Coastal Erosion and Mangrove Degradation in the Mekong Delta, Vietnam

MDP 351

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Cover: Manrove forest near the waterline west of the Nha Mat canal in the Bac Lieu province, Vietnam.
Style: TU Delft Report Style, with modifications by Daan Zwaneveld

Preface

This research project is conducted as a part of our Master of Science programs at the Delft University of Technology. The project was carried out at the Thuy Loi University in Hanoi. It gave us the opportunity to contribute to a better assessment of the problem regarding coastal erosion in the Mekong Delta, for which we are very grateful.

We are very thankful to the Thuy Loi University and the Delft University of Technology. We got to research a very interesting and urgent topic while exploring the beautiful areas and culture that Vietnam has to offer. We are amazed by the positivity and kindness that the Vietnamese people showed us during the project. We would like to thank our supervisor Dr. Ir. Hayo Hendrikse for his support and his critical views on our progress. We would also like to thank our supervisor Dr. Thom Bogaard for being able to supervise us on such a short notice, while having such a full schedule himself. Lastly we would like to express our sincere gratitude to Dr. Son Hong Truong, who helped us immensely with this research and with getting accustomed to Vietnam.

Geert de Klerk
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Abstract

The Vietnamese Mekong Delta, a vital region in the country's economy, faces the dual challenges of coastal erosion and mangrove degradation, which threaten its long-term sustainability and flood protection capabilities. This research focuses on the coastal area of the Bac Lieu province, characterized by severe erosion and degrading mangrove forests. The study investigates the applicability and potential impacts of hydraulic measures to decrease the net rate of coastal erosion, utilizing numerical modeling with Delft3D and a comprehensive socio-economic analysis.

The research hypothesizes that the coastal erosion is partly driven by the placement of a sea-dike to protect aquaculture farms, initiating a positive feedback loop. This loop explains the relation between coastal erosion and mangrove degradation. The proposed hydraulic measures to interfere with this feedback loop are a porous detached breakwater, a shoreface nourishment and the removal of the existing sea-dike. The socio-economic analysis involves questionnaires for local residents, field investigations, and insights from experts in Ho Chi Minh City. While the questionnaires provide inconclusive results, the overall socio-economic impact of the nourishment and breakwater is deemed positive and worth further exploration, particularly in light of the critical role of mangroves in future flood protection. On the other hand it is concluded that the measure of removing the sea-dike will have a negative impact on the coastal area of Bac Lieu due to the intensive land-use and the lack of individual protection of the farms and villages. Therefore, this measure is not modelled.

Numerical modeling with Delft3D assesses the hydraulic impact of the breakwater and nourishment on the heavily eroded and partially eroded coasts of Bac Lieu. Results indicate that the nourishment method exhibits a positive effect in reducing net erosion, especially in low energy conditions. Conversely, the porous breakwater shows minimal impact on cumulative erosion and sedimentation. Since this is against all expectations, the validity of the schematization of the porous breakwater is questioned. It is observed that the schematization does not grasp the complex behaviour of the breakwater and therefore it is concluded that Deft3D is not a suitable modelling tool for modelling a porous breakwater.

The findings suggest that the nourishment method is a promising approach for reducing erosion in Bac Lieu, benefiting both the heavily and partially eroded coasts. To determine the best course of action for Bac Lieu, further research into the long-term effects and configurations of nourishment is recommended. Additionally, informing local inhabitants on the threats of relative sea-level rise and flood protection, and fostering consensus between the government and engineering agencies on the importance of protecting the Mekong Delta and its mangrove ecosystems are essential steps toward a more resilient future.

Contents

1
Introduction

1.1. The Mekong Delta

The Vietnamese Mekong Delta (hereafter: Mekong Delta), located in the southernmost part of the country, covers a vast triangular area of 40,500 km^2 stretching from the border with Cambodia in the northwest to Ho Chi Minh City in the northeast and Ca Mau province in the south (Figure 1.1). In Cambodia, the Mekong River divides into two main branches: the Mekong (Tien River) and the Bassac (Hau River) [67]. With complex multichannel systems these rivers end in estuaries reaching the South China Sea at the eastern coast of the Mekong Delta.

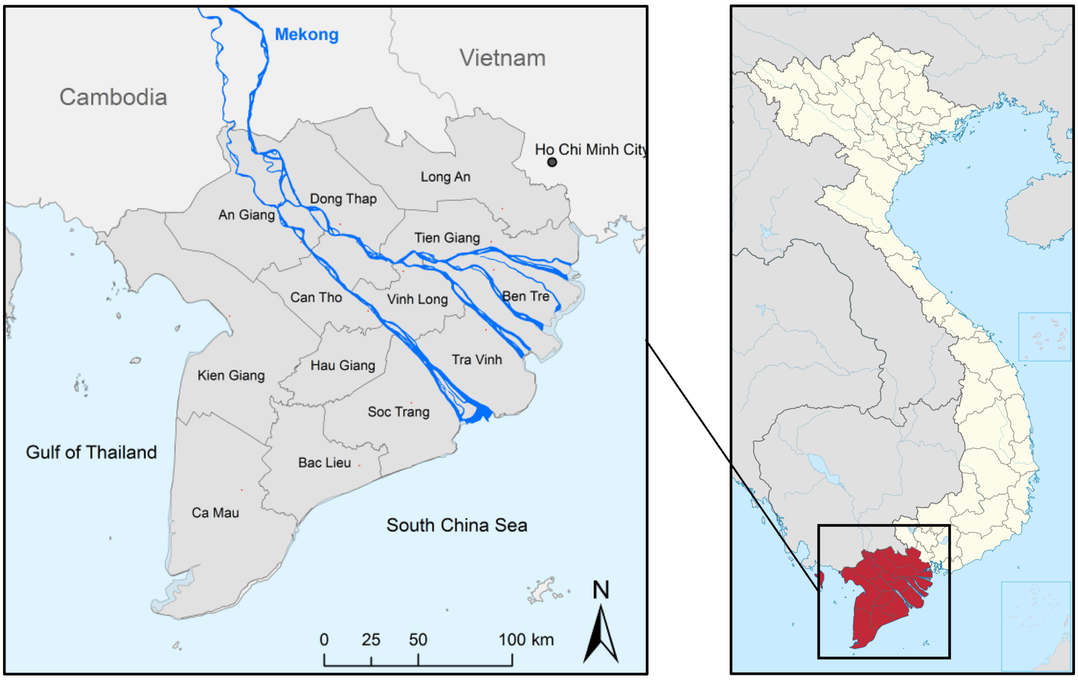


Figure 1.1: The Mekong Delta, Vietnam [34]

As of 2018, the Mekong Delta has a population of 17.43 million people and accounts for 12% of Vietnam's gross domestic product [55]. Furthermore, 70.97% of the water surface area for aquaculture and 47.86% of planted area for cereal production in Vietnam is located in the Mekong Delta [55]. Therefore, it goes without saying that the Mekong Delta region is an important link in Vietnam's economy. Additionally, the region is home to at least 247 bird species, 924 fish species and hundreds of plant species [16]. The combination of the vast area of agri- and aquaculture, and large biodiversity make the Mekong Delta a very important region in Vietnam.

The Mekong Delta is a flat region with an average elevation level of 0.82 meter (Figure 1.2), making it prone to inundation. Through climate forecast modelling, the sea-level in the South China Sea is expected to rise between 40 and 64 cm by the year 2100 [28]. Additionally, the region experiences rapid land surface subsidence with rates of up to 30 mm/year [75], largely due to groundwater extraction. Because of this, the relative sea-level rise is even larger than the sea-level rise, increasing the threat of large scale inundation.

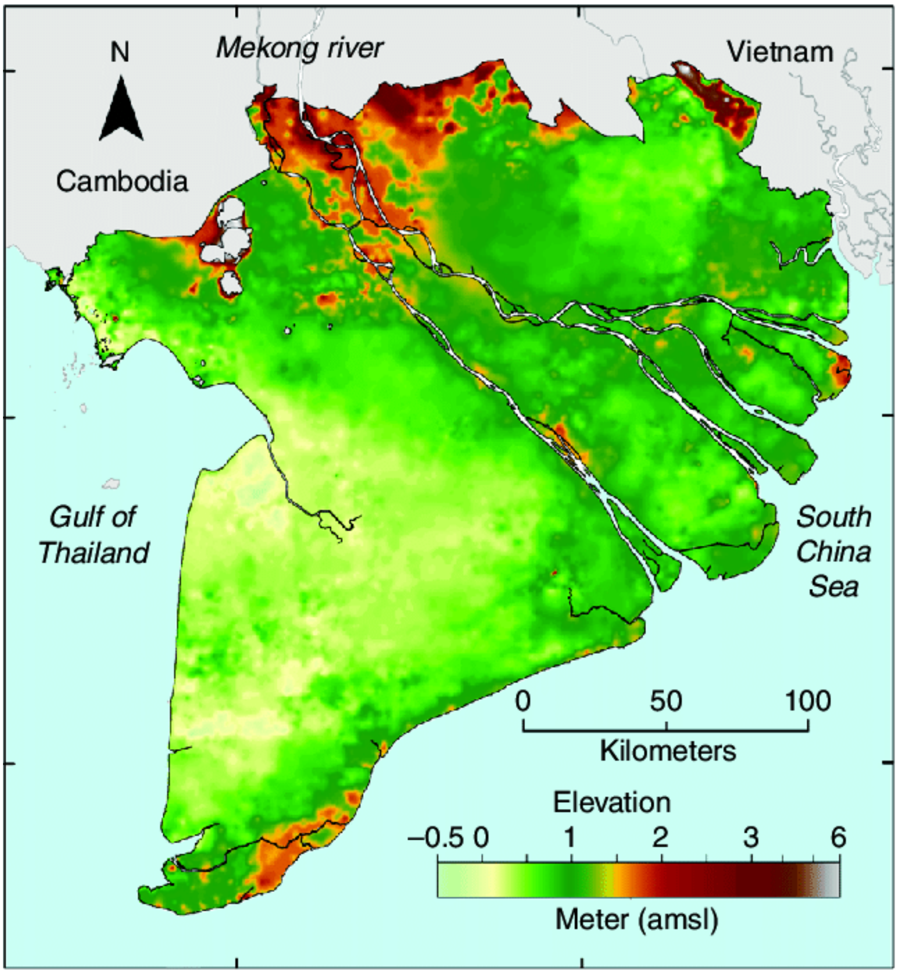


Figure 1.2: The elevation levels of the Mekong Delta [51]

To protect the Mekong Delta from the threats mentioned before, coastal protection is paramount. Coastal regions around the world are home to different inter-tidal ecosystems that offer natural coastal protection. In temperate high-latitudes, salt marshes occur and in (sub) tropical latitudes mangrove forests thrive [77]. Because of its location, the coastal Mekong Delta is characterised by vast mangrove forests. These mangrove forests provide natural flood protection by diffusing wave energy in high energy conditions such as storms and tsunamis [46].

In addition to the aforementioned relative sea-level rise, the coastal Mekong Delta is subject to severe coastal erosion. Up to 50% of the Mekong Delta's shoreline is eroding, with rates of up to 20 meters per year [4][42]. Consequently, the coastal erosion degrades the inter-tidal ecosystems that provide natural flood protection. A key driver for this coastal erosion is a decrease of sediment outflow of the Mekong River system, mainly caused by sand-mining and upstream hydro-power dams. Furthermore, Phan et al. (2015) hypothesizes that coastal mangrove squeeze due to the construction of a sea-dike along the eastern coast of the Mekong Delta is an important driver for the region's mangrove loss [57]. This sea-dike is built to protect coastal aquaculture.

1.2. Problem definition

The increased rate of coastal erosion and subsequent mangrove degradation is considered as the main problem this report addresses. The coastal region near Nha Mat (Bac Lieu province) is specified as the focus area. To the east of Nha Mat a heavily degraded mangrove forest (A) is observed and to the west of Nha Mat a healthy mangrove forest (B) is observed (Figure 1.3). The aim of this research is to analyse the applicability of hydraulic measures and their potential impact on the rate of coastal erosion, on both a heavily eroded coast as well as on a (relatively) partially eroded coast. This is analysed and quantified using the numerical modelling tool Delft3D (Deltares). In addition, during a two-week excursion a socio-economic survey of the research area is conducted and data is collected.

Figure 1.3: Research area Nha Mat, Bac Lieu

The research question is formulated as follows:

What are the hydraulic and socio-economic impacts of implementing coastal hydraulic measures aimed at reducing coastal erosion in Bac Lieu?

This research question is divided into four sub-questions:

1. *What is the socio-economic effect of different hydraulic measures on the inhabitants of the Bac Lieu province?*
2. *What is the effect of different hydraulic measures on the rate of net coastal erosion and subsequent mangrove degradation on the heavily eroded coast east of Nha Mat, according to the numerical model Delft3D?*
3. *What is the effect of different hydraulic measures on the rate of net coastal erosion and subsequent mangrove degradation on the partially eroded coast west of Nha Mat, according to the numerical model Delft3D?*
4. *What is the best course of action for Bac Lieu according to the findings of the numerical model and the socio-economic analysis?*

The answers to these research questions are found by means of the aforementioned numerical model, a literature research and a site investigation, which are all done with the guidance of the *Thuy Loi University* in Hanoi, Vietnam.

1.3. Outline

In chapter 2, theoretical background of mangrove forests and coastal erosion is discussed. Additionally, the stakeholders are discussed. chapter 3 introduces the proposed hydraulic measures that are analysed. The two weeks of field work that is conducted, is elaborated in chapter 4. chapter 5 introduces Delft3D and the model set-up. The results of the Delft3D models are discussed in chapter 6. Finally, chapter 7 and chapter 8 include the conclusions, discussion and recommendations.

2 Background

In this chapter, relevant background information is introduced. First, the stakeholder analysis is introduced. Afterwards the Vietnamese aquaculture is assessed, for the aquaculture sector is both a contributor to the problem this research addresses as well as an important sector for Vietnam's economy. Next, theoretical background about coastal erosion and mangrove forests in the Mekong Delta is discussed.

2.1. Stakeholders

The main stakeholders for conducting a hydraulic project on the coast of Southern Vietnam are stated in Appendix C. The most important stakeholders are considered to be:

- **Government**: When conduction a civil engineering project, the government is responsible for the execution and final result. Therefore, the government's wishes in terms of, for example, economical feasibility and duration of construction, have to be taken into account when such a project is executed. In this research, the government is not directly involved.
- **Inhabitants**: Inhabitants of the Bac Lieu province have to deal with any introduced flood protection measure, and the inhabitants have to suffer the consequences if this measure fails. Therefore a socio-economic analysis of the hydraulic measures on the inhabitants of the Bac Lieu province is conducted.

2.2. Aquaculture in the coastal Mekong Delta

Since the end of the Vietnam war in 1975, the aquaculture sector has been promoted nation-wide for it's importance in providing food and generating income [68]. Since then, the aquaculture sector has grown into the fourth largest aquaculture market in the world, after China, India and Indonesia [61]. One of the main contributors to this success is the yearly flooding of the Mekong Delta. During what is known as the 'floating season' [48] large areas of the delta will be flooded which then provides a natural source of fish for the local fisheries. This fish source used to be sufficient for the Vietnamese fish-market to sustain itself. However, due to global change, this has severely changed over the years. The water-level fluctuations in the Mekong Delta have become much more irregular due to the unpredictable amounts of water that the rivers transport to the ocean. This irregular water level results in a dwindling fish resource. Under these changing circumstances the farmers started to adapt. A recent trend with farmers in the Mekong Delta is to switch to hybrid farming; farming rice as well as fish and other marine animals [48]. The rice farmers recognized that there was more demand for fish then the local fisheries could supply, so they farm fish in their organic paddies to ensure a constant supply of rice, vegetables and fish. Another trend is that fish farmers started farming saltwater-fish and shrimp near the coast, where former rice farmers have left due to disappointing harvests caused by salt intrusion. Aquaculture can be offshore (Figure 2.2) and onshore (Figure 2.1).

Figure 2.1: An example of onshore aquaculture. These are shrimp farming ponds in Vietnam. [17]

Figure 2.2: An example of offshore aquaculture. These are offshore fisheries off the coast of Vietnam. [41]

2.2.1. Economical importance of Vietnamese aquaculture

According to VASEP [59], the bulk of Vietnam's aquaculture exports come from the Mekong Delta. In particular, this region accounts for about 95% of the total pangasius production and 80% of shrimp production. As of 2022, the Mekong Delta was home to 70.97% of a total of 1.1 million hectares of aquaculture in Vietnam [14][55].

The Vietnamese fisheries account for approximately 5% of the national Gross Domestic Product, and approximately 10% of the gross export revenue [59][55]. The Mekong Delta is the main contributor to this economy, estimated to provide a revenue of more than 11 billion US dollars per year (export and domestic consumption) [1] and this share is expected to grow again next year [55]. As displayed in Table 2.1, the top seafood export markets in 2022 have all had a significant growth in comparison to 2021, with China expecting to become the largest importer of Vietnamese seafood in 2023 [14].

Market	**Value (Billion US$)**	**Increase compared to 2021 (%)**
United States	2.1	5
China	1.8	55
EU	1.3	22
Korea	0.9	18

Table 2.1: Vietnam's top seafood export markets in 2022 [14]

2.2.2. The future of aquaculture in Vietnam

In August 2022, the Prime Minister of Vietnam issued a decision on the 'National Program on Aquaculture Development for the period 2021-2030' [35]. This broadly outlines a development plan for the fishing and aquaculture sector, including targets for two five-year periods [14]. These targets are shown in Table 2.2.

Target	**2021-2025**	**2026-2030**
Total aquaculture production	5.6 million tons per year	7.0 million tons per year
Export value	7.8 billion US$ per year	12.0 billion US$ per year
Growth rate of aquaculture value	4% per year	4.5% per year

Table 2.2: Future 5-year targets of the aquaculture market in Vietnam [14]

In order to successfully meet these growth goals, export deals with foreign countries must be maintained. This became a threat when Vietnam received a so called *yellow card* from the European Union in October 2017 [14]. Vietnamese fisheries broke EU rules regarding Illegal, Unreported and Unregulated fishing (IUU). If the necessary steps were not taken to remedy IUU fishing, Vietnam could have received a *red card*, which would have banned all fishing products from Vietnam in the EU. This would have caused Vietnam to lose it's third biggest export market. However, in October 2022, EU inspectors in Vietnam determined that sufficient progress had been made to avoid issuing a red card.

The complications with the EU showed the weaknesses in the Vietnamese aquaculture, which is why the government is investing in more than just expanding the aquaculture. The plans as presented by the Prime Minister [35] show, amongst others, efforts to improve the overall quality of the products, the sustainability and the safety of consuming the products.

2.2.3. Negative consequences of expanding the aquaculture

Along the coast of the Mekong Delta, crab and shrimp farms are the most common form of aquaculture. To protect the hinterland from rising relative sea-levels and high energy conditions, a sea-dike is constructed. Large areas of mangrove forest are cut down to make place for the sea-dike and the aquaculture behind. This phenomenon is called mangrove squeeze and is extensively researched by Phan et al. (2015), who hypothesises it to be the main driver of mangrove degradation in the coastal Mekong Delta [57]. Additionally, Hamilton et al. stated that 77% of all mangrove removal is caused by the aquaculture industry [26]. To elaborate on this relation, sediment dynamics and mangrove hydrodynamics are discussed in the following sections.

2.3. Coastal erosion in the Mekong Delta

Due to high deposition rates of fine sediments and fast compaction rates, the Mekong Delta has been migrating approximately 200 km in seaward direction over the last 4000 years, creating the Ca Mau peninsula [64]. However, studies by Marchesiello et al. (2019) [42] and Anthony et al.(2015) [4] have shown that over 50% of the Mekong Delta coast line is now eroding and that the erosion rates are up to 20 meters per year. These papers also classify different regions in the Mekong Delta as either eroding or accreting regions (Figure 2.3).

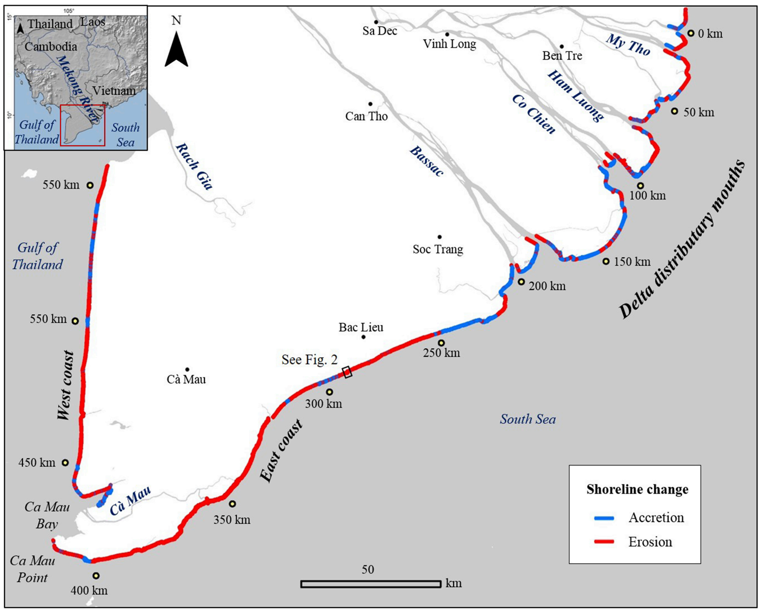


Figure 2.3: Shoreline change in the Mekong Delta due to erosion and accretion (Anthony et al., 2015) [4]. The results show a great erosion area near the city of Bac Lieu

Coastal erosion can have drastic consequences for the environment and inhabitants of the delta. Not only does the land become more vulnerable for flooding, but also the economic and social consequences of the land loss are substantial [21]. To get a better understanding of the processes and dynamics that drive this erosion, the next two subsections will focus on the theory behind sediment dynamics and the main natural and anthropogenic drivers of erosion in the Mekong Delta.

2.3.1. Sediment dynamics

Shoreline evolution is the result of changes in spatial gradients of net sediment transport rates. Sediment transport can be defined as the movement of sediment particles through a defined plane during a certain time [10].

The movement of sediment is determined by two important parameters: The grain size and the fall velocity. A study by Thanh et al. (2017) showed that the median grain size for the east coast of the Mekong Delta is around $10 \mu m$ [65]. The fall velocity is defined as the constant velocity a particle reaches when it settles in still water. The formula of the fall velocity is presented in appendix E.1.

In order for a particle to be suspended and carried through the water, a certain critical shear stress has to be exceeded. The critical shear stress is determined by the grain size. The forces initiating shear stress on the particle are directly proportional to the horizontal velocity induced by the waves and currents, squared (u^2). In order for a particle to settle again, a certain critical shear stress has to be reached and maintained for a certain time. Since the the particles in the Mekong Delta are very small, they are highly cohesive and therefore the critical shear stress for settling is smaller than for suspension [10]. This means that along the shoreline of the Mekong Delta, during high energy conditions, erosion is dominant and, during low energy conditions, sedimentation is dominant.

Next, the sediment dynamics in the Mekong Delta through the longshore and cross-shore plane are discussed.

Longshore sediment transport

A longshore current is defined as a current parallel to the shore line and depth contour lines. The direction and velocity magnitude of this current is determined by the tides and wave breaking in the surf zone and is therefore strongly influenced by the wind directions and different seasons the Mekong Delta and South China Sea are facing [10]. The Indian monsoon season corresponds with low-energy waves coming from the southwest while during the dry season, high-energy waves are coming from the north east [7]. Therefore the dominant net longshore current on the east coast of the Mekong Delta is in a southwest direction [78]. For the area of interest in this research this means that the main longshore sediment supply is coming from the Hau river. The mathematical background of the longshore sediment is presented in appendix E.1.1. From this it should be noted that the rate of sediment transport is highly influenced by the wave height and phase speed.

Cross-shore sediment transport

Under tidal conditions only, the cross-shore profile of a healthy mangrove forest is a convex-up mudflat. However, due to the influence of waves, the profile becomes dynamic and sediment transport takes place in the cross-shore direction. Appendix E.1.2 presents the mathematical background of cross-shore sediment transport. It clearly shows that the flow velocity induced by waves in the cross-shore direction plays an important role in the sediment transport.

Tidal sediment transport

The Mekong Delta is tide dominated, meaning that the sediment distribution in the Mekong Delta is highly influenced by the tides. The tide on the west side of the Mekong Delta can be classified as mixed, but mainly semi diurnal due to M_2 and K_1 tidal waves [53].

Research by Phan et al. (2019) [56] further investigated the properties of the tidal wave propagation in the Mekong Delta and concluded that flow velocities during flood are higher than during ebb (Figure 2.4). This implies an asymmetry in the horizontal tide and a longer falling period than rising period. Therefore the tidal wave can be classified as flood dominant. For flood dominant tidal systems, the net sediment transport induced by the tidal wave is directed in the flood direction. [10]

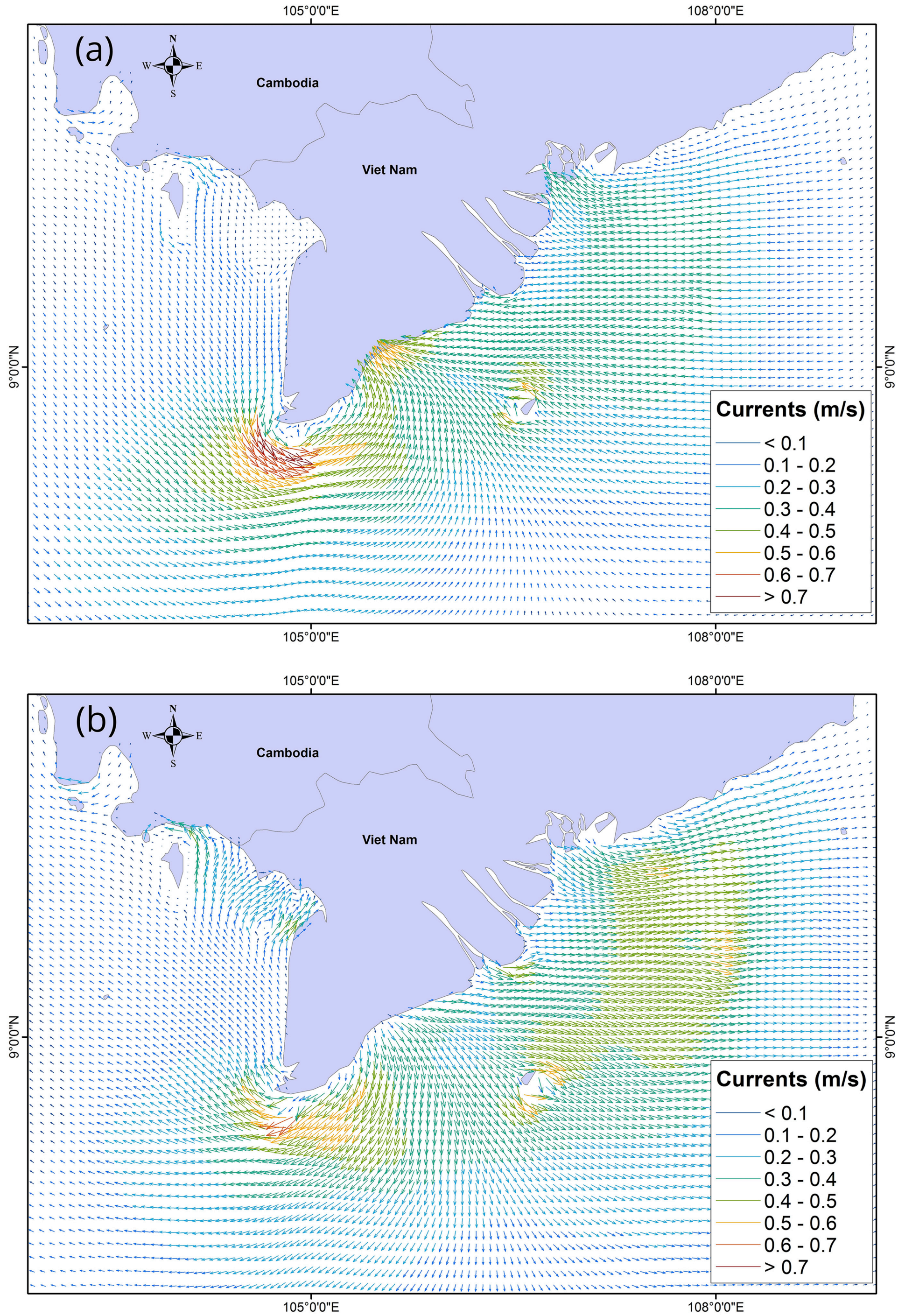


Figure 2.4: Flow velocities during flood (a) and ebb (b) in the Mekong Delta [56]

2.3.2. Main drivers of increased coastal erosion in the Mekong Delta

The drivers of coastal erosion in the Mekong Delta can be classified into natural and anthropogenic. The five main drivers for coastal erosion in the Mekong Delta as recognised by Marchesiello et al. (2019) [42] are mentioned and briefly explained below.

- **Sea level rise and land subsidence:** Groundwater extraction in the Mekong Delta has been increasing rapidly over the last decades [20]. When groundwater is extracted from the soil, pore pressures will decrease and consequently, the soil becomes more compact. This leads to subsidence of the surface. On top of that, global sea levels are rising, leading to a relative land subsidence with an average rate of up to 1.6 cm per year, which will result in a retreat of the shore-line [20].

- **Reduction of sediment fluxes:** The Mekong river is the most important source of sediment for the progradation of the Mekong Delta. In 2019, 86 dams for generating hydropower had been built and 30 others are in the planning stage [49]. Due to the building of these upstream dams sediment will be trapped in basins and will not be transported to the coastal system of the Mekong Delta. Next to that, about $55Mt$ of sediment gets mined per year for construction purposes [13]. It is argued by Van Manh et al. (2015) [70] that these two drivers will lead to a future reduction of delta sedimentation of about 90%.
- **Tidal flow restriction:** In mudflats, such as the Mekong Delta, tidal asymmetries and processes such as settling- and scour-lag play an important role. Since the Mekong Delta is facing a flood dominated tidal regime, tides tend to cause a net onshore sediment transport. Therefore, if the tidal range is shortened, the net import of sediment will reduce. This topic is further investigated in section 2.5.
- **Natural redistribution:** Deltas are generally unstable hydro-morphodynamic systems that experience phases of growth and retreat at multi-decadal timescales [74]. This can cause differences in shoreline locations.
- **Mangrove squeeze:** This is the main topic of this research. Mangrove squeeze refers to the size reduction of a mangrove forest and will be discussed in more detail in the next two sections of this chapter.

2.4. Mangrove forests in the Mekong Delta

Mangrove forests are complex ecosystems with an important role in sustaining a healthy coastal environment in (sub) tropical latitudes. They provide natural habitat for various animal and plant species, help ensure a stable shoreline, store carbon and provide natural coastal protection. Phan et al. (2015) states that the critical minimum width of a coastal mangrove forest strip to be stable is *140 m* on average [57]. Over the past 50 years, the Mekong Delta coastal mangrove forests have decreased significantly. In 1973, the total area of mangrove forests in the Mekong Delta was 185,800 ha, of which 102,160 ha was left in 2020 [58]. Drivers such as aquaculture (section 2.2), agriculture, urban development and coastal erosion (section 2.3) have caused this large-scale mangrove deforestation [3].

Furthermore, mangrove forests are subject to long-term influences such as relative sea-level rise, changes in sediment flux and climate oscillations [3] [24]. From CMIP5 models, it is predicted that the sea-level in the South China Sea will rise between 40.9 cm (RCP2.6) and 64.1 cm (RCP8.5) by the end of this century [28], and according to the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) [22] of the Mekong Delta, the average elevation of the Mekong Delta plain is 0.82 m above the Hon Dau tidal datum (Vietnam) [51]. From this, it becomes clear that relative sea-level rise in the Mekong Delta plain is a critical influence on the preservation of the Mekong Delta. McIvor et al. (2013) gives the following three relations between the relative sea level rise and mangrove growth [47]:

- If the rate of accretion in the mangrove forest is higher than the local rate of sea-level rise, terrestrial plants will invade the mangroves but inter-tidal flats and banks will accrete seawards to allow for mangrove colonization and expansion.
- If the rate of sediment accretion is in equilibrium with the local rate of sea-level rise, the mangrove forest is stable.
- If the rate of accretion in the mangrove forest is lower than the local rate of sea-level rise, the forest drowns at the sea side, but invades newly flushed areas by tides at the land side.

Consequently, the relation between sediment flux and relative sea-level rise within coastal mangrove forests is key in the preservation of these ecosystems, especially if the land side is constrained by a sea-dike.

2.4.1. Hydrodynamics in coastal mangrove forests

As mentioned before, mangrove forests inhabit an inter-tidal area, meaning that the ecosystem is aquatic during high tide and terrestrial during low tide. Therefore, the tidal hydrodynamics within mangrove forests can not be defined using a single model or be treated as a continuous flow [45]. Mangrove forests along the shorelines of the Mekong Delta are so called *fringe forests* or *F-type forests*. F-type forests face the open sea and are thus exposed to both tidal waves and sea waves. Therefore, (the uncertainties in) tidal and wave-hydrodynamics in mangrove forests are explained in this section. Details on the mathematics are elaborated in section E.2.

Tidal hydrodynamics in mangrove forests are highly influenced by the roots and trunks of the mangrove trees. Mazda (2009) has proposed a control volume V in a mangrove forest, from which a drag coefficient C_D can be derived using engineering practise. A detailed description of the mathematical derivation is given in Appendix E.

In large stretches of the coastal Mekong Delta, mangroves are the first line of defence against sea-level rise and catastrophic events. Coastal mangrove forests have been recognized to have the capability of dampening waves to minimize destruction from erosive waves, storms and tsunamis. Over short distances (less then 500 meters) mangroves reduce the height of wind and swell waves, and over long distances (several kilometers) reduce storm surge water levels [46]. For instance, a healthy mangrove strip with a width of 500 m can reduce the wave height of wind and swell waves by between 50 and 100% [46]. The characteristic root systems, canopy and trunk geometries of mangrove forests play an important role in achieving this [32].

Few measurements are available for the rate of reduction of large waves and storm surge water levels by mangroves [46]. However, numerical models such as the WAPROMAN model (Vo-Luong et al., 2008) and the SWAN model (Booij and Holthuijsen, 1999. Main wave model in Delft3D.) are suitable to predict wind wave reduction in mangrove forests [40][9]. Vo-Luong et al. (2008) has used small amplitude wave theory to predict wave propagation through non-uniform mangrove forests in Nang Hai in the Can Gio mangrove Biosphere Reserve (Ho Chi Minh, Vietnam), resulting in a predicted wave energy reduction of 50 to 70% in the first 20 m of mangroves [40].

Furthermore, an empirical method by Mendez et al. (2003, Figure 2.5) for wave transformation on vegetation fields shows wave height evolution for different theories [50]. From this, it is observed that the relative wave height ($H_{rms}/H_{rms,0}$) decreases quicker with respect to the relative sea-level (h/h_0) for situations including vegetation (shoaling vs. shoaling + vegetation, and shoaling + breaking vs. shoaling + vegetation + breaking).

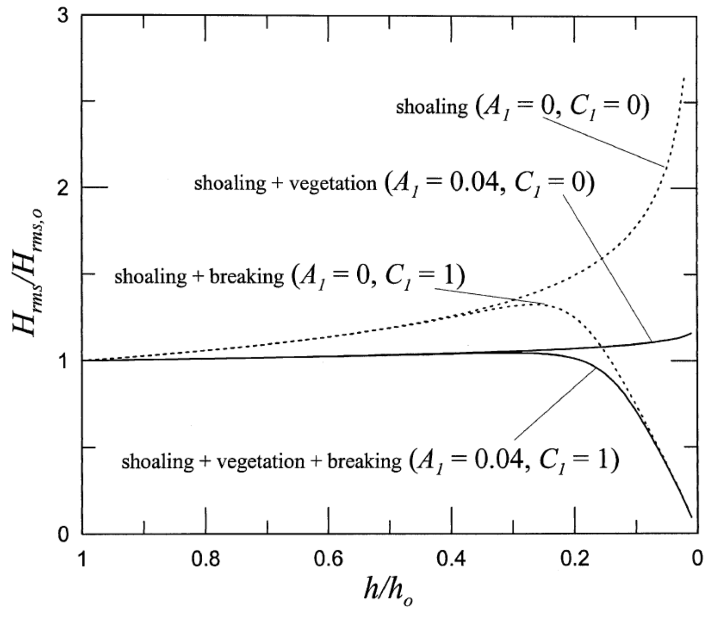


Figure 2.5: Nondimensional root-mean-square wave height evolution over a plane sloping beach for different theories [50]

It is clear that vegetation in the form of a mangrove forest influences tidal hydrodynamics and has the capability to reduce incoming wave energy and wave height. In the following subsection, the relation between mangrove degradation and coastal erosion is discussed.

2.5. The effect of mangrove squeeze on coastal erosion

As stated in section 2.2, over 77% of all mangrove forest loss is caused by aquaculture. After a strip of the mangrove trees is cut down, a dike is built to protect the farms from the high tides and waves at the new shoreline Figure 2.6.

Figure 2.6: Satellite image of mangrove forest and fish farms separated by a dike (in yellow). Image from Google Earth.

As explained in section 2.4, mangrove forests can dissipate wave energy and therefore reduce wave-induced coastal erosion (section 2.3). Removing a part of the mangroves will therefore lead to more erosion. Next to that, the dike reduces the tidal volume and due to the fact that the tides are flood dominant (subsection 2.3.1), consequently reduces the sediment inflow. Winterwerp et al. (2013) [73] calculated for an arbitrary but characteristic mudflat that building a dike at the high water line can reduce sediment import by 10% for every tidal cycle. Therefore, it can be said that the deforestation of mangrove forests for aquaculture leads to the gross increase of sediment export as well as the gross decrease of sediment import, leading to a net export of sediment.

2.5.1. Mangrove erosion feedback loop

The erosion in the mangrove forest will result in a transformation of the cross-shore profile of the mud bed. Mangroves thrive on flat, convex-up shaped profiles (Figure 2.7). However, due to the erosion initiated by the loss of mangroves as described above, this profile will change into a concave-up shaped profile (Figure 2.8).

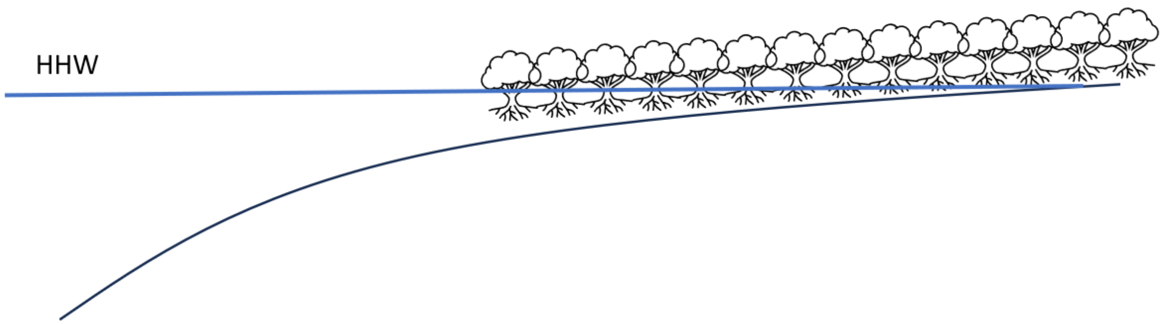


Figure 2.7: Schematized original situation of the mangrove forests growing on a convex-up mudflat profile with the absence of the sea-dike. The shown water level is Higher High Water level.

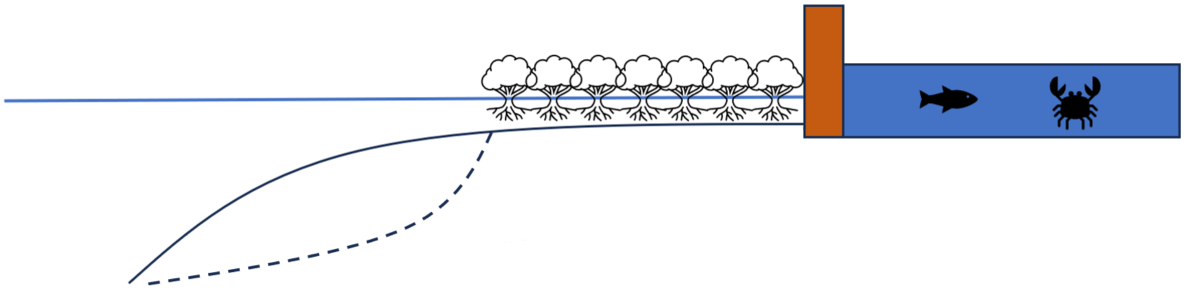


Figure 2.8: The mudflat profile changes from convex-up to concave-up (dotted line) due to the presence of a sea-dike.

Due to this effect, the water depth increases, which results in waves being able to penetrate further towards the coast and cliff erosion to happen at the start of the concave-up profile, enhancing the initial erosion, leading to more mangrove loss, etc. This phenomenon, first described by Winterwerp et al. (2013) [73], can be classified as a positive feedback loop (Figure 2.9).

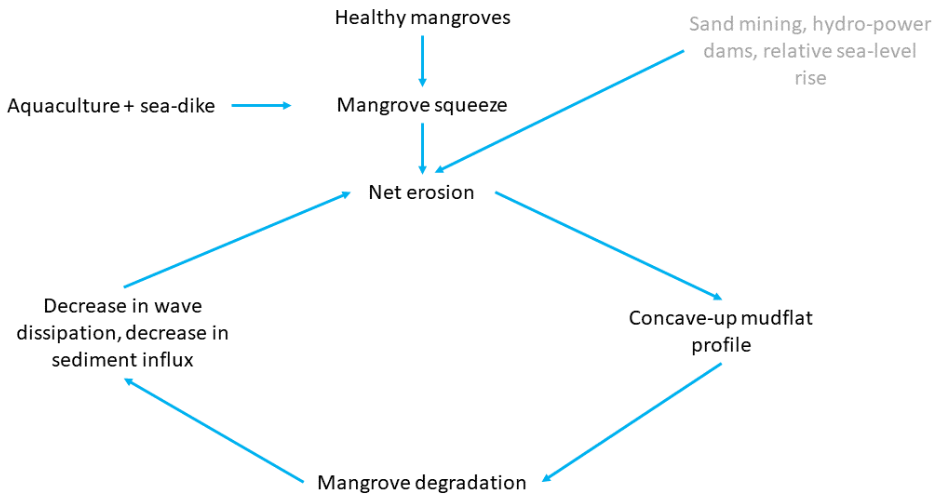


Figure 2.9: Positive feedback loop for coastal erosion induced by mangrove squeeze, based on [73].

2.6. Recent developments on coastal erosion in the Mekong Delta

From section 1.2 it is clear that the coastal area near Nha Mat shows notable differences in the state of coastal erosion and mangrove degradation. In this section, recent developments on coastal erosion in the Mekong Delta are discussed.

In 2013, *Shoreline Management Guidelines* in the Lower Mekong Delta introduced the use of geotube breakwaters [2]. This type of breakwater essentially consists of easy-to-construct sandbags, which are low in costs and use local resources. These geotube breakwaters can reduce the impact of the incoming waves and therefore dissipate wave energy. They are however highly impermeable, meaning that this type of breakwater has a very low potential to allow for sediment transportation to the shore. The conditions for the restoration of the mangroves were therefore far from optimal, since there was no net import of sediment.

Additionally, projects with pile-rock breakwaters have been conducted in Nha Mat and Ganh Hao (Bac Lieu), the Ca Mau province and the Soc Trang province. This type of breakwater is made from concrete piles that are linked with each other and filled with granite rocks [37]. Additional to dissipating wave energy, very fine sediment can flow through the structure because this structure is slightly permeable. However, these breakwaters were built continuously next to each other for long stretches. The overall sediment transport towards the shoreline was therefore not favourable enough for the mangroves to grow back [36]. Therefore, this project was not successful in decreasing the coastal erosion.

The authorities of the Mekong Delta and, more specifically, the Bac Lieu province, have plans to fight (coastal) erosion [52]. In the presented plans, it was suggested to construct 16 erosion-prevention projects along rivers and canals, 9 coastal erosion-prevention projects, 1 residential resettlement project for erosion-affected households, and 1 project to repair and upgrade the transport system, all in the time frame of 2021-2025. The province has about 15 kilometres of shoreline that erodes year round. It has three ”acutely dangerous” coastal erosion sites and one coastal erosion site described as ”dangerous”.

Phạm Văn Thiều, chairman of the provincial People’s Committee, stated that localities should develop prevention plans and closely co-operate with departments and agencies to inspect and monitor rivers and canals and coastal areas that have a high risk of erosion. Localities should inform the public about erosion sites and encourage and help households in erosion-prone areas to relocate to safe areas, he stated. They should also establish plans to relocate residential areas and move construction projects out of erosion-prone areas. In other words, the government seems to be making steps to move the population away from the coast, all due to increased coastal erosion.

To conclude: previous research projects and experiments regarding coastal erosion have been conducted in Nha Mat (Bac Lieu), but the results have not yet been positive. Previous experiments and measures have failed, and the reason why this specific portion of the coast (east of Nha Mat, Figure 1.3) is so affected by erosion still seems unclear. Therefore, it is interesting to model a number of specific measures that have not yet been tested in this area. This way, more data on the subject can be collected and some new insights in possible solutions can be found.

3

Proposed hydraulic measures

This chapter discusses three hydraulic measures that are hypothesized to interfere with the positive feedback loop described in subsection 2.5.1. These hydraulic measures are based on three different criteria that decrease the net rate of coastal erosion.

3.1. Criteria for decreasing the net rate of coastal erosion

There are several main drivers of coastal erosion in the Mekong Delta, as stated in section 2.3. Based on these drivers, three hypothetical ways to interfere with the positive feedback loop are identified; dissipating wave energy, increasing the sediment budget and increasing the tidal volume.

3.1.1. Dissipating wave energy

Sediment settling is linked to wave energy (subsection 2.3.1); when more wave energy dissipates, net erosion decreases. The Thuy Loi University has stated that previous attempts have been made to increase wave dissipation off the coast of Bac Lieu by means of a solid breakwater, as confirmed in section 2.6. This type of breakwater was unsuccessful to counter coastal erosion, but the university is keen to discover the potential of different kinds of breakwaters. Therefore, a hydraulic measure in the form of a new type of breakwater will be assessed. This is analyzed further in section 3.2.

3.1.2. Increasing sediment budget

Mangroves need a convex-up mudflat shape to thrive. When the amount of sediment that is available for sedimentation (the sediment budget) is too low, net erosion will occur and the convex-up mudflat profile changes to a concave-up profile over time. If the sediment budget is significantly increased, the rate of sedimentation could become larger then the rate of erosion, leading to a net accretion on the mudflat. This could lead the mudflat profile to change to a convex-up shape again over time. As stated in subsection 2.3.2, one of the main drivers of the reduction of coastal sedimentation is found in the rivers upstream in the delta. Increasing the sediment budget on the coast can thus be achieved by increasing the sediment influx from the river delta, or by increasing the sediment influx from the sea. Since the river delta is outside the scope of this research, a hydraulic measure is found offshore. Implementing a nourishment in front of the shoreline is a hydraulic measure that artificially increases the sediment budget on the mudflat.

3.1.3. Increasing tidal volume

As discussed in section 2.5, the initial squeeze of the mangroves, which is caused by the placement of a sea-dike, reduces the tidal volume. Therefore it is interesting to propose a hydraulic measure that increases the tidal volume. This can be done by removing the sea-dike, which would also create more space for the mangroves to spread. When this hydraulic measure is implemented, other forms of protection for the coastal aquaculture and residents against the sea must be found. A nature-based way to do this is to use the spread of the mangroves to offer natural protection from the sea for the individual aquaculture farms. In this project, the potential of mangrove integrated aquaculture is analyzed (section 3.4).

The following sections discuss the three proposed hydraulic measures and their potential to reduce coastal erosion and the degradation of mangroves.

3.2. Detached breakwaters

Breakwaters are designed to protect the shoreline from incoming waves. Attached breakwaters are made from concrete and are perpendicularly placed to the shoreline. However, they can have a negative impact on the longshore hydrodynamics and sediment processes along the coast [38]. This mainly causes a decrease in sediment inflow, which subsequently increases the net coastal erosion and degradation of mangroves. For breakwaters to therefore be a successful hydraulic measure, a different design has to be made that will also allow for a net import of fine-grained sediment.

Tu Le Xuan et al. (2022) [38] tested the effect of detached breakwaters on incoming waves and the transport of sediment, using the numerical model MIKE21-FM. This type of breakwater consists of traditional solid concrete breakwaters, but parallel to the shoreline. The detached breakwater was even tested in a submerged state and with a specified gap between the structures. The outcome of this research showed that detached breakwaters can reduce the height and velocity of attacking waves by over 50%, compared to the situation without breakwaters. The model also showed that the breakwaters increase the sedimentation input behind the structures along the coast. This was even the case for strong currents and waves during the monsoon season, coming from the north-east.

The study of Tu Le Xuan et al. (2022) also concludes that several detached breakwaters next to each other can reduce the incoming wave height from 0.7 m to 0.3 m. Additionally, the breakwaters can decrease the velocity near the shore from 0.5 m/s to 0.2 m/s. Regarding the increase in sediment accumulation, the model showed an accretion of 0.3-0.4 m (Figure 3.1). This amount of sediment deposition is considered to be an encouraging amount for mangroves to grow [38].

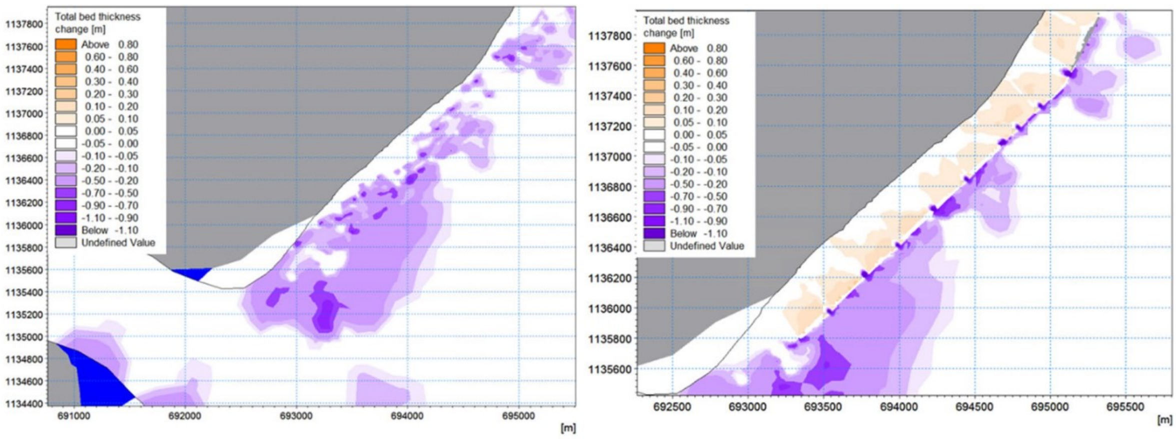


Figure 3.1: The decrease of bed thickness for the current situation (seen left) and the increase in bed thickness along the shore with the application of detached breakwaters (seen right) [38].

As a side note to the positive outcome of this research, erosion around the breakwaters close to the gaps is observed. To prevent this from happening, extra care regarding the protection of the toe of the breakwater should be considered.

In the following subsections three different types of detached breakwaters are discussed. As stated in subsection 3.1.1, a different type of breakwater than already applied before is an interesting hydraulic measure. The main difference should be the allowance of sediment flux through the breakwater. The considered types of breakwaters are therefore not only detached, but also porous.

3.2.1. Hollow porous triangle breakwater

The first type of detached breakwater is a hollow porous triangle breakwater (HTB), see Figure 3.2. This type of breakwater has already been studied and tested in a physical model on the capacity to reduce wave transmission and increase the dissipation of the incoming waves, while sediment transport through the breakwater is possible [39].

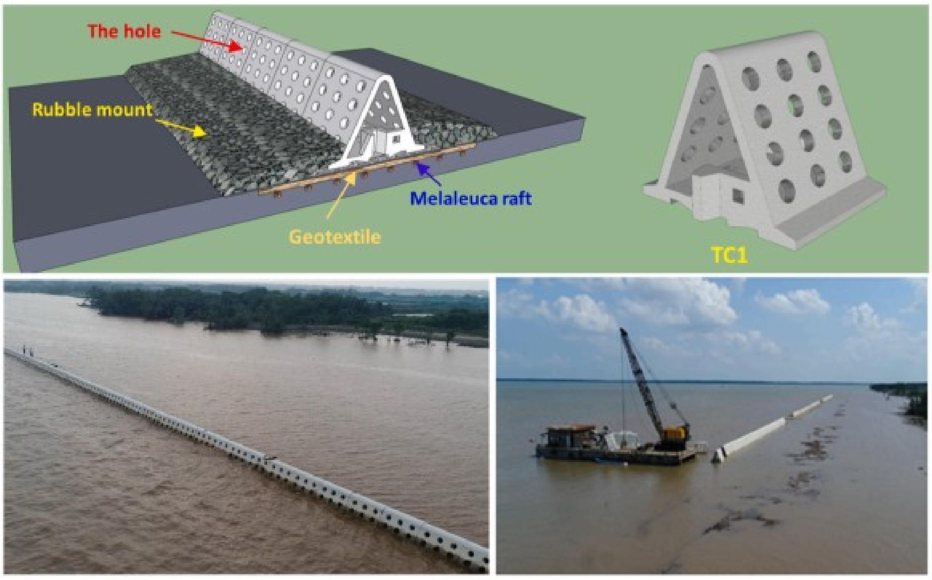


Figure 3.2: The hollow (porous) triangle breakwater, HTB [39]

From the results of the physical model, it was observed that the breakwater can reduce the height of the incoming waves by 66% compared to the height of the transmitted waves behind the breakwater structure. Furthermore, it was concluded that the porous structure was effective in decreasing the reflection of the waves and thereby decreasing the wave disturbances in front of the structure. This is favourable for the stability of the structure. After doing measurements in the field as well, it was established that the HTB is able to dissipate most of the wave energy carried by short waves, and allowing long waves to pass through the porous structure. This improves the sediment input behind the structure and therefore reduces the erosion along the coast.

3.2.2. Concrete pillar breakwater

A concrete pillar breakwater consists of a number of rows of reinforced concrete pillars piled into the seabed. It is hypothesized that it dissipates incoming wave energy while still allowing for sediment transport towards the shoreline, thus decreasing the net coastal erosion.

The concrete pillar breakwater is derived from the pile-rock breakwater (Figure 3.3). The pile-rock breakwater has been physically tested on the west coast of Ca Mau and on the coast of Bac Lieu (section 2.6) [36] [54]. This breakwater consists of two rows of reinforced concrete pillars, filled with granite rocks. The mentioned projects in Ca Mau and Bac Lieu have shown that this type of breakwater is successful at dissipating the incoming waves. However, the breakwater was not considered permeable enough, since it resulted in a high amount of reflected waves and very little sedimentation capacity [36] [54].

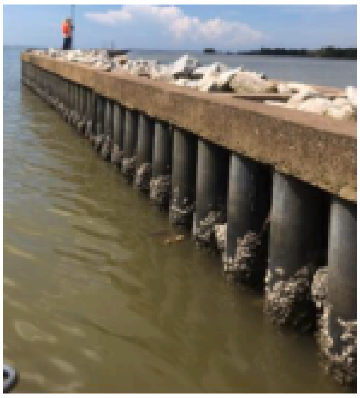


Figure 3.3: A pile-rock breakwater in Bac Lieu [54]

In this research it is hypothesized that, when placing multiple rows of circular concrete pillars instead of the breakwater being filled with granite rocks, the required wave dissipation is achieved while also keeping wave reflection to a minimum which should result in a higher sediment influx.

3.2.3. Bamboo fence breakwater

For the third type of detached breakwater, a fence model is discussed. This type of breakwater can be constructed from local material such as bamboo, which makes it a more nature based, sustainable and economically viable type of breakwater (Figure 3.4). This fence has an outer frame of thick bamboo poles, with an infill of smaller bamboo sticks.

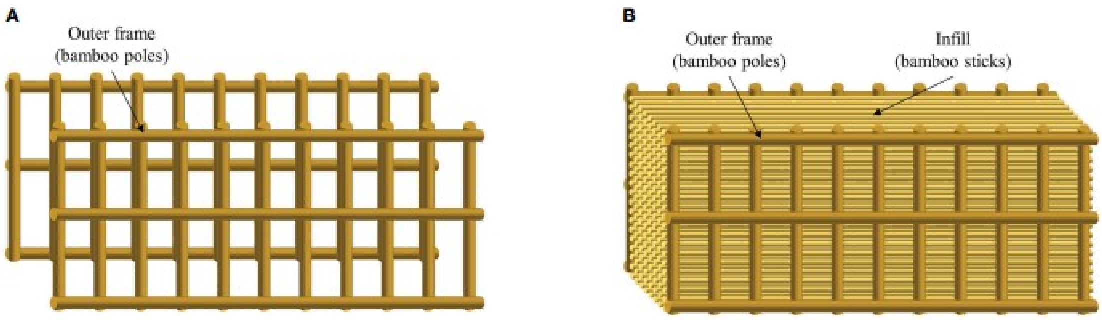


Figure 3.4: The offshore breakwater fence made out of bamboo [63]

It is found that a fence with high amount of infill, meaning a high density, is better in dissipating wave energy. However, it is also established that the higher the density, the more the incoming waves were reflected [63]. This again leads to a decrease in sediment transport through the fence. Anping Shu et al. (2023) concluded that the amount of infill plays an important factor in the efficiency of wave reduction and mangrove restoration [63]. Furthermore, it was proposed that an increasing width of the fence improves the dissipation of waves inside the fence, while decreasing the amount of reflected waves.

3.2.4. Application

Previous research has evidently shown that the types of detached porous breakwaters mentioned in this chapter can be effective in the effort to dissipate the incoming wave energy and increase the net import of sediment behind the structure. They satisfy the first criteria as discussed in section 3.1. The research also made clear that a lot of different variables, such as the porosity, width, length, height and distance from the coast are important factors regarding the ability to achieve these efforts. This project will examine if these detached porous breakwaters can be effective in the researched area, by using a model in Delft3D. This will eventually show the possibility for the coastal erosion to decrease and the mangroves to spread again.

3.3. Nourishment of the eroded banks

A way to increase the sediment budget on a mudflat is to artificially nourish the mudflat. Next to an increased sediment budget, nourishment can also directly provide an increase in wave dissipation due to the local decrease of the water depth, which increases the rate of sedimentation towards the shoreline. The idea behind nourishment is therefore to turn an eroding, reflective beach into a wider, dissipative beach, effectively increasing the sediment influx onto the beach [10]. This process slows down the rate of net erosion, but does not stop it completely. The newly nourished banks will continue to erode over time, until all nourished soil is removed. If the mudflats are to be maintained, then nourishment as a stand-alone hydraulic measure requires long-term maintenance effort by re-nourishing the affected area [76].

Mangroves need a convex-up mudflat profile to thrive. A convex-up mudflat profile entails that the entire area of the mangroves is shallow and tide dominated, as opposed to a concave-up mudflat profile which is relatively deep and wave dominated. As stated in subsection 2.3.1, increased erosion causes convex-up mudflats to transform into concave-up mudflats. As soon as a mudflat has a concave-up profile, it is impossible for mangrove ecosystems to sustain on the mudflat. This transformation can be stopped by nourishing the mudflat. If successful, this can enable mangroves to grow and spread again. There are two main ways in which nourishment can be applied in this case; beach nourishment or shoreface nourishment (Figure 3.5).

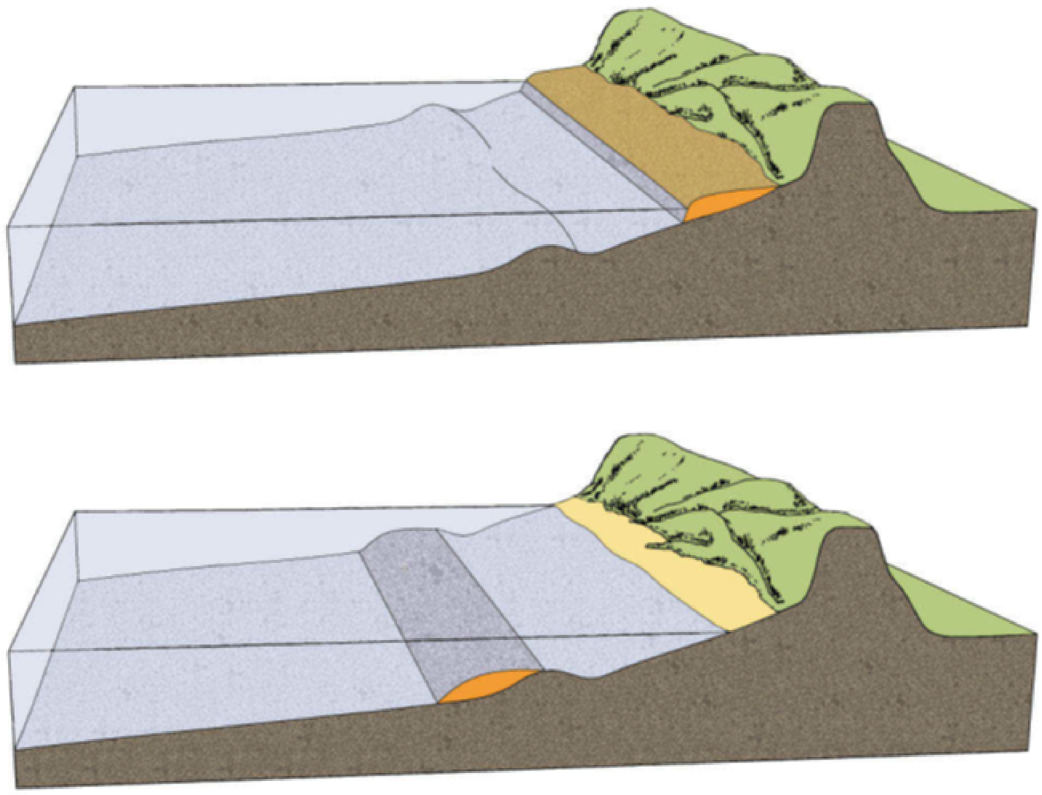


Figure 3.5: Beach nourishment (up) and shoreface nourishment (down). [10].

Beach nourishment entails implementing nourishment directly on the eroded shoreline. For the mangrove lined coasts, this would mean dropping sediment directly at the boundary of the mangroves and the sea. This way, sediment is directly used to extend the mudflat to create space for the mangroves to spread. Beach nourishment is therefore a more immediate hydraulic measure, but will erode away over time and thus shows less potential for a long-term process such as the regrowth of mangroves. Shoreface nourishment entails dropping sediment further offshore. This locally increases the bed profile, causing waves to dissipate energy, which increases sedimentation near the shore. Over time, the nourished sediment will be transported towards the shoreline, potentially leading to a new natural equilibrium where mangroves can thrive. Therefore, the shoreface nourishment is considered to be a more more natural and sustainable option for this research.

3.3.1. Nourishment specifications

The required amount of soil, the type of soil and the nourishing method all depend on the specific location of the nourishing. The soil must be of the same type as the soil that the mangroves grow in, especially in terms of the oxygen content, salinity and acidity of the soil. Otherwise the ability for the mangroves to spread will be restricted. The best way to ensure this is to dredge the soil near the targeted area. Applying the soil could be done with a dredger using the rainbow technique, or through dumping using floating slurry pipelines. This all depends on the availability of space to approach the mangroves. The required volume of nourishment is also dependent on the location; a close analysis of the current mudflat profile (bathymetry) is needed. This can be compared with the ideal mudflat profile that the mangroves in the specific area need to estimate the total amount of nourishment needed to achieve a convex-up profile shape.

3.4. Mangrove-integrated aquaculture

The third criterion to potentially decrease coastal erosion is increasing the tidal volume on the coast. The feedback loop as presented in chapter 2.5.1 is set in motion by the presence of a sea-dike. Removing the sea-dike increases the tidal volume and therefore increases the gross sediment influx. Next to that, removing the sea-dike reduces wave reflection and therefore reduces the gross out-flux of sediment. This limits the amount of coastal erosion and might allow the mangroves to freely grow and spread over time.

In this section the concept of integrated mangrove aquaculture, also called silvo-fisheries, is discussed. Several options are considered and their applicability around the coast of the Mekong Delta is analyzed. Furthermore, it is debated if this hydraulic measure is effective in protecting the farms and if this option is economically viable for the farmers.

3.4.1. Feasibility

Selvam (2012) and Joffre et al. (2015) define two types of silvo-fisheries; separated silvo-fisheries and mixed silvo-fisheries [60] [31]. In both cases, additional space is created for the mangroves to grow by allowing land to be flooded, creating an environment for mangroves to grow around the farms.

- **Separated silvo-fisheries:** In this case, a pond is being surrounded by a dam that encloses the area of that pond/farm. Around this dam, mangroves are planted and able to grow and spread. The enclosed aquaculture ponds can now be flooded by the tides in a controlled manner with canals and sluices. This way a more natural aquatic environment can be mimicked. [31]
- **Mixed silvo-fisheries:** For this type of farming the mangroves are not only placed around the pond, but also inside the pond. This option allows for an improvement of the water quality in the pond and can limit disease outbreaks among the shrimp and/or fish [31]. However, this also means that a part of the farming area needs to be allocated to the mangrove trees, meaning a smaller area to farm shrimp and/or fish.

(a) Separate [29] (b) Mixed [11]

Figure 3.6: Seperate and mixed silvo-fisheries in Indonesia

3.4.2. Application

In this section, separated silvo-fisheries are considered. Mixed configurations are left aside, as mangroves inside a pond do not contribute to the decrease of coastal erosion. Whether the concept of separated silvo-fisheries for coastal aquaculture is applicable in Bac Lieu depends on multiple factors:

- **Flood protection:** Since the sea-dike will be removed, the only flood protection system for the coastal aquaculture are the mangrove forests surrounding the farms and the dam that separates the farms from the surrounding mangroves and sea water. For this concept to be feasible, the mangroves should provide enough flood protection to ensure the protection of the aquaculture.
- **The needed space:** As observed in Figure 3.6a, a large area around a farm is required to house mangroves. In the Mekong Delta, large parts of the coast are riddled with aquaculture built very densely together, resulting in a lack of space for mangroves to grow (Figure 3.7).
- **Money:** Farms need to transform into a silvo-fishery, which costs money. If the farmers are not willing or able to pay for this themselves, this forms a problem. There are, however, examples where authorities support the farmers with payment [62]. This makes it possible for farmers to make the transition and keep a stable income.
- **Time:** Growing and spreading mangroves takes time. A mangrove tree can take between 10 and 20 years to fully mature [12], so the planning of a transformation into a silvo-fishery is essential to maintain protection of the coastal aquaculture.

Figure 3.7: A google maps screenshot showing the lack of space in between farms to place mangroves in South Vietnam.

Silvo-fisheries are an interesting option because it is completely nature based. If the concept proves to work, this hydraulic measure is purely about letting nature find an equilibrium between coastal erosion and the growth of mangroves. It is important to note that the farmers themselves have to be on board with the development, because such a transformation takes a significant time to show results. Their patience and trust in the process is important to the success of such an operation.

3.5. Interfering with the positive feedback loop

To conclude; the three proposed hydraulic measures all meet a different criterion for decreasing the net rate of coastal erosion. Furthermore, the hydraulic measures interfere with the feedback loop on different positions as well (Figure 3.8). The green arrow points to the primary point of interference with the loop.

A detached breakwater interferes with the loop primarily by increasing wave dissipation, leading to a decrease in the net erosion. The primary effect a nourishment has on the shoreline is to increase the sediment budget. This stimulates the rate of sedimentation and decreases net erosion. The loop is primarily set in motion by the presence of a sea-dike, which causes the mangrove squeeze. By removing this main initial driver, the tidal volume is increased and wave reflection is decreased.

It is important to state that without the approval and support of society, such mangrove restoration projects will not be successful [15]. The authorities and public often want to see results within a couple of years, while these restoration projects can take longer. The support of the public is therefore fundamental in making a project socially feasible.

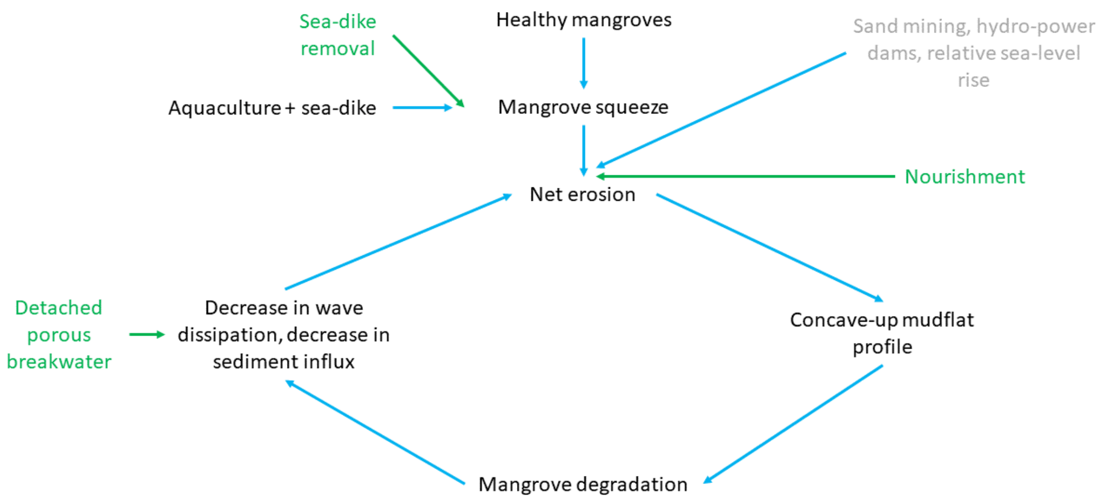


Figure 3.8: Amendment of the positive feedback loop initially presented in Figure 2.9. The three different hydraulic measures are introduced in the loop in green.

4
Field research

To get a better understanding of the socio-economic and hydraulic conditions regarding the research question, a two-week field research is conducted in Ho Chi Minh City and Bac Lieu province. The main goals of this field trip are to do a feasibility study of the proposed hydraulic measures as explained in chapter 3, and to obtain necessary data to complete the numerical model. Further elaboration about the numerical model and the required data can be found in chapter 5. In the first part of the feasibility study, expertise from institutes with experience in the Mekong Delta is obtained. This is done by visiting two institutes and an engineering company in Ho Chi Minh City. In the second part of the feasibility study, inhabitants are interviewed. The required data for the numerical model is partly acquired from the aforementioned institutes, as well by measurements performed in the mangrove forests on the coast of Nha Mat. The most important take aways are stated in this chapter. The full field report is presented in Appendix A.

4.1. Practical feasibility

This section elaborates on the steps that are taken during the field research to come to a conclusion on which proposed hydraulic measures are practically feasible.

4.1.1. Detached breakwater

The goal of this part of the feasibility study is to determine which detached breakwaters are feasible for the coast of Nha Mat, and whether the detached breakwater has to be emerged or (partially) submerged. These choices are made with the help of advise and expertise of the research institutes and Thuy Loi University (TLU). *The Institute of Coastal & Offshore Engineering* (ICOE) in Ho Chi Minh City elaborated on the previously applied detached breakwaters in the Bac Lieu province. From section 2.6 it is concluded that a detached breakwater is generally feasible, because it has been implemented in the same area before. However, solid breakwaters do not have the desired effect. ICOE argues that this is caused by the fact that the breakwater blocks sediment and therefore decreases the sediment budget. Therefore, only porous breakwaters are considered. As explained in chapter 3, there are three kinds of detached porous breakwaters considered; the hollow porous triangle concrete breakwater, the concrete pillar breakwater and the bamboo fence.

A porous bamboo fence is made out of bamboo poles. Since this type of breakwater uses local material, this fence is a sustainable and cheap option. However, ICOE was very sceptical about this hydraulic measure. According to the institute, it has been attempted at the coast of Nha Mat, but failed during high energy conditions. A bamboo fence requires too much maintenance and offers too little resistance during high energy conditions. Therefore, the bamboo fence is not considered feasible.

Royal HaskoningDHV (RHDHV) in Ho Chi Minh City also provided advice on building a detached breakwater. It was implied that a partially submerged porous breakwater can potentially work for controlling the sediment dynamics near the shore, as well as protecting the mangroves on the coast. Such a breakwater does, however, need a lot of maintenance (at least once per year).

To summarize, a detached breakwater has the potential to decrease the rate of coastal erosion and thus potentially allow the mangroves to grow back. The breakwater dissipates the incoming wave energy when the waves cross the breakwater. However, from the expertise of the above-stated institutions it is clear that the previously attempted and currently implemented breakwaters do not allow sufficient sediment influx, or fail during high energy conditions. For this project, a concrete porous breakwater is therefore considered as most feasible for this area. Furthermore, it is argued that the breakwater should be partially submerged. Due to the sedimentation on the coast being flood dominant, it is considered important that the breakwater is submerged during standard high tide (no storm surge). This way, sediment can pas through and over the breakwater during high tide to increase the sediment budget, while still dissipating wave energy. The specific dimensions of the breakwater are explained in chapter 5.

4.1.2. Nourishment

From chapter 3 it is known that a nourishment can be implemented to control coastal dynamics in terms of sediment transport. Therefore, a nourishment is a high potential hydraulic measure for reducing the rate of coastal erosion, especially over a longer period of time. In combination with the fact that it has not yet been tested in the Mekong Delta, nourishing the mudflats is interesting to further investigate. To determine whether the mudflat is suitable for shoreface nourishment, the bathymetry obtained from the *Southern Institute of Water Resources & Planning* (SIWRP) is analysed (Appendix G).

Practicality

The practicality of nourishment depends on the accessibility of the mudflat for dredging vessels. Because shoreface nourishment is considered in this study, dredging ships do not not need to be able reach the beach. The location of the nourishment will be several kilometers offshore. The specifics of the applied nourishment are stated in chapter 5. Bathymetry data from the SIWRP shows that the slope of the sea bed off the coast of Nha Mat is very flat. The water depth 1000 meter offshore is approximately 3 meters during high tide, and reaches 0 meters during low tide. Trailing suction hopper dredgers generally have a dredging draft of approximately 7 meters which makes rainbowing impossible, as the vessels can not get close enough to shore [6][5]. However, dumping through floating pipelines using guidance barges is possible (draft often below 2 meters [43]).

4.1.3. Mangrove-integrated aquaculture

Mangrove-integrated aquaculture resulting from the removal of a sea-dike is a hydraulic measure that has very rarely been applied anywhere in the world. On paper, this is a very interesting hydraulic measure to investigate. The implications with respect to flood protection are straightforward; the primary structure providing flood protection (sea-dike) is removed, resulting in the mangroves remaining as the only form of flood protection. This is a very drastic hydraulic measure, especially for the inhabitants and businesses of the hinterland. Therefore, it is paramount to asses the land-use at the Nha Mat shoreline.

RHDHV is very critical about the removal of the sea-dike, because of the extensive land-use and little to no (space for) individual flood protection. Additionally, it takes years for a degraded mangrove strip to regrow and provide sufficient flood protection properties (flood protection properties of mangroves are discussed in section 2.4). This is confirmed during the site investigation (Appendix A).

4.2. Socio-economic feasibility

The second part of the feasibility study focuses on the socio-economic consequences of the proposed hydraulic measures. During the interviews with the aforementioned institutes, discussions were held about related topics.

As mentioned before, RHDHV was very sceptical about removing the sea-dike. Due to the intensive land use behind the dike, the removal of the dike would not only be impractical but would also have a lot of influence on the daily life of the inhabitants and the work of farmers. Moreover, ICOE mentioned that the local authorities want Nha Mat to be ”The centre of aquaculture” and is investing in the sector, leading to even more intensive land use in the future. Multiple observations of building projects during the field research confirm the statements made by the institutes.

In terms of the socio-economic feasibility of mangrove restoration projects in general, ICOE made a comment about the support base of the inhabitants and local authorities. From their experience, inhabitants often agree with the government when new restoration plans are made, and don't have an opinion on how exactly this is done. However, some local authorities are sceptical about the urgency of mangrove restoration. They argue that making an investment in such projects is redundant, since the dike already brings enough coastal protection and the mangroves offer no economic value.

In order to confirm or contradict the statements of the institutes and to get a better understanding about the social and economic values of the inhabitants and farmers that live near the sea-dike, interviews are conducted. It is considered important for this research to assess the sentiment that the inhabitants of Bac Lieu have towards artificially interfering with the increased erosion. It is also assessed whether certain proposed hydraulic measures are more favourable than others, and how much the inhabitants of Bac Lieu are affected by the increased flooding in the area. The results can be used for assessing the socio-economic impact of the proposed hydraulic measures (sub-question 1). To conduct these interviews, the English questionnaires provided in Appendix B are translated into Vietnamese.

The results of the questionnaires are given in subsection A.4.1. There were 9 correctly filled out questionnaires by inhabitants and there was 1 correctly filled out questionnaire by a farmer. This is not sufficient for a representative statistical analysis. However, some interesting observations are made:

- *We would like you to give a score to the statements below.* From 9 correctly filled out questionnaires by inhabitants, *I am concerned about the loss of mangroves* scored highest.
- *What kind of action should be taken to reduce the negative effects of flooding?* From 9 correctly filled out questionnaires by inhabitants, restoration of mangroves as a hydraulic measure against flooding was scored as most important or second most important a total of 8 times.
- *The government should invest more money in…* From 9 correctly filled out questionnaires by inhabitants, investing in the aquaculture sector and the protection of nature was generally agreed with, whereas investing in other local business was strongly disagreed with a total of 6 times.

4.3. Collecting data

The data required to create a model of the Nha Mat coast in Delft 3D is listed in Table 4.1 (raw data included in Appendix G), along with the source from which the data is obtained. The field measurements have been conducted together with a research team from TLU, supervised by Dr. Trung. More specifically, bathymetry measurements have been conducted by sampling the bed level of the mangrove forest every five meters between the sea-dike and the waterline. During this, mangrove characteristics have been determined as well. Specifics about the measurements within the mangrove forest are elaborated in Appendix A.

	Unit	**Sampling**	**Source**
Mangrove bathymetry	z-coordinate (Cartesian)	$\frac{1}{5}m^{-1}$	Measurements in the field
Offshore bathymetry	z-coordinate (Cartesian)	km^{-2}	SIWRP
Significant wave height	m	$\frac{1}{1800}s^{-1}$	SIWRP
Current speed	$\frac{m}{s}$	$\frac{1}{1800}s^{-1}$	SIWRP
Wave direction	degrees (nautical)	$\frac{1}{1800}s^{-1}$	SIWRP
Current direction	degrees (nautical)	$\frac{1}{1800}s^{-1}$	SIWRP
Mangrove trunk diameter	m	-	Measurements in the field
Number of trunks per m^2	-	-	Measurements in the field

Table 4.1: List of collected data

The mangrove characteristics are obtained by determining the spatial density of mangrove trunks and roots ($\frac{n}{m^2}$), and the average diameter. The complete measurements are given in Appendix A. The mangrove characteristics used in the numerical model are listed in Table 4.2 and Figure 4.1 gives an impression of the measurement location.

Criteria	Value
Average trunk density (n/m^2)	0.625
Average trunk diameter (m)	0.07
Average root density (n/m^2)	100
Average rood diameter (m)	0.005

Table 4.2: Mangrove characteristics

Figure 4.1: Impression of measurement location.

4.4. Field research conclusions

The conclusions from the field research are important for the remainder of this research and are stated below.

- Removing (part of) the sea-dike is not feasible. The inhabitants of Nha Mat and it's surroundings live too densely together. The many aquaculture farms are too densely packed together as well. They have no intention of moving away from the coast, and their houses and farms offer no protection against any type of flood. Therefore, the removal of the dike is not considered as a potential hydraulic measure for the remainder of this report.
- Implementing a bamboo fence is not feasible. Expertise from the ICOE in Ho Chi Minh City showed that such a breakwater has already been implemented near Nha Mat in the past, without any success. Therefore, a bamboo fence is not considered as a potential hydraulic measure for the remainder of this report
- Nourishment of the mudflat and a porous offshore breakwater are practically feasible.

- The results of the questionnaires are inconclusive. Possible reasons are discussed in chapter 8.
- Local authorities and research institutes don't agree on whether restoring the mangroves is the most suitable action for reducing flood risk.

5
Numerical model

The second and third sub-questions of this research are answered by implementing the numerical model *Delft3D*, as stated in section 1.2. In order to quantify the effects of different hydraulic measures on the rate of net coastal erosion near the coast of Nha Mat, the Delft3D-FLOW module is used. Delft3D-FLOW is a multidimensional hydrodynamic simulation program which simulates flow phenomena linked to tidal and meteorological forcing on a boundary fitted grid [18]. The Delft3D-FLOW module has the option to be coupled to the Delft3D-WAVE module, making it possible to simultaneously simulate the effects of flow and wave forcing on the modelled coast.

To reduce computational time and unwanted complexity, the model represents a schematization of reality. Therefore, assumptions and simplifications are made. First of all, the model is simplified to a 2DH model, meaning that all properties are assumed to be constant over depth. Therefore, hydrostatic pressure is assumed, which means that baroclinic processes are not taken into account. Next to that, the model assumes steady state conditions, which implies that the boundary conditions do not change in time. Finally, linear wave theory is assumed, since Delft3D-WAVE is based on the SWAN wave model.

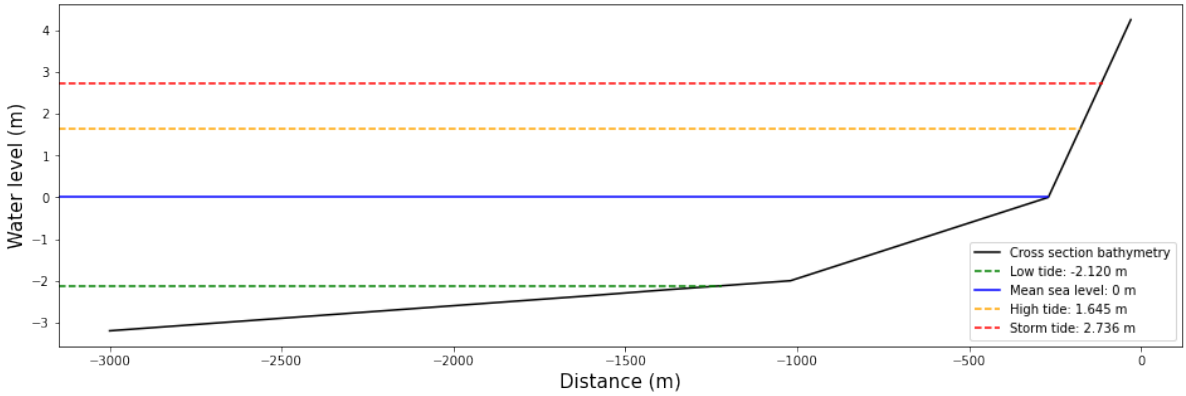
In order to properly simulate the forcing and effects of the proposed hydraulic measures (chapter 3), model-specific assumptions and boundary conditions are defined. This is elaborated in the following subsections. Additionally, validation of the numerical model is discussed.

5.1. Grid and bathymetry

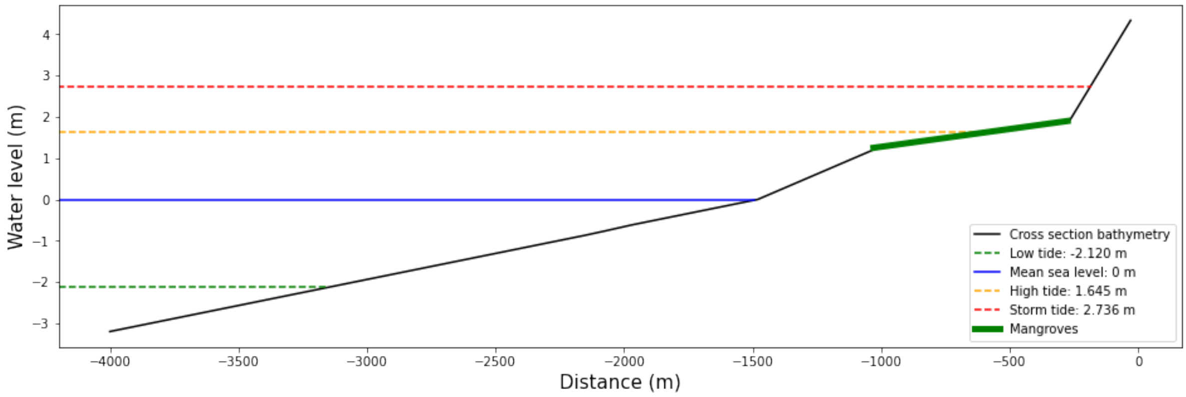
The domains for the two governing situations (heavily eroded coast and partially eroded coast) are defined with different grids. The domain for the heavily eroded coast has a size of *5000 m* in the longshore direction by *3000 m* in the offshore direction. As the mangrove strip on the partially eroded coast has a width of approximately *1000 m*, the corresponding grid is enlarged to *5000x4000 m* to be able to sufficiently visualise the morphological changes.

Delft3D-WAVE generates linear waves at the boundaries of a specified domain (section 5.2). In order to have an accurate wave profile, it is desired to create a secondary, larger domain. The grid and bathymetry of the secondary domain is coupled to the primary grid and bathymetry through *grid nesting*. This allows waves generated at the boundaries of the secondary domain to be used in the computations for the primary domains. In Appendix D, the details of the primary and secondary domains are listed.

For each grid, a bed profile is specified. To define the bed profile, bathymetry data from SIWRP and TLU is analysed (section 4.3, data processing elaborated in section D.2). For simplicity, the bathymetry is assumed to be constant in the longshore direction. Also, since Delft3D is not able to accurately calculate the hydraulic en morphological effects near steep slopes, the observed cliff at the sea-side of the mangroves *and* the sea-dike are modelled with a flatter slope than in reality. In Figure 5.1, the bathymetries (as modeled) for the partially eroded- and heavily eroded mudflats are plotted as a cross section at the center of the respective domains. The tidal range, including storm tide, is plotted for reference.



(a) Cross section of the heavily eroded coast east of Nha Mat



(b) Cross section of partially eroded coast with mangroves West of Nha Mat

Figure 5.1: Cross sections of heavily eroded and partially eroded coasts near Nha Mat. With water levels.

5.2. Boundary conditions

The domain consists of four boundaries. More specifically, one land boundary and three open boundaries. At the open boundaries, Delft3D-FLOW and Delft3D-WAVE require specific boundary conditions that represent the hydrodynamics of the outside world. In section 2.3 it is argued that the sediment dynamics and morphological processes in the Mekong Delta are different for high and low energy conditions. Therefore, the effect of different hydraulic measures on the rate of coastal erosion is investigated for both low energy conditions *and* high energy conditions by defining two unique sets of boundary conditions for both Delft3D-FLOW and Delft3D-WAVE.

5.2.1. Delft3D-FLOW

In Delft3D-FLOW, the offshore boundary is modelled as a *water level type* boundary where the flow conditions are modelled as tidal constituents. From Phan et al. (2019) [56] and Hu et al. (2001) [30], eight main tidal constituents influencing the Mekong Delta coast are defined. Furthermore, for high energy conditions an additional constituent for sea level rise (A_0) is included to represent the storm surge water level [69]. The details of the tidal constituents are listed in Table D.2 and the tidal range is shown in Figure 5.1.

The cross-shore boundaries are modelled as *Neumann type* boundaries. A Neumann boundary is used to describe a longshore water level gradient and can only be used in combination with a water level type boundary at the offshore boundary. The flow- and transport conditions are modelled as time-series, however, these are set to default values because no data is available to create representative time-series.

5.2.2. Delft3D-WAVE

In Delft3D-WAVE, the boundary conditions representing the incoming offshore waves are assigned using cardinal orientation (north, east, south, west). The offshore boundary is the southern boundary and the cross-shore boundaries are the eastern and western boundaries, respectively. Each boundary condition is defined with a set of wave conditions. The data used to obtain the wave conditions is obtained from the Copernicus Climate Change Service program *ERA5 monthly averaged data on single levels from 1940 to present* data-set [19][27] and Tung et al. (2019) [69]. The representative values for an average monsoon season, and a monsoon storm (Beaufort 11, return period 100 years) are listed in Table D.3.

5.3. Physical and numerical parameters

In order for the model to represent the real-world situation as well as possible, a set of physical parameters is defined. As Delft3D is a numerical modelling tool, numerical parameters are defined as well. Finally, the implementation of mangroves in Delft3D-FLOW and -WAVE is discussed.

5.3.1. Physical parameters

Delft3D-FLOW requires five types of physical parameters to be defined (constants, roughness, viscosity, sediment and morphology). The constants are set to default values, as they are not site specific. From Pham et al. (2023), a Chézy coefficient of $57.5\frac{m^{\frac{1}{3}}}{s}$ is defined. For viscosity, default values are applied. As the Mekong Delta coast has a thick sediment layer at the bed and a high concentration of suspended sediment, the sediment layer thickness at the bed is set to $5m$. Finally a morphological scale factor and spin-up interval is introduced. For high energy conditions, the morphological scale factor is set to 1. For low energy conditions, the morphological scale factor is set to 20.

Delft3D-WAVE requires four types of physical parameters to be defined (constants, wind, processes, various). The constants, processes and various sections are set to default values, as they are not site specific. The wind characteristics result from data analysis (Table D.3), and are different for low energy conditions and high energy conditions.

5.3.2. Numerical parameters and time-frame

The numerical parameters in both Delft3D-FLOW and -WAVE are set to default values.

Delft3D-FLOW and -WAVE are coupled, resulting in their time-frames being the same. However, the time-frames for the high- and low energy conditions are different. In low energy conditions, a 48 hour period within an average monsoon season is simulated. With the aforementioned morphological scale factor of 20, the morphological changes in this simulation will represent a 40 day period. In high energy conditions, a monsoon storm (Beaufort 11, 100 year return period) is simulated for 24 hours without an increased morphological scale.

Additionally, a specific time-step is specified. Through the convergence condition by Courant–Friedrichs–Lewy (CFL), the time-step is related to the grid cell size to reduce convergence errors. This results in the time-step being different depending on the weather condition and implemented hydraulic measure. In Table 5.1, the most important parameters are listed.

Shoreline type	Hydraulic measure	Condition	Simulation duration [hours]	Morphological factor [-]	Timestep [min]
Heavily eroded	-	Normal	48	20	0.2
		Storm	24	1	0.1
	Nourishment	Normal	48	20	0.2
		Storm	24	1	0.1
	Breakwater	Normal	48	20	0.06
		Storm	24	1	0.03
Partially Eroded	-	Normal	48	20	0.2
		Storm	24	1	0.1
	Nourishment	Normal	48	20	0.2
		Storm	24	1	0.1
	Breakwater	Normal	48	20	0.06
		Storm	24	1	0.03
Number of simulations: 12					

Table 5.1: Planned simulations using Delft3D

5.3.3. Mangroves

To include the effects of mangroves into the model, a separate vegetation file is created and added to the model as an additional parameter. The vegetation file takes five input characteristics; the area where the mangroves are growing, the plant density, the average diameter, the height and the drag coefficient C_D. The C_D is set to the default value. It is observed that the mangroves grow from the dike to the high tide water line, this is thus specified to be the area. The mangrove density, average diameter and height are obtained by measurements (subsection A.3.2) and are listed in section D.4.

5.4. Validation

The model is validated by comparing results of a simulation without hydraulic measures with in-situ measurements made by SIWRP. As sedimentation and erosion is related to the wave height and flow velocity, these model outputs are validated. Next to the comparison with real-time data, the simulation is also analysed to see if it's behaviour is conform the expectations in terms of the cumulative erosion and sedimentation throughout the cross section of the mudflat. The full validation process is documented in (section D.5).

5.5. Integration of hydraulic measures

Results from the field trip show that the detached porous breakwater and shoreface nourishment are feasible solutions to investigate further. In this section the exact specifics of these solutions, and how they are modelled are discussed.

5.5.1. Detached porous breakwater

The dimensions of the porous breakwater are chosen with the aim to satisfy the following criteria:

- Under low-energy, high tide conditions the breakwater has to be submerged with at least $0.5m$. This way, sediment can pas through the breakwater as well as over it, further improving the rate of sedimentation on shore.
- The breakwater must not be placed too close to the shore, as there must be room for the mangroves to spread in offshore direction. It is argued that a mangrove forest needs at least a $500m$ width to optimize their wave dampening effects (section 2.4). Previous research has shown that the positive effects of breakwaters are reduced when placed more than $150m$ offshore due to new wave fields being formed behind the breakwater [72]. However, this effect is considered negligible due to the small water depths and slope of the focus area.

As concluded from the field research, the bamboo fence breakwater is not a feasible option (section 4.4). Therefore, the hollow porous triangle and the concrete pillar breakwater remain as feasible options. Since Delft3D does not allow for a representative implementation of the hollow porous triangle breakwater, this option is not modelled. The concrete pillar breakwater, however, can be modelled schematically in Delft3D. This type of breakwater is therefore used in the Delft3D model.

To model the concrete pillar breakwater in Delft3D, for both the partially and heavily eroded coast, partially submerged cylindrical piles are modelled along a width of $3m$ and with a length of $2000m$ parallel to the shoreline. In a previous project along the west coast of Ca Mau, the piles used for a pile-rock breakwater had a diameter of $0.35m$ [54]. In this model the diameter of the piles are therefore chosen to be $0.35m$. With a spacing of $0.18m$ between the piles in horizontal direction, the amount of concrete piles are $4/m^2$. Since the concrete piles are cylindrical and the flow is turbulent, the drag coefficient takes a value of 1 [25].

Heavily eroded coast

The breakwater interferes with the feedback loop introduced in subsection 2.5.1 primarily by increasing the dissipation of incoming waves. The placement of the breakwater is therefore determined by the development of the significant wave height in cross-shore direction, abiding by the criteria mentioned in subsection 5.5.1. From the significant wave height under high energy conditions, it is determined that the concrete pillar breakwater is placed at a distance of $1150m$ from the beginning of the sea-dike. At this distance the breakwater is expected to dissipate the incoming wave energy and stimulate sediment influx.

Under low-energy, high tide conditions the breakwater has to be submerged to at least $0.5m$ below high tide. At high tide, the water level reaches $1.6m$ above mean sea level. At $1150m$ offshore, the water depth is $2.1m$. A $0.5m$ gap between the top of the breakwater and the high tide water level results in a height of the breakwater of $3.2m$. This breakwater is visualized schematically in Figure 5.2.

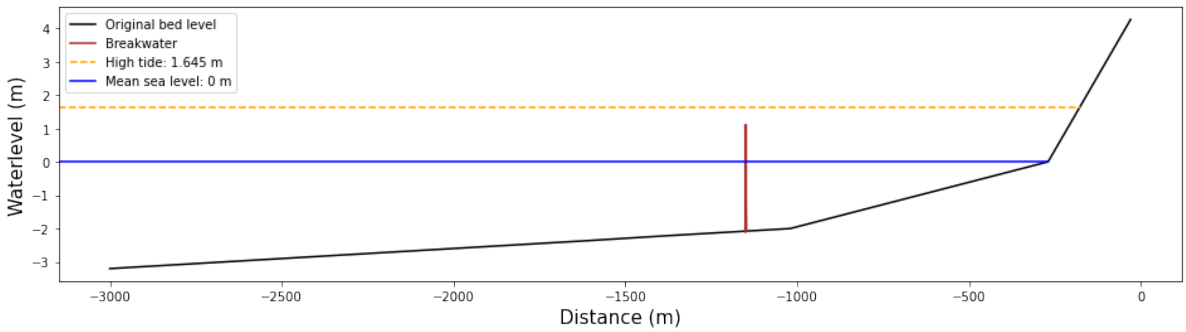


Figure 5.2: The cross section of the heavily eroded mudflat with the modelled breakwater.

Partially eroded coast

The placement of the breakwater on the partially eroded coast is determined in a similar manner as for the heavily eroded coast. From the significant wave height in high energy conditions conditions, it is determined that the concrete pillar breakwater is placed at a distance of $1610m$ offshore of the sea-dike. At this distance the breakwater is expected to dissipate the incoming wave energy and stimulate sediment influx.

At high tide, the water level reaches $1.6m$ above the mean sea level. At $1610m$ offshore of the sea-dike, the bed level is $-0.2m$ with respect to mean sea level. Similar to the breakwater on the heavily eroded coast, a $0.5m$ gap between the top of the breakwater and the high tide water level in low energy conditions is maintained. The height of the breakwater then becomes $1.3m$. This breakwater is visualized schematically in Figure 5.3.

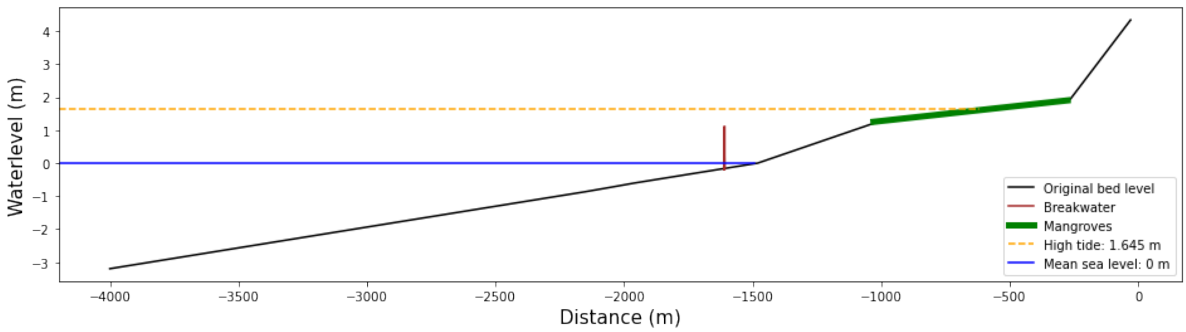


Figure 5.3: The cross section of the partially eroded mudflat with the modelled breakwater.

Input values

The model input values for the partially submerged porous breakwater are listed in Table 5.2

Parameter	Partially eroded coast	Heavily eroded coast
Distance from the sea-dike in offshore direction (m)	1610	1150
Height (with respect to bed level) (m)	1.3	3.2
Width (m)	3	3
Length along the coast (m)	2000	2000
Pile density (n/m^2)	4	4
Diameter of the piles (m)	0.35	0.35
C_D $(-)$	1	1

Table 5.2: Input values for the breakwater in Delft3D

The breakwater is simulated for both low energy and high energy conditions. It is expected that during high energy conditions the breakwater has a positive effect on wave dissipation and thus reduces erosion. Because of the porosity of the breakwater, it is expected that during low energy conditions the negative influence on the sediment inflow is low.

5.5.2. Shoreface nourishment

Shoreface nourishment is simulated for both the partially eroded and heavily eroded coast under high- and low energy conditions to model the effect of a higher sediment budget on the rate of net erosion.

According to Bles (2022) on nourishment implementation to rehabilitate mangroves, the best configuration to improve accretion near the shore is with a *plateau of sediment* [8]. The level of the plateau is horizontal over the entire length, thus having a uniform bed level. It is expected that, next to transporting sediment to the shoreline, this configuration increases wave dissipation due to the locally increased slope on the offshore-side of the nourishment.

The plateau of sediment needs to be implemented on the active profile of the coast for the sediment to be transported. As for the entire part of the coast for both the partially eroded and heavily eroded model during low energy conditions intermediate water conditions apply, the plateau is naturally implemented on the active profile.

Heavily eroded coast

The dimensions of the sediment plateau are based on the bathymetry and cumulative erosion and sedimentation of the control simulation under low energy conditions (subsection D.5.3). From this, nearshore erosion and offshore sedimentation are observed. It is argued that this is because of the reflective properties of the heavily eroded coast. In order for sediment to be transported towards the shore, the nourishment is placed on the flatter sloped section of the bed profile. Therefore, the nourishment is placed between $1500m$ offshore ($2.2m$ water depth) and $2500m$ offshore ($3m$ water depth). The visualization of the nourishment is shown in Figure 5.4.

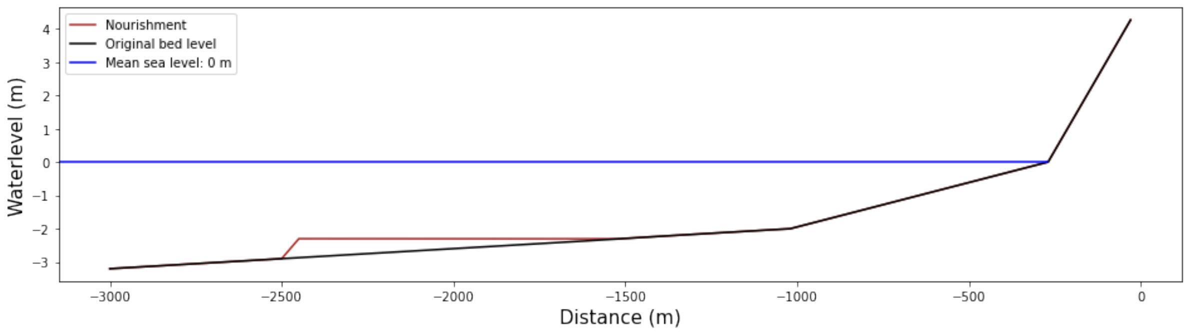


Figure 5.4: The cross section of the heavily eroded mudflat with the modelled nourishment.

Partially eroded coast

The dimensions of the nourishment on the partially eroded coast are determined in a similar manner as for the heavily eroded coast. From subsection D.5.3, it is known that in the control situation most erosion takes place between $2000-2500m$ offshore. At $2000m$ offshore, the water depth is approximately $0.65m$. This is considered to be too shallow for a nourishment to be placed. Therefore, the nourishment is placed between $2250m$ offshore ($1m$ water depth) and $3250m$ offshore ($2.25m$ water depth). The visualization of the nourishment is shown in Figure 5.5.

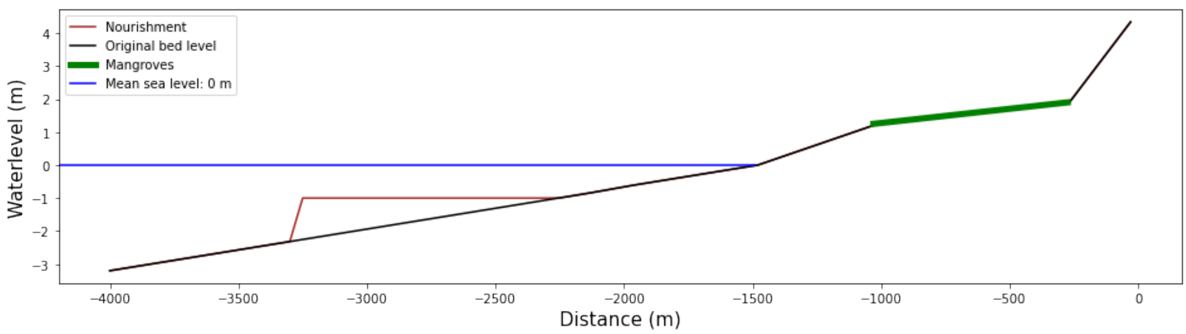


Figure 5.5: The cross section of the partially eroded mudflat with the modelled nourishment.

For low energy conditions it is expected that, next to transporting sediment to the shoreline, the implementation of a nourishment also leads to an increase in wave dissipation due to the locally increased slope on the offshore side of the nourishment. However, since the spreading of the nourished sediment takes a long time (section 3.3), it is expected that for both coasts the effects of the nourishment on net erosion at the shoreline are minimal during high energy conditions. Therefore, high energy conditions are simulated to asses the effect on wave dissipation and overall stability of the nourishment. The nourishment is considered unstable if an increase in erosion is observed over the whole length of the nourishment, compared to the control situation.

6
Results

In this chapter the model results are presented and interpreted. The cumulative erosion and sedimentation for every combination of shoreline type and weather condition, with and without the hydraulic measure in question, is plotted. These plots are then discussed. Furthermore, all the plots are cross sections from the middle of the grid. This is to minimize the effect of the boundaries on the results. Additional results of the amount of wave dissipation of the simulations are shown in appendix F.

6.1. Heavily eroded coast

In this section the simulation results of the heavily eroded coast are presented. For each of the two modelled hydraulic measures, simulation results for high energy and low energy conditions are discussed.

6.1.1. Detached porous breakwater

To gain insight into the effect of a breakwater on the net rate of erosion on the heavily eroded coast, the cumulative erosion and sedimentation is visualised for the situation with (red line) and without (blue, dotted line) a breakwater, for both low and high energy conditions. Negative values (below the gray dotted line) indicate erosion and positive values (above the gray dotted line) indicate sedimentation.

Low energy conditions

Figure 6.1 shows the cumulative erosion and sedimentation over the cross section of the heavily eroded coast, plotted for low energy conditions.

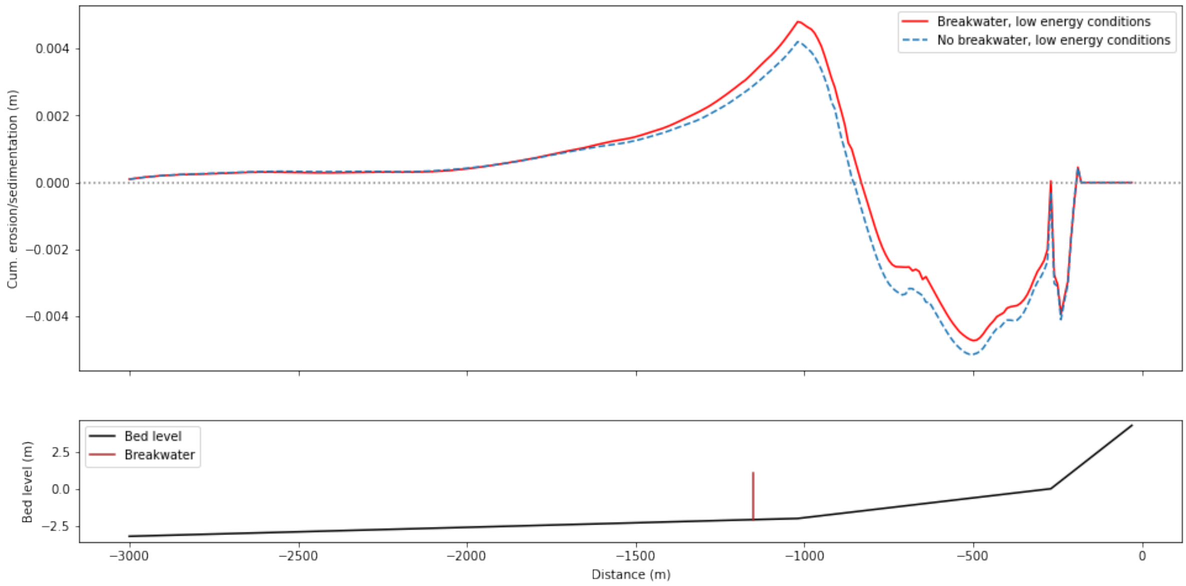


Figure 6.1: The cumulative erosion/sedimentation during low energy conditions on the heavily eroded mudflat, with and without a detached, porous breakwater.

From Figure 6.1 two observations are made:

- **Sedimentation:** The figure shows that the breakwater causes increased sedimentation between approximately $-1600m$ and $-800m$. It is observed that sedimentation is increased both at the offshore and onshore side of the breakwater.
- **Erosion:** For the part of the mudflat that was already eroding without a breakwater (between approximately $-800m$ and $-300m$), a decrease in erosion is observed.

However, when plotting the amount of wave dissipation over the cross section (appendix F, Figure F.3) there is no difference between the simulations with and without the breakwater. It is possible that this is caused by the breakwater being ill-dimensioned (porosity, location, height, pile diameter). However, the results also raise questions about the validity of the schematization of the porous breakwater in Delft3D and therefore the results are considered to be invalid. This is further discussed in chapter 8.

High energy conditions

Figure 6.2 shows the cumulative erosion/sedimentation over the cross section of the heavily eroded mudflat, plotted for high energy conditions.

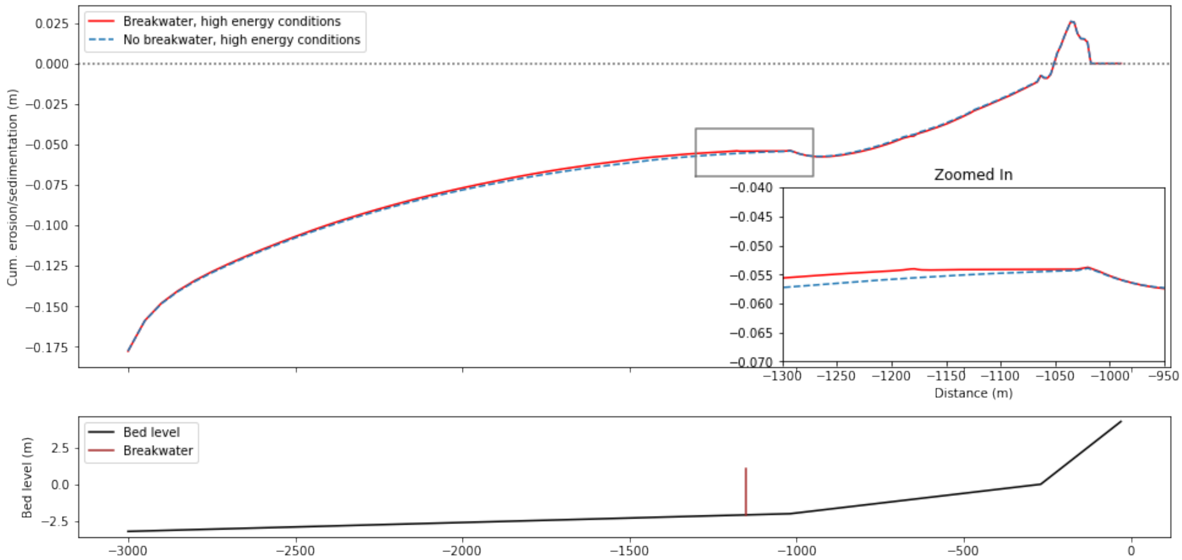


Figure 6.2: The cumulative erosion/sedimentation during high energy conditions on the heavily eroded mudflat, with and without a detached, porous breakwater.

From Figure 6.2, it is observed that no significant differences in the cumulative erosion and sedimentation take place when the breakwater is included in the model. When zooming in, minimal differences in erosion are observed. These differences can not solely be attributed to the effect of the breakwater, but can also be attributed to other factors such as numerical errors and discrepancies. Therefore the breakwater does not behave as expected during high energy conditions (subsection 5.5.1). It is likely possible that the breakwater is ill-dimensioned (porosity, location, height, pile diameter). However, the results also raise questions about the validity of the schematization of the porous breakwater in Delft3D and therefore the results are considered to be invalid. This is further discussed in chapter 8.

6.1.2. Nourishment

To gain insight into the effect of the nourishment on the net erosion rate on the heavily eroded coast, the cumulative erosion and sedimentation is visualised for the situation with (red line) and without (dotted blue line) nourishment, for both low and high energy conditions. Negative values (below the gray dotted line) indicate erosion and positive values (above the dotted grey line) indicate sedimentation.

Low energy conditions

Figure 6.3 shows the cumulative erosion and sedimentation over the cross section of the heavily eroded mudflat, plotted for low energy conditions.

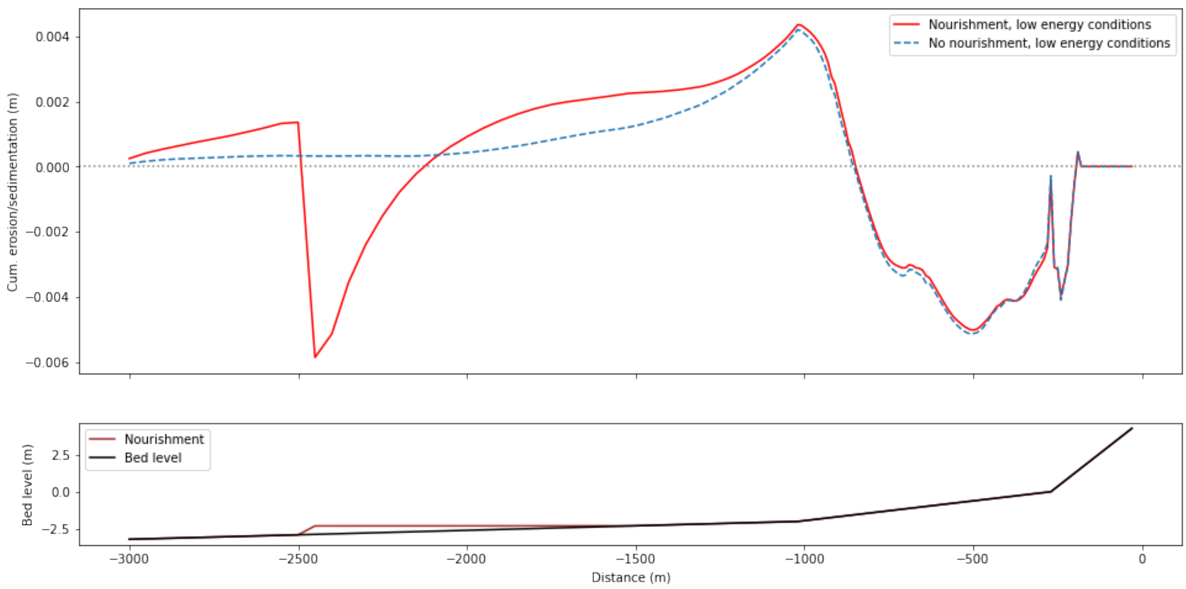


Figure 6.3: The cumulative erosion and sedimentation during low energy conditions on the heavily eroded mudflat, with and without nourishment.

From Figure 6.3 the following observations are made:

- **Sedimentation:** Increased sedimentation is observed at the offshore side of the toe of the nourishment ($-3000m$ to $-2500m$) and behind the nourishment plateau ($-2100m$ to $-1000m$). This is expected because the toe of the nourishment plateau traps sediment, and because of the flood dominant character of the tide.
- **Erosion:** On top of the plateau of sediment (-2500 to around $-2100m$) an increase in erosion is noted. This is conform the expectations, since there is an increased bed sediment layer thickness and thus an increased sediment budget.

From these observations it follows that the nourishment behaves as expected during low energy conditions. It shows that when increasing the sediment budget, more sediment is transported onshore and therefore decreasing the net erosion. Net erosion is further decreased by the increase of wave dissipation due to the local decrease of the water level on the nourishment plateau (appendix F, Figure F.1). This is in line with the hypothesized position in the feedback loop presented in Figure 3.8.

High energy conditions

Figure 6.4 shows the cumulative erosion and sedimentation over the cross section of the heavily eroded mudflat, plotted for high energy conditions.

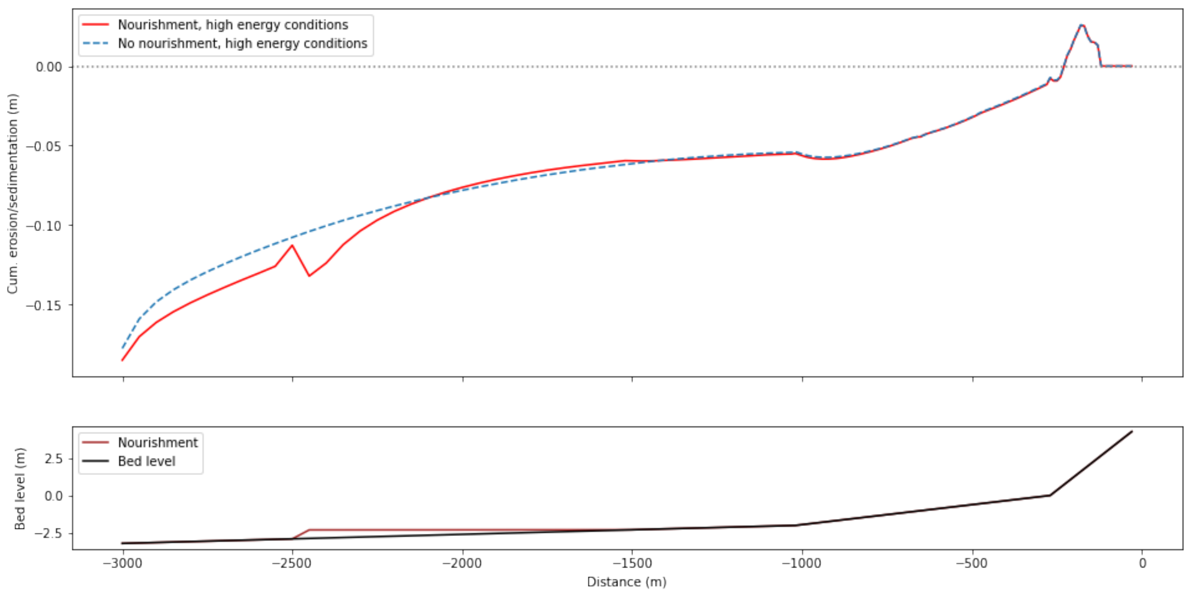


Figure 6.4: The cumulative erosion and sedimentation during high energy conditions on the heavily eroded mudflat, with and without nourishment.

From Figure 6.4 the following observations are made:

- **Erosion:** In front and on top of the nourishment plateau ($-3000m$ to $-2100m$) it is observed that the cumulative erosion increases. This is expected because of the wave dominant characteristics during high energy conditions, possibly causing wave reflection on the nourishment. There is a small decrease in cumulative erosion noticeable between $-2100m$ and $-1500m$, due to the increased sediment budget. From $-1500m$ to $0m$ there is no change in sedimentation observed. This is as expected, because the simulated time is too short for the effect of the nourishment to reach the shore.
- **Fluctuation:** The sudden fluctuation at $-2500m$ can be explained by the sediment entrapment at the toe of the nourishment as well as an increased erosion at the top of the nourishment.

The above mentioned findings are as expected. The erosion rates on the nourishment increase slightly compared to the control situation. However, the effect is very small and not constant over the whole nourishment. Therefore, the nourishment can be considered as stable.

6.2. Partially eroded coast

In this section the simulation results of the partially eroded coast are presented. For each of the two modelled hydraulic measures, simulation results for high energy and low energy conditions are discussed.

6.2.1. Detached porous breakwater

To gain insight into the effect of the breakwater on the net rate of erosion on the partially eroded coast, the cumulative erosion and sedimentation is visualised for the situation with (red line) and without (dotted blue line) breakwater, for both low and high energy conditions. Negative values (below the dotted grey line) indicate erosion and positive values (above the dotted grey line) indicate sedimentation.

Low energy conditions

Figure 6.5 shows the cumulative erosion and sedimentation over the cross section of the partially eroded coast, plotted for low energy conditions.

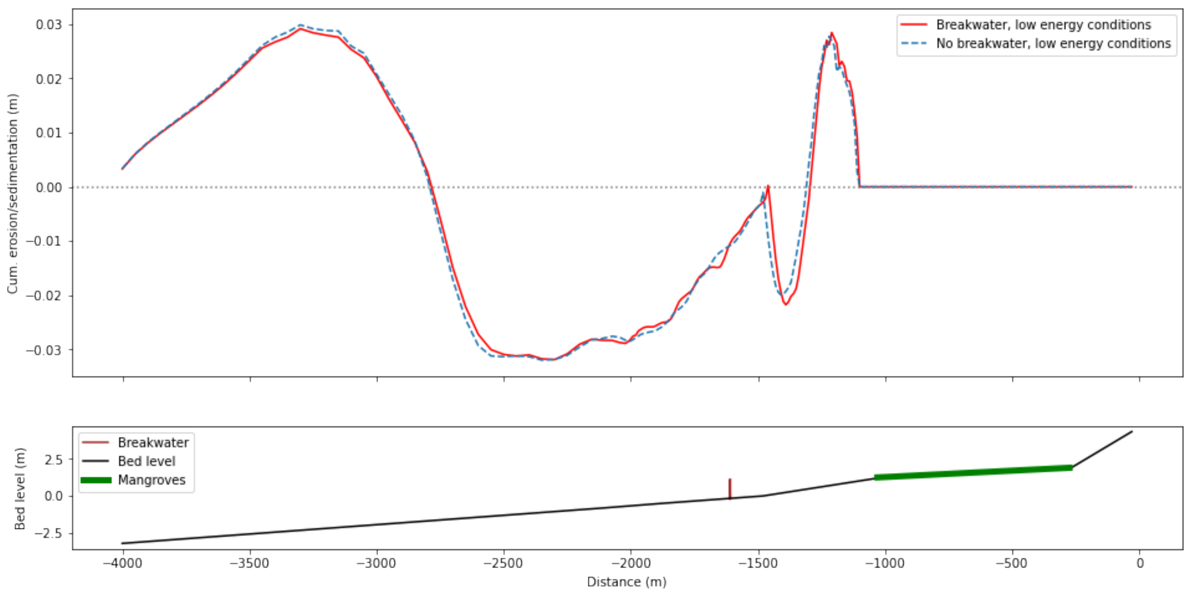


Figure 6.5: The cumulative erosion and sedimentation during low energy conditions on the partially eroded mudflat, with and without a detached porous breakwater.

In Figure 6.5, the trend is similar for both situations. However, small discrepancies over the full length of the graph are observed. These differences could be due to the difference in wave dissipation between the two simulations (appendix F.7). However, these differences can not solely be attributed to the effect of the breakwater, but can also be attributed to other factors such as numerical errors and discrepancies. Therefore, the breakwater does not behave as expected during low energy conditions. It is likely possible that the breakwater is ill-dimensioned (porosity, location, height, pile diameter). However, the results also raise questions about the validity of the schematization of the porous breakwater in Delft3D and therefore the results are considered to be invalid. This is further discussed in chapter 8.

High energy conditions

Figure 6.6 shows the cumulative erosion and sedimentation over the cross section of the partially eroded coast, plotted for high energy conditions.

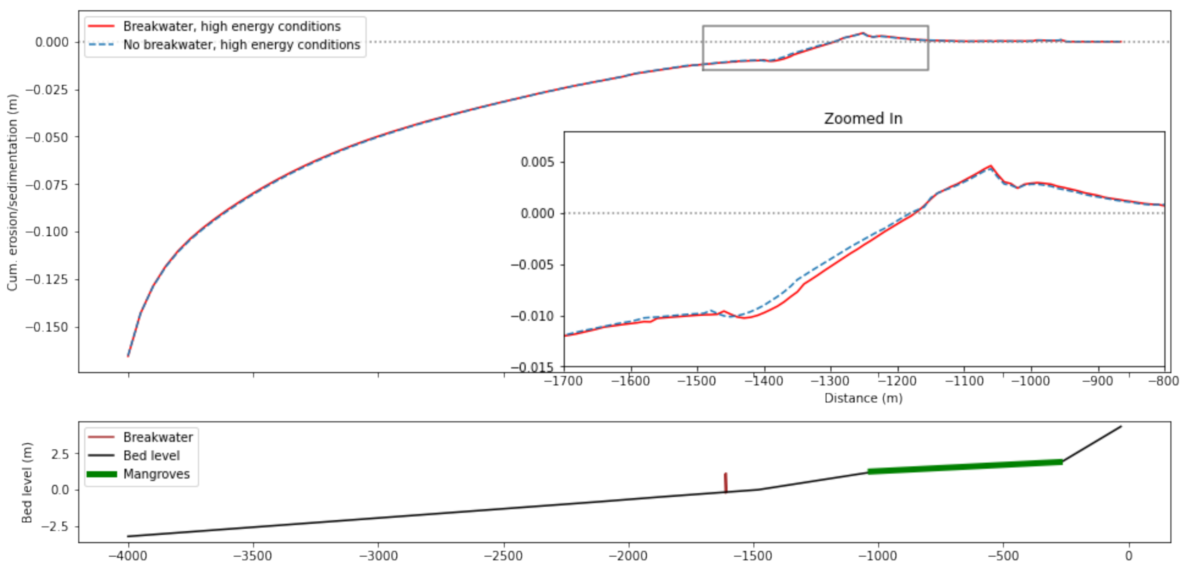


Figure 6.6: The cumulative erosion/sedimentation during high energy conditions on the partially eroded mudflat, with and without a detached porous breakwater.

From Figure 6.6, it is observed that no significant differences in the cumulative erosion and sedimentation take place when the breakwater is included in the model. When zooming in, minimal differences in erosion are observed. These differences can not solely be attributed to the effect of the breakwater, but can also be attributed to other factors such as numerical errors and discrepancies. Therefore the breakwater does not behave as expected during high energy conditions (subsection 5.5.1). It is likely possible that the breakwater is ill-dimensioned (porosity, location, height, pile diameter). However, the results also raise questions about the validity of the schematization of the porous breakwater in Delft3D and therefore the results are considered to be invalid. This is further discussed in chapter 8.

6.2.2. Nourishment

To gain insight into the effect of the nourishment on the net erosion rate on the partially eroded coast, the cumulative erosion and sedimentation is visualised for the situation with (red line) and without (dotted blue line) nourishment, for both low and high energy conditions. Negative values (below the dotted grey line) indicate erosion and positive values (above the dotted grey line) indicate sedimentation.

Low energy conditions

Figure 6.7 shows the cumulative erosion and sedimentation over the cross section of the partially eroded mudflat, plotted for low energy conditions.

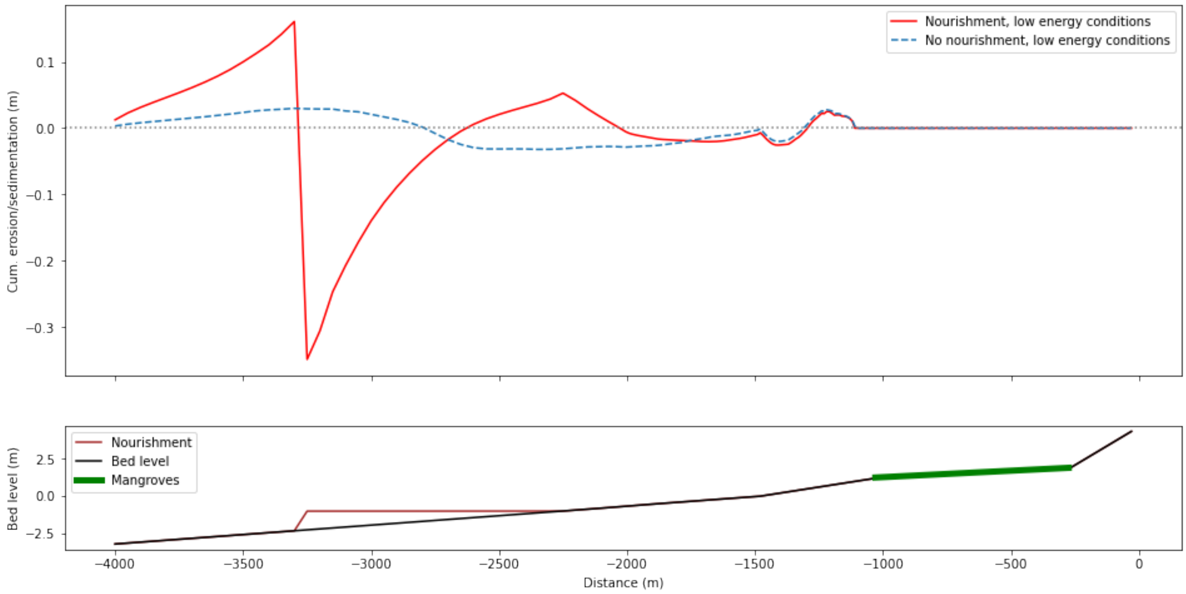


Figure 6.7: The cumulative erosion and sedimentation during low energy conditions on the partially eroded mudflat, with and without nourishment.

From Figure 6.7 two observations are made:

- **Sedimentation:** Increased sedimentation is observed in front of the toe of the nourishment ($-4000m$ to $-3300m$) and behind the nourishment plateau ($-2700m$ to $-1800m$). This is expected because the toe of the nourishment plateau traps sediment, and because of the flood dominant character of the tide.
- **Erosion:** Increased erosion is observed on top of the nourishment plateau ($-3300m$ to $-2700m$). This is expected because of the locally increased bed sediment layer thickness.

From these observations it follows that the nourishment behaves as expected during low energy conditions. It shows that when increasing the sediment budget, more sediment is transported in onshore direction and therefore decreasing the net erosion. This is in line with the hypothesized position in the feedback loop presented in Figure 3.8

High energy conditions

Figure 6.8 shows the cumulative erosion and sedimentation over the cross section of the partially eroded mudflat, plotted for high energy conditions.

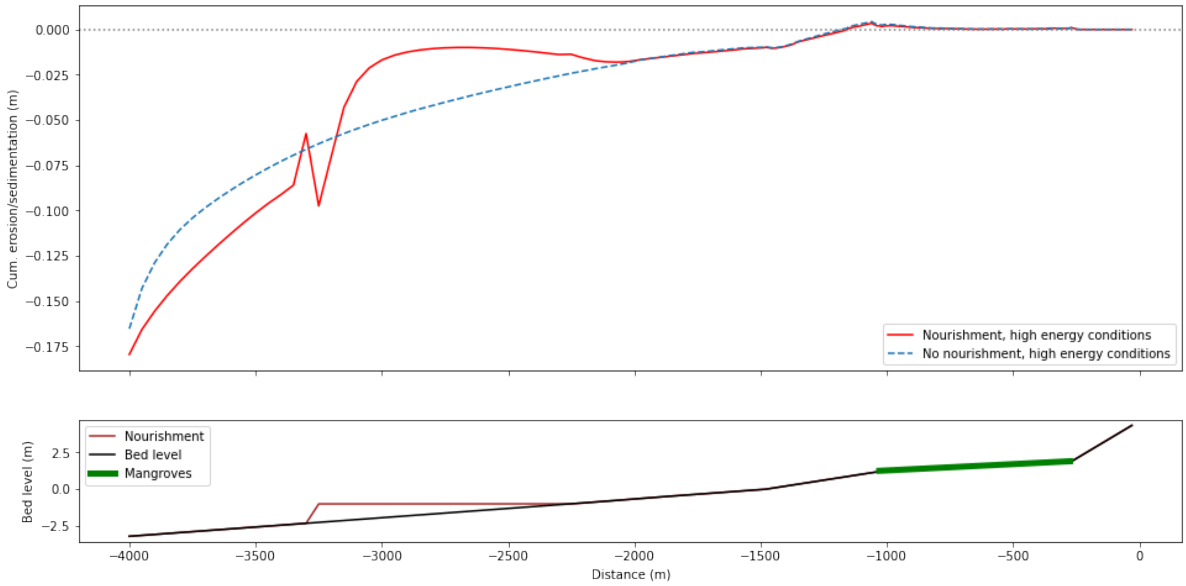


Figure 6.8: The cumulative erosion/sedimentation during high energy conditions on the partially eroded mudflat, with and without nourishment.

From Figure 6.8 two observations are made:

- **Erosion:** In front of the nourishment ($-4000m$ to $-3250m$) it is observed that the cumulative erosion increases. Decreased cumulative erosion is observed on top of the nourishment ($-3200m$ to $-2250m$). This is expected because of the wave dominant characteristics during high energy conditions, possibly causing wave reflection on the nourishment. From $-2000m$ to $0m$ there is no change in sedimentation observed. This is as expected, because the simulated time is too short for the effect of the nourishment to reach the shore.
- **Fluctuation:** The sudden fluctuation at $-3250m$ can be explained by the sediment entrapment at the toe of the nourishment as well as an increased erosion at the top of the nourishment.

The above mentioned findings are as expected. The erosion rates in front and on the toe of the nourishment increase compared to the control situation. However, the erosion rate is decreased over the rest of the nourishment. Therefore, the nourishment can be considered to be stable. Another positive results of this nourishment plateau is shown in the wave dissipation plot in appendix F, Figure F.6, which shows an increase in wave dissipation on the nourishment plateau, which can lead to increased sediment settling.

7 Conclusion

This research addresses the current situation regarding coastal erosion and subsequent mangrove degradation in the Bac Lieu province. Mangroves form an extra layer of flood protection (next to the sea-dike) and can therefore be critical in protecting the Mekong Delta from the rising sea level and threat of inundation. An increase in the rate of coastal erosion over the years has increased the degradation of the coastal mangrove forests of the Mekong Delta. Interfering with the rate of coastal erosion is a complicated operation and might have severe consequences for the coastal dynamics of the area as well as on the inhabitants of Bac Lieu. Therefore, this report aims to answer the following question: *What are the hydraulic and socio-economic impacts of implementing coastal hydraulic measures aimed at reducing coastal erosion in Bac Lieu?* The answer to this question is divided into four parts, as stated in section 1.1.

The socio-economic analysis that is conducted comprises of questionnaires filled out by the inhabitants of the coastal area of the Bac Lieu province, hands-on sources and advice from institutes with expertise in the area, and by a site investigation. The goal of the questionnaires is to asses if there is any general consensus the locals might have on flood protection, implementing hydraulic measures and saving and restoring the mangrove forests. However, the results proved to be inconclusive and unusable to draw any conclusions from. Therefore, the conclusions on the socio-economic impact of the proposed hydraulic measures are based solely on the expertise of institutes and on findings in the field.

It is argued by the institutes that the proposed hydraulic measure of removing the sea-dike would have a negative impact on the coastal area of Bac Lieu due to the lack of individual protection of the farms and villages. This statement is confirmed during the site investigation and additionally, a lack of space to create the proposed silvofisheries was observed. As a result, it is concluded that this hydraulic measure is not feasible and is therefore not modelled. The other two hydraulic measures (porous breakwater and nourishment) have a comparable socio-economic impact. This is concluded from the experiences by the Institute of Coastal and Offshore Engineering. They stated that the inhabitants of Bac Lieu have no strong opinion on what happens behind the sea-dike, as long as they are protected. From this statement, together with the assumption that the mangrove forests provide extra protection from the rising sea level in the future, it is concluded that the proposed breakwater and nourishment have a positive socio-economic impact and are thus worth investigating further.

Next to the socio-economic analysis, the morphological impact of the proposed hydraulic measures are analysed on the heavily and partially eroded coast (east and west of Nha Mat, respectively) by means of a numerical model. As Delft3D does not have a built in feature for implementing porous breakwaters, a schematization is made. The results show only a minimal difference in cumulative erosion and sedimentation after the implementation of the porous breakwater. Since this is against all expectations, the validity of the schematization of the porous breakwater is questioned. It is observed that the schematization does not grasp the complex behaviour of a porous breakwater and therefore it is concluded that Deft3D is not a suitable modelling tool for modelling a porous breakwater.

For both the partially and heavily eroded coast, the modelled nourishment shows increased sediment transport towards the shore in low energy conditions. Therefore, the modelled nourishment shows a positive effect on the net rate of coastal erosion in low energy conditions. In high energy conditions, the nourishment shows a decrease in cumulative erosion on the onshore side of the nourishment plateau, and an increase in erosion on the offshore side of the plateau. Therefore the nourishment behaves as expected and is considered stable for both coasts and weather conditions.

From the socio-economic analysis it is concluded that the breakwater and the nourishment have the same positive socio-economic impact on the Bac Lieu province. Additionally, for the nourishment, the morphological analysis shows a positive impact in terms of reducing net erosion on the heavily eroded coast and the partially eroded coast. The results of the porous breakwater are inconclusive and therefore no decisive conclusions about this hydraulic measure can be made.

According to this research, nourishing the coast to prevent coastal erosion and subsequent mangrove deforestation shows potential. However, it has not yet been attempted in this area, and the specific practicalities are unknown. Therefore, the best course of action for the Bac Lieu province based on the findings of this research is to investigate the long-term effects, possible configurations and practicalities of implementing a nourishment. Additionally, it is advised keep the inhabitants of Bac Lieu accurately informed on the threat of flooding due to relative sea level rise. Finally, research institutes and the (local) authorities seem to have different opinions on whether building with nature and implementing (and protecting) mangroves in flood protection systems is relevant. A general consensus between the authorities and research institutes on the protection and restoration of mangrove forests adds an important link to the protection of the Mekong Delta against global change.

8 Discussion

This chapter focuses on the assumptions and limitations of this research and provides ideas for possible future research.

8.1. Limitations

The limitations of this research are divided into model limitations and field research limitations.

8.1.1. Model limitations

This research assesses the hydraulic- and socio-economic impact of different hydraulic measures on the rate of coastal erosion. It is concluded in chapter 6 that the modelled breakwater does not behave as expected and that this is most likely due to an invalid schematization of the porous breakwater. Delft3D does not have a built-in feature for including porous breakwaters in the model. On top of that, very little research has been done on modelling porous breakwaters in Delft3D. Therefore, the breakwater was schematized in a similar way as the mangroves. Despite the theoretical similarity in schematizing pillars and mangroves, this approach may not accurately represent a concrete porous breakwater. Two possible reasons are:

- 3D effects: Since the model is schematized as 2DH, the 3D effects such as turbulence and vertical mixing are not accurately represented. Therefore underestimating the breakwater's wave dissipation capabilities.
- Wave structure interactions: Delft3D primarily focuses on hydrodynamics and sediment transport. While it can simulate wave propagation, it does not offer the same level of sophistication in modeling wave-structure interaction. Delft3D calculates wave breaking by using the water depth. Since the breakwater is modelled as pillars on the bed and not as an increased bed level, it is likely possible that the waves did not 'feel' the pillars, and therefore underestimating the wave dissipation capabilities of the breakwater.
- Submergence of the breakwater: The approach of modelling mangroves has been validated for both the flow and wave module of Delft3D. Mangroves are rather tall and reach above the water, even during high tides. This means that waves propagate through the mangroves. The breakwater, however, is (partially) submerged, meaning that the waves are partially propagating over the breakwater. Therefore, using the approach applied for modelling mangroves might not be valid for modelling breakwaters.

Next to the validity of the schematization as discussed above, three design choices that can negatively influence the behaviour of the breakwater are listed below:

- The porosity of the breakwater is too high
- The breakwater is too deeply submerged.
- The breakwater is placed at the wrong location.

In addition to the modelling of the breakwater, the model has other more general limitations. First of all, assumptions were made regarding the hydrodynamics and boundary conditions (chapter 5). In order to validate the model, in-field measured wave height and flow velocity data sets were used. Nonetheless, for a morphological model, it would be more comprehensive to also include the validation of sediment transport and water levels. However, this data was not available. Additionally, the model is calibrated for the grid cell size and time step, but misses an extensive calibration for physical parameters such as the viscosity and diffusivity.

Furthermore, it is important to note that two different bathymetry data sets are combined and that the water depth is assumed to be constant in the longshore direction. This is a simplification of reality and therefore a limiting factor to the model. Also, the mangrove input values are based on averages of simple field measurements and therefore have a larger error margin.

It is expected that when more accurate data is available and the validation and calibration of the aforementioned parameters is included, the model would be more accurate. However, since this research is mostly qualitative and indicative, these limitations are assumed to not have a significant influence on the conclusion of this report.

8.1.2. Field research limitations

The biggest limitation of the socio-economic analysis is that the results are mostly based on statements of third parties. One of the goals of the field research is to confirm or contradict these statements by interviewing inhabitants by means of questionnaires. It is concluded that the results of the questionnaires are inconclusive since there are not enough correctly filled out questionnaires. Several possibilities for this are discussed below:

- The questions and explanations were incorrectly translated: The questionnaires are translated using artificial intelligence and are checked for errors by an employee of SIWRP in Ho Chi Minh city. However, given that the interviews are conducted in Bac Lieu and language use in Vietnam is diverse, small subtleties in dialect and language use may have caused the questionnaires to be unclear for the inhabitants of Bac Lieu. This limitation can resolved by having the questionnaire checked by someone who lives near the research area.
- The questions were ill-posed: The questionnaires provided no context of the problem. This, in combination with the use of jargon, could have made it difficult for the participants to understand the questions. By providing more context and writing the questions in layman terms, the questionnaires become easier to understand.
- No additional guidance could be given to the participants: When it became apparent that a participant did not fully grasp the questionnaire's purpose, the language barrier made it impossible to provide clarification. This limitation can be addressed by engaging the services of a translator.

8.2. Future research

Several opportunities (for example for a MDP or MSc thesis) to further assess the possibility of reducing coastal erosion in the Mekong Delta are discussed:

- Very little bathymetry and sediment data is available for the Bac Lieu coastal area. To create a more accurate model of the bed profile, high resolution (10m) bathymetry data has to be obtained. For accurate sediment dynamics, detailed sediment samples and additional knowledge on cross- and longshore transport dynamics are required.
- Since Delft3D assumes linear wave theory, near-shore shallow water calculations are inaccurate. Processes such as wave breaking and shoaling, especially during high energy conditions, are not represented accurately. For further research on the coast of Bac Lieu, it is therefore advised to use a program such as *XBeach* (Deltares), in addition to Delft3D. This way, more accurate results of short-term (during a storm) morphological changes and hydro-dynamical effects can be obtained.
- This research aims to show the potential impact of the proposed hydraulic measures and not its optimal design. The nourishment and breakwater are therefore not modelled for more than one configuration. However, the nourishment already shows a high potential for decreasing the net coastal erosion. Regarding the breakwater, it can not be excluded that the design and placement

is the main reason why the results from Delft3D are inconclusive. For further research, the optimal design for a nourishment and a porous breakwater can be interesting to investigate by modelling different configurations.

- Shoreface nourishment programmes contribute to the long-term sand balance of the coastal zone. In this research, the influence of a nourishment on the rate of coastal erosion is modelled for two days (with a morphological scale factor of 20). Therefore, it is interesting to investigate the long-term (years) impact of a nourishment on the sediment dynamics and bed profile of the Nha Mat coast. This way, the potential of mangrove regrowth can be included as well.
- The tidal range in Nha Mat is around $3.7m$ in low energy conditions. Because of the flat profile of the mudflat, the horizontal retreat of the waterline is magnitudes larger (kilometers). This has a large impact on the practicality of realizing a nourishment. It is advised to investigate the required time frames and minimum water depths for dredging vessels to dump sediment, or determine other viable methods of dumping such as floating pipelines.

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A
Field report

A.1. Introduction

To get a better understanding of the situation and the surroundings regarding the area of this project, a field research in the Mekong Delta has been conducted to analyze the environment. During this trip the current situation regarding the flood risk, the aquaculture and the mangroves themselves has been examined. Furthermore, different groups of people and stakeholders have been interviewed to get a better understanding of their way of thinking on this matter and their involvement in this project.

This field research consists of two parts. In the first week (30-09-23 until 07-10-23) different research institutes in Ho Chi Minh City were visited to discuss the problem of coastal erosion in the Mekong Delta. In the second week (10-10-23 until 13-10-23) a site investigation and measurements were done in the towns of Bac Lieu and at the coast in Nha Mat.

A.2. Research institutes in Ho Chi Minh City

While staying in Ho Chi Minh City, meetings and interviews with different research institutes were conducted to gain more insight in their experience and expertise in hydraulic operations in the Mekong Delta. The companies in question are the Institute of coastal and offshore engineering, Royal Haskoning DHV and the Southern institute of water resources and planning. All these companies have done relevant research in the Mekong Delta or Bac Lieu in particular.

A.2.1. Institute of coastal and offshore engineering

The institute of coastal and offshore engineering has done many projects about coastal erosion in Bac Lieu and specifically in Nha Mat. During a meeting with researcher Phan Hung and his colleagues (03-10-2023) different insights about the area's hydraulic boundary conditions, social-economic values and general information about the Mekong Delta were gathered. The most important findings of the meeting are described below.

General information about the Mekong Delta, Bac Lieu and Nha Mat

- According to their data with measurements taken over 20 years, there is a sea level rise of 4 mm/year and a 8-10 mm/year land subsidence. This means a relative sea level rise of over 1 cm/year
- Over the years less storms per year are occurring. Nowadays there is on average one storm per 2 years. Subsequently, the total precipitation is less, but the intensity is higher.
- Over the years the upstream water level has been decreasing, but downstream (near the region of Can Tho) the water level has been increasing.
- In Bac Lieu the amount of rainfall is considered average with a precipitation of 1600 - 1800 mm/year.

- Data shows that over the years there are occurring more smaller floods than bigger floods. This is because of the dams that are being build in the rivers upstream.
- In a previous project, bamboo fences were build along the coast in front of the mangroves, but they failed due to strong waves destroying the fences. Currently there is a solid breakwater in place for 2-3 years, but the specific effectiveness is not known yet. What they could conclude is that the breakwater does not (yet) show the behaviour that they hoped in the last years.
- The sea-dike was built around 1980-2000 and the wind farm was built in 2015.
- From 2010 onwards a lot of erosion has occurred. At some locations mangrove forests with a width of 1 km have disappeared.

Hydraulic conditions relevant for the model

- Their measurement data shows that the high tide increased 40 cm in 22 years and low tide 20 cm in 22 years.
- They provided bathymetry data of nearby areas.

Views on social-economic values

- Floods have occurred for over 5000 years in the area. People are very used to it and have adapted to it.
- High floods are good for rice production
- Heavy flooding also brings negative effects such as loss of property.
- The local government wants Nha Mat to be ”The centre of aquaculture”. There have been many investments in new technology and promotion, such as upgrading the dike.
- The government is currently often investing in flood protection and mangrove restoration at the same time. These two investments at the same time sometimes raises questions with the locals as to why this can not be done with just one investment in one solution.
- Most of the times the local people agree with government when it is decided to build a breakwater. They agree that this breakwater also protects the coastal area where they are living.

A.2.2. Royal HaskoningDHV

Royal HaskoningDHV is one of the biggest consultancy agencies in the world in the field of water management, hydraulic engineering and other fields such as energy, sustainability and environment. RHDHV has offices all around the world. Amongst them is the office in Ho Chi Minh City. Amongst others, RHDHV is involved in projects in the Mekong Delta, where they focus mainly in climate resilience of the delta. RHDHV is a big company with a lot of expertise, so their opinion on this research topic is highly valued. From the extensive meeting (04-10-2023) the following pointers came up as critical for the Mekong Delta, as RHDHV views it.

- It is deemed impossible to reverse the processes that have been set in motion by climate change, such as the higher water level in the delta. Next to climate change there are big problems that the delta is facing such as land subsidence. RHDHV is working on the adaptation of the delta to these circumstances, rather then tackling these problems at their source.
- The problems in the Mekong Delta go much further then only erosion. The main problems in RHDHV’s eyes is land subsidence, sand mining and hydro-power dams that block sediment flow in the delta system. A proposed hydraulic measure (whem implemented in real life) should be carefully tested and modelled with the presence of all these problems.
- There is not one hydraulic measure that will form the solution for the entire Mekong Delta. Every portion of the coast must be analysed seperately to find the optimal solution for that location.

RHDHV advises Vietnam to fully focus on *Building with Nature* solutions in the form of mangrove strips along the coast. They believe that enough mangroves can find an equilibrium with coastal erosion. The problem definition, as stated by RHDHV, is two-fold:

- How can the mangroves be allowed to grow and spread?
- How can the growing and spreading mangroves be protected from heavy sea states until they are fully grown?

Lastly, the proposed hydraulic measures were discussed. Stated below is the take of RHDHV on these hydraulic measures.

- *Nourishment of the mudflats*: RHDHV has no critical experience with nourishment in the Mekong Delta. However, they were optimistic about the possibility to restore mudflats with nourishment in areas where the coast is more heavily eroded.
- *Porous breakwater*: RHDHV is a fan of using breakwaters to protect the mangroves. It was stated that when applied right, breakwaters can trap the sediment near the shore to make sure that the mudflats will remain in the right shape for the mangroves to grow. The downside of breakwaters is that they need a lot of maintenance, at least once per year.
- *Silvofisheries*: RHDHV is very sceptical about removing the sea-dike to create the silvofisheries. It is stated that there is no knowledge about how far the sea and the mangroves will grow land-inward. The land reclamation by nature might be a lot greater then desired. next to that, in some areas the population is too dense for this hydraulic measure. However, RHDHV does acknowledge that this hydraulic measure could be a viable option in areas where the population density is lower, and the relative land-height is higher.

A.2.3. Southern institute of water resources and planning (SIWRP)

SIWRP is an institute that has done many research and projects in the Mekong Delta and Bac Lieu. With this institute a meeting with researcher Nguyen Van Hinh (05-10-2023) was held about different aspects of the project and mainly about certain data that would be valuable for the model. During this meeting, Hinh also introduced a colleague of his from the Ministry of agriculture and rural development. They performed measurements off the coast of Bac Lieu (including Nha Mat) and were able to share bathymetry, ocean and sediment data. Furthermore they shared reports, which included more data that could help to validate some aspects of the model.

From the many data files that were received from the institute, the data that was of service can be seen in Appendix D.

A.3. Analysis of the surroundings and environment of research area

To get a better sense of the surroundings and environment of the project area, the town of Nah Mat in Bac Lieu and the coastal parts east and west of Nha Mat were visited. During this period, general, hydraulic and mangrove related data and information about the area was acquired. During this stay in Bac Lieu, professor Le Hai Trung and his team helped and supported with the field measurements taken in the mangrove forests.

A.3.1. General findings of the surrounding and environment

When arriving in Bac Lieu, the area has been scouted to get a first impression of the area. It is important to get an understanding of how close and well the mangroves and local aquaculture can be approached, as well as, where they are and where measurements can be made. Next to that, an inspection of the current sea-dike was done. The most important findings are shown below.

On 10-10-2023, when firstly arriving in Bac Lieu, it was observed that it was a lively town with a lot of local businesses and almost no (foreign) tourism. From Bac Lieu there is a main road going south to the coast at Nha Mat. In Nha Mat there is a crossing with a road to the east or to the west and drive along the coast. The west is the less eroded part of the coast, where more healthy mangroves live. To the east is the more eroded part of the coast, where there is a wind farm in front of the mangroves.

First, the wind farm was visited (Figure A.1a). During the drive across the sea-dike to the wind farm location, the following findings stood out:

- A lot of variation in healthy and unhealthy mangroves.
- A lot of new fish/shrimp farms are under construction.
- There overall feeling of the area along this route was mainly desolate and bleak. There were a lot of projects going on, but they looked quite delayed and aimlessly, see Figure A.1b.

- There was a quite big and newly looking distribution center of Viet Uc Seafood Corporation. Unfortunately they were not open for conversation, but according to their website they stand for a technologically advanced and sustainable Vietnamese shrimp industry and they have the largest shrimpseed market share in Vietnam [71].

(a) The wind farm located at the eroded part of the coast of Bac Lieu.

(b) One of many construction projects, making the area look dreary and sad.

Figure A.1

At the location it was possible to walk into the wind farm and look at the coast from the sea side. From this point of view the following observations were made:

- There was almost no wind and waves. During the rest of our stay in Bac Lieu it was found that especially the wind speed was very irregular.
- The coast was heavily eroded, see Figure A.2 and the shape of the shoreline looked irregular.
- The mangroves looked irregular as well as to their height and health.

Figure A.2: The eroded part of the coast, east of Nha Mat, seen from the wind farm.

After having done enough observations of the general surroundings, the other more healthy and less eroded part of the coast west of Nha Mat was scouted. Here the following was found:

- On this side of the coast there were a lot of fish/shrimp farms on the land side behind the dike as well.
- However, on the sea side there were also some mangrove integrated fish/shrimp farms (Figure A.3a).
- In these integrated farms different kind of mangroves are present then the mangroves that grow in front of it near the sea.
- There were a lot of canals in and along the integrated farms, making it difficult to access the mangroves closer to the sea.
- Although the mangroves on this side of the coast looked healthy, there was cliff erosion happening which was degrading the mangrove forest (Figure A.3b).

(a) A mangrove integrated fish/shrimp farm with canals and small dams surrounding the mangroves.

(b) Cliff erosion at the sea side of the mangrove forest.

Figure A.3

A.3.2. Measuring mangrove characteristics

On the first day (10-10-2023), like stated in subsection A.3.1, the area was investigated. During this general investigation, 6 different locations were scouted to enter the mangroves. In the end it was decided to enter the mangroves and do measurements at locations 2, 3, 4 and 6 (Figure A.4). These locations were chosen for relatively easy accessibility and a good division between heavily eroded (location 2 & 3) and only partially eroded (location 4 & 6) coasts.

Figure A.4: Scouted locations to enter mangroves in Nha Mat area

When inspecting the sites, it was observed that two types of mangroves inhabit the area; the *Avicennia Germinans* and the *Rhizophora stylosa*, see Figure A.5. The *Rhizophora stylosa* grows predominantly at the land-side of the mangrove strip, while the *Avicennia Germinans* grows at the sea-side. Both types of mangroves were measured and analyzed.

(a) The Avicennia Germinans

(b) The Rhizophora stylosa

Figure A.5: The two different types of mangroves at the coast of Nha Mat

In order to model the influence of the mangroves, the characteristics of the mangroves need to be determined. Delft3D takes three measurable mangrove parametrizations as input; The trunk density, the height and average trunk diameter. The density is determined by counting the number of trunks within one square meter. The average diameter of the trunk is determined by measuring the diameter of 8 different trunks within one square meter. This process is repeated 8 times at each location and is averaged to give representative values for the mangrove characteristics at that location. In order to do these measurements measuring tape, pen and paper were used. Next to that, the mangrove species is determined. All the trees were observed to be higher than the dike and therefore their height is not of importance for the model. For the *Avicennia Germinans* (or black mangrove) also the density, height and diameter of its air roots is measured. The results are shown in Table A.1 and Table A.2

Location	Mangrove species	Trunk density (n/m2)	Average trunk diameter (m)
2	Rhizophora stylosa	25.67	0.0188
3	Avicennia Germinans	0.58	0.12
4	Rhizophora stylosa	17.75	0.026
6	Avicennia Germinans	0.625	0.07

Table A.1: Results of mangrove characteristics measurements

Location	Root density (n/m2)	Average root diameter (m)	Root height (m)
3	100	0.005	0.168
6	100	0.005	-

Table A.2: Results of air root characteristic measurements

A.3.3. Analyzing bathymetry data

At the previously described locations in subsection A.3.2, dr. Le Hai Trung and his team executed bathymetry measurements inside the mangroves. With this data the slope of the bed inside the mangroves is known and this was used to model the bed of the coast inside the healthy mangroves in Delft3D. The data is shown in section D.2

A.4. Stakeholders in Bac Lieu and Nha Mat

In order to get a better understanding about the views and opinions of the local people of the area, interviews are conducted in the form of questionnaires. Two different questionnaires are made (Appendix B); one for the (aquaculture) farmers and one for regular inhabitants of the area. The results of these questionnaires are stated below.

A.4.1. The farmers in Bac Lieu and Nha Mat

While visiting Bac Lieu and Nha mat, many undertakings to talk and interview farmers with the questionnaires were tried. Unfortunately the farmers were not easy to approach or contact. The one time a farmer was successfully approached, he was very skeptical about the project. He did however, fill in the questionnaire correctly once it was clear to him what the project was about and the result can be seen below:

Statement	Score
Flooding occurs regularly in my farm	1
I encounter negative consequences from floods	1
I am concerned about (more) flooding	5
I am concerned about the loss of mangroves	5
Mangroves are important for protecting my farm	5

Table A.3: Results of the average rating of the different statements with a score between 1 and 5

Below are the results of the second part of the questionnaire. For this part the farmer had to rank different answers to a question in the order of what he agreed with the most. For the first ranking question (Table A.4) however, the farmer wrote that all statements are equally highly important to him. So the farmer agreed with all the statements the most, meaning all the statements would have a score of 5.

Statement
I want to produce as much fish/shrimp as possible
I want to make sure I produce fish/shrimp of the best quality
I want to produce with the lowest costs possible
I want my farm to comply with the rules and norms that the government sets
I want my farm to contribute to a healthy ecosystem

Table A.4: Results of ranking the answers in order of what you agree with the most (1: disagreeing with the most, 6: agreeing with the most)

The answers to the two other ranking questions are shown in Table A.5 and Table A.6

What kind of measure should be taken to secure your farming business:	Average score
Building a stronger dike between the coast and the farm	4
Building a breakwater in front of the coast, so the mangroves can grow back	5
Moving the farm away from the coast	3
Nourishing the mudflat in front of the coast, so the mangroves can grow back	6
Turning my farm into a silvofishery (a mangrove integrated farm)	2
Doing nothing, the farm is already secure	1

Table A.5: Results of ranking the answers in order of what you agree with the most (1: disagreeing with the most, 6: agreeing with the most)

What are your future plans for your farm:	Average score
Expand my farming business	5
Make my farm more environmental friendly	4
Find a different job	1
Move my farm to another location	3
Not change anything, everything is good	2

Table A.6: Results of ranking the answers in order of what you agree with the most (1: disagreeing with the most, 5: agreeing with the most)

Regarding the farms themselves, an useful inspection was done. It became clear that in the province of Bac Lieu there are roughly two types of aquaculture; the farms behind the dike (at the land side) and the farms that are in front of the dike (at the sea side). The farms behind the dike are fairly simple and mainly made up of big holes in the ground, sometimes overlain with a tarp and filled with water. In these ponds, mostly shrimp are farmed. It is noticeable that there are multiple construction projects ongoing with the aim to build more shrimp farms near the dike.

The farms in front of the dike are only present at parts of the coast where the mangroves seem to be healthy and abundant. These farms are silvofisheries; they all have their own small dams and dredged canals to separate them from each other and from the sea, as can be seen in Figure A.3a. In these farms, the Rhizophora mangroves can grow freely. These farms are solely protected from the sea water by the Avicennia mangroves in front. Especially for these portions of the coast it is essential for the local aquaculture to maintain the mangrove forest.

A.4.2. The inhabitants of Nha Mat

The inhabitants were friendly and gladly wanted to help us with the project by filling in the questionnaires. However, it was noted that the ranking questions were not very well understood and some people did not even understand the questionnaire at all. Therefore, there were only 9 correctly answered questionnaires. Below in Table A.7 are the results from the statement questions.

Statement	Average score
Flooding occurs regularly in my village/city	3.333
I encounter negative consequences from floods	3.1
I am concerned about (more) flooding	2.9
Mangroves are important for flood protection	3.7
I am concerned about the loss of mangroves	3.9

Table A.7: Results of the average rating of the different statements with a score between 1 and 5

Below are the results of the second part of the questionnaire. For this part the inhabitants had to rank different answers to a question in the order of what they most agree with.

What kind of action should be taken to reduce the negative effects of flooding:	Average score
Enough is being done already	2.222
Mangroves have to be restored	4.111
A big dam should be built in front of the coast	3.444
People should move away from the coast	3
It is the people's own responsibility to protect themselves against flooding	2.333

Table A.8: Results of ranking the answers in order of what you agree with the most (1: disagreeing with the most, 5: agreeing with the most)

The government should invest more money in...:	Average score
Aquaculture	3.556
Tourism	3.111
Protecting and maintaining nature	3.556
Agriculture	3
(Other) local businesses	1.556

Table A.9: Results of ranking the answers in order of what you agree with the most (1: disagreeing with the most, 5: agreeing with the most)

B
Questionnaires

B.1. Questionnaire inhabitants

The aim and relevance of the questions are explained below:

General questions:
The first three open questions are used to make sure a representative group of people is interviewed. It is also used to asses whether people of different age, profession or village, answer differently on the same questions. Next to that, they are used to begin the questionnaire with some basic questions that are easy to answer. This way, the questionnaire does not start off too much in-depth.

Statement questions:
The first five statement questions are used to get an understanding of their view on flooding and mangroves in general. The inhabitants have to give a score in order to answer the question. This way, it can be assessed to what extent issues about flooding and mangroves play a role in their lives. This gives an idea about how important the problem this project addresses is to the inhabitants of Bac Lieu.

Ranking the statements: For the last part of the questionnaire, the inhabitants of Bac Lieu were asked to rank 5 given statements. By letting them rank the statements instead of picking one with which they agree most, a better comparison between the answers can be made.

- **First ranking question:** This project focuses on the restoration on mangroves for coastal protection. However, it has not been assessed yet whether this (nature based) option for coastal protection has enough support base with the inhabitants of the research area. The question lets the inhabitants rank five different actions in the area; no action (1), nature based option (2), man made hard structure (3), relocation of the population (4), people's own responsibility (5). The outcome of this question can be used to asses how people rate a nature based solution compared to the other options and therefore helps understanding the social feasibility of this project.
- **Second ranking question:** The second ranking question asks people to rank potential investments of the local government. This question gives an insight in how people rate the importance of coastal protection with respect to aquaculture and other important sectors in the area and therefore says something about the socio-economic feasibility of the project.

The questionnaire is included on the following pages.

Questionnaire Coastal Erosion & Mangrove deforestation in Bac Lieu

Hello! We are Axel, Geert, Sam and Gillis, four students from the Netherlands who are doing a research project about aquaculture and mangroves in Bac Lieu. For our research we highly value the opinion of the inhabitants of Bac Lieu about this topic. Would you mind answering a few questions for our research? Thank you so much!

General questions	**Your answer**
In which city / village do you live?	
How old are you?	
What is your profession?	

Next, we would like you to give a score to the statements below. 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree

Statement 1: Flooding occurs regularly in my village / city.
Your score: 1 2 3 4 5

Statement 2: I encounter negative consequences from floods.
Your score: 1 2 3 4 5

Statement 3: I am concerned about (more) flooding.
Your score: 1 2 3 4 5

Statement 4: Mangroves are important for flood protection.
Your score: 1 2 3 4 5

Statement 5: I am concerned about the loss of mangroves.
Your score: 1 2 3 4 5

For the last part we ask you to read the statements below. Please rank these statements in order of what you agree the most with.

What kind of action should be taken to reduce the negative effects of flooding:

1. *Enough is being done already*
2. *Mangroves have to be restored*
3. *A big dam should be built in front of the coast*
4. *People should move away from the coast*
5. *It is the people's own responsibility to protect themselves against flooding*

Disagree Agree

The government should invest more money in…:

1. *Aquaculture*
2. *Tourism*
3. *Protecting and maintaining nature*
4. *Agriculture*
5. *(Other) local businesses*

Disagree Agree

B.2. Questionnaire farmers

The aim and relevance of the questions are explained below:

General questions:

The first three open questions are used to asses whether farmers with different experience, products and living situation answer differently on the same questions. Next to that, they are used to begin the questionnaire with some basic questions that are easy to answer. This way, the questionnaire does not start off too much in-depth.

Statement questions:

The first five statement questions are used to get an understanding of their view on flooding and mangroves in general and with respect to their farm. The farmers have to give a score in order to answer the question. This way, it can be assessed to what extent issues about flooding and mangroves play a role in their lives and farming business. This gives an idea about how important the problem this project addresses is to the farmers.

Ranking the statements:

- **First ranking question:** The first question asks farmers to rank statements about what aspect of their farming business they find the most important. This gives an indication on how they value the importance of the ecosystem they are in compared to economic and legal aspects. Therefore it gives a insight in the socio-economic feasibility of thus project.
- **Second ranking question:** This project focuses on the restoration on mangroves for coastal protection. However, it has not been assessed yet whether this (nature based) option for coastal protection has enough support base with the farmers of the research area. The question lets the farmers rank six different actions in the area; no action (6), nature based option (2, 4, 5), man made hard structure (1), relocation of the farm (3), The outcome of this question can be used to asses how the farmers rate a nature based solution compared to the other options as well as ranking the proposed hydraulic measures. Therefore it helps understanding the social feasibility of this project and the proposed hydraulic measures.
- **Third ranking question:** The first ranking question asks farmers on how they see their farms in the future. This gives an indication on the future land use of the research area and therefore says something about the urgency and socio-economic feasibility of the different hydraulic measures.

The questionnaire is included on the following pages.

Questionnaire Coastal Erosion & Mangrove deforestation in Bac Lieu

Hello! We are Axel, Geert, Sam and Gillis, four students from the Netherlands who are doing a research project about aquaculture and mangroves in Bac Lieu. For our research we highly value the opinion of the farmers of Bac Lieu about this topic. Would you mind answering a few questions for our research? Thank you so much!

General questions	**Your answer**
For how long have you been farming?	
Do you live close to your farm?	
What products do you produce?	

Next, we would like you to give a score to the statements below. 1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, 5 = strongly agree

Statement 1: Flooding occurs regularly in my farm.
Your score: 1 2 3 4 5

Statement 2: I encounter negative consequences from floods.
Your score: 1 2 3 4 5

Statement 3: I am concerned about (more) flooding.
Your score: 1 2 3 4 5

Statement 4: I am concerned about the loss of mangroves.
Your score: 1 2 3 4 5

Statement 5: Mangroves are important for protecting my farm.
Your score: 1 2 3 4 5

For the final part we ask you to read the statements below. Please rank these statements in order of what you agree with the most.

1. *I want to produce as much fish/shrimp as possible*
2. *I want to make sure I produce fish/shrimp of the best quality*
3. *I want to produce with the lowest costs possible*
4. *I want my farm to comply with the rules and norms that the government sets*
5. *I want my farm to contribute to a healthy ecosystem*

Disagree Agree

What kind of measure should be taken to secure your farming business…:

1. *Building a stronger dike between the coast and the farm*
2. *Building a breakwater in front of the coast, so the mangroves can grow back*
3. *Moving the farm away from the coast*
4. *Nourishing the mudflat in front of the coast, so the mangroves can grow back*
5. *Turning my farm into a silvofishery (a mangrove integrated farm)*
6. *Doing nothing, the farm is already secure*

Disagree Agree

What are your future plans for your farm:

1. *Expand my farming business*
2. *Make my farm more environmental friendly*
3. *Find a different job*
4. *Move my farm to another location*
5. *Not change anything, everything is good*

Disagree Agree

C

Stakeholder analysis

In this appendix, an analysis of the stakeholders in such a hydraulic project are presented. The stakeholders will shortly be discussed to asses what their involvement is and how much power and interest they have in the project. The stakeholders are then mapped in a power/interest grid to give a clear overview, see Figure C.1.

National government
The national government needs to protect its land and its people. They will have the final say in whether any flood protection project can be conducted or not. They will have to pay for the project and make sure that the people's tax money is well spent. The national government has to be convinced of the potential of a proposed solution. Since they can also pull the plug on the project at any given time, they should be managed closely.

Local government
The provincial government wants to help its people and is responsible for providing the space to execute the project. They will need to help execute the project and maintain the proposed hydraulic measure in the future. They have to be kept in a close loop and therefore managed closely.

Inhabitants of Bac Lieu
The inhabitants of the coastal area of Bac Lieu are at risk of losing their homes and even jobs if the floods in the Mekong Delta get worse. The proposed hydraulic measures can have a changing effect on the flood risk, which can have consequences for the inhabitants of the delta. This is why the locals should be kept informed.

Water research institutes
Water research institutes can consult on the project. The institute can give their opinion on which solution they think is best. They have a lot of knowledge on the matter and can therefore influence the decision makers on what hydraulic measure to choose. However, they can not make decisions themselves and their advice can be ignored. The research institutes should therefore be very well informed, but not necessarily closely managed.

Civil engineering contractors
The contractor is the company that will build, construct and/or execute the proposed hydraulic measure. They do not get to decide what solution will be built, but they do have a fair say in what is possible to build and in what time frame. They should be kept very well informed.

Aquaculture companies
The aquaculture companies are the ones that buy the fish and shrimp from the farmers and then sell and export it. These companies will have some interest in the hydraulic measure when it affects the aquaculture farms, since this will affect their business, but otherwise not too much. Additionally, a big part of the economy evolves around aquaculture, which means there will be companies with some

power to lobby or pressure the people who make the decisions. However, this is not considered to be minimal and therefore these companies should be kept informed.

Environmental organizations (NGOs)
These organizations will want the most sustainable and durable solution, with the least amount of impact on the climate. They are therefore interested in the consequences the hydraulic measure has on the climate. They can protest, sign petitions and lobby to pressure decision-making stakeholders to cancel the project or choose their favorable green and environmental friendly solution. It is, however, not totally clear how much power these organizations and NGOs have, since there are reports that they are pressured by powerful stakeholders from above or face arrests [66]. They should therefore definitely be kept satisfied.

Wildlife organizations
These organisations will want the solution that has the least amount of negative impact on wildlife. They are in favor of the hydraulic measure that disrupts and interferes the least with the wildlife surrounding the project area. They can protest, sign petitions, lobby, etc., to pressure decision-making stakeholders to cancel the project or choose an animal-friendly solution. They should be kept satisfied.

Vietnamese population
Since the project will (probably) be funded by the tax money that the Vietnamese people pay nationwide, the project should be communicated and presented clearly to the people, to show that their money is well spent. However, they have little to no power in the matter of national flood protection. Additionally, the Vietnamese people that don't live in the Mekong Delta are less engaged and have less interest, therefore they can be monitored.

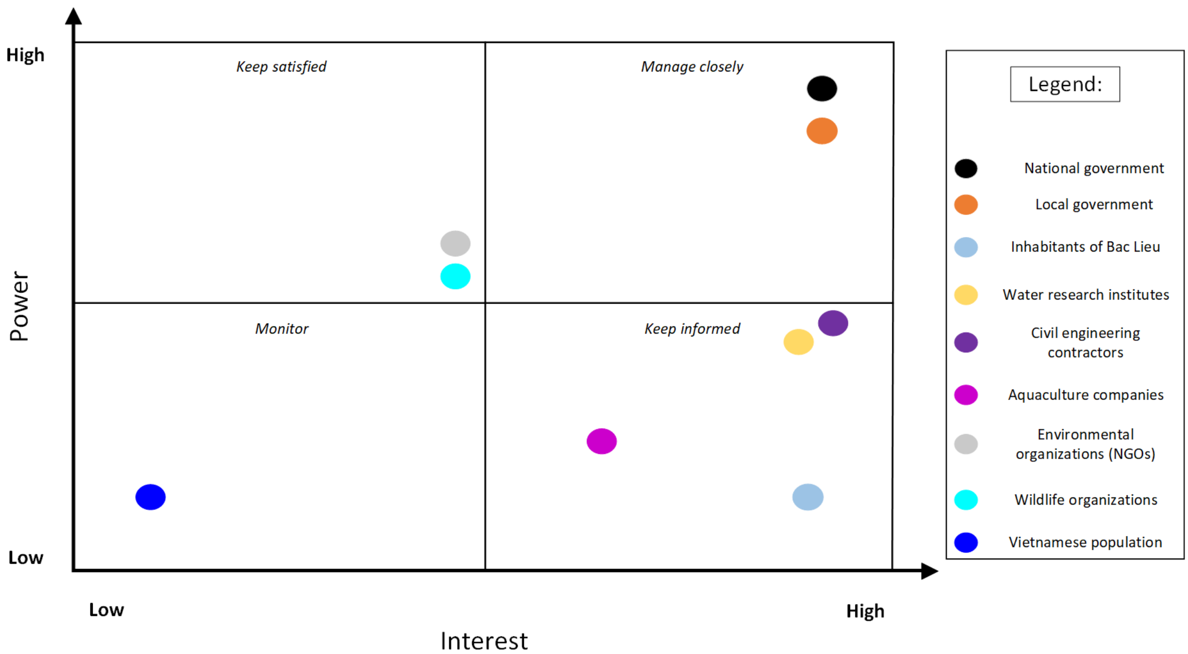


Figure C.1: Power-interest grid, showing the level of interest and power for each stakeholder

D

Delft3D specifications

D.1. Grid details

Direction	No. of cells	Cell size [m]	Total size [m]
Partially eroded (primary)			
M (longshore)	500	10	5000
N (offshore)	412	*refined & smoothed*	4000
Heavily eroded (primary)			
M (longshore)	500	10	5000
N (offshore)	444	*refined & smoothed*	3000
Grid nesting (secondary)			
M (longshore)	150	200	30000
N (offshore)	90	200	18000

Table D.1: Grid details

D.2. Bathymetry data

As mentioned in Appendix A, bathymetry data of the Nha Mat coast stretching $20km$ offshore is obtained from SIWRP. This data is processed using AutoCAD, resulting in representative *.xyz* (cartesian coordinates, including depth) data points stretching $18km$ offshore (as measured from the sea-dike). This data-set is imported into Delft3D-QUICKIN, where it is linearised for two locations (partially eroded coast and heavily eroded coast) to obtain a representative cross section for each location. Two bathymetries, uniform in the longshore direction, are obtained by assuming that the cross sections are constant in the longshore direction. The raw data is included in Appendix G.

D.3. Boundary conditions

Tidal constituent	Name	Amplitude [m]	Phase [deg]
Semidiurnal			
Principal lunar	M_2	1.08	118
Principal solar	S_2	0.39	177
Lunar-elliptical	N_2	0.07	65
Lunar-solar declinational	K_2	0.05	180
Diurnal			
Lunar-solar declinational	K_1	0.67	3
Principal lunar	O_1	0.45	310
Principal solar	P_1	0.16	340
Other			
Semiannual	S_a	0.16	280
Storm surge (high energy conditions) [69]	A_0	1.1	0

Table D.2: Main tidal constituents [56][30]

Condition	Monsoon season	Storm (Beaufort 11) [69]
Significant wave height [m]	0.56	7.36
Peak period [s]	3.82	10.3
Nautical direction [deg]	143.86	143.86
Directional spreading [-]	4	4
Wind speed [$\frac{m}{s}$]	5.1	29
Wind direction [deg]	143.86	143.86

Table D.3: Wave and wind properties

D.4. Mangrove characteristics

	Trunks	**Air roots**
Plant density (n/m^2)	0.625	100
Average diameter (m)	0.07	0.005
Height (m)	7	0.17
C_D ($-$)	1	1

Table D.4: Input values for mangroves in Delft3D. Based on measurements from Appendix A

D.5. Validation

The model is validated by comparing results of a simulation without hydraulic measures with in-situ measurements made by the Southern Institute of Water Resources and Planning (SIWRP). Since sedimentation and erosion is caused by wave height and flow velocities, these model outputs are validated with data obtained by SIWRP. Since the data from SIWRP was obtained under low energy conditions at a location $4km$ offshore from a coast with mangroves, it is compared with the Delft3D output of a model representing mangroves and low energy conditions at a location $4km$ offshore. Next to the flow velocity and significant wave height validation, it would be comprehensive to also add a validation of the water levels and sediment transport. However, this data is not available. Therefore, the sediment transport will be validated in a qualitative way.

D.5.1. Flow velocity

The real-time data for a time span of two weeks on a location $4km$ offshore in Bac Lieu is used for the validation of the flow velocities. The measurements were done on the bottom, on the surface and in the middle of the water column. The absolute values per time step (independent of direction of the flow) are plotted over time in Figure D.1. The average of the full time series is plotted as well. From this analysis follows that the average absolute (independent of flow direction) flow velocity in this location is equal to $0.241 m/s$. To reduce computational power, one full tidal cycle is simulated in Delft 3D, corresponding to 24 hours. From this simulation, the absolute depth averaged flow velocity is obtained per time step. This yields one value per hour, 24 values in total. These values are averaged, resulting in $0.140 m/s$ (Figure D.1).

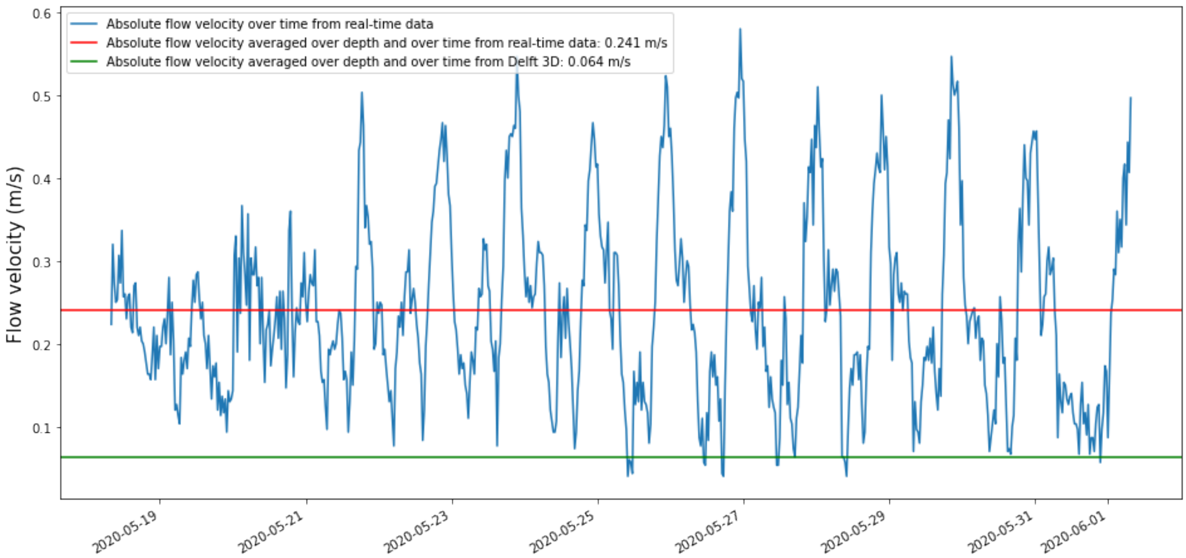


Figure D.1: Real-time flow velocity data (blue) and it's time average (red), and the time average that follows from Delft 3D (green). Image by author.

It is concluded that the values obtained from SIWRP and Delft3D are within the same order of magnitude, and that, considering the fact the simulation time is a lot smaller than the measurement time, this difference is acceptable.

D.5.2. Significant wave height

The real-time data for a time span of two weeks on a location $4km$ offshore in Bac Lieu is used for the validation of the significant wave height. The values per time step are plotted over time in Figure D.2. The absolute average of the full time series is plotted as well. From this analysis follows that the average significant wave height in this location is equal to $0.478m$. To reduce computational power and time, one full tidal cycle is simulated in Delft 3D, corresponding to 24 hours. From this simulation, the significant wave height is obtained per time step, in the same location as where the data from SIWRP was measured. This yields one value per hour, 24 values in total. These values are averaged, resulting in $0.358 m/s$ (Figure D.2).

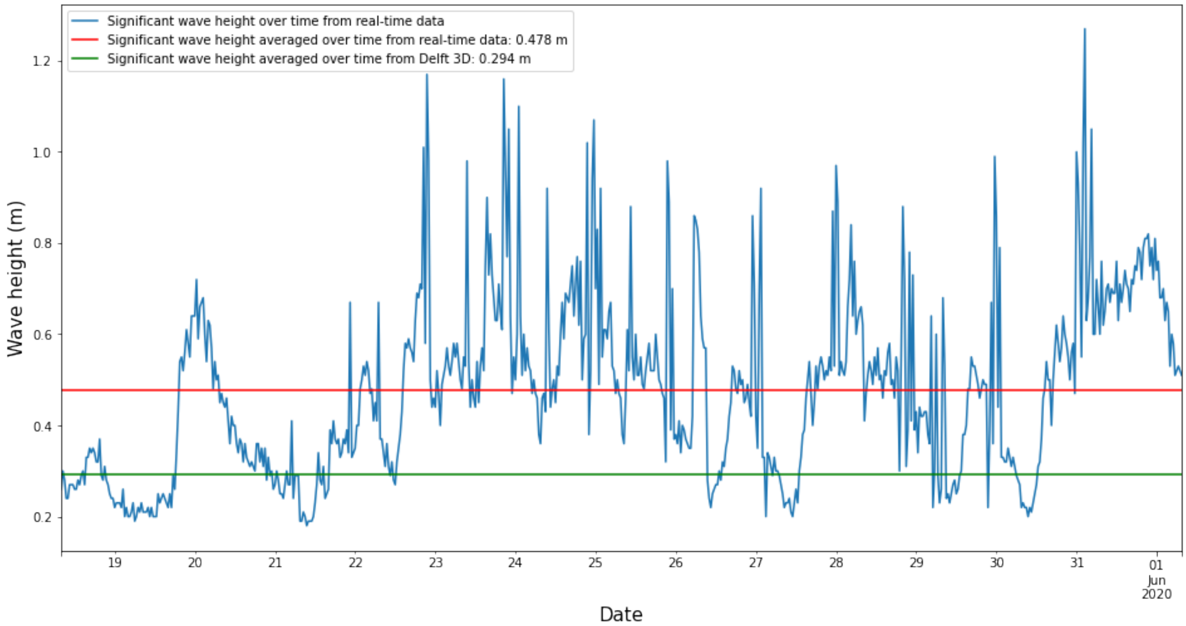


Figure D.2: Real-time significant wave height data (blue) and it's time average (red), and the time average that follows from Delft 3D (green). Image by author.

It is concluded that the values obtained from SIWRP and Delft3D are within the same order of magnitude, and that, considering the fact the simulation time is a lot smaller than the measurement time, this difference is acceptable.

D.5.3. Erosion & sedimentation

As explained in section 2.3, it is expected that during low energy (tide dominated) conditions, the sediment is transported to the shore and that during high energy (wave dominated) conditions, erosion will occur over the whole mudflat. Next to that is expected that close to the dike or erosion will occur due to the wave reflection as explained in section 2.5. These statements are tested for the control simulation by modelling the partially eroded shoreline (with a mangrove strip of 1 km wide) and heavily eroded shoreline under high and low energy conditions. The results from these simulations in terms of cumulative erosion/sedimentation over the cross section of the mudflat are compared.

The blue line in the top plot in Figure D.3 shows the cumulative erosion/sedimentation on the heavily eroded shoreline for low energy conditions. Due the tide dominance It is conform the expectations that from -3000 till around $-1000m$ there is cumulative sedimentation. Furthermore, there is cumulative erosion in front of the dike till $-1000m$ offshore. Since the profile of the bed is concave-up and waves reflect on the dike, it is in line with the expectations that erosion occurs on this part of the mudflat.

The red line in the plot in Figure D.3 shows the cumulative erosion/sedimentation on the heavily eroded shoreline for high energy conditions. It is expected that cumulative erosion is occurring from the dike on wards in offshore direction, since there higher energy waves. The small sedimentation on the dike is considered irrelevant since the dike is schematized with a smaller slope than in reality.

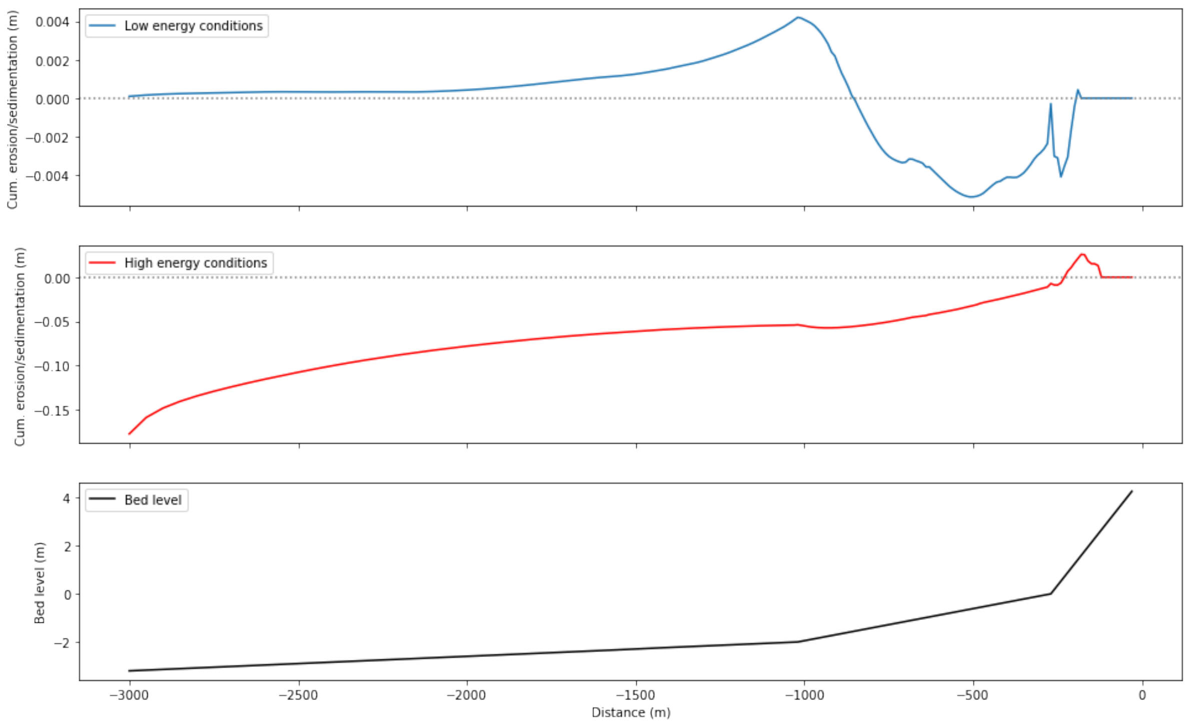


Figure D.3: The cumulative erosion/sedimentation on the heavily eroded mudflat, for the high and low energy conditions, compared to the bed level.

The blue line in the top plot in Figure D.4 shows the cumulative erosion/sedimentation on the partially eroded shoreline for low energy conditions. From this plot it can be seen that Cumulative sedimentation takes place between $-4000m$ and $-2750m$. This is as expected due to the tidal dominance during low energy conditions. Between $-2750m$ and $-1250m$ cumulative erosion takes place. This due to the wave reflection at the cliff near the mangroves. The downward peaks at around $-1300m$ can be explained by the sudden increase of wave dissipation due to the increased slope. The increased erosion between $-1250m$ and $-1000m$ is considered to be an effect of the low flow velocities and tide dominance.

The red line in the plot in Figure D.4 shows the cumulative erosion/sedimentation on the partially eroded shoreline for high energy conditions. It is as expected that cumulative erosion is occurring over the whole coast.

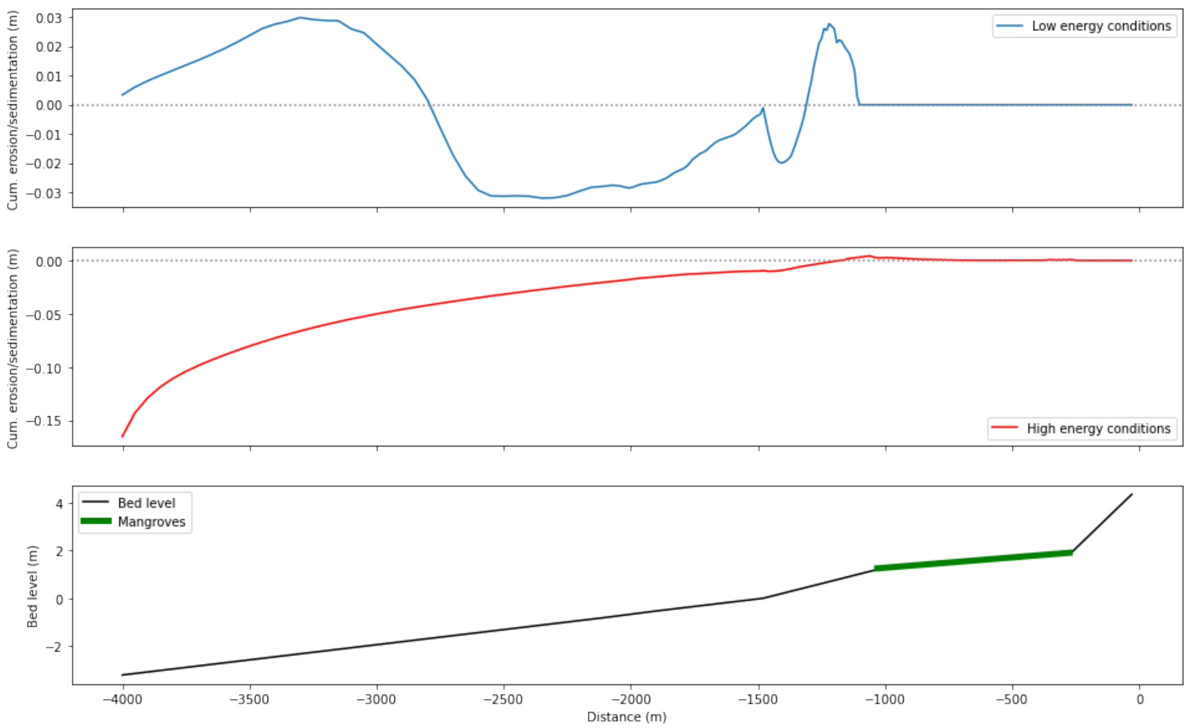


Figure D.4: The cumulative erosion/sedimentation for the partially eroded mudflat, for high and low energy conditions, compared to the bed level.

E

Mathmatical background sediment transport and mangrove hydrodynamics

E.1. Sediment transport

The fall velocity (w_s) can be calculated with Equation E.1 [10].

$$w_s = \frac{(s-1)gD^2}{18v} \tag{E.1}$$

where: s = relative density of particle (-)
g = gravitational constant (m/s^2)
D = particle diameter (m)
v = viscosity (m^2/s)

E.1.1. Longshore sediment transport

Theoretically, the net longshore transport of suspended sediment is given by Equation E.2 [10].

$$\langle s_y \rangle = \int_a^h V(z) \cdot C(z) dz \tag{E.2}$$

where: s_y = net longshore sediment transport excl. pores ($m^3/m/s$)
$V(z)$ = longshore current velocity at height z above the bottom (m/s)
$C(z)$ = time-averaged sediment concentration at height z (m^3/m^3)
a = thickness of bed load layer (m)
h = local (still) water depth (m)

Equation E.2 computes the longshore transport at a certain cross-shore location of suspended sediment. In order to determine the total longshore transport, Equation E.2 should be integrated over the width of the surfzone.

A, more practically used bulk longshore transport formula is the adjusted CERC-formula (Equation E.3) [33].

$$S = \frac{I}{\rho g(s-1)(1-p)} = \frac{K}{\rho g(s-1)(1-p)}(Enc)_b \cos\varphi_b \sin\varphi_b \tag{E.3}$$

where: I = the immersed (underwater) weight of sediment transported (N/s)
S = the deposited volume of sediment transported (m^3/s)
ρ = density of water (kg/m^3)
s = the relative density of sediment (-)
p = porosity
g = gravitational acceleration (m/s^2)
K = coefficient (-)
E = wave energy (J/m^2)
c = the wave phase velocity (m/s)
n = the ratio between group and phase velocity (-)
φ_b = the wave angle of incidence when breaking (-)

The biggest limitation of the CERC-formula is the fact that it only considers the longshore current driven by wave breaking and doesn't account for the tidal effect. However, both Equation E.2 and Equation E.3 can be used to understand the effects of certain measures and processes on the longshore sediment transport in the Mekong Delta. It clearly shows the influence the wave energy and phase speed have on the sediment transport.

E.1.2. Cross-shore sediment transport

The equilibrium cross-shore profile is given by Equation E.4 [23]

$$Z_b(x) = \begin{cases} a_0\,(x/L_r - 1) & \text{for x} \leq \text{L}_\text{r} \\ a_0 \sin\{x/L_r - 1\} & \text{for x} \geq \text{L}_\text{r} \end{cases} \tag{E.4}$$

where: $Z_b(x)$ = Water depth at location $x(m)$
a_0 = Tidal amplitude (m)
L_r = Reference length: length of the intertidal mudflat below mean sea level (m)

However, due to the influence of waves, the profile becomes dynamic and sediment transport takes place. The near bed velocity in the cross-shore direction is assumed to be consisting of three components: (Equation E.5) [10].

$$u = \underbrace{\bar{u}}_{\substack{\text{time-averaged component} \\ \text{(streaming outside surf zone,} \\ \text{undertow in surf zone)}}} + \underbrace{u_{lo}}_{\substack{\text{low-frequency motion} \\ \text{at wave group scale}}} + \underbrace{u_{hi}}_{\substack{\text{oscillatory motion} \\ \text{at short-wave scale}}} \tag{E.5}$$

In order to determine the net direction of the sediment transport, the relative contribution of each of the velocity components needs to be calculated.

Next, the sediment transport (I_s) can be calculated with Equation E.6

$$I_s = \frac{\varepsilon_s c_f \rho}{w_s}\frac{u^3|u|}{(1-\gamma u)} \quad \text{with} \quad \gamma = \frac{\tan\alpha}{w_s} \tag{E.6}$$

where: c_f = friction coëfficient (-)
w_s = sediment fall velocity (m/s)
ε_s = efficiencies for bed and suspended load (-)
ρ = sediment density (kg/m^3)
u = near bed flow velocity (m/s)
α = slope of the bed (-)

Although Equation E.6 is a simplification of reality, it can be used for understanding the different processes and effects of certain measures in the cross-shore profile of the area of interest of this report. It clearly shows that the flow velocity induced by waves in the cross-shore direction plays an important role in the sediment transport.

E.2. Mangrove hydrodynamics

E.2.1. Tides

Although each species of mangrove tree has a unique root and trunk system, Mazda (2009) [45] has proposed a control volume V in a mangrove forest. The control volume schematized in Figure E.1 is defined as:

$$V = V_M + V_W = H \cdot \Delta x \cdot \Delta y \qquad \text{(E.7)}$$

where: V = Control volume in m^3
V_M = Volume of mangroves in m^3
V_W = Volume of water in m^3
H = Height control volume in m
Δx = Width control volume in m
Δy = Depth control volume in m

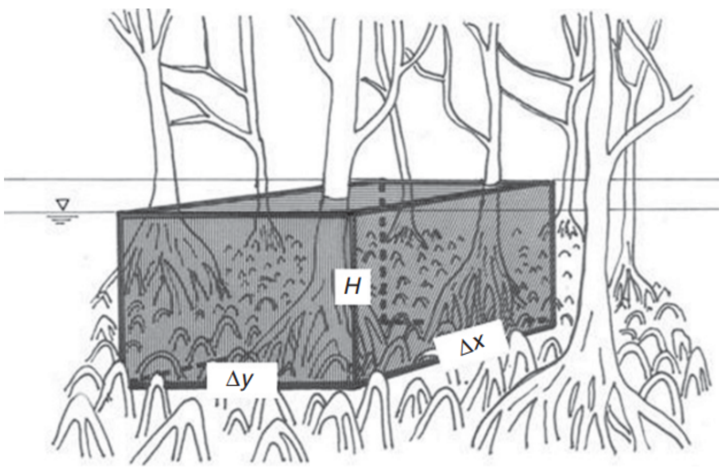


Figure E.1: Sketch of the control volume in a mangrove forest [45]

The volume of water in the control volumes is then used in the momentum equation. Simplification of the momentum equation results in the following approximation for the drag force by mangroves [44]:

$$g\frac{\delta\zeta}{\delta y}V_W = F_{D,y} \qquad \text{(E.8)}$$

where: g = Gravity constant (m/s^2)
ζ = Water surface elevation (m)
V_W = Volume of water in (m^3)
$F_{D,y}$ = Drag force in (N)

From engineering practise, the drag force is parameterised as follows:

$$F_{D,y} = -\frac{1}{2} C_D A v|v| \tag{E.9}$$

where A is the total projected area of the roots and trunks of the mangroves, and v is the tidal current speed. Finally, this results in the following formulation for the drag coefficient C_D [44]:

$$C_D = -2g \frac{\delta\zeta}{\delta y} \frac{\frac{V_W}{A}}{v|v|} \tag{E.10}$$

The relationship between the magnitude of the drag coefficient C_D and the Reynolds number Re is depicted in Figure E.2.

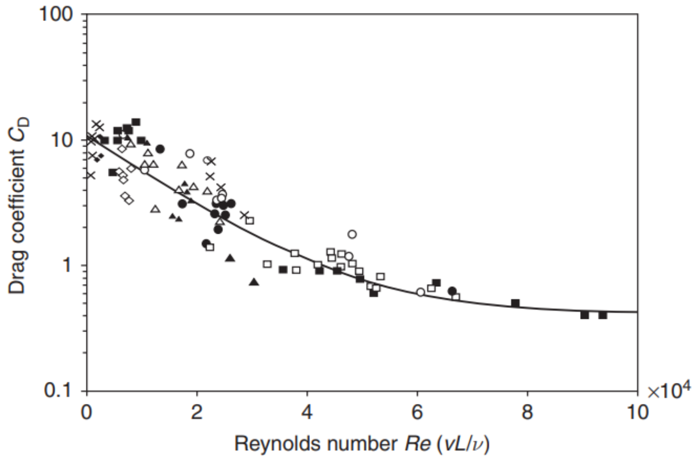


Figure E.2: Relation between the drag coefficient C_D and the Reynolds number Re [40]

E.2.2. Waves

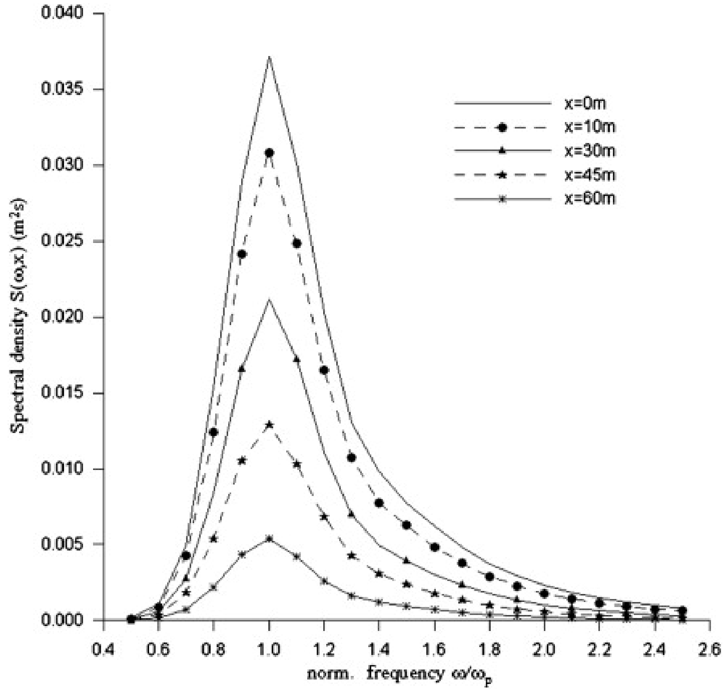


Figure E.3: Wave spectrum at different propagation depths in mangrove forest [40]

$$\delta H_{rms}^2 h^{\frac{1}{2}} \delta x = -C_1 H_{rms}^7 h^5 - A_1 H_{rms}^3 h^{\frac{1}{2}} \tag{E.11}$$

where: $A_1 = \frac{2C_D b_v N\alpha}{3\pi}$
$C_1 = \frac{3\pi B^3}{2\gamma_b^4 T_p g^{\frac{1}{2}}}$

A_1 is essentially the submerged frontal area of the mangroves multiplied by the drag coefficient. Therefore, when A_1 is nonzero vegetation is included in the model. Similarly, C_1 is a breaking coefficient comprising of the width of the sample space, the peak wave period and a bottom friction coefficient.

F

Additional Delft3D results for wave dissipation

F.1. Heavily eroded shoreline, east of Nha Mat

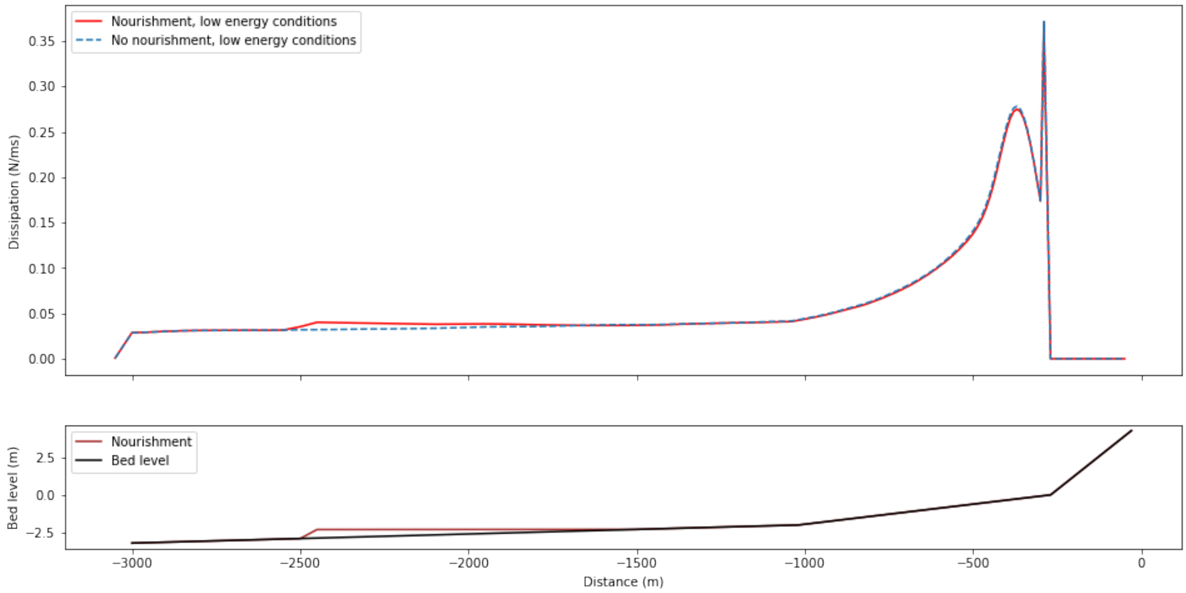


Figure F.1: The wave dissipation over the cross section of the heavily eroded mudflat at high tide during low energy weather conditions, plotted for the situation with (red) and without (dotted blue) the nourishment.

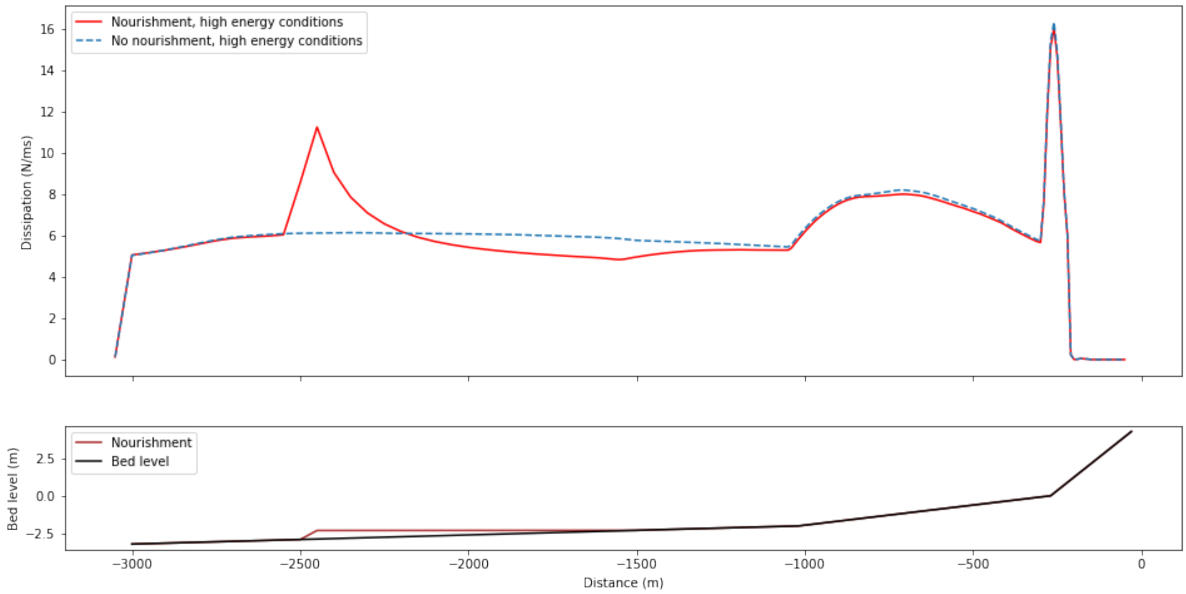


Figure F.2: The wave dissipation over the cross section of the heavily eroded mudflat at high tide during high energy weather conditions, plotted for the situation with (red) and without (dotted blue) the nourishment.

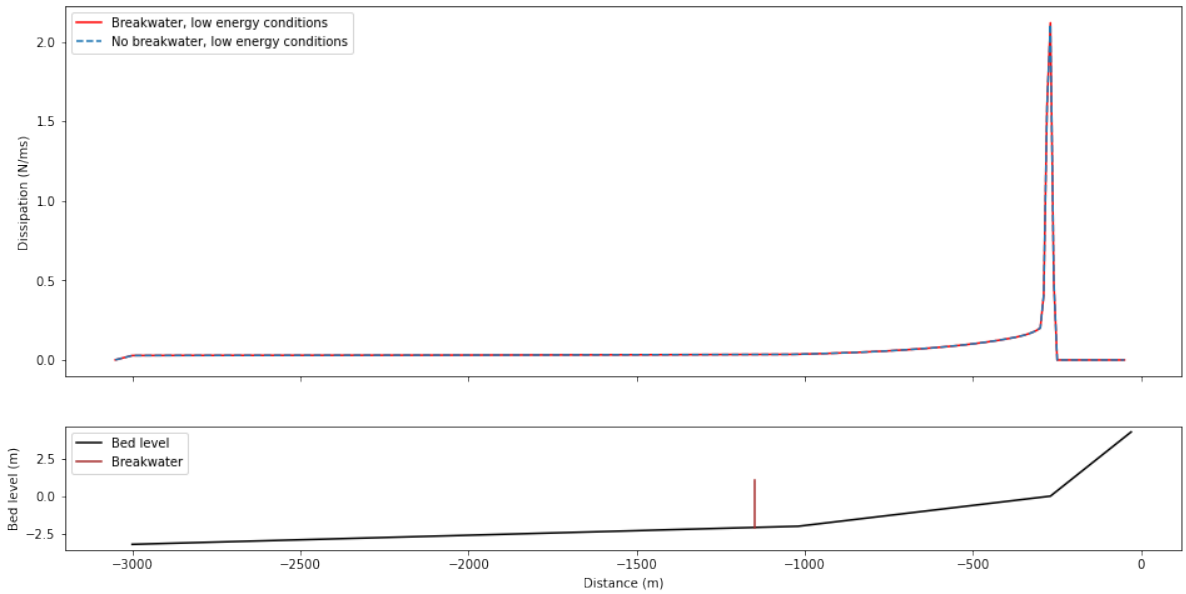


Figure F.3: The wave dissipation over the cross section of the heavily eroded mudflat at high tide during low energy weather conditions, plotted for the situation with (red) and without (dotted blue) the porous breakwater.

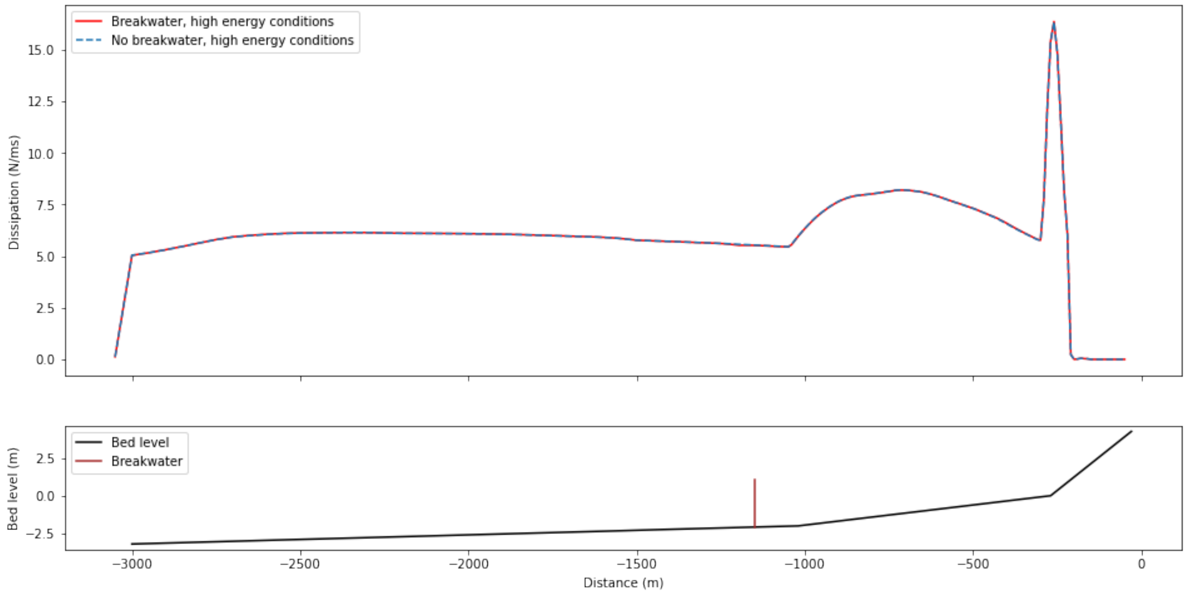


Figure F.4: The wave dissipation over the cross section of the heavily eroded mudflat at high tide during high energy weather conditions, plotted for the situation with (red) and without (dotted blue) the porous breakwater.

F.2. Partially eroded shoreline, west of Nha Mat

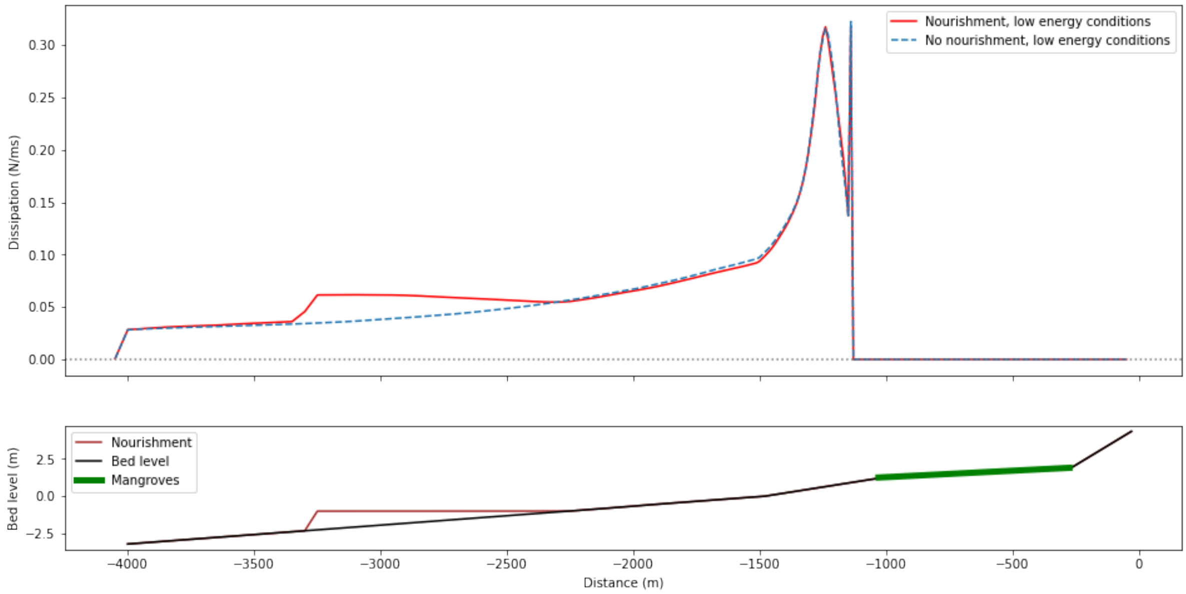


Figure F.5: The wave dissipation over the cross section of the partially eroded mudflat at high tide during low energy weather conditions, plotted for the situation with (red) and without (dotted blue) the nourishment.

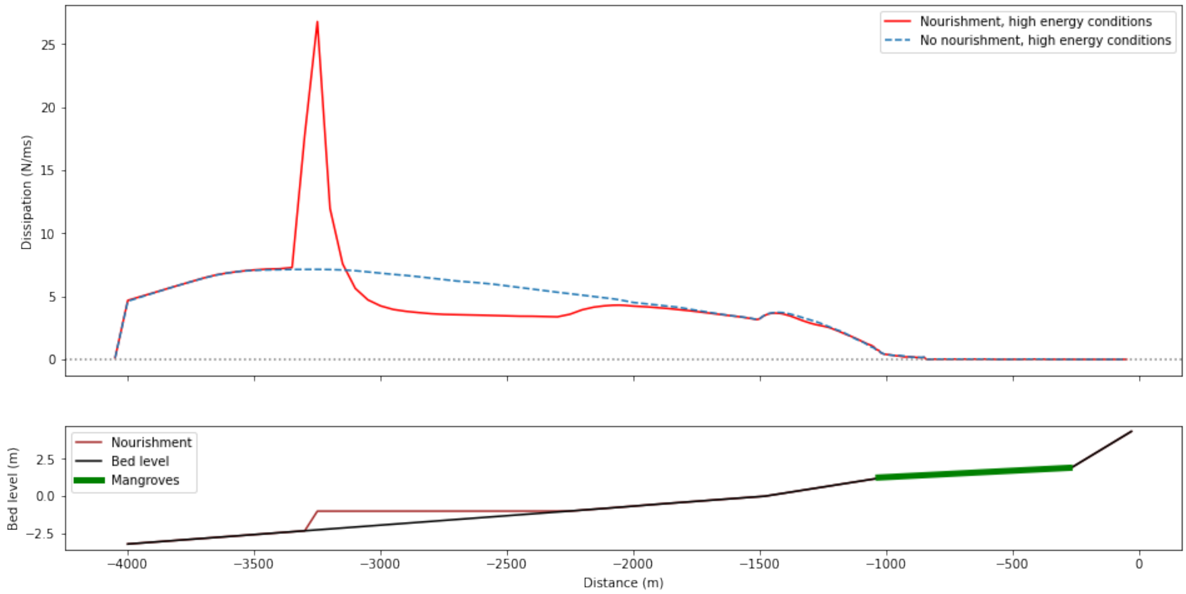


Figure F.6: The wave dissipation over the cross section of the partially eroded mudflat at high tide during storm energy weather conditions, plotted for the situation with (red) and without (dotted blue) the nourishment.

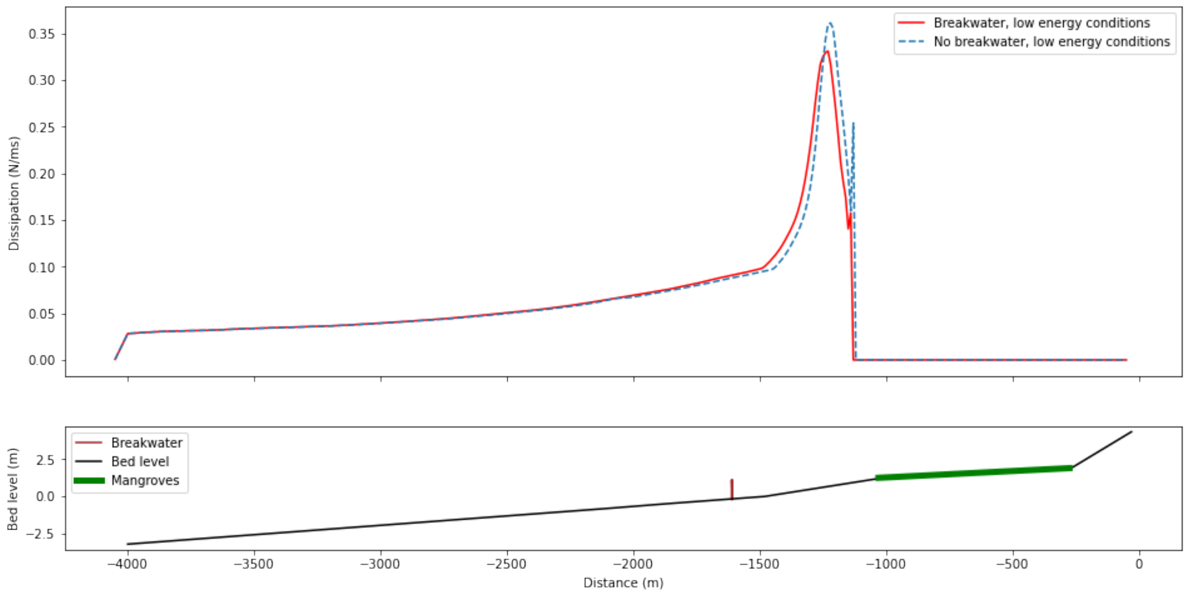


Figure F.7: The wave dissipation over the cross section of the partially eroded mudflat at high tide during low energy weather conditions, plotted for the situation with (red) and without (dotted blue) the porous breakwater.

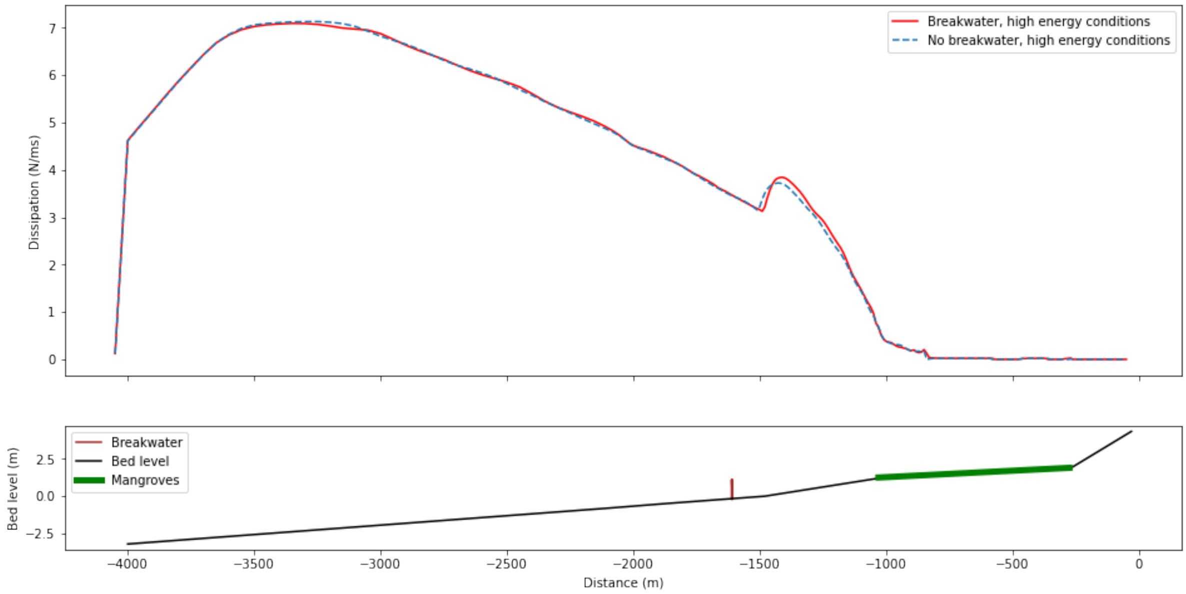
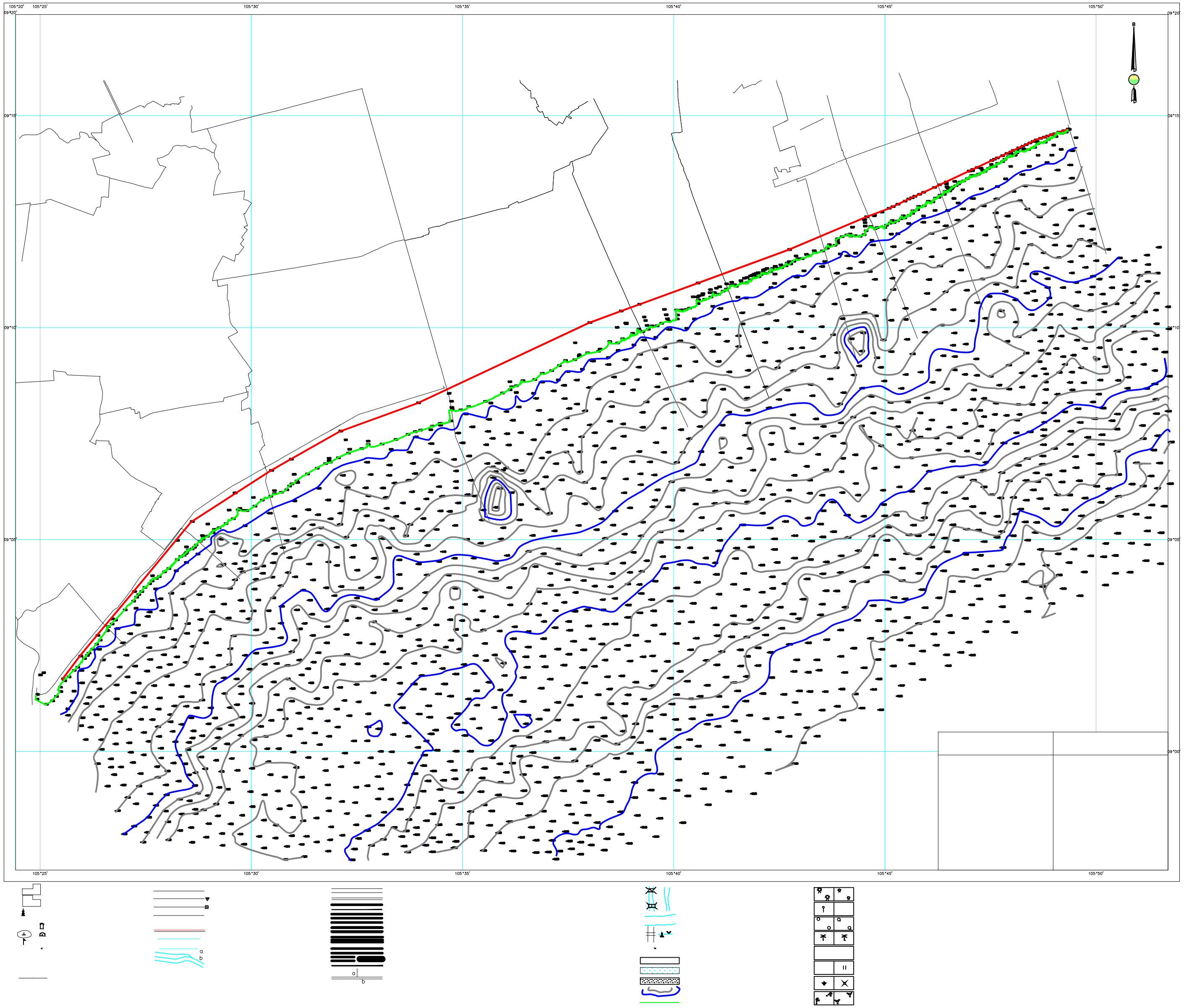


Figure F.8: The wave dissipation over the cross section of the heavily eroded mudflat at high tide during high energy weather conditions, plotted for the situation with (red) and without (dotted blue) the porous breakwater.

G
Bathymetry data SIWRP and TLU

The bathymetries of the mangrove forest (TLU) and offshore area (SIWRP) are included in the following pages.


105°20'
105°25'
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105°40'
105°45'
105°50'
09°20'
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