.

6.1 CONCLUSIONS

In this section the analysis of the Lagos coast is summarized. First, the general findings on the Lagos coast are presented very briefly. Thereafter, the answers to the research questions are provided.

- **The Lagos coast**
  The coast at Lagos is part of the West African Barrier-Lagoon-Complex. The Lagos Lagoon backing the coast is one of the biggest lagoons in West Africa. One tidal inlet, the Commodore Channel, connects the lagoon to the South Atlantic Ocean. The position of the Commodore Channel is fixed by three moles, being the West Mole, the Training Mole and the East Mole. West of the tidal inlet the Lighthouse Beach is situated and east of the tidal inlet the Bar Beach is located. The natural behaviour of the coast is erosive, due to the high rates of relative sea level rise.

- **What are the governing processes and mechanisms determining the long-term and large-scale morphological behaviour of the Lagos coast?**
  1) Persistent and high-energy swell waves with a mean direction of 188° induce a mean eastward longshore sediment transport in the range of 600,000 m^3/year to 700,000 m^3/year. The occurring volume of longshore sediment transport (LST) can differ circa 100,000 m^3/year to 200,000 m^3/year from the mean value, depending on the coastal orientation.
  2) The sediment trapping at the West Mole limits the sediment bypass along the mole. Over the years the Lighthouse Beach expands, enabling some more sediment to bypass the mole. The exact amount of sediment trapping is assumed to lie in between 65 and 100 per cent of the total volume of LST.
  3) The coast of Lagos is composed of relatively young sediments that are still subject to natural dewatering and compaction; together with the Eustatic sea level rise this induces a high (relative) sea level rise. Thereby, sediment accumulation space is created in the Commodore Channel and the Lagos Lagoon, which induces sediment import into the lagoon and tidal inlet. The required sediment volume of circa 10 per cent of the total volume of LST is extracted from the longshore sediment transport.
  4) Dredging of the Commodore Channel disturbs its morphodynamic equilibrium. Thereby, additional sediment accumulation space is created, which leads to a sediment import of roughly 15 to 25 per cent of the total volume of LST into the channel, extracted mainly from the longshore sediment transport.
  5) Dredging of the Lagos Lagoon disturbs the morphodynamic equilibrium of the lagoon, leading to sediment import. However, the location the sediment is extracted from and the volume of the sediment import are subject to doubt.

  Concluding: the sediment volume bypassing the East Mole is principally determined by the size of the sink formed by the sediment trapping at the West Mole and the sediment import into the Lagos Lagoon and the Commodore Channel.

- **What was the influence of the construction of the Lagos Harbour Moles and other human interferences on the historical coastline development?**

  1) Lagos Harbour Moles

  The first significant interference at the coast is the construction of the Lagos Harbour Moles around 1910. In 100 years the Lighthouse Beach accreted about 70 million m³, yielding beach expansion rates of more than 800 m. Erosion of the Bar Beach reached net volumes of 47 million m³, accompanied by a maximum coastal retreat of almost 900 m.

  2) Nourishments

  As of 1960, the erosion is counteracted by nourishments, which prevented significant erosion volumes. Approximately 600 m of erosion downstream of the East Mole is prevented. All nourished sediment, a total volume of more than 28 million m³, has been eroded away between 1960 and 2010.

  3) Land reclamation in the Lagos Lagoon

  The extraction of large sediment volumes in the Lagos Lagoon for the purpose of land reclamation could have entailed large erosion volumes downstream the East Mole, as a large sink is created by dredging of the lagoon. However, the exact role of the land reclamations on the sediment fluxes around the inlet has to be investigated further.

- **How does the construction of Eko Atlantic City change the present morphological processes?**

  The coast downstream the inlet suffers erosion independent of the presence of Eko Atlantic City. The construction of the project does not alter the total erosion volume. The revetment of Eko Atlantic City retains the newly created land and prevents further erosion at its location. Thereby, the project shifts the erosion of the Bar Beach downstream; leading to a local increase of the erosion rates downstream of the project.

  The increase in local erosion volume downstream the Eko Atlantic City project is equal to the prevented erosion volume at the Bar Beach. The erosion volume downstream the project is, however, more concentrated at one location than the prevented erosion downstream the East Mole. Therefore, the erosion rates occurring directly downstream of the project are generally higher than the erosion rates prevented by the project at the Bar Beach location.

  The erosion rate and volume occurring downstream Eko Atlantic City are depending on the volume of sediment that bypasses the East Mole.

- **Future development of erosion**
  If in the future no bypassing occurs along the East Mole, the erosion volume and the erosion rates directly downstream Eko Atlantic City slightly decrease over the years. The coastline orientation approaches the equilibrium orientation (relative to the governing waves). Hereby, the length of the erosion wave gradually increases; whereby the erosion is shifted further downstream over the years.

6.2 RECOMMENDATIONS

In this section recommendations are given to the Lagos State and several recommendations are provided to improve follow-up studies.

6.2.1 RECOMMENDATIONS FOR LAGOS STATE

- **Mitigation measures**
  Analysis of the impact of Eko Atlantic City shows that mitigation measures to cope with the shift of erosion are necessary. This is mainly due to the valuable hinterland and the presence of the Kuramo Waters backing the coast. A breakthrough to these waters would be catastrophic

  If a nourishment scheme is opted to counteract the erosion, an annual volume of at least 600,000 m^3/year is necessary to prevent a breakthrough to the Kuramo Waters. This volume also seems sufficient to provide a stable coast on the longer term.

  As nourishments are normally not applied annually, but for instance once per five years, it has to be investigated whether a nourishment volume of 30 million m^3 per five year is also sufficient to ensure a stable coast downstream of the project.

- **Alpha Beach**
  The Alpha Beach is located in the influence zone of Eko Atlantic City. To protect this valuable coastal stretch, a groyne scheme or revetment can be constructed. Thereby, the erosion occurring downdrift Eko Atlantic City is shifted further downstream. The coast downdrift of Alpha Beach is considered less valuable than the coastal stretch between Eko Atlantic City and Alpha Beach, so the shift of erosion is said to be allowed to occur.

  To provide for a stable beach in between the two revetments, a nourishment volume of roughly 600,000 m^3/year must be applied. By constructing the Alpha Beach revetment in combination with the nourishment scheme, the coastal stretch until circa 10 km downstream of Eko Atlantic City will be stabilised.

- **Monitoring**
  In general, monitoring of the coast downstream of the Eko Atlantic City project is recommended. Besides the additional advantage of acquiring more data of the Lagos coast, by monitoring the coastal development one can also react quickly to undesired scenarios. The analysis of the effects of the construction of Eko Atlantic City reveals the expected shift in erosion by the project, which can be counteracted by nourishments. However, small deviations of the predicted erosion rates can lead to disastrous effects. Therefore, also the effects of the nourishments should be monitored to ensure a stable beach downstream of the Eko Atlantic City project.

6.2.2 RECOMMENDATIONS FOR FURTHER STUDIES

In this study a lot of assumptions are made, due to lack of data or lack of time to further investigate certain parameters. Therefore, some recommendations can be given for further scientific studies.

- **Data acquisition**
  Although a lot of research into the Lagos coastal area is performed, still several data can be improved:

  1) Sediment characteristics
  Because sediment characteristics play an important role in the longshore sediment transport computations in Unibest, improvement of the knowledge on sediment data of e.g. the Lighthouse Beach and the Bar Beach can possibly provide more reliable model results.

  2) Wave climate
  Although the simplification of the wave climate imposed in the Unibest model has been justified by the very narrow directional spreading, it can be interesting to create a model on which the original wave climate is imposed. Also the manual transition the offshore wave climate to the nearshore locations can be checked by e.g. a more advanced model. Thereby, the outputs of the model constructed in this study can be verified.

  3) Tidal data
  In this study it is assumed that longshore tidal currents can be neglected and that tidal currents are of importance only around the tidal inlet. However, if more data is obtained on e.g. the velocities of the tidal currents in the surf zone, it can be investigated whether the sediment transport capacity of the tidal currents is indeed negligible.

  4) Submergence
  One of the most important factors in the determination of the relative sea level rise is the submergence of the land. In this study it is kept in mind that the relative sea level rise at Lagos is high, due to the natural soil dewatering and compaction and due to the water extraction by man.

But the rates of the relative sea level rise used in the study are based on assumptions rather than measured data. So, if one acquires data on the submergence, more reliable calculations of the effects of relative sea level rise can be made.

5) Dredging volumes Commodore Channel

The dredged volumes in the Commodore Channel are based on siltation rates, meaning they are not completely random, but if one could obtain data on the dredged volumes, a better verification of the sink the dredging constitutes can be made.

6) Sediment discharge of Ogun River

In the consideration of the sediment balance at the Lagos coast, the possible sediment input by the Ogun River is neglected, because very little data on the (sediment) discharge are available. Conducting of measurements of the sediment concentration and the discharge of the river can possibly provide more insight in the sediment source this river could constitute.

- **Software model**

  If more and better data on e.g. the tide and sediment characteristics could be acquired, the application of a more advanced 2D or 3D model could provide more insight in the complex currents and fluxes occurring in and around the tidal inlet.

  Also the currents at the transition of the Eko Atlantic City project to the coast downstream could be modelled in more detail using a more advanced model. It could be expected that the erosion downstream the project could then be modelled even more realistically.

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Part 0 – Introduction
Part I – Literature Study and Data Collection
Part II – Nearshore Wave Modelling Report
Part III – Flow Modelling Report
Part IV – Morphological Modelling Report and Coastal Erosion Mitigation Strategy

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APPENDICES

A RESULTS "COASTAL ANALYSIS REPORT"

Referring to the objective of this thesis, the long-term impact of the presence of Eko Atlantic City on the adjacent coast at Lagos is of main interest.

As has been mentioned in section 1.3, Royal Haskoning conducted an intensive study on the coastal processes around Lagos and in the vicinity of Eko Atlantic City for its client SENL, in May and later in 2008. In the study of Royal Haskoning, the initial, short-term impact of the presence of Eko Atlantic City on the (evolution of the) adjacent coastline was assessed. Besides the study, also a proposal for a coastal defence strategy concerning the expected coastal impacts of Eko Atlantic City was developed. Both the study results and the coastal defence strategy were presented in the "Coastal Analysis Report" in January 2011 (Royal Haskoning [1], 2011, Part 0-IV).

The results of the study performed by Royal Haskoning can serve as a basis to set up hypotheses about the long-term development of the coast at Lagos. Therefore, in this section a summary of the study of Royal Haskoning is provided.

A.1 SET-UP STUDY OF ROYAL HASKONING

In the study, three different situations are considered: the situation without Eko Atlantic City (the so-called baseline scenario) and two situations with different layouts for the land reclamation, the so called layout I and layout II scenarios. The difference between the layout I scenario and the layout II scenario is the way the transition between Eko Atlantic City and the adjacent coast is designed, see Figure 0-1 and Figure 0-2.

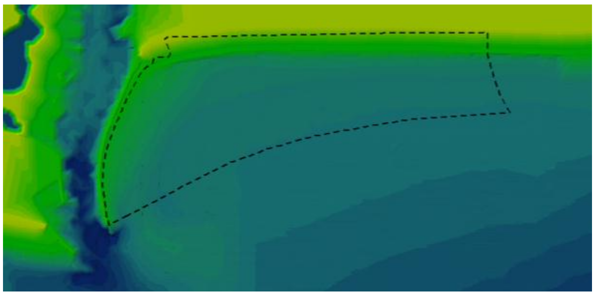

Figure 0-1: Eko Atlantic City layout I [after (Royal Haskoning [1], 2011, Part IV)]

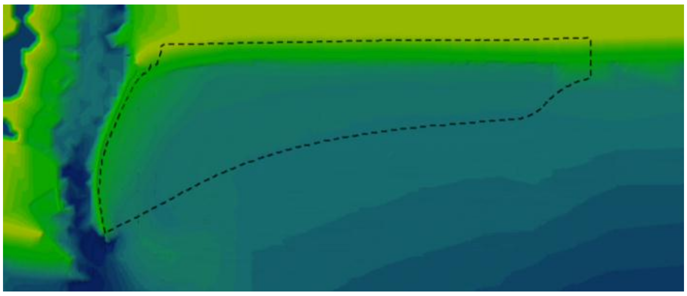

Figure 0-2: Eko Atlantic City layout II, the S-shaped transition [after (Royal Haskoning [1], 2011, Part 0-IV)]

The layout I scenario consists of a quite abrupt end of the reclamation, that connects to the shore almost perpendicular, see Figure 0-1. The layout II scenario has a smoother, S-shaped transition between the reclaimed land and the adjacent beach, which is depicted in Figure 0-2.

In the models used the initial morphological effects are simulated. Conclusions are drawn about the initial differences in the gradients in longshore sediment transport and about occurring erosion and/or accretion, just after construction of the project.

A.2 RESULTS COASTAL ANALYSIS REPORT

One of the main conclusions arising from the modelling study is that the S-shaped layout results in the least severe impact (in the form of extra erosion) on the coast downdrift of the project. The layout I scenario results in sedimentation directly downdrift of the project area, due to a calm shadow zone induced by the abrupt transition. However, further downdrift, the erosion increases significantly due to the decrease in amount of sediment in the littoral drift (caused by the sedimentation in the shadow zone). Besides these results, it is also showed that the coast updrift is barely affected by the presence of Eko Atlantic City, independent of the layout.

With the S-shaped layout, the flow pattern along the coast and the project area is changed. It is assumed that this leads to more efficient sediment bypassing around the Commodore Channel and thereby less sediment would be 'lost' from the littoral drift to the tidal inlet. The S-shaped transition is therefore pointed out as the best option, since it has the least negative effects downstream of the project.

In this study on the long-term impact of the Eko Atlantic City project, the layout with the S-shaped transition is therefore used, also because of the fact that the construction of the Eko Atlantic City has already begun, using this layout.

In the aforementioned report of Royal Haskoning it is also concluded, from the modelling done, that the most negative impact of the presence of Eko Atlantic City is manifested in the occurrence of severe erosion at the coastal stretch of 500 m directly downdrift of the project.

Furthermore, it is suspected that further downstream, over a distance of in total 10 km, some erosion occurs, with the first three kilometres next to the project suffering the most erosion. In Figure 0-3 the expected initial morphological effects due to Eko Atlantic City are depicted, which are obtained by the modelling study performed by Royal Haskoning. The authors of the Royal Haskoning report emphasize that it has to be mentioned that the expected sedimentation shown in this figure is likely to become reduced strongly by the rapid increase in water depth in front of the project and by the strong eastward longshore currents.

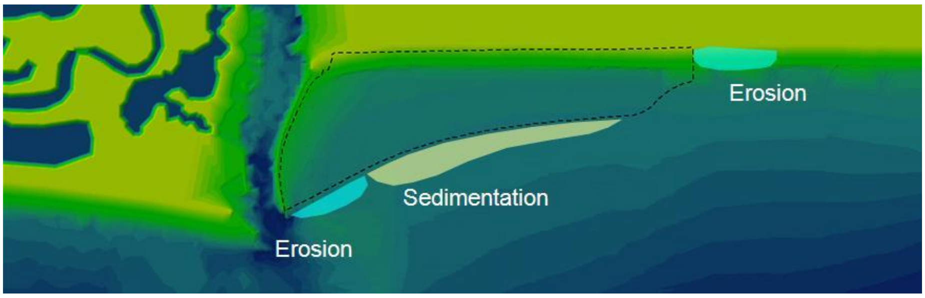

Figure 0-3: Expected morphological effect of Eko Atlantic City [after figure 5-22 (Royal Haskoning [1], 2011, Part IV)]

In the aforementioned report it is computed that the total sediment transport in the Commodore Channel decreases by thirty to fifty per cent. This is the result of a change in the longshore current, which does not bend sharply around the Moles (to follow the former coastline) but follows the orientation of Eko Atlantic City instead. This subsequently induces a seaward shift of the turbulent eddy, caused by the presence of the East Mole, allowing more sediment to bypass the moles and, at the same time, resulting in less local erosion due to eddy formation. An indication of these differences is shown in Figure 0-4 and Figure 0-5.When more sediment bypasses the moles, instead of settling in the Commodore Channel, more sediment is present in the littoral drift, which could induce a decrease in the erosion downstream. The total sediment transport rate along the coast is computed to be around 700,000 m^3/year.

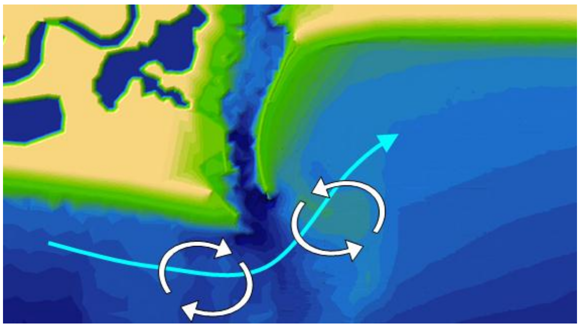

Figure 0-4: Impression of longshore current and eddies without the presence of Eko Atlantic City [after figure 5-27 (Royal Haskoning [1], 2011, Part IV)]

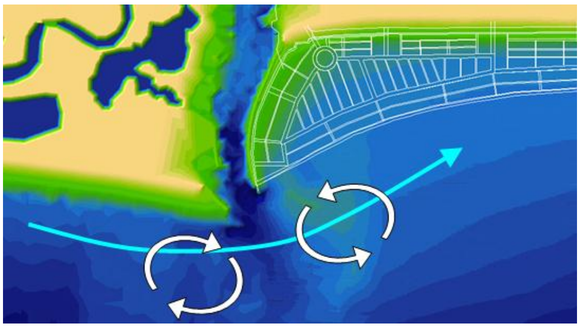

Figure 0-5: Impression of longshore current and eddies with the presence of Eko Atlantic City [after figure 5-27 (Royal Haskoning [1], 2011, Part IV)]

A.3 ARTIST'S IMPRESSION EKO ATLANTIC CITY

In this section two artist's impressions of Eko Atlantic City are depicted. Both figures are made by Royal Haskoning.

Figure 0-6: Artist's impression of Eko Atlantic City, as seen from the South

Figure 0-7: Artist's impression of Eko Atlantic City, as seen from the South-Southwest

B TIDAL INLET

B.1 EBB-TIDAL DELTA CLASSIFICATION

The classification of ebb-tidal deltas by Oertel (1985) is made on the basis of the comparison of the delta configuration to the relative magnitudes of the longshore current, the offshore current and the onshore current. In Figure 0-8 the configuration of the ebb-tidal delta and the relative forces of the currents, represented by the length of the arrows, are depicted.

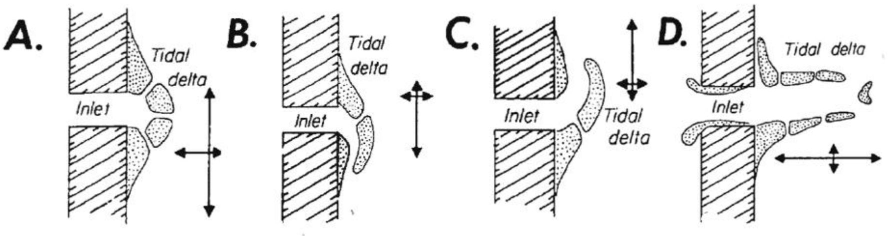

Figure 0-8: The four types of ebb-tidal deltas according to the Oertel classification [after fig. 4 Oertel (1985)]

Via comparison of Figure 0-8 to the natural appearance of the Lagos coast, as depicted in Figure 2-9, it can be concluded that the coast of Lagos resembles the situation B or C the most. The force of the longshore current is dominant over the cross-shore currents, which is reflected in the layout of the tidal delta.

B.2 VOLUME OF EBB-TIDAL DELTA

In order to obtain a notion of the potential amount of sediment present in the ebb-tidal delta (or also called the outer delta) of the tidal inlet at Lagos, a graph made by Jarrett (1976)[28] is used. The graph is represented in Figure 0-9.

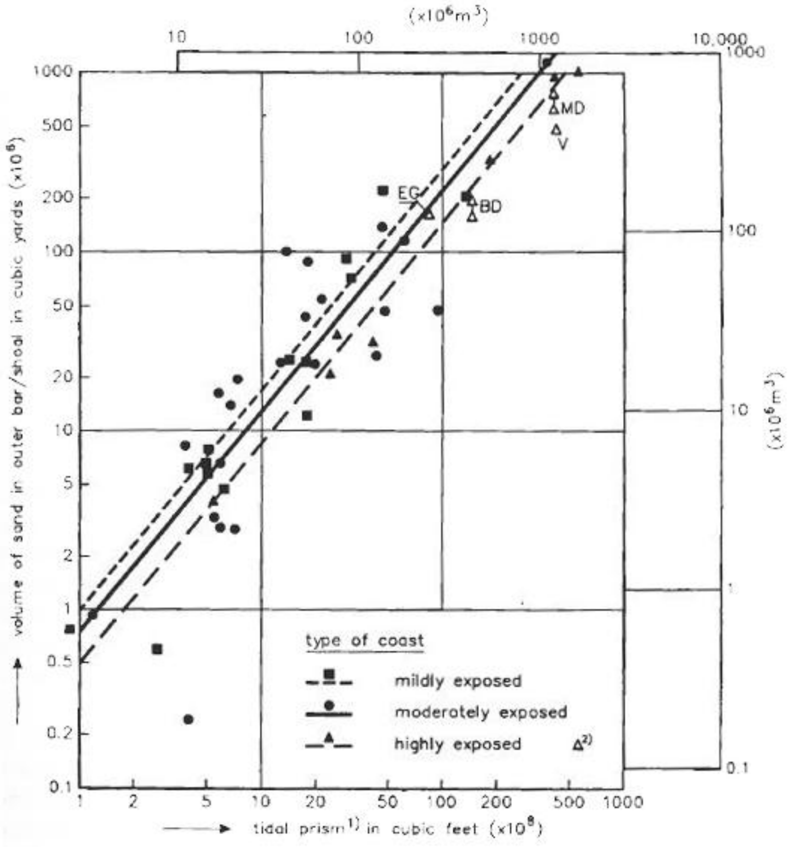

Figure 0-9: Empirical relationship between tidal prims and volume of the ebb-tidal delta [after figure 9-20 Bosboom and Stive (2010)]

This graph shows the equilibrium volume of the delta dependent on the tidal prism. In this study two values for P are used, so also two values for the equilibrium volume of the delta are obtained.

A tidal prism of $140 \cdot 10^6$ m^3 would lead to a volume of $50 \cdot 10^6$ m^3. And a tidal prism of $200 \cdot 10^6$ m^3 would induce an equilibrium volume of $80 \cdot 10^6$ m^3.

It is discussed in section 2.2.1 that, before human interference at the Lagos coast, in the 'natural' condition, the Lagos Lagoon would already have had a sediment demand.

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[28] Depicted in Bosboom and Stive (2010).

Therefore, it is assumed that the sediment volume stored in the ebb-tidal delta would not have been as big as its equilibrium volume, as, already before human interference, it would have functioned as a sediment source for the longshore current. However, above figures do indicate that the potential volume in the delta would have been sufficiently great, such that it could have formed a sediment source of importance.

B.3 TYPE OF BYPASSING

If a tidal inlet is considered, there are generally two types of sediment bypassing. The first is mainly via the tidal flow. The flood current transports the sediment into the inlet, and (maybe several tidal cycles later) the ebb current carries the sediment back to the sea or the longshore current. The second bypassing manner is via the bars of the ebb-tidal delta, which migrate from updrift to downdrift direction (Bosboom and Stive, 2010). A rough approximation of the type of bypassing is obtained via:

$$r = \frac{P}{M}$$

Where: P is the (spring) tidal prism [m^3] and M is the sediment volume transported by the longshore current [m^3/year]. The following classification is made:

If P/M is bigger than 150, the bypass mainly goes via the tidal flow.

If $50 < P/M < 150$, the bypass is a combination of tidal flow and bar bypassing.

If P/M is smaller than 50, the bar bypassing is the main bypassing mode.

At Lagos, the tidal prism is in calculated to lie in between $140 \cdot 10^6$ m^3 and $200 \cdot 10^6$ m^3. The volume of LST is about $0.6 \cdot 10^6$ m^3/year. The value of r is computed to lie in a range of 233 to 333. Therefore, it can be concluded, as a first approach, that the bypassing occurs mainly via the tidal flow. But it could be very well possible that a part of the bypassing also occurs via the components of the ebb-tidal delta. However, it is assumed that this estimation shows that the tidal flow is an important factor in the consideration of the sediment transport.

Another aspect of the P/M ratio is that it tells something about the inlet (overall) stability.

For the $P/M > 150$ ratio at the Lagos tidal inlet, the stability is classified as good, with little bar forming and good flushing of the channel (Seabergh, 2002).

C CONCEPTUAL MODEL

C.1 'SINGLE LINE THEORY'

The 'single line theory' of Pelnard-Considère (1956)[29] is used for a quick assessment of the impact on the adjacent coastline development of coastal structures. As mentioned in section 3.1.2, the basic assumption in the single line theory is that the cross-shore beach profile does not change its shape. Therefore, the coastline is schematised as a single line that either moves seaward or landward. If one considers small changes in angle of wave attack and looks at the accretion near the moles, while assuming no sand bypasses the structures, the growth of the coastline near the structure, in cross-shore direction, can be estimated by:

$$L(t) = 2\sqrt{\frac{\varphi' St}{\pi d}}$$

Where ϕ' is the angle of wave incidence relative to the coastline [rad], S is the sediment transport [m^3/year] , t is the time [year] and d is the height of the active zone [m].

In Figure C-1 the parameters are represented graphically.

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[29] The theory is extracted from Bosboom and Stive (2010)

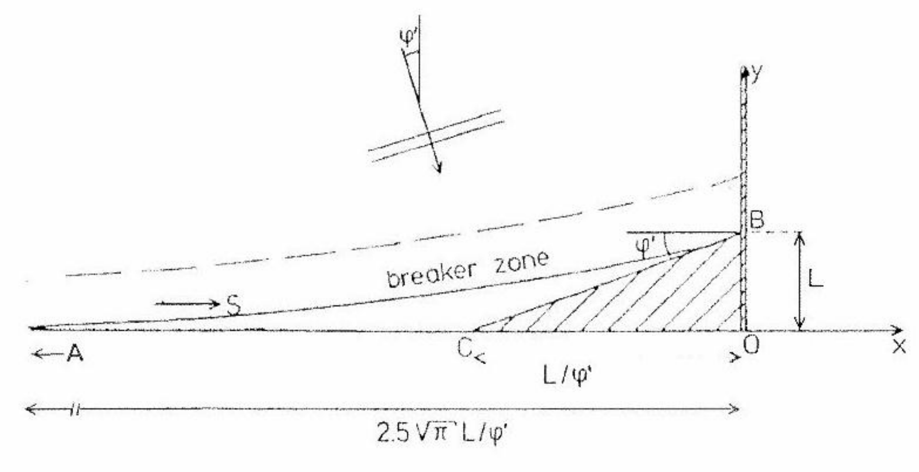

Figure 0-10: Definition of parameters of the Pelnard-Considère (1956) theory [after figure 8-12, Bosboom and Stive (2010)]

It is assumed that the height of the active zone can be approximated by the sum of the closure depth and the berm height. The depth of closure is defined by (Hallermeier, 1978) as the seaward limit of the littoral zone. Beyond the depth of closure no significant depth changes occur, because there are no longshore or cross-shore transports due to littoral transport processes. (Hallermeier, 1978) provides the following formula for the depth of closure:

$$h_c = 2.28H_e - 68.5\left(\frac{H_e^2}{gT_e^2}\right)$$

Where H_e and T_e, respectively, are the effective nearshore significant wave height [m] and the wave period [s] that are exceeded only 12 hours per year. With H_e equal to 3 m and T_e as 14 seconds, the closure depth h_c becomes 6.5 m. Comparing this value with the value used by (Dibajnia and Nairn, 2004) for their study of the coast of Cotonou, it turns out the values correspond quite well (which was also as expected, since the coasts are part of the same stretch of the West African coast). A berm height of 3.5 m is added[30], coming to a total active profile height of 10 m.

The length of the coastline over which the structure has influence (in longshore direction, see Figure 0-10) can be approximated by:

$$2.5\sqrt{\pi}L/\varphi'$$

Where L is as defined by above discussed formula and also ϕ' is as defined above. In Figure 0-10 this distance is schematised by the length AO.

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[30] This value is deducted from a map made by Royal Haskoning.

COTONOU COAST

The harbour of Cotonou lies approximately 100 km west of Lagos. Whether the sediment trapping by the harbour moles of Cotonou has an impact at the Lagos coastal morphology is investigated via the single line theory. The harbour was constructed in 1962, so its influence is investigated until 60 years after construction.

In (Tilmans *et al.*, 1993) it is stated that the volume of LST at the Cotonou coast is about 1.25 million m^3/year and the mean angle of wave incidence is about 22°.

The alongshore length impacted by the moles is about 22 km. Hence, the effects of the Cotonou Harbour are not reaching the Lagos coast in 2020.

LAGOS COAST

In a calculation of the coastline growth L, a volume of 600,000 m^3/year is used for the longshore sediment transport (LST). This value lies in the range of LST values found in literature for the Lagos coast. The general angle of wave incidence relative to the coastline orientation used in the study is about 10°, which is approximately 0.17 rad.

Using above discussed formula, over a time span of 110 years (i.e. until 2020), the coastline increases its width by approximately 1,200 m due to the construction of the harbour moles. If one considers the development of the coast over the years, it can be seen that the coast updrift expanded less. Instead, it expanded about 720 m. This indicates that the ‘zero bypass assumption’, underlying the theory, is not completely valid. So not all sediment transported by the littoral drift is trapped by the West Mole and a part of the transport sediment volume can bypass the West Mole.

As a preliminary approach, the relative wave angle of incidence updrift and downdrift the inlet used here is the same as for the Cotonou coast.

The single line theory provides an updrift and downdrift distance of 30 km that is influenced by the moles. However, because bypassing occurs it is assumed that the accretion does not reach this far upstream. Therefore, the width of the project area is set 50 km wide.

C.2 VOLUME OF LST

The range in volume of longshore sediment transport (LST) found in literature is quite broad: an average LST of 500,000 to 1,000,000 m^3/year is usually estimated. With help of Argoss wave data and the well-known CERC sediment transport formula Rosati *et al*. (2002), an estimation can be made regarding the potential longshore sediment transport rate.

The Argoss sea and swell wave data, extracted offshore of Nigeria (5.00°N; 3.75°E) over a period between 1992 to 2007, are presented in Table C-1.

The CERC formula, based on the longshore component of the wave energy flux, used to compute the LST is:

$$S = K\left(\frac{\rho\sqrt{g}}{16\gamma^{1/2}\left(\rho_s-\rho\right)(1-n)}\right)H^{5/2}\sin(2\alpha_b)$$

Where K is an empirical proportionality coefficient [-], ρ is the mass density of water [kg/m^3], g is the gravitational acceleration [m/s^2], γ is the breaker index H_b/h [-], ρ_s is the mass density of sediment [kg/m^3], n is the porosity [-], H is the wave height [m] and α_b is the wave breaker angle relative to the shoreline [°].

Table C-1: Joint probability of occurrence Hs and θ offshore Nigeria [source: Argoss, after (Royal Haskoning [1], 2011, Part II)]

		Direction [degr. N]																			
		55	65	75	85	95	105	115	125	135	145	155	165	175	185	195	205	215	225	235	245	
Hs [m]		65	75	85	95	105	115	125	135	145	155	165	175	185	195	205	215	225	235	245	255	ALL
0	0.25																					
0.25	0.75						0.002		0.002	0.006	0.004	0.015	0.053	0.284	0.695	0.702	0.051					1.81
0.75	1.25		0.009	0.006	0.013	0.002	0.019	0.013	0.006	0.019	0.011	0.013	0.09	1.632	13.61	16.99	6.173	1.123	0.156	0.002		39.89
1.25	1.75	0.004	0.017	0.011	0.006	0.009		0.002			0.002	0.004	0.053	1.335	11.7	18.27	7.326	1.651	0.351	0.079	0.006	40.83
1.75	2.25												0.009	0.625	4.475	6.325	2.498	0.449	0.141	0.015	0.004	14.54
2.25	2.75													0.12	0.98	1.044	0.299	0.107	0.002	0.011		2.56
2.75	3.25													0.017	0.158	0.103	0.06	0.006				0.34
3.25	3.75															0.013						0.01
3.75	4.25																					
4.25	4.75																					
4.75	5.25																					
5.25	5.75																					
5.75	6.25																					
6.25																						
		0.004	0.026	0.017	0.019	0.011	0.021	0.015	0.008	0.025	0.017	0.032	0.205	4.013	31.62	43.45	16.41	3.336	0.65	0.107	0.01	99.99

The Argoss data provide the joint probability of occurrence of H_s and the wave direction (θ). Taking into account this probability, the potential longshore sediment transport rate each combination of H_s and θ induces can be obtained. The sum off all these contributions provides roughly the yearly sediment transport rate. It has to be kept in mind however, that some uncertainties exist in determining the values for the parameters used. For instance, the rate of transport depends linearly on the factor K, which is an empirical coefficient, therefore, by definition, it induces uncertainty here. Using the general comment that K is smaller for coarser grain and the example presented in (Rosati *et al.*, 2002), a value of 0.12 is used for K. Considering the breaker index γ, the general comment that this factor increases with increasing beach slope and, again, looking at the example presented in Rosati *et al*. (2002), it is decided to use a value of 1 for γ.

Other values used are: ρ is 1025 kg/m^3, g is 9.81 m/s^2, ρ_s is 2650 kg/m^3, n is 0.4 and the orientation of the coast, with respect to the geographic North, is taken as 90°. With these values, the total annual longshore transport rate becomes $1.2 \cdot 10^6$ m^3/year. However, it has been mentioned above that in setting the factors used in the formula a lot of uncertainty arises. It can also be concluded that the coastline orientation is of importance: changing its orientation 5 degrees (to 95°), reduces the potential LST rate to $0.9 \cdot 10^6$ m^3/year. Therefore, as a first approach in this study, it is assumed that the range in LST rates found in literature is representative.

C.3 SEDIMENT TRANSPORT EAST OF BAR BEACH

In literature various ideas exist about the destination of the sediment transported eastward by the longshore current. A sediment volume of approximately 600,000 m^3/year is transported to the eastern boundary of the Barrier-Lagoon-Complex, while almost no sand is present at the adjacent Mahin Transgressive Mud Coast. Bakker (2009) conducted a thorough study of the coast at the proposed Olokola Liquefied Natural Gas (OKLNG) export facility, located approximately 100 km east of Lagos[31]. In her study, Bakker (2009) found that the coast near the OKLNG facility advances 3 to 7 metres per year, while the coast west of the OKLNG area remains roughly stable. This could be explained by the fact that the coast starts to change its orientation with respect to the dominant wave angle of incidence some fifty kilometres east of Lagos. This leads to a gradual reduction in longshore sediment transport capacity, because of a reduced relative angle of wave incidence. And subsequently sediment, transported by the longshore current, is deposited nearshore. This theory is also described by, among others, Jakobsen *et al*. (1989).

On the contrary, other authors, like (Ibe, 1988) and (Ihenyen, 2003), suggest that most of the sediment transported by the littoral drift is channelled into the Avon Canyon, which would act as an enormous sink. However, this statement is declined by, for instance, Jakobsen *et al*. (1989).

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[31] This is approximately at the eastern end of the Barrier Lagoon Complex.

They state that the Avon Canyon only functions as a sink for very fine material. Because of the large water depth at its head, the canyon does not reach the active littoral zone where most of the sand transport occurs and therefore, it does not channel the coarser sediment offshore.

If one takes the relative sea level rise (SLR) and the 'Bruun rule' (Bruun, 1962) into account, this could explain why the coast does not advance much, although sediment from the longshore current gets deposited nearshore.

According to the 'Bruun rule', in the long-term a cross-shore profile responds to an increased mean sea level (MSL) such that a new equilibrium upper shoreface profile develops relative to the new MSL. The coast recedes as result of the SLR, because the SLR causes more sediment accommodation space. This seems to induce erosion of the coast, due to the landward shift of the profile. Though, the 'Bruun rule' is assumed to be valid for a two-dimensional setting only (i.e. in cross-shore direction), without a gradient in the longshore sediment transport being present. Applying the rule at the Nigerian coast is therefore a rude simplification. However, because not many other relationships are available (Dean *et al.*, 2008) and in order to provide some tool to obtain an estimation of the 'erosion' volumes due to SLR, the rule is applied in this study.

As stated above, the coast far east of Lagos, near the border with the Mahin Transgressive Mud Coast, advances instead of erodes. Therefore, at the eastern end of the Barrier-Lagoon-Complex, the coast should receive sediment from the longshore current.

A calculation presented in appendix C.7, shows that, theoretically, the longshore sediment transport east of Lagos indeed can supply sufficient sediment to the coast, such that no erosion due to SLR occurs. Hence, most of the sediment eroded from the Bar Beach and subsequently transported eastward by the longshore current, becomes gradually deposited at the coast. And thereby the erosion rates induced by SLR are opposed.

Concluding, in this study it is assumed that the Avon Canyon does not import sand, and therefore, can be left out of the analysis of the Lagos coastal system.

C.4 BRUUN RULE

Bruun (1962) provided a simple, empirical relationship between the rate of sea level rise (SLR) and the recession of the coast. Underlying this relationship is the assumption that a cross-shore beach profile reacts to an increase in the mean sea level (MSL) by developing a new equilibrium upper shoreface profile, relative to the increased MSL. This leads to sediment exchange between the upper and lower shoreface, through which is seems as if the coast is eroding.

The relationship presented by Bruun (1962) is now widely called the 'Bruun rule' (Dean *et al.*, 2008):

$$R_\infty = S\frac{L_*}{h_* + B}$$

Where R_∞ is the equilibrium shoreline response [m], S is the rate of SLR [m], L_* is the width of the active profile [m], h_* is the height of the active profile [m] (assumed to be equal to the earlier mentioned depth of closure) and B is the berm height [m]. The width of the active profile can be defined via the formula:

$$W_* = \left(\frac{h_*}{A}\right)^{3/2}$$

Where W_* is the width of the active profile (defined as L_* in the above formula), h_* is as defined above and A is a sediment scale parameter [$m^{1/3}$]. A can be obtained using a graph made by Dean (1978, 2001)[32]. A mean grain particle diameter of 0.56 mm (Royal Haskoning [1], 2011, part I) corresponds to a value of 0.17 $m^{1/3}$ for A. In appendix C.1, the depth of closure is calculated as 6.5 m. The width of the active profile is thus about 240 m.

This implies that the shoreface would have an average slope of 1:35, which matches well to the values found in literature. For instance, in (Ibe, 1988) and in Dibajnia and Nairn (2004) the average slope of the shoreface is given as 1:20 to 1:50.

As it is hard to determine the rate of sea level rise, and maybe even more tough to determine the land subsidence, the calculations are made with two different values for the SLR: a high SLR of 10 mm/year and a low SLR of 5 mm/year. If the SLR would be 5 mm, this would lead to a recession of the coast of 0.12 m. In the same way, it is found that the coastal recession is around 0.24 m if the SLR equals 10 mm per year. In appendix C.7 the effects of SLR are discussed further.

C.5 ACCRETION AND EROSION VOLUMES

The erosion respectively sedimentation volumes are obtained in three steps.

As has been mentioned in sections 3.3 and 3.4, the volumes of accretion and erosion of the Lagos beaches are obtained via the values of cross-shore expansion respectively retreat of the beach. This is the first step.

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[32] Original source not used; graph is depicted in: (Dean *et al.*, 2008)

Once the accretion (or erosion) values are obtained, the accretion (or erosion) volume is calculated via:

$$V = \Delta y_{mean} \cdot h_{ac} \cdot \Delta x$$

Where V is the sediment volume [m^3], Δy_{mean} is the mean value of cross-shore expansion (or retreat) [m], h_{ac} is the active profile height [m] (as defined earlier) and Δx the length of the coast [m]. In Figure 0-11 a sketch of the calculation is presented.

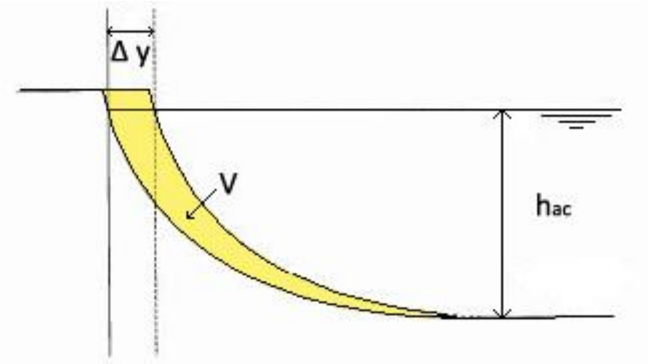

Figure 0-11: Calculation of erosion respectively accretion volume, using the single line theory [after figure 8-7, Bosboom and Stive (2010)]

Secondly, once this volume is obtained (via the literature data), it is checked how much of the total volume the literature data represent. Via the earlier applied theory of Pelnard-Considère (1956), the length of coast influenced by the mole is calculated. Therefore, the distance OC, which is L/ϕ', (as depicted in the sketch in Figure 0-10) must be obtained. Then this value is compared to the length of coast the literature data cover, and a decision is made on what percentage of accretion (or erosion) the data represent.

The last step is to check what volume theoretically would have been eroded or accreted, according to the Pelnard-Considère (1956) theory. The change in shoreline position (i.e. the distance of coastal expansion or retreat) is used to estimate the percentage of sediment transport that bypassed the moles. Then the accreted sediment volume is obtained via the percentage of the longshore sediment transport that became trapped by the mole. For erosion this is a little abstract application of the Pelnard-Considère (1956) theory, but, as the theory assumes an erosion profile that is the mirrored accretion profile, it can be used as a check.

All steps are further clarified in the calculations discussed in the sections below.

BETWEEN 1910 AND 1960

ACCRETION

To provide an overview, the accretion values after the first 50 years after construction of the moles are repeated:

- 440 m directly west of the West Mole
- 340 m at 2 km upstream the West Mole
- 280 m at 5 km upstream the West Mole

In Figure 0-12 the accretion values of Lighthouse Beach, after 50 years, are depicted.

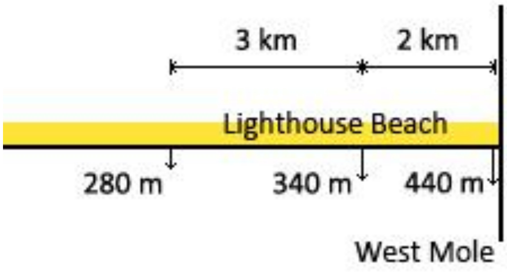

Figure 0-12: Sketch of accretion rates at Lighthouse Beach, between 1910 and 1960, extracted from Figure 1-5 and Figure 3-3

Via the manner described above, the volume accreted in the direct vicinity of the West Mole is computed as:

$(390 \cdot 10 \cdot 2000) + (310 \cdot 10 \cdot 3000) = 7.8 \cdot 10^6 + 9.3 \cdot 10^6 = 17.1$ million m^3.

However, via the earlier mentioned ‘single line theory’, it is found that, after 50 years, the influence of the West Mole reaches theoretically until 12 km upstream, while the data only cover the first 5 km upstream. Thus, as stated in the introduction of this section, it has to be investigated what percentage of the total accreted volume is given by the data.

Therefore, the theory of Pelnard-Considère (1956) is applied again, to obtain the percentage of bypassing in the first 50 years after construction of the moles. The formula for the cross-shore expansion is repeated here:

$$L(t) = 2\sqrt{\frac{\varphi' S t}{\pi d}}$$

Where all parameters are as defined earlier, see appendix C.1. However, the value of S in this formula is set as:

$$S = \beta S_0$$

Where $(1-\beta)$ is the percentage of LST that bypasses the West Mole [-] and S_0 is the initial amount of sediment transport [m^3/year].

Via this adjustment, it is investigated for which value of β the value of accretion directly west of the West Mole equals 440 m, after 50 years.

If $\phi' = 0.087$ rad (= 5°), $d = 10$ m and $S_0 = 600{,}000$ m^3/year, it is calculated that after 50 years for $\beta = 0.6$ the correct accretion width is obtained. The bypassing of the LST along the West Mole is then 40 per cent.

The total sediment volume trapped by the West Mole is calculated via:

$$V = \beta S_0 \cdot t$$

Hence, after 50 years, theoretically, the stored sediment volume is $18 \cdot 10^6$ m^3.

It turns out that via the theory of Pelnard-Considère (1956), the total volume of accretion lies in the same order of magnitude as the volume calculated via the data acquired from literature. To come to a final estimation of the accreted volume, the theory of Pelnard-Considère (1956) is studied a little more. According to the theory, 64 per cent of the total accreted volume lies in the surface area OCB (see Figure 0-10 and Figure 0-13).

At Lagos after 50 years the distance OC (which is L/ϕ') equals about 5 km, which means that the literature data (as depicted in the sketch in Figure 0-12) cover an area somewhat greater than the area OCB (see also Figure 0-13). Though the literature data reach to a distance of 5 km upstream, the accretion value at point C is not equal to zero and thereby, the volume covered by the literature data is greater than 64 per cent of the total accreted volume.

In order to estimate which percentage of the total accreted volume the literature data represent, it is assumed that the division of accreted volumes as showed in Figure 0-13 can be applied:

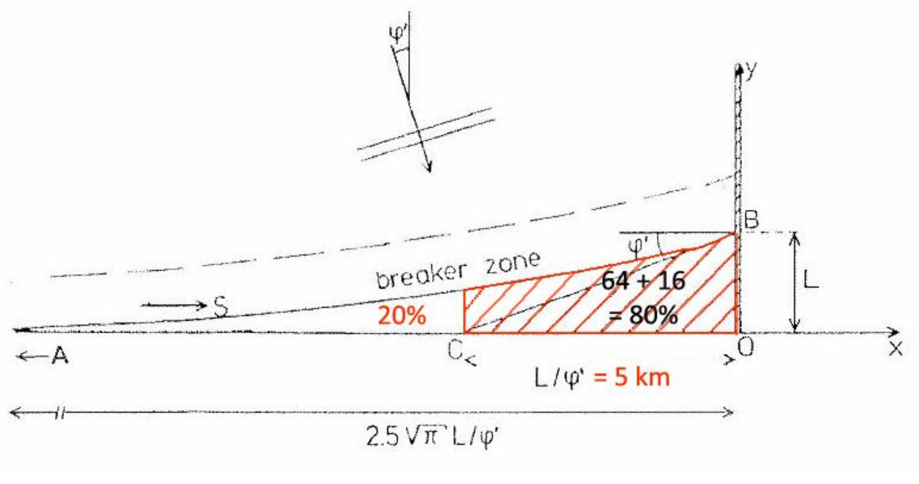

Figure 0-13: Division in accreted volumes, after 50 years

So, if one applies this assumption, the literature data cover about 80 per cent of the total accreted volume. To come to the total volume of accretion for this time span, the accreted volume between 5 km and 12 km upstream has to be added, which has a value of 20 per cent of the total accreted volume, according to this approach.

Therefore, the total accretion volume is calculated as $(17.1 \cdot 10^6 \text{ m}^3 + 4.3 \cdot 10^6 \text{ m}^3) = 21.4 \cdot 10^6 \text{ m}^3$ in the first fifty year after construction of the moles.

To decide what value is used as accretion value, it is assumed that the 'real' accreted volume must lie in between the two calculated values: $18 \cdot 10^6 \text{ m}^3$ and $21.4 \cdot 10^6 \text{ m}^3$. A value of $20 \cdot 10^6 \text{ m}^3$ is therefore used to represent the total accreted sediment volume in the first fifty years after construction of the moles.

This comes down to an annual accretion volume of approximately 400,000 m^3/year. If the total annual sediment transport is 600,000 m^3/year, the accretion volume can be schematised as 65 per cent of the total volume of LST.

Tarkwa Bay

As mentioned in section 2.2.2, the Tarkwa Bay (i.e. the small beach between the West Mole and the Training Mole) accreted 500 m in approximately 70 years.

The total volume this 500 m wide beach accreted is: $(500 \cdot 10 \cdot 500) = 2.5 \cdot 10^6 \text{ m}^3$. This is roughly $0.04 \cdot 10^6 \text{ m}^3$/year, which is considered negligible compared to the great sediment volumes accreted on the Lighthouse beach and eroded from the Bar Beach.

EROSION

As stated in section 3.2, not only in Figure 3-3 but also in Figure 1-5 the accretion and erosion rates of the Lagos coast are depicted. Comparison of these two figures shows that the accretion values are approximately matching. The values of erosion, on the contrary, do not seem to correspond very well. Therefore, both figures are used to determine the erosion values.

For reasons of convenience both figures are presented again:

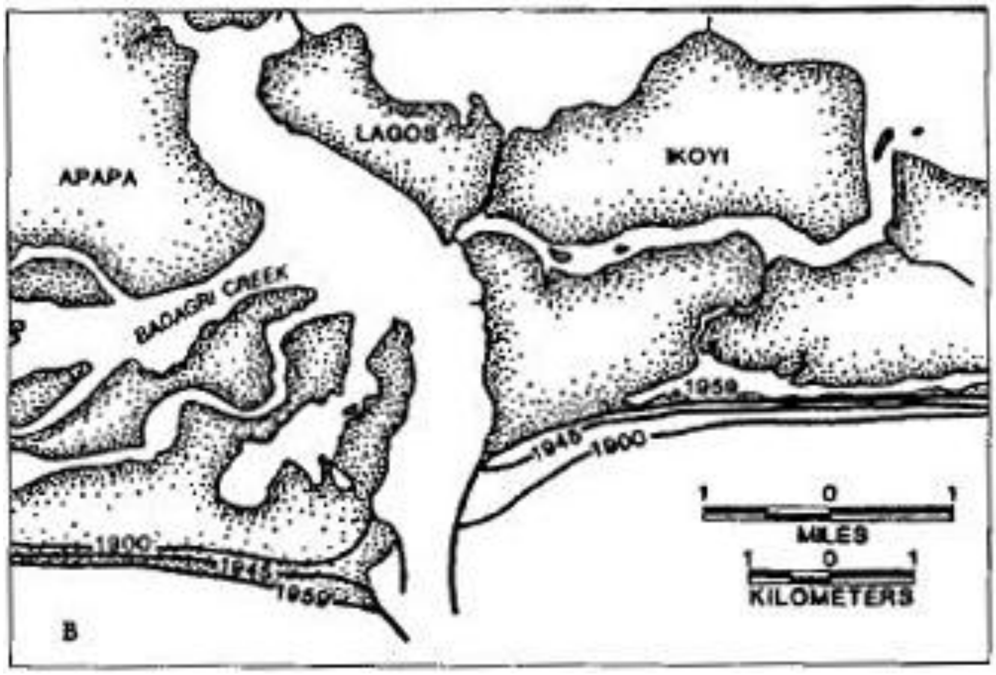

Figure 0-14: Lagos coast with the harbour moles, in 1959 [equal to Figure 1-5]

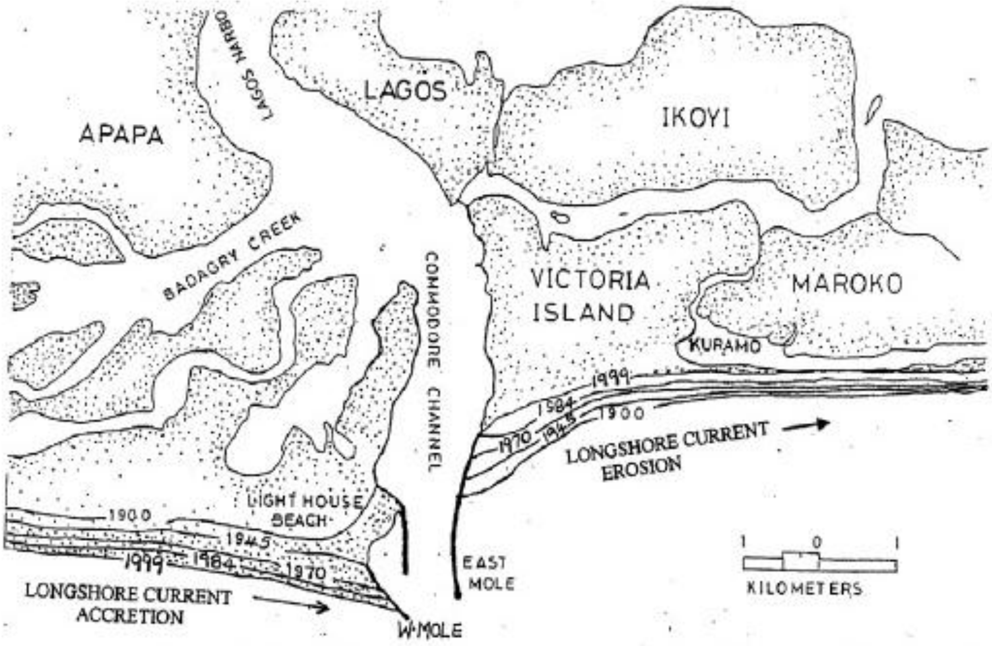

Figure 0-15: Accretion and erosion of the Lagos coast, between 1900 and 1999 [equal to Figure 3-3]

Using Figure 0-14, the following erosion rates are obtained:

- 690 m directly east of the East Mole
- 370 m at 2 km downstream the East Mole
- 260 m at 5 km downstream the East Mole

The erosion values are depicted in the sketch of Figure 0-16.

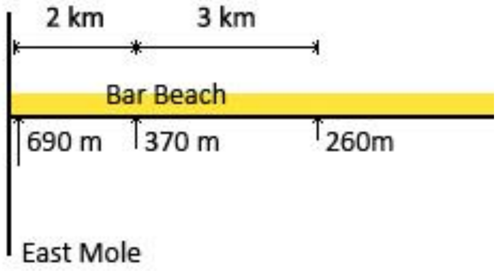

Figure 0-16: Sketch of erosion rates at Bar Beach, between 1910 and 1960, extracted from Figure 0-14

The erosion volumes are calculated the same way as the accretion volumes. The volume of erosion of Bar Beach, between 1910 and 1960, is calculated via:

$(530 \cdot 10 \cdot 2000) + (315 \cdot 10 \cdot 3000) = 10.6 \cdot 10^6 + 9.5 \cdot 10^6 = 20.1$ million m^3.

Again, the inconvenience is that the data obtained from the figures only cover the first five kilometres downstream. This means that the total erosion is probably bigger than 20.1 million m^3. The same theory as used to calculate the total accretion volume is used to obtain the total volume of erosion.

To obtain an idea about the percentage of erosion the data cover, the length OC of the Pelnard-Considère (1956) theory (see Figure 0-10 and Figure 0-13), L/ϕ' is computed. The ϕ' (i.e. the angle of wave incidence relative to the coastline [rad]) of the Bar Beach is different than the ϕ' of the Lighthouse Beach. According to this theory, the length of influence is 690/0.192 = 3.6 km, along which about 64 per cent of the total eroded volume is located. So, since the data cover about 5 km, this means that much more than 64 per cent is taken into account. The division as depicted in Figure 0-17 is assumed:

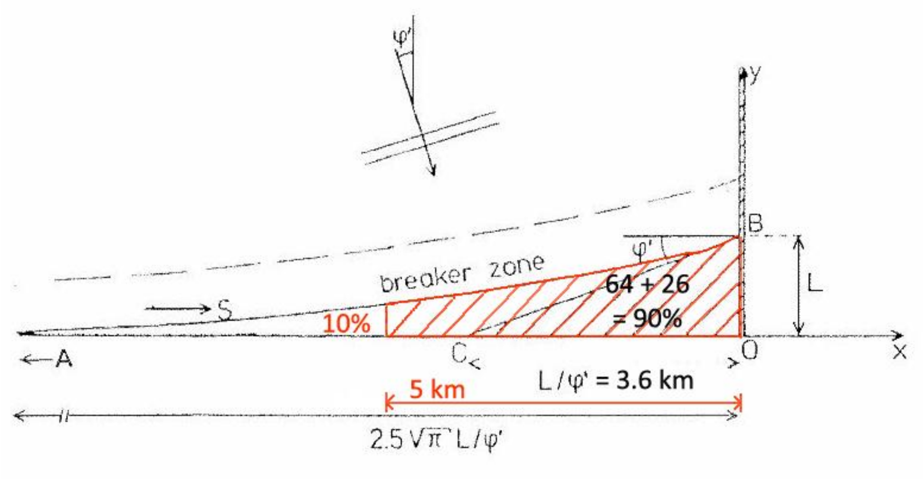

Figure 0-17: Division in eroded volumes, after 50 years. Please note that the 'real' eroded situation is mirrored.

Using this assumption, 20.1 million m^3 constitutes 90 per cent of the total volume, thus a total volume of 22.3 million m³ is eroded, in the first fifty years. Annually, this is approximately a volume of 450,000 m³/year, which equals about 0.75 · S.

Although it is an abstract concept, the theory of Pelnard-Considère (1956) is also applied to obtain the erosion volume. Instead of the volume that is trapped by the mole, the formula is now used to calculate the erosion volume. Or, in other words: it is investigated what volume of sediment must be transported away, to reach a retreat of the beach of 690 m directly next to the East Mole. The formula for cross-shore changes is repeated:

$$L(t) = 2\sqrt{\frac{\varphi' St}{\pi d}}$$

Where all parameters are as defined earlier, see appendix C.1. But in this calculation, L(t) is the retreat, instead of the expansion. Again, the value of S in this formula is:

$$S = \beta S_0$$

Where the same definitions as defined earlier this section are valid. The factor β now represents the percentage of the initial sediment transport (S_0) that is eroded from Bar Beach. Hence, the erosion volume is calculated via:

$$V = \beta S_0 \cdot t$$

With $\phi' = 0.192$ rad (= 11°), $\beta = 0.65$ provides the correct value of retreat. This means that the eroded volume, after 50 years, is $(0.65 \cdot 600{,}000 \cdot 50) = 19.5 \cdot 10^6$ m^3.

Concluding, the erosion values obtained via theory of Pelnard-Considère (1956) agree quite well to the data measured in Figure 0-13.

Considering Figure 0-14, the erosion rates are as given below:

- 430 m directly east of the East Mole
- 190 m at 2 km downstream the East Mole
- 150 m at 5 km downstream the East Mole

In Figure 0-18, a sketch of these values is presented.

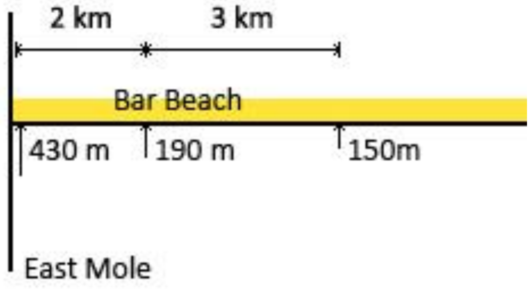

Figure 0-18: Sketch of erosion rates at Bar Beach, between 1910 and 1960, extracted from Figure 0-15

The total eroded volume, using these data becomes:

$(310 \cdot 10 \cdot 2000) + (170 \cdot 10 \cdot 3000) = 6.2 \cdot 10^6 + 5.1 \cdot 10^6 = 11.3$ million m^3.

At a first view, this volume seems to be very small. Also compared to the accreted volume in this same time span (i.e. roughly 20 million m^3), the erosion volume is expected to be bigger.

The erosion volume is also calculated via the theory of Pelnard-Considère (1956) for cross-shore shoreline changes. In order to obtain a retreat of 430 m, the value for β should be 0.25. The eroded volume, after 50 years, then becomes:

$(0.25 \cdot 600{,}000 \cdot 50) = 7.5 \cdot 10^6\ m^3$.

This calculation also supports the notion that the data extracted from Figure 0-15 are incorrect, as the data suggest very little erosion.

To summarize, it is concluded that the rates of erosion presented in Figure 0-14 are more reliable than the values depicted in Figure 0-15. Therefore, the erosion rates as calculated with the first figure are used in this study.

And, after the sediment balance of this period is investigated, it becomes clear that the volume of erosion as calculated using the data of Figure 0-15 indeed suggest too low erosion values.

BETWEEN 1960 AND 2010

ACCRETION

Since Figure 0-14 only depicts the coastlines until 1959, the accretion values for the time span 1960 – 2010 are obtained from Figure 0-15. The values of the beach expansion are depicted in Figure 0-19, and repeated:

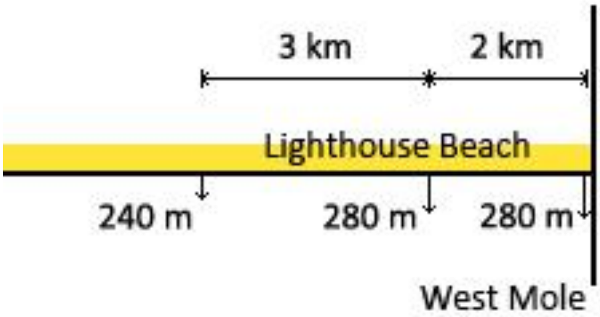

Figure 0-19: Sketch of accretion rates at Lighthouse Beach, between 1960 and 2010, extracted from Figure 0-15

- 280 m directly west of the West Mole
- 280 m at 2 km upstream the West Mole
- 240 m at 5 km upstream the West Mole

In the same manner as explained in the beginning of this section, the volumes of accretion in this time span are calculated. The volume accreted in the direct vicinity of the West Mole is computed as:

$(280 \cdot 10 \cdot 2000) + (260 \cdot 10 \cdot 3000) = 5.6 \cdot 10^6 + 7.8 \cdot 10^6 = 13.4$ million m^3.

It is also checked what percentage of the total accretion is covered by the data. Therefore the length OC of the Pelnard-Considère (1956) theory (see Figure 0-10 and Figure 0-13), L/ϕ' is computed. The length of the coast influenced most by the West Mole is 280/0.087 = 3.2 km. So in the 3.2 km closest to the mole, about 64 per cent of the total accreted volume is stored. This means that the data represent much more than 64 per cent of the total volume.

Using another application of the theory of Pelnard-Considère (1956), the value of β, for which the cross-shore expansion of the beach equals 280 m after 50 years, is investigated.

If β is 0.25, the accretion in the direct vicinity of the mole is about 280 m. Hence, of the total longshore transport, only 25 per cent is trapped by the West Mole and 75 per cent is able to bypass the West Mole.

So theoretically only 7.5 million m^3 is trapped by the West Mole in this period. This value is much smaller than the volume calculated with the data of Figure 0-15.

However, as there are no other data sources available, it is assumed that the 'real' volume of accretion lies somewhere in between these two calculated values.

If the accreted volume would be 13.4 million m^3, the mean accreted volume would be $13.4 \cdot 10^6 / (50 \cdot 600{,}000) = 45$ per cent. The bypassing volume would thus be 55 per cent.

It is estimated that the bypassing rate between 1960 and 2010 lies in the range of 55 to 75 per cent. Therefore, the mean value, which is 65 per cent, is used to represent the bypass in the conceptual model.

The accreted volume in the time span 1960 – 2010 is then:

$(0.35 \cdot 600{,}000 \cdot 50) = 10.5 \cdot 10^6$ m^3.

This is equal to an annual volume of 210,000 m^3/year, which is approximately 35 per cent of the total longshore sediment transport.

EROSION

Equal to the accretion rates, the erosion rates for the time span 1960 – 2010 have to be deducted from Figure 0-15, as no other data sources are available. The following rates, also depicted in Figure 0-20, are used:

- 480 m directly east of the East Mole
- 290 m at 2 km downstream the East Mole
- 190 m at 5 km downstream the East Mole

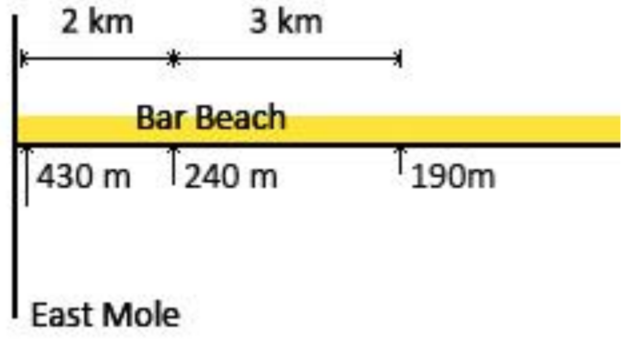

Figure 0-20: Sketch of erosion rates at Bar Beach, between 1960 and 2010, extracted from Figure 0-15

In the same way as done for the previous time span, the eroded volume is calculated:

$(335 \cdot 10 \cdot 2000) + (215 \cdot 10 \cdot 3000) = 6.7 \cdot 10^6 + 6.5 \cdot 10^6 = 13.2$ million m^3.

Via the Pelnard-Considère (1956) theory, it is checked what percentage of the total eroded volume the data represent.

The length OC (see Figure 0-10 and Figure 0-13) is calculated: L/ ϕ' = 2.6 km. Hence, the literature data represent a much greater percentage than 64 %. It is therefore assumed that the remaining percentage is negligible, compared to the percentage the data cover.

As a final check, the theoretical eroded volume is calculated, via the theory of Pelnard-Considère (1956) for cross-shore shoreline changes. A value of 0.25 for β provides a retreat of 430 m. The eroded volume, after 50 years, then becomes:

$(0.25 \cdot 600{,}000 \cdot 50) = 7.5 \cdot 10^6 \text{ m}^3$.

The theoretically eroded volume is a little smaller than the erosion volume obtained by the literature data. In the same way as done to estimate the accretion volume between 1910 and 1960, it is assumed that the 'real' erosion volume must lie in between the two values. Therefore, the mean value of $10.4 \cdot 10^6 \text{ m}^3$ is used as the eroded volume, between 1960 and 2010.

Annually, this is an erosion volume of about 200,000 m^3, which is schematised as $0.35 \cdot S$.

AFTER 2010

As stated in section 3.6, the West Mole is being rehabilitated in 2010. The seaward end is restored and heightened to CD +5 m, over a length of 100 m.

Using the single line theory, it can also be estimated what percentage of the longshore sediment transport is able to bypass the West Mole, in the period from 2010 to 2020. In a similar way as performed earlier this section, the value for β is obtained.

First, it is investigated for several values of β after how many years the accretion of the Lighthouse Beach reaches 100 m. Subsequently, the number of years in which full bypassing occurs is known. Then, it is calculated what would be the total bypassing volume in ten years; via the multiplication of (β · 'the number of years until full bypassing') + ('the number of years with full bypassing' · (1 – β)). Thereafter, the mean value for β is obtained by dividing the total bypassing volume in ten years by ten. In Table C-2, the calculation with the various values for β is presented.

Table C-2: Overview of calculation of β between 2010 and 2020

β	# years until 100 m accretion	# years with full bypassing	Bypassing volume in 10 years	Mean value β
0.35	4	6	$4 \cdot 0.65 + 6 \cdot 1 = 8.6$	0.86
0.30	5	5	$5 \cdot 0.70 + 5 \cdot 1 = 8.5$	0.85
0.25	6	4	$6 \cdot 0.75 + 4 \cdot 1 = 8.5$	0.85
0.20	7	3	$7 \cdot 0.80 + 3 \cdot 1 = 8.6$	0.86
0.15	10	0	$10 \cdot 0.85 = 8.5$	0.85

It can be concluded that in the ten years after rehabilitation of the West Mole, the mean bypassing volume is $0.85 \cdot S$.

C.6 TIDAL WAVE PROPAGATION IN LAGOS LAGOON

The time it takes the tidal wave to reach the end of the Lagos Lagoon (i.e. at the eastern part, where the lagoon gets very narrow) can be obtained by:

$$t_* = \frac{L_b}{\sqrt{g d_b}}$$

Where t_* is the propagation time [s], L_b is the basin length [m] and d_b is the mean depth of the basin [m].

If L_b is 2 km and d_b is 3 m, than it takes the tidal wave approximately 1 hour to reach the end of the basin. According to the classification used by (Seabergh, 2002), the basin can be assumed to have a more or less simultaneously fluctuating bay level. This means that the theories concerning the tidal inlet characteristics can be applied on this situation.

C.7 SEDIMENT IMPORT INTO LAGOON AND COMMODORE CHANNEL

The Lagos Lagoon and the Commodore Channel function as a sediment sink in the Lagos coastal system, due to several causes, described earlier. In this section, the dimensions of the sinks are defined according to the causes of the specific sinks.

SEA LEVEL RISE

The volume of sediment import into the lagoon is assumed to be:

$$\Delta V = \frac{\delta \zeta}{\delta t} A_b$$

Where ΔV is the volume of sediment import [m^3], $\delta\zeta/\delta t$ is the SLR [m] and A_b is the basin area [m^2]. Considering the area of the basin, it is estimated that not the whole Lagos Lagoon contributes to the withdrawal of sediment from the littoral drift. Close to the end of the Commodore Channel, the width of the lagoon rapidly increases, causing the flow velocity, and thereby the sediment transport capacity, to quickly decrease. Therefore, the basin area significant for this computation is set as 15 km^2.

First, a computation is made for the low SLR. If the (relative) SLR would be around 5 mm per year, the annual sediment import into the Lagos Lagoon would be 75,000 m^3/year. Comparing this value with the total volume of annual longshore sediment transport, the sediment import is about 12.5 per cent of the total LST. An approximation of 10 per cent is used here. The same calculation can be made for a high SLR. Hence, if the sea level would rise about 10 mm annually, the lagoon would start to import about 150,000 m^3. This is schematised as 25 per cent of the total LST.

To the erosion rate due to the Bruun effect, the effect of the sediment import into the Lagos Lagoon due to the SLR should be added (see section 3.4.2). This is done via the expression presented by (Stive and Wang, 2003):

$$c_{pr} = \frac{\delta \zeta}{\delta t}\frac{L_{ac}}{h_{ac}} + \frac{\delta \zeta}{\delta t}\frac{A_b}{h_{ac} \cdot L_{ac}}$$

Where C_{pr} is the rate of shoreline recession [m], $\delta\zeta/\delta t$ is the SLR [m], L_{ac} is the length of the adjacent coast impacted [m], h_{ac} is the height of the active cross-shore profile [m] and A_b is the basin area [m^2]. Because no further information is provided in how to determine L_{ac}, it is chosen to use the length of the coastal stretch impacted by the Lagos Harbour Moles (see appendix C.1).

If the sea level would rise with 5 mm/year, the sediment import into the Lagos Lagoon would induce an additional coastal recession of 0.3 m. So, in total a 5 mm/year SLR would cause a recession of the coast of approximately 0.4 m/year. Considering a high SLR of 10 mm/year, the additional coastal recession due to sediment import into the lagoon would be 0.6 m/year. Summarized, the high SLR would cause a recession of the coast of 0.85 m/year.

In order to obtain a notion about the required volume of sediment for the coast to cope with this SLR-induced erosion, a rough schematisation of the volume of erosion per running meter coast is made.

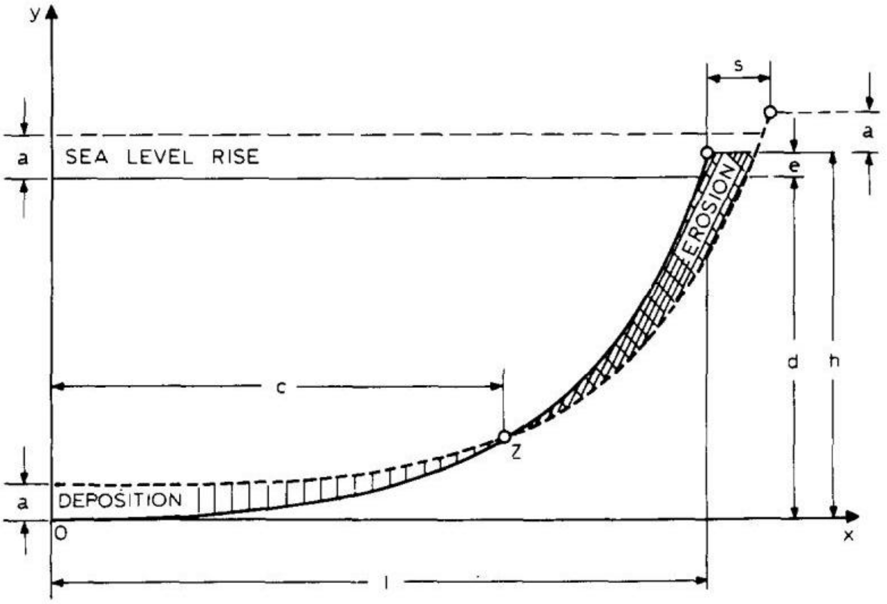

Figure 0-21: Principles of the Bruun rule [after figure 1, Bruun (1983)]

The calculation of the erosion volume per running meter coast is done similar as the calculations to obtain the accretion respectively erosion volumes:

The sediment volume per running meter, V [m^3/m'] is obtained by multiplying the mean value of erosion Δy_{mean} [m] by is the active profile height h_{ac} [m] (as defined earlier), see Figure 0-11.

Hence, with a SLR of 5 mm/year, the erosion volume is 4 m^3/m' and a SLR of 10 mm/year induces an erosion volume of 8.5 m^3/m'.

It can be checked whether the volume of the eastward transported longshore sediment transport is able to cope with the erosion induced by the SLR.

Therefore, the coastal stretch that is not influenced by the harbour moles is considered. The total stretch of coast between the Lagos tidal inlet and the transition of the Barrier-Lagoon-Complex to the Mahin Transgressive Mud Coast is about 100 km. The moles have an impact on a stretch of circa 25 km, hence 75 km of coast is beyond the influence of the moles.

A rough schematisation of the sediment volume available per running meter is then:

$$600{,}000 \text{ m}^3 / 75{,}000 \text{ m} = 8 \text{ m}^3/\text{m}'$$

This volume lies in the range of the above calculated erosion volumes. So, although this is a very rude approximation, it does suggest an explanation for the fact that the eastern part of the Barrier-Lagoon-Complex does not advance or accrete significantly.

DREDGING OF THE COMMODORE CHANNEL

In order to obtain a notion about what influence the dredging of the entrance channel to the Lagos Harbour has, an estimation is made of the potential dredging capacity of one of the dredgers used in the Lagos Harbour.

On the website of (Visser, 2007), some characteristics of the three dredgers used by the Nigerian Port Authority are presented. One of the bigger TSHD is used to make the estimation. The theory for this calculation is provided by van der Schrieck (2011).

As the width of the fairway and the length of the channel part that needs to be dredged are known, the dredged volume is obtained via the dredging layer thickness. If the production is divided by the surface of the dredging, the dredged layer thickness is obtained.

The production of the dredger [m^3/s] is obtained via the product of:

Suction velocity [m/s] · diameter of suction tube [m^2] · concentration of sediment in the mixture [-]

With an average suction velocity of 5 m/s, two suction tubes, with both a pipe diameter (Ø) of 0.6 m, and an average sediment concentration of 30 per cent, the production becomes 0.9 m^3/s.

The layer thickness is calculated as:

Width of the head of the dredger [m] · dredger sailing velocity [m/s]

The width of the dredgers head is approximated as 5Ø and the sailing velocity is generally 1 m/s (van der Schrieck, 2011). A dredged surface of 3 m^2/s is calculated with these values.

This gives a dredged layer thickness of 0.9 [m^3/s] / 3 [m^2/s] = 0.3 m.

C.8 SEDIMENT TRANSPORT CAPACITY OF FLOOD TIDAL CURRENT

To check what volume of sediment the flood tidal current is able to transport, the formula of Engelund-Hansen (1972)[33] is applied:

$$F = \frac{0.05|u|^4 u}{\sqrt{g}C_z^3(s-1)^2 d_{50}}$$

Where F is the volumetric sediment transport per meter width of bed per unit time [m³/m'/s], u is the depth-averaged velocity [m/s], g is the gravitational acceleration [m/s²], C_z is the Chézy coefficient [$m^{½}$/s], s is the relative density of the grains (compared to the water density) [-] and d_{50} is the mean grain diameter.

The Chézy friction coefficient is obtained by:

$$C = 18\log\left(\frac{12h}{r}\right)$$

Where h is the average water depth [m] and r is the bottom roughness [m]. The bottom roughness is approximated by $2 \cdot d_{50}$. The grain diameter is taken as the average of the Bar Beach and the Lighthouse Beach sediment, which is about 0.38 mm. With an average channel depth of 15 m, the Chézy coefficient becomes: 96.7 $m^{½}$/s.

The other values used for the parameters are a depth averaged velocity of 1 m/s and a relative density of 2.57.

Then, F becomes $1.88 \cdot 10^{-5}$. Multiplied by a channel width of 700 m and by $365 \cdot 24 \cdot 60^2$, this provides an annual transport volume of 0.42 million m³/year.

It has to be remarked that this calculation of potential sediment transport is a rude approximation. However, the output does indicate the high potential sediment transport capacity of the tidal currents.

C.9 NOURISHMENT VOLUMES OVER THE YEARS

In section 2.2.3 the frequency and volumes of nourishments on the Bar Beach are summarized. To investigate the distribution of sediment replenishment over the years, the nourishment data, as schematised in Table C-3, are plotted in Figure 0-22.

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[33] Quoted in S.M. van Leeuwen *et al*. (2003)

Table C-3: Schematised nourishment volumes

Year	What	Volume [10^6 m^3]
1960	Permanent pumping station built on the East Mole, supplying an average of 0.66 million m^3/year of sediment from the Commodore Channel to the beach.	0.66
1961	As in 1960.	0.66
1962	As in 1960.	0.66
1963	As in 1960.	0.66
1964	As in 1960.	0.66
1965	As in 1960.	0.66
1966	As in 1960.	0.66
1967	As in 1960.	0.66
1968	As in 1960.	0.66
1974	3 million m^3 of sand dumped and spread on the beach, with a self-discharging Trailing Suction Hopper Dredger (TSHD).	1.5
1975	As in 1974.	1.5
1981	2 million m^3 of sand dumped and spread on the beach.	2
1985	3 million m^3 of sand dumped on the beach, with the use of a TSHD and a Cutter Suction Dredger (CSD). Before the start of the works in April, the culvert to the main boulevard parallel to the shoreline was already being undermined by the waves at some locations.	1.5
1986	As in 1985.	1.5
1990	5 million m^3 of sand dumped on the beach, with the use of a TSHD, a CSD and a booster station. Before the work started in August 1990, almost all of the sand of the former nourishment had been eroded.	2.5

1991	As in 1990.	2.5
1994	4 million m^3 of sand, dredged 29 km offshore, deposited on the beach, with the use of a TSHD, a CSD and a booster station.	2
1995	As in 1994.	2
1996	Approximately 2 million m^3 of sand deposited on the beach, with the use of a TSHD, a CSD and a booster station. The beach obtained a width of 115 m. In September 1999, however, it was observed that this sediment had been washed away.	1
1997	As in 1996.	1
1999	2 million m^3 of sand dumped and spread on the beach, with the use of a TSHD, a CSD and a booster station.	2
2002	More than 2 million m^3 of sand dredged and a renovation of the Ahmadu Bello Way (the road along the Bar Beach).	1
2003	As in 2002.	1

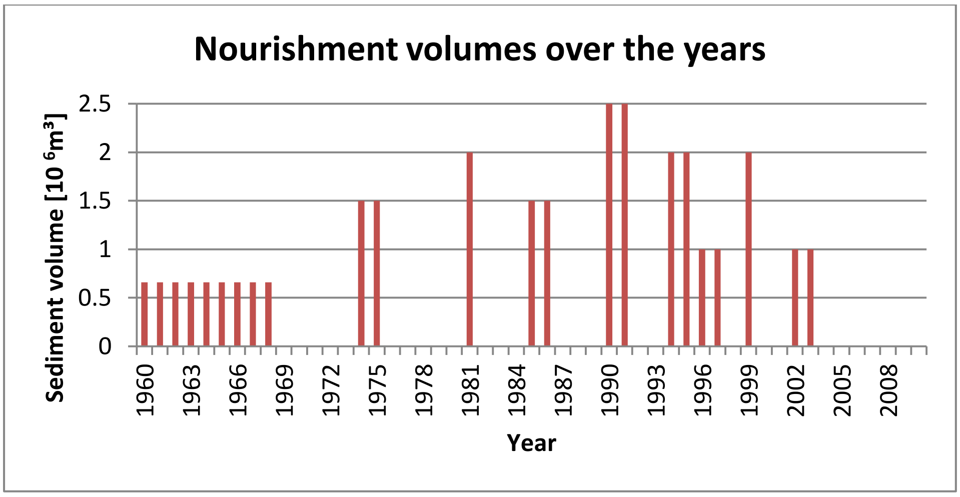

Figure 0-22: Distribution of nourishments over the years

C.10 THEORETICAL DEVELOPMENT OF EROSION WAVE OVER THE YEARS

In Figure 0-23 the schematic shoreline development as defined by Mangor (2004)[34] is depicted. The difference in accretion volumes and erosion volumes can clearly be distinguished.

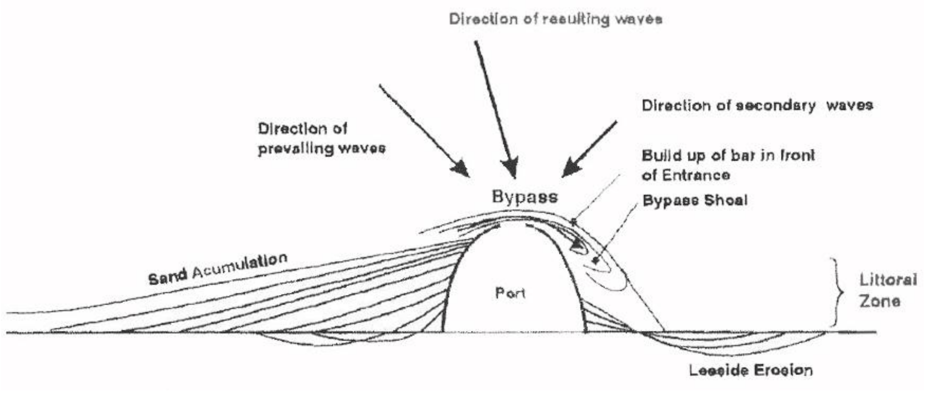

Figure 0-23: Schematic shoreline development [after Mangor (2004), depicted in Bosboom and Stive (2010)]

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[34] Quoted in Bosboom and Stive (2010): MANGOR, K. (2004) *Shoreline Management Guidelines*, 3rd Ed., DHI, Denmark

D UNIBEST MODEL SETUP

D.1 CROSS-SHORE PROFILES

As stated in section 4.2, the Unibest CL model is defined by ten different profiles, localized along the coast.

CHARACTERISTICS CROSS-SHORE PROFILES

Some characteristics of the profiles are presented in Table D-1 and Table D-2. The coordinates of the locations presented in the tables, represent the seaward ends of the locations. Hence, these are the locations where the wave climates are imposed. Also the depth at the end of the profiles is presented in the tables.

Table D-1: Characteristics of the profiles located along the coast

Profile number	East 1	East 2A	East 2	East 3	West 4	West 5	West 6
Location	N 566549 E 707155	N 555649 E 706855	N 547649 E 706855	N 545599 E 706007	N 543599 E 706007	N 533799 E 705956	N 522999 E 705956
Initial coast angle [°]	179	179	175	169	183	181	179
Depth seaward end [m]	14.0	12.4	9.7	9.5	11.8	11.2	11.0

Table D-2: Characteristics of the profiles in the shadow zone of the East Mole

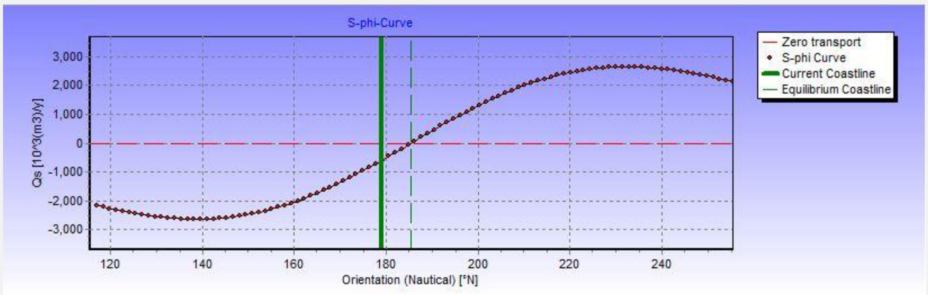
Profile number	East 3-1	East 3-2	East 3-3	East 3-4
Location	N 545599 E 709010	N 546099 E 709010	N 546599 E 709010	N 547099 E 709010
Initial coast angle [°]	167	164	169	174
Depth seaward end [m]	9.5	8.1	8.6	9.8

S-Φ CURVES

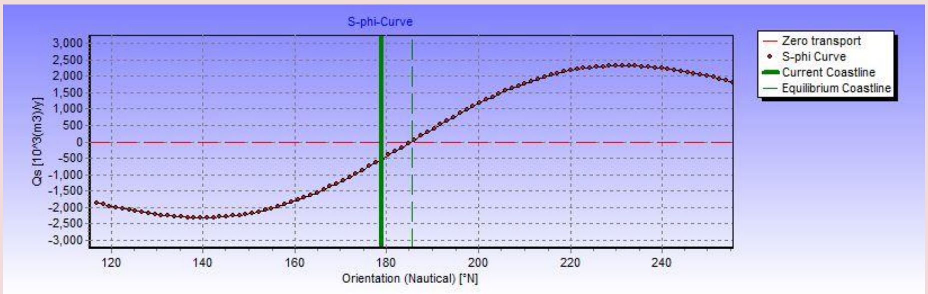
The S-ϕ curves are depicted per cross-shore profile in Table D-3.

Table D-3: S-ϕ curves per cross-shore profile

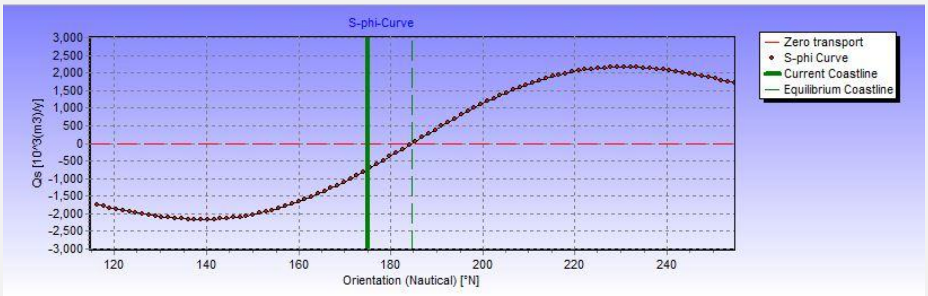
East 1



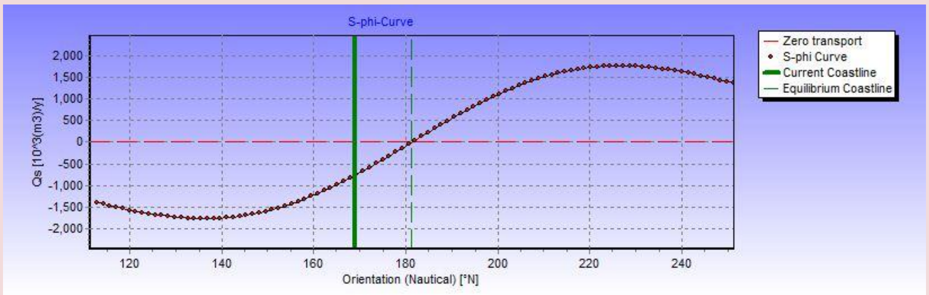
East 2A



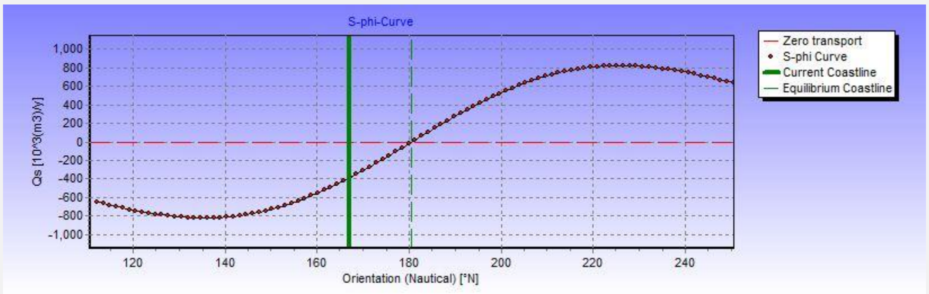
East 2



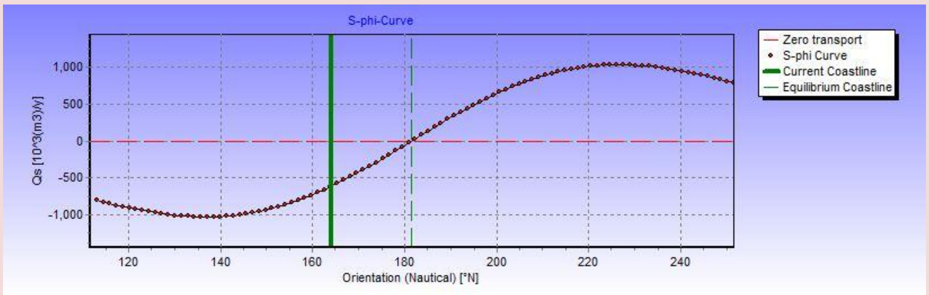
East 3



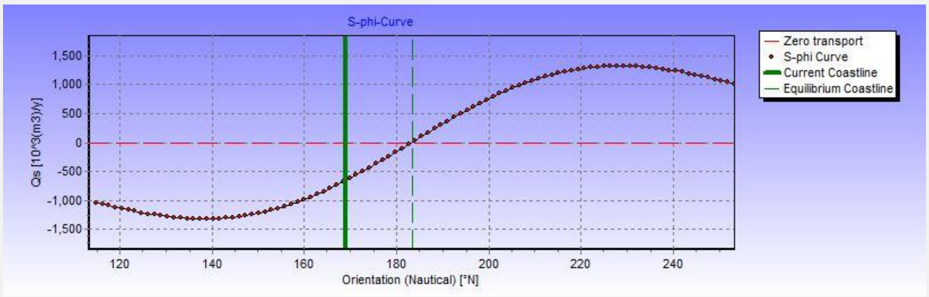
East 3-1



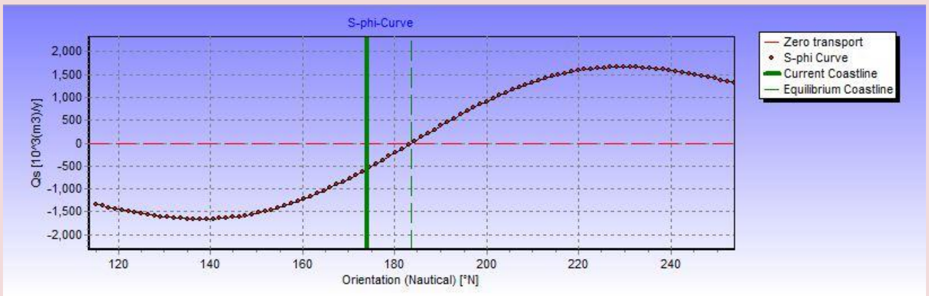
East 3-2



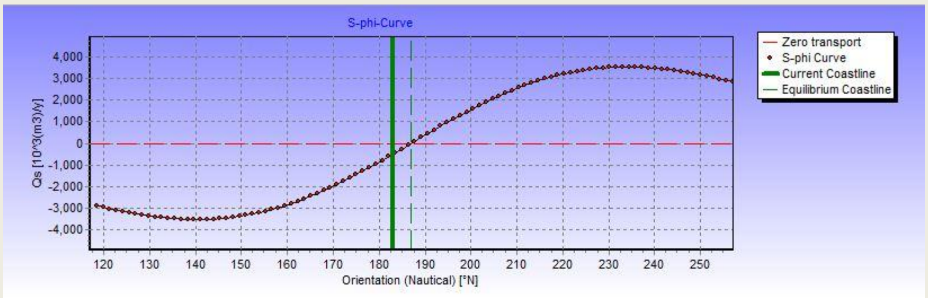
East 3-3



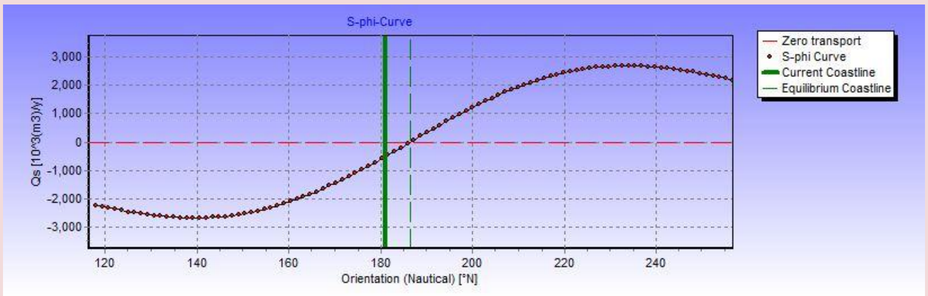
East 3-4



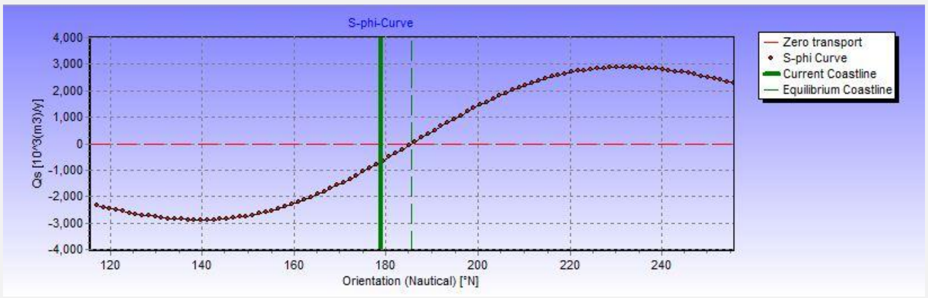
West 4



West 5



West 6



D.2 WAVE CLIMATE PROPAGATION

The wave climate used by Royal Haskoning is defined at a depth of 30 m. As the profiles used in the Unibest model have an offshore depth of roughly 10 m, the wave climate as used by Royal Haskoning has to be adjusted. In Table D-4 the initial wave climate is depicted.

Table D-4: Lagos wave climate at 30 m depth

Percentage of occurrence [%]	Wave height H_{m0} [m]	Wave angle θ [°]	Wave period T_p [s]
0.897	0.75	172.5	8.616
2.676	0.75	187.5	9.748
6.133	0.75	202.5	11.03
0.458	0.75	217.5	9.463
2.417	1.25	172.5	9.512
20.85	1.25	187.5	10.878
30.824	1.25	202.5	11.738
1.984	1.25	217.5	6.488
0.822	1.25	232.5	4.565
0.025	1.25	247.5	4.282
0.685	1.75	172.5	10.54
13.204	1.75	187.5	11.972
13.322	1.75	202.5	12.566
0.632	1.75	217.5	5.554
0.813	1.75	232.5	5.064
0.109	1.75	247.5	4.863
0.084	2.25	172.5	12.94
2.068	2.25	187.5	12.822
1.576	2.25	202.5	12.907
0.171	2.25	217.5	5.839
0.1	2.25	232.5	5.484
0.14	2.75	187.5	12.933
0.01	2.75	202.5	13.728

REFRACTION AND SHOALING[35]

The wave climate is propagated manually (with help of Excel) by calculating the effects of shoaling and refraction. The propagated wave height is calculated via:

$$H_i = H_0 \cdot K_s \cdot K_r$$

Where H_0 is the incident deep water wave height [m], K_s is the shoaling coefficient [-] and K_r is the refraction coefficient [-].

Regarding the refraction, it is assumed the bottom has straight and parallel contours, such that Snell's law can be applied:

$$\frac{\sin\theta}{c} = constant$$

Where θ is the wave angle of approach [°] and c is the wave celerity [m/s]. As this term is constant, also the following expression applies:

$$\frac{\sin\theta}{c} = \frac{\sin\theta_0}{c_0}$$

Where in general, the subscript 0 refers to the deep water conditions.

The following expressions are used to calculate the deep water wave conditions:

$$c_0 = \frac{gT}{2\pi},$$

$$c_{g0} = nc_0 = \frac{1}{2}c_0$$

$$L_0 = \frac{gT^2}{2\pi}$$

Where c is the wave celerity [m/s], c_g is the wave group velocity [m/s], T is the wave period [s], d is the water depth [m] and L is the wavelength [m].

The wavelength L at an arbitrary depth is found iteratively, via the expression:

$$L = \frac{gT^2}{2\pi}\tanh\left(\frac{2\pi d}{L}\right)$$

---

[35] The theory presented by Vincent *et al*. (2002) is the main source of this section.

Per seaward end of the profiles, the water depth differs. Therefore, the wave climate differs slightly per profile. The wave height, wave direction and wave period are known for the offshore wave climate. The first step in the propagation of the wave climates is to calculate the corresponding wavelength, per wave, per location.

If the wavelength is known, then the wave celerity can be computed via:

$$c = \frac{gT}{2\pi}\tanh(\frac{2\pi d}{L}) = \frac{L}{T}$$

Once the wave celerity is obtained, the wave group velocity is acquired by:

$$c_g = nc = \frac{1}{2}\left(1 + \frac{4\pi d / L}{\sinh(4\pi d / L)}\right)c$$

The shoaling coefficient K_s is subsequently calculated as:

$$K_s = \sqrt{\frac{c_{g0}}{c_g}}$$

To calculate the refraction coefficient K_r also the wave angle at the specific depth must be known. This wave angle is obtained via:

$$\sin\theta = \frac{c\sin\theta_0}{c_0}$$

The refraction coefficient can then be obtained via:

$$K_r = \left(\frac{1-\sin^2\theta_0}{1-\sin^2\theta}\right)^{\frac{1}{4}}$$

If both the shoaling and refraction coefficient are obtained, the wave height at the specific depth is can be calculated.

These calculations are done for each profile, such that at the seaward end of each profile the proper wave climate can be imposed.

DIFFRACTION

In the shadow zone of the East Mole, the wave climate is changed, due to diffraction of the waves along the tip of the East Mole. Kamphuis (1992)[36] presented a simple theory to adjust the wave climate, in order to take the diffraction effects into account. So, firstly the wave climate is propagated from the offshore 30 m depth location to the seaward end of the profiles, such that refraction and shoaling are accounted for. This provides four slightly different wave climates, as the depth of the seaward end of the profiles differs a little. Then, secondly, the Kamphuis (1992) method is applied to adjust the wave climates due to diffraction.

The wave climates are calculated per profile, at a location 500 m off the coastline, as shown in Figure 4-4.

The diffracted wave height is calculated via:

$$H_d = K_d \cdot H_i$$

Where H_d is the diffracted wave height [m], K_d is the diffraction coefficient [-] and H_i is the incident wave height [m], in which refraction and shoaling have been taken into account (as calculated in the previous section).

Depending on the wave angle of incidence, three different expressions for K_d are presented:

$$K_d = 0.69 + 0.008\theta \qquad \text{for } 0° \geq \theta \geq -90°$$

$$K_d = 0.71 + 0.37\sin\theta \qquad \text{for } 40° \geq \theta \geq 0°$$

$$K_d = 0.83 + 0.17\sin\theta \qquad \text{for } 90° \geq \theta \geq 40°$$

Where θ is the angle between the straight line between the point of interest and the diffraction point (i.e. the tip of the East Mole), α_d, and the incident wave direction, α_i [°]. In Figure 0-24 a schematisation of the parameters is presented.

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[36] Quoted in an appendix of (WL|Delft Hydraulics, 1998). Kamphuis, J.W. (1992) Computation of coastal morphology, ICCE 1992, Venice, Italy

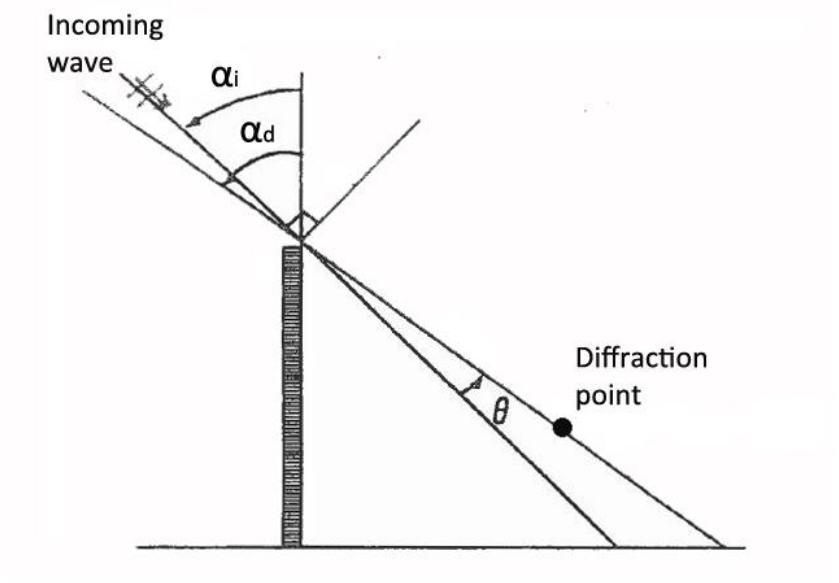


Figure 0-24: Definition of parameters used by Kamphuis (1992)

MEAN WAVE ANGLE OF INCIDENCE

Using the data presented in Table D-4, the mean angle of wave incidence is approximated, while taking into account the probability of occurrence. The directions are multiplied by their probability of occurrence, and subsequently the sum of these values is divided by the total sum of the probabilities of occurrence.

The dominant wave has a direction of 188°. This value is used in, among others, the calculations done with the 'single line theory'.

E UNIBEST MODEL RESULTS

E.1 REVIEW OF CONCEPTUAL MODEL

The output of the Unibest model is used to check the assumptions and calculations applied in the setup of the conceptual model. The assumption that is checked first, is what part of the total accretion (or erosion) volume is covered by the data from Figure 3-3. The assumption made for the period 1910 – 1960 is repeated in Figure 0-25:

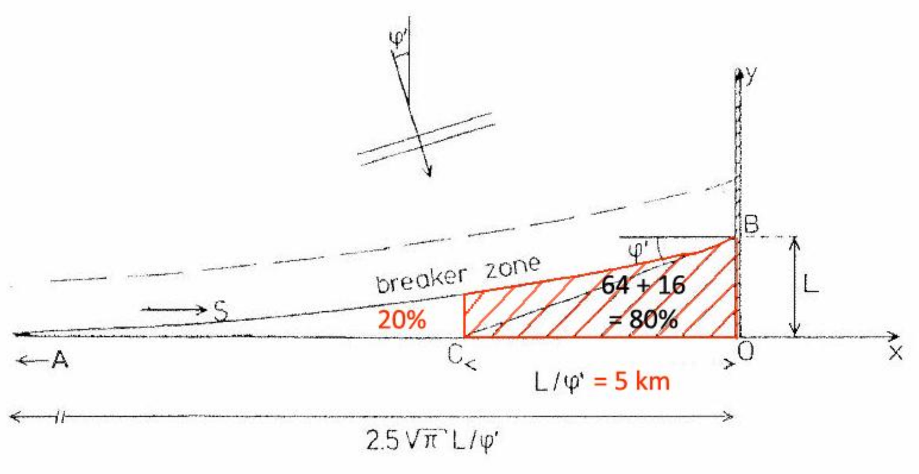


Figure 0-25: Division in accreted volumes, after 50 years [equal to Figure 0-13]

The output of the Unibest model is compared to this figure in Figure 0-26, where also the length 'OC' (i.e. 5 km) and the area covered by the literature data are shown.

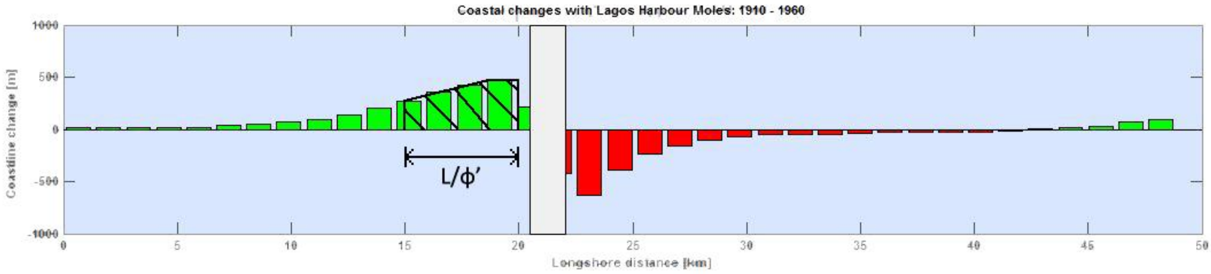


Figure 0-26: Output of Unibest model for 1910 – 1960 for comparison to Figure 0-25

The volume of accretion located in the marked area in Figure 0-26 is roughly 20 million m³, which is approximately 55 per cent of the total volume of accretion over this time span (i.e. 36.1 million m³). So according to the Unibest output, the literature data of 18 million m³ do not cover about 80 per cent, but only 55 per cent. Then the total volume of accretion obtained from the literature data (i.e. Figure 3-3) does match quite reasonably to the Unibest data: 18/0.55 = 33 million m³.

The analysis of the period 1960 – 2010 is made likewise and depicted in Figure 0-27.

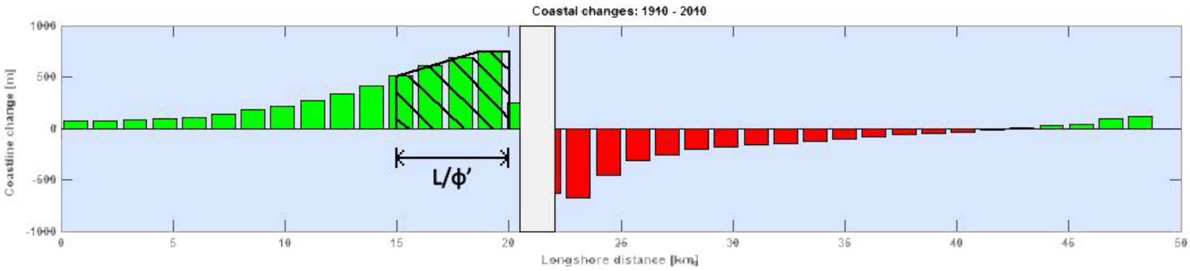


Figure 0-27: Output of Unibest model for 1910 – 2010

The accreted volume located in the marked area is about 36 million m³, meaning the volume accreted between 1960 and 2010 is about 16 million m³. In this period the total accretion volume is about 34.1 million m³, thus the marked area represents circa 45 per cent of the total volume.

The volume of the marked area found in the conceptual model is 13.4 million m³. If this represents about 45 per cent of the total volume (as found via the Unibest results), the total volume is about 13.4/0.45 = circa 30 million m³. Again, this value matches quite well to the Unibest data.

Above analysis of the assumptions underlying the conceptual model shows that with some reconsideration of the setup of the conceptual model, the values obtained by the conceptual model match reasonably well to the output of the Unibest model.

E.2 IMPACT OF LAGOS HARBOUR MOLES

The impact of the Lagos Harbour Moles is obtained by comparison of the coastal situation in 2010 with the moles to the hypothetical coastal situation in 2010 without the moles, see Figure 0-28.

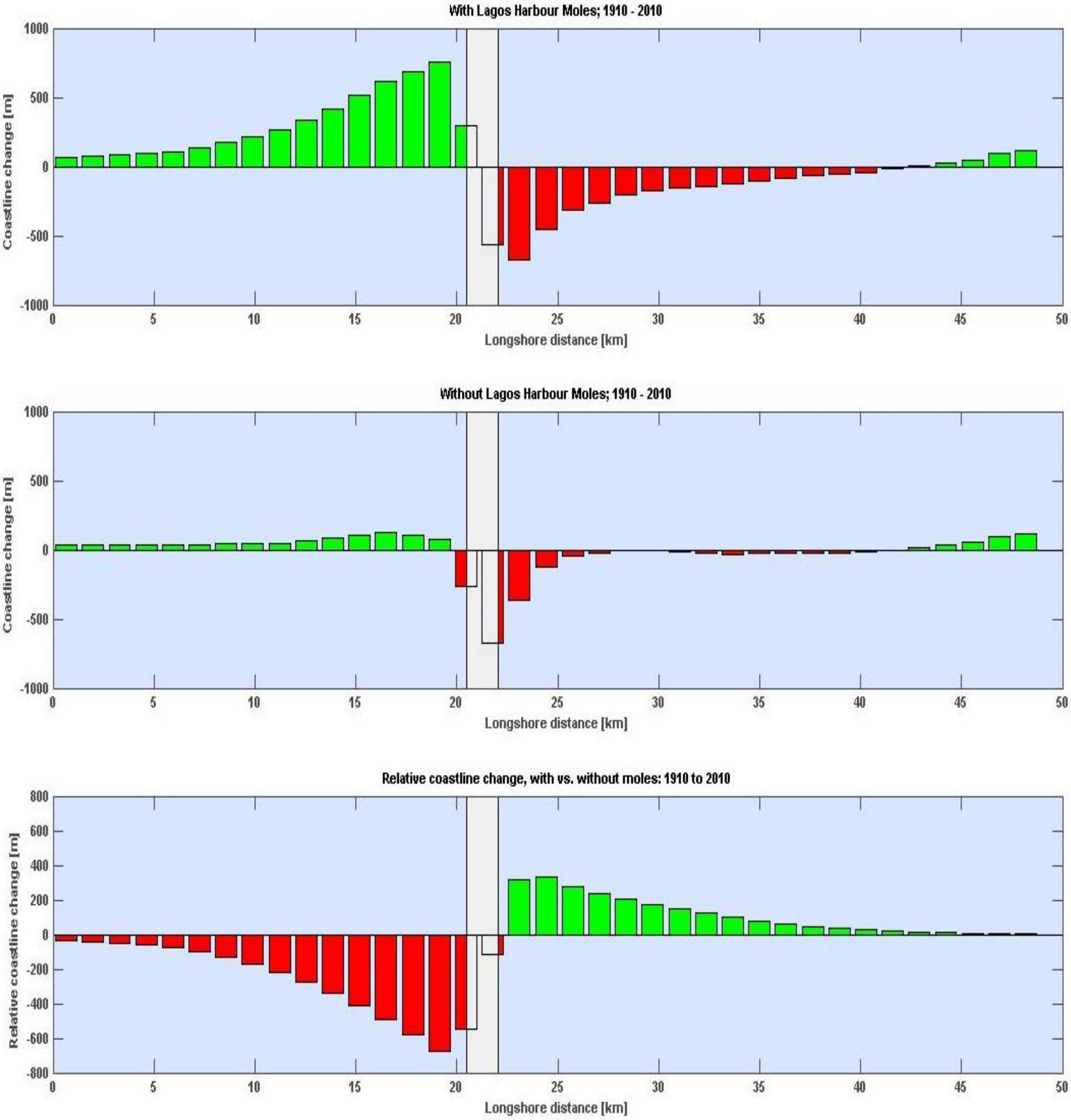


Figure 0-28: Above: absolute coastline change, between 1910 and 2010, for scenario with moles. Middle: absolute coastline change, between 1910 and 2010, for scenario without moles. Below: relative coastline change between both scenarios, between 1910 and 2010

E.3 INFLUENCE OF NOURISHMENTS

In Figure 0-29 the changes in coastline location, relative to the coastline location of 1910, for the scenario including the nourishments are depicted. And in Figure 0-30, the coastline changes, relative to the 1910 coastline, for the scenario without any nourishments can be seen.

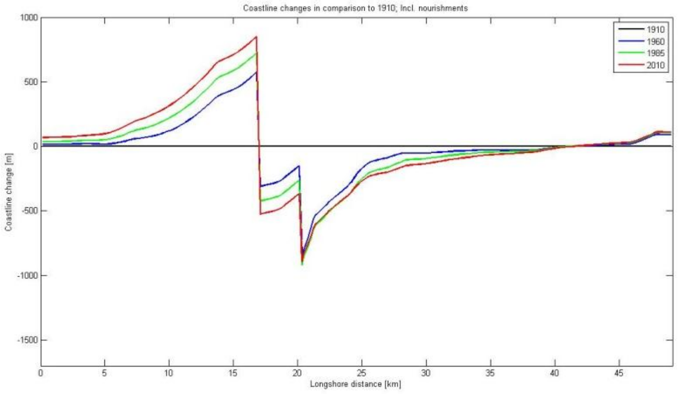


Figure 0-29: Coastline changes for scenario with nourishments, compared to the 1910 situation. Blue line represents 1960, the green line 1985 and the red line 2010

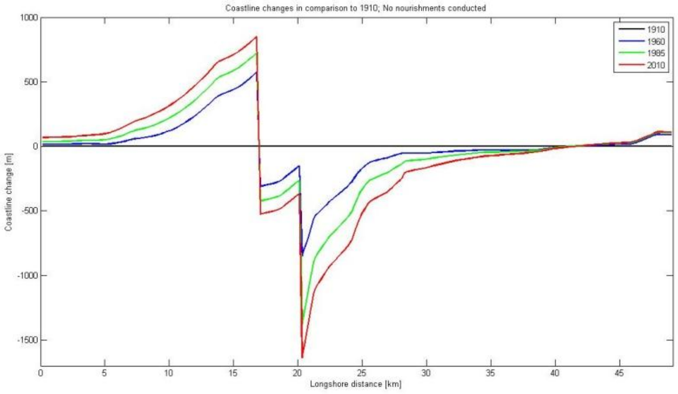


Figure 0-30: Coastline changes for scenario without nourishments, compared to the 1910 situation. Blue line represents 1960, the green line 1985 and the red line 2010

Consideration of these two figures clearly indicates the immense erosion rates if the nourishments would not have been conducted. Locally, just downdrift of the East Mole, the erosion rates would have almost doubled.

In Figure 0-31 the coastline changes of each scenario, compared to the coastline location of 1910, are depicted in the first figure and the second figure. The relative coastline change between the two scenarios is depicted in the last figure. The erosion rates are now averaged over the bar width, which is 1.32 km.

The accretion of the Lighthouse Beach is represented by the green (positive) bars, and the erosion of the Bar Beach is visible in the red (negative) bars. The inlet is schematised in the figures by the light grey surface. The western boundary of the model is positioned at longshore distance 0 km.

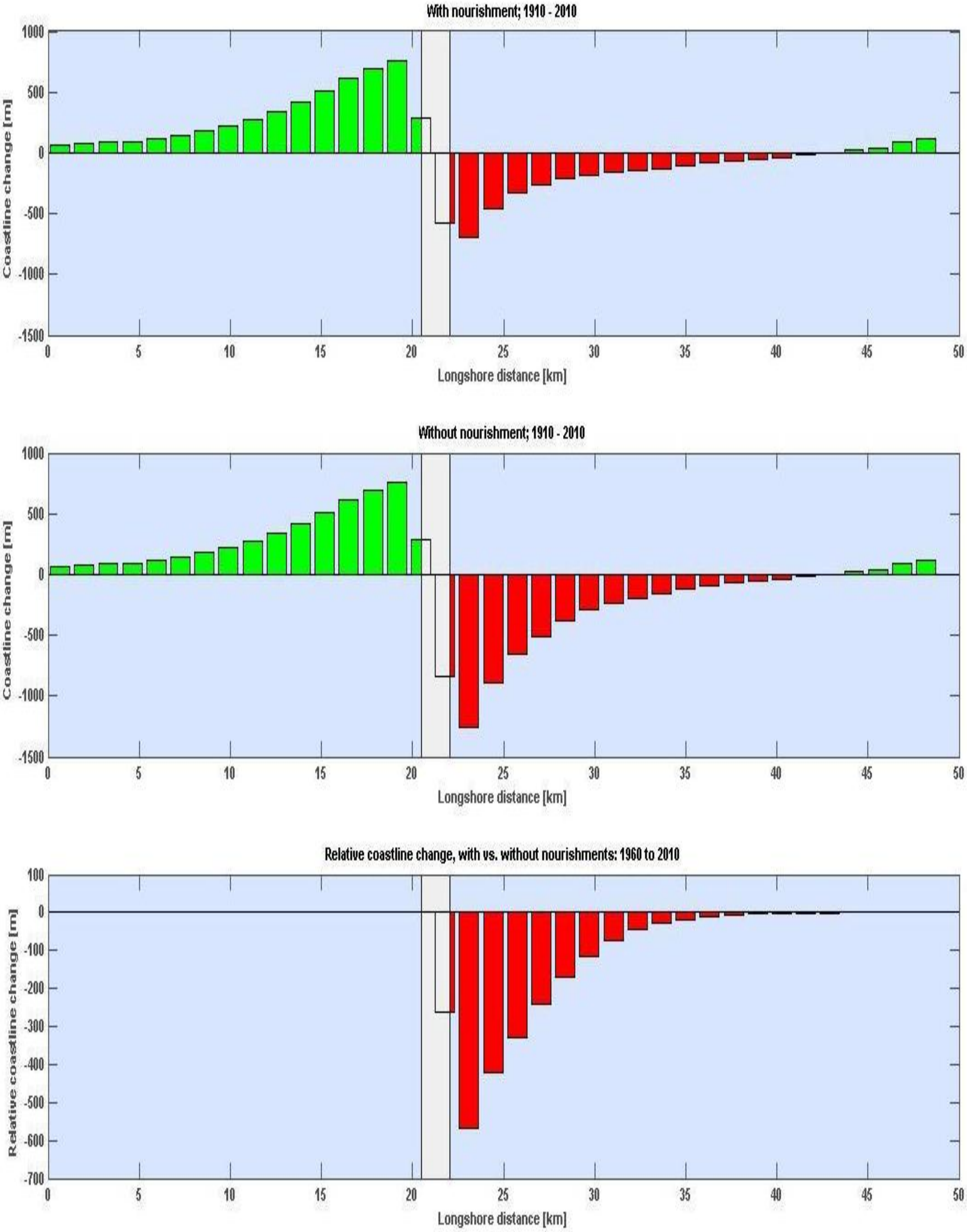


Figure 0-31: Above: absolute coastline change, between 1910 and 2010, for scenario with nourishments. Middle: absolute coastline change, between 1910 and 2010, for scenario without nourishments. Below: relative coastline change between both scenarios, between 1960 and 2010

E.4 IMPACT OF LAND RECLAMATION

Using Figure 0-32, the additional erosion rates and volume due to the land reclamation, accompanied by dredging of large sediment volumes, in the Lagos Lagoon.

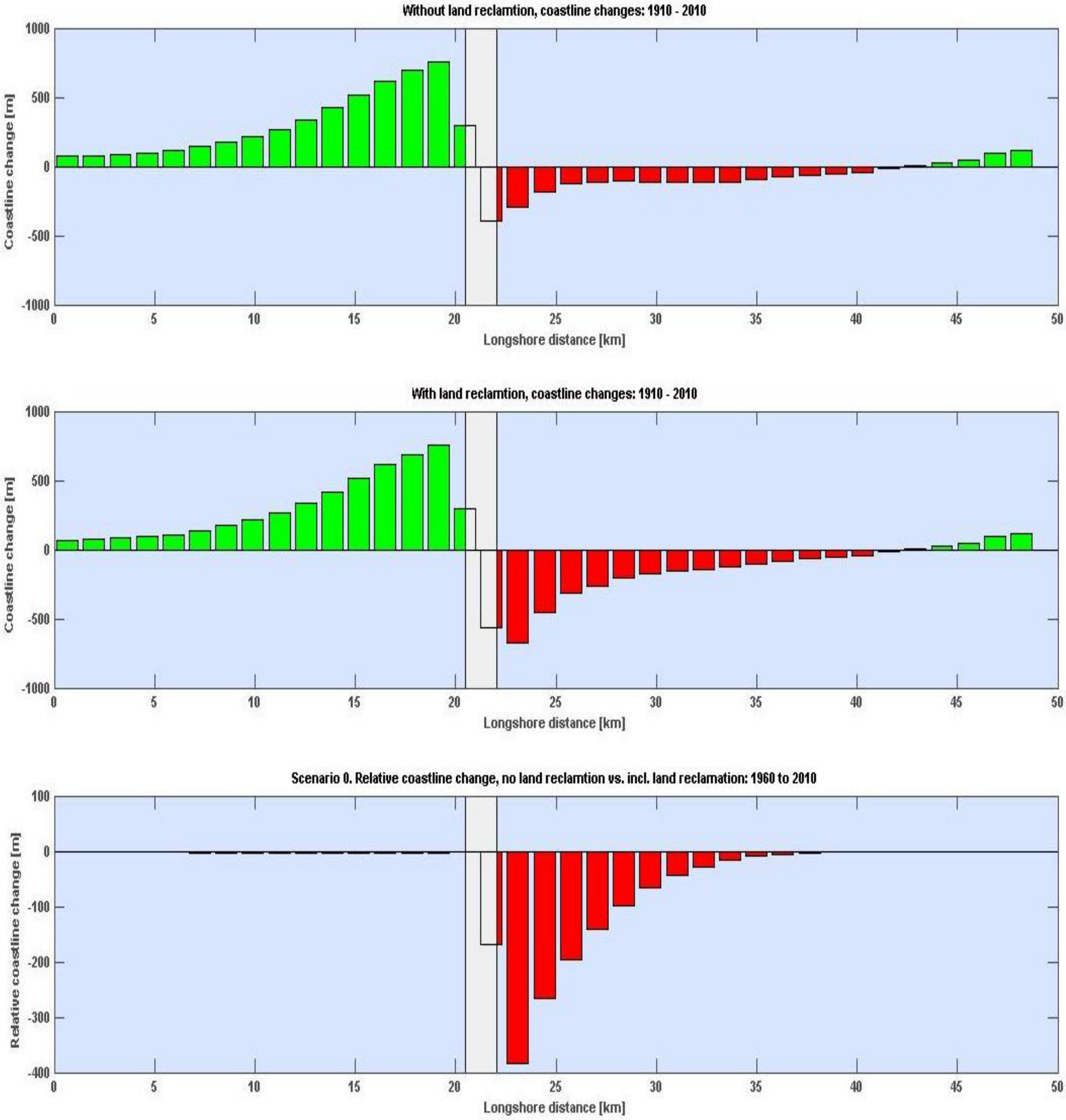


Figure 0-32: Above: absolute coastline change, between 1910 and 2010, for scenario without land reclamation. Middle: absolute coastline change, between 1910 and 2010, for scenario with land reclamation. Below: relative coastline change between both scenarios, between 1960 and 2010

E.5 OUTPUT UNIBEST RESULTS 1910 – 2010

In the following appendices the output plots of every model run is depicted. The same approach as in section 5.1 is applied: first the relative impact of the human intervention that is analysed, is investigated. This means that the coastal situation in the output year of the model runs (i.e. in most of the runs the year 2020) with the human intervention (i.e. in most of the runs Eko Atlantic City project) is compared to the output of the model run without the intervention, in the same output year.

And secondly, the absolute impact of the intervention is investigated. Thus, the differences between the coastline in 2010 and the coastline in the output year (i.e. in most of the runs the year 2020) are considered. This means that in the investigation of the absolute impact, the output of every model run is compared to the same coastal situation: namely the 2010 coastal situation; and this situation is the same for every scenario, as the differences are in the period 'After 2010'.

Therefore, the absolute changes of the coastline between 1910 and 2010 are depicted once in this section in Figure 0-33 and not in every following appendix. By doing this, it is tried to prevent a repetition of similar figures.

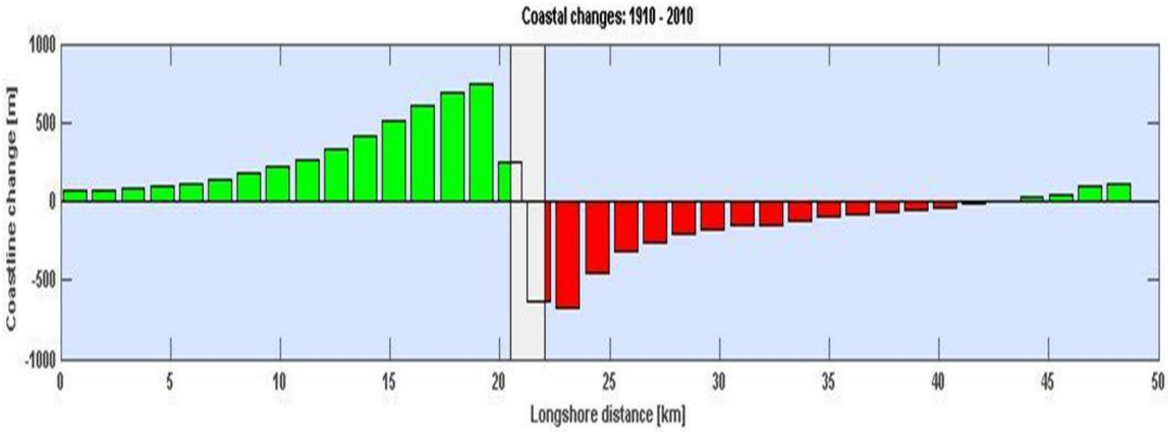


Figure 0-33: Absolute coastal changes between 1910 and 2010

Concluding, the investigation of the absolute coastal changes in the Unibest model runs is made by comparison of the coastal situation in the output year of the model runs to the coastal situation in 2010 (depicted in Figure 0-33).

E.6 SCENARIO 0

The lowest figure of Figure 0-34 shows the location and value of the maximum erosion rate in 2010 - 2020, without Eko Atlantic City.

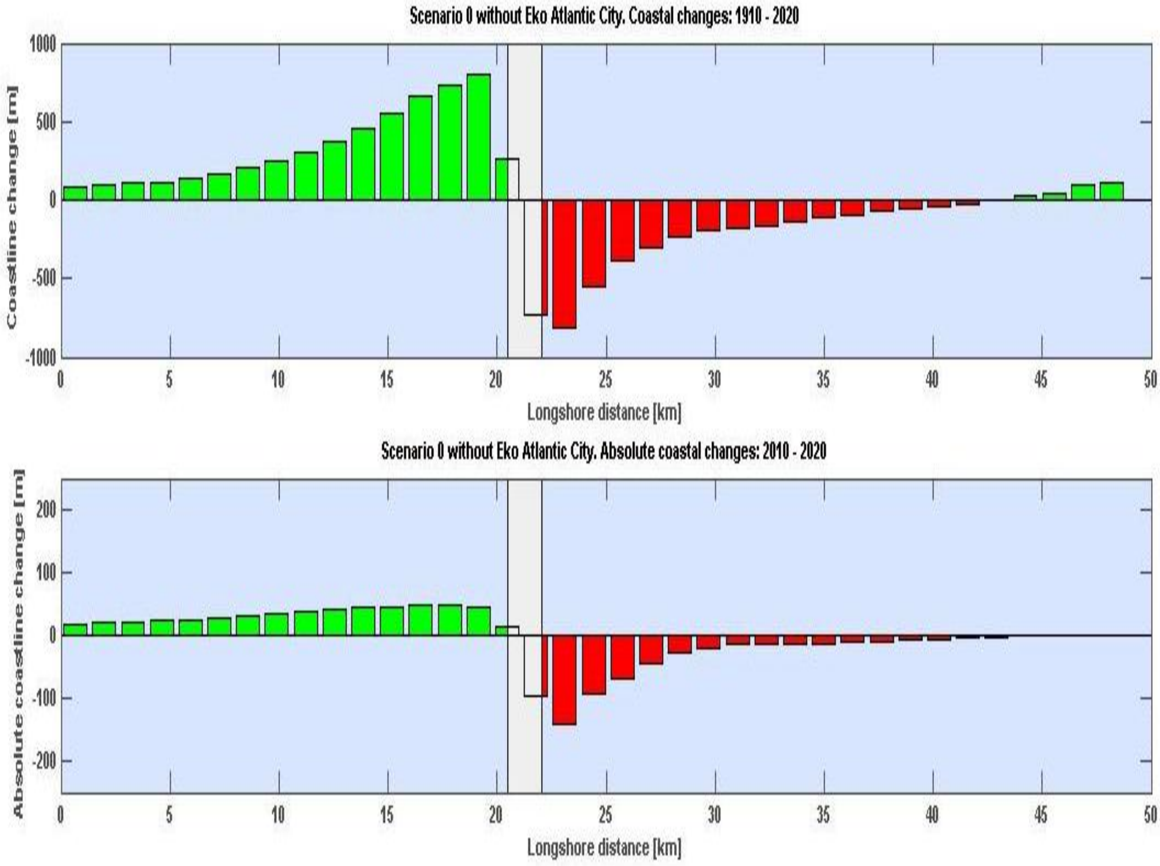


Figure 0-34: Above: absolute coastline change, between 1910 and 2020, for scenario 0 with Eko Atlantic City. Below: absolute coastline change in scenario 0, between 2010 and 2020, without Eko Atlantic City present

E.7 SCENARIO 1

In Figure 0-35 the coastline position in 2020 is depicted, for both the scenario 1 runs with and without Eko Atlantic City. The 2020 coastline without Eko Atlantic City present is shown in yellow, while the red line represents the 2020 coastline if the revetment is constructed.

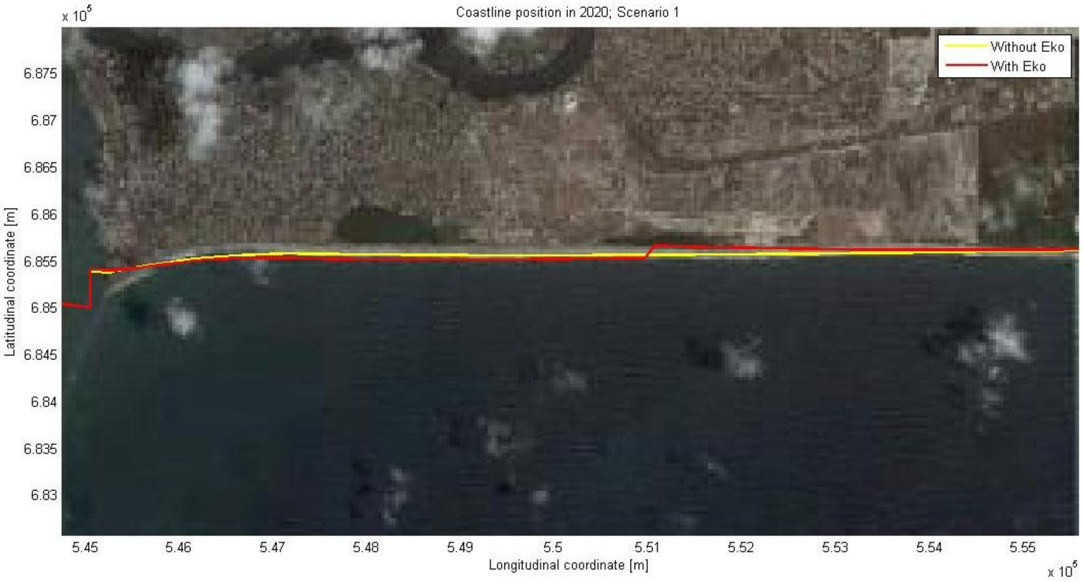


Figure 0-35: Coastline in 2020, for scenario 1. In yellow is the result of the model run without Eko Atlantic City, and in red with the land reclamation constructed

The coastline changes, relative to the 1910 coastline, per model run for scenario 1 are depicted in Figure 0-36. In the upper figure, the coastline changes between 1910 and 2020 are shown for the scenario 1 without Eko Atlantic City. The middle figure depicts the coastline changes for the same time span, but now with the Eko Atlantic City project present. The lowest figure represents the relative coastline differences, between the two runs made for scenario 1, in 2020.

The absolute coastline changes are investigated with help of Figure 0-37. The coastline changes between 1910 and 2020, with presence of Eko Atlantic City, are shown in the above figure. The second figure represents the absolute values of accretion and erosion, from 2010 to 2020. In Figure 0-38, the same parameters are depicted for the situation without Eko Atlantic City present.

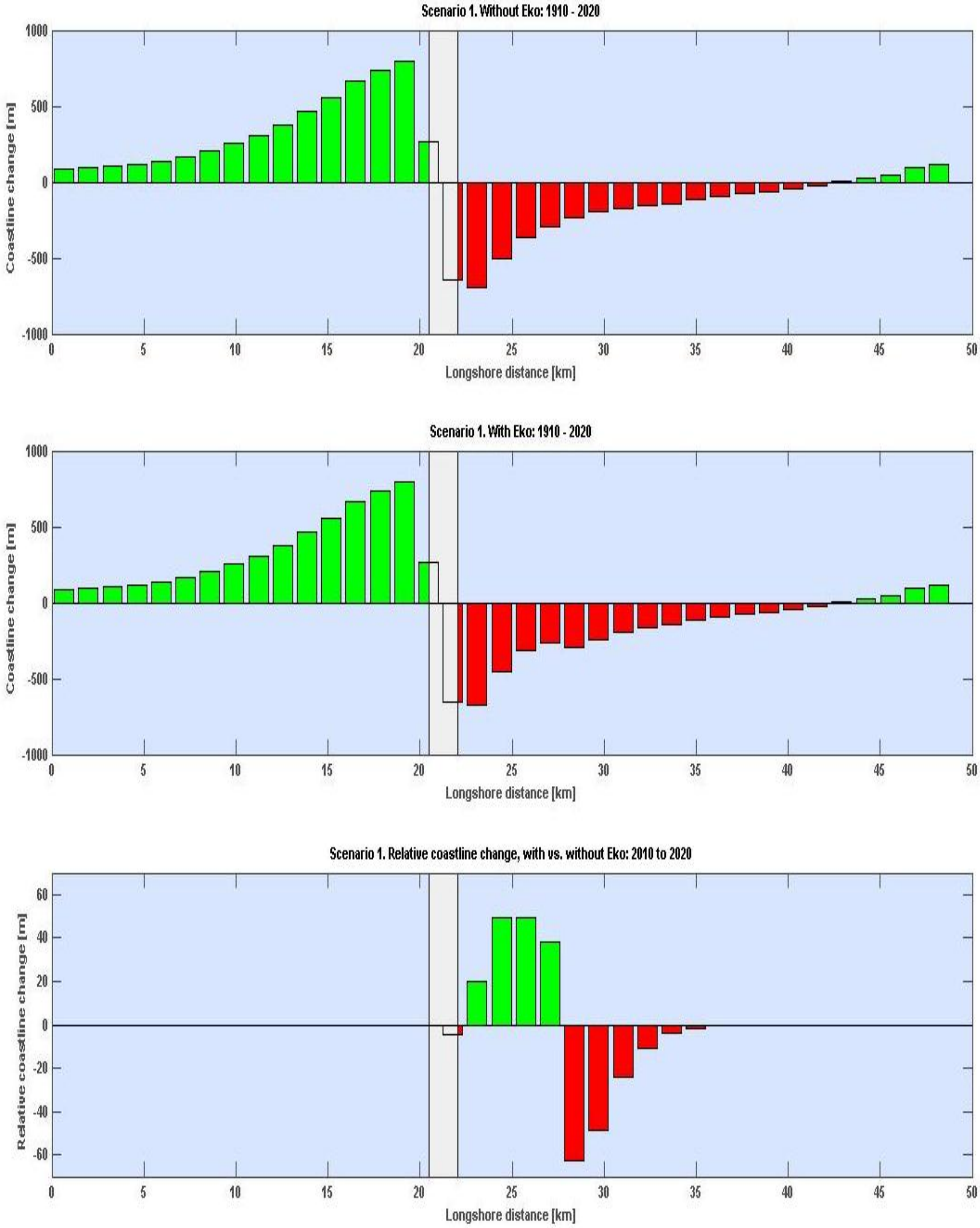


Figure 0-36: Above: absolute coastline change, between 1910 and 2020, for scenario 1 without Eko Atlantic City. Middle: absolute coastline change, between 1910 and 2020, for scenario 1 with Eko Atlantic City. Below: relative coastline change between both scenarios, between 2010 and 2020

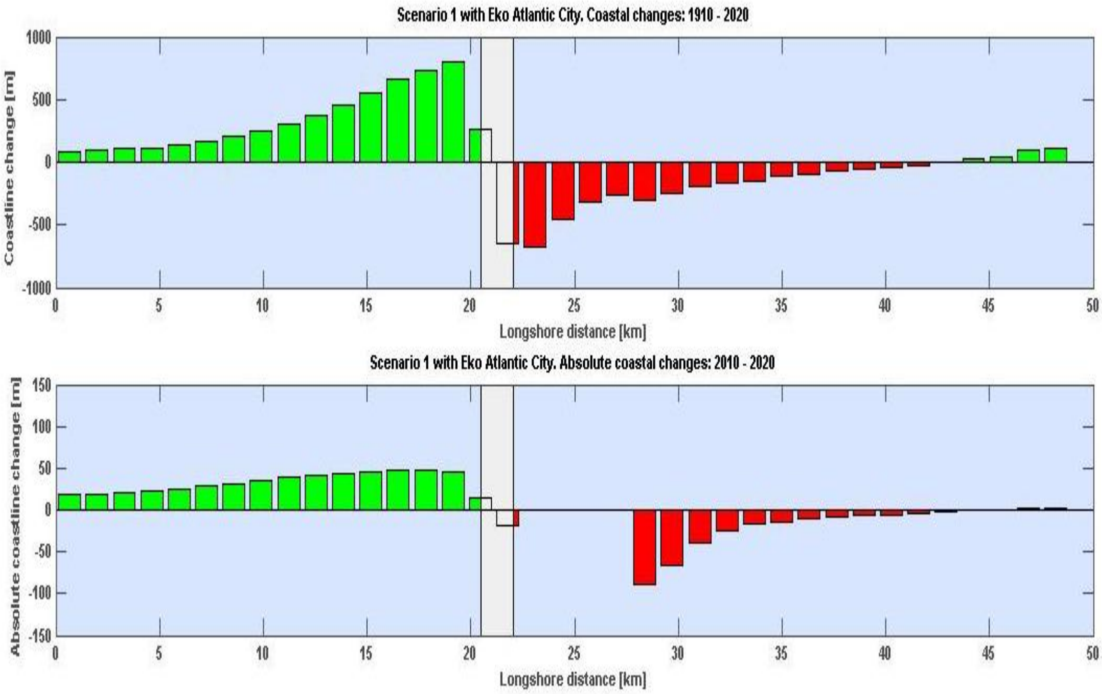


Figure 0-37: Above: absolute coastline change, between 1910 and 2020, for scenario 1 with Eko Atlantic City. Below: absolute coastline change in scenario 1, between 2010 and 2020, with Eko Atlantic City present

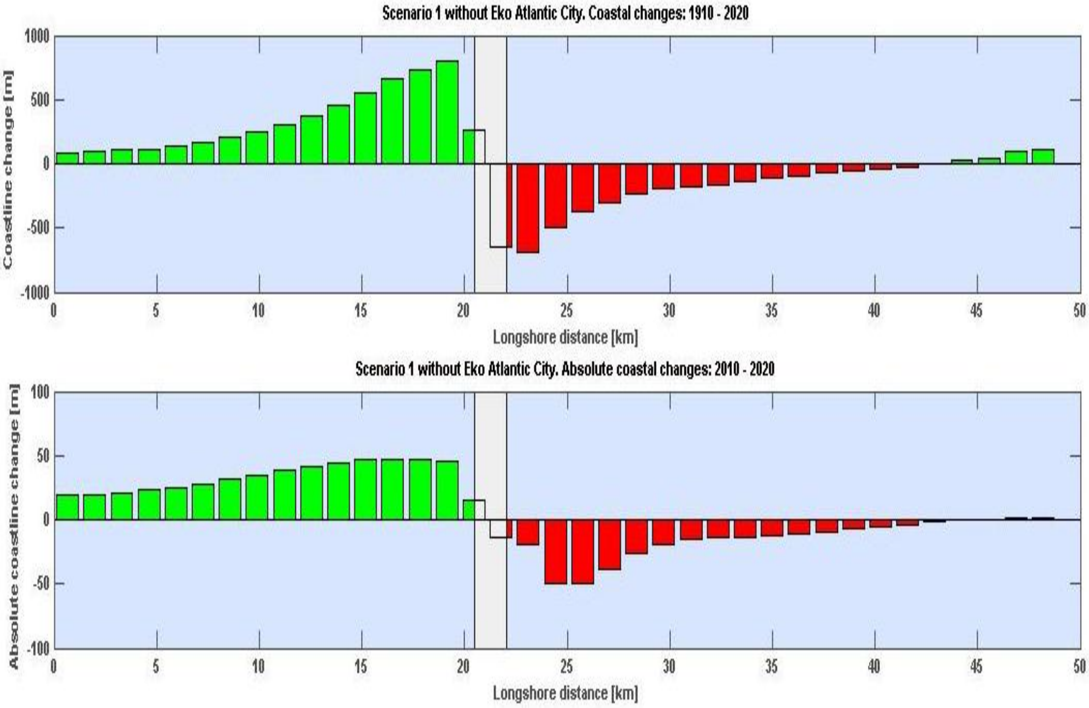


Figure 0-38: Above: absolute coastline change, between 1910 and 2020, for scenario 1 without Eko Atlantic City. Below: absolute coastline change in scenario 1, between 2010 and 2020, without Eko Atlantic City present

E.8 SCENARIO 2

In Figure 0-39 the yellow line represents the coastline in 2020 without the presence of Eko Atlantic City, and the red line depicts the coastline at the same moment, in the scenario in which Eko Atlantic City is present.

Figure 0-39: Coastline in 2020, for scenario 2. In yellow is the result of the model run without Eko Atlantic City, and in red with the land reclamation constructed

In Figure 0-40 the relative changes between the two model runs of scenario 2 in 2020 are depicted in the lowest figure. The change in coastline position in 2020 for scenario 2, relative to the 1910 coastline is depicted in the upper two figures. The top figure represents the scenario without the land reclamation, and the middle figure shows the scenario with the presence of Eko Atlantic City.

In Figure 0-41 and Figure 0-42 the accretion and erosion between 1910 and 2020 are depicted in the upper figure, for the model run with the presence of Eko Atlantic City (Figure 0-41) or without the project (Figure 0-42). Subsequently, the absolute rates of erosion and accretion between 2010 and 2020 are shown in the lowest figures.

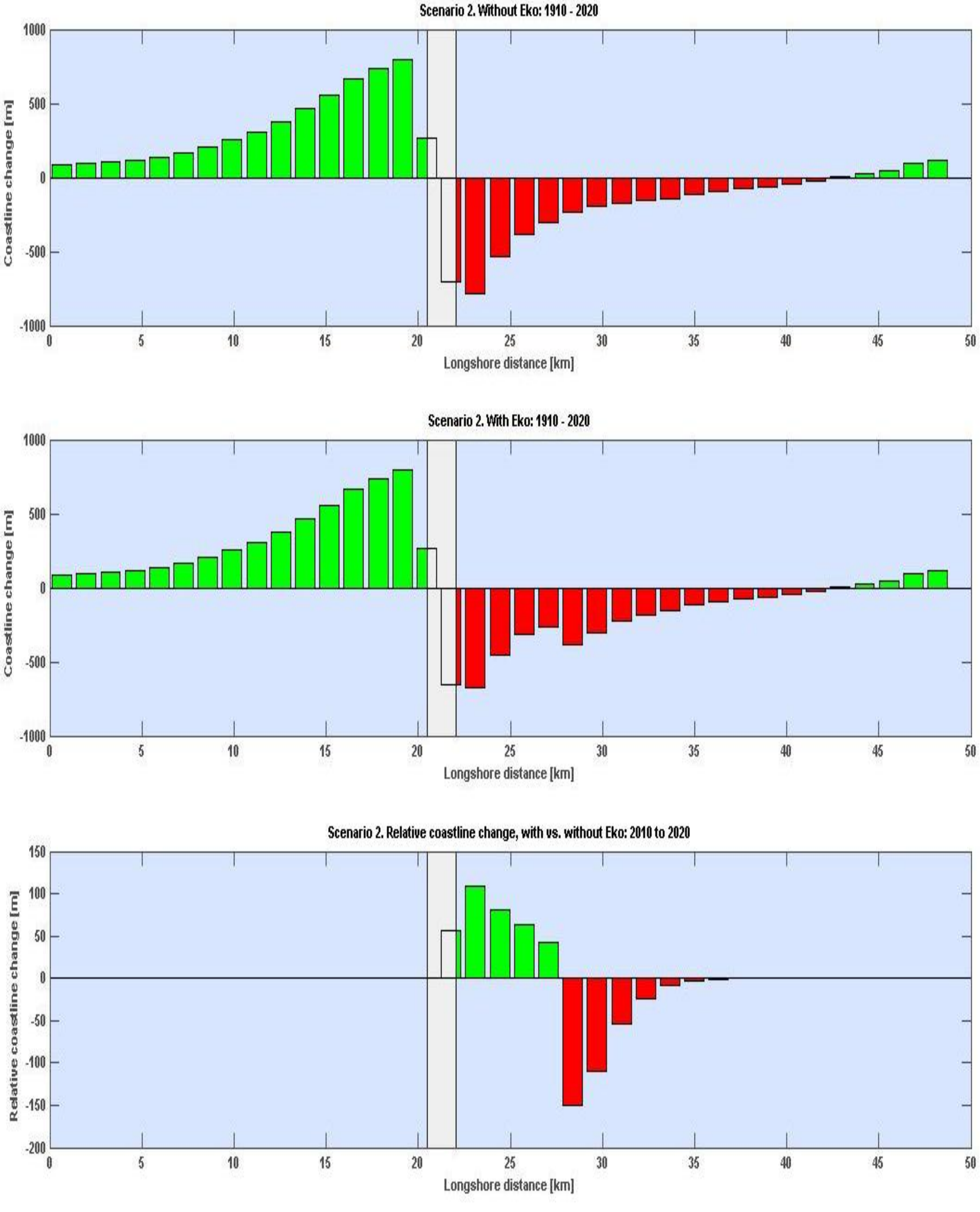


Figure 0-40: Above: absolute coastline change, between 1910 and 2020, for scenario 2 without Eko Atlantic City. Middle: absolute coastline change, between 1910 and 2020, for scenario 2 with Eko Atlantic City. Below: relative coastline change between both scenarios, between 2010 and 2020

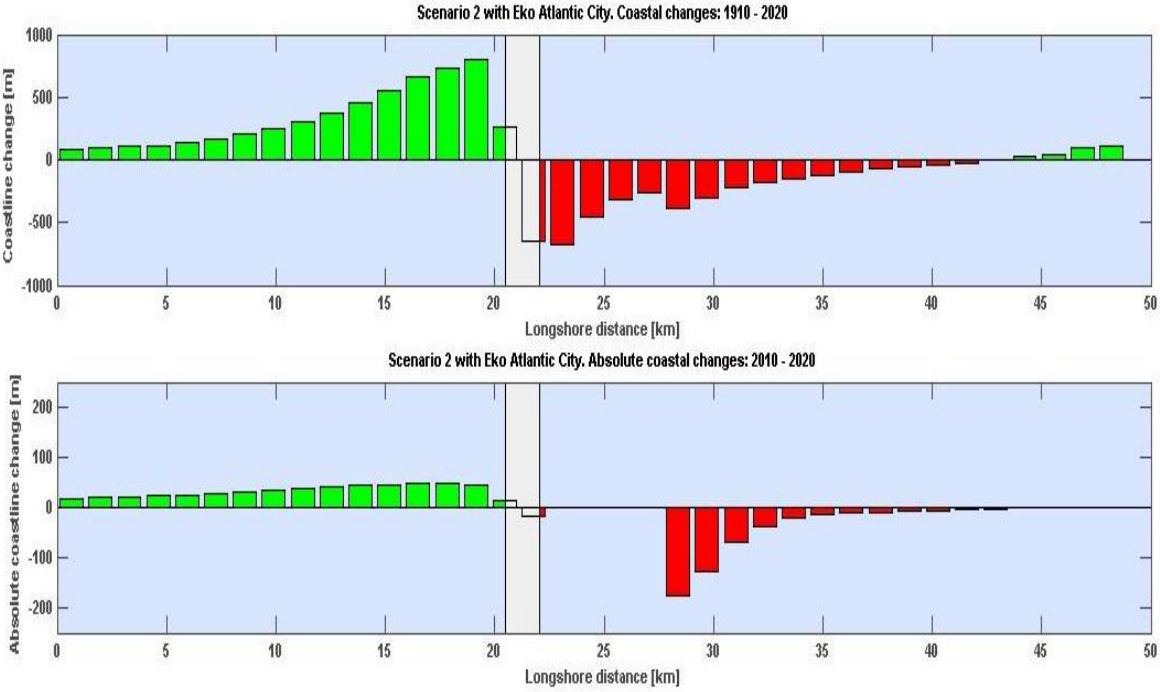


Figure 0-41: Above: absolute coastline change, between 1910 and 2020, for scenario 0 with Eko Atlantic City. Below: absolute coastline change in scenario 2, between 2010 and 2020, with Eko Atlantic City present

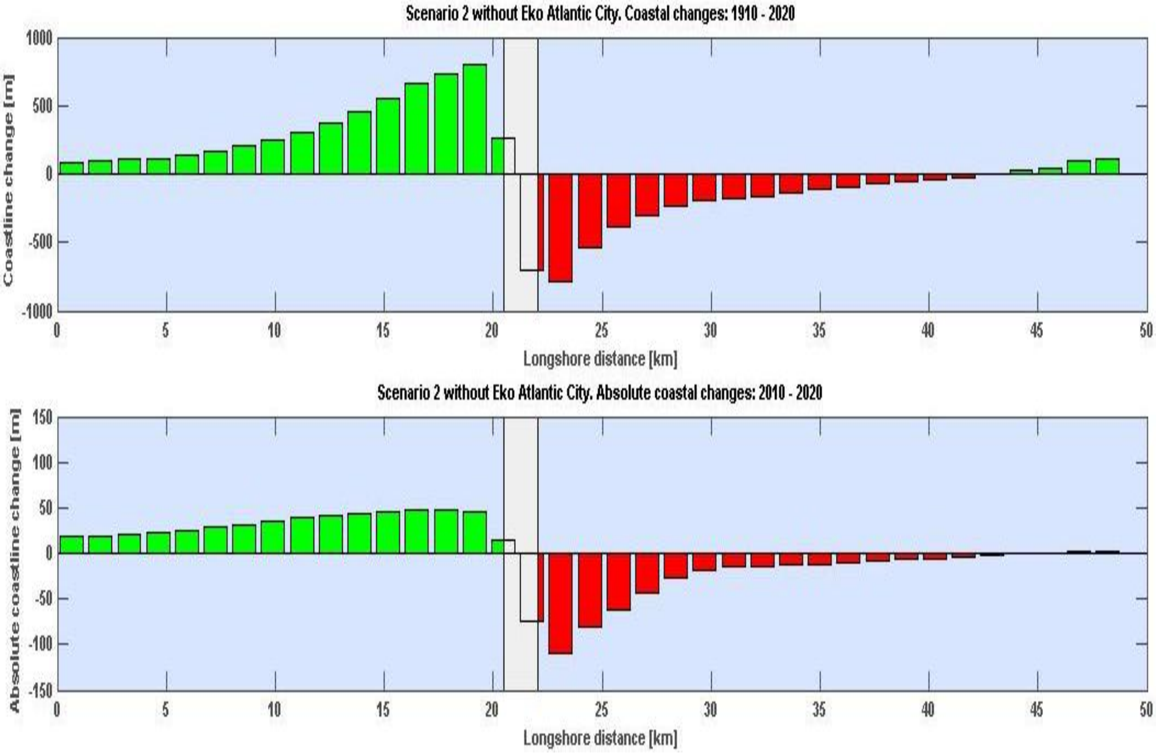


Figure 0-42: Above: absolute coastline change, between 1910 and 2020, for scenario 2 without Eko Atlantic City. Below: absolute coastline change in scenario 2, between 2010 and 2020, without Eko Atlantic City present

E.9 SCENARIO 3

Figure 0-43 presents the coastline position in 2020, for both models runs of scenario 3. Depicted in yellow is the coastline position if no revetment is present, and the red line represents the simulated coastline location if the Eko Atlantic City project is constructed.

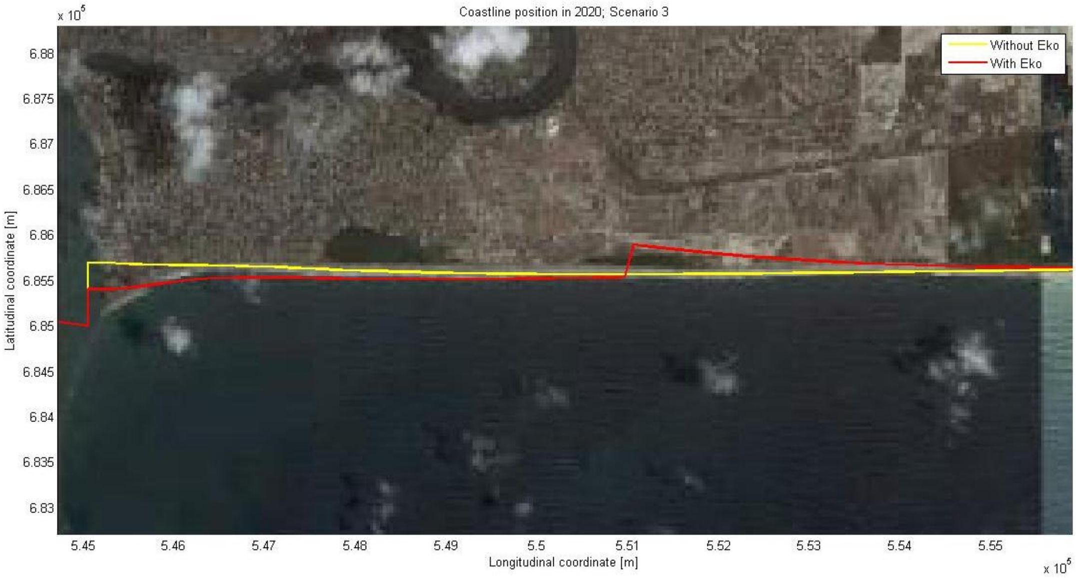


Figure 0-43: Coastline in 2020, for scenario 3. In yellow is the result of the model run without Eko Atlantic City, and in red with the land reclamation constructed

Depicted in the upper figure in Figure 0-44 is the change in coastline position in 2020, compared to the 1910 coastline, for the scenario 3 model run without the presence of Eko Atlantic City. The middle figure represents the same output for the scenario 3 model run once Eko Atlantic City is constructed. Just as at the other scenarios, the last figure shows the relative differences between the two model runs made for scenario 3 in 2020.

The top figures in Figure 0-45 and Figure 0-46 depict the coastal changes for the time span 1910 – 2020, with the presence of Eko Atlantic City (Figure 0-45) or without the revetment (Figure 0-46). The lowest figure depicts the absolute values of coastal changes between 2010 and 2020.

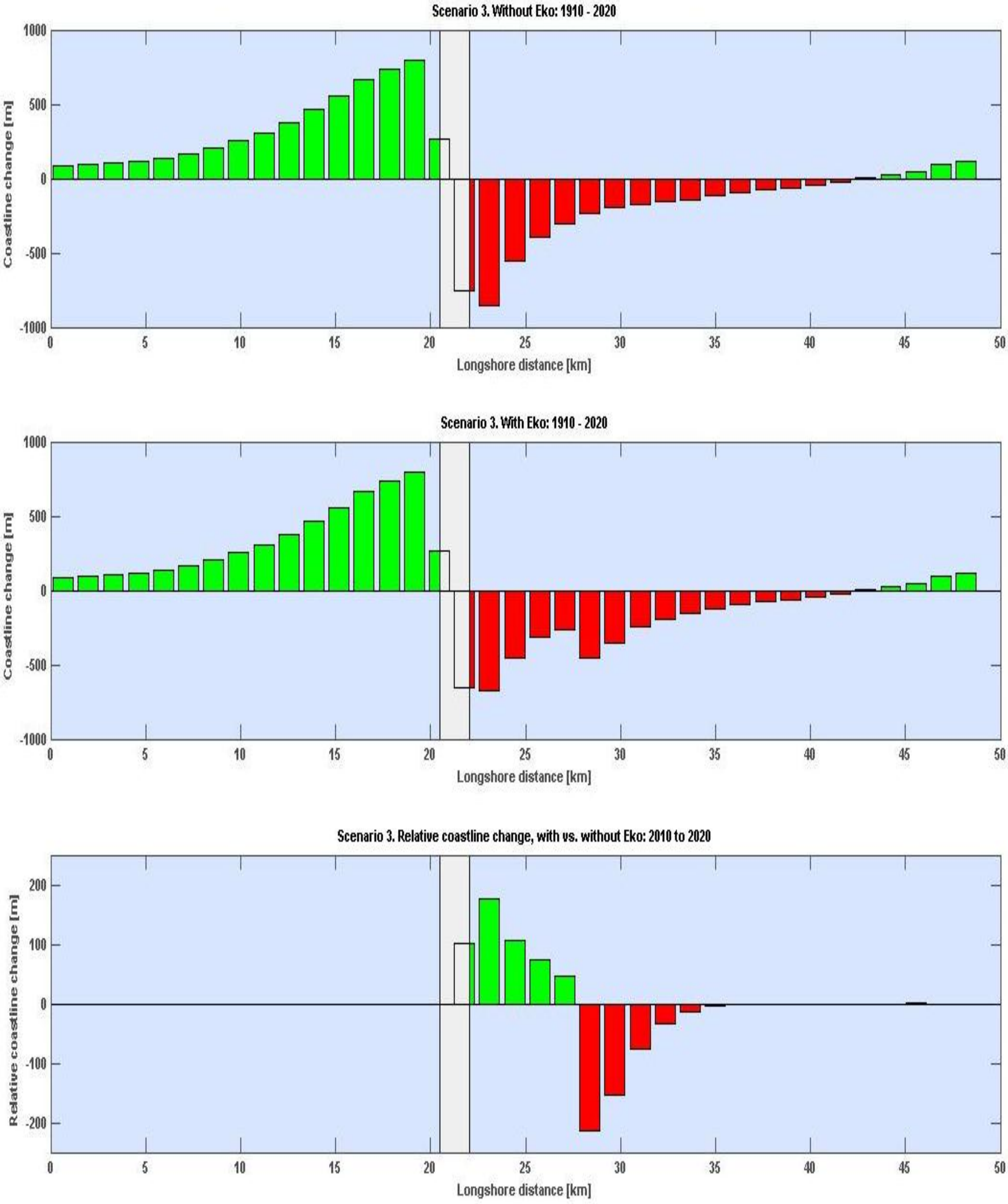


Figure 0-44: Above: absolute coastline change, between 1910 and 2020, for scenario 3 without Eko Atlantic City. Middle: absolute coastline change, between 1910 and 2020, for scenario 3 with Eko Atlantic City. Below: relative coastline change between both scenarios, between 2010 and 2020

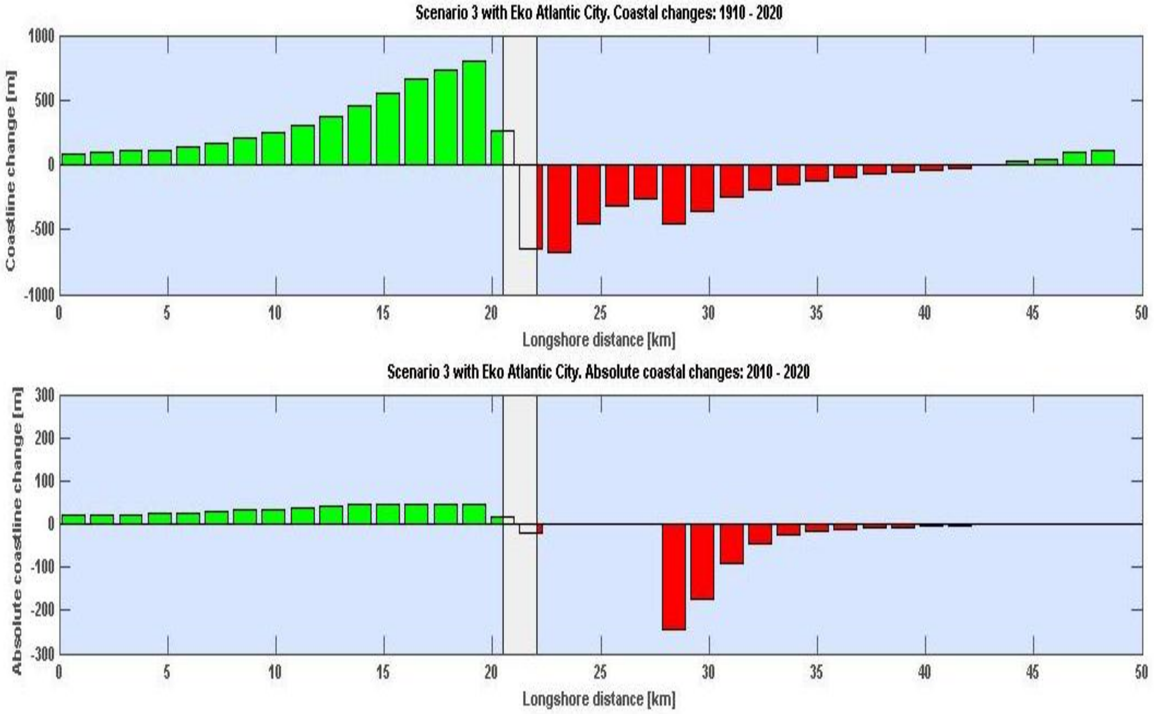


Figure 0-45: Above: absolute coastline change, between 1910 and 2020, for scenario 0 with Eko Atlantic City. Below: absolute coastline change in scenario 3, between 2010 and 2020, with Eko Atlantic City present

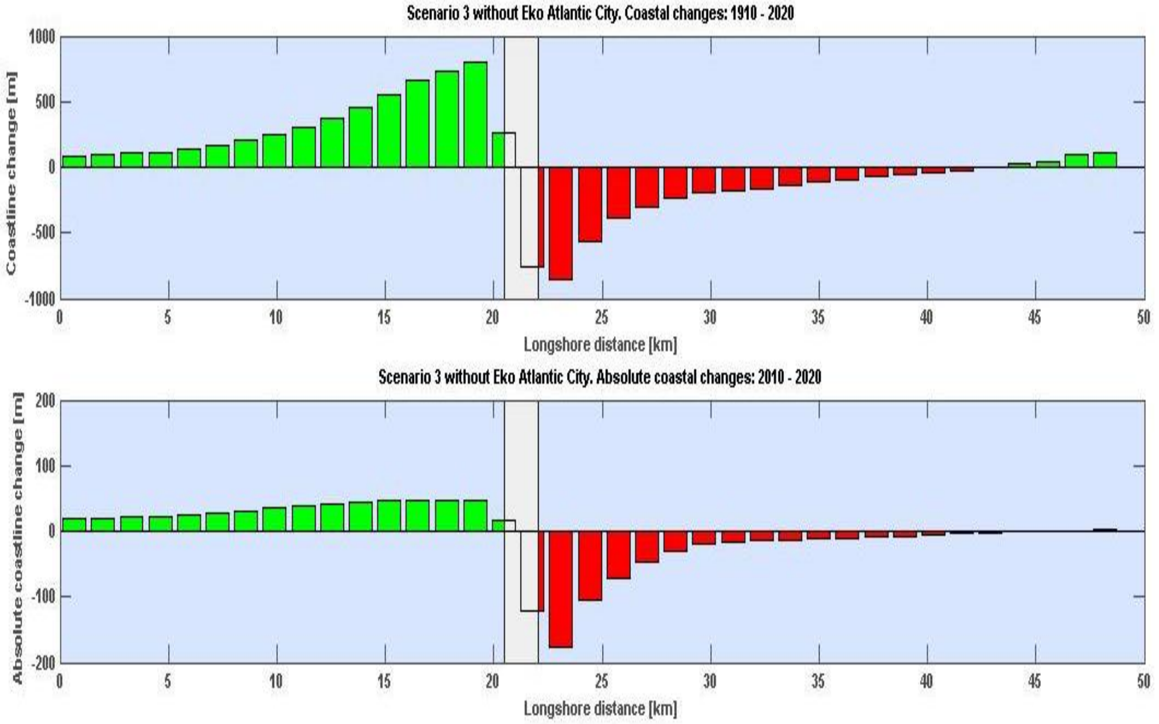


Figure 0-46: Above: absolute coastline change, between 1910 and 2020, for scenario 3 without Eko Atlantic City. Below: absolute coastline change in scenario 3, between 2010 and 2020, without Eko Atlantic City present

E.10 SCENARIO 4

The expected impact of the Eko Atlantic City land reclamation, after 10 years, on the downdrift coast can be seen in the layout of the red line in Figure 0-47. The yellow coastline represents the 2020 coast position if Eko Atlantic is not built. Comparison of the output for the coastal situation of 2020 from the two model runs made for this scenario provides the relative impact of the land reclamation.

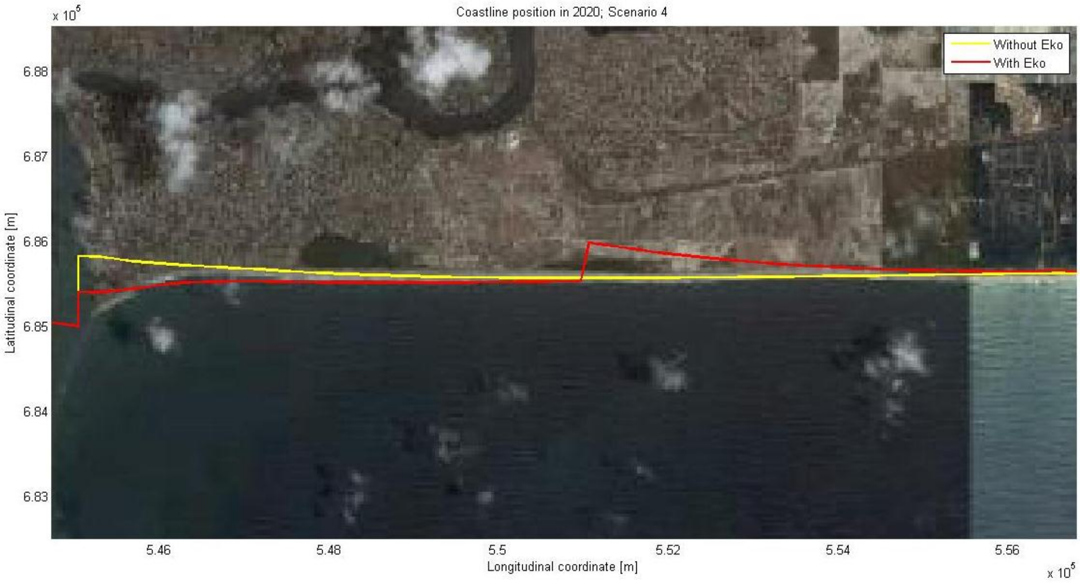


Figure 0-47: Coastline in 2020, for scenario 4. In yellow is the result of the model run without Eko Atlantic City, and in red with the land reclamation constructed

In Figure 0-48 the accretion and erosion between 1910 and 2020 are depicted for both runs made for scenario 4. The top figure depicts the output for the model run without Eko Atlantic City, and the middle figure shows the output if the revetment is constructed. In the third figure, the relative changes between both model runs are depicted.

Figure 0-49 depicts the absolute coastal changes between 1910 and 2020 for the scenario with Eko Atlantic City, represented in the upper figure. The lowest figure subsequently depicts the absolute accretion and erosion in the period 2010 – 2020. In Figure 0-50 similar plots are made, however, for the scenario 4 without Eko Atlantic City.

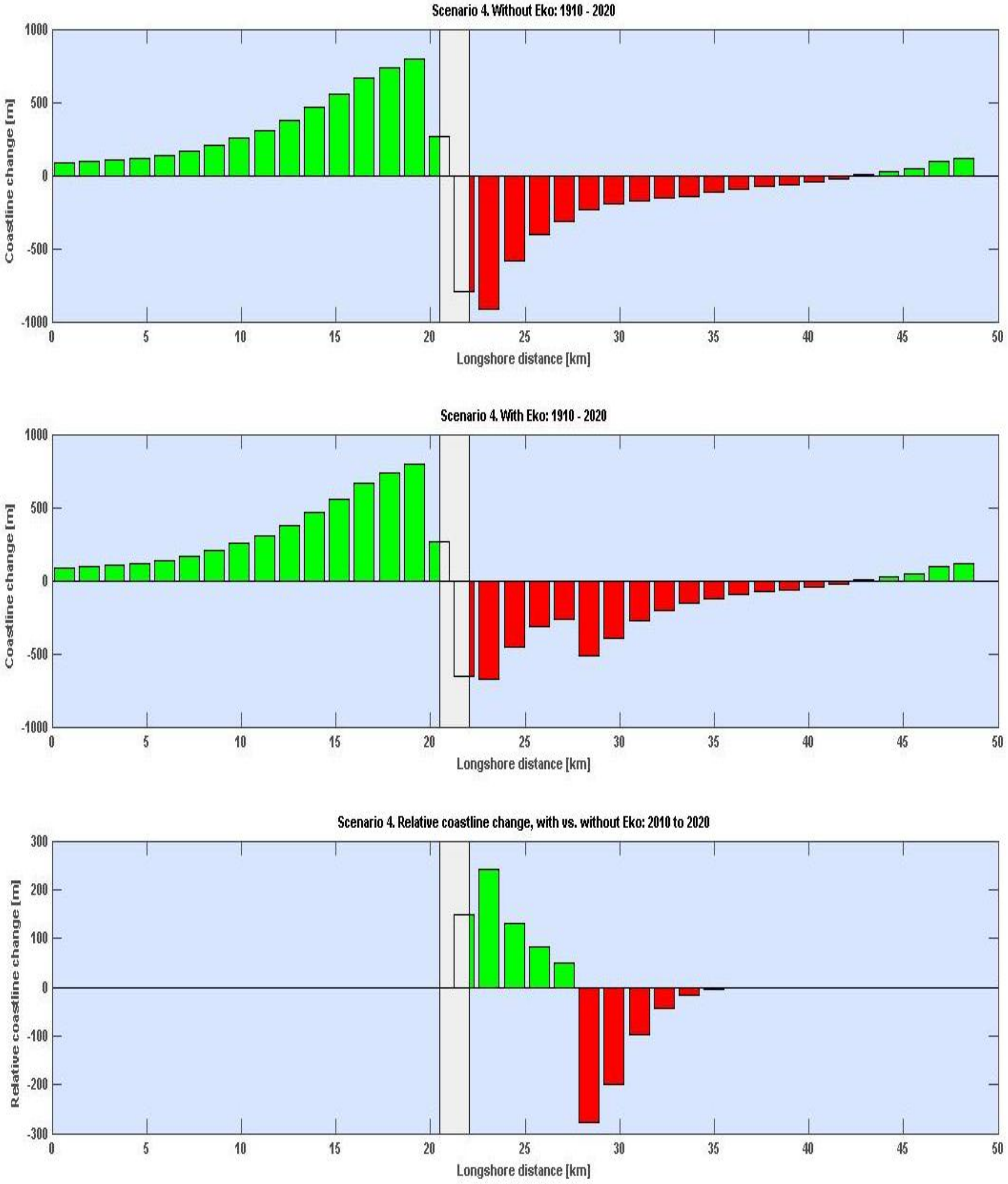


Figure 0-48: Above: absolute coastline change, between 1910 and 2020, for scenario 4 without Eko Atlantic City. Middle: absolute coastline change, between 1910 and 2020, for scenario 4 with Eko Atlantic City. Below: relative coastline change between both scenarios, between 2010 and 2020

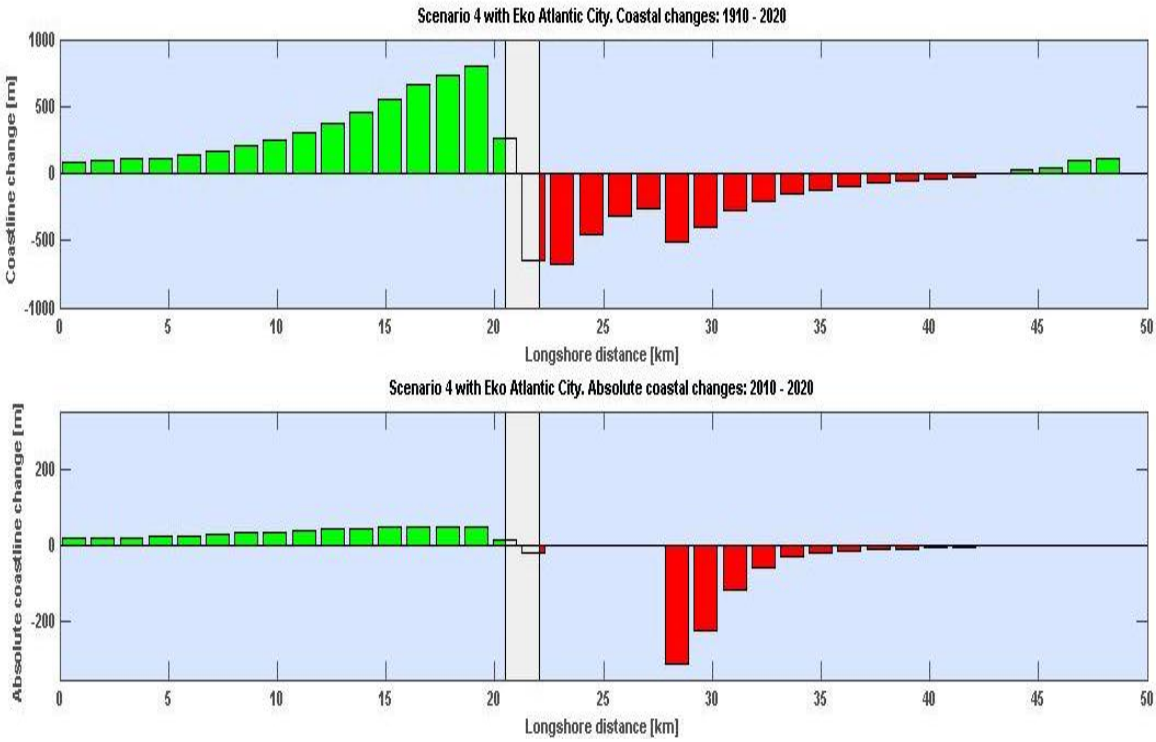


Figure 0-49: Above: absolute coastline change, between 1910 and 2020, for scenario 0 with Eko Atlantic City. Below: absolute coastline change in scenario 4, between 2010 and 2020, with Eko Atlantic City present

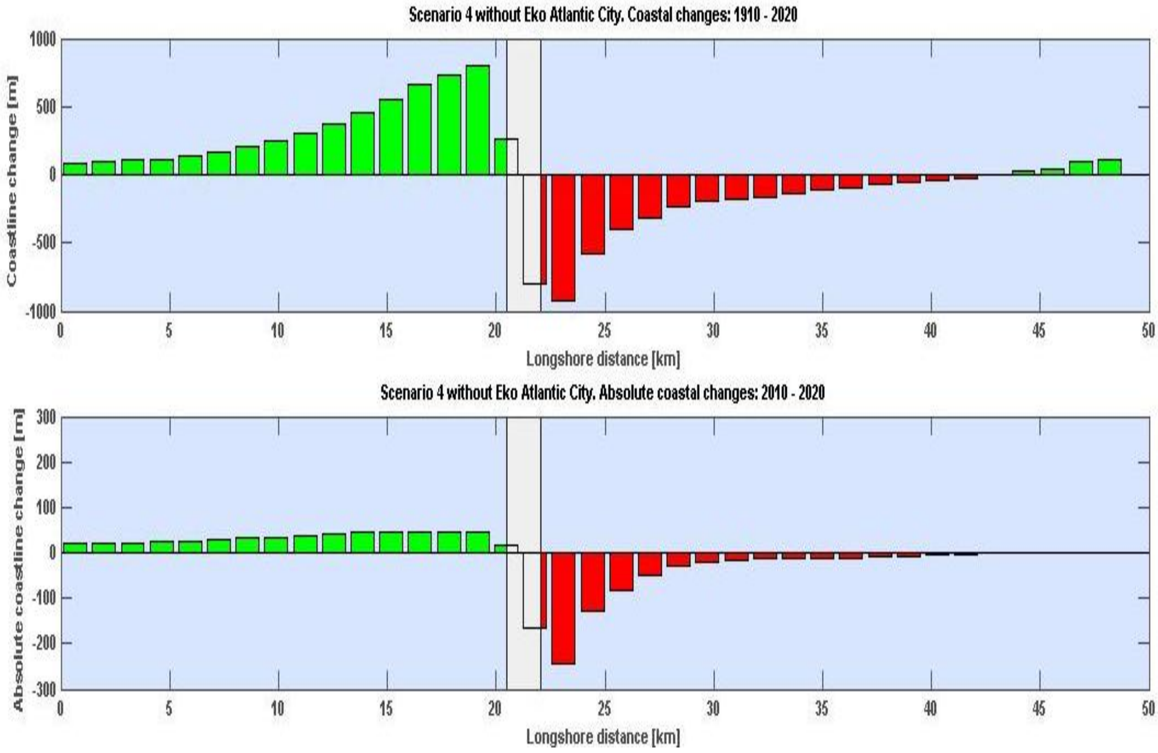


Figure 0-50: Above: absolute coastline change, between 1910 and 2020, for scenario 4 without Eko Atlantic City. Below: absolute coastline change in scenario 4, between 2010 and 2020, without Eko Atlantic City present

E.11 FUTURE DEVELOPMENT OF EROSION

In this section, the output for the extended scenario 0 runs is presented for the output years 2030, 2040, 2050 and 2060. Similar to the analysis presented in section 5.1, first the relative impact is depicted and thereafter, the absolute impact of the project is shown.

If the relative impact is considered, the differences between the scenario 0 with Eko Atlantic City and the scenario 0 without Eko Atlantic City are investigated for a certain year (i.e. the end year of the model run).

The absolute coastline changes are obtained by comparison of the coastline in a certain year (i.e. the end year of the model run) to the coastline in 2010, the year of construction of the Eko Atlantic City project.

2030

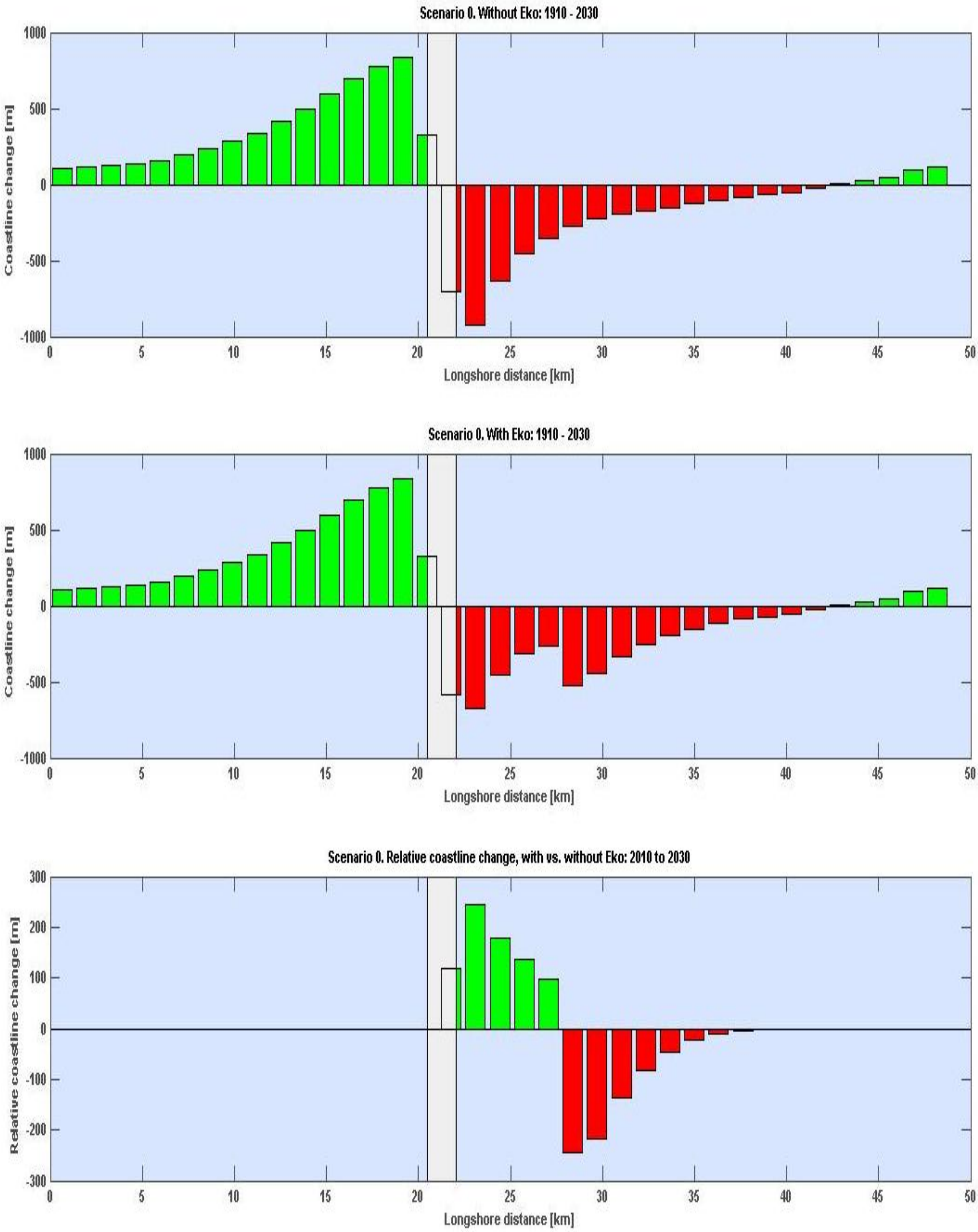


Figure 0-51: Above: absolute coastline change, between 1910 and 2030, for scenario 0 without Eko Atlantic City. Middle: absolute coastline change, between 1910 and 2030, for scenario 0 with Eko Atlantic City. Below: relative coastline change between both scenarios, between 2010 and 2030

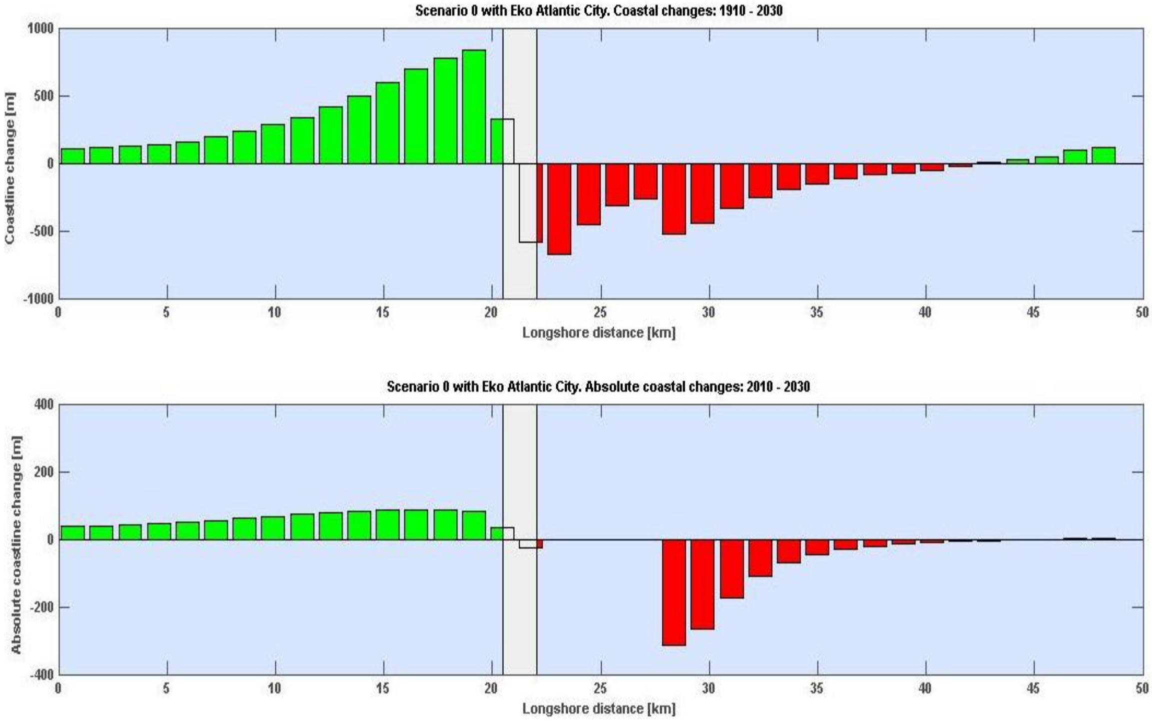


Figure 0-52: Above: absolute coastline change, between 1910 and 2030, for scenario 0 with Eko Atlantic City. Below: absolute coastline change in scenario 0, between 2010 and 2030, with Eko Atlantic City present

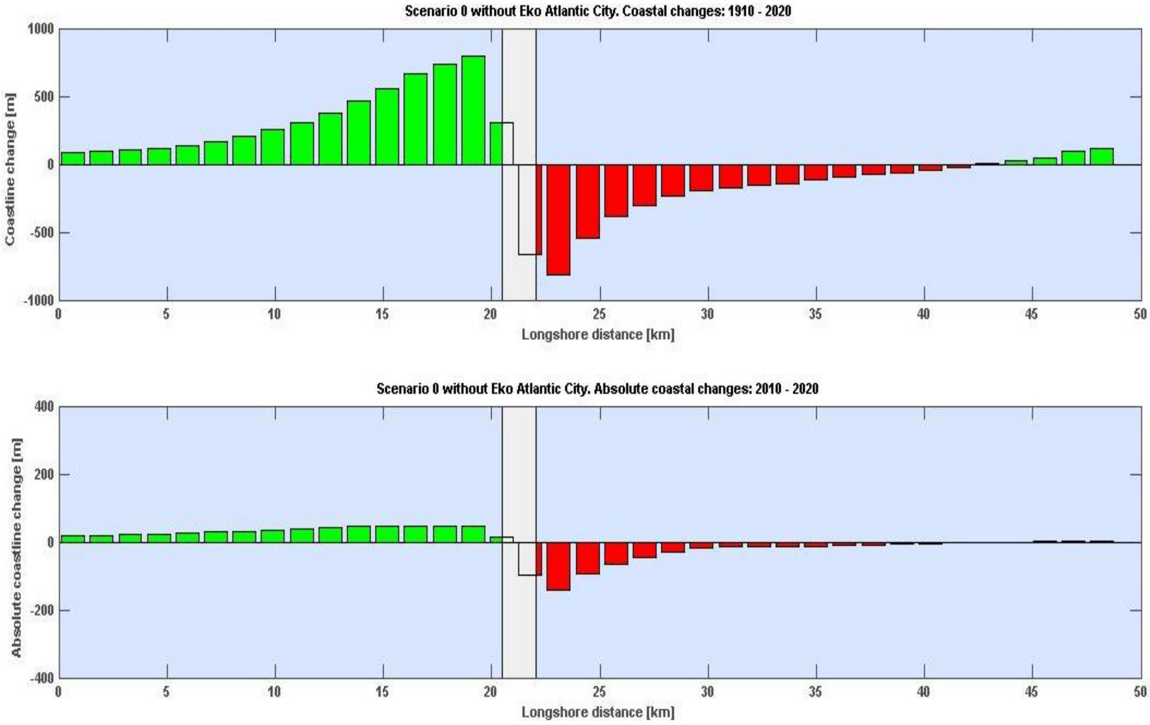


Figure 0-53: Above: absolute coastline change, between 1910 and 2030, for scenario 0 without Eko Atlantic City. Below: absolute coastline change in scenario 0, between 2010 and 2030, without Eko Atlantic City present

2040

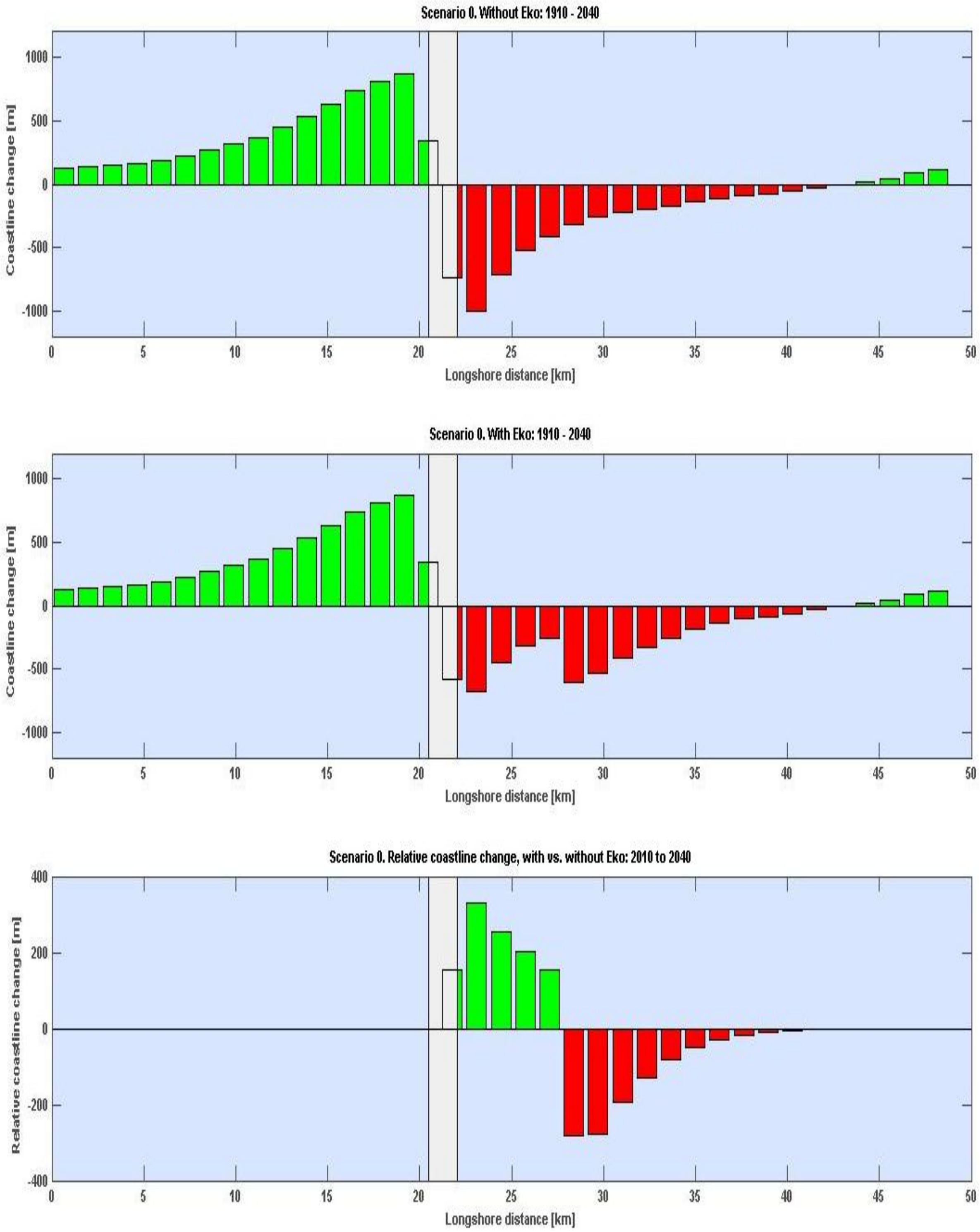


Figure 0-54: Above: absolute coastline change, between 1910 and 2040, for scenario 0 without Eko Atlantic City. Middle: absolute coastline change, between 1910 and 2040, for scenario 0 with Eko Atlantic City. Below: relative coastline change between both scenarios, between 2010 and 2040

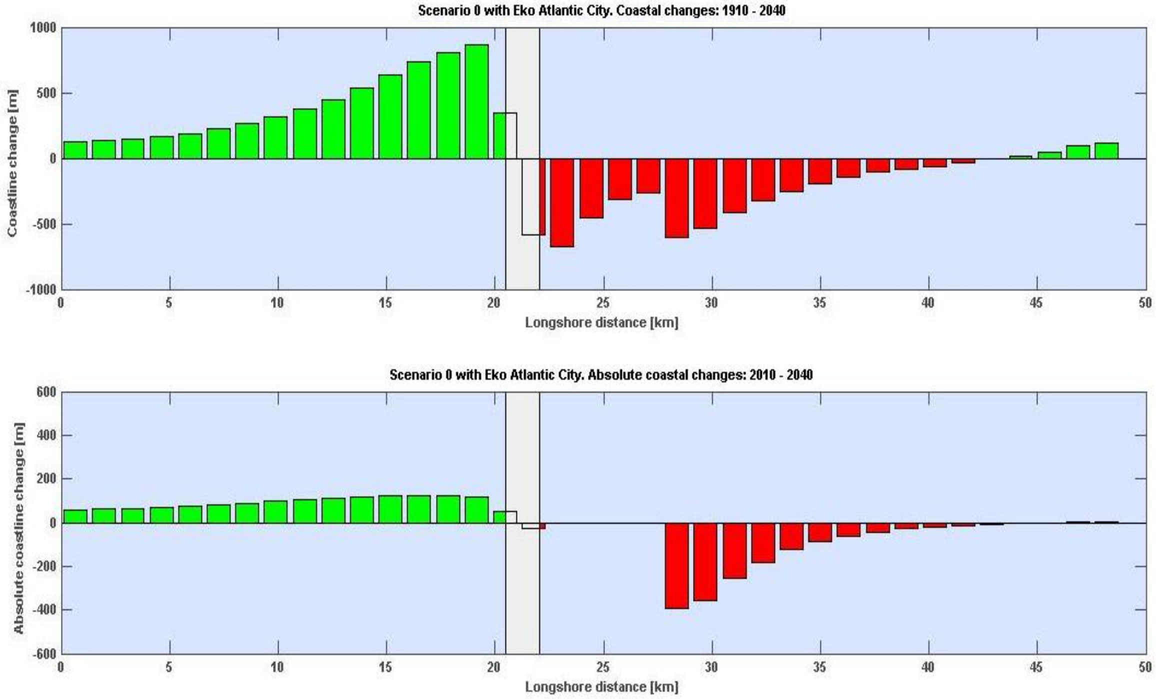


Figure 0-55: Above: absolute coastline change, between 1910 and 2040, for scenario 0 with Eko Atlantic City. Below: absolute coastline change in scenario 0, between 2010 and 2040, with Eko Atlantic City present

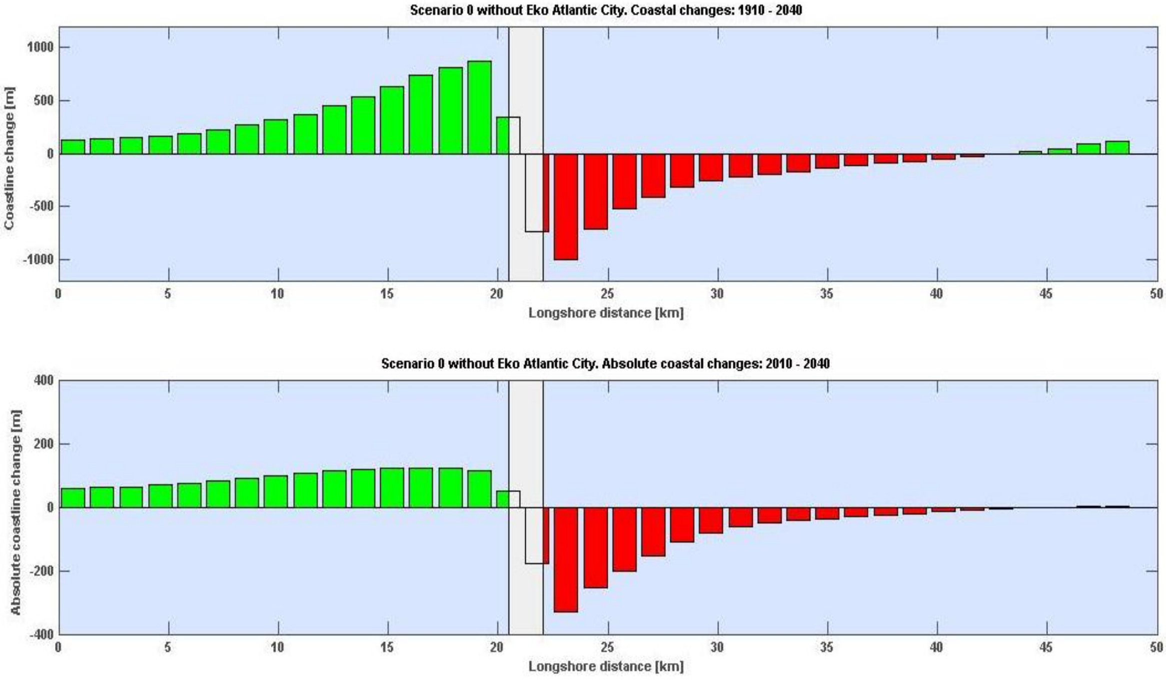
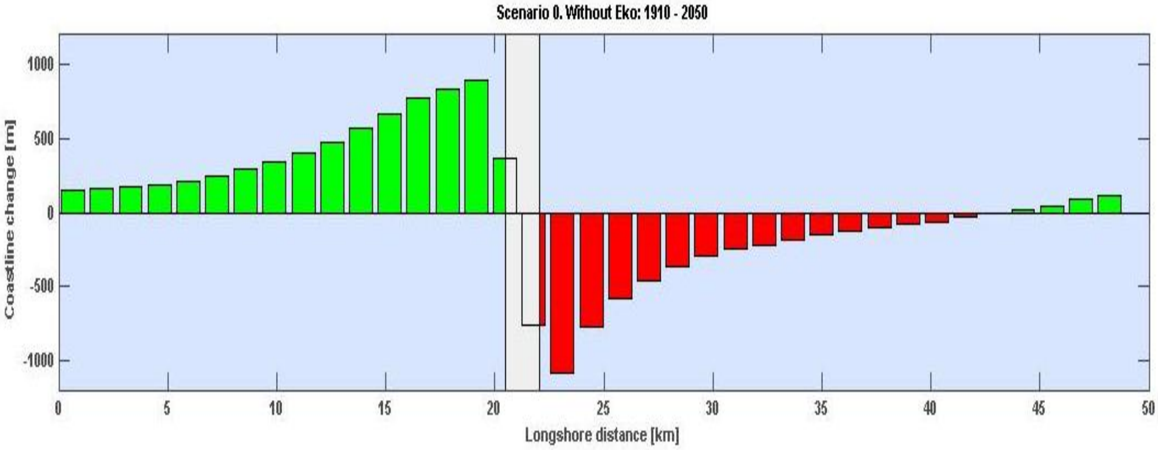
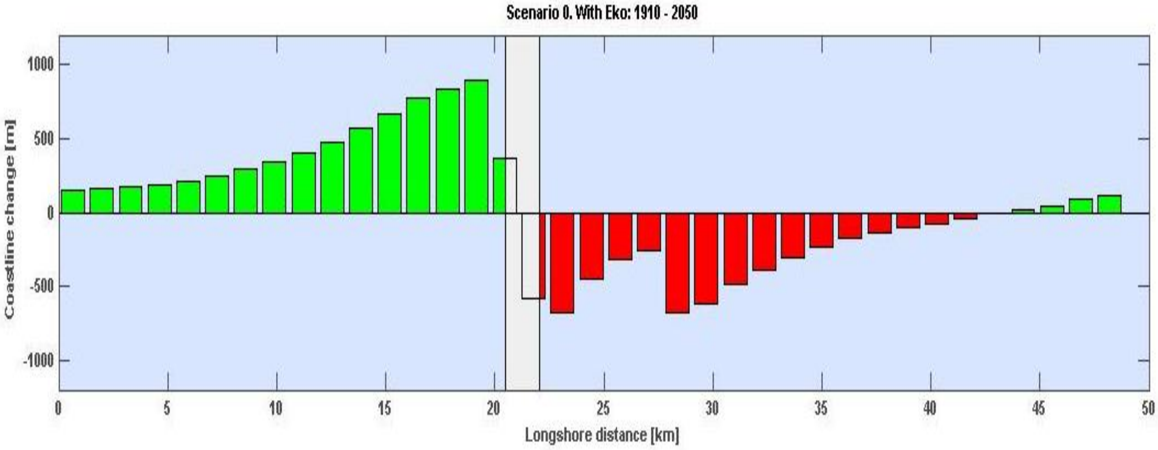


Figure 0-56: Above: absolute coastline change, between 1910 and 2040, for scenario 0 without Eko Atlantic City. Below: absolute coastline change in scenario 0, between 2010 and 2040, without Eko Atlantic City present

2050





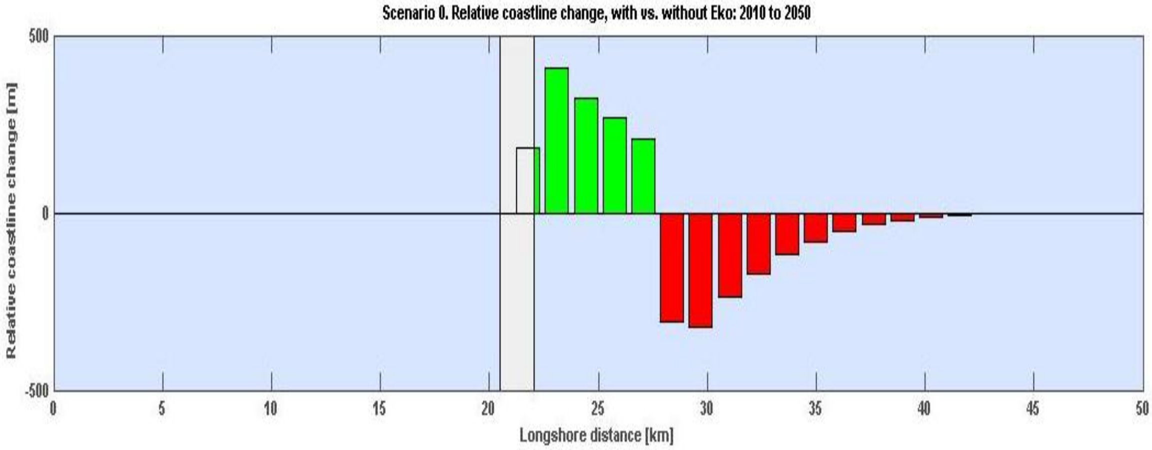


Figure 0-57: Above: absolute coastline change, between 1910 and 2050, for scenario 0 without Eko Atlantic City. Middle: absolute coastline change, between 1910 and 2050, for scenario 0 with Eko Atlantic City. Below: relative coastline change between both scenarios, between 2010 and 2050

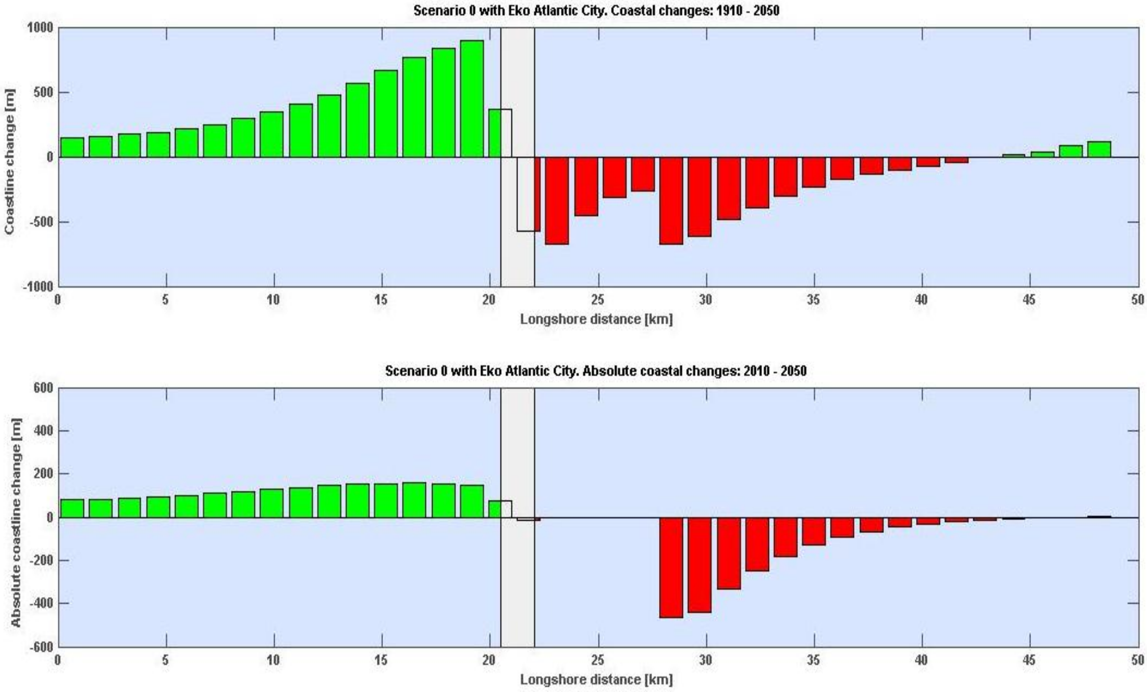


Figure 0-58: Above: absolute coastline change, between 1910 and 2050, for scenario 0 with Eko Atlantic City. Below: absolute coastline change in scenario 0, between 2010 and 2050, with Eko Atlantic City present

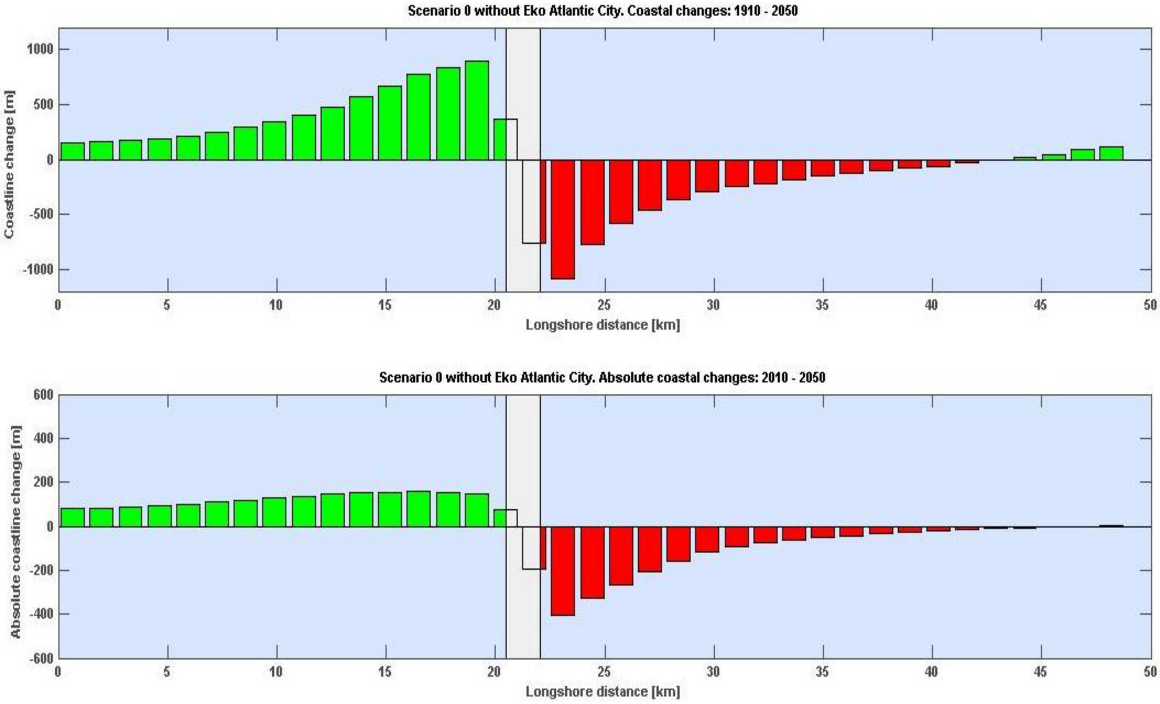


Figure 0-59: Above: absolute coastline change, between 1910 and 2050, for scenario 0 without Eko Atlantic City. Below: absolute coastline change in scenario 0, between 2010 and 2050, without Eko Atlantic City present

2060

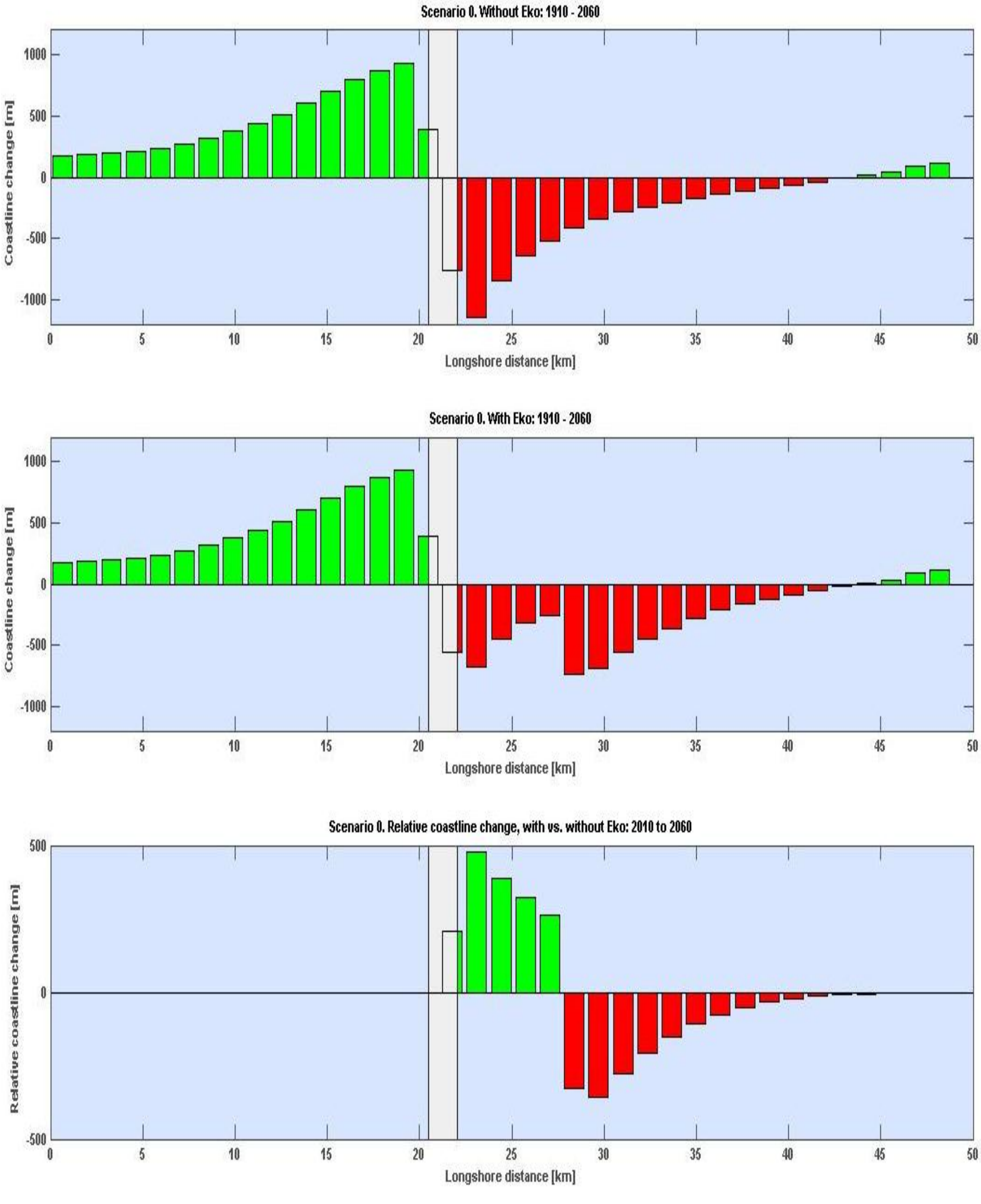


Figure 0-60: Above: absolute coastline change, between 1910 and 2060, for scenario 0 without Eko Atlantic City. Middle: absolute coastline change, between 1910 and 2060, for scenario 0 with Eko Atlantic City. Below: relative coastline change between both scenarios, between 2010 and 2060

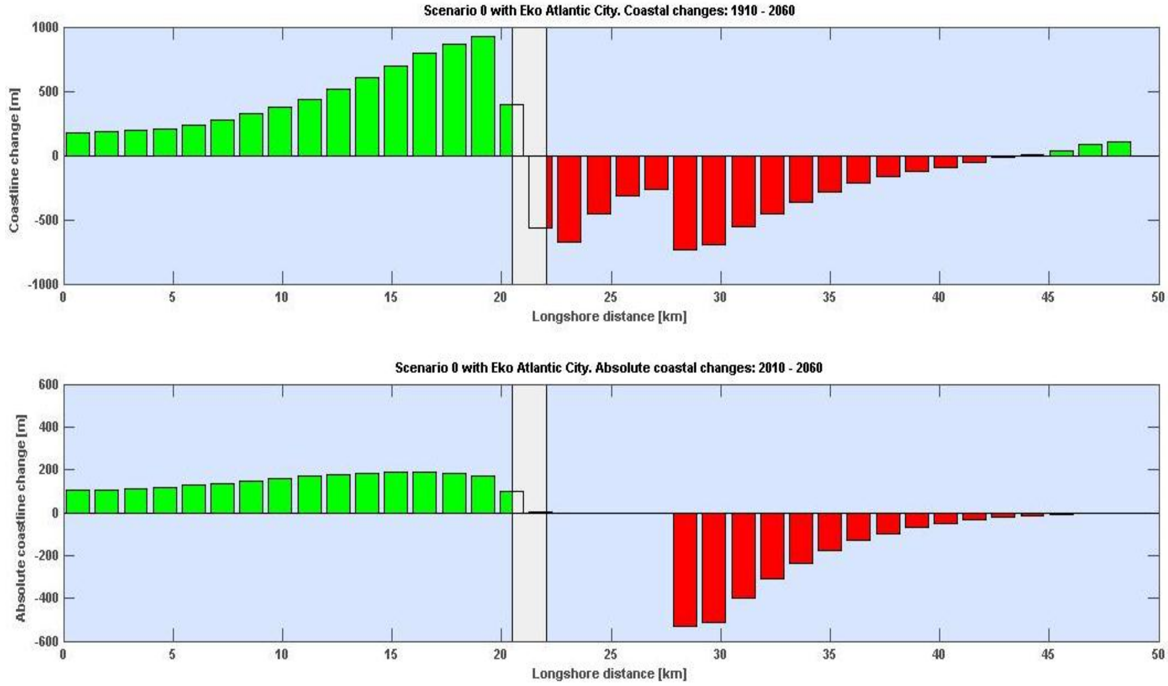


Figure 0-61: Above: absolute coastline change, between 1910 and 2060, for scenario 0 with Eko Atlantic City. Below: absolute coastline change in scenario 0, between 2010 and 2060, with Eko Atlantic City present

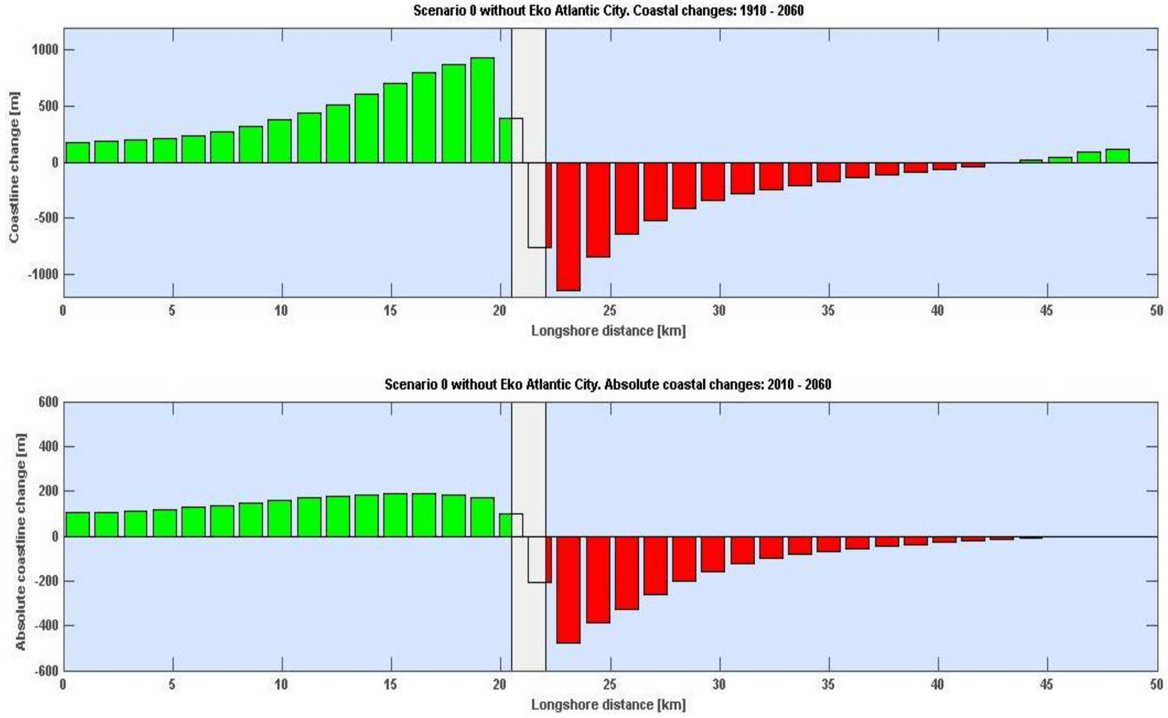


Figure 0-62: Above: absolute coastline change, between 1910 and 2060, for scenario 0 without Eko Atlantic City. Below: absolute coastline change in scenario 0, between 2010 and 2060, without Eko Atlantic City present

DEVELOPMENT OF EROSION OVER THE YEARS

In Table5-6 the rates and volumes of erosion on the longer-term are presented. Using these values, it is checked what the development of the erosion rates over the future is. The development of the erosion rates over the years is summarized in Figure 0-63. In Figure 0-64 the development of the erosion volumes is presented. And the development of the erosion wave over the years is plotted in Figure 0-65.

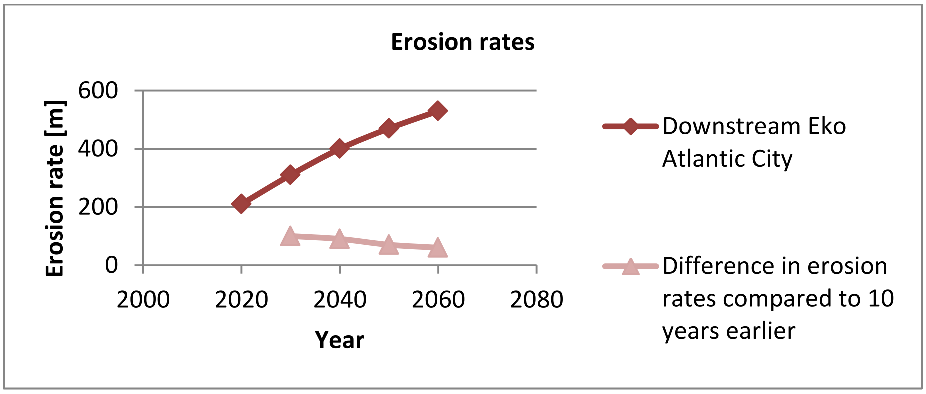


Figure 0-63: Development of maximum erosion rate downstream Eko Atlantic City over the years

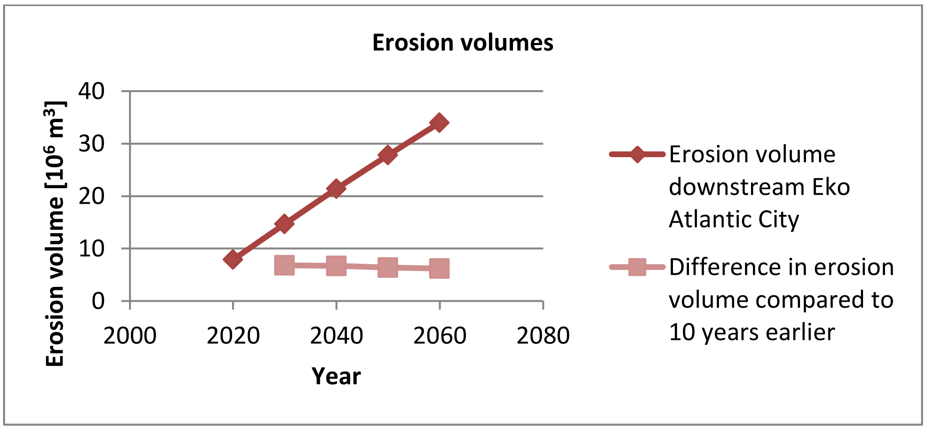


Figure 0-64: Development of erosion volume downstream Eko Atlantic City over the years

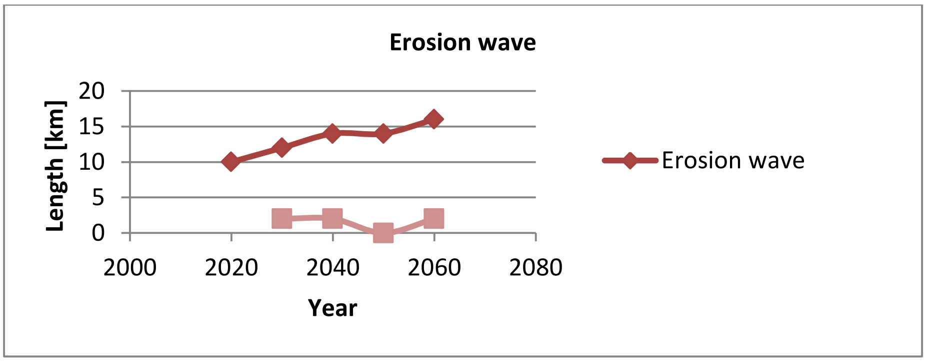


Figure 0-65: Development of erosion wave downstream Eko Atlantic City over the years

F MITIGATION MEASURES

F.1 NOURISHMENTS

Similar to the analysis of the different scenarios, the absolute impact of the mitigation measures is investigated by investigation of the absolute changes in coastal situation between the output year and 2010. Therefore, in the plots depicted in this section, the coastal situation in the output year is compared to Figure 0-33.

300,000 M^3/YEAR

In Figure 0-66 the influence of a nourishment volume of 300,000 m^3/year can be seen in the differences in 2020 coastline position. The yellow line indicates the 2020 coastline position without nourishments performed and the red line represents the 2020 coastline including nourishments.

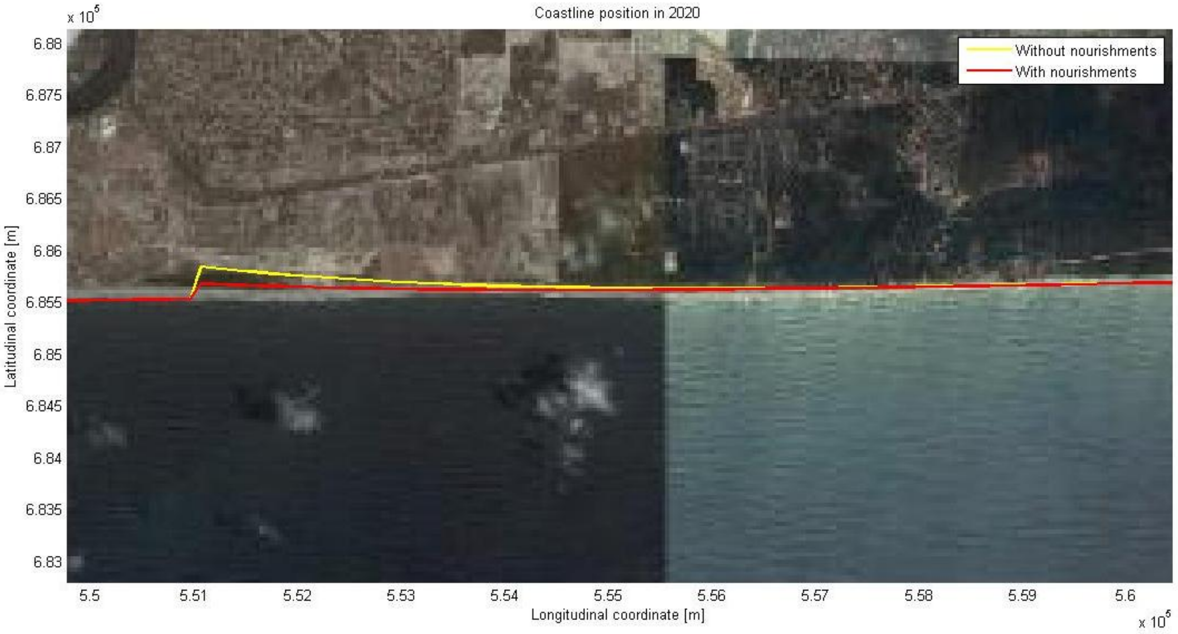
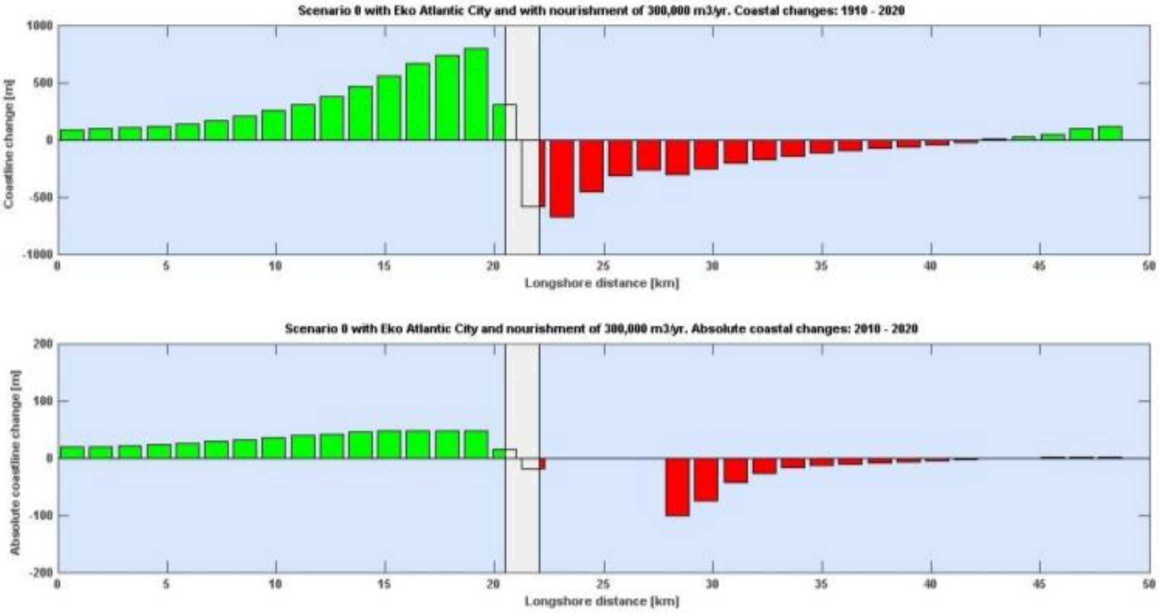

Coastline position in 2020

Figure 0-66: Coastline in 2020, for scenario 0 with Eko Atlantic City. In yellow is the result of the model run without the nourishments, and in red the nourishments are included


Scenario 0 with Eko Atlantic City and with nourishment of 300,000 m3/yr. Coastal changes: 1910 - 2020

Scenario 0 with Eko Atlantic City and nourishment of 300,000 m3/yr. Absolute coastal changes: 2010 - 2020

Figure 0-67: Above: absolute coastline change, between 1910 and 2020, for scenario 0 with nourishment of 300,000 m³/year. Below: absolute coastline change in scenario 0, between 2010 and 2020, with nourishment of 300,000 m³/year

600,000 M^3/YEAR

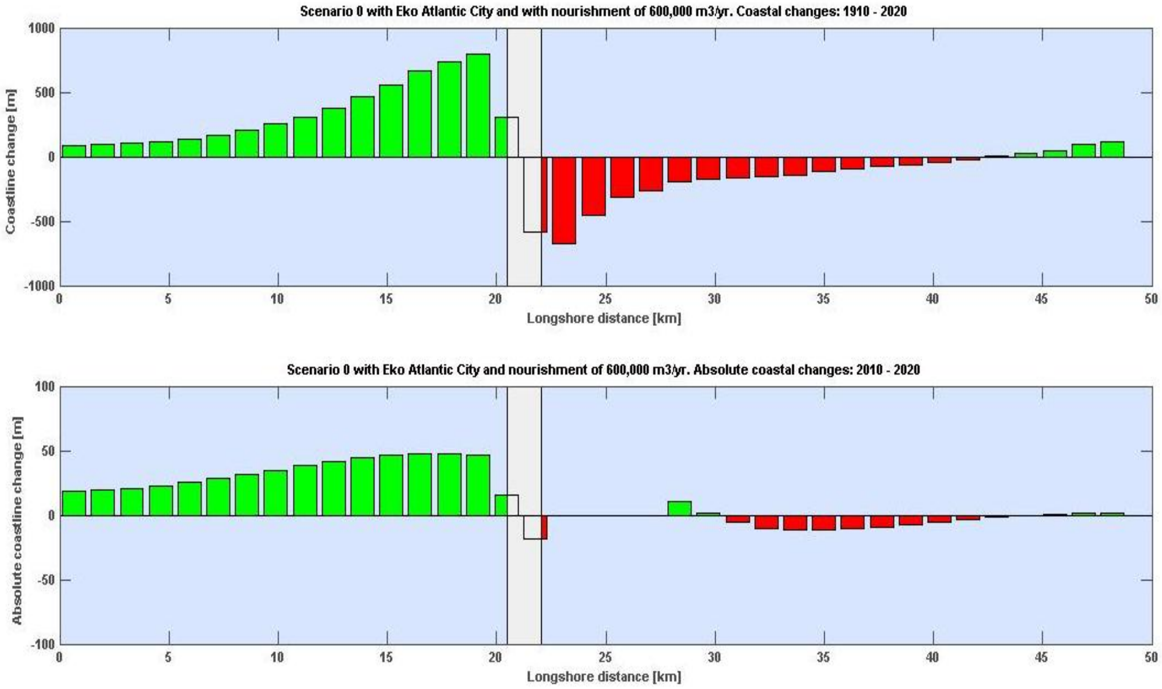


Figure 0-68: Above: absolute coastline change, between 1910 and 2020, for scenario 0 with nourishment of 600,000 m^3/year. Below: absolute coastline change in scenario 0, between 2010 and 2020, with nourishment of 600,000 m^3/year

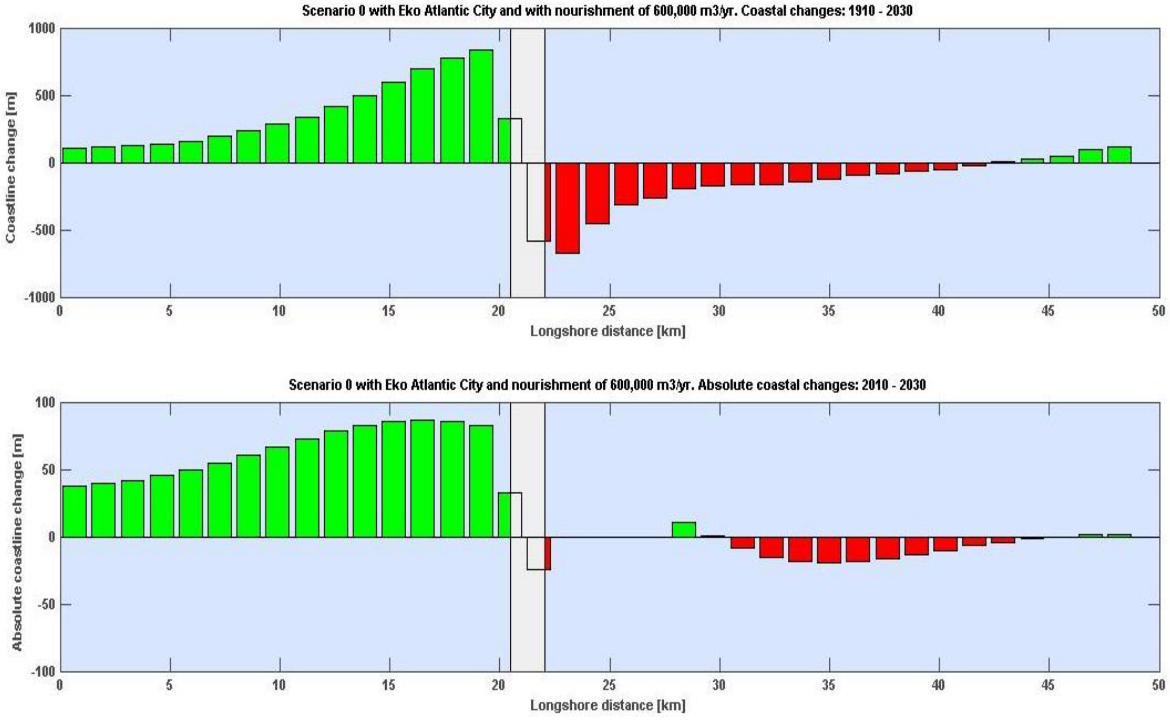


Figure 0-69: Above: absolute coastline change, between 1910 and 2030, for scenario 0 with nourishment of 600,000 m^3/year. Below: absolute coastline change in scenario 0, between 2010 and 2030, with nourishment of 600,000 m^3/year

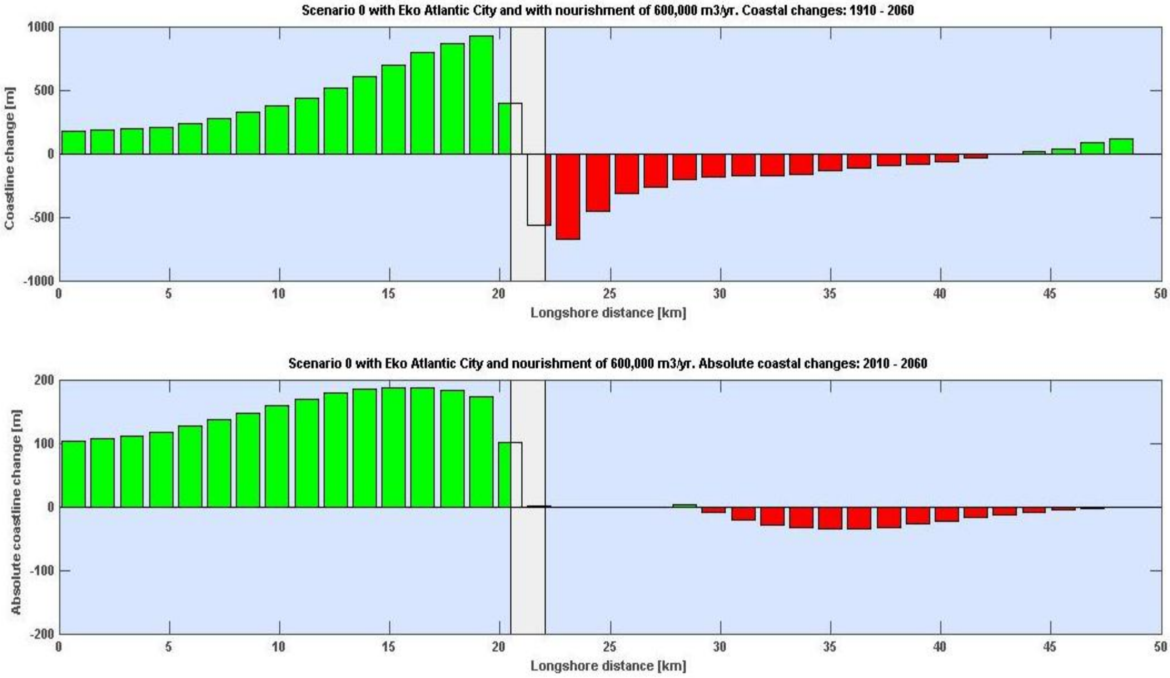


Figure 0-70: Above: absolute coastline change, between 1910 and 2060, for scenario 0 with nourishment of 600,000 m³/year. Below: absolute coastline change in scenario 0, between 2010 and 2060, with nourishment of 600,000 m³/year

F.2 ALPHA BEACH

2020

The coastline position in 2020 is compared for two scenarios: one with the Alpha Beach revetment, and one without. Figure 0-71 represents the coastline in 2020, both for the scenarios with (depicted in red) and without (shown in yellow) the Alpha Beach revetment.

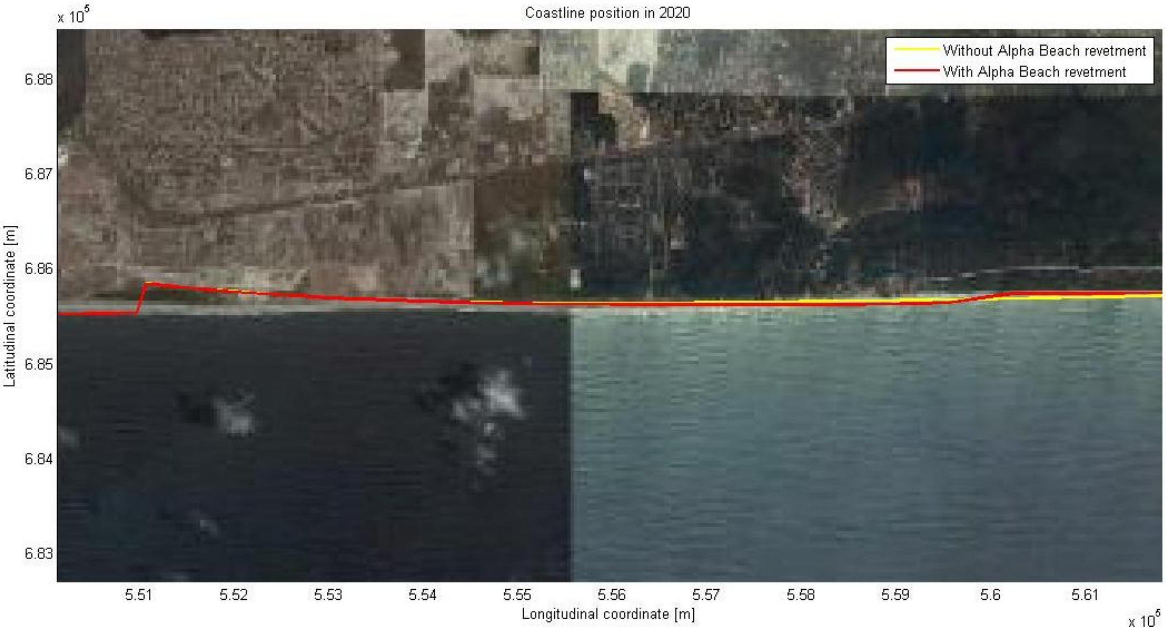


Figure 0-71: Coastline in 2020, for scenario 0 with Eko Atlantic City. In yellow is the result of the model run without the Alpha Beach revetment, and in red the revetment is included

The impact of Eko Atlantic City can clearly be distinguished in the left part of the figure. However, the influence of the Alpha Beach revetment is less visible. This can be explained by the fact that, in 2020, the influence of Eko Atlantic City just reaches the Alpha Beach.

But, considering the relative change in erosion rates, the Alpha Beach revetment does change the erosion rates compared to the scenario without the revetment, see Figure 0-72.

The relative impact of the Alpha Beach revetment in 2020 is depicted in Figure 0-72. The upper two figures show the absolute coastline changes from 1910 to 2020, for the scenario 0 (with Eko Atlantic City) with and without the Alpha Beach revetment.

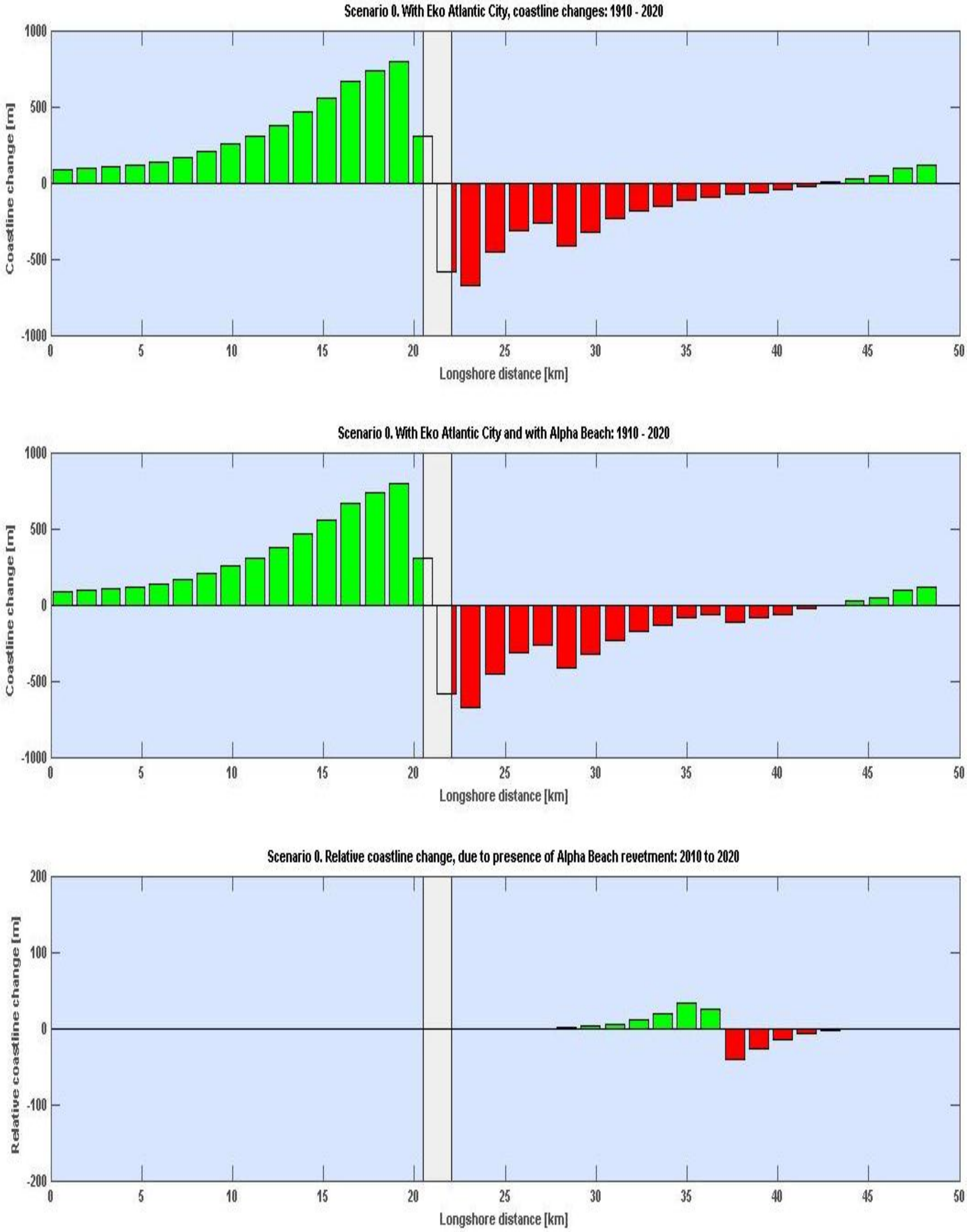


Figure 0-72: Above: absolute coastline change, between 1910 and 2020, for scenario 0 without Alpha Beach revetment. Middle: absolute coastline change, between 1910 and 2020, for scenario 0 with Alpha Beach revetment. Below: relative coastline change between both scenarios, between 2010 and 2020

Downstream the revetment, a relative increase of erosion of maximum 40 m occurs. The additional erosion volume of approximately 1.3 million m³ is spread out over a distance of circa 5 km.

The absolute erosion rates are investigated in the same way as done for all other scenarios. In Figure 0-73 the absolute changes in coastline position are depicted.

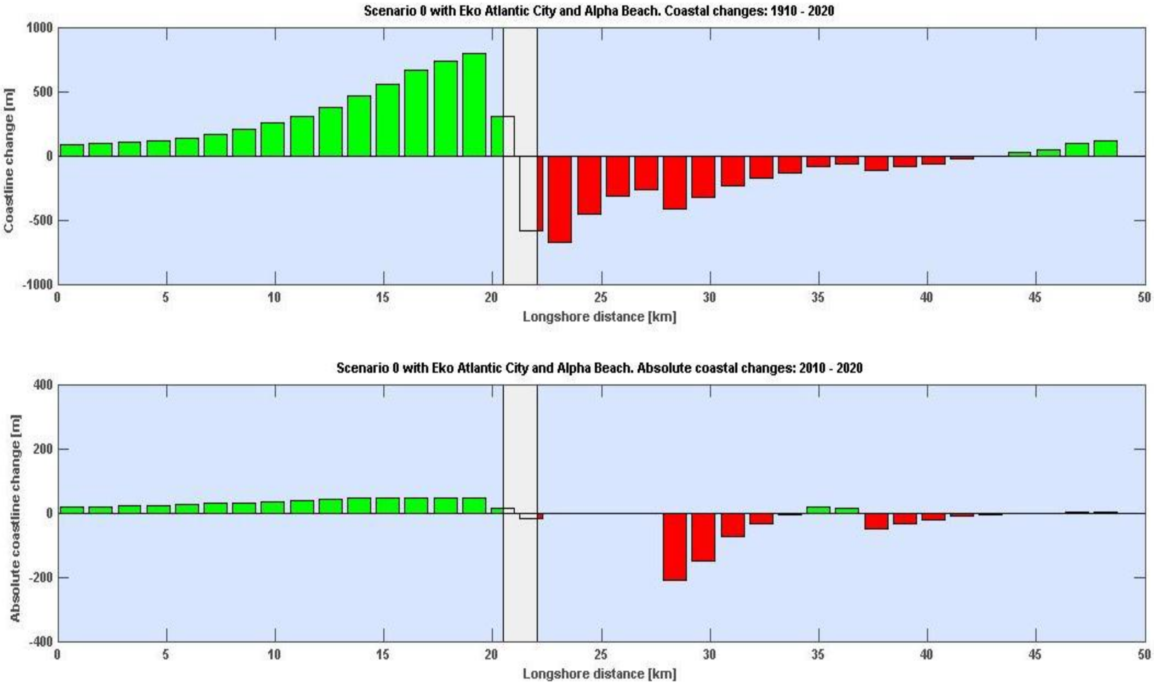


Figure 0-73: Above: absolute coastline change, between 1910 and 2020, for scenario 0 with Alpha Beach revetment. Below: absolute coastline change in scenario 0, between 2010 and 2020, with Alpha Beach revetment

In 2020 the (additional) shift in erosion, from the location downstream Eko Atlantic City towards east of the Alpha Beach revetment, has a volume of approximately 1.6 million m³. This volume occurs over a longshore distance of 4 km, and it induces a maximum retreat of the coast of roughly 50 m.

The erosion rates directly downstream of Eko Atlantic City are not altered by the presence of the Alpha Beach revetment; the maximum rate of erosion stays about 180 m.

2030

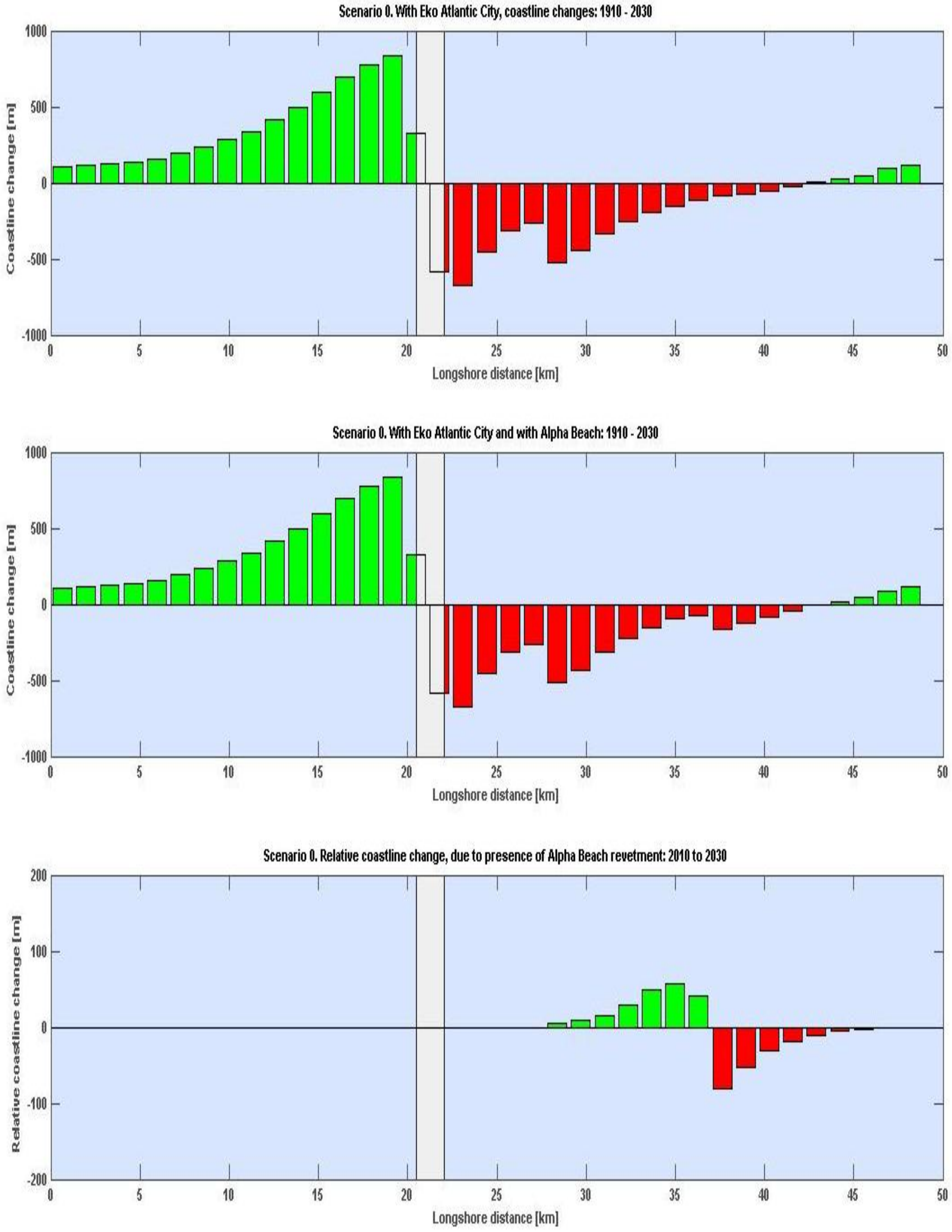


Figure 0-74: Above: absolute coastline change, between 1910 and 2030, for scenario 0 without Alpha Beach revetment. Middle: absolute coastline change, between 1910 and 2030, for scenario 0 with Alpha Beach revetment. Below: relative coastline change between both scenarios, between 2010 and 2030

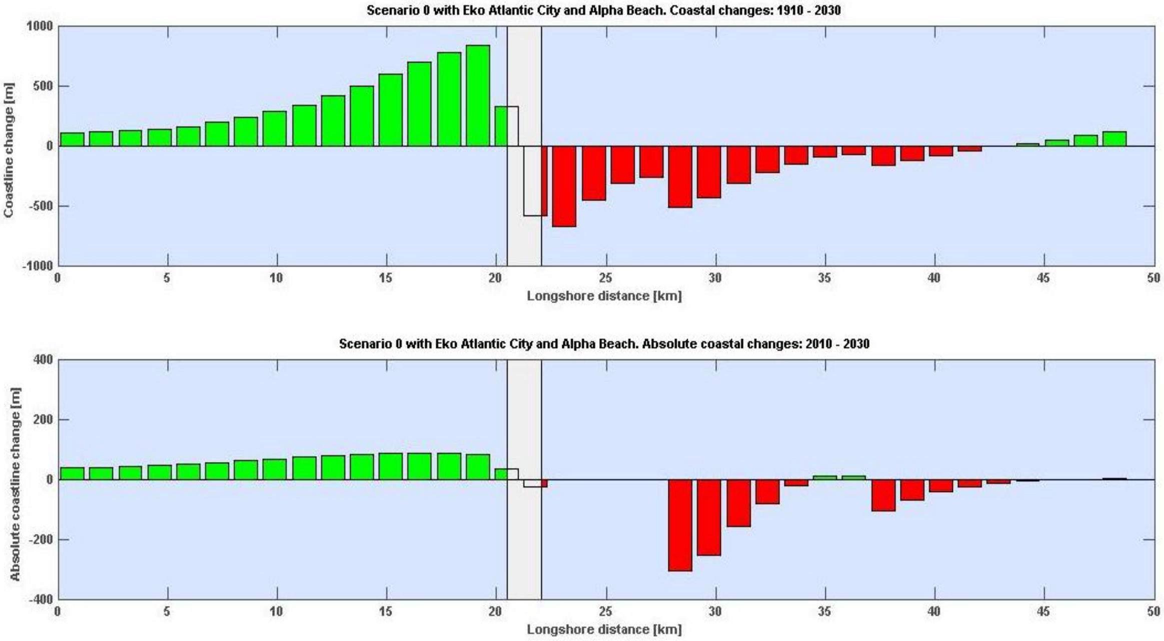


Figure 0-75: Above: absolute coastline change, between 1910 and 2030, for scenario 0 with Alpha Beach revetment. Below: absolute coastline change in scenario 0, between 2010 and 2030, with Alpha Beach revetment

2060

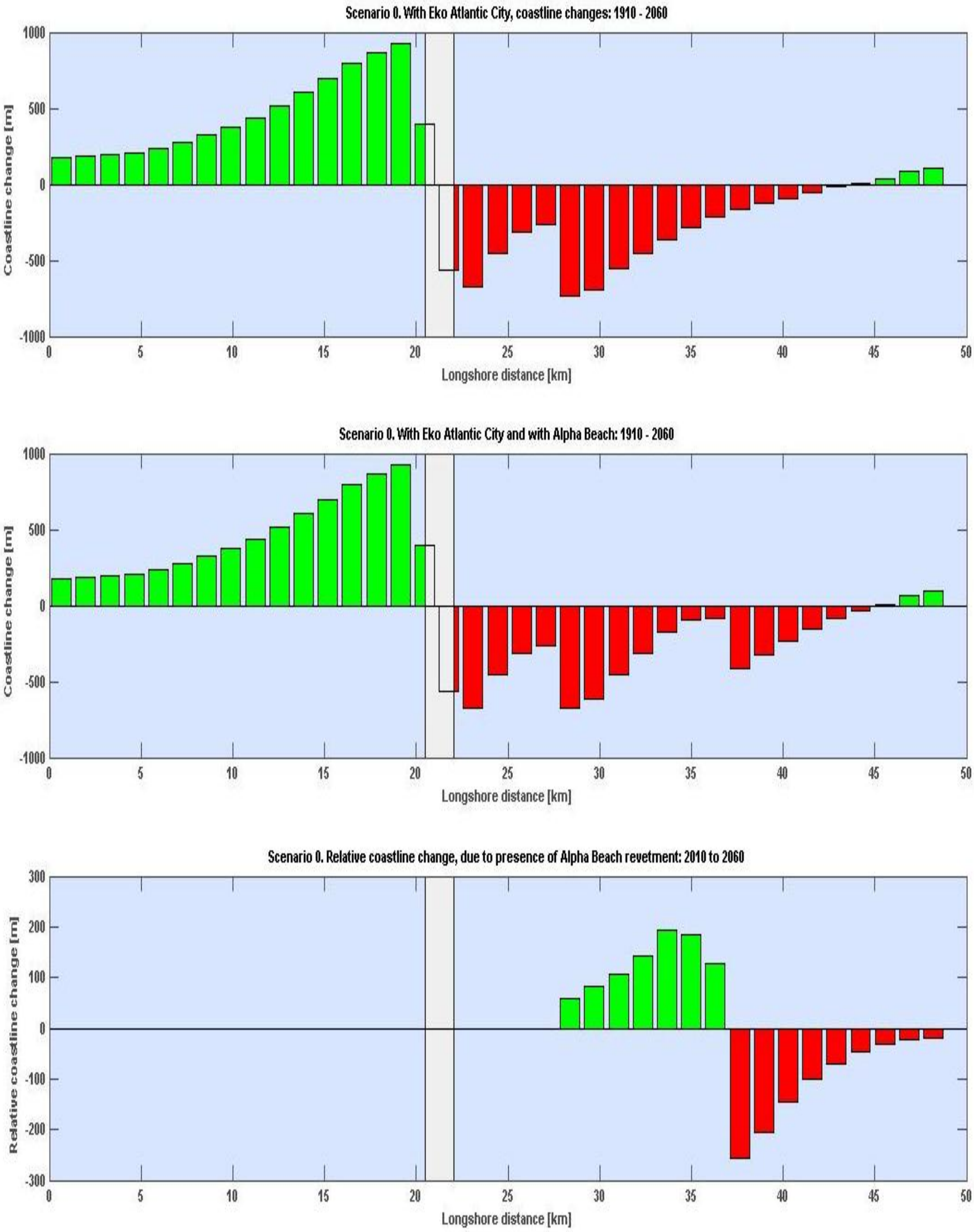


Figure 0-76: Above: absolute coastline change, between 1910 and 2060, for scenario 0 without Alpha Beach revetment. Middle: absolute coastline change, between 1910 and 2060, for scenario 0 with Alpha Beach revetment. Below: relative coastline change between both scenarios, between 2010 and 2060

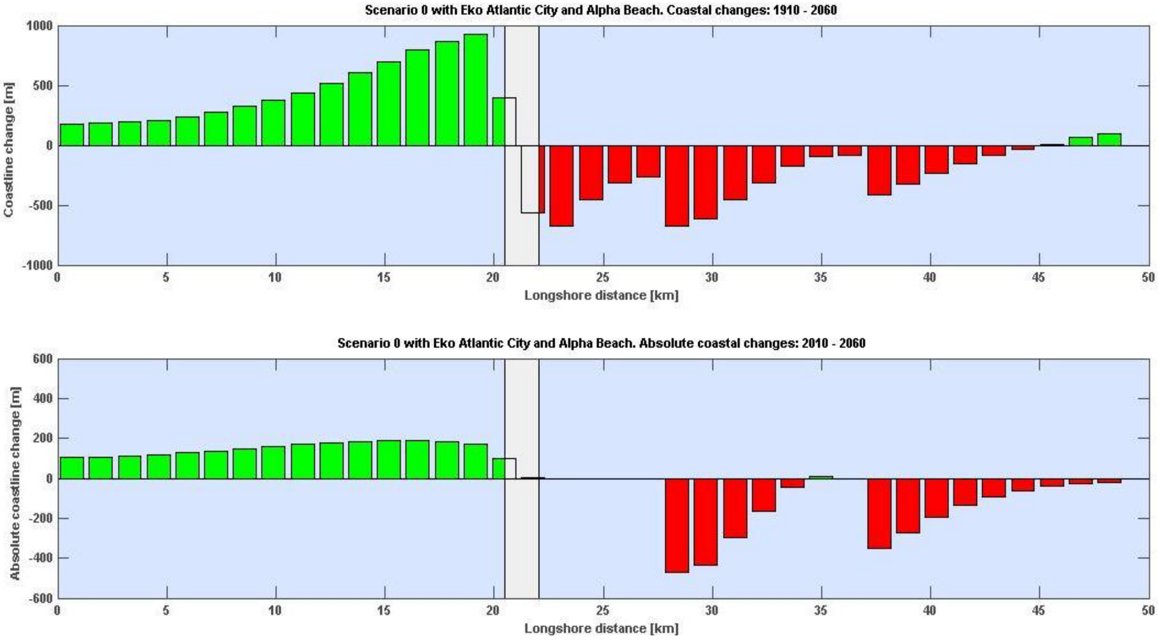
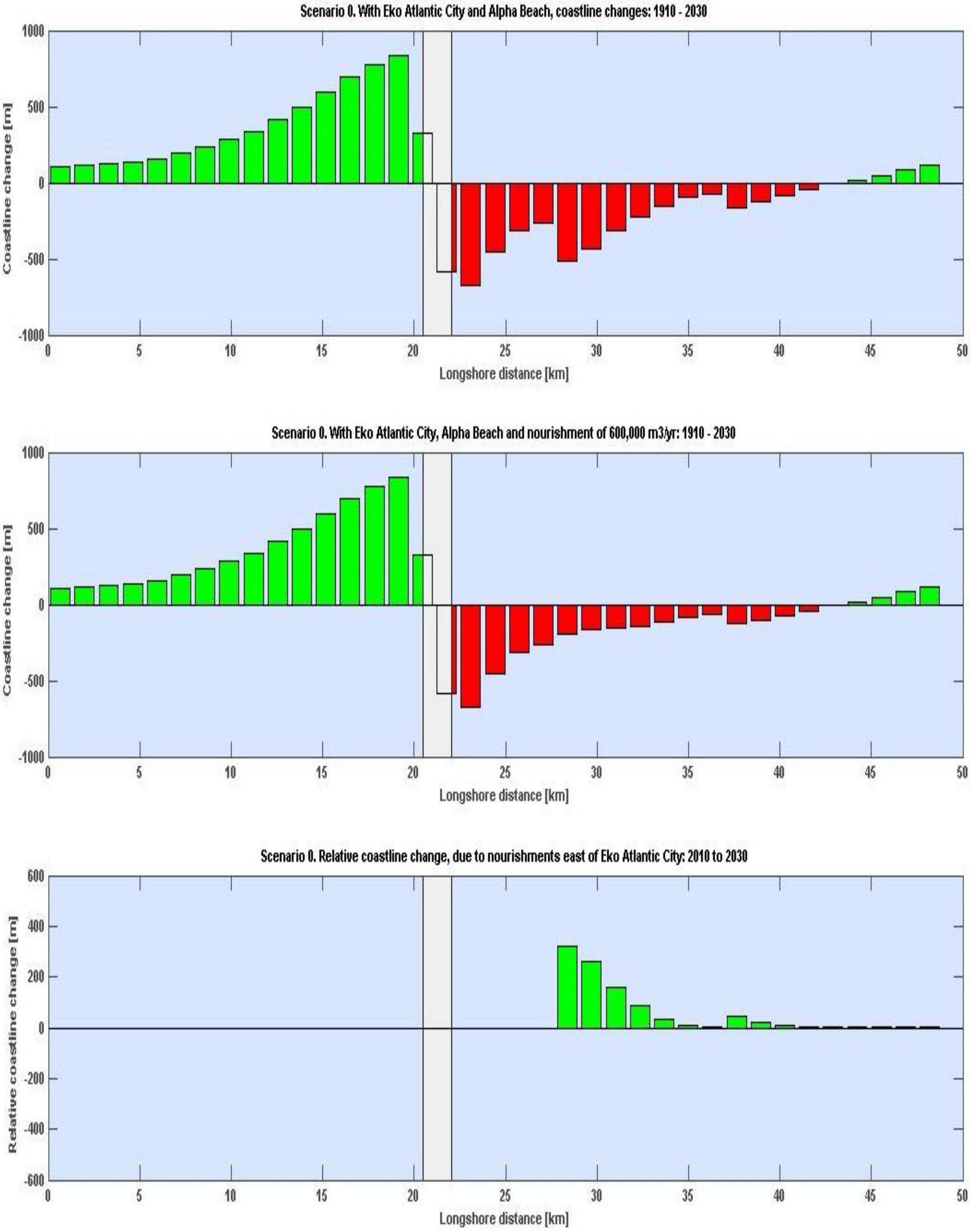


Figure 0-77: Above: absolute coastline change, between 1910 and 2060, for scenario 0 with Alpha Beach revetment. Below: absolute coastline change in scenario 0, between 2010 and 2060, with Alpha Beach revetment

2030 INCLUDING NOURISHMENTS



Scenario 0. With Eko Atlantic City and Alpha Beach, coastline changes: 1910 - 2030

Scenario 0. With Eko Atlantic City, Alpha Beach and nourishment of 600,000 m3/yr: 1910 - 2030

Scenario 0. Relative coastline change, due to nourishments east of Eko Atlantic City: 2010 to 2030

Figure 0-78: Above: absolute coastline change, between 1910 and 2030, for scenario 0 without nourishments. Middle: absolute coastline change, between 1910 and 2030, for scenario 0 with nourishments. Below: relative coastline change between both scenarios, between 2010 and 2030

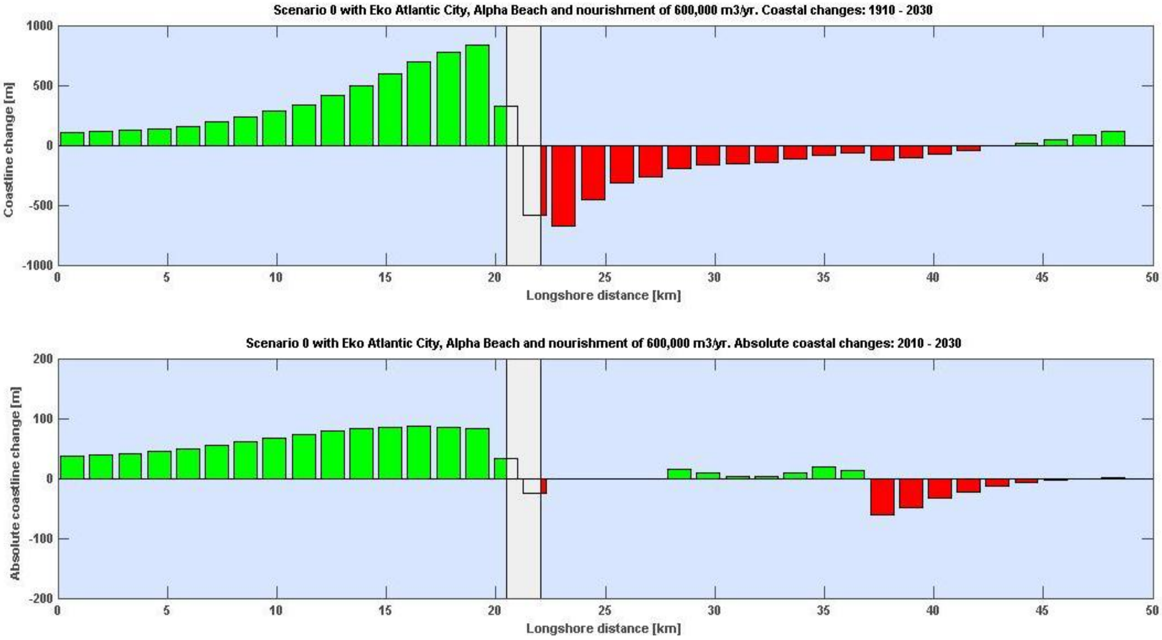


Figure 0-79: Above: absolute coastline change, between 1910 and 2030, for scenario 0 with Alpha Beach revetment and nourishments. Below: absolute coastline change in scenario 0, between 2010 and 2030, with Alpha Beach revetment and nourishments

2060 INCLUDING NOURISHMENTS

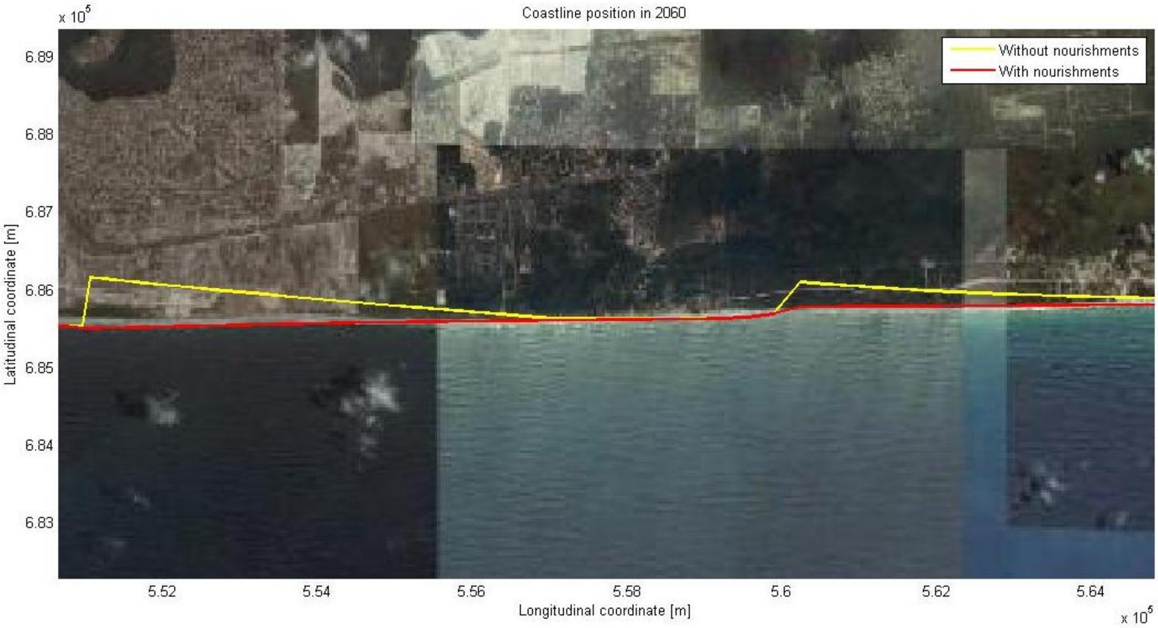


Figure 0-80: Coastline in 2060, for scenario 0 with Eko Atlantic City and Alpha Beach. In yellow is the result of the model run without the nourishments and in red the nourishments are included

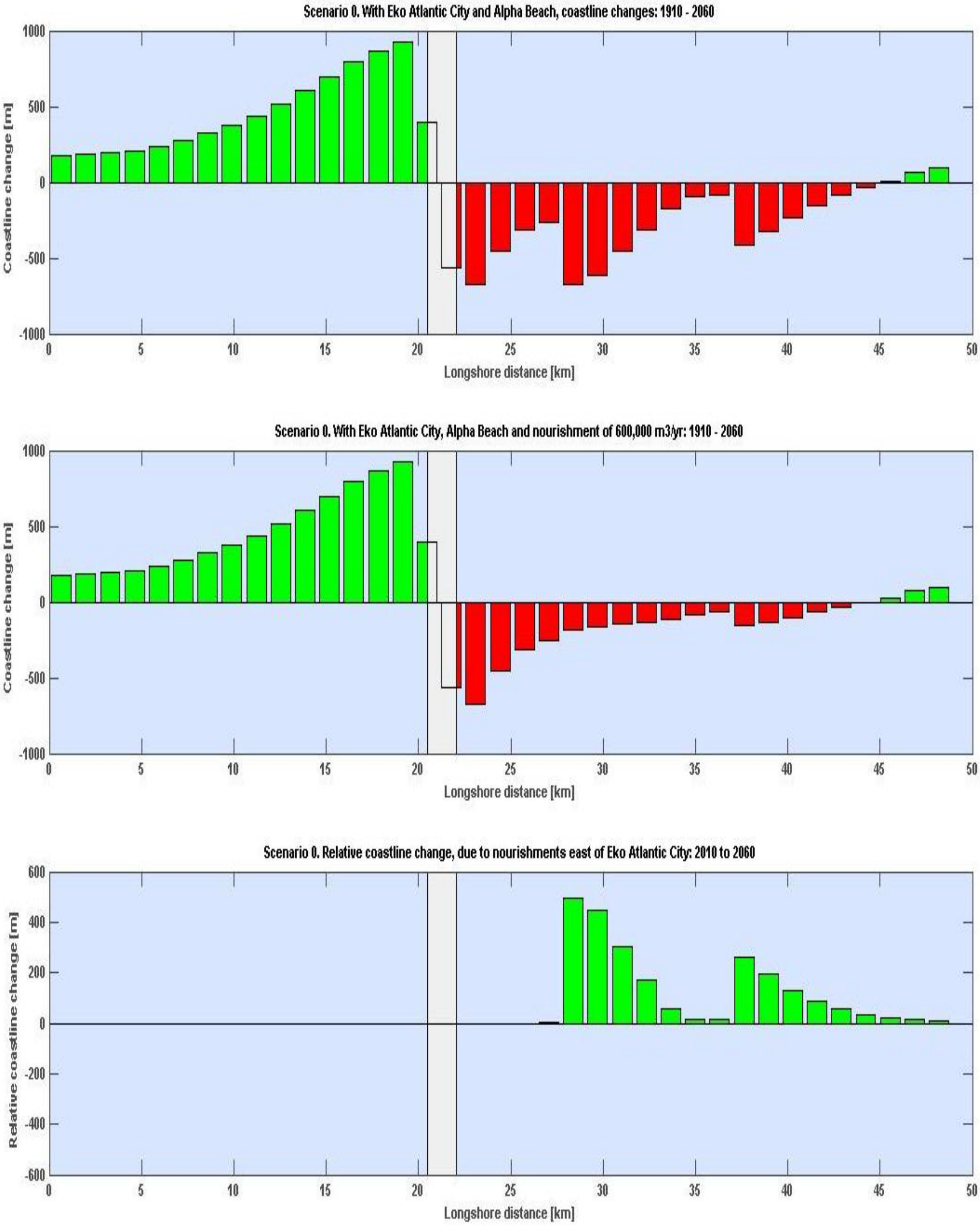


Figure 0-81: Above: absolute coastline change, between 1910 and 2060, for scenario 0 without nourishments. Middle: absolute coastline change, between 1910 and 2060, for scenario 0 with nourishments. Below: relative coastline change between both scenarios, between 2010 and 2060

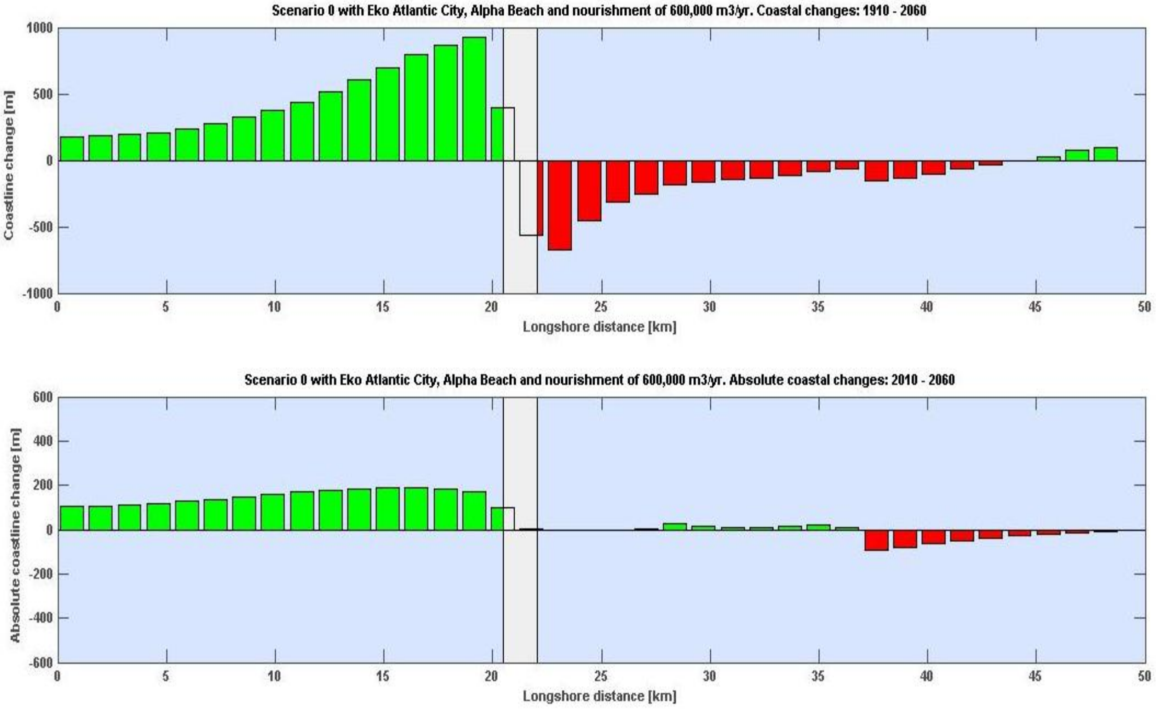


Figure 0-82: Above: absolute coastline change, between 1910 and 2060, for scenario 0 with Alpha Beach revetment and nourishments. Below: absolute coastline change in scenario 0, between 2010 and 2060, with Alpha Beach revetment and nourishments