Room for the Wadden Sea

Analysis of a building with nature approach to strengthen the foreshore at Koehool-Lauwersmeer

N.A.M. Hartman

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by

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to obtain the degree of Master of Science
at the Delft University of Technology.

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N.A.M. Hartman

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Abstract

A significant part of the Netherlands lies below sea level. The Dutch have protected their land against seawater since the 10th century to prevent the land from flooding. Nowadays, the Netherlands is protected by 3800 km of primary flood defences, preventing flooding from the sea, rivers, and lakes. Since the Flood Defences Act was included in the Dutch law in 1996, all flood defences are tested against the national safety standards every twelve years. If a flood defence does not meet the national safety standards, it has to be reinforced. In the latest assessment round, a 47 kilometres long stretch of a Wadden Sea dike in the northern part of the Netherlands dike section, from Koehool to Lauwersmeer, did not meet the requirements. It is rejected to multiple foreshore influenced failure mechanisms.

The dike area of Koehool-Lauwersmeer consists of cultural heritage in means of historical dikes and historical land reclamation structures. The (embanked) salt marshes that are present at the foreshores of the dike section, are of great value for both ecology and water safety in the area. The length of the dike section and the unique project location, provide an opportunity to explore alternative solutions for the dike strengthening project. Innovative dike strengthening solutions can potentially minimize the anthropogenic influence of the reinforcement projects, increase the systems adaptability potential to sea level rise and contribute to the ecological values of the area. In this research, an explorative study is conducted to find an alternative dike strengthening design and to assess the morphological developments and ecological opportunities of such a design. Based on the criteria to contribute to both flood safety and ecological value, a slufter alternative is chosen to be studied further. The slufter alternative engages an inland area between two dikes into the Wadden Sea by an artificial dike breach. The area is regularly inundated, creating opportunities for ecosystems to evolve.
A depth-averaged (2DH) Delft3D model is used to explore the morphological developments of the slufter area and the potential to add to the ecological value of the area.

The project area is characterized by a sediment-rich environment and a flood dominant tide. Higher flood than ebb velocities are present, causing an import of sediment into the slufter area. Model results indicate that the net sediment import of the slufter area mainly depends on the suspended sediment concentration, the critical shear stress and the tidal prism of the slufter area. The initial geometry of the slufter area influences the behaviour of the system, as it determines the tidal prism of the slufter area. A geometry that causes an increase in the flow velocity shows higher suspended sediment concentrations that lead to higher amounts of sediment import.

Under the influence of a sea level rise (SLR) of +1m, the sediment transport increases with a factor of 2 to 3, depending on the initial geometry. SLR enhances the sediment trapping of the area. Depending on the applied geometry the slufter area can potentially keep up with SLR. Assuming an equal distribution of sediment over the slufter area, the average growth rate of the bed level is between 0.22 (minimum sediment import, maximum expected SLR) and 21.12 (maximum sediment import, minimum expected SLR) times SLR. Applying the slufter intervention adds 60 ha to the intertidal area of the Wadden Sea. Depending on the applied geometry this results in 30 to 50 ha between MLW and MHW (lower marsh) and 10 to 30 ha above MHW (middle and upper marsh). The slufter alternative creates opportunities for new ecosystems and contributes to the Natura 2000 goals to create more gradual transition areas between the Wadden Sea and the surrounding land by creating an area with a gradual wet-dry transition. These potentially add to the biodiversity of the area as they create opportunities for specific plant species and waders.

It is concluded that creating a slufter area at the Koehool-Lauwersmeer dike, provides opportunities for sediment trapping due to the flood dominance of the system and the high sediment concentrations. The amount of sediment trapping is strongly influenced by the critical shear stress, the area's tidal prism, and the suspended sediment concentrations. SLR increases the amount of sediment trapping. Depending on the applied geometry, the bed level growth rate is larger than SLR. Creating a slufter area creates an opportunity to improve both the flood safety and the ecological value in one design.

1

Introduction

1.1. Background

A significant part of the Netherlands lies below sea level. To prevent the Dutch land from flooding, it has been protected against sea water since the 10th century (Van der Spek, 1995). As time passed, the sea level rose, storm events occurred more frequently, and the Dutch population increased. Protecting the land has become one of the main challenges for the Dutch. Nowadays, the Netherlands is protected by 3800 km of primary flood defences, preventing flooding from the sea, rivers, and large lakes (Jonkman et al., 2018). Since the Flood Defences Act was included in the Dutch law in 1996 all flood defences are tested against the national safety standards every twelve years. These safety requirements are described by the legal assessment instrument named 'Wettelijk Beoordelingsinstrumentarium' (WBI) and are updated each assessment round. If a flood defence does not meet the requirements stated in the WBI, it has to be reinforced (Rijksoverheid, 2017).

One of the Dutch primary flood defences is a Wadden Sea dike, located in the northern part of the Netherlands. During the newest assessment round, WBI2017, a section of this dike, from Koehool to Lauwersmeer (Figure 1.1), did not meet the requirements. 'Wetterskip Fryslân' (the Frisian water board) is the responsible authority for this dike and is therefore responsible for the reinforcement. The dike section from Koehool to Lauwersmeer has a length of 47 kilometres, which together with the diverse surrounding areas makes this a challenging project.

Figure 1.1: The location of the dike section Koehool-Lauwersmeer in The Netherlands, Europe (NASA, 2020; Witteveen+Bos, 2020)

The Wadden Sea is a nature conservation area that is part of the UNESCO world heritage and the Natura 2000 network because of its unique geological and ecological values (Rekenkamer, 2013). A chain of barrier islands provides shelter to the Wadden Sea and the dike area. The dike area of Koehool-Lauwersmeer consists of cultural heritage in means of historical dikes and historical land reclamation structures ('kwelderwerken'). The (embanked) salt marshes that are present at the foreshores of the Wadden Sea and the dike area are of great value for both ecology and water safety in the area (van Reijn and Franssen, 2020).

Adjustments to sea dikes should continually be made to guarantee flood safety. As stated by Schroor et al. (2017a), "without future human intervention it is unlikely that the adjacent barriers and coasts can supply sufficient sediment to regain and keep the Wadden Sea in dynamic equilibrium to relative sea-level rise". Although the existing (engineered) structures have proven to be effective to guarantee flood safety, climate change and the associated increasing water levels and more frequent flood events together with the high safety standards (Dutch Water Act, introduced in 2009 (Rijksoverheid, 2020b)), asks for reinforced structures. Reinforcement of the existing structures asks for stronger, bigger and taller structures. The great length of the dike section and the unique project location, provide an opportunity to explore alternative solutions for the dike strengthening project. Innovative design solutions that add to flood safety can create added value for the area and minimize the anthropogenic influence (Chu et al., 2012; Barbier et al., 2011; van Loon-Steensma and Schelfhout, 2017).

1.2. Problem definition and research questions

The Wadden Sea is a unique system that is of great ecological value. For sustainable management of the Wadden Sea system in the future, it is important to recognise that natural processes can only reign free within fixed boundaries. These boundaries are set by the flood defences protecting the Netherlands from flooding. To guarantee flood safety with the changing conditions, these flood defences have to be improved and reinforced continuously. The anthropogenic influence of these reinforcement projects can potentially be decreased by the use of innovative designs. In addition, innovative solutions can potentially increase the systems adaptability potential to sea level rise (SLR) and can contribute to the ecological values of the area.

This study is inspired by the Koehool-Lauwersmeer dike strengthening project. It explores the options to use the dike strengthening project as an opportunity to add to the ecological value of the area and increase the resilience to SLR. General ideas for such alternative dike strengthening designs exist, however proof of concept is often missing. To this end, a pilot study is conducted to find an alternative dike strengthening design and to assess the morphological developments and ecological opportunities of such a design in this area.

The main objective of this study is to find a dike strengthening design for the dike area of Koehool-Lauwesmeer, that improves both the flood safety and the ecological value of the area. To that end, the secondary objective is to select a pilot location and design alternative that are convenient to investigate such a design. Background information is required about the hydrodynamic conditions present at the study area, the ecological opportunities of the area, the failure mechanisms that apply to the Koehool-Lauwersmeer dike section and the design solutions that suit the problem statement. This information is obtained with a literature study and interviews with ecologists. After selection of a pilot location and an alternative design, the morphological development is studied and ecological opportunities are explored.

These objectives leads to two research questions that are answered with several sub-questions. These questions are given below.

What is the most suitable pilot location and design alternative?

- **Q1.1** What are the requirements for a pilot location and design alternative to investigate a flood defense system that improves the flood safety and the ecological value?
- **Q1.2** What is the most suitable pilot location and design alternative to be explored at the Koehool-Lauwersmeer dike section?

What is the contribution of the design alternative to sediment trapping and the ecological value of the area?

- **Q2.1** How do the driving forces influence the sediment trapping of the area?
- **Q2.2** How does the initial geometry influence the sediment trapping of the area?
- **Q2.3** What is the expected effect of SLR on the sediment trapping?
- **Q2.4** What is the initial morphological evolution of the project area after intervention?
- **Q2.5** What does the design alternative add to the ecological value of the area?

1.3. Approach and report outline

First, the problem and its environment are analyzed with a literature study. With this literature study, the boundary conditions and the scope of the research are determined. Different solutions for the problem statement are investigated and information is gained from case studies of nature-based flood protection designs. In addition, interviews with ecologists are held to determine the ecological opportunities for the project area and to determine how ecology can be taken into account. One alternative design solution is chosen to be studied further. The Delft3D modelling software from Deltares is used to investigate the morphological effects of the considered solution to the pilot location.

This thesis starts by introducing the project (Chapter 1). Next, the background of the study area (Chapter 2) is given. This is followed by an overview of the boundary conditions and opportunities of the project in which possible dike reinforcing techniques, common failure mechanisms and ecological aspects are discussed (Chapter 3). Subsequently, the methodology that is used to choose a suitable pilot location, an alternative design solution and the ecological assessment standards, is given (Chapter 4). The resulting pilot location, the considered alternative and the resulting ecological assessment standards are explained after (Chapter 4.2). Further, the numerical model study is considered. In this part of the research the model set-up is described (Chapter 5) followed by the model results (Chapter 6). Finally, the discussion (Chapter 7), conclusions and recommendations (Chapter 8) are given.

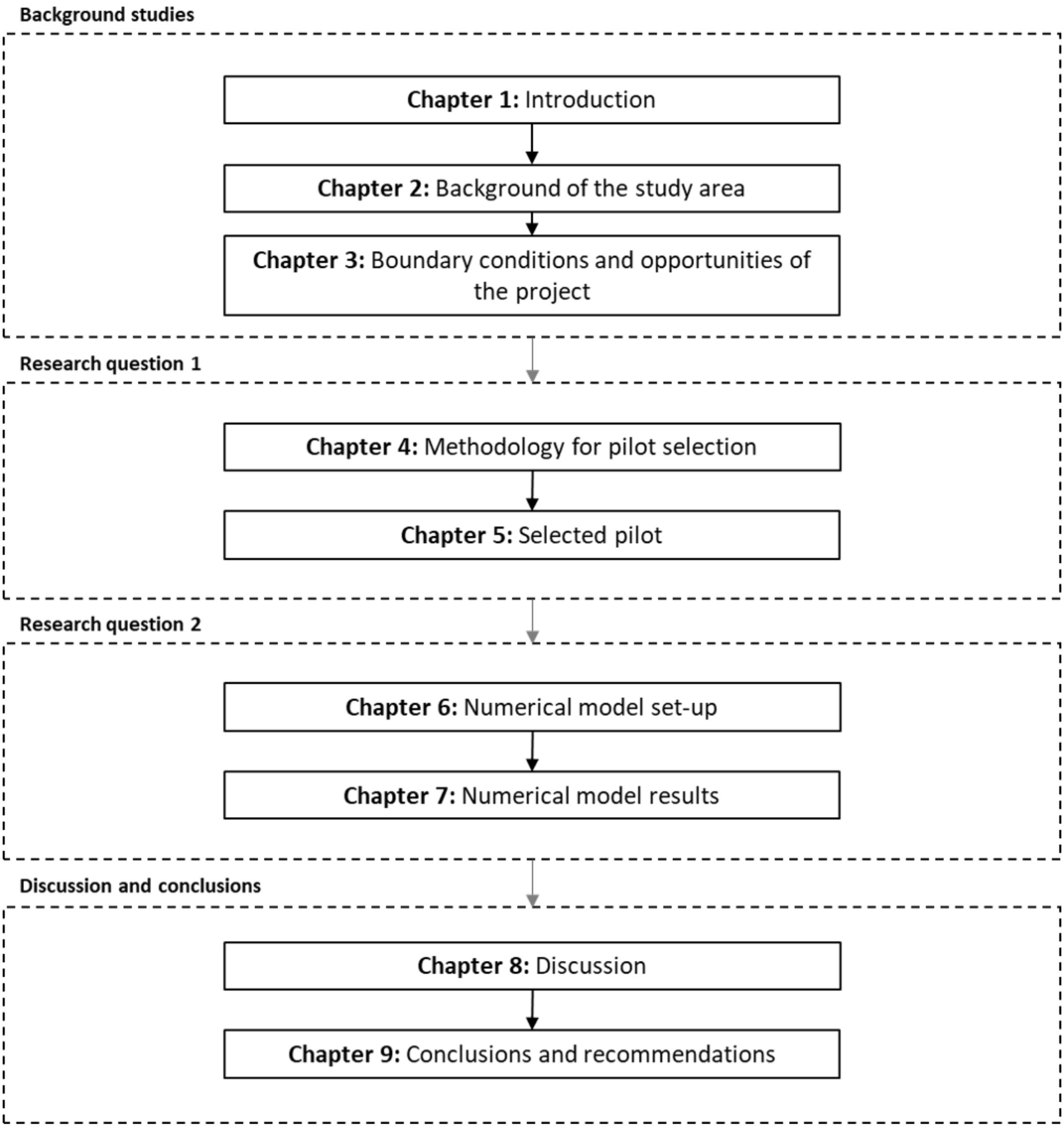


Figure 1.2: Outline of the thesis

2

Background of the study area

2.1. Wadden Sea

The Wadden Sea covers a 500 km long stretch of the North Sea coast from the Netherlands to Denmark. It is the largest uninterrupted system of tidal flats and barrier islands in the world and is part of the UNESCO world heritage because of its unique geological and ecological values. The Dutch Wadden Sea (referred to as Wadden Sea) reaches from Den Helder, in the Northern part of the province of North-Holland, to the German border at the Ems-Dollard estuary, see Figure 2.1. On the southern side of the Wadden Sea, the Afsluitdijk forms its border with the fresh water lake, the IJsselmeer. A chain of barrier islands provides shelter to the dynamic landscape of the Wadden Sea that is continuously shaped by wind and tides. Figure 2.2 shows the main tidal inlets of the Wadden Sea. The Wadden Sea comprises several tidal basins that consist of extensive systems of branching channels, tidal flats and salt marshes. Each tidal cycle, a large volume of water runs in and out of the basins through the tidal inlets, which are characterized by deep channels. Wind causes a significant exchange of water between the different tidal basins (Duran-Matute et al., 2014). The Wadden sea, and in particular the intertidal areas, have a high ecological value containing multiple habitats that support a broad range of biodiversity. (Elias et al., 2012; Vermeersen et al., 2018; van der Spek and van den Berg, 2018; Common Wadden Sea Secretariat, 2020).

Figure 2.1: An overview of the Dutch Wadden Sea (Elias et al., 2019)

2.1.1. History

The Wadden Sea area has a long history of human settlement. The earliest signs of settlement originate from the Pleistocene, and evidence shows how the Wadden Sea area has been inhabited permanently for almost 3000 years. Though the human impact was hardly present until about 1000 years ago, when first dike construction began (Schroor et al., 2017b; Elias et al., 2012).

The tidal basins of the Wadden Sea were formed during the early Holocene, when due to sea level rise, the Pleistocene valley system was gradually flooded (Vos and Knol, 2015). When around 2000 years ago the rise in sea level slowed down, the sediment infill of the basins was sufficient to keep up with sea level rise. On the landward edges sedimentation was even faster, resulting in a seaward extend of the land of marsh areas (Van der Spek, 1996; Oost et al., 2017). These marsh areas consist of salt marshes ('kwelders') and embanked marshes ('polders') (Schroor et al., 2017a).

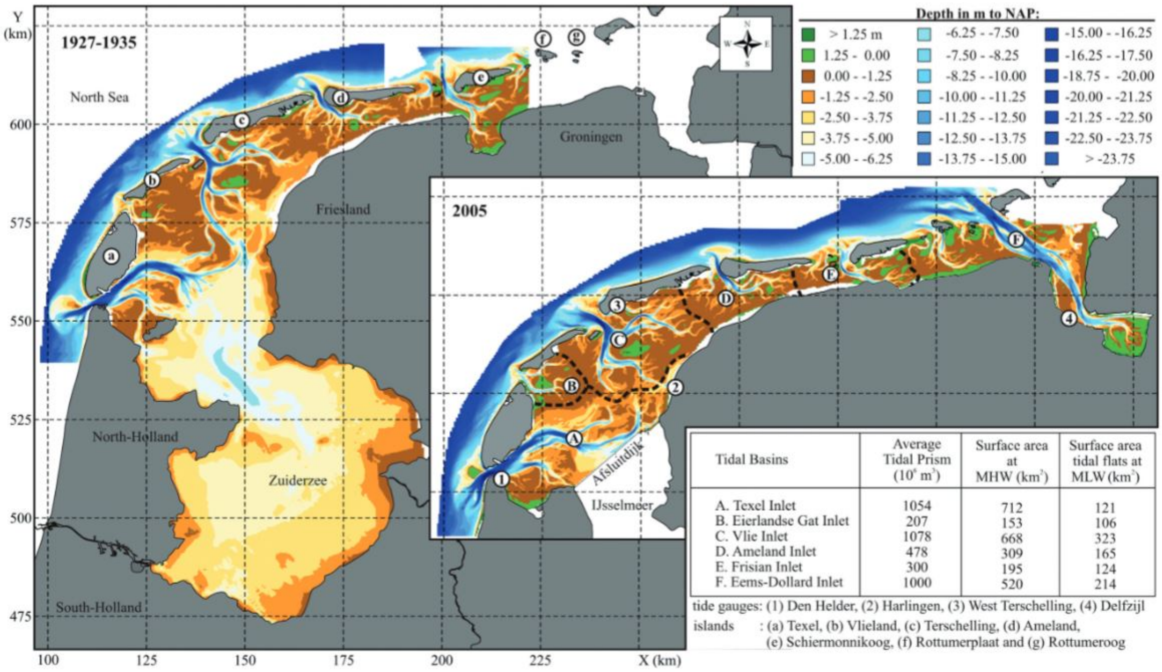


Figure 2.2: Representative maps of the Dutch Wadden Sea illustrating the configuration of the inlets, basins, channels and shoals for the years 1927-1935 (large figure) and 2005 (lower right). The main characteristics of the individual inlet systems are indicative for the present situation and based on Louters and Gerritsen (1994) (Elias et al., 2012).

The Wadden Sea area was frequently flooded before dike building began in the 10th century. The human impact gradually increased when dike building intensified and land reclamation projects were executed. The closure of the Zuiderzee (1932) and the Lauwerszee (1969) are considered to be the most significant human interventions in recent history influencing the morphological development of the Wadden Sea. The effects of both closures still influence the large scale morphological development and the sediment budget of the system (Wang et al., 2009).
Since 1990, the Dynamic Preservation policy prescribes that the North-Sea coastlines of the barrier islands may not retreat landward of a reference line that is based on their 1990 position. Therefore sand nourishments are conducted to counteract the coastline erosion and to keep the barrier islands in place. The execution of erosion control measures have more or less fixed the coastline of the Wadden Sea (Van der Spek, 1996; Van Koningsveld and Mulder, 2004; Elias et al., 2012).

2.1.2. Sediment

Most sediment in the Wadden Sea origins from the North Sea. Contribution of other sources are of minor influence. Mud is mainly brought in with North Sea water, while the sandy sediments are predominantly supplied by erosion of the ebb-tidal deltas, the barrier islands and the adjacent shore of the province of North-Holland (Van Straaten and Kuenen, 1957). The Wadden Sea is a sediment sharing tidal inlet system, meaning that sediment is transported from one basin to another (Oost et al., 2017).

Sediment composition

Sediments are classified in two groups; noncohesive and cohesive. Noncohesive sediments are usually the coarse sediments such as gravel and sand. Finer sediments such as clay and fine silt, are usually cohesive due to inter-particle electrochemical forces. Mud is the name used for a mixture of clay and silt combined with organic materials (Pye, 1994; Winterwerp and Van Kesteren, 2004). As with other tidal flat areas, the sediments along the inner coast of the Wadden Sea mainly consist of clayey material. The tidal flats of the Wadden Sea are mainly composed of sand (90%) and muddy sediments (10%) (Van Straaten and Kuenen, 1957; Elias et al., 2019). The sediment size decreases and the mud fraction increases from the tidal inlets towards the Wadden Sea shores and towards the watersheds behind each barrier island due to the settling lag effects of suspended sediments (Postma, 1961; Van Straaten and Kuenen, 1957). This can also be seen from Figure 2.3, that shows the mud fraction in the Wadden

Sea.

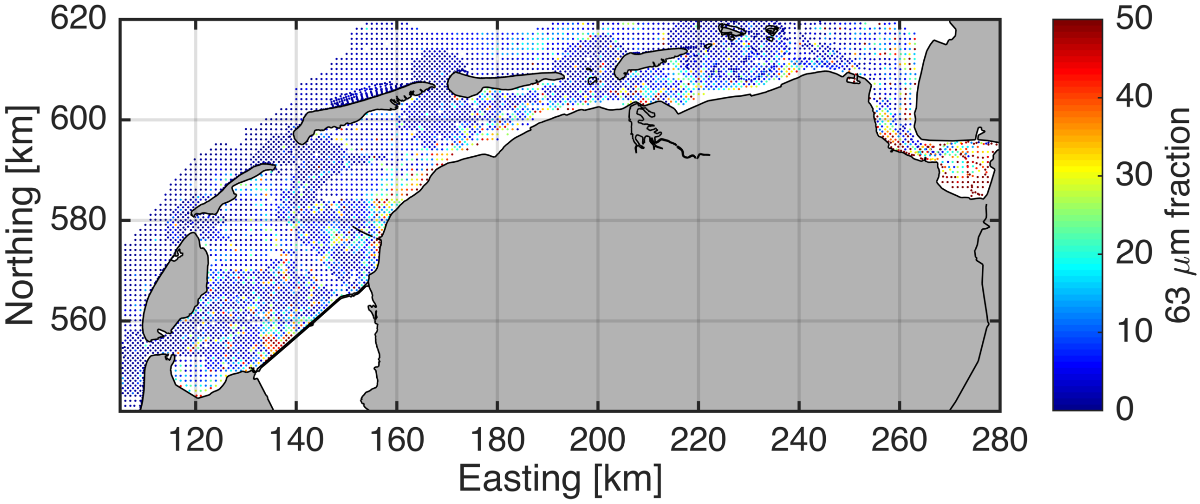


Figure 2.3: Mud fraction in the Dutch Wadden Sea (Sedimentatlas)

Sediment transport
Postma (1954) has studied sediment transport in the Dutch Wadden Sea. The amount of suspended materials present in the water, is dependent on the current velocity, which varies periodically with the tide. The stronger the current, the more material is brought into suspension. The suspended material has a delayed reaction to changes of the current velocity, with the delay for silt particles being longer compared to sand particles. This delay causes the suspension rate to reach it minimum value at a later moment in time compared to the current velocity. This minimum value is reached shortly after water slack. The maximum value is reached shortly after the tide is at its height.
In addition to the tide, the wind-wave driven transport has a significant influence on the suspension rates as well. The influence of the wind can be seen from the fact that the eastern Dutch Wadden Sea, which is better sheltered for strong winds compared to the western Wadden Sea, is both more silty and has higher quantities of suspended silt (Postma, 1954, 1961).

Morphological evolution
Over the years, an increase of the sediment volume in the Wadden Sea and a decrease of the volume of the ebb-tidal deltas is observed. Figure 2.4 shows a sedimentation-erosion map of the Wadden Sea over the period of 1927/1935 to 2005 (Elias et al., 2012). It is seen that sedimentation mainly occurred in closed-off channels and along the basin shoreline (Elias et al., 2012; Oost et al., 2018). Oost et al. (2017) states that for some tidal basins of the Wadden Sea the sedimentation is up to four times faster than the observed sea level rise. This is often the result of anthropogenic influence (Ley Bay, Zuiderzee and Lauwerszee). Although many research is done, still insufficient information is available to give a concluding answer whether the Wadden Sea is able to keep up with relative sea level rise or not (Dissanayake & Wurpts, 2013; Dissanayake et al., 2012).

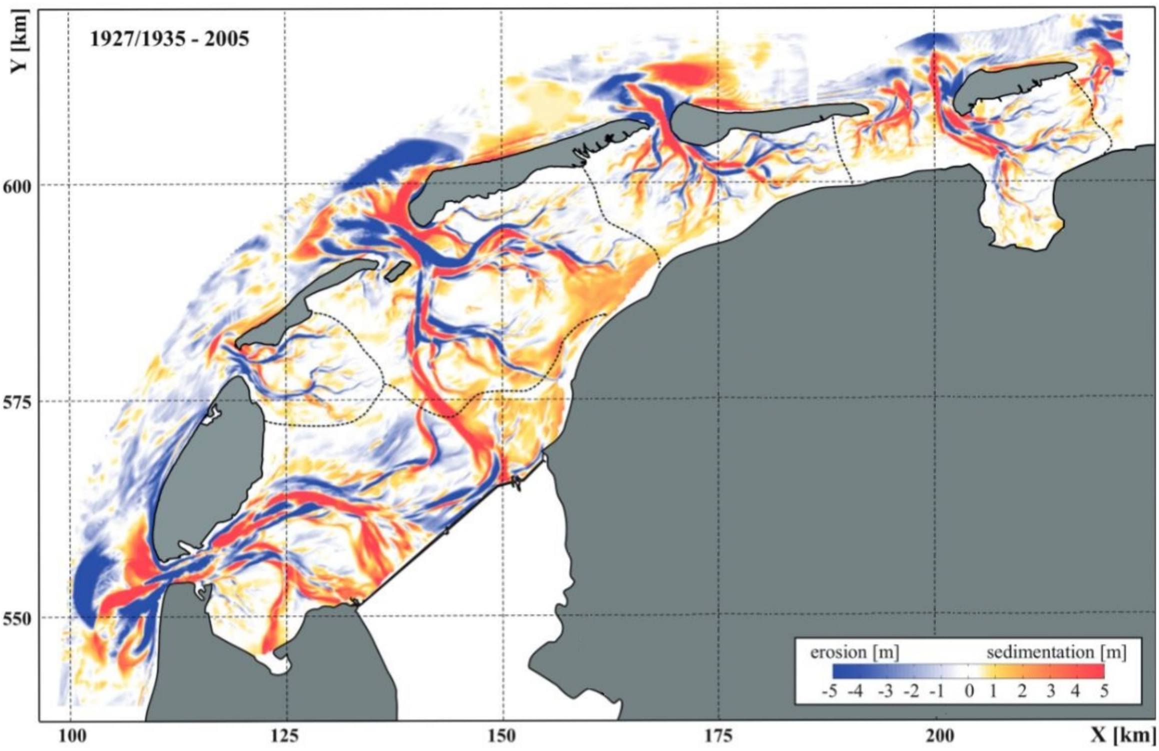


Figure 2.4: Representative sedimentation-erosion map of the Dutch Wadden Sea over the periods 1927/1935 till 2005 (Elias et al., 2012)

2.1.3. Hydrodynamic conditions

In this section a general introduction to the hydrodynamic conditions in the Wadden Sea is given. The specific coastal system characteristics that apply to the pilot location are further elaborated in Chapter 5.2.2. The Wadden Sea system owes its shape to the interaction of both tides and waves. According to the classification of Davis and Hayes (1984), the inlets of the Wadden Sea qualify as mixed-energy wave-dominated, even under spring-tide conditions (Wang, 2018). The mean tidal range increases from 1.4m to 2.5m from the southwest (Den Helder) to the east (Eems-Dollard). The fractal channel patterns that are present in the system, are driven by the tidal processes of flooding and draining (Cleveringa and Oost, 1999; Marciano et al., 2005; Wang, 2018).

Wave climate

The wave climate in the Wadden Sea, mainly consists of wind-generated waves that are locally generated in the shallow North Sea basin. These waves have an average significant wave height of 1.37 m and a peak wave period of 7 seconds (Wang, 2018).

Sea level rise

After a period of minimal sea level rise between 2000 and 300 years ago, the local mean sea level has been rising at increasing rates since about 300 years ago. Different scenarios for the prediction of how the sea level rise will evolve, exist (Vermeersen et al., 2018; Mai and Bartholomä, 2000). The projected rise in mean sea level for 2100 with relation to 2018 for Den Helder and Delfzijl is 0.41m, 0.52m and 0.76m for the Representative Concentration Pathway (RCP) climate scenarios RCP2.6, RCP 4.5 and RCP 5.8 respectively (van der Spek, 2018).

2.1.4. Natura 2000

Natura 2000 is a network of protected nature areas within the European Union, that aims to preserve biodiversity (Government of the Netherlands, 2020). Studies are done to investigate the measures needed to reach the Natura 2000 goals for the Dutch Wadden Sea region. The results of these studies, together with the suggested measures to reach these goals, are presented in the "Natura 2000-beheerplan Waddenzee". The boundaries of the Natura 2000 area for the Wadden Sea region are located at the sea side of the dikes (Ministerie van Infrastructuur en Milieu, Noord-Nederland, Rijkswaterstaat, 2016).

From the Natura 2000-beheerplan Waddenzee, two main goals are distinguished. The first is to strengthen and optimize the physical and ecological qualities of the area. The second goal is to stimulate and create room for economical development, which is outside of the scope of this research. For each Natura 2000 area, several core tasks (”kernopgaven”), are marked. The core tasks set for the Wadden Sea, Table 2.1, add to the first main goal and to the Wadden Sea’s demand for a maximum dynamic coastal zone. Following these core tasks, the Natura 2000 beheerplan Waddenzee strives for more gradual transition areas between the Wadden Sea and the surrounding land, the presence of all salt marsh zones and sufficient resting, foraging and breeding habitats (Ministerie van Infrastructuur en Milieu, Noord-Nederland, Rijkswaterstaat, 2016).

Table 2.1: Core tasks for the Natura 2000 Wadden Sea region translated from Ministerie van Infrastructuur en Milieu, Noord-Nederland, Rijkswaterstaat (2016)

Core task	**Description of the task**
Landscape coherence and internal completeness (North Sea, Wadden Sea and Delta)	Maintain or restore spatial cohesion in deep water, creeks, gullies, shallow water, flats, salt marshes or meadows, beaches and associated sedimentation- and erosion processes. Maintain openness, rest and darkness. For birds this is sufficient rest and space for foraging and sufficient quiet high water refuge areas at short distance from foraging areas in the intertidal area.
Flooded shoals & biogenic structures	Qualitative improvement of permanently flooded shoals (tidal area) H1110A with a.o. biogene structures with mussels. Also important as habitat for common eider (eider , A063) and common scoter (zwarte zee-eend, A065) and as breeding ground for fish.
Fresh-salt water transitions (Wadden Sea area)	Restore fresh-salt water transitions (e.g. with flushing regime and fish ladders) in particular at the fish entry of the Afsluitdijk, the Westerwoldse Aa and Lauwersmeer/Reitdiep in relation to Drentsche Aa (Rivierprik H1099).
Hinterland twaint shad (fint)	Maitaining the connection with the Schelde and the Eems for spawning of the twaint shad (H1103).
Diversity of tidal flats	Qualitative improvement of tidal flats and shoals (tidal area, H1140A) for increased diversity
Resting and foraging area	Preserve tidal flats and shoals for resting and foraging non-breeding birds such as the dunlin (bonte strandloper, A149), bar-tailed godwit (rosse grutto, A157), Eurasian oystercatcher (scholekster A130), red knot (kanoet, A143), ruddy turnstone (steenloper (A169) and common eider (eider, A603) and resting areas for harbor seal (gewone zeehond, H1365) and grey seal (grijze zeehond, H1364).
Breeding habitat	Preserve undisturbed resting areas and optimized breeding areas (amongst others the ’embryonale duinen’, H2110) for common ringed plover (bontbekplevier, A137), Kentish plover (strandplevier, A138), pied avocet (kluut, A132), sandwich tern (grote stern, A191), little tern (dwergstern, A195), common tern (visdief, A193) and grey seal (grijze zeehond, H1364).
Diversity of salt marshes and meadows	Preserve (Wadden Sea) and restore (delta) of the salt marshes and saline grasslands (outside the dikes, H1330_A) with all stages of succession, fresh-salt transitions, diveristy in substrate and tidal regime together with high-water refuge areas.

2.2. Wadden Sea Dike at Koehool-Lauwersmeer

In this research the option to use a foreshore optimizing technique for a sea dike strengthening project is investigated. The dike section of Koehool-Lauwersmeer forms part of the southern border of the eastern part of the Dutch Wadden Sea (Figure 1.1). To find an appropriate location along this dike section where the technique can be tested, two requirements should be met. First, the location should have potential for a foreshore to evolve. Second, the part of the dike section has to be rejected to the WBI 2017 assessment based on failure mechanisms that can be influenced by the foreshore.
Figure 2.5 shows an indication of the different cross-sections that are currently present at the dike section Koehool-Lauwersmeer.

Figure 2.5: Cross section of the Wadden Sea Dike at Koehool-Lauwersmeer for the situation of (i) a dike with a flat (top picture), (ii) a green dike with a foreshore (middle) and a top view of the entire dike section with indications of the cross-section situation (bottom picture) (Witteveen+Bos, 2020)

Foreshore

The Koehool-Lauwersmeer dike section contains a large foreshore that is of great added value for ecosystems and water quality (van Reijn and Franssen, 2020). A large part of the foreshore of Koehool-Lauwersmeer has traditionally been used for land reclamation. Brushwood dams were built to stimulate sedimentation of silt, creating salt marshes ('kwelders') (van Reijn and Franssen, 2020). Salt marshes are areas formed in the intertidal zone of low-energy shorelines. They consist of silty soils, are covered with salt resistant vegetation and are mostly found on mid- to high-latitude coasts where moderate climates are present (Bosboom and Stive, 2015). From Figure 2.8 it can be seen that a large extent of the dike section contains salt marshes or has potential for salt marshes to develop. From Figure 2.5 an indication is obtained of how the foreshore varies over the dike section. At the outer edges of the section almost no foreshore is present, whilst in the middle part a largely extended salt marsh is present.

History

Salt marshes are seen as cultural historical value of the Wadden Sea area (Vollmer et al., 2001). Bazelmans et al. (2012) describes the evolution of the environment and society in the Wadden Sea area from 11 700 BC until 1800 AD. According to Bazelmans et al. (2012), already in about 7000 BC the first natural coastal marshes developed. It was in the 13th century, when land was reclaimed from

Figure 2.6: An example of the salt marshes ('kwelders') along the Wadden Sea (POV Voorlanden,2019)

the Wadden Sea for the first time. Coastal areas were stimulated to silt up by the use of brushwood dams and were subsequently endiked. Many new polders were reclaimed this way. For the Province of Friesland this resulted in large reclaimed areas and a seaward displacement of the primary dikes. This technique has been practiced for many years. Resulting in a dike that consists of parts constructed in different times between the 13th and 18th century (see Figure 2.7). In that same time the population rose, the maritime economy strengthened and the coastal region of the Wadden Sea became one of the most successful agricultural areas in Europe (Bazelmans et al., 2012; Westerdahl, 1992; Knottnerus, 2001). The brushwood dams are still seen today. Some are still maintained, others are exposed to nature. The traces of this land reclamation history however, can be seen from many places in the landscape of the Wadden Sea area (van Reijn and Franssen, 2020; Vroom, 2013; Roode et al., 2019).

Figure 2.7: An overview of the Koehool-Lauwersmeer dike section with an indication of the year of construction for each part of the dike (Witteveen+Bos, 2020).

Ecology

Salt marshes provide ecosystem services by giving home to (edible) vegetation, creating habitats for birds, fish and invertebrates, improving the water quality and enhancing carbon sequestration (Zedler et al., 2008; Gedan et al., 2009; Mcleod et al., 2011).

Vegetation contributes significantly to the development process of salt marshes. When a mud or sand flat reaches an elevation just below the mean high water tide (MHT), pioneer plants start to grow. The pioneer plants reduce the flow of water and stimulate the sedimentation of silt particles. Consequently, more, and different types of vegetation develop and an increasing amount of sediment is trapped (Bakker, 2014). In addition, vegetation can play an important role for flood safety. Both an increase of the bottom friction and the vegetation drag lead to wave energy dissipation Vuik et al. (2016). The impact of salt marshes on the flood safety is elaborated in Section 3.1

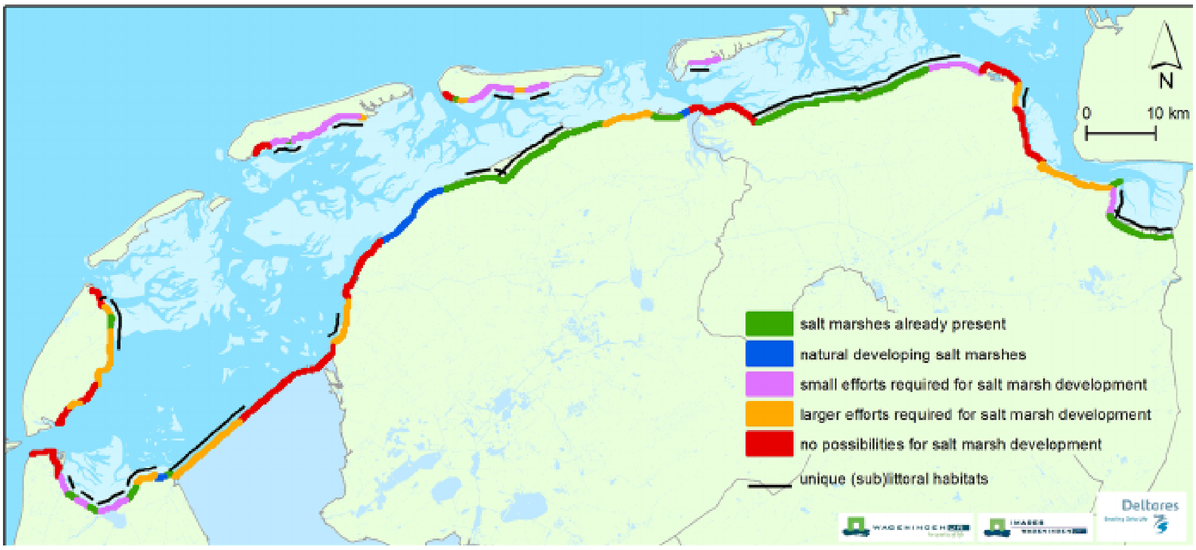


Figure 2.8: 'Salt marsh potential map' with an indication of the locations along the Dutch Wadden Sea coast where marshes have or have no potential (Van Loon-Steensma, 2015)

3

Boundary conditions and opportunities of the project

3.1. Flood safety

According to the Dutch Water Act ('Waterwet'), managers of primary flood defences must assess at least once every twelve years whether their defence meets the legal safety requirements (Rijksoverheid, 2020b). For each round, the requirements for the primary flood defences are described by Rijkswaterstaat in the so-called 'Wettelijk Beoordelingsinstrumentarium (WBI)'. The current assessment round runs from 2017 to 2023 which results in the name WBI 2017. Due to new safety standards that were introduced on 1 January 2017, this round is more drastic than previous ones (Rijksoverheid, 2017).

If a flood defence does not pass the WBI assessment, it can be signed up to the National Flood Protection Program ('Hoog-waterbeschermingsprogramma', HWBP). In this program the central government, the regional water authorities, the provincial governments and the municipalities work together to improve and reinforce the flood defences that have failed to meet the requirements of the WBI. Within the HWBP, several so-called Project Transcending Intelligence innovations are present (POV). Two of these are the POV Foreshores and POV Wadden Sea dikes. Both POV's cotain information about how the effect of foreshores should be included in the design and assessment of sea dikes (Rijksoverheid, 2020a).

Failure mechanisms

The potential influence of the foreshore on the flood safety of the dike, is described using the failure mechanisms. Failure mechanisms are relevant ways that a dike (or other kind of structure) could fail to fulfil its water-retaining function (Jonkman et al., 2018). Although more failure mechanisms exist, only the ones that are potentially influenced by the foreshore, will be considered. An overview of these failure mechanisms is given in Figure 3.1. These correspond with the failure mechanisms of the WBI2017 as indicated in Table 3.1. In addition, Table 3.1 shows the effects of the foreshore on these failure mechanisms.

Table 3.1: An overview of the foreshore influenced failure mechanisms as stated by the WBI2017, together with their abbreviations and the effect of the foreshore on each failure mechanism (POV Voorlanden,2019)

Failure mechanism	Abbreviation	Foreshore influence
Asphalt revetment failure (caused by wave impact)	AGK	Reduced wave impact by reduced wave height
Grass revetment failure (caused by wave impacts)	GEBU	Reduced flow velocities by reduced wave height
Gras revetment failure (caused by wave run-up)	GEKB	Reduced wave setup and overtopping discharge by change in wave height and period
Block revetment failure (caused by wave impacts)	ZST	Reduced wave impact by change of wave height and period
Shearing of the inner slope	GABI	Indirect reduction of probability of occurence by reduced overtopping discharge
Shearing of the outer slope	GABU	Indirect reduction of probability of occurence by reduced pressure fluctuation by waves
Slope instability land side slope (macro instability)	STBU	Smaller probability of occurence of slip circle due to mass of foreshore and damping of the phreatic level
Slope instability inner slope (macro instability)	STBI	No contribution to probability of failure for waterlevels below foreshore level and damping of phreatic level
Internal erosion (uplift, heave and piping)	STPH	Increase of seepage length

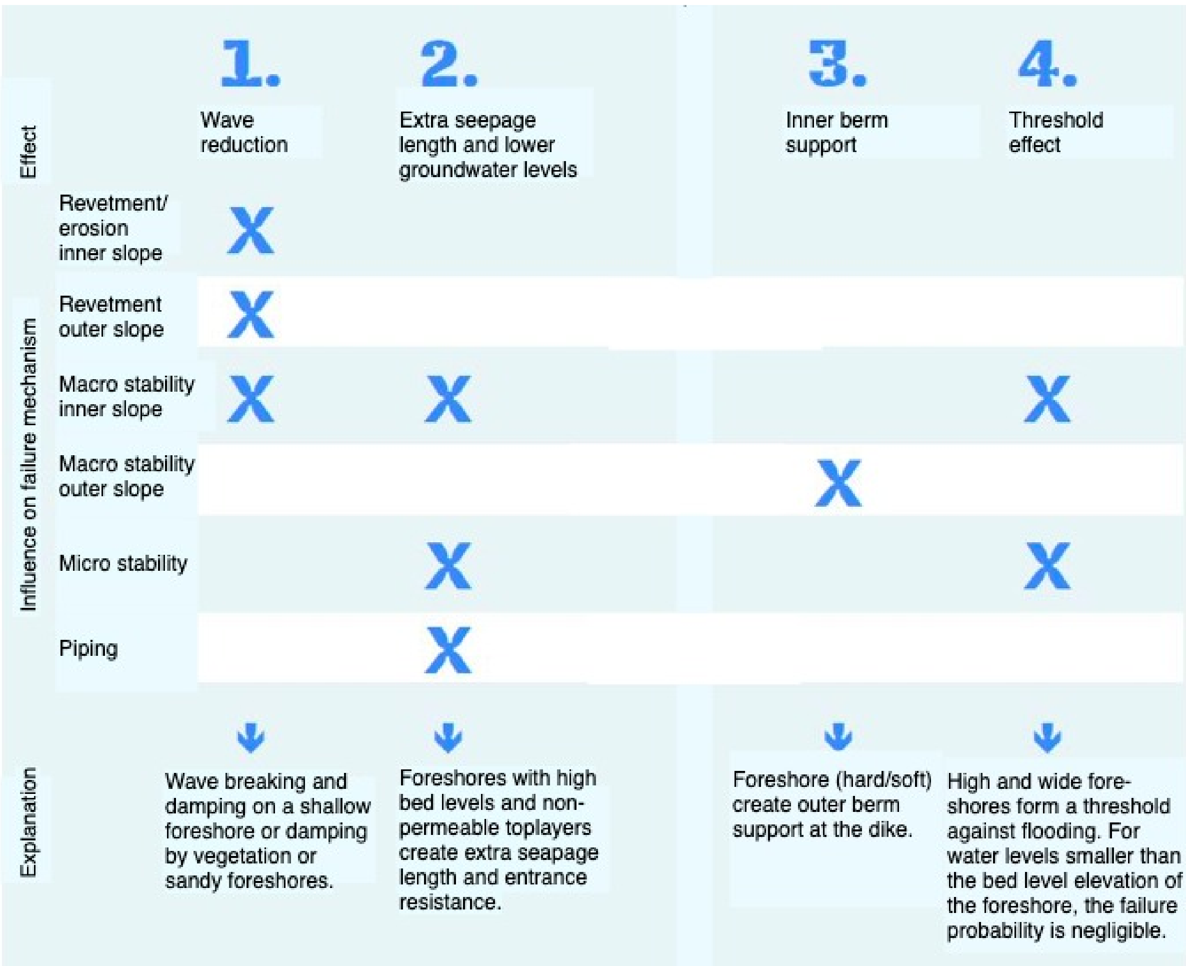
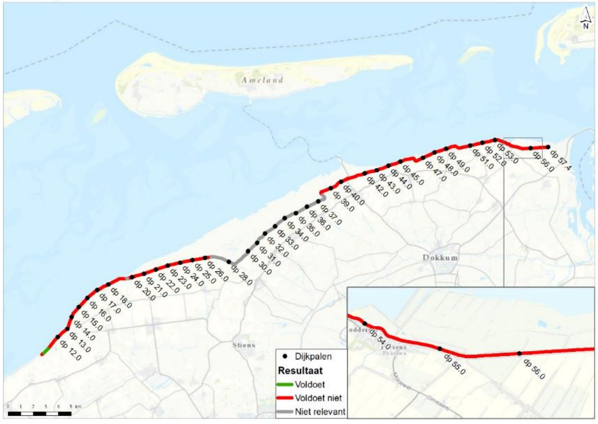


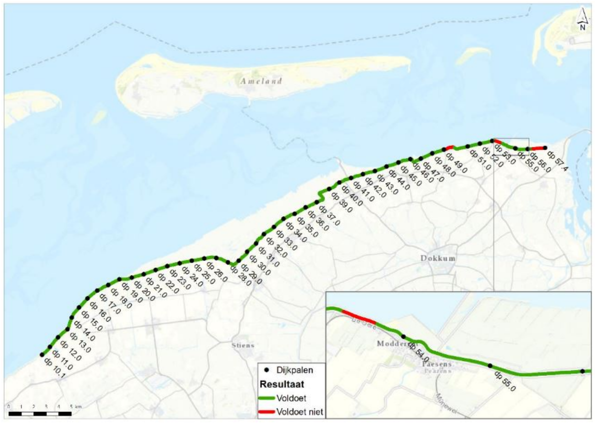
Figure 3.1: An overview of the effects of the foreshore on the failure mechanism (POV Voorlanden,2019)

WBI2017 results

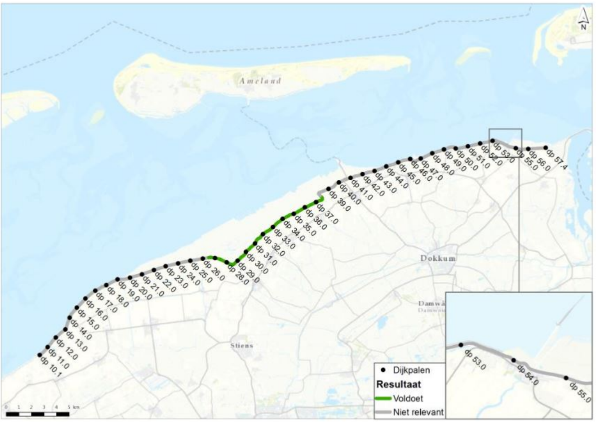
The entire dike section of Koehool-Lauwersmeer did not meet the safety requirements of WBI 2017 and is therefore signed up to the HWBP. The dike manager, Wetterskip Fryslân, holds responsibility for this dike reinforcement project. The results of the failure mechanisms of importance from the WBI2017 assessment, are shown in Figure 3.2 and 3.3. A possible failure of the foreshore itself is not included in the assessment results (Wetterskip Fryslân, 2018).



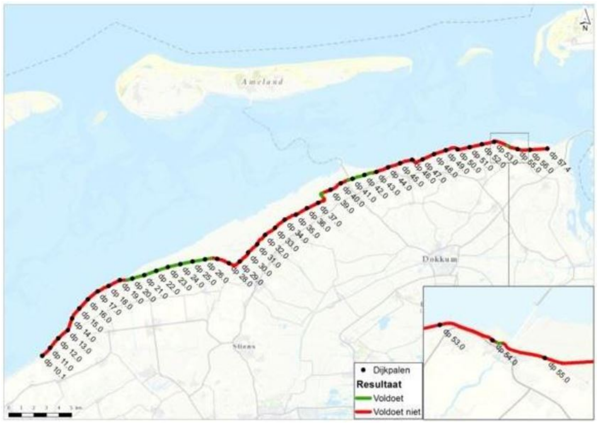
(a) The results of the AGK failure mechanism



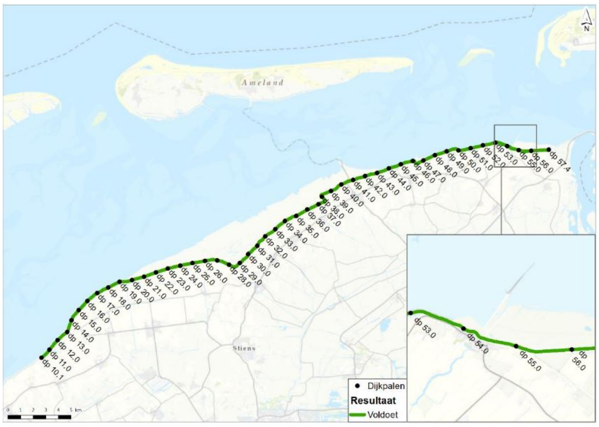
(b) The results of the GABI failure mechanism



(c) The results of the GABU failure mechanism



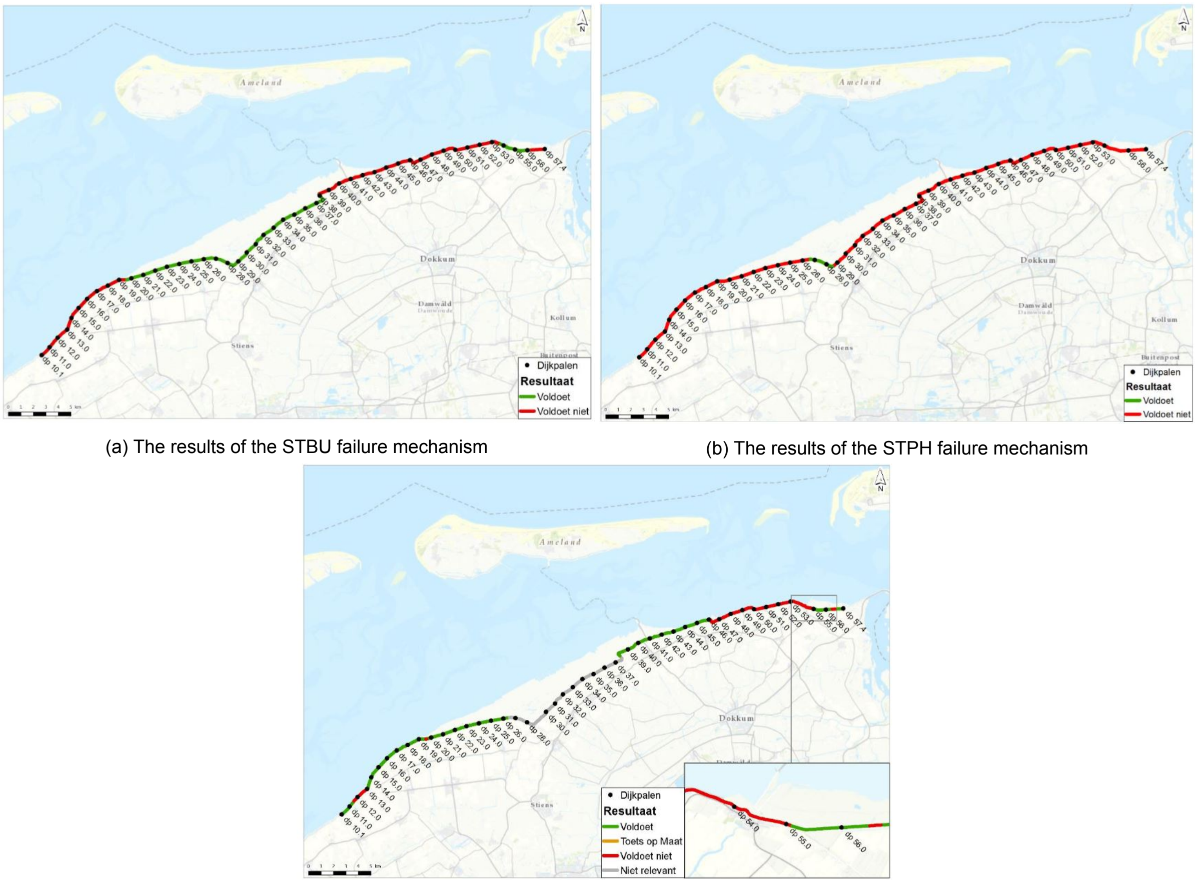
(d) The results of the GEBU failure mechanism



(e) The results of the GEKB failure mechanism

(f) The results of the STBI failure mechanism

Figure 3.2: The results of the WBI2017 assessment for the dike section of Koehool-Lauwersmeer for each foreshore influenced failure mechanism (part 1) (Wetterskip Fryslân, 2018)



(a) The results of the STBU failure mechanism

(b) The results of the STPH failure mechanism

(c) The results of the ZST failure mechanism

Figure 3.3: The results of the WBI2017 assessment for the dike seciton of Koehool-Lauwersmeer for each foreshore influenced failure mechanism (part 2) (Wetterskip Fryslân, 2018)

3.2. Dike reinforcement techniques

Over the years, many coastal protection structures are developed. These structures can be ranked from fully engineered to nature-based. One of these structures are sea dikes, which are engineered structures (van der Nat et al., 2016). Most dikes that are present along the Wadden Sea coast, are traditional dikes. Figure 3.4 shows a cross-section of a traditional dike. These dikes are soil-based structures. Their core is made of sand. The seaward slope (approximately 1:4) is covered by a layer of clay and grass at the crest, and asphalt or stones revetment at the middle and lower part. The toe of the dike is protected by a revetment of stones. Sometimes a foreland is present adjacent to the dike. The function of the cover layer is to protect the dike against wave impact. The land side slope (approximately 1:3) of the dike is covered by clay and grass to resist overflow and overtopping discharge (van Loon-Steensma and Schelfhout, 2017).

Alternative designs

Water levels increase due to sea level rise, and flood events occur more frequently. Together with the high safety standards (Dutch Water Act), this makes that the coastal protection structures have to be reinforced to become stronger, bigger and taller (Chu et al., 2012). The need to reinforce the dikes together with the need to enhance the nature and landscape values of the Wadden Sea, ask for innovative designs (Delta Programme Wadden Region, 2011, van Loon-Steensma et al. (2014)). In addition, reinforcement of the dikes leads to an increasing amount of material that is needed for the constructions. Ecosystems can contribute to effective flood protection, with the potential to use less raw materials and increase the systems adaptability potential to sea level rise (Chu et al., 2012; Barbier et al., 2011; van Loon-Steensma and Schelfhout, 2017).

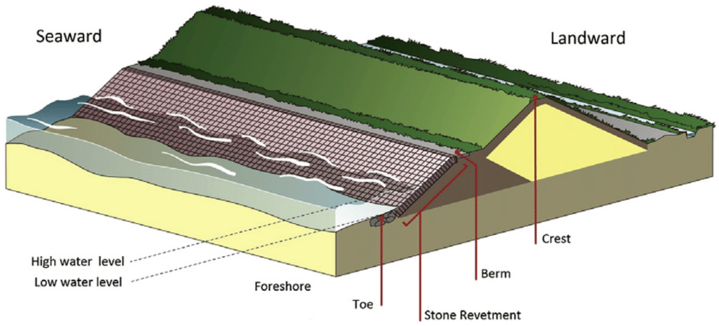


Figure 3.4: A cross-section of a traditional dike design (Burcharth et al., 2015)

3.3. Ecology

As mentioned in Section 2.1, the Wadden Sea area is of great ecological value. The barrier islands, tidal flats, salt marshes and sand dunes present in the area, create habitats that support a broad range of biodiversity. The ecosystem of the Wadden Sea is yearly visited by millions of birds and gives home to, among others, shrimps, fish, seals, mussels, oysters, worms and thousands of species of plants and fungi (Kabat et al., 2012; Reise et al., 2010).

In this section the theoretical opportunities for the project area to preserve and develop the ecosystems of the Wadden Sea are investigated. These opportunities focus on adding to the goals set by Natura 2000 (Section 2.1.4). The main goal is to soften the edges of the Wadden Sea. This can be done by creating more gradual transition areas between the Wadden Sea and the surrounding land, restoring the natural dynamics of the Wadden Sea system, connecting the hinterland with the Wadden Sea in a smart manner and by restoring underwater nature and the food web (Witteveen+Bos, 2020b; Ministerie van Infrastructuur en Milieu, Noord-Nederland, Rijkswaterstaat, 2016). These opportunities are obtained from the report for integral combined opportunities between water safety and ecology for Koehool-Lauwersmeer from Witteveen+Bos (2020b).

Examples of measures that can be taken to soften the edges of the Wadden Sea are clay extraction, freshwater storage at the landside part of the dike, creating a ”wisselpolder” to stimulate sedimentation of silt at the land-side part of the dike, green and rich dikes, optimized salt marsh development and beneficially re-use dredged sediment to enhance salt marsh development (mudmotor). A so-called ”wisselpolder” is a dynamic exchange area that is depoldered. It is based on the principle of sediment trapping in low-lying areas at the landside part of the dike. The goal is to create larger transition zones that add to the flood safety of the land behind the dikes. The above mentioned measures add to ecological opportunities that relate to the Natura2000 goals. The ecological opportunities that are distinguished, are listed together with the ecological value they incorporate and the possible measures that are related (Witteveen+Bos, 2020b; Luiten, 2004).

Create fresh-salt water transitions

By building dikes along the borders of the Wadden Sea, the transition from fresh to salt water became sharper. A more gradual fresh-salt water transition has a positive influence on the biodiversity of the area. It improves the conditions for species that can adapt to changing conditions, inducing an increased biodiversity and improved robustness of the ecosystem. A lack of gradual fresh-salt water transitions is often seen as a bottleneck in the development of a well functioning ecosystem. Gradual transitions are important for fish species that benefit from changing fresh-salt conditions. Gradual transitions can be created both by measures at the seaward and the landward side of the dike. Examples of measures at the seaward side of the dike are brackish ”wisselpolders” and passages in primary flood defenses (Witteveen+Bos, 2020b; Janssen, 2000).

Create wet-dry transitions and dynamic systems

Just as a fresh-salt water transition, a wet-dry transition has a positive influence on the biodiversity of the area. It improves the conditions for species that can adapt to changing conditions, inducing an increased biodiversity and improved robustness of the ecosystem. A gradual wet-dry transition is created by a mild slope of the intertidal zone. This gradual transition is of importance for plant species that require specific conditions and create a unique fauna. In addition this gentle slope is of importance for waders (”steltlopers”). An optimized wet-dry transition has a very gradual transition from permanently inundated shoals to permanently dry green dikes. In addition to the wet-dry transition, the wet-dry dynamics of the system is of importance. It is for example of added value to have incidental salt water inundations at the higher parts of a salt marsh. Gradual wet-dry transitions can be created by measures at the seaward side of the dike. Examples of measures are creating gently sloped foreshores, breaches in the summer dikes or gullies and pools at the seaward side of the dike (Witteveen+Bos, 2020b).

Enhance underwater nature
The underwater nature can be enhanced by creating a diverse substrate. The soft substrate present in the Wadden Sea can be qualitatively and quantitatively improved by increasing the intertidal area. Aside from the soft substrate, hard substrate can be added to add to the biodiversity by increasing the habitat heterogeneity and giving home to an increased number of species. Another optional measure is creating mussel banks which can also give home to hard substrate species. In addition they create lee, creating opportunities for sea grass to grow. Examples of measures are placing dike revetments, brushwood dams or mussel beds or excavating existing salt marshes to increase the intertidal area (Witteveen+Bos, 2020b; Gotje et al., 2016)

Create brackish zones
Improving fresh-salt water transitions increases brackish zones. Creating brackish zones, both at the landward as the seaward side of the dike, contribute to unique habitats for species that benefit from changing conditions. In addition, brackish zones at the landward side of the dike create foraging, resting and breeding areas for birds. These brackish areas are part of the transition zone between the fresh land and the salt Wadden Sea and therefore contribute to softening the edges of the Wadden Sea. Examples of measures at the landward side of the dike are extracting clay at the landward side combined with creating habitat for birds and fish, creating brackish ”wisselpolders” and creating passages in primary flood defenses (Witteveen+Bos, 2020b).

Create high-water refuge areas for shorebirds
Birds need high-water refuge areas (”hoogwatervluchtplaatsen”, HVP’s) to flee to and rest on during high tide. HVP’s with a good connection to the land are exposed to people and predators. Therefore islands are more convenient as resting areas. The presence of foraging areas near HVP’s creates a suitable habitat for bird populations. With the expected sea level rise (Section 2.1.3) these HVP’s will probably become more scarce, inducing an increased need for HVP’s. Examples of measures that can be taken at both the seaward and the landward side to enhance the bird habitat, are creating gullies and pools, creating ”wisselpolders” and creating freshwater wetlands (Witteveen+Bos, 2020b; Van der Hut et al., 1982).

Create breeding area for shorebirds
Studies show that the area of salt marshes along the Wadden Sea that is used as breeding area has been decreasing due to an increased amount of predation and overgrowth of vegetation. The absence of sufficient convenient breeding areas hinders the development of bird populations in the Wadden Sea region. Similar to high-water refuge areas, islands can be used to create areas that are free of predators. In addition, a well functioning breeding area requires some shelter from vegetation as well as some vegetation free areas to guarantee sufficient view on possible threats. Examples of measures that can be taken at both the seaward and the landward side to enhance the bird habitat, are creating gullies and pools, creating ”wisselpolders” and creating freshwater wetlands (Witteveen+Bos, 2020b; Van der Hut et al., 1982).

Enhance foraging areas in brackish zones
The presence of foraging areas close to breeding and resting areas is important for a well developed bird population. Improving the quantity and quality of the foraging areas can be done by increasing the nutrient-rich areas and creating fresh and brackish shallow water both at the seaward and the landward side of the dikes. The exact layout of these areas strongly depends on the species. Examples of

measures that can be taken at both the seaward and the landward side to enhance the bird habitat, are creating gullies and pools, creating ”wisselpolders” and creating freshwater wetlands (Witteveen+Bos, 2020b; Van der Hut et al., 1982).

Increase area of pioneer zone
Overgrowth of vegetation and ongoing sedimentation on existing salt marshes induce a decrease in biodiversity of the area. In contrast to the higher marsh, the pioneer zone of a salt marsh has a high ecological value by contributing to the biodiversity and in addition adds to the goal to soften the edges of the Wadden Sea. Examples of measures that can be taken to increase the area of pioneer zone are by excavating existing salt marshes to stimulate a new development of the pioneer zone, by stimulating new salt marshes to develop and by creating intended breaches of the summer dike to create pioneer zones on the current summer polders (Witteveen+Bos, 2020b).

Create spawning and breeding areas for fish
Shallow water areas serve as spawning and breeding areas for fish and provide shelter for juvenile fish. A sufficient amount of oxygen is important for appropriate spawning conditions. Shallow water areas contribute to the development of fish populations, and as a consequence contribute to the food chain of fish eating birds. Examples of measures that can be taken to create spawning and breeding areas for fish are to excavate parts at both the landward and seaward side of the dike to create shallow waters and ’wisselpolders’. In addition fish passes are required to enable migration from the landward ’wisselpolders’ to the Wadden Sea (Witteveen+Bos, 2020b).

Create future proof biodiversity on salt marshes
A high biodiversity is created by a diverse area in which all different zones of a salt marsh are represented as each zone provides a different flora and fauna. In the current situation, mostly high marshes are present which decreases the biodiversity. Examples of measures that can be taken to increase the area of pioneer zone are by excavating existing salt marshes to stimulate a new development of the pioneer zone, by stimulating new salt marshes to develop, by creating intended breaches of the summer dike to create pioneer zones on the current summer polders and by creating or enhancing the HVP’s and breeding areas for birds (Witteveen+Bos, 2020b).

Enhance nature present on the current dike
Aside from providing flood safety, dikes have the ability to provide ecological value. This ecological value can be created in three zones that are the underwater zone, the intertidal zone and the above-water zone. The zone above water can be enhanced by applying differentiated maintenance to the dikes to stimulate a broader spectrum of species to develop. Examples of measures that can be taken to enhance the nature present on the current dike are adjusting the maintenance works, sowing flowery seed blends and adding structures to provide shelter for small mammels and birds (Witteveen+Bos, 2020b).

This chapter introduces an overview of the boundary conditions and opportunities of the project. The obtained information about the possible dike reinforcing techniques, common failure mechanisms and ecological aspects is required for the selection of a pilot location and alternative which is done in the next chapter.

4

Pilot selection

Figure 4.1 shows a flow chart of the methodology for this research. First, the possible pilot locations, alternative design solutions and ecological assessment standards are explored by literature research and interviews with ecologists. This chapter explains the options and the criteria that are used for the pilot selection. Second, in Chapter 4.2 a pilot location, design alternative and ecological assessment are chosen and described.

4.1. Methodology for pilot selection

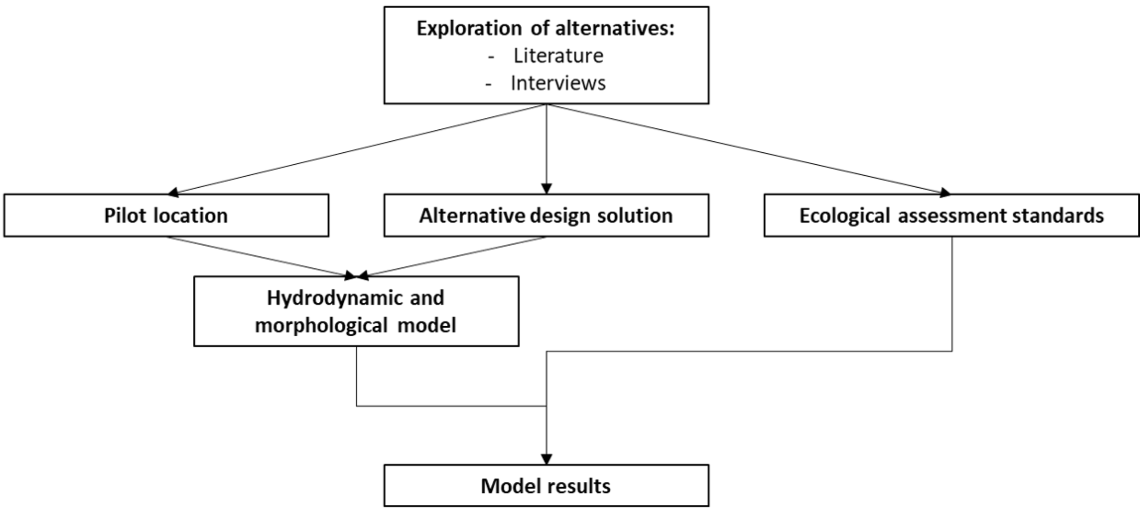


Figure 4.1: Flow chart of the methodology for the selection and execution process of the pilot study

4.1.1. Pilot location

The first criterion for the pilot location is that the location should have the potential for salt marshes to develop. The second criterion is that the dike stretch at the location should have the potential for the foreshore to influence flood safety. This is the case when the dike is rejected to multiple foreshore influenced failure mechanisms. The information for these criteria is introduced in Chapter 2 and 3. Figure 4.2 shows the combined result of the potential salt marsh areas and the foreshore influenced failure mechanisms. It shows that nearly the whole dike stretch has the potential for salt marshes to evolve. The western and eastern end of the dike section are the parts of the dike that are most affected by foreshore influenced failure mechanisms. Therefore, these two locations are potential pilot locations.

An important difference between the two locations is the geographic location. The western end of the

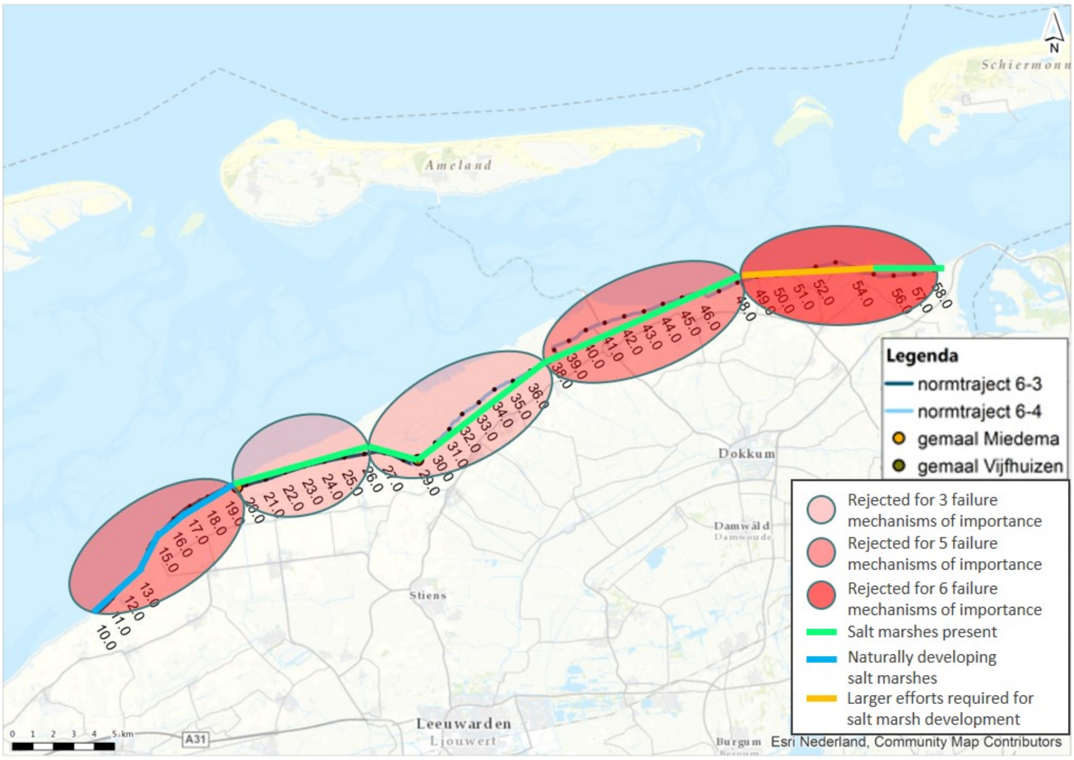


Figure 4.2: An overview of both the number of failure mechanisms that each section of the dike is rejected for and the potential of salt marshes to grow; based on the information provided by Wetterskip Fryslân (2018), Witteveen+Bos and Van Loon-Steensma (2015)

dike section is sheltered by the barrier island of Terschelling, while the eastern end of the dike section is in front of the Frisian Inlet. The different geographic locations result in different wave climates, with the eastern location being more exposed to waves than the western one. An additional difference between the two locations is the presence of a former primary water defence at the western location. It is located behind the current dike and creates opportunities for the alternative design. The last and most important criterion for the pilot location is that the location has to be appropriate to implement the desired alternative design solution.

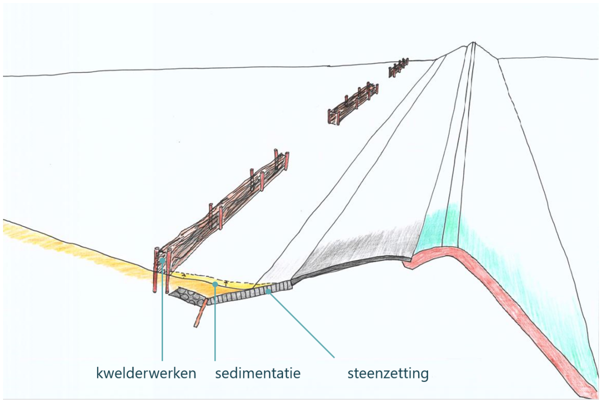
4.1.2. Alternatives

In this research four alternative dike strengthening designs are considered. All four make use of the foreshore to contribute to flood safety. One of these alternatives is investigated with a hydrodynamic and morphological model. This alternative is chosen based on its potential contribution to flood safety, the ecological value of the area, and the resilience to sea level rise.

The first two alternatives are based on strengthening or developing the foreshore in front of the current dike. The second two alternatives are based on a replacement of the current primary water defence and developing the foreshore/ the land that is in between the current and the new primary water defence. Given the conceptual framework that is introduced by Hendriks et al. (2020), all four alternatives affect the distribution of fines by focusing on an improvement of the accumulation potential. An improved accumulation potential stimulates the sedimentation of the foreshore. In addition, all alternatives potentially reduce the hydrodynamic impact on the primary water defence directly or indirectly. This way all alternatives are considered to have the potential to contribute to flood safety, ecological value and sea level rise.

Alternative 1 - Stimulating nourishment

The first alternative makes use of traditional brushwood dams to create a lee area that improves the accumulation potential so the foreshore can develop. This traditional technique is widely applied in the northern part of the Netherlands and thus information is available about the application and the effects of this design (Van Loon-Steensma, 2015; Bazelmans et al., 2012; Winterwerp et al., 2020). The brushwood dams can be combined with a nourishment to create a first layer of sediment. The brushwood dams can be placed both in the alongshore and cross-shore direction.



(a) Artist impression of alternative 1 (Witteveen+Bos, 2020a)

(b) Impression of the implementation of alternative 1 at the pilot location

Figure 4.3: Impression of alternative 1: A basic dike in combination with alongshore brushwood dams

Alternative 2 - Barrier islands
The second alternative makes use of barrier islands to create a lee area. Barrier islands can be used as high-water refuge areas for birds (Section 3.3) and reduce the hydrodynamic conditions which improve the accumulation potential in front of the dike and imply a reduced impact on the dike.

(a) Artist impression of alternative 2 (Witteveen+Bos, 2020a)

(b) Impression of a possible implementation of alternative 2 at the pilot location

Figure 4.4: Impression of alternative 2: a green dike in combination with an elevated foreshore, high-water refuge areas and the placement of brushwood dams

Alternative 3 - Extended Wadden Sea
This alternative focuses on the same principle as alternative 2 but instead, this one makes use of another location for the primary water defence. The old dike that lies further land inward, is designed to be the new primary water defence. The current primary water defence is breached at several locations. In front of the current primary water defence, high water refuge areas are constructed the same way as with Alternative 2. Material from the current primary water defence and the land in between can possibly be used to create the high water refuge areas.

(a) Artist impression of alternative 3 (Witteveen+Bos, 2020a)

(b) Impression of a possible implementation of alternative 3 at the pilot location

Figure 4.5: Impression of alternative 3: A green dike with an elevated and dynamic foreshore that is created by several breaches in the summer dike combined with the construction of high-water refuge areas

Alternative 4 - Slufter

The fourth alternative is also based on the principle of changing the location of the primary water defence to the old, more landward dike. In this design, the current primary water defence is breached at one location. A meandering gully is constructed in between the two dikes, to create a 'slufter' principle (Nieuwaal, 1999; Durieux, 2004). This solution holds the potential to contribute to stimulating salt marsh growth in between the dikes. In addition, it is expected that the current primary water defence reduces the hydrodynamic impact on the new primary water defence. Therefore it adds to flood safety.

(a) Artist impression of alternative 4 (Witteveen+Bos, 2020a)

(b) Impression of a possible implementation of alternative 2 at the pilot location

Figure 4.6: Impression of alternative 4: A green dike in combination with an artificial breach of the summer dike and a network of tidal gullies in the 'slufter' area

4.1.3. Ecological assessment

Information about the ecological opportunities in the area is obtained from the literature (Section 3.3). In addition to the literature research, interviews with ecologists are done to gain a broad understanding of the ecological opportunities that arise when implementing alternative design solutions in the Wadden Sea area. Three ecologists shared their opinions and thoughts about alternative dike strengthening solutions, building in the Wadden Sea area and how ecological value can be added to the Wadden Sea area. For privacy reasons, the ecologists stay anonymous. However, their identity is known with the researcher.

The first ecologist made a clear point that no additional intertidal zone can be created by adding to the foreshore since the intertidal zone is already present in the drying and flooding flats of the Wadden Sea area. The only possibility to add to the ecological value is by upgrading the quality of the intertidal zone, which will only make a minor difference. To really contribute to the ecological value of the area, the primary dike should be replaced inland. This way, gradual transitions (fresh/salt and wet/dry) at the edges of the Wadden Sea can be created without taking another part of the Wadden Sea.

According to this ecologist, in the Wadden Sea area, the most ecological value can be added by creating dynamic marshes and pioneer zones. Dynamic marshes can for example be created by the excavation of existing salt marshes so vegetation can redevelop. The embanked salt marshes form hard transitions at a large part of the edges of the Wadden Sea, making dynamic intertidal areas scarce. An important aspect that is often underexposed with alternative designs is the amount of maintenance that is needed for an alternative solution. This should be taken into account to make a project successful. Another aspect is the morphological influence of an intervention on the surrounding Wadden Sea. The ecological value can best be quantified by looking at the hypsometry of the area.

The second ecologist also prefers a solution that focuses on depoldering part of the Wadden Sea area. It is a way of creating an area for valuable fresh/salt and wet/dry transitions. Worries are about the development of the surrounding Wadden Sea area. One project will probably not disturb the system drastically, but multiple projects together will pull the Wadden Sea out of its desired balance. Another note that this ecologist shared is the importance of maintenance: “The most common problem of building with nature solutions is the lack of proper predictions for the maintenance that is needed. Who is responsible for the maintenance?” Maintenance is essential for the success of an intervention. For example, breeding areas are mostly in pioneer vegetation, which needs lots of maintenance as the value strongly decreases in case of overgrowth.

For the quantification of the ecological value, calculations of the potential carbon sequestration of the area are suggested. This can be of added value from the economic point of view, as it may give opportunity for grants. From an ecologic point of view, a healthy salt marsh consists of all zones: pioneer, high marsh and low marsh and all with the optimal slope. These can be quantified with the hypsometry and the slope of the area. It should be noted that salt marshes are not necessarily more valuable than unvegetated mudflats.

The third ecologist is mostly interested in the possibility to create breeding areas or a foreshore that is combined with the trapping of clay. Breeding areas and high water refuge areas at the shore, create gradual transitions at the edges of the Wadden Sea area. Another option is to combine wetlands in the areas inland of the dike with wetlands outside of the dikes or to support the growth of a foreshore with the traditional brushwood dams. Inland wetlands are the most valuable solutions for ecology. There are multiple projects known for inland wetlands, both unintended as intended. These show that the areas develop quite well as long as the water can reach the area.

In the case of unvegetated mud shores, there is an added value in the presence of brackish zones, the transition area between fresh and salt. It is expected that there will be little diversity in the animal species but the species present will be of great value. When well designed and maintained, breeding areas and high water refuge areas can be very valuable. The most valuable area is obtained by creating an initial situation as close to a natural situation as possible, for example with meandering gullies. The pioneer zone can be kept constant by excavating on regular basis. This way sediment can be trapped and the valuable pioneer zone can be preserved. The trapped sediment can possibly be used for

dike strengthening. Common pitfalls for projects like these are the legal aspects (different interests). Therefore it is very important to find support for the measures.
To quantify the ecological value of such a project can be done best by calculating the gained area of certain bed level heights (in relation with the water level elevations; the highest ecological value is at the mid-marsh). It is even possible to link this bed level elevation to literature and check for the species that typically exist at this elevation. In addition, the ecological value can be determined based on the Natura2000 goals or an MCA can be done.

Concluding, all three ecologists marked the high ecological value of the different intertidal zones. They all point out the interest in solutions that focus on depoldering. For the quantification of the ecological value, the general advice is to look at the hypsometry of the study area and the contribution to the Natura2000 goals.

4.2. Selected pilot

Based on the aforementioned criteria, a pilot location, design alternative and ecological assessment are chosen.

4.2.1. Pilot location

The chosen pilot location is at the western end of the dike section, from Koehool to Westhoek (Figure 4.7). At this location, the full dike section is rejected for five foreshore influenced failure mechanisms; AGK, GEBU, STBI, STBU, STPH. Part of the dike section is also rejected for ZST (Section 3.1). This means at this location, an improvement of the foreshore can positively influence the flood safety of the dike. In addition, Figure 4.2 shows that the location provides options for salt marshes to develop naturally. Compared to the eastern location, at the western location, a calmer wave climate is present as it is sheltered by the barrier island of Terschelling.

Figure 4.7: The pilot location from Koehool to Westhoek with red lines indicating the current and former primary dike

The pilot location at the western end of the dike is convenient for exploring both the option to strengthen the current foreshore, as well as the option to change the primary flood defence to a more landward one. Figure 4.7 shows the former dike that is present from Koehool to Westhoek. Together with the current primary dike, it encloses an area that provides the opportunity to explore alternative 3 and 4.

4.2.2. Considered alternative

Alternative 1 and 2 are more traditional solutions. Model studies are already done for similar projects indicating the expected developments for such an alternative. This is not the case for alternative 3 and 4. Therefore it is expected that executing a hydrodynamic and morphological model for alternative 3 and 4 is of greater added value. In addition, alternative 3 and 4 are most appreciated by the ecologists. However, they point out the high maintenance that is needed for the breeding areas and high water refuge areas.

Based on the expected positive effect on flood safety, the great amount of opportunity to add to the ecological value and the low maintenance works, alternative 4 is chosen. Two geometrical variations of this alternative are considered. One with a excavated gully and one in which the whole area between the dikes is excavated. The situation with gully is created to observe the effects when the expected natural development of a meandering gully is already present. The situation without gully is created to observe how the natural development will shape the area. The application of both geometrical variations in the model study is further explained in Chapter 5.

4.2.3. Ecological assessment standards

According to the ecologists' opinions, it is most valuable to determine the ecological value of the alternative by comparing it to the Natura 2000 core tasks and observing the intertidal area that is gained by applying the alternative. The core tasks are scored in four categories; no influence, negative influence, potential influence, positive influence. The scores are based on the model observations. The amount of added intertidal area and the development of the bed level elevations is observed by a hypsometric curve. In addition the influence on the opportunities defined for the Natura 2000 core tasks (Chapter 3) are discussed.

In this chapter the location, design alternative and ecological assessment standards for the pilot study are defined. The morphological development and ecological opportunities of this pilot study are studied further. The next chapter describes the set-up of the numerical model that is used.

5

Numerical model set-up

To predict the morphological developments of the area after implementation of the alternative, a hydrodynamic and morphological Delft3D model is set up. Delft3D is a software program that can carry out simulations of flow sediment transport and morphological developments (Deltares, 2018).

5.1. Model background

Delft3D consists of multiple modules. For this research the Delft3D-FLOW and Delft3D-WAVE module are used (version 4.04.01). The FLOW-module is the main module within Delft3D. It is a multi-dimensional (2D or 3D) simulation program that calculates the hydrodynamic conditions as a result of tidal forcing within a boundary fitted grid. The WAVE-module simulates the propagation of wind-generated waves (Deltares, 2018a,b).

5.1.1. Delft3D-FLOW

Delft3D-FLOW solves the Navier Stokes equations for an incompressible fluid, under the shallow water and the Boussinesq assumptions. For this research a 2DH model is used, therefore the vertical momentum equation is reduced to the hydrostatic pressure equation (Deltares, 2018a).

5.1.2. Delft3D-WAVE

For the two way) interaction between waves and currents the FLOW-module is coupled with the WAVE-module. The WAVE-module uses the third generation SWAN model to simulate wind-generated waves. The online WAVE module used in this study, accounts for wind generation, dissipation by wave breaking, white-capping and bottom friction, non-linear wave-wave interaction and wave propagation through obstacles. The SWAN model uses only implicit numerical schemes, making the computations unconditionally stable. It is based on the discrete spectral action balance equation, which in Delft3D-WAVE is per default used in the stationary mode (Deltares, 2018b). A JONSWAP-type density spectrum is used as a boundary condition in this research.

5.1.3. Sediment transport

Sediment transport is calculated simultaneously with the flow calculations by the online sediment version of Delft3D-FLOW. In this research, for the suspended and bed-load transport of the non-cohesive sediment (sand), the formulations of Van Rijn (2007) are used. For the suspended transport of the cohesive sediment (mud) the formulations of Partheniades and Krone are used (Partheniades, 1965). Both formulations take the combined effect of waves and currents into account. More information on both formulations can be found in Van Rijn (2007) and Partheniades (1965).

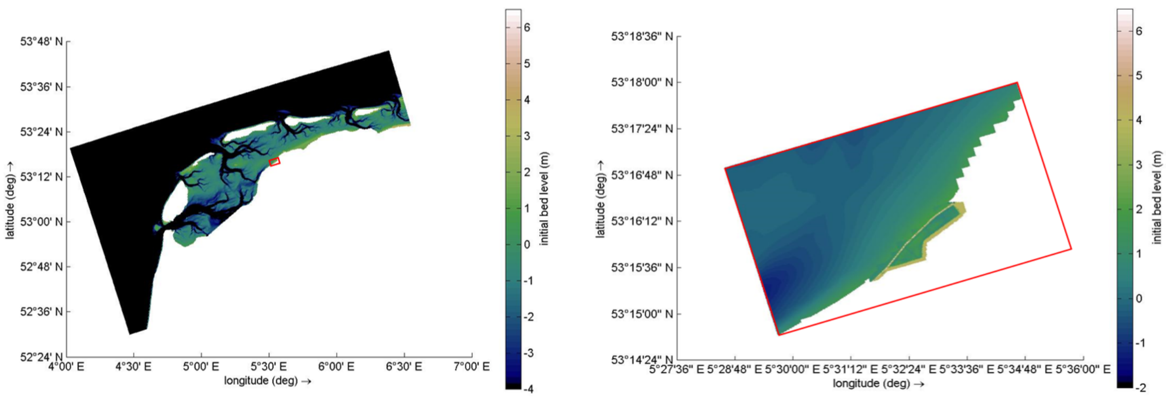
5.2. Model description

The existing Waddenzee Pace model (Delft3D FLOW model from Rijkswaterstaat, 2013, referred to as overall model) is used to set up the model for this research (referred to as nested model). The overall model is a 3D baroclinic tidal hydrodynamic model of the Dutch Wadden Sea that has been developed for reference year 2009 with water level (and optional wind) forcing by de Boer, 2013. The model details are described by Duran-Matute et al. (2014). In this research, both models are executed in a depth-averaged mode (2DH), because no baroclinic processes are taken into account, it reduces the computational time and using the 2DH mode has not led to significantly different results in similar studies than 3D models (Lesser et al., 2004; Fiechter et al., 2006).

5.2.1. Grid and bathymetry

The grid of the nested model is defined in the same coordinate system as the overall model, which is rotated 17° in anticlockwise direction with respect to the east-West axis. The grid of the overall model (Figure 5.1a) is an equidistant orthogonal grid with a grid size of 200 meter using the Rijksdriehoek projection (Duran-Matute et al., 2014). The grid of the nested model (Figure 5.1b) is created by cropping the overall grid to the area of interest and extending it for the inland area between the current and the former dike. The model area is chosen large enough to prevent boundary disturbances to enter the area of interest, but small enough to reduce computational time. The nested grid is refined twelve times to obtain an equidistant grid with a grid size of 16.67 meter.

The depth points of both models are defined at the center of the grid cells. The bathymetry data for the overall model is obtained by interpolating the 20 meter Rijkswaterstaat Vaklodingen data that is provided by OpenEarth (2002 to 2012) (Wiegman et al., 2005; Duran-Matute et al., 2014). For the nested model the depth points of the overall model are used. At the area of interest these depth points originate from the Vaklodingen dataset of 2009 (the same year as the boundary conditions data). The bathymetry data for the extended part is obtained from "Actueel Hoogtebestand Nederland" (AHN) data for the year 2015. The bathymetry is completed by triangular interpolation and smoothening of the combined data. Figure 5.1b shows the resulting bathymetry for the nested model.



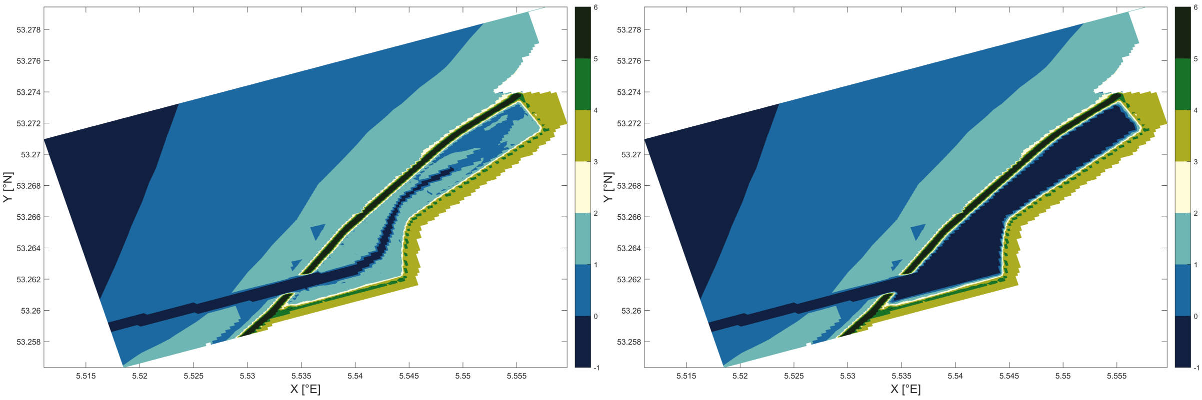
(a) The domain and bathymetry of the larger model obtained from RWS, with the red rectangle indicating the domain of the nested model

(b) The domain and bathymetry of the nested, refined model created with Delft3D

Figure 5.1: An overview of the overall and the nested model domain

Geometrical variations

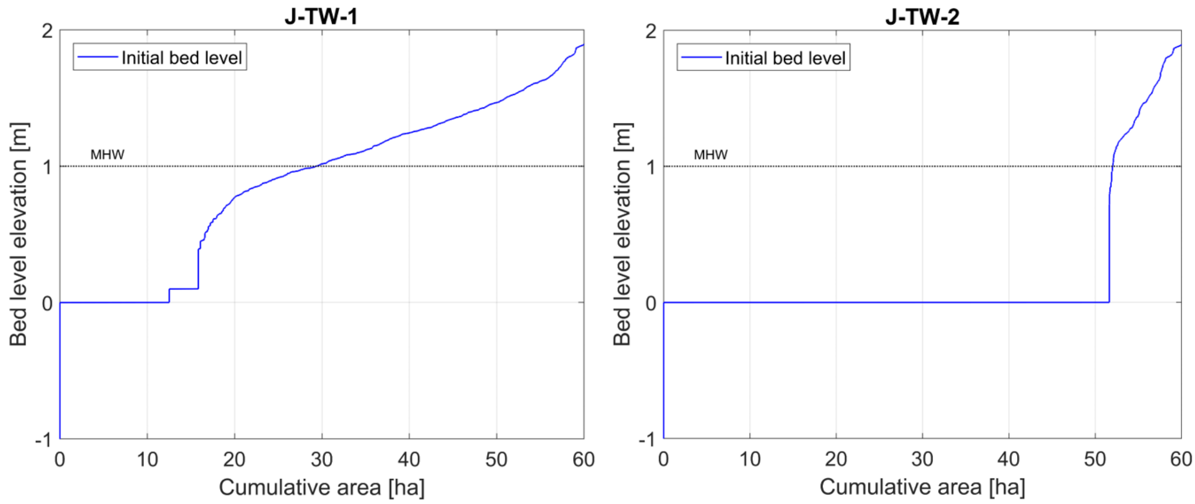
Three different bathymetry situations are modelled; the current bathymetry, a bathymetry of the slufter alternative with gully and a bathymetry of the slufter alternative without gully. Figure 5.2 shows the bathymetry for both geometries of the slufter alternative. For the slufter alternative an intended dike breach is created in the current primary dike, together with an entrance gully towards the dike. For the situation with gully, a meandering gully in between the two dikes is excavated at 0m NAP (Figure 5.2a). For the situation without gully, the whole area in between the dikes is lowered to 0m NAP (Figure 5.2b). Figure 5.3 shows the resulting hypsometry of the area in between the two dikes, that is added to the intertidal area of the Wadden Sea by applying the slufter alternative. These are (together with the development of the hypsometry) discussed with the results in Chapter 6.



(a) Bathymetry of the project area for the situation with gully, showing the areas between certain ranges of bed level elevation

(b) Bathymetry of the project area for the situation without gully, showing the areas between certain ranges of bed level elevation

Figure 5.2: Bathymetry of the project area of both geometrical variations indicated with ranges of 1 meter



(a) Hypsometry of the slufter area for the situation with gully, right after intervention, showing the area that is added.

(b) Hypsometry of the slufter area for the situation without gully, right after intervention, showing the area that is added.

Figure 5.3: The hypsometry of the slufter area right after intervention shows the area that is added to the intertidal zone by applying the alternative design.

5.2.2. Boundary conditions

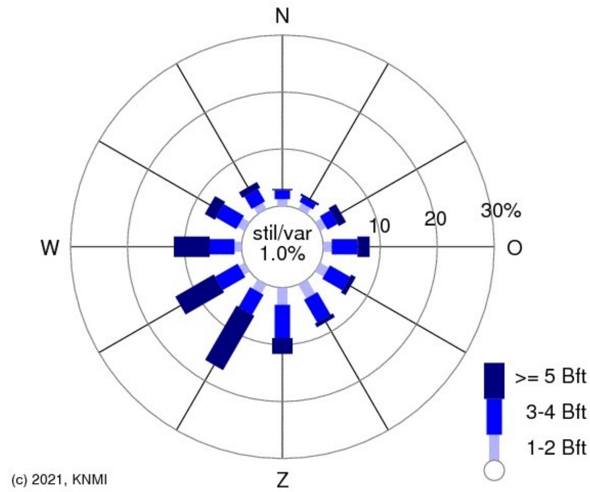
The coastal system characteristics present at the pilot location, determine the hydrodynamic forces and the morphological development. The general coastal system characteristics for the Wadden Sea are discussed in Chapter 3. The boundary conditions at the open boundaries of the nested model are obtained by nesting the model with the overall model. The overall model is a 3D baroclinic tidal hydrodynamic model of the Dutch Wadden Sea that has been developed for reference year 2009. It is as realistic as possible with values given for bathymetry, atmospheric forcing, fresh-water discharges and boundary conditions for water level elevation (Duran-Matute et al., 2014). Monitoring stations are obtained in the overall model and are linked to boundary support points in the nested model. Water level boundary conditions and velocity boundary conditions are used at the west and east boundary and the north boundary respectively.

Wind

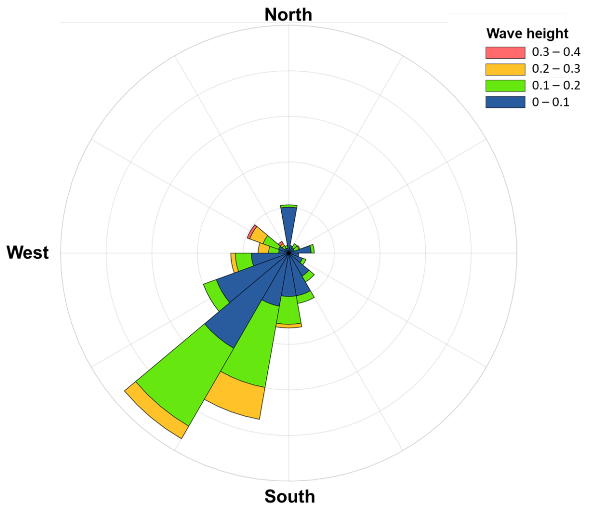
For the wind, the same data is used as is used for the overall model. The data is obtained from the operational forecast model of the German Weather Service (DWD). The used variables are wind speed and direction, which are discretized in a grid with a resolution of 1/16° and have a temporal resolution of three hours. The surface stresses are calculated from the wind velocity and are used to set the dynamic boundary condition at the surface (Duran-Matute et al., 2014). Figure 5.4a shows the wind rose that gives an indication of the wind direction and speed used in the model. It is based on the long term averaged wind data for the month of January (KNMI, 2021).

Waves

Only wind generated waves are used in the model. No waves are applied at the boundaries of the model. Figure 5.4b shows the wave rose of the resulting wave directions and heights that are observed in the model. The waves most frequent waves come from southwest direction with a wave height between 0 and 0.3m. The highest waves (0.3-0.4m) come from northwest direction.



(a) The long term averaged wind rose (1991-2020) for the month of January at measuring station De Kooy (Den Helder) shows that during the largest period of time wind comes from southwest direction. In addition, the highest wind speeds come from southwest direction (KNMI, 2021)



(b) The wave rose that is obtained at an offshore location within the modelled area, presents the direction and the significant wave height of the waves that are generated in the modelled 28 days. It shows that most waves come from the south west and the highest waves come from the north west

Figure 5.4: The wind and wave rose of the data used in the model show comparable directions

5.2.3. Model parameter settings

Table 5.1 shows the main model parameters settings. Most important are the sediment settings. The morphological time scale factor (MorFac) is used to increase the time scale of the simulations without causing an increase in simulation time. The MorFac multiplies the erosion and deposition fluxes from the bed to the flow and vice-versa at each computational time-step. A MorFac of 6 is applied to the simulations without waves, creating a simulation time of 5.5 months (six times 28 days). For the simulations with waves a MorFac of 1 is applied. Applying a higher MorFac would imply a 5.5 month storm season which for the project area is an unrealistic situation. More information on this parameter can be find in Lesser (2009).

Two sediment fractions are used in the model, sand and mud. The thickness of the sediment layer is set to 5 meter for both sediment fractions. This results in a bed composition with a volume fraction of 50% sand and 50% mud. The critical bed shear stress for erosion of mud is set to 0.5 N/m^2. This is a typical bed shear stress for surface erosion of consolidated mud-sand mixtures. In addition a simulation is carried out for a critical shear stress of 0.1 N/m^2 to check the sensitivity of the morphological results for critical shear stress. At the boundaries of the model a concentration of 0.05 kg/m^3 is applied (based on measurements from Schulz and Gerkema (2018)).

Table 5.1: Overview of the main model parameter settings

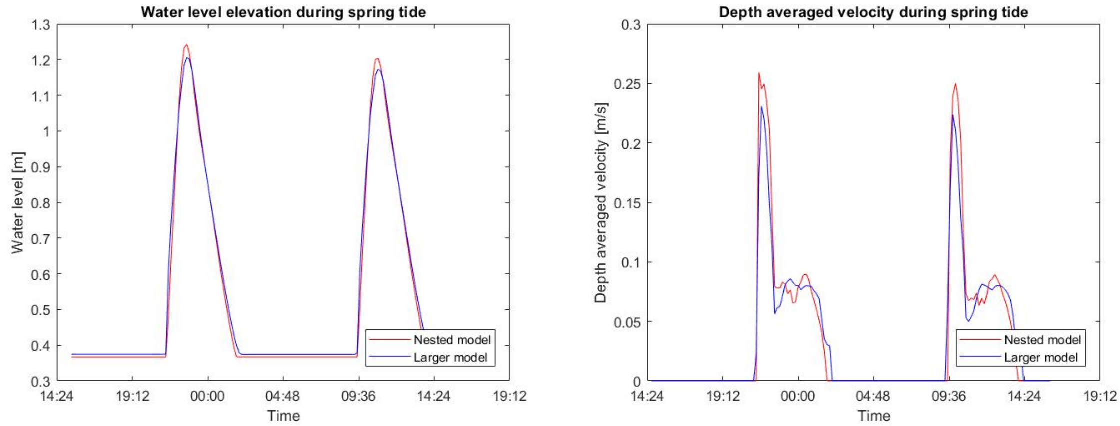
Module	Parameter	Value	Description
Flow	Δt	12	Computational time step $[s]$
	ρ_w	1025	Density of water $[kg/m^3]$
	ρ_a	1.25	Air density $[kg/m^3]$
	Roumet	C, Chezy	Type of bottom friction formulation $[-]$
	Ccofu	65.0	Uniform bottom roughness in u-dir $[m^{1/2}/s]$
	Ccofv	65.0	Uniform bottom roughness in v-dir $[m^{1/2}/s]$
	Vicouv	1.0	Uniform horizontal eddy viscosity $[m^2/s]$
	Dicouv	10	Uniform horizontal eddy diffusivity $[m^2/s]$
	ROUwav	FR84 (Fredsøe, 1984)	Bottom stress formulation due to wave action $[-]$
	Dryflc	0.12	Threshold depth for drying and flooding $[m]$
Wave	WaveForces	dissipation 3d	Method of wave force computation [-]
	GenModePhys	3	Generation mode of physics $[-]$
	Breaking	true	Include wave breaking, B&J model $[-]$
	BreakAlpha	1	Alpha coefficient for wave breaking $[-]$
	BreakGamma	0.73	Gamma coefficient for wave breaking $[-]$
	Triads	false	Include triads $[-]$
	BedFriction	JONSWAP	Bed friction type $[-]$
	BedFricCoef	0.067	Bed friction coefficient $[-]$
	Diffraction	false	Include diffraction $[-]$
	WindGrowth	true	Include wind growth $[-]$
	WhiteCapping	Komen	Formulation for white capping $[-]$
	Quadruplets	true	Include quadruplets $[-]$
	Refraction	true	Include refraction $[-]$
	FreqShift	true	Include frequency shifting in frequency space $[-]$
Sediment	MorFac	6 / 1	Morphological scale factor $[-]$
	Morstt	720	Spin-up interval for start of morphological changes [min]
	MorUpd	true	Update bathymetry during FLOW simulation [-]
	EqmBc	true	Equilibrium concentration profile at inflow boundaries [-]
	DensIn	false	Include effect of concentration on fluid density [-]
Sand	D_{50}	200	Median grain diameter [μ m]
	RhoSol	2650	Specific density [kg/m^3]
	CDryB	1600	Dry bed denisity [kg/m^3]
	IniSedThick	5	Initial sediment layer thickness at bed [m]
	TraFrn	VanRijn2007	Sediment transport formula $[-]$
Mud	RhoSol	2650	Specific density [kg/m^3]
	CDryB	500	Dry bed denisity [kg/m^3]
	IniSedThick	5	Initial sediment layer thickness at bed [m]
	Boundary C	0.05	Boundary concentration [kg/m^3]
	WS0	$2.5*10^{-4}$	Settling velocity fresh water [m/s]
	TcrEro	0.5 / 0.1	Critical bed shear stress for erosion [N/m^2]
	TraFrn	Partheniades-Krone	Sediment transport formula $[-]$

5.3. Verification of the model

The accuracy of the overall model is determined by comparing the results with observational data sets. These data sets possess sea surface elevation for every 10 minutes during the whole simulation period. The accuracy of the simulations are quantified using the coefficient of determination R^2 and the root-mean-square (rms) error ϵ_{rms}. For the Dutch Wadden Sea the error is below 0.12 m for R^2>0.96. In addition, the amplitude and phase of the tidal constituents at all tidal stations is compared. The errors that are found are all in an acceptable range. As the model results agree with the observational data sets it is concluded that the model reproduces well the sea surface heights and current velocities of the modelled area (Duran-Matute et al., 2014).

The water levels and depth averaged velocities of the nested model are compared with the overall model at several locations. Figure 5.5 shows the water level and depth averaged velocities at one of these locations. The results of both models are comparable and the overall model is validated and calibrated.

In addition, sensitivity analysis are done for the time step and boundary concentrations of mud. For both parameters similar results are obtained for different values. Based on these findings it is concluded that the nested model can be used with confidence for this research.



(a) The water level plot shows almost identical results for the nested and overall model

(b) The depth averaged velocities show similar results for the nested and overall model

Figure 5.5: The results of the overall and nested model show similar results (used observation point is [477,311] for the overall and [272,188] for the nested model)

This chapter described the set-up of the numerical model that is used to study the morphological development of the pilot. The next chapter discusses the results of the numerical model.

6 Numerical model results

Model simulations are carried out to observe the hydrodynamics, sediment transport, morphological development, and ecological development of the slufter alternative.

6.1. Model simulations

Different simulations are carried out with the model to observe the effects of mild conditions, extreme conditions, and sea level rise on the development of the reviewed alternative. Based on the KNMI long-term averaged wind data over the years 2009 to 2020 (Chapter 5), southwest is the governing wind direction and thus it is assumed to be the governing wind wave direction as well. The most common storm direction is northwest.

Data from two months is used for the analysis, January and April 2009. The first scenario is one that represents mild conditions and uses data from April 2009. This scenario (April, tide only, A-T) is used to predict the results of a situation in which no extreme events are present. Only water level forcing is included in this scenario. As no wind and waves are taken into account, the influence of a mean spring neap cycle is reviewed. The second scenario (April, tide only, SLR, A-TS) is based on the same water level forcing, without extreme events, but one meter sea level rise is added. The third scenario represents storm conditions. This scenario is used to predict the results of a situation in which extreme events are present. For this end data from January 2009 are used. For this scenario water level, wind and (wind)wave forcing are included (January, tide, wind and waves, J-TWW). To observe the effects for wind and waves separately, this scenario is also carried out only with water level forcing (January, tide only, J-T) and with water level and wind forcing (January, tide and wind, J-TW). Table 6.1 gives an overview of the simulations that are carried out.

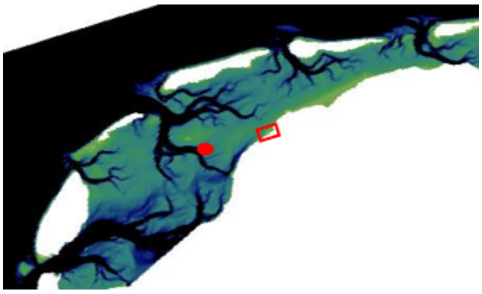
For the simulations with only water level forcing no wind input is used in both the overall and the nested model. However, wind is taken into account in the models that are used to set up the boundary conditions for the overall model. Therefore there still are some wind effects such as storm-surge present in these simulations 'without wind'. These effects are returned as non-harmonic effects in the water level observations.

Table 6.1: Overview of the executed simulations and the processes included in each simulation

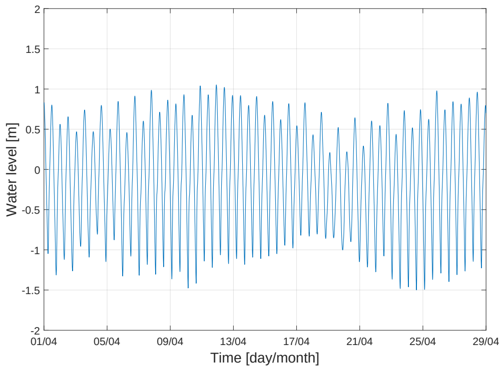
		Simulated processes				Simulated geometry
Simulation	**Simulation month**	**Tide**	**Wind**	**Waves**	**SLR**	(0 = reference case, 1 = with gully, 2 = deep, without gully)
A-T	April	yes	no	no	no	0,1,2
A-TS	April	yes	no	no	yes	0,1,2
J-T	January	yes	no	no	no	1,2
J-TW	January	yes	yes	no	no	1,2
J-TWW	January	yes	yes	yes	no	1,2

6.2. Hydrodynamics

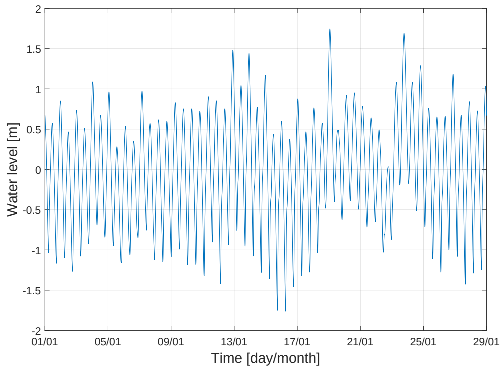
Figure 6.1 shows the resulting water level in the Wadden Sea at Blauwe Slenk (model output location Blauwsot), for the full simulation period (two spring neap cycles) of simulation A-T and J-T (only tidal forcing). The water level in April varies between -1.5m and +1m. It clearly shows the semi-diurnal character of the tide. Non-harmonic effects are small. The water level in January varies between -1.75m and +1.75m. Non-harmonic effects are clearly present. For simulation J-TW and J-TWW the wind is taken into account in both the overall and the nested model. In addition, wind waves are taken into account in simulation J-TWW. Figure 5.4b shows the wave climate of waves that are generated in simulation J-TWW. The wind speeds and direction obtained from the model correspond to the long-term average data from KNMI.



(a) The location of the measuring station Blauwsot (red dot) with respect to the project location (red rectangel)



(b) The water level at Blauwsot in April 2009 for simulation A-T



(c) The water level at Blauwsot in January 2009 for simulation J-T

Figure 6.1: The water level elevation at the offshore location Blauwe Slenk (measuring station Blauwsot) for the simulations with only water level forcing

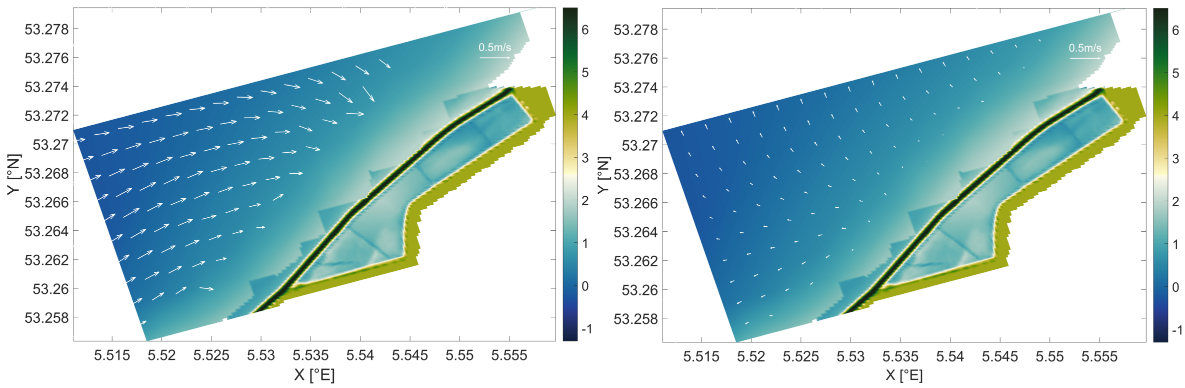
The water levels and depth-averaged velocities at an offshore location are compared for all simulations. To distinguish between the differences for each simulation, one (spring) tide is analyzed in detail (see Appendix Figure A.1 for the water levels and depth-averaged velocities offshore). This is done for both the analysis of the calm conditions and the storm season conditions. All simulations show a higher maximum flood velocity compared to the maximum ebb velocity. This induces a flood dominant system at the project location, as is also shown by Baptist et al. (2019).

In addition, for the analysis of storm season conditions, the influence of both the most common situation (southwest wind and waves, moderate conditions), as well as the most common storm situation (northwest wind and waves, strong conditions), are analyzed separately. Therefore two tidal periods are considered; one tidal period during spring tide, at which the wind and wave direction is southwest (referred to as period SW), and one tidal period at which the wind and wave direction is northwest (referred to as period NW). It should be noted that the wind and wave direction are not the only variables that change between these periods, but two different situations are present. The time series that is used for the boundary conditions results in a water level elevation, depth-averaged velocity, wind speed and wave height that differ as well.

Flow patterns

Flow patterns are shown for simulation A-T-0 and A-T-1 (April tide only, reference situation and situation with gully, see Figure 6.2 and Figure 6.3 respectively). For both simulations, the depth-averaged velocity is given at the moment in time at which maximum flood velocity and maximum ebb velocity occur at the offshore location shown in the Appendix in Figure A.1a. During this simulation, the water does not reach the dike due to the bathymetry of the area and the water level elevation. The flow is directed towards the east-northeast during flood flow, and towards the southwest and northwest during ebb flow. In the area outside of the slufter area, the flow pattern for the situation with gully shows similar results as the flow pattern for the reference situation. Inside the gully, the depth-averaged velocity is higher than outside of the slufter area. The bed level of the gully outside of the slufter area remains equal to 0m NAP.

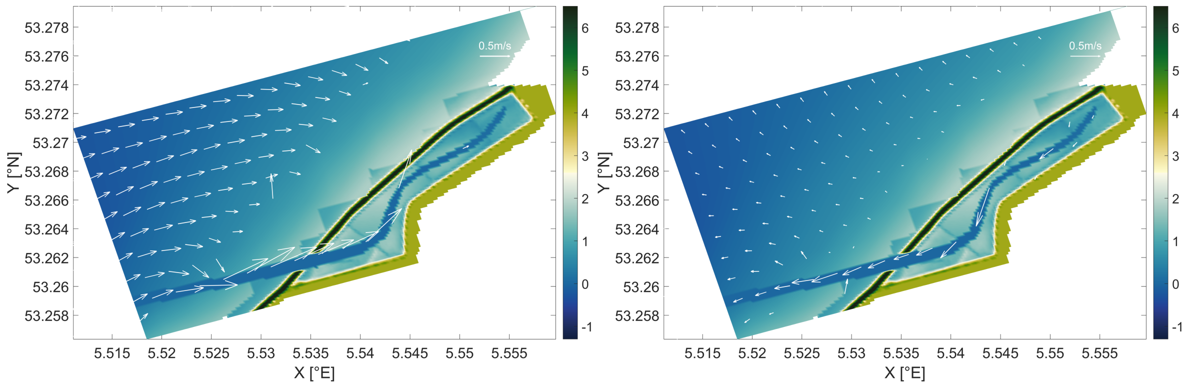
In the small entrance of the slufter area, higher ebb flow velocities are present than in the surrounding area. When a part of the tidal flats in front of the slufter area is already running dry during ebb tide, water is still flowing outside of the slufter area. This is because of the lower bed level of the gully compared to the surrounding area. Figure 6.4 shows the water level elevation in the entrance of the slufter area for simulation A-T-1 (April, tide only, with gully) and the bed level height of the flats in the slufter area. The water level elevation in the gully does not reach zero during a tidal cycle. The difference between the minimal water level elevation and the horizontal line at the bed level height of the gully in Figure 6.4 illustrates the remaining water in the gully. The water level in combination with the bed level heights of the flats and the bathymetry maps (Figure 5.2a) gives an impression of the small size of the area inundated during spring tide. Only the gully itself and a small part of the flats is inundated. In addition, Figure 6.4 shows how the water level elevation during maximum flood velocity (≈0.6m) is significantly lower than the water level elevation during maximum ebb flow velocity (≈1.1m). The difference in water depth during flood and ebb flow, partly explains the lower ebb than flood velocity. In addition, the difference in flow is caused by the water level gradient produced by the tide.



(a) Flow pattern of the depth averaged velocity during maximum flood velocity

(b) Flow pattern of the depth averaged velocity during maximum ebb velocity

Figure 6.2: Flow patterns for Simulation A-T-0 (tide only, reference geometry)



(a) Flow pattern of the depth averaged velocity during maximum flood velocity

(b) Flow pattern of the depth averaged velocity during maximum ebb velocity

Figure 6.3: Flow patterns for Simulation A-T-1 (tide only, with gully)

The resulting water levels and depth-averaged velocities are compared with the results from the other simulations. Figure 6.5a and 6.5b and Figure 6.6a, 6.6b, 6.7a and 6.7b show the water level elevation and the depth-averaged velocity at the entrance of the slufter area during spring tide for simulation A-T and A-TS and simulation J-T, J-TW and J-TWW (SW-wind and NW-wind) respectively. All simulations are displayed for both interventions, with (1) and without gully (2).

Figure 6.4 showed the small inundation area during simulation A-T-1. Although simulations A-TS, J-T, J-TW and J-TWW consider higher water level elevations than simulation A-T, for the situation with gully (-1), the higher flats (bed level elevation of ≈2m) are only fully inundated for the simulation with SLR (simulation A-TS1). For the situation without gully (-2, Figure 5.2b), the whole slufter area is inundated during spring tide for all simulations.

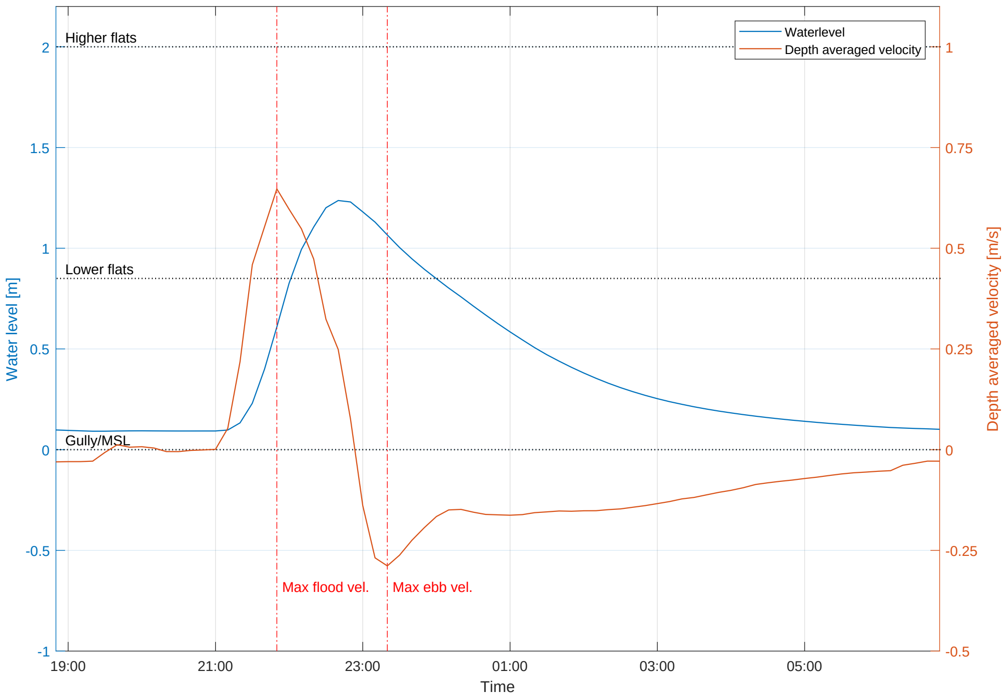
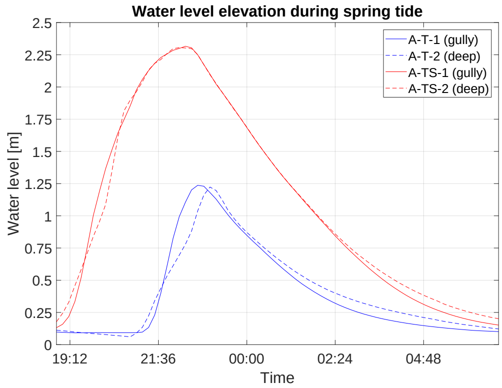
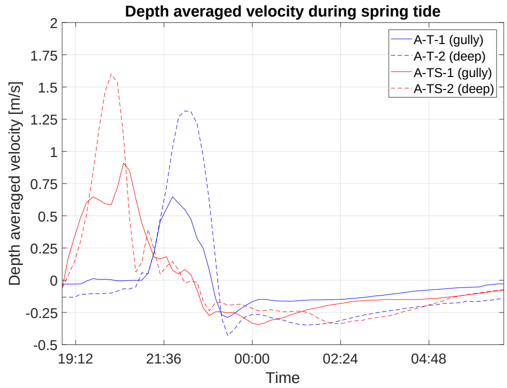


Figure 6.4: The water level elevation and depth averaged velocity at the entrance of the slufter area (location shown in Figure 6.8a) for simulation A-T-1 (April, tide, with gully) with an indication of the bed level elevation of the gully, the lower flats, and the higher flats in the slufter area.

Figure 6.5a, 6.5b, 6.6a, 6.6b, 6.7a and 6.7b show a horizontal tidal asymmetry; the falling period of the tide is longer than the rising period. This is also shown by the depth-averaged velocity, which shows that the flood velocity (positive) is higher than the ebb velocity (negative). The depth averaged velocity plots (Figure 6.5b and 6.6b) show a much longer low water slack period than high water slack period. Simulations with 1m SLR (A-TS) have a longer inundation time compared to simulations without SLR (A-T). The slight (both relative and absolute) increase in depth-averaged flood velocity increases the flood dominance of the system under the forcing of sea level rise. The depth-averaged velocity of Simulation A-TS-1 (April, SLR, with gully) shows a double peak. This is a consequence of an increase in the inundated area, due to inundation of the flats.

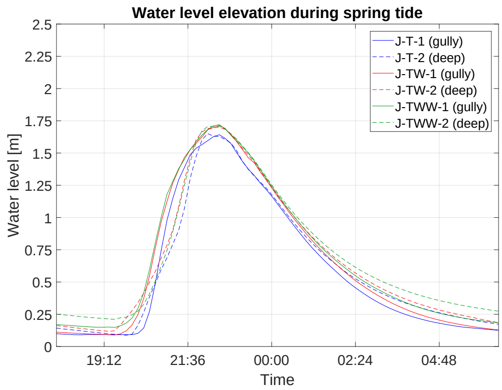


(a) Water level elevation

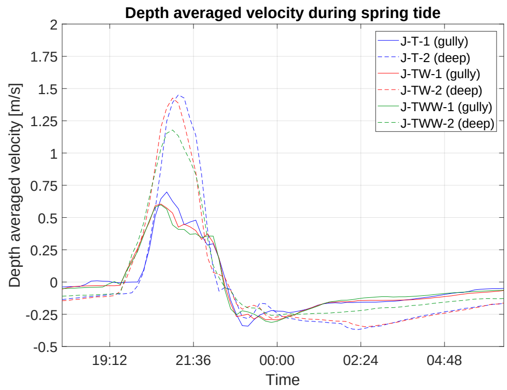


(b) Depth averaged velocity

Figure 6.5: The water levels and depth averaged velocities at the entrance of the slufter area for simulation A-T and A-TS for one tidal cycle during spring tide

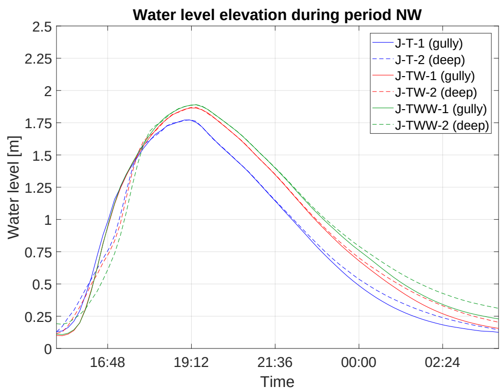


(a) Water level elevation

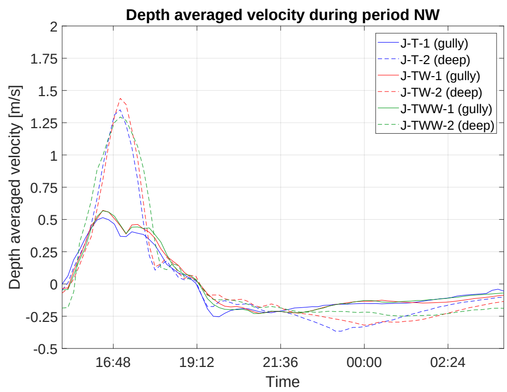


(b) Depth averaged velocity

Figure 6.6: The water levels and depth averaged velocities at the entrance of the slufter area for simulation J-T, J-TW and J-TWW for one tidal cycle during spring tide with wind (and waves) in the governing direction, southwest (J-TW and J-TWW).



(a) Water level elevation

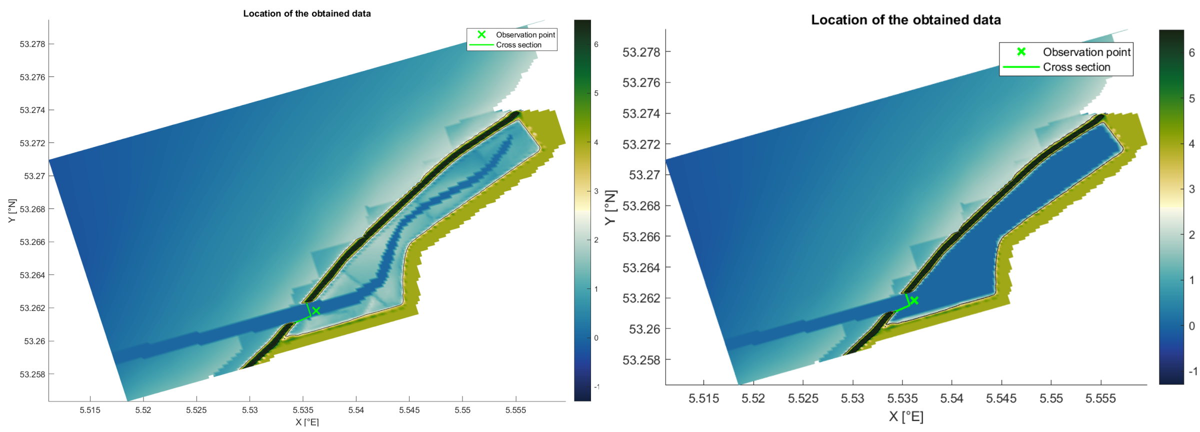


(b) Depth averaged velocity

Figure 6.7: The water levels and depth averaged velocities at the entrance of the slufter area for simulation J-T, J-TW and J-TWW for one tidal cycle with wind (and waves) in the most common storm direction, northwest (J-TW and J-TWW).

6.3. Sediment transport

To analyze the sediment transport into the slufter system, the water levels and the sediment transport rates in the entrance of the slufter are analyzed. Figure 6.8 shows the bathymetry for both geometrical situations and the location of the measurement points at which the sediment transport of all simulations is observed.



(a) Bathymetry with gully

(b) Bathymetry without gully

Figure 6.8: Location of the observation point and cross section in the entrance of the slufter area that are used for the analysis of the sediment transport

6.3.1. Mild conditions (Simulation A-T and A-TS)

Figure 6.9 and 6.10 show the depth-averaged velocity (u), the total suspended sediment concentration (c, including both sand and mud), and the total sediment flux (u*c) observed in the entrance of the slufter area for Simulation A-T-1 and A-T-2 (April, tide, with and without gully). In both cases, the concentration plot shows relatively high concentrations during flood compared to the concentrations during ebb. The lower ebb flow velocities cause lower transport rates and therefore only a fraction of the imported sediment is exported.

The suspended sediment fluxes from Figure 6.9 and 6.10 show both relative and absolute differences. The absolute values in the simulation without gully are a factor two larger for both the concentrations and the velocities, which translates to higher transport rates as well. In addition, an increase of the flood to ebb sediment concentration rate is observed. This scales with the higher flood to ebb velocity ratio, which induces a relatively higher amount of up stirring of the sediment during flood than ebb due to an increase of the bed shear stresses. Both aspects lead to higher sediment transport rates for the situation without gully.

The observation of net sediment import due to the higher flood than ebb concentrations for both geometries is supported by the observed instantaneous transport rates into the slufter area that are shown in Figure 6.11. For all scenarios, there is both an import of sand and mud through the entrance of the slufter system. The sediment transport rates during flood are significantly higher than during ebb, causing an import of both sediment fractions.

Comparing the sediment transport for simulation A-T and A-TS in Figure 6.11 shows a larger amount of sediment transport with SLR (simulation A-TS) for all geometries. This is a consequence of the very low ebb velocities, while the area is still inundated (so that sediment can settle over a longer period of time) (Figure 6.5b). A longer inundation time of the slufter area, combined with the low depth-averaged ebb flow velocities, increases the settling potential of the sediment. A slight increase in depth-averaged flood velocities increases the flood dominance which implies a relative increase in net sediment transport. SLR increases the water level which leads to higher depth-averaged velocities and thus more sediment transport.

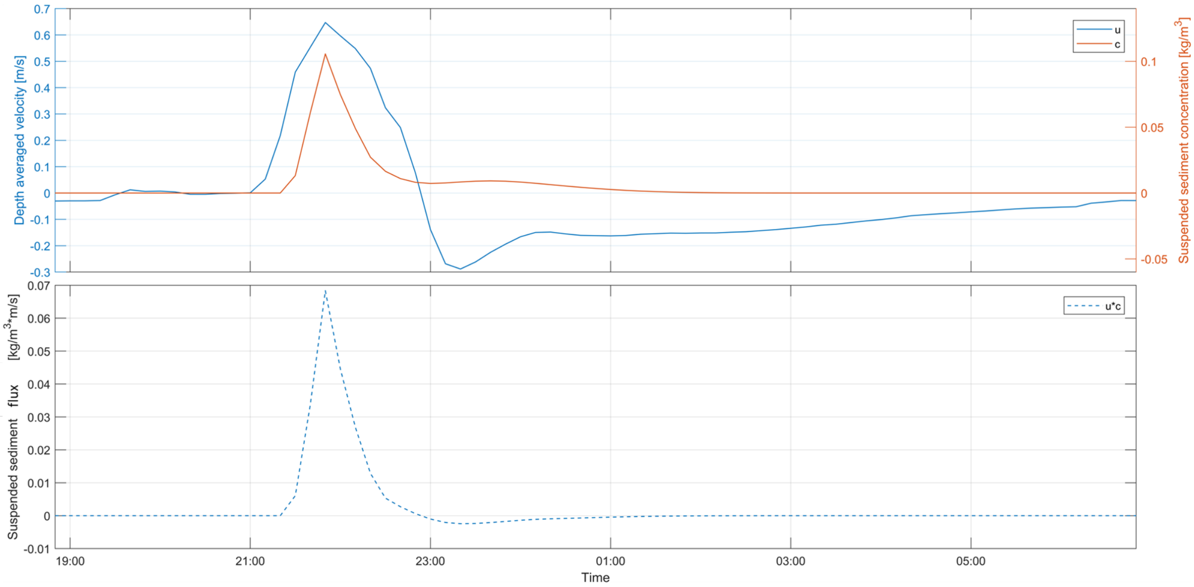


Figure 6.9: Suspended sediment concentration, depth averaged velocity, and the suspended sediment flux determined by u*c. A higher depth-averaged suspended sediment concentration during flood tide compared to ebb tide induces a net import of suspended sediment into the slufter area for simulation A-T-1 (with gully; mind the scale!)

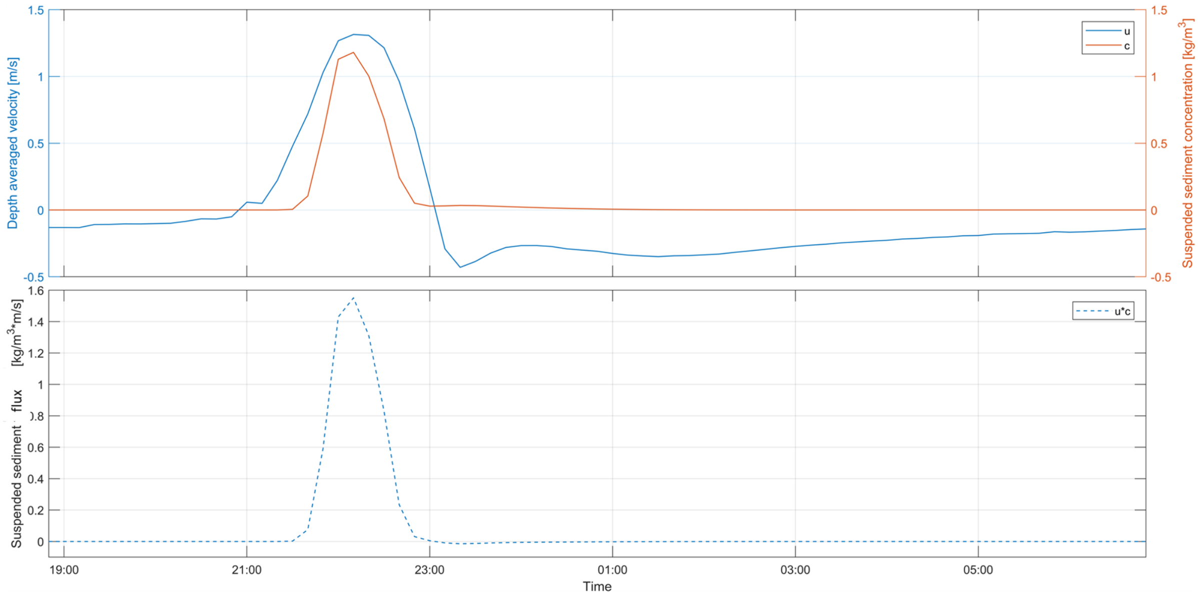
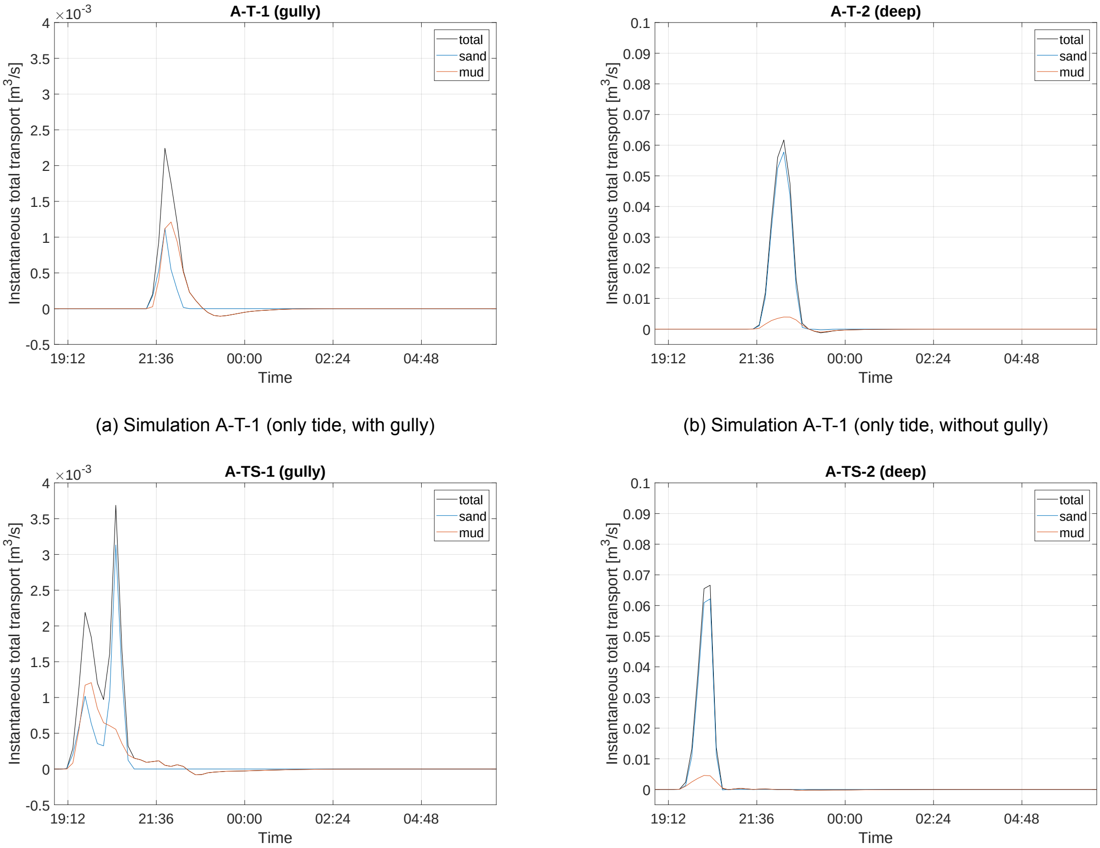


Figure 6.10: A higher depth-averaged suspended sediment concentration during flood tide compared to ebb tide induces a net import of suspended sediment into the slufter area for simulation A-T-2 (without gully; mind the scale!)

All simulations show an import of sediment into the slufter area for both the situation with as without gully. Geometry changes that cause an increase of the flow velocities, lead to a higher amount of sediment import. The increase of the water level by sea level rise increases the amount of sediment import to a lesser extent because it increases the flow velocities to a lesser extent.



(a) Simulation A-T-1 (only tide, with gully)

(b) Simulation A-T-1 (only tide, without gully)

(c) Simulation A-TS-1 (sea level rise, with gully)

(d) Simulation A-TS-2 (sea level rise, without gully)

Figure 6.11: Instantaneous total transport in the entrance of the slufter area for Simulaton A and B showing slightly higher transport rate for SLR and significantly higher transport rates for a system without gully compared to a system with gully.

6.3.2. Storm conditions (Simulation J-T, J-TW and J-TWW)

As mentioned in Section 6.2, two tidal periods are observed during the simulations of the storm season conditions, one for governing wind/wave direction and one for the most common storm wind/wave direction.

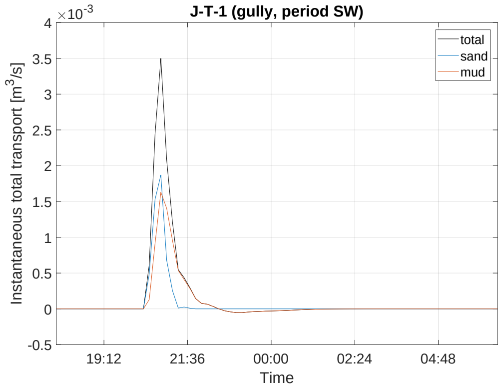
Figure 6.12 and 6.13 show the instantaneous total transport rates for simulation J-T, J-TW and J-TWW during period SW and NW respectively. Similar to mild conditions (simulation A-T and A-TS, Figure 6.11) they show that the instantaneous total transport is higher during flood than during ebb for all sediment fractions for both with and without gully. This causes an import of both sediment fractions into the slufter area for all simulations.

Period SW

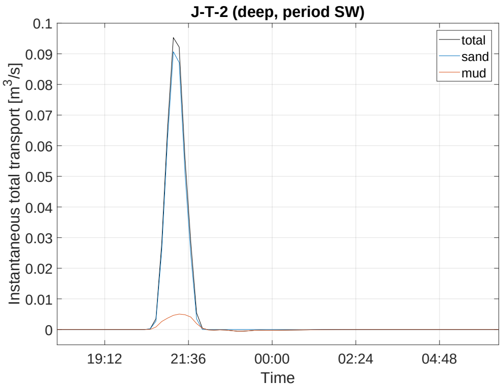
Figure 6.12a, 6.12c and 6.12e show the instantaneous total transport rates for the storm season simulations with gully during period SW (governing conditions). The depth-averaged velocities during period SW (see Figure 6.6b) slightly decrease for simulation J-TW and J-TWW (tide with wind and with wind and waves) compared to simulation J-T (tide only). Lower depth-averaged velocities induce lower bed shear stresses and thus lower suspended sediment concentrations. Higher suspended sediment concentrations for waves (J-TWW) compared to only wind (J-TW), are caused by the increased bed shear stress due to the influence of the waves.

The simulation for storm season conditions with only tidal forcing (J-T-1, see Figure 6.12a) shows higher transport rates compared to A-T-1 (April, tide only). Similar to A-T-1, simulation J-T-1 shows comparable sand and mud transport rates. However, taking the southwest wind into (J-TW-1) account decreases the instantaneous total transport rates. Especially the sand fraction is decreased significantly. Leading to a relatively higher import rate of mud compared to sand. Taking the southwest waves into account as well results in higher transport rates for mud but slightly lower transport rates for sand, increasing the relative difference between the mud and the sand fraction of the instantaneous total transport. In addition, the transport rates of mud during ebb flow increase under the influence of waves.

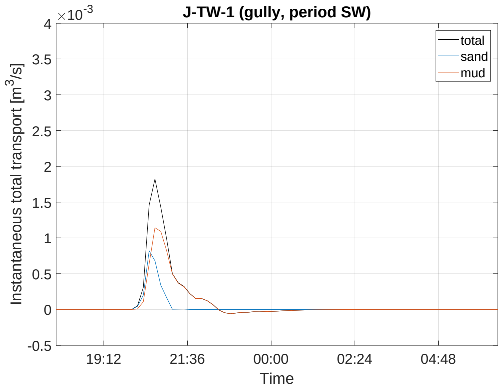
Figure 6.12b, 6.12d and 6.12f show the instantaneous total transport rates for the storm season simulations without gully during period SW (governing conditions). The depth-averaged velocities are in decreasing order of J-T-2, J-TW-2 to J-TWW-2 (Figure 6.6b). This shows that the wind and waves decrease the flow velocity, resulting in decreasing bed shear stresses as well. This would cause decreasing instantaneous total transport rates in the order of J-T-2, J-TW-2 to J-TWW-2 as well. However, an increase of the bed shear stress as a result of the waves leads to higher suspended sediment concentrations and thus comparable instantaneous total transport rates are present for J-TW-2 and J-TWW-2. The waves have a relatively higher influence on mud transport compared to sand transport.



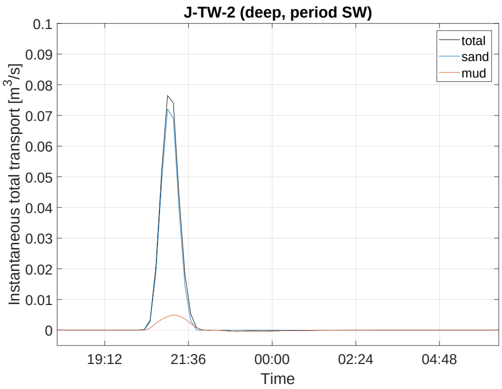
(a) An almost equal amount of sand and mud is present in the instantaneous total transport for only tidal forcing



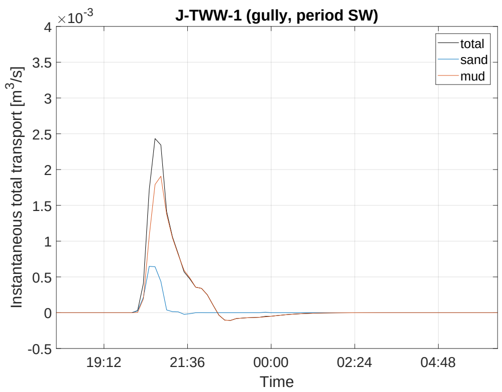
(b) A very small fraction of the total instantaneous total transport is mud



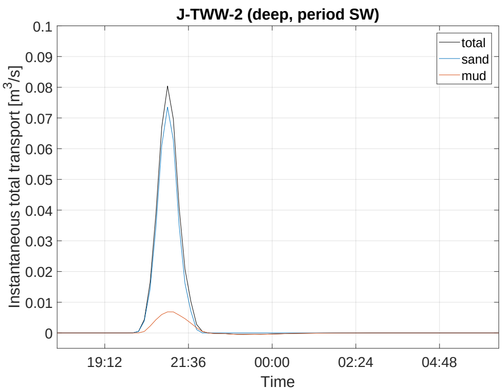
(c) The instantaneous total transports decrease due to the southwest wind



(d) The instantaneous total transports decrease due to the southwest wind, but to a much lesser extent compared to the situation with gully



(e) The instantaneous total transport rates of mud increase with about 50% when waves are taken into account



(f) The instantaneous total transport rates of mud increase with about 50% due to the influence of waves, but is still a small fraction of the total instantaneous total transport

Figure 6.12: Instantaneous total transport in the entrance of the slufter area for Simulation J-T, J-TW, J-TWW with southwest wind and waves, show a decrease in sediment transport when wind and waves are taken into account. The influence of waves however, is positive in the situation with gully and slightly positive for the situation without gully.

Period NW

The depth-averaged velocities during period NW slightly increase for wind and waves compared to only tide (Figure 6.7), inducing higher sediment concentrations for wind and waves. Figure 6.13a, 6.13c and 6.13e show the instantaneous total transport rates for the storm season simulations with gully during period NW. Figure 6.13b, 6.13d and 6.13f show the instantaneous total transport rates for the storm season simulations without gully during period NW. Both simulations show an increasing amount of instantaneous total transport from simulation J-T to J-TW, to J-TWW.

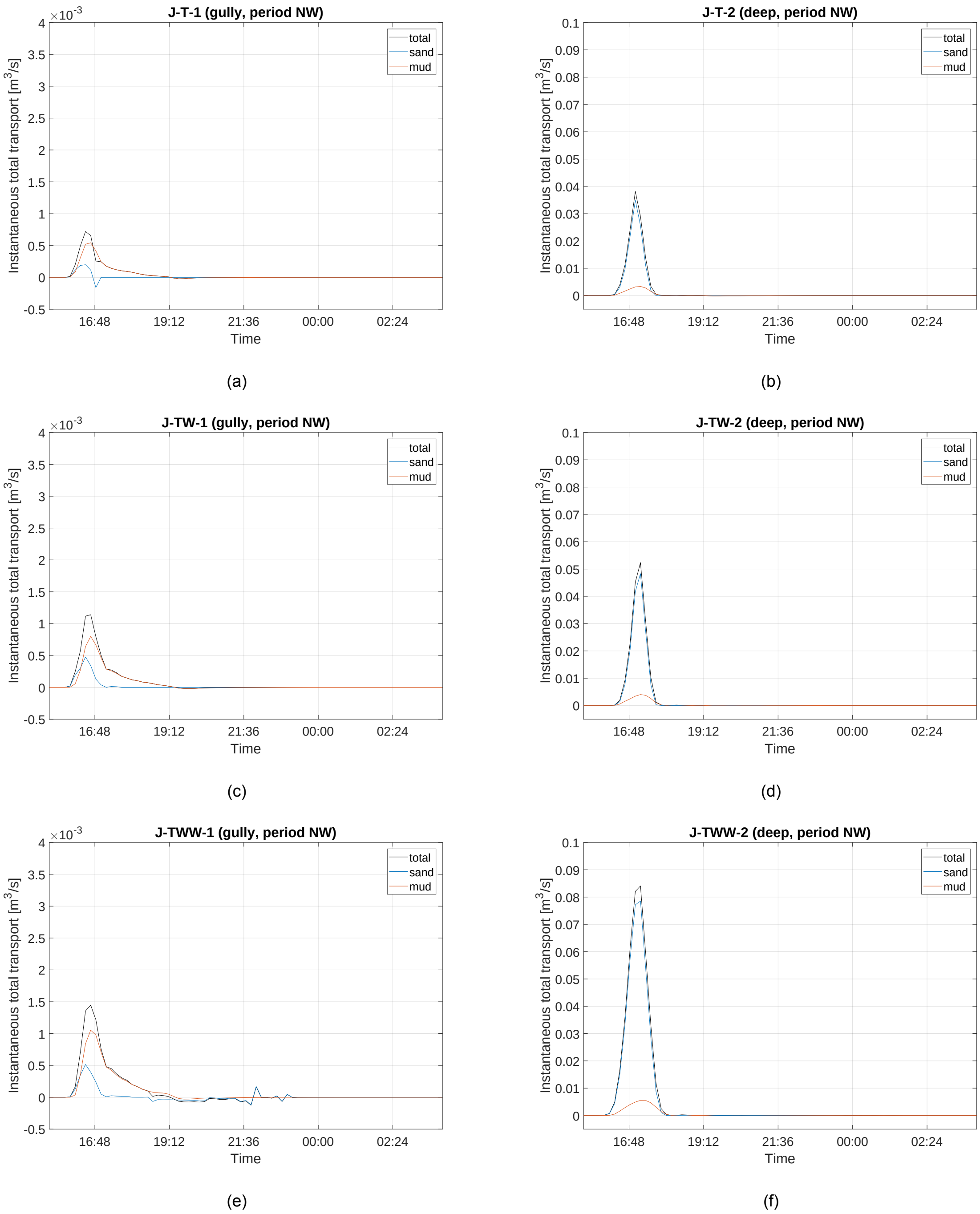


Figure 6.13: Instantaneous total transport in the entrance of the slufter area for simulation J-T, J-TW, J-TWW with northwest wind and waves, shows an increase in sediment transport when wind and waves are taken into account.

6.3.3. Cumulative transport

Figure 6.14 shows the cumulative total transports over the full simulation period for all simulations. This is for both sediment fractions (sand and mud) and both the bed load transport and the suspended sediment transport. The simulations done for the geometry with gully result in a much lower cumulative total transport into the slufter area compared to the simulations without gully. The cumulative total transports after the simulation period of 28 days are given in Table 6.2.

If we assume that the total transport is equally distributed over the slufter area (60 ha), we can define an average bed level change. (Local) differences caused by density variations and consolidation are not taken into account. Extrapolating the total transport results of the simulation period of 28 days gives a yearly bed level increase of $2*10^{-3}$ m (A-T-1, minimum import) to 0.11 m (A-TS-2, maximum import). This is for extrapolating the conditions of one simulation over the period of a whole year and assuming an even distribution of the sediment over the slufter area. Time and space varying conditions will influence the actual results. Therefore this can only be seen as a range of the system's expected ability to import sediment. The expected SLR as introduced by the RCP climate scenarios (Chapter 2) is 0.5, 0.63 and 0.93 cm per year for climate scenario RCP2.6, RCP4.5 and RCP5.8 respectively. For the slufter area of 60ha, 230 m3 of sediment is needed to grow with the minimum expected SLR, and 428 m3 of sediment is needed to grow with the maximum expected SLR. This means all simulations without gully import enough sediment. The simulations with gully however do not import enough sediment to grow with SLR, only the simulation with SLR imports enough sediment to grow with the minimum expected SLR. This conclusions is however based on the assumption that the imported sediment is averaged over the total slufter area. If the sediment is only assumed to be distributed over the flooded area (only 15 ha for the situation with gully), a minimal yearly bed level increase of the flooded area of 7.5*10-3 m is expected. This means that the yearly bed level increase of the flooded area for the simulations with gully is as well larger than the expected yearly SLR.

Distinguishing between the calm conditions (A-T) and storm conditions (J-T, J-TW and J-TWW) shows that the differences are small for the simulation with gully. For the simulations without gully however, the presence of wind and waves increase the total transport. The cumulative total transport for the simulation with storm condition water levels (J-T-2) is almost equal to the transport for calm conditions (A-T). The presence of wind increases the total transport by a factor of 1.2. The presence of both wind and waves increases the total transport by a factor of 1.8.

As discussed, the actual total amount of sediment import will vary due to a combination of calm and storm conditions and the influence of wind and waves. Assuming an equal distribution of the sediment over the slufter area and not taking the SLR simulations into account, the expected increase of the bed levels will vary between 0.20cm/year and 0.25 cm/year with gully and between 4.83 cm/year and 8.62 cm/year without gully.

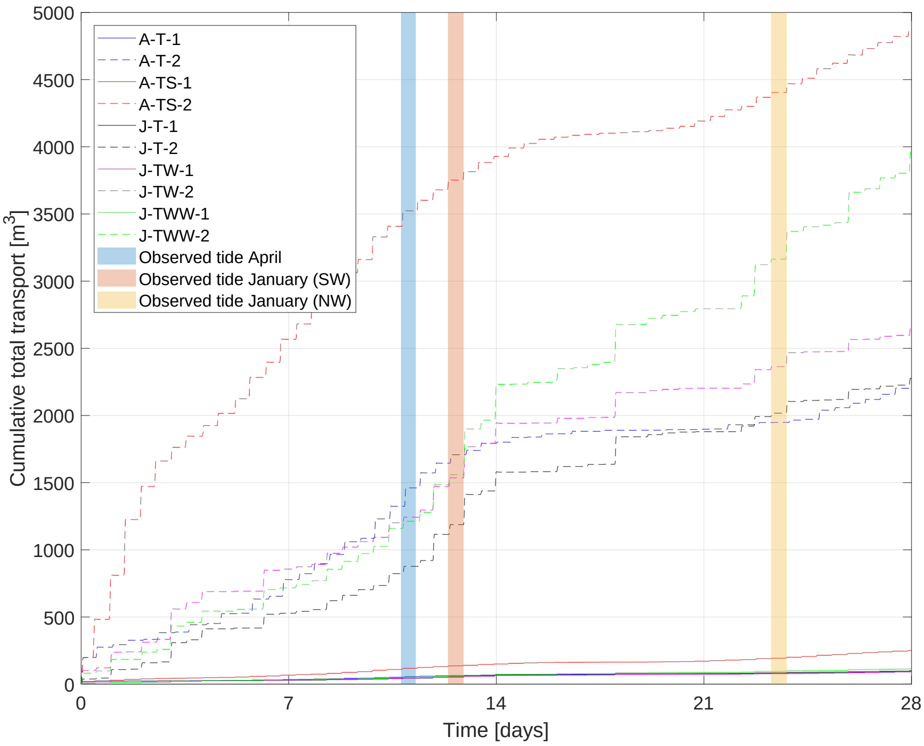


Figure 6.14: Cumulative total transport over the entrance of the slufter system over a period of one spring neap cycle (28 days) for all simulations for both with and without gully. Large differences are present between the simulations with and without gully.

Table 6.2: Cumulative total transports

Simulation	Gully/Deep	Cumulative total transport (28 days) [m^3]
A-T	Gully	93
	Deep	2223
A-TS	Gully	252
	Deep	4861
J-T	Gully	101
	Deep	2276
J-TW	Gully	96
	Deep	2654
J-TWW	Gully	117
	Deep	3969

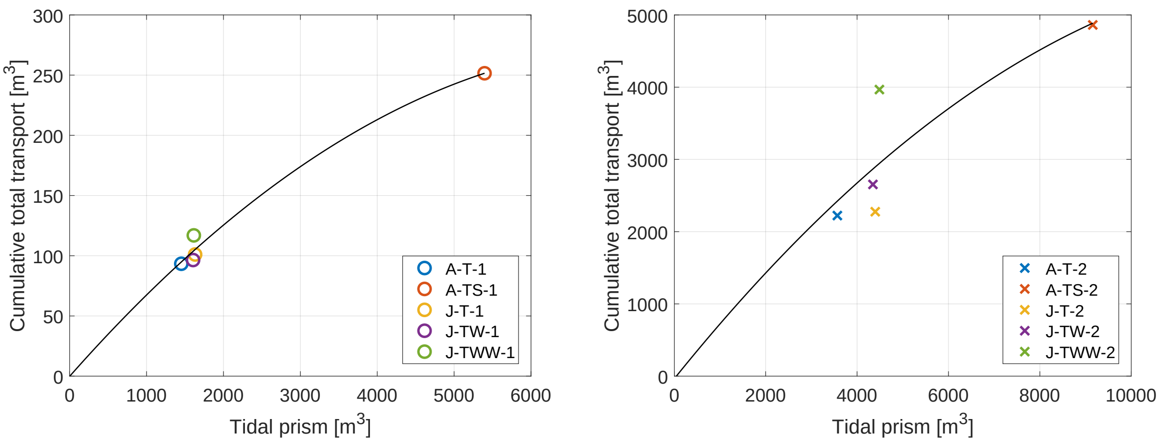
To compare the relative amount of cumulative total transport into the slufter area of all simulations, the cumulative total transport and the tidal prism of the area are plotted against each other (Figure 6.15). The relation between the tidal prism of the slufter area and the amount of sediment import also shows clear differences for the simulations with and without gully. In general, the simulations without gully have a relatively higher amount of cumulative total transport. The situations with SLR (A-TS) show the most extreme outliers.

Figure 6.15a and 6.15b show the tidal prism versus the cumulative total transport for the situation with and without gully respectively. Both figures show the relation between the tidal prism and cumulative total transport. However, all simulations in January show different amounts of cumulative total transport for an almost equal tidal prism. Table 6.3 shows the mean suspended sediment concentrations of both sediment fractions (sand and mud together) for all simulations averaged over the whole simulation period of 28 days. It shows large differences (factor 10) between the simulations with and without gully. In addition, it shows differences in the same order as the difference in total transport rates for the simulations with wind and waves, only wind, or tide only (Figure 6.15b). This partly explains the difference that for the same tidal prism, different cumulative total transports are observed. Therefore, it is confirmed that the amount of sediment transport into the slufter area strongly depends on the suspended sediment concentration as well.

Table 6.3: The mean suspended sediment concentrations of both sediment fractions (sand and mud together) for all simulations averaged over the whole simulation period. It shows large differences (factor 10) between the simulations with and without gully. In addition it shows differences in the same order as the difference in total transport rates for the simulations with wind and waves, only wind, or tide only.

Simulation	Mean suspended sediment concentration [kg/m^3]
J-T-1	0.0031
J-TW-1	0.0030
J-TWW-1	0.0039
J-T-2	0.0281
J-TW-2	0.0287
J-TWW-2	0.0400

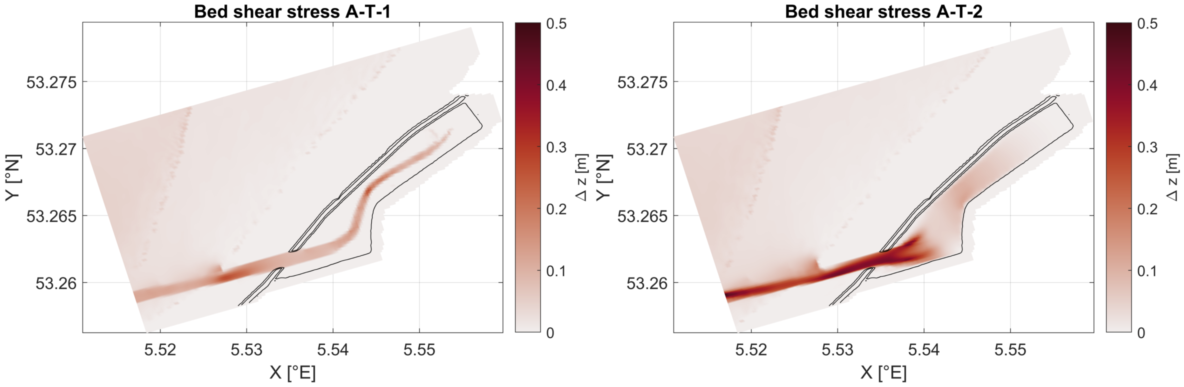
The mean values of the suspended sediment concentrations of the simulations without gully are ten times as high as the values for the simulations with gully. In addition to the relation between the size of the tidal prism and the amount of sediment import, this demonstrates the relation between the suspended sediment concentration and the amount of total sediment import. Both geometries (with and without gully) have the same access channel that leads to the entrance of the slufter area. A higher tidal prism of the slufter area leads to greater amounts of water that pass through the access channel. This leads to higher depth-averaged velocities and higher bed shear stresses. Figure 6.16 shows the mean bed shear stresses for simulation A-T-1 (tide only, with gully) and A-T-2 (tide only, without gully) over one (spring) tide. The bed shear stress around the entrance of the slufter area, for the simulation without gully is about three to four times higher than for the simulation with gully. This explains the (ten times) higher suspended sediment concentrations for the simulation without compared to the simulation with gully.



(a) The tidal prism versus the cumulative total transport that is imported into the slufter area during the whole simulation time for all simulations with gully shows a correlation between these two values. All simulations in January have almost equal tidal prisms but different amounts of cumulative total transport. Simulation A-TS-1 gives the most extreme value, but has a cumulative transport to tidal prism ratio that is close to the ratio of the other simulations.

(b) The tidal prism versus the cumulative total transport that is imported into the slufter area during the whole simulation time for all simulations without gully shows a correlation between these two values. All simulations in January have almost equal tidal prisms but different amounts of cumulative total transport. Simulation A-TS-2 gives the most extreme value, but has a cumulative transport to tidal prism ratio that is close to the ratio of the other simulations.

Figure 6.15: The tidal prism versus the cumulative total transport that is imported into the slufter area during the whole simulation time for all simulations shows a correlation between these two output values. Although, large differences are present for the situation with and without gully. The situation with SLR (A-TS) gives the most extreme outliers.



(a) The simulation with gully shows higher bed shear stresses in than outside the gully. The highest bed shear stresses are present in front of the entrance.

(b) The simulation without gully shows the highest bed shear stresses in the gully towards the slufter area and just after the entrance of the area.

Figure 6.16: The bed shear stresses averaged over a whole tide shows differences between the simulation with and without gully. In the gully towards the slufter area there are higher bed shear stresses for the simulation without gully.

6.4. Morphological development

The morphological development of the slufter area is observed for all simulations without waves. The morphological development is observed over a time of 5.5 months. Figure 6.17 shows the sedimentation/erosion patterns for the simulations for mild conditions. In addition, the morphological development of the slufter area for simulation A-T is observed over different cross-sections that are displayed in Figure 6.17. The cross-sections are shown in Figure 6.18 and 6.19 for the situation with and without gully respectively.

For the situation with gully, the cross-sections show some erosion of the center of the gully and slight sedimentation at the edges/banks of the gully. This effect is most significant in the middle of the slufter area at CRS-2. The flats have barely changed. For the situation without gully some sedimentation is seen over all three cross-sections, being almost zero at CRS-3 but more significantly present in CRS-1 (up to 0.3m).

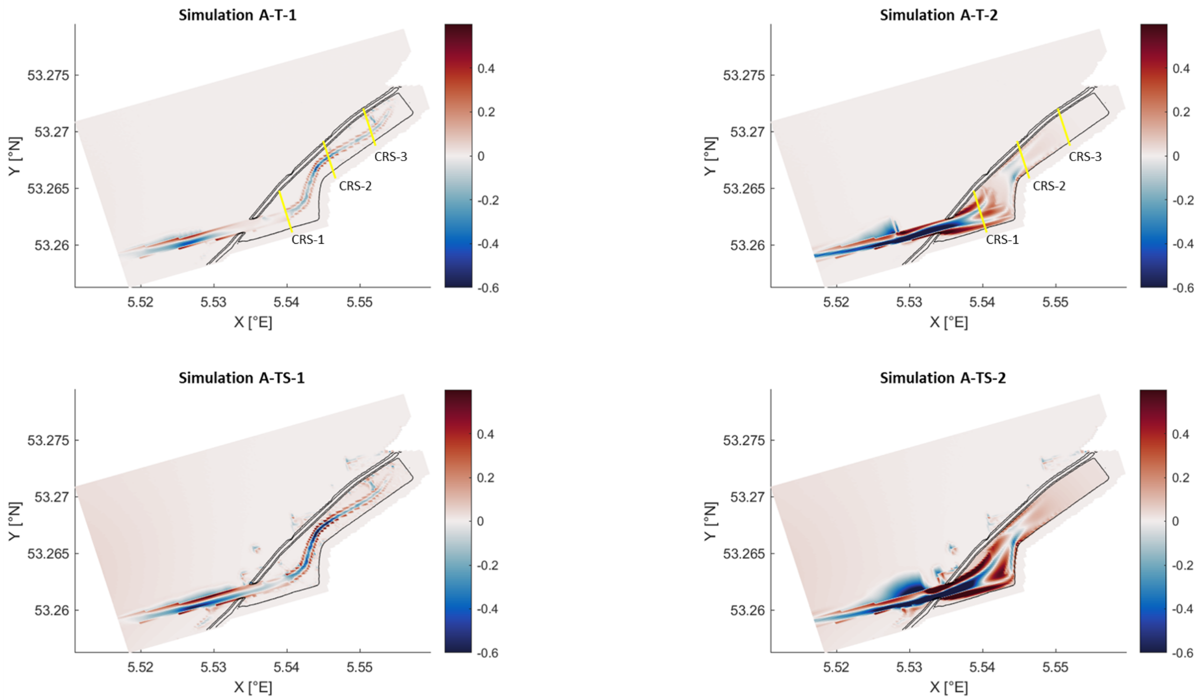
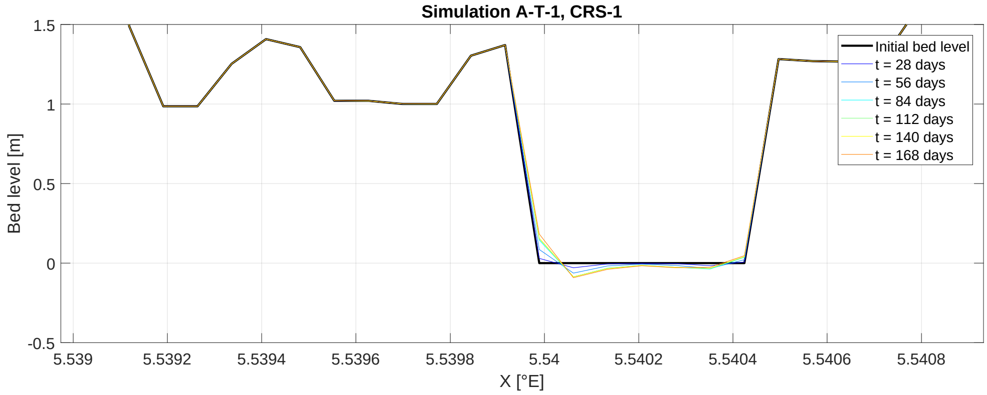
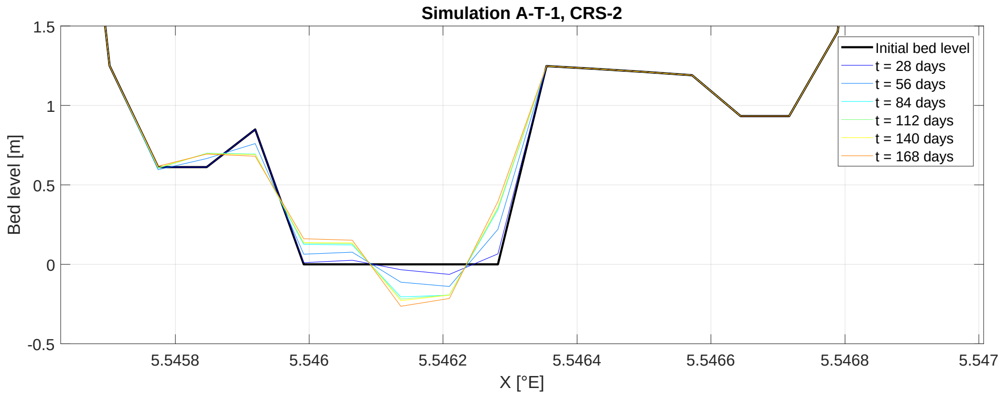


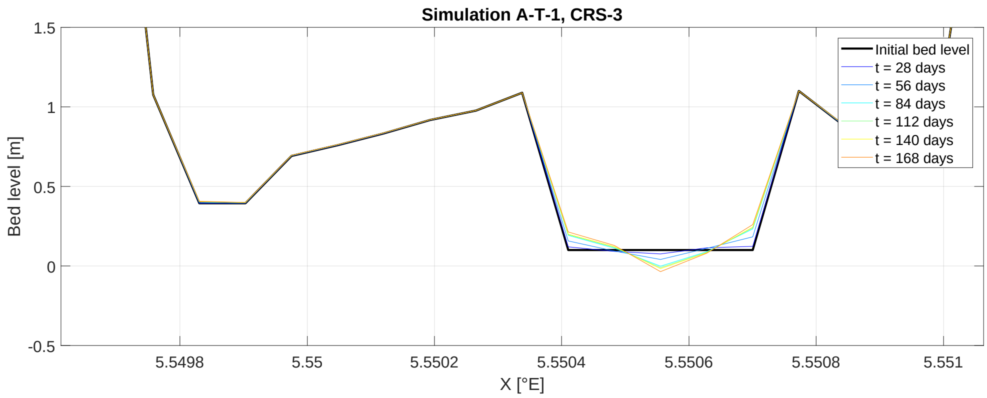
Figure 6.17: Sedimentation/erosion patterns for simulation A-T (upper figures) and A-TS (lower figures) with the location of the cross sections shown. The situation without gully (right) shows significantly more morphological development than the situation with gully (left). The situation with SLR shows more morphological development as well.



(a) CRS-1 only shows minor bed level changes over the simulation period. Small amounts of erosion are seen in the centre of the gully. Small amounts of sedimentation are seen at the edges of the gully.

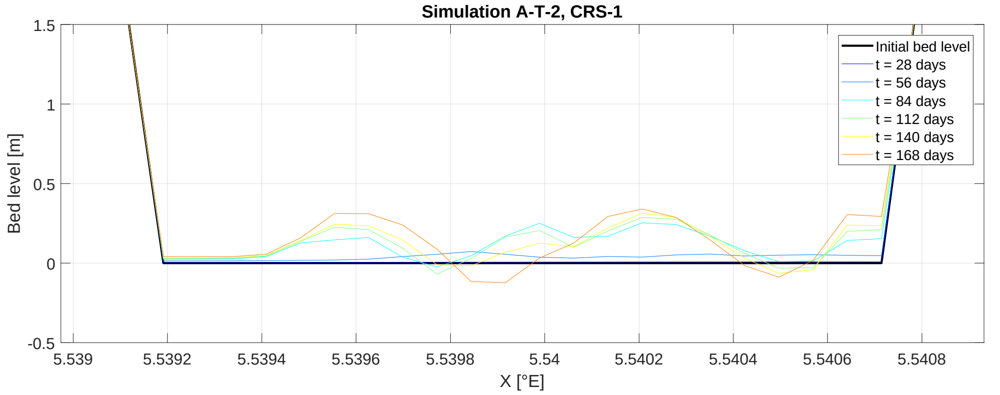


(b) CRS-2 shows erosion in the centre of the gully. Sedimentation is observed at the edges. The left bank is smoothened over time.

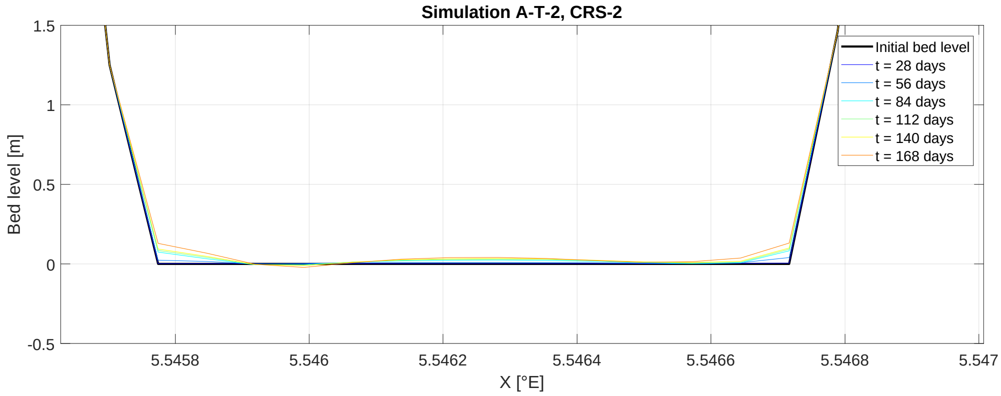


(c) CRS-3 shows little erosion in the centre of the gully and little sedimentation at the edges of the gully.

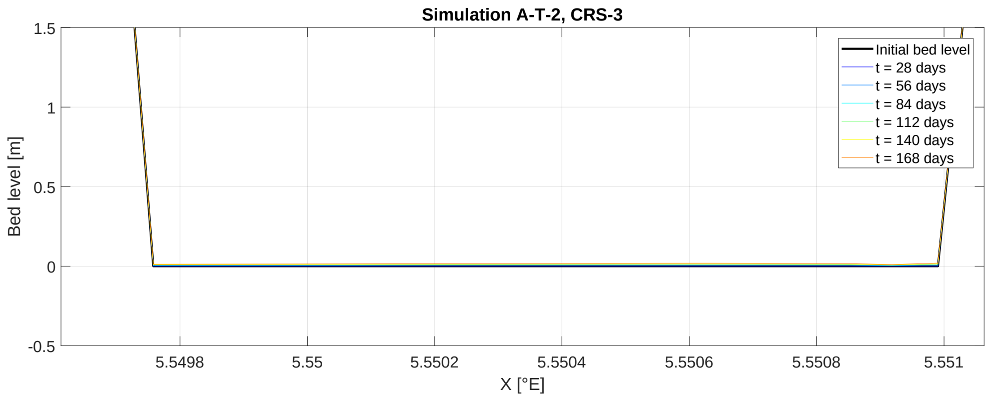
Figure 6.18: Three cross-sections in the slufter area for simulation A-T-1 (April, tide only, with gully) showing the morphological development over the whole simulation period. The locations of the cross-sections are shown in Figure 6.17.



(a) In CRS-1 the formation of three gullies and three flats in the slufter area is observed.



(b) In CRS-2 the formation of two gullies and one flat are distinguished. The bed level changes are however small.



(c) In CRS-3 a small sedimentation is observed over the whole cross-section.

Figure 6.19: Three cross-sections in the slufter area for simulation A-T-2 (April, tide only, without gully) showing the morphological development over the whole simulation period. The locations of the cross-sections are shown in Figure 6.17.

Sand/mud contribution to the morphological development

Figure 6.20 shows the contribution of sand and mud to the bed level changes over the entire simulation period. The contribution of sand is larger, therefore the patterns can be seen more clearly than for mud. Figure 6.21 shows the change in volume fractions of mud for both simulations (A-T-1 and A-T-2) on a smaller scale. For the situation with gully, the amount of sand decreases inside the gully and increases at the edges of the gully. The volume fraction of mud decreases in front of the slufter area and increases inside (/over the largest part of) the slufter area.

For the situation without gully, the same patterns are seen. Sedimentation is present at the banks of the gully. For the simulation without gully, natural gullies evolve in the entrance area of the slufter. At places where gullies evolve, sand is eroded. In the back part of the slufter area, mud is deposited.

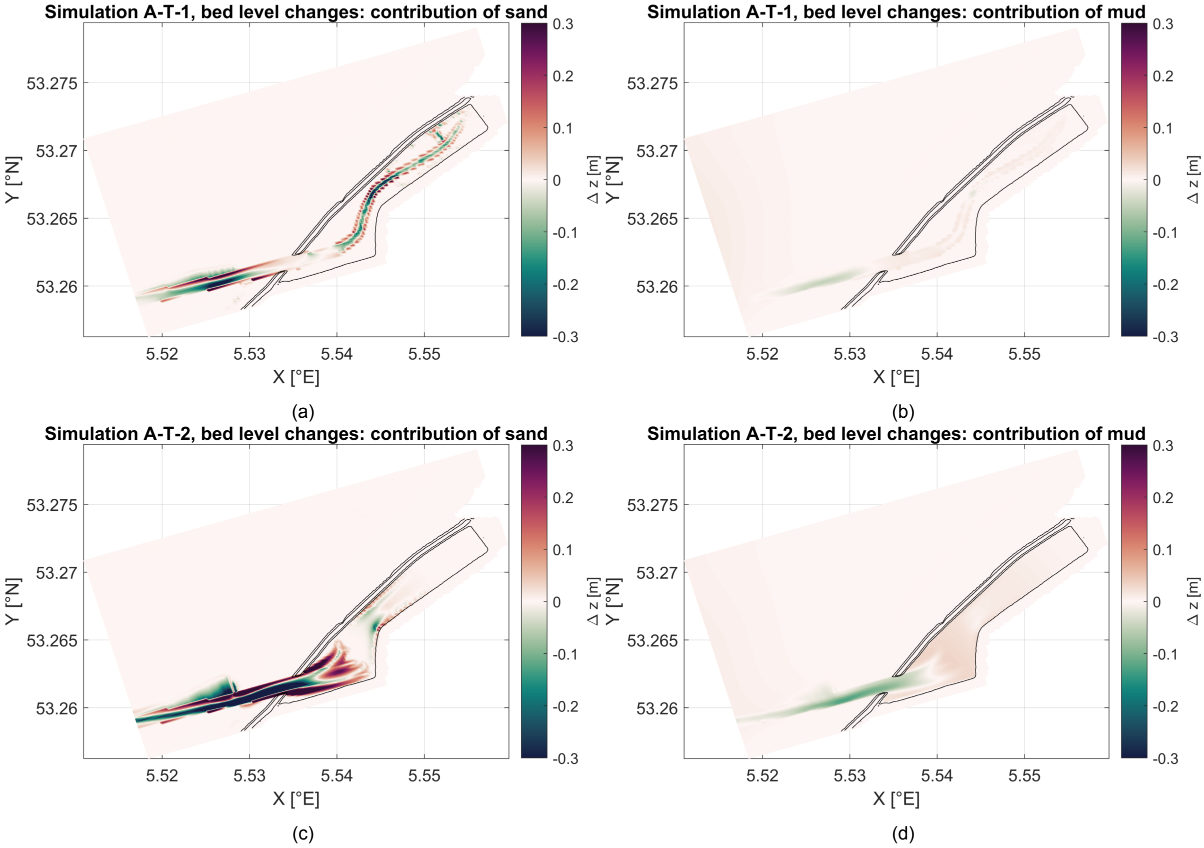


Figure 6.20: The contribution of sand and mud to the bed level changes for simulation A-T after 5.5 months

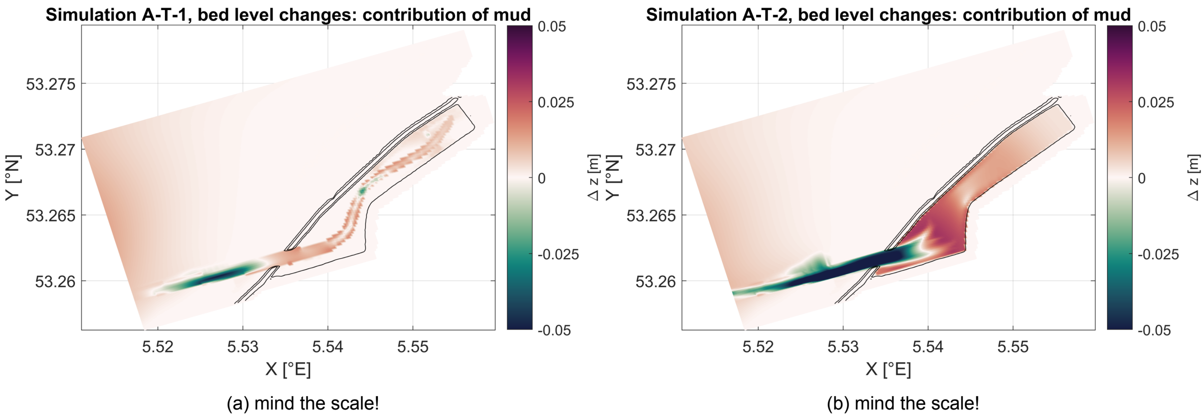
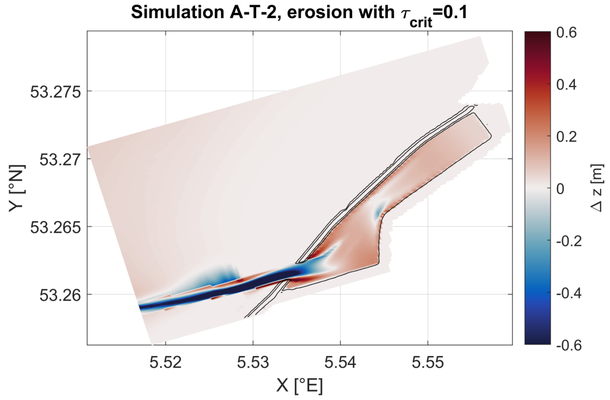
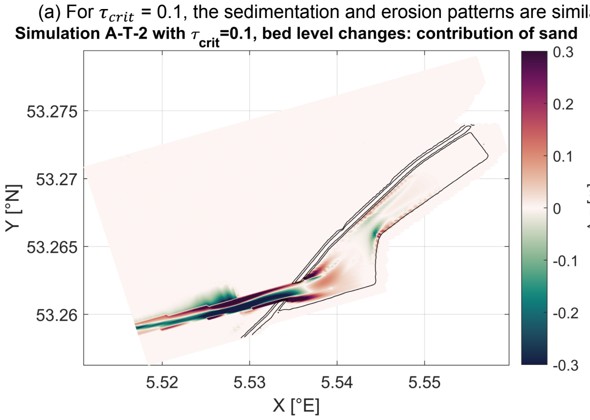


Figure 6.21: The contribution of sand and mud to the bed level changes for simulation A-T after 5.5 months, displayed on a smaller scale

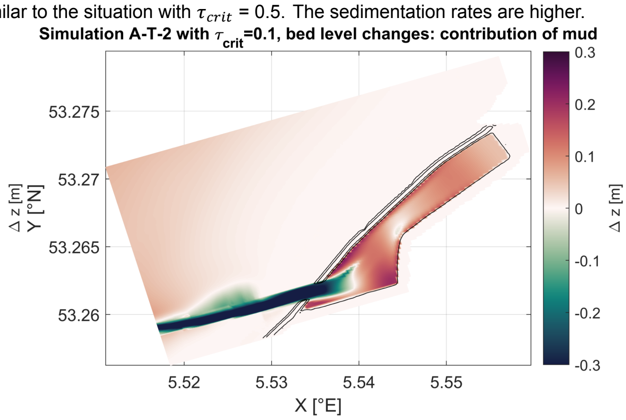
As discussed in Chapter 5, the critical shear stress (τ_{crit}) used for the mud fraction in all simulations is 0.5. In addition simulation A-T-2 is done for a lower critical shear stress, τ_{crit} = 0.1. Figure 6.22 shows the sedimentation erosion map of the slufter area for this simulation and the changes in volume fractions of sand and mud. These figures are compared with the results for simulation A-T-2 with τ_{crit} = 0.5 (sedimentation erosion map in Figure 6.17, change in volume fraction of sand in Figure 6.20c and change in volume fraction of mud in Figure 6.20d). Lower critical shear stresses lead to higher sedimentation rates in the slufter system. The pattern of the morphological developments is similar for both critical shear stresses. It is expected that the area will silt up in a shorter period of time when lower critical shear stresses are present. In addition, the results show that the higher mud transport rates cause a relative decrease in the sand transport rates.



(a) For τ_{crit} = 0.1, the sedimentation and erosion patterns are similar to the situation with τ_{crit} = 0.5. The sedimentation rates are higher.



(b)



(c)

Figure 6.22: Morphological development for simulation A-T-2 with a critical shear stress of 0.1 shows higher sedimentation rates compared to a higher critical shear stress.

In this chapter the morphological developments observed from the numerical model are discussed together with the ecological opportunities that are created with the applied slufter alternative. The next chapter discusses the limitations of this research, the relation with similar studies and a conceptual model of the general research findings.

6.5. Ecological development

Based on the literature study (Chapter 3) and the interviews with ecologists (Chapter 4), the slufter alternative is scored to the amount that it adds to the ecological value of the area.
The Natura 2000 goals are introduced in Chapter 2. The main goal is to soften the edges of the Wadden sea. This main goal is split up into core tasks that focus on creating a maximum dynamic coastal zone. Based on model observations, Table 6.4 shows the influence of the slufter alternative on the core tasks in four categories: no influence, negative influence, potential positive influence, positive influence. The first task that is positively influenced by the slufter alternative is the task for landscape coherence and internal completeness is to maintain or restore spatial cohesion in deep water, creeks, gullies, shallow water, flats, salt marshes or meadows, beaches and associated sedimentation- and erosion processes and to maintain areas of openness, rest and darkness. From the model results of the slufter area development of gullies and flats is observed due to sedimentation- and erosion processes. It is therefore concluded that the slufter alternative has positive influence on this core task. The second task is the task for diversity of tidal flats. Its task is to qualitatively improve the tidal flats and shoals for increased diversity. Application of the slufter design adds area to the intertidal zone and creates opportunity for new and diverse ecosystems to evolve. A quantitative improvement is observed from the model results in terms of the added intertidal area. As this area is currently not involved in the Wadden Sea, it is considered to be a qualitative improvement as well. The qualitative development of the added area is however dependent on the ecological development of the area. This is not observed in the model. The third task that is positively influenced is the task for diversity of salt marshes and meadows. This is to preserve and restore all zones of the salt marshes and saline grasslands. By depoldering the slufter area to the Wadden Sea, (former) salt marsh area is restored. In addition, the core tasks for fresh-salt water transitions, restoring and foraging area and breeding habitat can potentially be positively influenced. This depends on the ecological development of the area and the presence of supplementary aspects in the design such as the creation of high water refuge areas. It is concluded that applying the slufter alternative adds value to the Natura 2000 goals and thus contributes to creating a more dynamic coastal zone at the Wadden Sea.

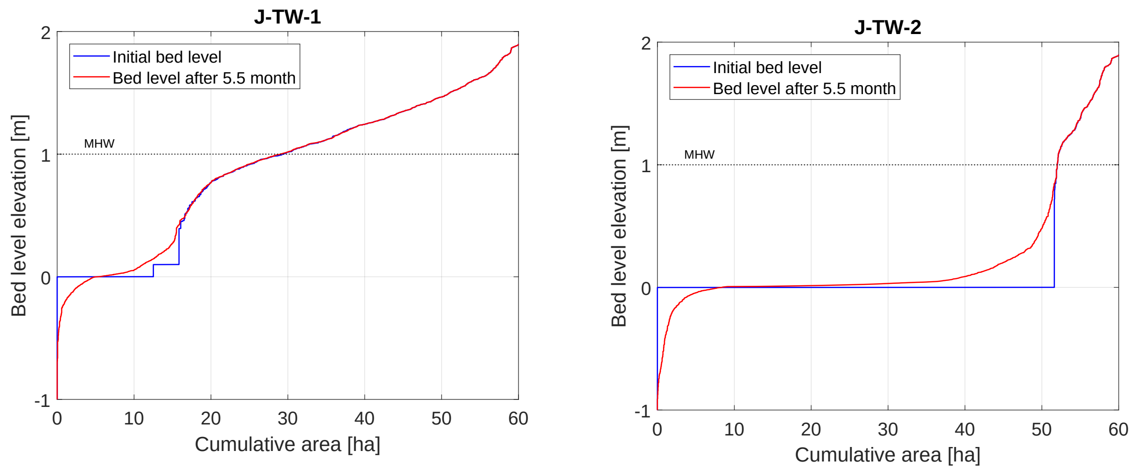
In Section 3.3 opportunities to contribute to these core tasks are discussed. The opportunities that the slufter intervention can possibly add to are: create fresh-salt water transitions, create wet-dry transitions and dynamic systems, create brackish zones, increase the area of pioneer zone, create future proof biodiversity on salt marshes. In addition, the slufter intervention can possibly add to the opportunities to create high-water refuge areas for shorebirds, create breeding areas for shorebirds, enhance foraging areas in brackish zones, as for these opportunities creating gullies and ”wisselpolders” are suggested examples of measures. However, due to the specific needs for bird species such as the slope and the (amount of) vegetation, these opportunities are not further elaborated within this research.

It can be discussed that the slufter intervention creates more gradual fresh-salt water transitions and wet-dry transitions and dynamic systems as due to the hypsometry the inundation frequency varies over the area. However, in order to create gradual fresh-salt water transitions to a larger extent, (connection with) a fresh water storage/source is required. This can for example be obtained with catchment areas for fresh water or with the application of a pumping station. The area of pioneer zone and lower marsh (area with bed level elevation between mean low water level (MLW) and MHW) is increased by the application of the slufter alternative. This is seen from the hypsometric curves shown in Figure 6.23. It shows the hypsometric curves for the simulations of January. Directly after the application of the slufter alternative, an area of 60 ha is added to the intertidal area of the Wadden Sea. Depending on the applied geometry this results in an added area of 30 to 50 ha between MLW and MHW (pioneer zone and lower marsh) and an area of 10 to 30 ha above MHW (middle and upper marsh).

Table 6.4: The influence of the slufter alternative on the core tasks of the Natura 2000 Wadden Sea region that are introduced in Chapter 3.

Core task	Negative influence	No influence	Potential positive influence	Positive influence	Additional note
Landscape coherence and internal completeness (North Sea, Wadden Sea and Delta)				X	
Flooded shoals & biogenic structures		X			
Fresh-salt water transitions (Wadden Sea area)			X		Requires (connection with) fresh water storage(/source)
Hinterland twaint shad (fint)		X			
Diversity of tidal flats			X	X	Quantitative improvement, dependent on the ecological development also qualitative improvement
Resting and foraging area			X		Dependent on the ecological development of the area
Breeding habitat			X		Dependent on the ecological development of the area
Diversity of salt marshes and meadows			X	X	Quantitative improvement, dependent on the ecological development also qualitative improvement

The initial hypsometry of both situations (with and without gully) shows abrupt changes in bed level elevation due to the excavation of the area. The resulting hypsometry after the simulation period of 5.5 months shows a more gradual hypsometry. It is expected that after a longer period of time the hypsometry will become more gradual due to the sediment trapping of the area. For the core tasks of fresh-salt water transitions, diversity of tidal flats and diversity of salt marshes and meadows, it is of importance that the bed level elevation inside the slufter area is such that the area gets inundated regularly.



(a) The hypsometric curve of simulation J-TW-1 (with gully) shows an increase of the intertidal area of 30 (between MLW and MHW) to 60 ha compared to the reference hypsometry due to implementation of the intervention. During the simulation time the hypsometry only shows minor changes. A clear development is seen around the 0m level. After the simulation period the gradient of the hypsometry is smoothened, due to erosion and sedimentation of the gully area that is initially excavated at 0m NAP.

(b) The hypsometric curve of simulation J-TW-2 (without gully) shows an increase of the intertidal area of 50 ha compared to the reference hypsometry due to implementation of the intervention. During the simulation time the hypsometry only shows minor changes. A clear development is seen around the 0m level. After the simulation period the gradient of the hypsometry is smoothened, due to erosion and sedimentation of the gully area that is initially excavated at 0m NAP.

Figure 6.23: Hypsometric curves of the simulations with wind and without waves in January (J-TW), compared to the reference hypsometry

7 Discussion

7.1. Model results

Geometrical influences

The results of the simulations with gully show significant lower total transport rates than the simulations without gully. A part of this difference is explained by the size of the tidal prism of the area and a part is explained by the differences in suspended sediment concentrations. Both geometries have the same access channel (same width and same bed level) that leads to the entrance of the slufter area. A larger tidal prism of the slufter area leads to larger amounts of water that pass through the access channel. This leads to higher depth-averaged velocities and thus higher sediment concentrations. The large difference (factor 10) in sediment concentrations for the situation with versus without gully, is probably caused by the fact that only 5.5 months are simulated. The slufter area and the access channel are working towards an equilibrium condition that is not reached in 5.5 months. The morphological development of the simulations without gully shows the growth of gullies in the entrance. In the simulations with gully, an initial flow pattern is already shaped and shows minor developments over the simulation period.

Comparison with similar cases

In (Siemes et al., 2020) the morphological development of salt marshes under artificial structures is modelled. This research proves the effectiveness of various configurations of artificial structures on sediment trapping.

For the depoldering of an area, several projects are known. One of them is the Noarderleech project, located in the middle part of the Koehool-Lauwersmeer dike section (Esselink et al., 2015). This experimental research has already proven the positive effect of such a project on the ecological value of the area. Another depoldering project is the Hedwigepolder project in the southwest of the Netherlands. This project shows some hopeful results for both ecological value and flood safety (Maximova and Vanlede, 2014; Elgün et al., 2019). The sediment import ranges of these projects should be compared.

7.2. Model limitations

Grid and bathymetry

A 16.67m grid is used for both the flow and the wave module. The bathymetry is obtained by interpolating and extending the bathymetry of the bigger RWS model (200m grid, bathymetry obtained from Vaklodingen data, 2009). The bathymetry data for the extended part is obtained from AHN data for the year 2015. Interpolating and smoothening of the bathymetry leads to inaccuracies. It is expected that the inaccuracies of the bathymetry do not influence trends in the development of the project area. Therefore the bathymetry is considered to be reasonable for this study.

The width of the entrance of the slufter area is about 70 m, as is the width of the access channel and the gully. The total slufter area is 60 ha. For the applied grid size of 16.67m, this corresponds to 4 to 5 grid cells over the width of the gully, which is reasonable for the application of the model (Deltares, 2018a; Siemes et al., 2020).

Erodibility of mud

The critical shear stress of mud varies both in time and space depending on e.g. the particle size, the consolidation level of the sediment, the type of clay, the amount of organic matter, the dry density. Lower critical shear stresses make the sediment easier erodible and thus cause more rapid morphological evolution. It is expected that the actual value of the critical shear stress varies between 0.05 and 1. However, in the used Delft3D model a constant value for the critical shear stress for mud of 0.5 N/m2 is applied. This is a typical bed shear stress for surface erosion of consolidated mud-sand mixtures. One simulation is done with a critical shear stress of 0.1 N/m2, showing that the model results are sensitive for the critical shear stress. It strongly influences the composition (sand mud ratio) and the quantity of the erosion and sedimentation in the project area. It does not influence the erosion and sedimentation patterns. It is therefore assumed that a constant critical bed shear stress of 0.5 N/m2 is applicable and gives a valuable indication of the expected morphological development of the area.

Sea level rise

For the simulation with SLR (A-TS), the initial bathymetry is used. In reality, when an actual SLR of +1m is present, the bathymetry has already evolved. This evolution is not taken into account within this research. Only the change in water level is taken into account. No morphological development of the slufter area or the surrounding Wadden Sea is taken into account. With this simplification, the effect of SLR is extracted to check if the slufter system drowns or strengthens under the influence of SLR. Taking morphological evolution (under the influence of SLR) into account will change the behaviour of the slufter system. Aside from the increasing water levels, climate change will increase the storminess of the area. These (and other climate change-related) effects are not taken into account within this research. It is assumed that executing the SLR simulation with the initial bathymetry gives a first estimate of the influence of SLR on the behaviour of the initial slufter system.

Water levels in drying areas

In the entrance of the slufter area and the slufter area itself, the water level never reaches zero during the whole simulation period, inducing that the flats are never fully dry. This is seen as a modelling artefact. Drying and flooding of intertidal areas causes disturbances in Delft3D (Deltares, 2018a). Another aspect that is noticed is the increase of the tidal asymmetry when approaching the slufter area from offshore. This can be a result of the decreasing depth towards the slufter area. The bottom friction decreases the low water propagation speed of the tide more strongly than the high water propagation speed, inducing an increase of the tide (Bonneton et al., 2012; Nidzieko and Ralston, 2012). Figure B.1b shows the water levels at different locations in the model grid (Figure B.1a), confirming these observations.

7.3. Conceptual model of research findings

Figure 7.1 shows a conceptual model of the main research findings. The figure consists of multiple sub-figures (indicated in the figure itself). Figure A and B show an impression of the two geometrical variations (with and without gully) of the design alternative that is studied together with the geometry specific findings. Figure C shows the morphological development of the area together with location specific findings. Figure D, E and F show the general observations that apply to the whole slufter area. Figure F shows the ecological opportunities of the design alternative.

For the simulations with gully, the gully (bed-level at 0m NAP) is fully inundated during a mean high water tide, whereas only a small part (the lowest part) of the flats is inundated. The higher flats do not get inundated regularly. For the simulations without gully, the whole slufter area (bed-level at 0m NAP) gets inundated with mean high water tide. The first general observation (Figure D) is that the area is flood-dominated. The flood velocities are way higher than the ebb velocities. Due to the high flood velocities, the suspended sediment concentrations during flood are way higher than during flood. Therefore higher sediment transport rates are present during flood than ebb, resulting in a net import of sediment. The amount of sediment import depends on several parameters (Figure F). To obtain the parameters on which the sediment import depends, the cumulative sediment transport rates are observed over the whole simulation period and compared for all simulations. In these total transport rates three trends are observed; simulations without gully import way more sediment than simulations with gully, the presence of SLR increases the amount of sediment import and a larger tidal prism increases the sediment import.

The first trend that is observed is the difference in sediment transport between the situations with and without gully. Therefore, the bed shear stresses (sub-figure A.1 and A.2) for both situations are compared. It is observed that the bed shear stresses for the situation without gully are way higher than for the situation with gully. Both situations have the same access channel (same width and bed level) towards the slufter area. For the situation without gully however, larger volumes of water are transported in and out of the slufter area. This leads to higher depth averaged velocities and thus higher bed shear stresses that cause higher suspended sediment concentrations. The difference in suspended sediment concentration for the situation with and without gully is a factor 10 ($c_{wogully} = c_{gully}$).

The second trend is the difference in tidal prism. Looking at all simulations with and all simulations without gully separately, a trend between the tidal prism and the cumulative transport is observed. Although, for some simulations with the same tidal prism (J-T, J-TW and J-TWW) show different amounts of cumulative transport. The explanation for this exception is found in the suspended sediment concentrations for these simulations. Simulation J-T (January, tide only) shows the lowest suspended sediment concentration averaged over the total simulation time and shows the lowest cumulative transport. Simulation J-TW (January, tide and wind) shows a higher suspended sediment concentration and cumulative transport. Simulation J-WW (January, tide, wind and waves) shows the highest suspended sediment concentration and cumulative transport.

Observing the resulting cumulative transport and tidal prism of all simulations, the coherence between these two parameters is seen. In case the simulations with SLR are left out, the coherence increases (Appendix Figure B.2. This is because both adjustments (SLR and different geometry) increase the tidal prism. However, by changing the geometry from a situation with to a situation without gully, the depth-averaged velocities increase to a higher extent (factor 2) compared to the situation with SLR (factor 1.2). SLR causes a small increase in the depth-averaged velocities and a small increase in the time over which small ebb velocities are present. Due to the higher dav's, higher bed shear stresses are present and higher transport rates are observed into the slufter. Due to the increase in time of small ebb velocities, there is more time for the sediment to settle inside the slufter area. These two processes combined cause an increase in the net import of sediment. Now that it is known what parameters influence the amount of sediment import, the relative amount of sediment import is discussed (Figure E).

Assuming that the sediment is equally distributed over the area, the annual bed level increase is calculated and compared with the expected SLR (according to the Representative Concentration Pathway

(RCP) climate scenarios). A yearly average bed-level increase over the whole slufter area of 2*10-3 m (A-T-1, minimum import) to 0.11 m (A-TS-2, maximum import) is expected, whereas the RCP scenarios expect a mean SLR between 5*10-3 m and 9.3*10-3 m per year. If the sediment is only assumed to be distributed over the flooded area (only 15 ha for the situation with gully), a minimal yearly bed level increase of the flooded area of 7.5*10-3 m is expected. These observations imply the feasibility for the system to grow with SLR.

Figure C shows the morphological development of the area for a simulation without gully. A system with tidal flats and gullies arises at the entrance part of the area. In the back of the area a general trapping of sediment is observed. Both sediment fraction (sand and mud) have specific contributions to these developments. The sand fraction has the largest influence in the development of flats and gullies in the entrance part. The mud fraction has the largest influence in the sediment trapping in the back part. For the situation with gully erosion patterns are observed within the gully itself and sedimentation patterns are observed at the edges of the gully.

The ecological development of the area (Figure G) is observed to contribute to several core tasks that are part of the Natura 2000 goals for the Wadden Sea to soften the edges of the Wadden Sea. The slufter alternative depolders a diked area that historically was part of the Wadden Sea area. An opportunity is created for the area to develop diverse salt marsh zones and tidal flats that add to the dynamic transitions of the edges of the Wadden Sea.

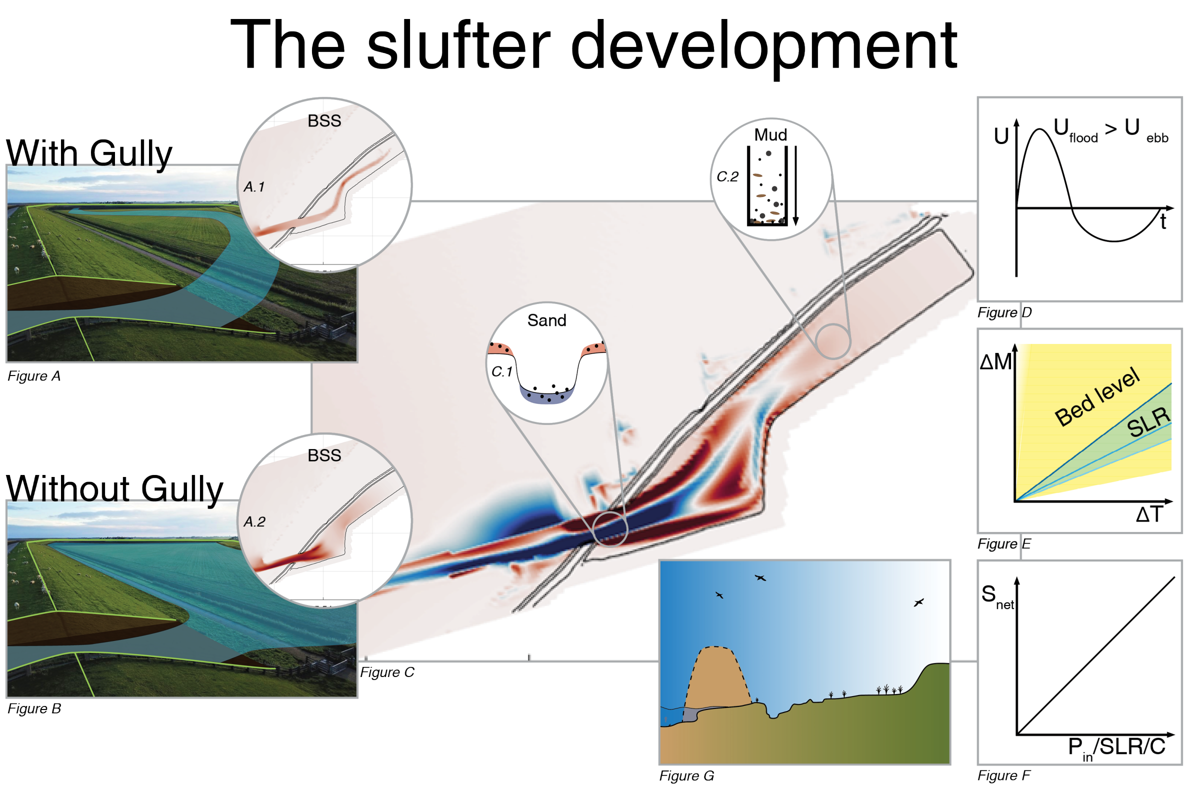


Figure 7.1: A conceptual model of the main research findings

8

Conclusions and recommendations

8.1. Conclusions

The Koehool-Lauwersmeer dike section is a 47km long dike stretch that is part of the Wadden Sea dike at Friesland. With the newest assessment round it did not meet the requirements as it was rejected to multiple failure mechanisms. The main objective of this study was to find a dike strengthening design for the dike area of Koehool-Lauwesmeer, that improves both the flood safety and the ecological value of the area. Therefore, the secondary objective was to select a pilot location and design alternative that are convenient to investigate such a design. The two research questions following from these objectives, Q1 and Q2, are answered by answering the sub-questions.

Q1: What is the most suitable pilot location and design alternative?
To answer this research question, sub-questions Q1.1 and Q1.2 have been introduced (Chapter 1). The answers and conclusions to the sub-questions are presented below.

- **Q1.1** *What are the requirements for a pilot location and design alternative to investigate a flood defense system that improves the flood safety and the ecological value?*

  The presence of a foreshore reduces the wave impact on the dike. Therefore, trapping sediment in front of a dike can add to the flood safety. If a dike is rejected to foreshore influenced failure mechanisms, this indicates that the flood safety can be improved by strengthening the foreshore. Therefore, the pilot location has to be a suitable location for a foreshore to evolve. The Wadden Sea area is characterized by a sediment-rich environment and a flood dominant tide, consequently a net import of sediment is observed. In combination with low hydrodynamic forcing it creates the opportunity to trap sediment.

  In addition, a foreshore (both vegetated and unvegetated) can add to the ecological value. The different intertidal zones all have their own specific values of which the mid marsh (between mean high water level and mean high water spring tide level) is considered to be the most valuable. Natura2000 has set a general goal for the ecological development of the Waden Sea to create a more dynamic coastal zone. The design alternative should add to the core tasks set for this goal. These are amongst others, fresh-salt water transitions, diversity of tidal flats, breeding habitat and diversity of salt marshes and meadows.

- **Q1.2** *What is the most suitable pilot location and design alternative to be explored at the Koehool Lauwersmeer dike section?*

  The requirements metioned for Q1.1 are found at the dike stretch from Koehool to Westhoek. The presence of a flood dominant tide, high sediment concentrations and low hydrodynamic forcing, creates the opportunity to import sediment at this location. The presence of a former dike at this location, gives the unique opportunity to explore a pilot study for depoldering a part of the inland area. The considered design alternative is a slufter area. An artificial dike breach combined with the excavation of (a part of) the area between the two dikes, adds intertidal area to the Wadden Sea that can contribute to the flood safety and the ecological value of the area.

Q2: What is the contribution of the design alternative to sediment trapping and the ecological value of the area?
To answer this research question, sub-questions Q2.1 to Q2.5 have been introduced (Chapter 1). The slufter design alternative is studied with a hydrodynamic and morphological model and the ecological opportunities are explored. The answers and conclusions to the sub-questions are presented below.

- **Q2.1** *How do the driving forces influence the sediment trapping of the area?*

  The net sediment import mainly depends on the suspended sediment concentration, the critical shear stress and the tidal prism of the slufter area. The suspended sediment concentration depends on the available amount of sediment and the bed shear stress. Higher bed shear stresses lead to higher suspended sediment concentrations. In this study, the initial available amount of sediment is set equal for all simulations. All simulations show higher suspended sediment concentrations during flood than during ebb flow. This leads to a net import of sediment into the slufter area.

  The critical shear stress strongly influences the amount of mud transport. A critical shear stress (τ_{crit}) of 0.1 N/m^2 compared to 0.5 N/m^2 results in five times higher sedimentation rates in the slufter area. The morphological patterns are similar. The actual critical shear stress will vary both in space and time. The actual sedimentation rates are therefore expected to be somewhere in between.

- **Q2.2** *How does the initial geometry influence the sediment trapping of the area?*

  Two different initial geometries have been studied. In the first geometry, a gully towards and in the slufter area is excavated at mean sea level (MSL) (, situation with gully). In the second geometry, the gully towards the slufter area and the whole slufter area itself are excavated at MSL (situation without gully, deep). The simulations show that for the situation without gully, depth-averaged velocities (factor 2) and suspended sediment transport are higher (factor 10) than for the situation without gully. A geometry that causes an increase in the flow velocity shows higher suspended sediment concentrations that lead to higher amounts of sediment import. Comparing the tidal prism of the slufter area to the total amount of sediment transport for all simulations shows that a larger tidal prism leads to higher sediment transport rates.

- **Q2.3** *What is the expected effect of SLR on the sediment trapping?*

  Under the influence of a sea level rise (SLR) of +1m, the sediment transport increases with a factor of 2 to 3, depending on the initial geometry. SLR enhances the sediment trapping of the area. Depending on the applied geometry the slufter area can potentially keep up with SLR (according to the RCP climate scenarios). The average growth rate of the bed level in the slufter area is between 0.22 (minimum sediment import, maximum expected SLR) and 21.12 (maximum sediment import, minimum expected SLR) times SLR. The slufter area tends to import more sediment with the presence of +1m SLR due to longer inundation periods and an increase in the depth-averaged velocities.

- **Q2.4** *What is the initial morphological evolution of the project area after intervention?*

  After the morphological simulation period of 5.5 months, the situation with gully shows that the centre of the gully is eroded. Sedimentation is present at the banks of the gully. For the simulation without gully, natural gullies evolve in the entrance area of the slufter. At places where gullies evolve, sand is eroded. In the back part of the slufter area, low hydrodynamic forcing is present, allowing mud to settle. It is seen that mud is deposited in the back part of the slufter area for both the simulations with and without gully. The total amount of sediment import in the area are compared with the expected SLR. It is concluded that for the simulations without gully, enough sediment is imported to make the bed level of the slufter area increase at a higher rate than SLR when assuming an equal distribution of the sediment over the whole slufter area.

- **Q2.5** *What does the design alternative add to the ecological value of the area?*

  By applying the slufter intervention, an area of 60 ha is added to the intertidal area of the Wadden Sea. Depending on the applied geometry this results in an added area of 30 to 50 ha between MLW and MHW (lower marsh) and an area of 10 to 30 ha above MHW (middle and upper marsh). Applying the slufter alternative adds value to the core tasks that are part of the Natura 2000 goal to soften the edges of the Wadden Sea. The slufter alternative depolders a diked area that historically was part of the Wadden Sea area. The slufter area has a positive influence on the development of diverse salt marsh zones and tidal flats that add to the dynamic transitions of the edges of the Wadden Sea. In addition, it has the potential to add to other core tasks. This depends on the ecological development of the area and the presence of supplementary aspects in the design such as the creation of high water refuge areas.

8.2. Recommendations

A feasibility study is to be done before the project can be executed. This (among other things) consists of a flood safety study, an estimation of the costs and an exploration of maintenance works. Little is known about the maintenance that is needed for similar projects. However, the requirement of maintenance are of great importance in the succeeding of a project. In addition, the required dike height of the dike on the landward side of the slufter area has to be calculated. In case that the required height is lower than the required dike height for the current dike (at the seaward side of the slufter area), this can save in costs and material for dike strengthening. In addition, the impact of the intended breach on the current dike is to be checked.

The location from Koehool to Westhoek is a suitable location to test a slufter alternative in the real world. The presence of the inland dike that encloses the area provides a unique opportunity to execute a pilot project. The dike that is already present and the absence of buildings possibly reduce the effort and costs needed to execute the project compared to other locations.

Longer morphological simulations are to be done to find the effects of the slufter alternative in the long term. In the executed simulations of 5.5 months, only the initial response is observed. Extrapolating the results gives large inaccuracies. To find more accurate predictions of morphological developments over a longer period of time, longer simulation periods are needed.

The boundary concentration values for mud are set to 0.050 kg/m3. This is not the exact concentration but gives an indication. Sensitivity analyses show that this does not influence the situation in the project area significantly. It is however recommended to obtain site-specific boundary concentration values. Executing simulations over a whole year combined with site-specific information leads to a more accurate model.

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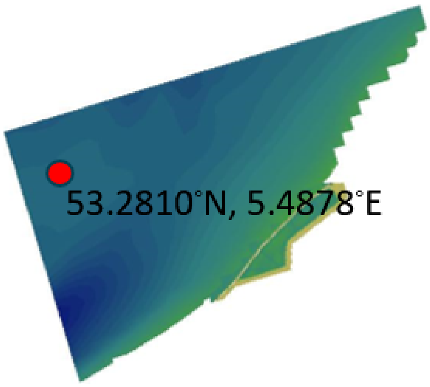
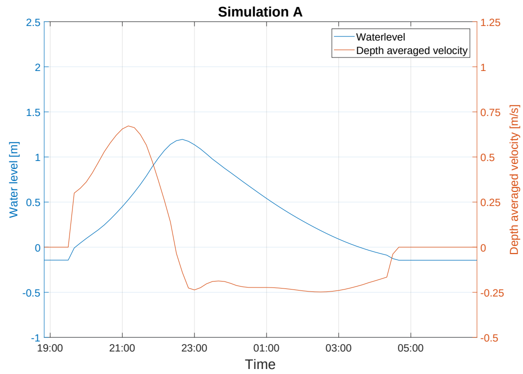
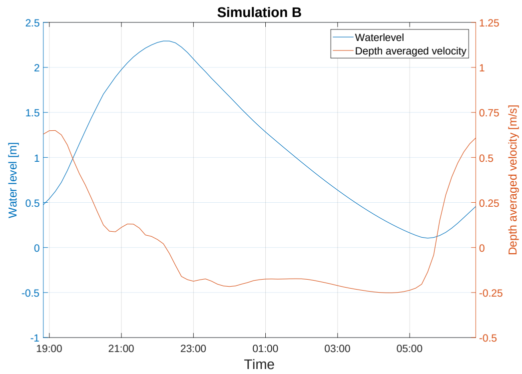
A
Model results



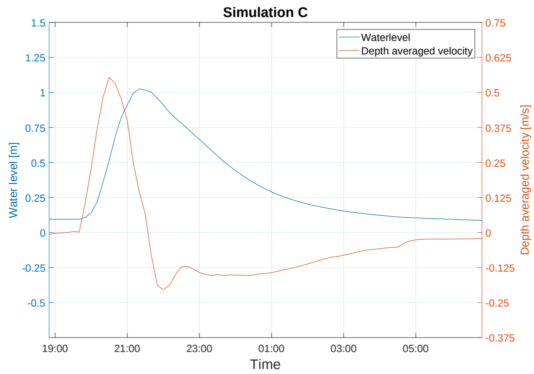
(a) The location offshore from Koehool at which the tide is observed in the model



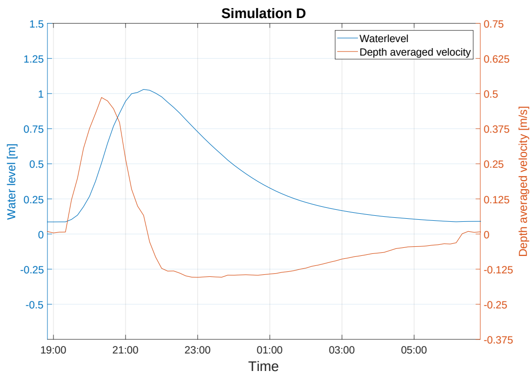
(b) Simulation A



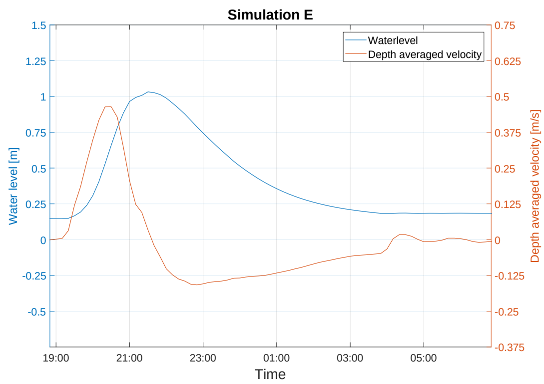
(c) Simulation B



(d) Simulation C



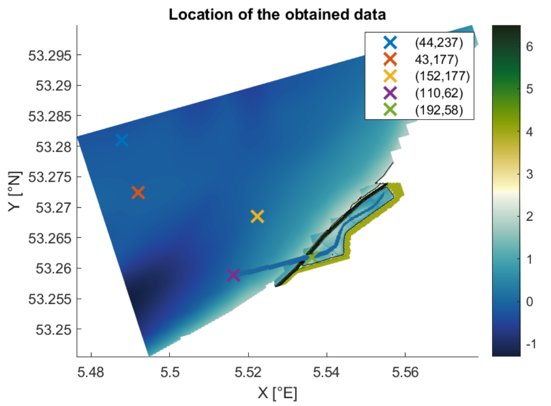
(e) Simulation D



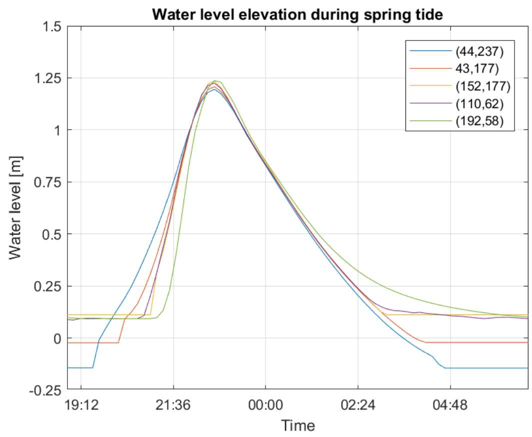
(f) Simulation E

Figure A.1: The water level elevation and depth averaged velocity during one spring tide and the offshore location at which the data is obtained. The depth averaged velocity is defined positive in the flood direction and negative in the ebb direction.

B Discussion



(a) The locations at which the water level data is obtained



(b) The water levels show an increase of the asymmetry of the tide when approaching the slufter area from offshore.

Figure B.1: The water levels at several locations in the modelled area.

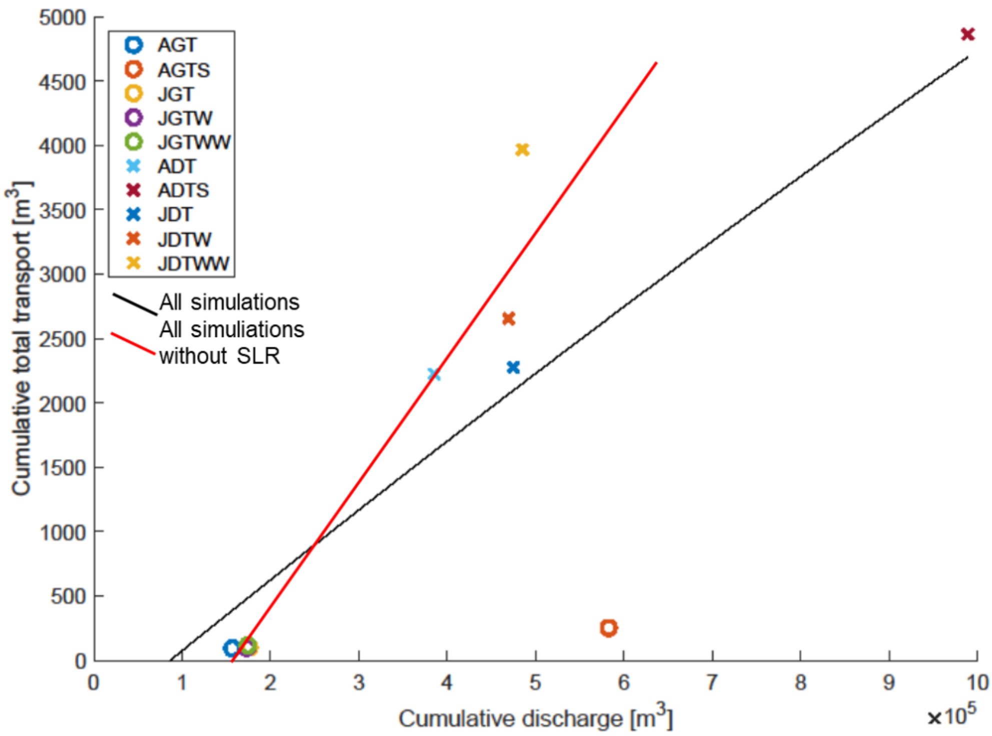


Figure B.2: The amount of cumulative sediment import and the tidal prism plotted against each other for all simulations with the trend lines for all simulations and all simulations without SLR indicated.