Evaluation of the Morphological and Ecological Response to a Conceptual Artificial Bypass System at IJmuiden Port

by

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C. Gielen
Delft, August 2023

Abstract

This thesis explores the potential of a fixed artificial bypass system for a sustainable and eco-friendly approach to coastal management in IJmuiden. The presence of the IJmuiden Port disrupts the natural processes, causing significant morphological changes to the coastal area. Current management practices require frequent dredging and nourishment to mitigate the erosion of the downdrift coast and maintain the depth necessary for navigation in the channel and port. These activities result in significant emissions and adverse ecological impacts. Particularly affecting benthic life, organisms living in or on the seabed.

Implementing a fixed artificial bypass system, already proven successful in similar projects globally, emerges as a potential solution to reduce dredging and nourishment activities. This system aims to restore the natural sediment transport by pumping sediment from the updrift to the downdrift side. In addition, its more continuous discharge of sediment is anticipated to be less disruptive for benthic life compared to traditional nourishment methods.

The best-case scenario calculation performed in this thesis presents that an artificial bypass system at IJmuiden could potentially reduce dredging activity by 3.5% and nourishment activity by 37%. To assess whether these reductions can be achieved, this thesis introduces a newly developed framework for assessing the effectiveness of sediment bypass concepts based on four performance indicators: (1) Dredging Activity of Channel and Port, (2) Sediment Demand of Downdrift Coast, (3) Impact on Benthic Community and (4) Feasibility.

This method includes simulating the response of the coastal system after implementing varying bypass concepts using a Delft3D model. The Delft3D model's applicability and predictive skill are assessed via hydrodynamic and morphodynamic validation. Concluding that the model can reproduce the general trends but introduces numerical errors in the exact quantification of the morphological development. Despite this limitation, the output from these Delft3D simulations was used to evaluate the response of different artificial bypass concepts based on the four performance indicators. The first two indicators are based on the simulated sediment transport values and assessments of the development of the bed. The evaluation of the third indicator is based on a calculation performed using the developed benthic evaluation tool, named the 'Benthimeter'. This newly developed tool provides a method that intends to visualize and quantify the impact on the benthic community induced by nourishment activity. Although the Benthimeter requires further calibration and validation, it marks a good first step towards integrating ecology into coastal management.

The results of this thesis demonstrate that the coastal system of IJmuiden allows for sediment withdrawal, where allready 10% of the required annual sediment trap was observed within one simulated month. Also northward sediment dispersal towards the downdrift coast was observed at simulations, indicating that such a system could reduce the sediment demand. These findings provide confidence that the principles of bypassing sediment around the port of IJmuiden hold. Consequently, it is anticipated that an artificial bypass system would, to some amount, reduce the need for dredging and nourishment activity. Also, the calculated impact on the benthic community confirms the hypothesis that a more continuous nourishment approach reduces the impact on the benthos. While the findings of this study provide an initial indication of the potential effectiveness of an artificial bypass system at IJmuiden, they do not provide long-term effect estimates. Further research is suggested to examine the primary drivers of dredging and nourishment activity, along with efforts to simulate the equilibrium state to evaluate the long-term effects.

The most important contribution of this thesis is the introduction of innovative tools, guidelines, and effective methods. This framework can be used in future research to improve our knowledge of sustainability and ecology in coastal practices.

Contents

1 Introduction

In response to the societal demand for sustainability, an ambitious ambition has been set to manage the Dutch coast with a net-zero emissions and substantially reduced ecological impact by 2030. This objective necessitates an innovative reevaluation of current coastal management practices.

The Dutch coastline is under continuous pressure from a rising sea-level, resulting in a structural eroding coastline (Herman et al., 2021). The situation is further complicated by human-made structures, such as ports, that interrupt natural sediment patterns. Frequent dredging and nourishing is needed to maintain the coastline. Current practices involve the addition of approximately 12 million m^3 of sand to the coastal system annually (Röbke et al., 2021a). With the anticipated rise in sea levels, coupled with land subsidence and urban development, the frequency of such dredging and nourishment activities is expected to increase further.

These activities are not without consequence. Besides the significant greenhouse gas emissions from the operations, typically conducted by vessels, the ecological impacts are substantial. Particularly affected are the benthic organisms, organisms living in and on the bottom of the sea. These organisms can get trapped under sediment layers during nourishment or communities be disrupted during dredging. Currently, predicting the potential impact on benthic communities remains challenging and is often overlooked during the design phases. Consequently, there is a pressing need for innovative impact estimation approaches, given the lack of standardized methods.

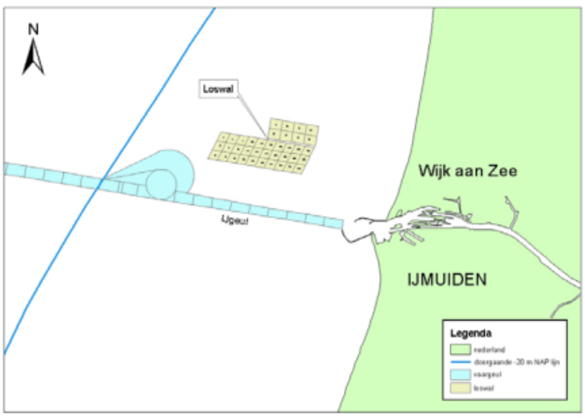


Figure 1.1: Overview of IJmuiden area with access channel (IJguel) and the location where the dredged sediment from channel and port is dumped (Loswal)

The coastal area near IJmuiden exemplifies the challenges faced along the Dutch coast. Here, significant erosion at the northern coast of IJmuiden necessitates frequent nourishment projects. In addition to the general drivers such as sea level rise, this erosion is amplified by the presence of the port. Notably, the port's breakwaters disrupt the alongshore sediment transport, leading to sediment accumulation on the southern side and a sediment deficit at the northern side.

Moreover, to ensure navigability, the channel and the port undergo frequent dredging (Reussink, Jeuken, and Tánczos, 2002). The dredged sediment is deposited at a designated unloading area north of the IJgeul, yet it is debatable whether this sand eventually contributes to coastal stability or is permanently lost from the system (See Figure 1.1).

Given this scenario, the IJmuiden coastal area emerges as a location with potential area for improvement in terms of reducing emissions and ecological disruption. Therefore, there is a compelling need to explore potential solutions to reduce the impact of the presence of the port.

A potential solution to reduce the impact the port is the implementation of an artificial bypass system. Used successfully in various projects globally, this system aims to restore the net natural alongshore sediment transport rates by transferring sediment from the updrift to the downdrift side (See example Tweed River, Figure 1.2). Such a process could reduce channel and port infilling while supplying sediment to the eroding coast. Notably, the more continuous sediment disposal approach of an artificial bypass system could potentially be less disruptive to benthic life than traditional foreshore nourishment. Moreover, when powered with green energy sources, this system could operate with net-zero emissions, substantially contributing to sustainable and eco-friendly coastal management at IJmuiden.

However, such systems could reduce the erosion caused by the alongshore sediment disruption of the breakwaters. Therefore, erosion can only be party mitigated by this solution since the Dutch coast faces a general eroding trend.

Besides, fixed artificial sediment bypass systems, have not yet been implemented along the Dutch coast. As such, the design guidelines are scarce, making it difficult to predict the potential effects on dredge and nourishment reduction. Additionally, the absence of tools or methods to assess the ecological impact of dredging or nourishments poses challenges in determining whether such a system could contribute to more eco-friendly coastal operations at IJmuiden.

Figure 1.2: Fixed sediment-bypassing jetty at Tweed River Entrance Project (Australia) (Government, 2022)

The focus of this thesis is to develop a method for evaluating the potential of an artificial bypass system at IJmuiden in reducing dredging and nourishment activity. This thesis will attempt to simulate the morphological changes compared to a base case (Do Nothing Scenario), by incorporating potential bypass concepts into a Delft3D model.

The Delft3D model in question is calibrated and validated by the Dutch Coastline Challenge (DCC) to simulate morphological development at the Dutch Coast (Deltares, 2022). However, adapting this model to assess the impacts of a fixed sediment bypass system at IJmuiden port is not without its challenges. The complexity, the long simulation times, and uncertain stability require innovative and creative problem-solving approaches.

In addition, a first step is made into the development of a benthic impact evaluation tool. This tool, named the 'Benthimeter', incorporates conceptual relations based on literature finding, to describe the interaction between morphological features and benthic diversity throughout time. The intention behind this tool is to provide a practical method to visualize and compare damage to benthic life for alternative nourishment strategies. Therefore, allowing to incorporate ecological considerations into the planning and decision-making process for coastal management strategies. Although the tool requires further calibration and is not yet validated, it marks a first step into modeling the very complex ecological interactions. In this thesis, the newly developed tool will be applied to evaluate the ecological impact.

1.1. Thesis Questions and Objectives

The primary goal of this research is to design a fixed sediment bypass system and evaluate its morphological and ecological impact.

To achieve this goal the following research questions are formulated:

Would the implementation of an artificial sediment bypass system be beneficial to the overall morphology and ecology?

Following subquestions:

i How might the impact of a fixed sediment bypass system effectively be evaluated?

   With particular focus on:

   a Dredging activity of the channel and port
   b Sediment demand of the adjacent coast
   c Impact on benthic community
   d Feasibility

ii What is the expected impact of implementing a fixed sediment bypass system at IJmuiden port?

   With particular focus on:

   (a) Dredging activity of the channel and port
   (b) Sediment demand of the adjacent coast
   (c) Impact on benthic community
   (d) Feasibility

By answering these questions, this study aims to contribute to our understanding of an artificial bypass system as a coastal management solutions. Particularly, in the context of maintaining navigability and reducing erosion, while minimizing environmental and ecological impacts.

1.2. Thesis Structure

The structure of this thesis is depicted in Figure 1.3. The study is organized as follows:

Chapter 2 provides an analysis of the existing system at IJmuiden, shedding light on the current state and challenges of coastal management in this area.

Chapter 3 delves further into a comprehensive study on the principles of bypass systems. This includes an examination of their global applications and a detailed discussion on the design of different bypass concepts. This chapter also presents the development of the design alternatives used in this study.

Chapter 4 outlines the construction of the model used in our study, the process of validation, and the simulation methodologies. The insights from Chapters 2 and 3 are integrated into the model for simulation.

Chapter 5 presents the development of the benthic impact evaluation tool. The chapter first presents the main literature finds followed by the incorporation of these findings into a evaluation tool.

Chapter 6 presents the formulation of performance indicators that will be used to assess the results of these simulations.

Chapter 7 Presents and evaluates the results of various concepts based on these performance indicators.

Chapter 8 concludes the study, drawing final conclusions based on our findings and discussions.

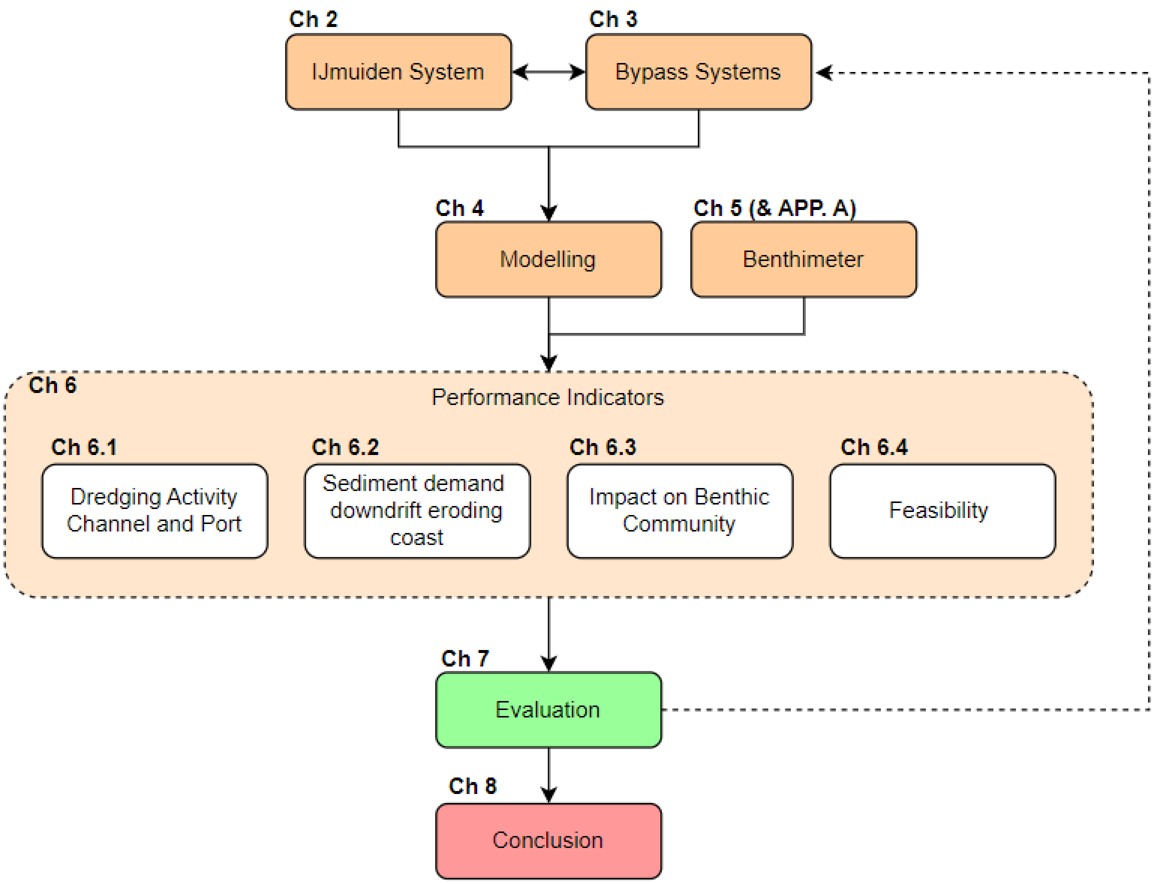


Figure 1.3: Thesis structure flowchart

In addition, it's important to note that this study led to the development of a novel ecological impact assessment tool, named the 'Benthimeter'. The design, calibration, and application of this tool are extensively described in a separate chapter, APPENDIX A. This is done since the detailed development process of the 'Benthimeter' is not directly necessary to understand the main findings and conclusions of this thesis. Appendix A can be read as an independent study.

In this study, reference are made to specific locations across the coastal profile. Different terms may be used in the literature to indicate these sections, which can lead to confusion. To ensure clarity, this report will adopt the terminology as depicted in Figure 1.4.

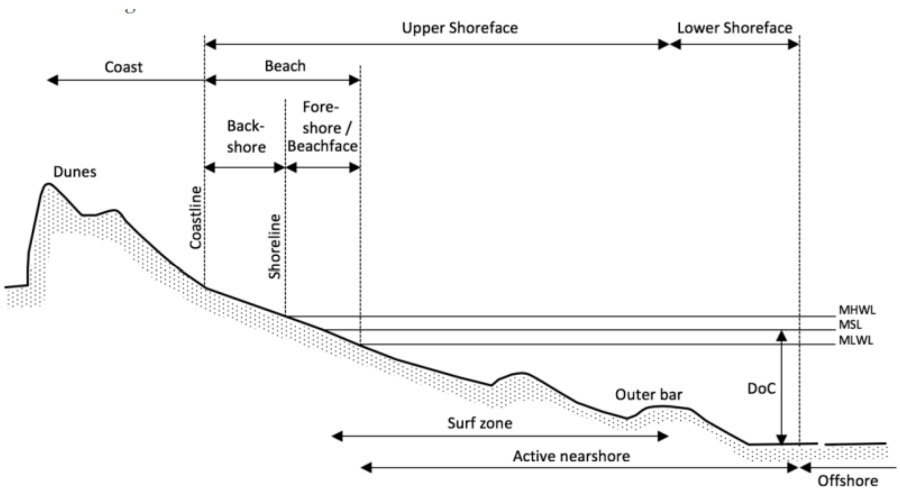


Figure 1.4: The coastal zone (Lambert, 2019)

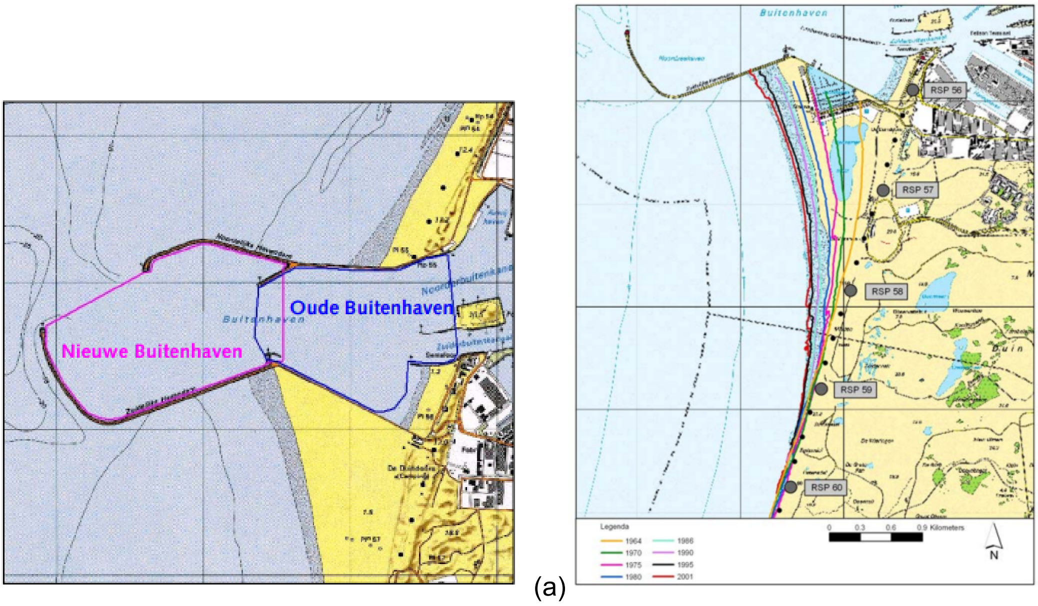
2

IJmuiden System Analysis

IJmuiden will be used as a case study to test the sediment bypass concept. This chapter will elaborate more on the background and process present at IJmuiden coastal area in order to provide appropriate background information for the design stage and modelling stage of the artificial fixed sediment bypass system.

2.1. Coastal context

The coastal region of IJmuiden, strongly influenced by the presetns of the port and breakwaters, presents a dynamic and complex environment.



(a) (a)

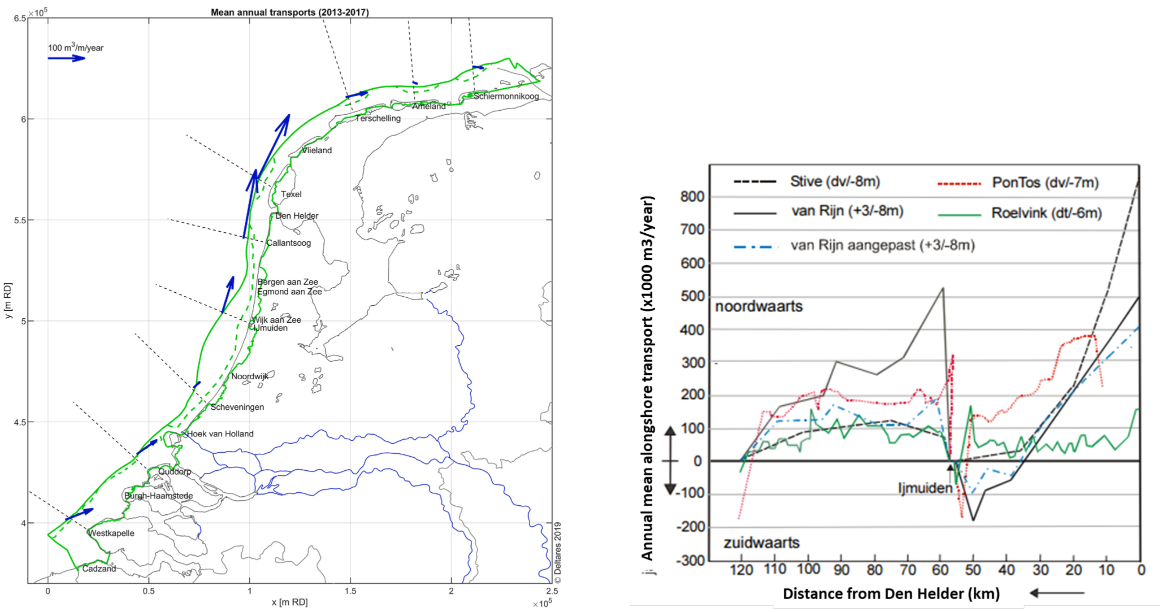
Figure 2.1: (a) Overview IJmuiden old port completed in 1876 and the extension of port in 1967 (Kruif and Keijer, 2003), and (b) overview of coastal area surrounding IJmuiden (Google Earth).

Completed in 1876, providing an accessible water route to Amsterdam. Originally, the southern and northern breakwaters stretched 1300 m and 1050 m respectively. However, after achieving a state of equilibrium, these were extended in 1967; the southern breakwater reaching 2800 m and the northern extending to 1850 m seawards (Kruif and Keijer, 2003). Figure 2.1 shows the initial harbor constructed in 1876, termed as the 'Oude Buitenhaven', alongside the subsequently extended breakwaters, known as the 'Nieuwe Buitenhaven'.

The consequence of these infrastructural developments has been the substantial alteration in sediment transport patterns, creating a complex situation at the Dutch coast where the general sediment transport from south to north is blocked by the port.

This caused serious significant accumulation of sediment at the southern and northern side of the breakwaters. At the southern side this accretion was so strong that the municipality decided to create a recreational area with a lake called Kennemermeer and a small seaport harbor.

The bypass system aims to restore natural alongshore sediment transport, therefore it crucial to determine the transport present. This is attempted by a number of studies and proven to be a difficult task (Rijn, 1997; Rest, 2004; Roelvink and Stive, 1991). The estimates in these studies vary significantly but a net northward transport is generally agreed upon, as presented in 2.2 (a). Figure 2.2 (b), derived from Rest (2004), summarises the sediment transport estimates of a number of well-known studies. The figure highlights the range of sediment transport estimates, from 80,000 to 500,000 $m^3/year$ arriving at the south of IJmuiden.



(a) (b)

Figure 2.2: Annual alongshore sediment transports at various locations on the Dutch coast, as reported by (a) Grasmeijer et al. (2022) and (b) Rest (2004), with quantities expressed in cubic meters per year ($m^3/year$).($m^3/year$)

However, this study assumes an design transport of 140,000 $m^3/year$, aligning with the findings of Luijendijk et al. (2011) and corroborated by Van Rijn (Luijendijk et al., 2011). The modelled sediment transport patterns near IJmuiden presented by Luijendijk et al. (2011) are depicted in Figure 2.3.

2.2. Environmental conditions

2.2.1. Wave and wind condition

The IJmuiden wave climate exhibits a prominent seasonal pattern, with notable differences in average wave height (H_m0) between winter (Nov-Jan) and summer (Apr-Aug) (Rest, 2004; Luijendijk et al., 2011). Winter months typically see an average H_m0 of 1.7 meters, while summer months display an average H_m0 of approximately 1 meter. Under calm conditions (H_m0 < 1.0m), waves predominantly originate from the NNW direction. In normal conditions (1.0m < H_m0 < 1.5m), waves primarily arrive from the SW and NW. High wave or storm conditions (1.5m < H_m0 < 4.5m) are characterized by waves

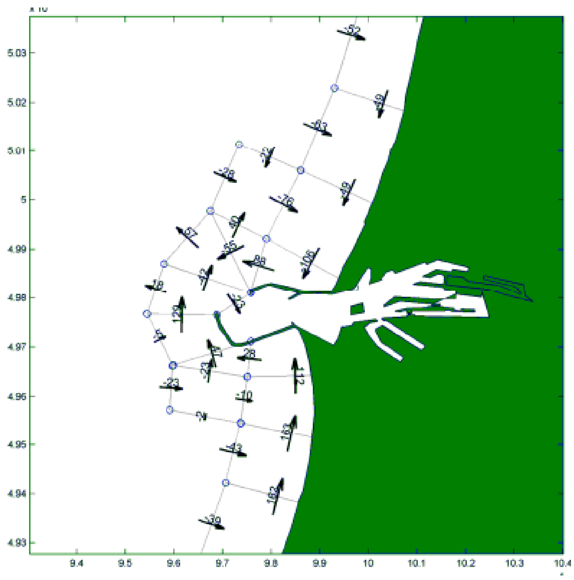


Figure 2.3: Annual transport patterns based on Delft3D modeling (in $10^3 m^3$) (Luijendijk et al., 2011)

from the ZW direction, with a smaller contribution from the NW. Extreme storm conditions ($H_{m}0$ > 4.5m) are dominated by waves from the NW direction. Rest (2004) presented the wave direction for different wave heights measured at IJmuiden (see Figure 2.4. The complete probability distribution of wave height, wave period, and direction can be found in Appendix B.1 and B.2.

2.2.2. Tide

The presence of harbor breakwaters introduces complexities to the tidal flow patterns in the area, leading to the formation of large eddies at the harbor entrance. Converging and diverging tidal currents occur around the breakwaters, resulting in turbulent mixing layers that extend downstream for approximately seven times the length of the port breakwaters (Luijendijk et al., 2011). This estimated length of the reattachment point may be overestimated due to the presence of a long shoal located just north of the northern breakwater (Luijendijk et al., 2011). According to Roelvink and Reniers (2011), the length of reattachment is within a few times the breakwater length.

The strong contracting tidal flow in front of the harbor entrance, combined with locally enhanced turbulence, causes sediment to be picked up, resulting in the development of a scour hole (Luijendijk et al., 2011).

Figure 2.6 provides a schematic representation of the flow convergence and divergence of tidal currents near IJmuiden harbor dams (Luijendijk et al., 2011).

The average tide at IJmuiden exhibits an asymmetric pattern, which is a result of the relative phase difference between the M2 and M4 components of the tide. As shown in Figure B.3, the flood tide occurs at a faster rate compared to the ebb tide. On average, the flow velocities during flood tide are greater than those during ebb tide. The maximum northward flow velocities reach 1.05 m/s during flood tide, while during ebb tide, they are around 0.75 m/s (Kruif and Keijer, 2003).

Figure B.4 presents the flow pattern described by Kruif and Keijer (2003). The presence of the eddy generated during flood in the harbor entrance is clearly visible. Also the difference in flow velocity can be observed.

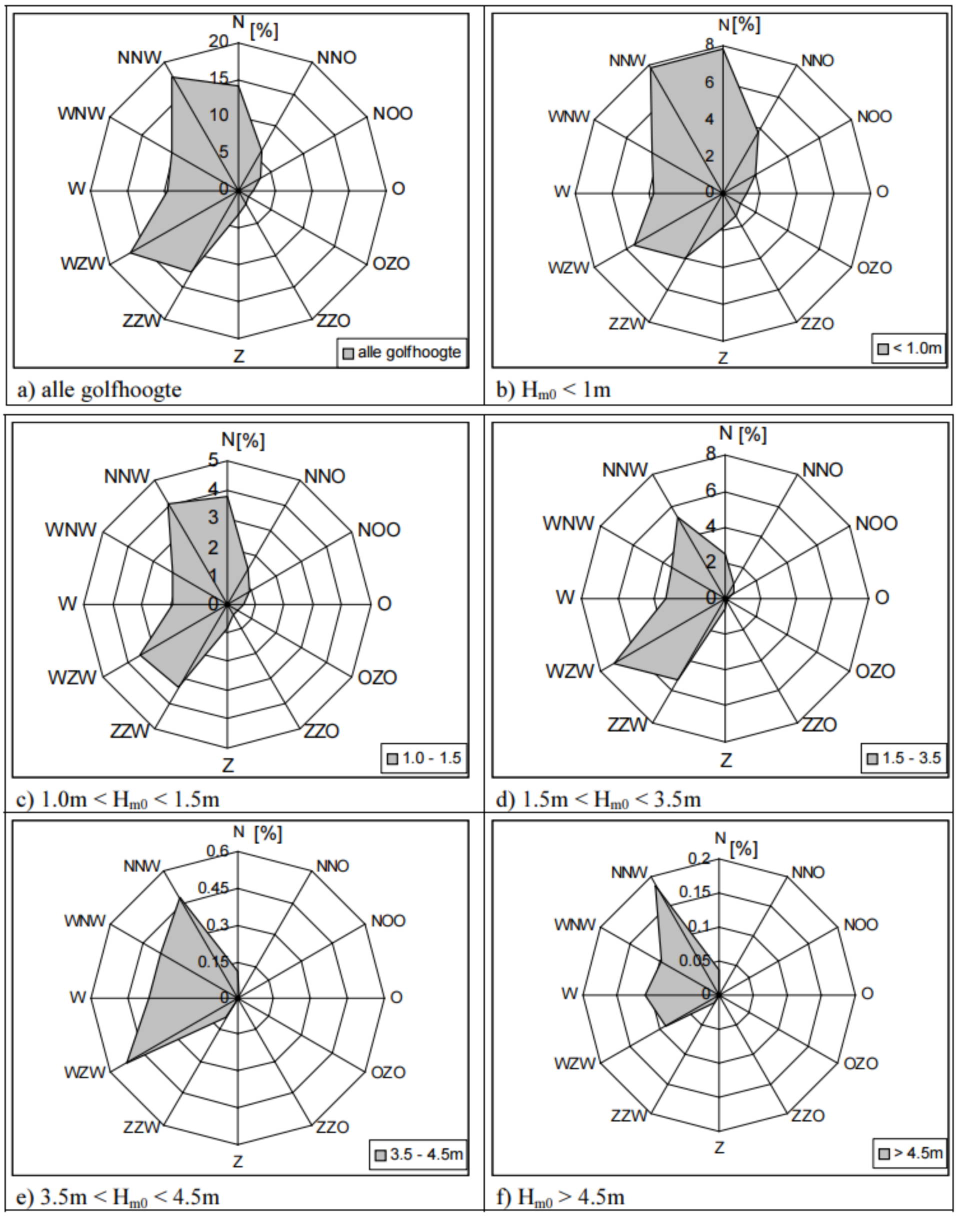


Figure 2.4: Percentage of occurence of waves per wave direction at IJmuiden. Rest, 2004

2.3. Morphological Evolution

2.3.1. Coastal stability

Significant accumulation directly south and north of the breakwaters was initiated by the construction of the breakwaters. However, after a distance of approximately 2 - 3 km the coast presents erosion at both sides of IJmuiden. Especcially at the northern side when going further north, this accretion decreases, and significant erosion becomes evident, starting from Raai 5200. Beaches located near Heemskerk and Castricum are marked by a notably eroding coastline (see Figures **??** & 2.8).Especially the northern side is known for its structural eroding trends (Kruif and Keijer, 2003).

Construction of the breakwaters induced significant accumulation directly south and north of these structures. However, beyond a distance of approximately 2 - 3 km, both sides of IJmuiden display erosion, particularly pronounced on the northern side (Kruif and Keijer, 2003). This erosion begins notably from Raai 5200 and extends towards the beaches near Heemskerk and Castricum, which exhibit a significantly eroding coastline (refer to Figure 2.8).

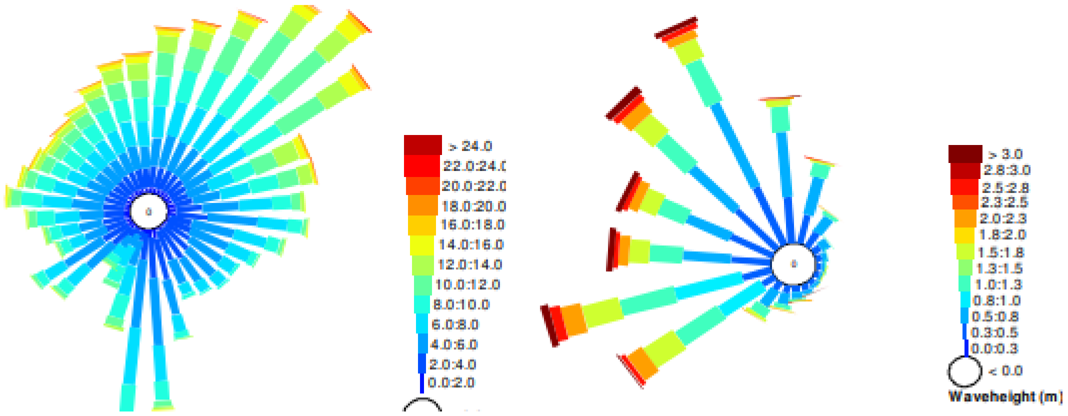


Figure 2.5: Wind rose (left) and wave rose (right) at IJmuiden (Luijendijk et al., 2011)

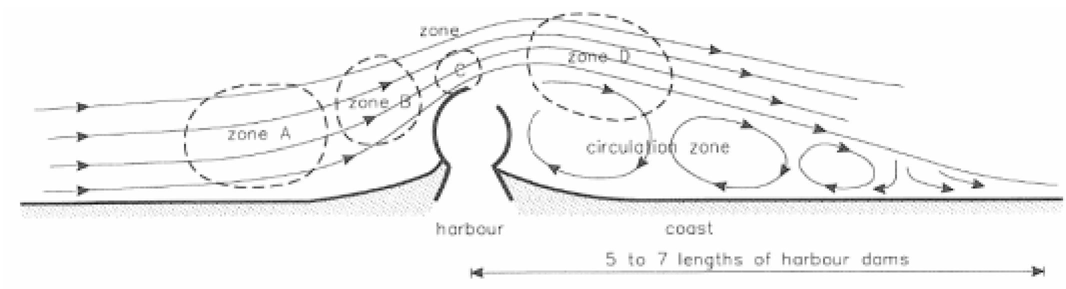


Figure 2.6: Converging and diverging tidal currents near IJmuiden harbour dams (Luijendijk et al., 2011)

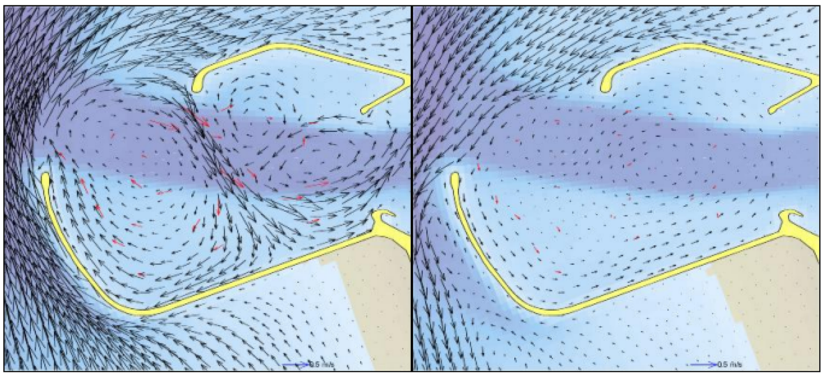


Figure 2.7: Tidal inflow patterns into and around the port of IJmuiden during flood flow and ebb flow. Black arrows present the modelled flow while red arrows represent the measured vectors (Bijlsma, Mol, and Winterwerp, 2007).

Based on the JARKUS-lodingen between 1964 untill 2001, Kruif and Keijer (2003) estimated the volume change over time in the area of IJmuiden. They segmented the area into 11 distinct subsections to better analyze the volume change over this period. The outcomes of their analysis are depicted in Figure 2.9.

Kruif and Keijer (2003) shortly summarized these volume changes. Sedimentation rate at the northern area is reducing; it seems that equilibrium has been reached. The southern is still characterized by strong sedimentation.

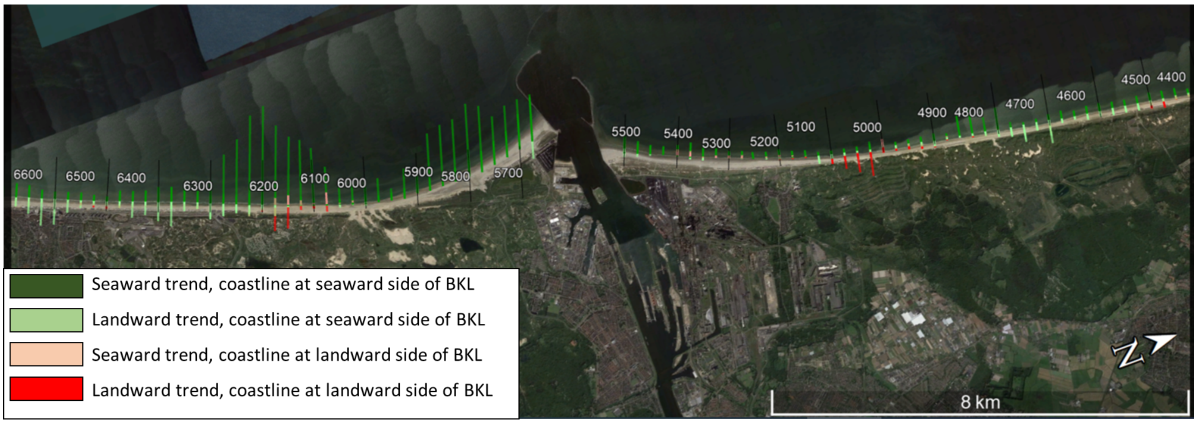


Figure 2.8: Erosion and accretion trends of the coast between 2021 and 1985. The reference coastline (BKL) is the coastline that we want to maintain.

The erosion and sedimentation trends are summarized in table 2.1.

Table 2.1: Erosion and sedimentation trends near IJmuiden

Section	**Location (raai)**	**Trend**
Beach (between -1 m- NAP and +3 m- NAP):		
Castricum to just before IJmuiden	4550 - 4925	Erosion
Directly northern of IJmuiden	4925 - 5025	Sedimentation
Foreshore (between -6 m- NAP and -1 m- NAP):		
Castricum to just before IJmuiden	4700- 4925	Erosion
Directly northern of IJmuiden	4925 - 5025	Sedimentation
Directly southern of IJmuiden	5625 - 5950	Sedimentation
Bloemendaal - Zandvoort	6050 - 6800	Erosion

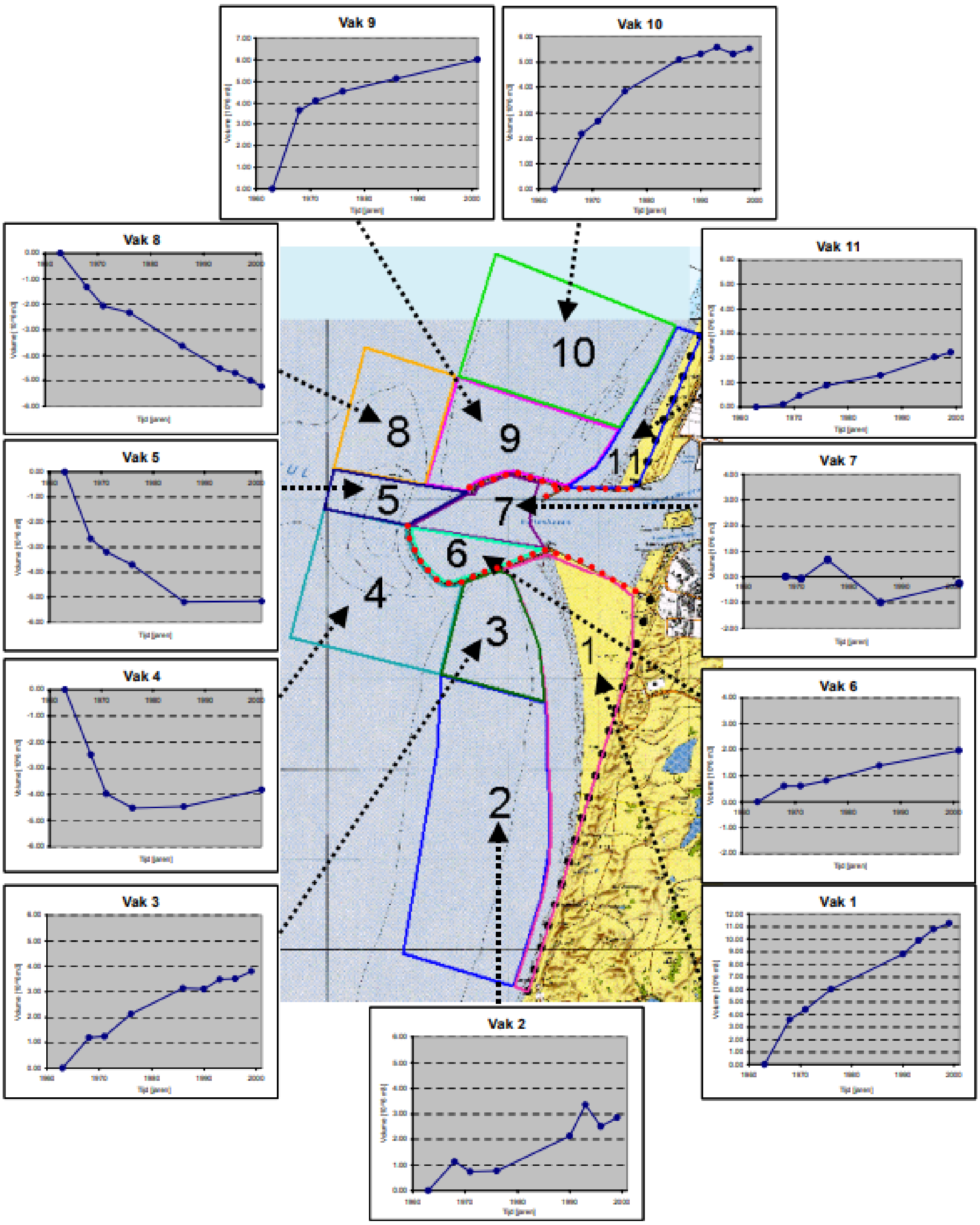


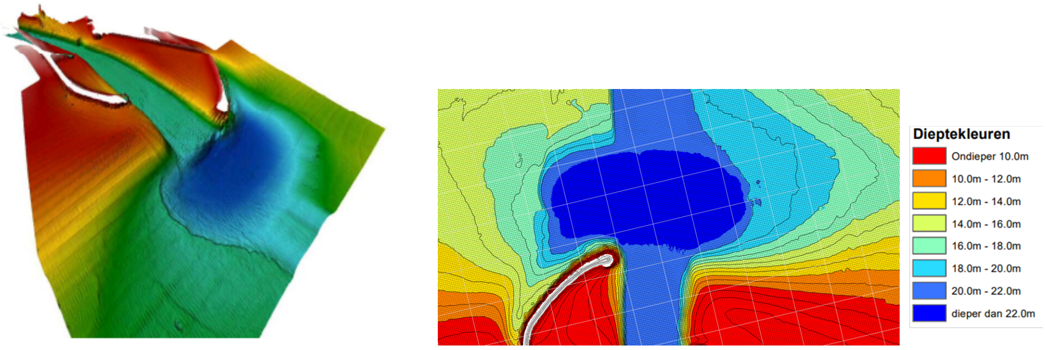
Figure 2.9: Study area divided into 11 sections, with graphs showing volume changes since 1963. Scale adjusted for section 1 due to larger volume changes (Kruif and Keijer, 2003).

2.3.2. Scour hole

A scour hole, resulted by flow contraction around the breakwaters, has evolved over time. Positioned in front of the southern breakwater's tip, the hole's depth is reportedly stable, as observed by the operational manager. Nevertheless, the scour hole exhibits an annual northward shift of about 10 meters (Lely, 2023). The 2002 multibeam survey representation of this scour hole is illustrated in Figure 2.10 (a)

A more recent bed topography of the scour hole, obtained from Rijkswaterstaat, is depicted in Figure

2.10 (b). From an initial visual examination, no substantial alterations can be discerned when comparing these images.



(a) (b)

Figure 2.10: (a) Bed topography of port and scour hole, measured in 2002 (Kruif and Keijer, 2003), and (b) Bed topography of scour hole, measured in 2020 (Rijkswaterstaat).

2.4. Connecting Environmental drivers to morphological development

This section aims to establish the link between the environmental drivers and the morphological changes observed in IJmuiden region that lead to dredge and nourish activity. By understanding these connections, we try to identify the key processes that should be addressed with the proposed solution.

Sedimentation of Southern and Northern Sides of Breakwater

- Flow obstruction: When reaching the breakwaters on the updrift side, the flow velocity slows down, causing sediment to settle.
- Recirculation at downdrift side: Recirculation near the downdrift side of the breakwater transports sediment towards it, leading to sedimentation.
- Divergence induced settling: The current flowing around the breakwaters contracts and diverges at the downdrift side, reducing the flow velocity and allowing sediment particles to settle.

These processes occur during both northward and southward flows. However, due to prevailing SW wave conditions and larger tidal flood currents around the breakwater, greater sedimentation is observed at the southern breakwater compared to the northern area.

Infilling of the port

- Eddy at harbor entrance: During flood, the flow does not directly enter the harbor due to the shelter provided by the southern breakwater. However, in the complex flow sitation an eddy is generated near the entrance that can pick up sediment and transport it into the port (Kruif and Keijer, 2003).
- Direct inflow during ebb: during ebb flow, currents can directly enter the harbor and contribute to the infilling. However the velocities during ebb flow are significantly smaller compared to flood flow (Kruif and Keijer, 2003).
- NW wave condition: Sediment located at the northern breakwater can be transported into the port in relatively large quantities during NW (storm) conditions (Kruif and Keijer, 2003; Lely, 2023).

Infilling of the Channel

- Contracted flow-induced sediment transport: The contracted flow picks up sediment, and as it increases in velocity. When the flow passes over the channel, its velocity slightly decreases, allowing sediment particles to settle.

- Wave-driven transport: Due to the reduced depth resulting from the sedimentation along the southern and northern coasts, wave-driven transport becomes more significant. Sediment can be transported from one side to the other, depending on the wave and wind direction, leading to sediment bypassing and transport into the channel and port.

Additionally, migrating sand waves can contribute to channel infilling over longer timescales. The migration that happens typically with 2 - 8 m/year falls outside the scope of this study since the focus is on shorter future (Van der Meijden et al., 2023).

Erosion of the Adjacent Coast

- Partial restraint of alongshore sediment transport: The presence of breakwaters partially restricts the alongshore sediment transport, resulting in a reduced sediment supply for northward transport compared to a scenario without a port.

- Sediment trapping by the channel: Sediment transported northward (and southward) can become trapped by the channel, which serves as a sediment sink. Although the dredged sediment is reintroduced into the system at the Loswal at -11 m NAP. It is questionable whether this sediment will reach the eroding coast and at what time-scale this will happen.

2.5. Implications and Impact of Operational and Maintenance

In this section it is attempted to describe the action taken to counteract the downdrift erosion and infilling of the channel and port and to estimate their effect on the environment, ecology and their costs. First the nourishment activity and continuous dredging activities in the harbor and channel will be quantified. From this the emissions and costs are roughly estimated. For the ecological impact estimation the Benthimeter is used. Although, a simplified calculation with 'Benthimeter' is performed it provides feeling on how this tool can be used to assess and visualize ecological impact.

The estimates of the impact as calculated in this section will serve as the impact of the Do Nothing scenario. And defines the baseline for the fixed sediment bypass concepts.

2.5.1. Nourishment strategies

The Dutch erosion mitigation approach is to maintain a aggreed-upon BKL [1]. To maintain this baseline as mentioned sediment is structurally added in the form of nourishments. In the past decades this frequently happend at Heemskerk. Table 2.2 provides an overview of the recent and ongoing projects obtained from Rijkswaterstaat (2021). The recurrence time visible between the projects (around 5 years) is in agreement with the average recurrence time along the central Dutch coast, namely 5.2 years (Brand, Ramaekers, and Lodder, 2022).

Table 2.2: Recent nourishment projects near Heemskerk (Rijkswaterstaat, 2021)

year	Location (raai)	quantity	Type
2012	4575 - 5000	1.6 Mm3	Foreshore nourishment
2017	4575 - 4975	1.0 Mm3	Beach nourishment
2022- 2024	4300 - 5150	3.0 Mm3	Foreshore nourishment

[1]BKL (Basis Kustlijn) refers to the agreed-upon baseline of the coastline that needs to be maintained, serving as a reference for coastal management and coastal engineering activities.

2.5.1.1. Calculation Emission and Costs

In this study the recurring time is assumed that the most recent nourishment of $3Mm^3$ must be repeated every five years.

According to Röbke et al. (2021b) the average associated costs of foreshore nourishment are €3.50 per m^3 and emissions are 3.0kg CO_2 per m^3. This amounts to a total cost of €10.5 million and a total emission of 9 million kg CO_2 every five years. Resulting in an average of **€2.1 million per year** and **1.8 million kg CO_2 per year**.

2.5.2. Port and channel maintenance

The port and channel at IJmuiden require regular dredging to maintain navigability, a necessity that has intensified over the years as the draughts of ships have increased. In its early years in 1870, the harbor and channel were maintained at a depth of -8.5 m NAP. However, as vessel sizes grew, the required depth increased to accommodate them. The depth was adjusted to -9.5 m NAP in 1893, -10.5 m NAP in 1905, -12 m NAP in 1952, -15.5 m NAP in 1967, and -19.2 m NAP in 1985 (Kruif and Keijer, 2003). Today, some areas require even greater depths.

In 1996, there was a shift in the dredging contract structure. Instead of the contractor receiving payment per cubic meter dredged, a new agreement was put in place. Now, the contractor is paid a fixed annual sum to ensure the depth requirements are consistently met.

H. Lely, the project leader of maintenance dredging for the IJmuiden Outer Harbor at Rijkswaterstaat, shares the impression of an increased sand deposition in the port and channel, which appears to be causing a rise in the volume of dredging activity (Lely, 2023). To illustrate this observation, data from various sources, including dredging records from Rijkswaterstaat and information from Reussink, Jeuken, and Tánczos (2002), were compiled into the figure 2.11. The dredged material from the harbor consist mainly of mud and has a 10 - 20 % sand-mud ratio (Reussink, Jeuken, and Tánczos, 2002; Lely, 2023). Where, the dredged material from the channel consists mainly of sand. The quantities per year are presented in APPENDIX B.1.

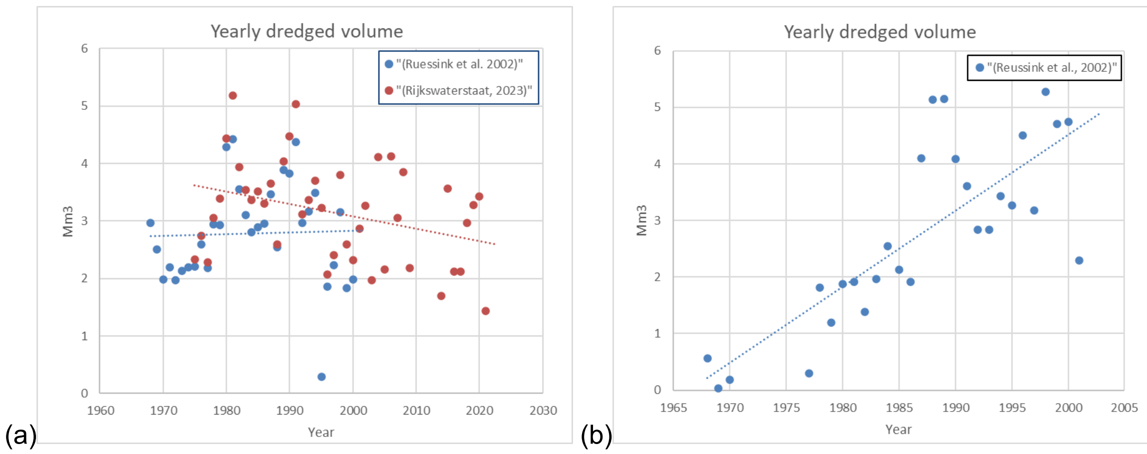


Figure 2.11: Figure illustrating the annual volume of sediment dredged from the IJmuiden port (a) and IJgeul (b). Data is obtained from Rijkswaterstaat and Reussink, Jeuken, and Tánczos (2002)

Figure 2.11 presents the increasing quantity of dredged material from the channel over time. This increasing trend, however, is not observed in the harbor dredging volumes. Kruif and Keijer (2003) suggest this discrepancy likely results from a change in dredging policy introduced in 1990.

Various factors could be driving the increasing trend in dredge quantities in the IJguel, such as the system moving towards equilibrium and thereby increasing bypassing volumes, or the increasing minimal depth requirement for navigation over the years contributing to infilling. Other potential contributing factors include changes in the hydrodynamic and morphodynamic behavior of the area. While identifying a single driver is challenging, the observation of increasing dredge quantities is supported by the dredging data. Furthermore, there is no indication of a decrease in these volumes in the foreseeable future. In fact, these volumes are expected to continue rising once the system reaches equilibrium and bypassing can freely occur (Kruif and Keijer, 2003; Reussink, Jeuken, and Tánczos, 2002).

2.5.2.1. Calculation environmental impact and costs

Current practices involve the dredging of around 2.5 Mm3 from the port and 4.0 Mm3 from the channel annually. Assuming the use of a relatively small trailing suction hopper dredger (TSHD), the most common vessel type for this operation, and a short sailing distance to Loswal, the estimated emissions are approximately 2.3 kg CO2 per m^3 dredged (Bilt, 2019). For the purposes of this study, dredging costs are assumed to be similar to nourishment costs, i.e., €3.50 per m^3. This results in an approximate total of **15.0 million kg CO_2/year** and **€22.8 million/year** for dredging activities.

2.5.2.2. Ecological impact

The ecological impact quantification from direct dredge activities and the subsequent disposal at the loswal is left out of scope. The reason for this exclusion is: firstly, the 'Benthimeter', our tool for ecological impact assessment, lacks the capacity to account for the relationship between dredging activities and benthic damage. Secondly, the Benthimeter is primarily calibrated for near-shore processes, thus rendering it potentially inappropriate for assessing impacts at the Loswal disposal site. Furthermore, the complexities linked with the Loswal disposal, such as potential harm to benthic life from contaminated dredge material, compound the difficulties of quantifying the ecological implications of dredging and disposal activities.

3
Designing Artificial Sediment Bypass systems: Background and Design

Artificial bypass systems offer an unique solutions for mitigating coastal erosion and preventing sediment accumulation in navigation channels, ports, or other coastal sediment sinks (Richardson and McNair, 1981). These systems aim to partially or completely restore alongshore sediment transport around a disrupted shoreline.

This chapter presents the development process of different potential fixed sediment bypass layouts for IJmuiden. First a general study into the background of sediment bypass systems is provided. The focus in this background is to assess what components are ther in such systems, what is their function and working principle.

To enrich this theoretical understanding with practical insight, projects where sediment bypass systems have been implemented are investigated. Specifically, it investigates the Tweed River Entrance Project, the Nerang River Project, and the Nqgura Port, shedding light on the practical aspects and learnings from these implementations.

The information presented in this chapter, together with the IJmuiden system analysis from Chapter 2, serves as a practical guide for the design of the bypass system for IJmuiden, which is also presented in this chapter.

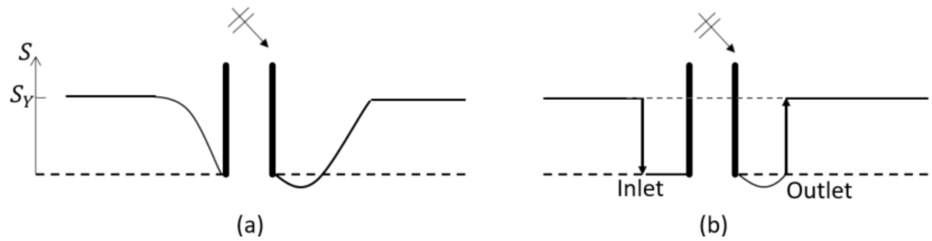


Figure 3.1: Working principle of sediment bypass system which aims to restore the along shore sediment transport around disrupted coast (S_y = 140 000 m^3). (a) presents alongshore sediment transport situation with breakwaters under obliquely incident waves, (b) present the restoration of alongshore sediment transport by implementing a sediment bypass system.

3.1. Components of an Artificial Bypass System

The main objective of an bypass system is to restore the alongshore sediment transport that is obstructed by a coastal disruption. To achieve this sediment is withdrawn from the updrift side and discharged at the downdrift side. Figure 3.1 presents this working principle of subtracting sediment and reintroducing it.

This section delves into the components and operational aspects of fixed sediment bypass systems. Detailed descriptions of the inlet, transport, and outlet systems of the bypass along with their design considerations and functioning are provided.

Although there are more types of bypass systems, fixed, mobile, and semi-mobile, this study focus on fixed systems only. Given the motivation of minimizing human intervention and emphasize the contrast with the current situation as much as possible. These systems are often preferred for their ability to function under a variety of conditions, potential for automation, and continuous operation, despite their potential high construction costs.

Fixed systems are site-specific, operating under various conditions, and can potentially be automated. Mobile systems offer relocation flexibility but require human-operated machinery and are susceptible to environmental conditions. Semi-mobile systems combine fixed and mobile features, providing some area mobility, yet often necessitating human guidance (Venture, 1997).

3.1.1. Background: Inlet system

In a fixed bypass system, the inlet system is responsible for dredging material at the updrift side. This is often done using hydraulic equipment, such as jet pump or dredge pump. The inlet system aims to capture sediment before it starts bypassing. To accomplish this, the sediment transport can be intercepted directly, or materials can be removed from a deposition area (also known as trap area). The latter is generally preferred, as it allows for a more flexible operating schedule (Richardson and McNair, 1981). Placing jet pumps in the path of active transport to create cones (craters) for trapping sand particles is an effective method for creating traps.

The fundamental components of a jet pump inlet system are presented in more detail in APPENDIX C. Figures 3.2 is a simplified representation of a land-based single jet pump system's components. While the illustration focuses on a land-based system, the principles apply to other systems as well, such as jetty-based systems or systems with multiple jet pumps. The components shown in the figures represent the elements of a basic land-based jet pump system.

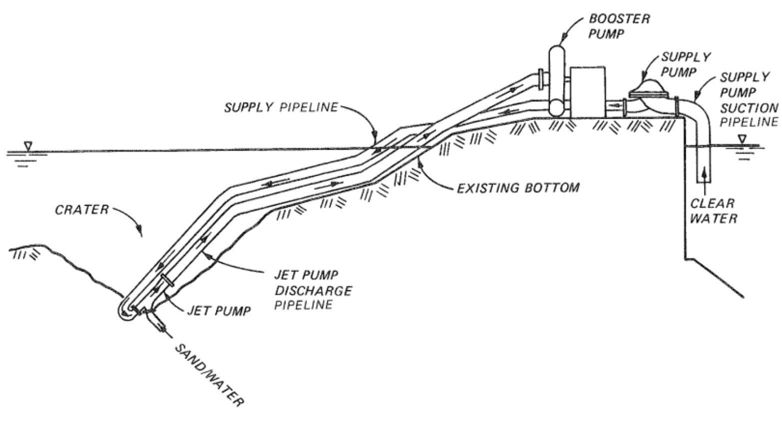


Figure 3.2: Conceptual elevation view of the components of a simple land based jet pump system (Richardson and McNair, 1981)

The components of the simple jet pumps shown in Figure 3.2 and their purposes are as follows:

- **Supply pump.** Water from the clear water intake (usually underground reservoir) is pumped via the supply pipeline to the jet pump.
- **Jet pump.** The pump inject clear water with high velocity into the bed. The high-velocity water

stirs up the sediment, forming a mixture of sand and water known as slurry. The jet pump then pumps this slurry through the jet pump discharge pipeline.

- **Crater.** Also commonly referred to as cones, these formations occur at the seafloor as a result of the excavation process. For rigid structures, jet pumps are buried in the bed, causing an excavation above. In the case of flexible pipelines, the jet pump trails down the bottom of the crater, extracting the sand. Maintenance of the crater involves regular dredging by the jet pump. This crater functions as a sediment trap, catching littoral drift that would otherwise bypass the area.
- **Booster pump.** This component's function is to furnish the necessary energy to transport the slurry to the predetermined discharge location. Depending on how far the slurry needs to be moved, one or more booster pumps may be utilized. Regular dredge pumps are often employed as booster pumps.

3.1.2. Background: Transport System

The primary objective of the transportation system is to convey the slurry mixture effectively and efficiently. This process is accomplished through a network of pipelines and pumps, designed to maintain constant pressure throughout the system. The number of pumps required depends on the transportation distance involved; as a general rule, for every 1000 meters, a booster pump is needed (Richardson and McNair, 1981).

Transportation of the slurry can occur over various terrains such as land, water, or even beneath the surface, depending on the specific requirements and site characteristics. Geographical and topographical considerations will often dictate whether the pipeline can be installed underground. Other influential factors may include recreational restrictions or potential obstructions to shipping routes.

To enhance efficiency and prevent energy losses, it is recommended to minimize the use of bends, valves, and other pipeline fittings (Richardson and McNair, 1981). The material selection for the pipeline also plays a critical role in optimizing functionality. Frequently, a combination of steel and polyurethane is preferred due to their durability and resistance to wear and tear (Soares, 2017).

3.1.3. Background: Outlet System

In designing the discharge system, the overarching aim is to restore the natural sediment transport processes, thereby preserving the ecological health and continuity.

This aim influences several aspects of the operation. Primarily, it is essential to ensure that bypassing operations do not substantially alter the flow characteristics, thereby avoiding the formation of large deposition mounds. Secondly, placing the discharge outlet too close to the leeward side of a structure may lead to sediment accretion on the downdrift side of the structure. Therefore, it is generally advantageous to establish the discharge at a safe distance from the leeward side of any structure. This strategy ensures broader dispersal of the sediment, contributing to erosion mitigation (Richardson and McNair, 1981).

Considerations should be made for potential impacts on benthic life due to sedimentation. Research has extensively studied the effects of nourishment activities on benthic life, a subject further discussed in section 6.3. Finally, a well-devised operation schedule, potentially incorporating bypassing during specific conditions or seasons, can enhance the efficiency of sediment dispersion.

3.2. Historical Overview and Existing Bypass Systems

Artificial bypass systems have long been an integral part of coastal management strategies. with the first system initiated at Viareggio Harbour, in Italy, in 1936. Since then 54 other systems have been realized (Soares, 2017). Boswood and Murray (2001) offers an extensive analysis of data from global sediment bypass systems until 1997. A timeline of projects around the world, utilizing fixed sediment bypass systems, is provided in Table APPENDIX C.1.

3.2.1. International Case studies

Various projects globally have effectively implemented fixed sediment bypass systems. This section gives an overview of such implementations, focusing on their key attributes and respective outcomes. Insights from these projects can help to optimize the design, operation, and impact assessment of proposed systems for IJmuiden.

For this thesis, three projects closely aligning with the proposed design are used for to further investigate, namely Nerang River (AUS),Tweed River (AUS), and Port of Nqqura (RSA). They all incorporate jet pumps mounted on a jetty and beach nourishment via pipeline. The Australian projects have been deemed successful in previous studies (Soares, 2017), while the Port of Ngqura in South of Africa presented more challenges.
An extensive case study with detailed description of the layouts and operation of the three studied cases are provided in the APPENDIX C.2. In this section the case studies will be shortly summarized.

3.2.1.1. Case Study Summary: Tweed River Entrance Project (TREP)

The Tweed River Entrance Sand Bypassing Project, a successful fixed system implementation, was initiated in 1995 in the southern Gold Coast of Australia. The project's primary objectives were to counter coastal erosion and to maintain the Tweed River Entrance's navigability (Castelle et al., 2009).

The project's layout, presented in Figure C.3, illustrates the system comprised of a updrift collection jetty equipped with 10 jet pumps to creating a 270 m sediment trap (Soares, 2017). Furthermore, the system contains 7km of pipeline, 2 booster pumps, a clear water intake pump, a control station, and four different outlet locations.

The system annually bypasses between 350,000 and 830,000 m^3, with an average cost of 6.17/m^3 per bypassed cubic meter. The total construction cost of the project was €25 million (Soares, 2017).

The project's effectiveness was observed in the mitigation of erosion at the downdrift beaches, with accrediting trends noticeable after only one year (Acworth and Lawson, 2011). The project also improved navigability, resulting in less dredging activity (Government, 2022). However, the exact reduction level of the dredging activity was not determined during the case study.

3.2.1.2. Case Study Summary: Nerang River Project

The Nerang River Project, launched to mitigate the northward progression to the river entrance and address the consequential erosion at the downdrift island, exemples a successful fixed system implementation (Boswood and Murray, 2001). An overview of the system layout is presented in Figure C.6

After construction, significant accretion was observed at the downdrift beach, and no channel maintenance dredging was required between 1986 and 2001, testifying to the system's efficiency (Boswood and Murray, 2001). The system is primarily operated during off-peak hours to take advantage of lower electricity rates. The specifics of the system at the Nerang River entrance are further detailed in APPENDIX C.2

Compared to the TREP system layout, the system of Nerang River has significantly smaller scale. It uses just 1.4 km of pipeline and no booster pump to transport the slurry to one of the three outlet locations (Boswood and Murray, 2001).

Although this system bypasses similar volumes as TREP, namely between 300 and 750 m^3 per year, significant lower costs are observed. Namely, just 0.84/m^3 bypassed sediment and a total construction cost of 4.3 million euros (Boswood and Murray, 2001).

Figure 3.3: Tweed river sediment bypass system overview Soares, 2017

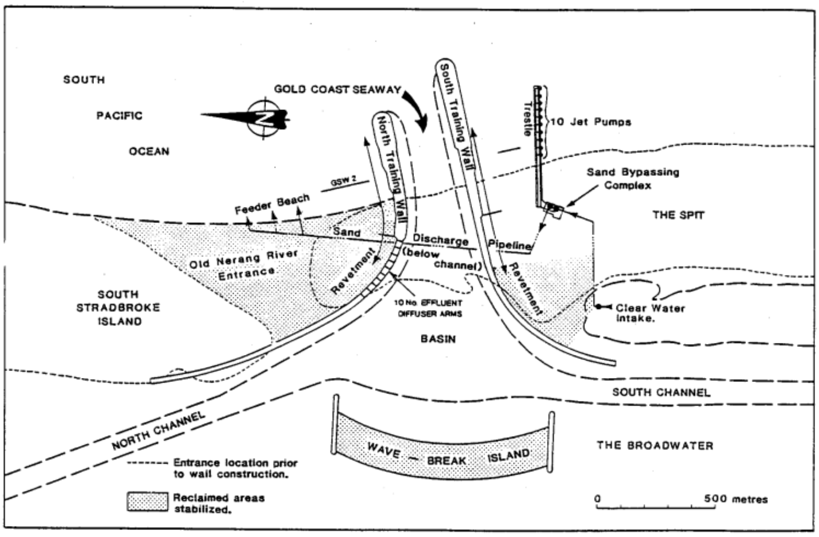


Figure 3.4: Overview of artificial sediment bypass system used at Nerang River entrance (Boswood and Murray, 2001)

3.2.1.3. Case Study Summary: Ngqura port bypass

The Ngqura Port Bypass system location in South Africa, the only fixed bypass system applied to a port, consists of a just 6 jet pumps. And has three booster pumps to transport slurry throuh a 3.8 km pipeline system, as displayed in Figure 3.5.

Operational challenges such as the inability to handle particles larger than 150mm necessitated periodic maintenance and dredging around the jet pumps (Schmidt, 2016). On average, the bypass system transports between 40 - 200 m^3 of sand per year, significantly lower than its original design capacity of 320,000 m^3/yr (Soares, 2017). This shortfall was attributed to a lack of sand replenishment, coarse material filling the sandtrap, operational issues with jet pumps, and frequent system downtime (Transnet, 2023).

The construction of this bypass system cost approximately 6.2 million euros (Soares, 2017). The average cost per cubic meter of sand transported was not determined during the case study.

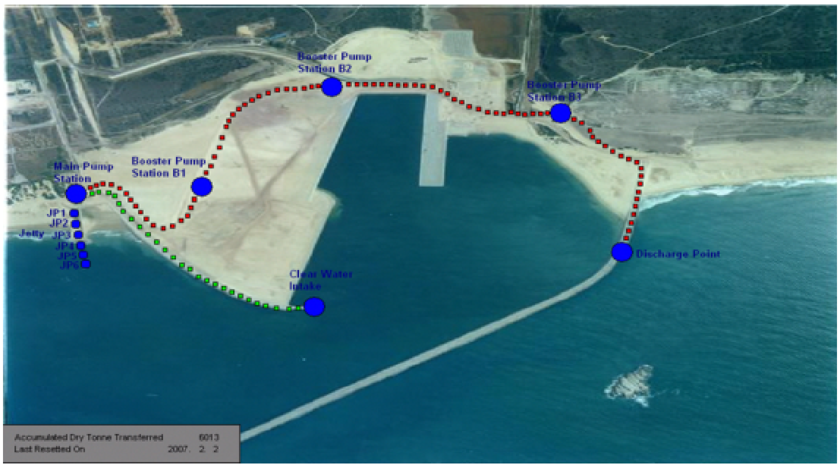


Figure 3.5: Schematic view of Port of Ngqura Sand Bypass system (Soares, 2017)

3.2.1.4. Lessons Learned

Across these three projects, several key lessons emerge. A principal observation is that sediment bypass systems can rapidly and significantly influence the nearshore morphology, as evidenced by the Australian case studies. The study of Acworth and Lawson (2011) showed that significant accretion of the adjacent coast was already observed after 1 year after initiation of the fixed system . However it must be noted that the nourishment projects were part of the project, which most probability contributed to the accretion (Castelle et al., 2009).

Keshtpoor et al. (2013) also observed this 1 - 2 year 'memory' of the shoreline during their study of the beach response to the fixed sand bypassing system at the Indian River Inlet.

Castelle et al. (2009) Compared the fixed bypass system to foreshore nourishment strategies and concluded that the first method have proven to be more efficient for stabilizing the downdrift beach. They discussed that this is due to that foreshore nourishment require extended periods of low energy conditions for the sediment to migrate shoreward and attach to the shore.

For both the Tweed and Nerang River project it is concluded that the navigability of the channels is improved (Acworth and Lawson, 2011). In other words, less infilling occured after construction of fixed systems. For Nerang River no maintenance dredging had to be done 16 years after installation (Boswood and Murray, 2001). At Tweed River this maintenance dredge still have to be performed, but volume is lower as mentioned by Castelle et al. (2009).

Concerning the cost of the projects, it the Tweed river installation cost as well as the average cost per m^3 bypassed sand is significantly larger. Soares (2017) justified this due the scale of the project. Where the pipeline system contains 7 km of pipeline, that is almost completely constructed into the ground. To transport the mixture of theses distances, large pressure pumps are required that use a lot of energy. Maintaining this complex system costs a lot.

The three case studies share a common focus on ecology, treating it as a crucial stakeholder during both the design and operational phases. Each project took into consideration the environmentally sensitive areas from the onset and continued monitoring throughout their operation.

For instance, the Tweed River project discovered that overpumping was causing reef burial. Adjustments in the operational scheme were made to prevent this issue. The precise ecological benefit is challenging to quantify. However, the consensus is that the decrease in dredging and nourishment projects reduces the environmental and ecological impact (Venture, 1997).

3.3. Considerations and Alternatives for IJmuiden System Design

This section outlines the process of developing alternative designs, taking into account the normative conditions as discussed in chapter 2. These conditions will serve as design framework. The primary focus is on South-West wave and wind conditions, which induce an annual net sediment transport of 140,000 m^3 from south to north near IJmuiden. The fixed system aims to bypass this volume to restore natural alongshore transport. Therefore, a volume of 230,000 m^3/year must be pumped from the bed at the southern side and be discharged at the norhtern side of the port. Namely, the volume of bypassed sand in granular state ($\frac{\rho_s}{\rho_{\text{granular}}} \times 140,000\, m^3/\text{year} = 230,000\, m^3/\text{year}$).

3.3.1. Inlet system

The inlet system aims to remove sediment before it bypassed, therefore preventing infilling of channel and port. For this purpose, jet pumps will be strategically placed along the path of active sediment transport, creating craters (or cones) that act as traps for sand particles.

3.3.1.1. Dredging Activity: Best Case Scenario

For the best case scenario it is assumed that the bypass system reduces dredging activity by 0.23 Mm^3 per year. Therefore, the total dredged volume per year will be 6.27 Mm^3 instead of 6.5 Mm^3, a minor decrease. See Table 3.1 for the estimated best case scenario benefit of a sediment bypass system for the dredging activity of the channel and port. During the calculation it is assumed that the sediment bypass system can operate without a net-zero emission.

Table 3.1: Calculated effect on channel and port dredging activity of an artificial bypass system at IJmuiden following the best case scenario.

Activity (per year)	Do Nothing	Fixed bypass
Total required dredging of Channel and Port ($\mathbf{Mm^3}$)	6.5	6.3
Withdrawn volume ($\mathbf{m^3}$)	0	230,000
Emission dredge activity (2.3 kg $\mathbf{CO_2/m^3}$)	15.0 million kg CO_2	14.5 million kg CO_2

3.3.1.2. Inlet system design

Location of inlet

The jet pumps system necessitate a land connection (Jetty). Which often originated from the beach, but from other structures like the breakwater is in theory also possible. As observed in Chapter 3, typically the extend of jetties are no longer than 500 m from land. for practicality a maximum of 700 m from shore shore is assumed for determination of the location.

Depth poses an additional constraint, with the sediment traps requiring significant depth compared to the surrounding sea floor. To give some perspective, the jet pumps at the Nerang River Entrance project were positioned 5 to 9 meters below surrounding sea floor while at Ngqura Port this 5 to 7 meters below surrounding sea floor (Rutherford, 2015). For practical reasons, we will not consider installing jet pumps at locations with depths less than -10 meters MSL. Figure C.10 illustrates the regions that could feasibly accommodate jet pumps, considering depth and proximity to the shore.

The design's main objective is to restore the natural south to north alongshore sediment transport. Consequently, the inlet location should be situated south of the southern breakwater. Two potential locations are proposed for sediment interception. The first is located approximately 700 meters south of the southern breakwater, positioned just outside the zone of southward sediment transport caused by the eddies resulting from flow obstruction near the breakwater. The second proposed location is closer to the breakwater, on the edge of the -10-meter depth contour, which is accessible from the southern breakwater. Both locations represent strategic points to capture sediment, thus minimizing bypassing and achieving the overall project objective.

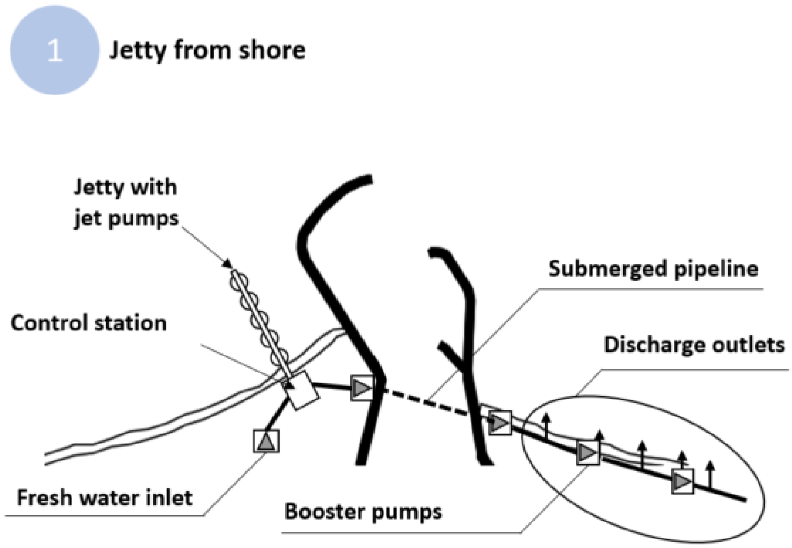


Figure 3.6: Schematic overview of fixed jetty system.

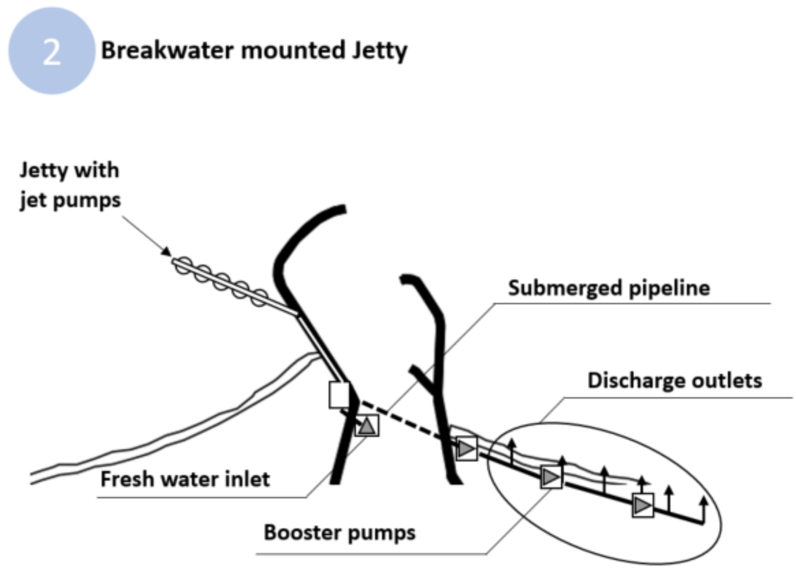


Figure 3.7: Schematic design of fixed jetty mounted to southern breakwater.

Sediment Trap Dimensioning

The sediment trap created by the jet pumps is integral to the inlet system. Prior projects, such as Nerang River Entrance and Tweed River, offer valuable design insights, with the Nerang River project proving particularly effective in sediment trapping. Richardson and McNair (1981)'s guidelines further assist in defining sediment trap dimensions.

At the Nerang River Entrance, the jetty equipped with ten jet pumps spaced 30 meters apart, creates a 270-meter trap length reaching from -2.0-meter and -6.0-meter MSL (most active zone). The jet pumps are positioned at -11.0 m- MSL to create effective sediment trap cones. With 30 meters between jet pumps, sufficient overlap is achieved for an effective sand trap (Venture, 1997)

(1): Jetty from beach

For alternative 1, where the jetty is situated from the beach, the shore exhibits a gentler slope compared to the coast at Nerang. Consequently, to form a sediment trap in the active shoreline, a jetty that extends further into the sea is required. The proposed sediment trap for this alternative spans 420m in length (with 15 jet pumps spaced 30 meters apart) and a depth range of -2 to -5 m- MSL. The width is assumed to be 30m, based on Richardson and McNair (1981)'s guidelines. Refer to figure **??** for the dimensions and layout of this proposed sediment trap.

(2): Breakwater mounted Jetty
For this concept a slightly shorter sediment trap length is assumed. This assumption is based on observation that the sediment transport pattern are contracting near relative close the breakwater. Therefore, extending the breakwater far into the sea is considered uneconomical.

3.3.2. Outlet system

The design of the outlet system aims to achieve maximum sediment dispersal for enhancing coastal stability and to minimize impact on benthic organisms, thereby reducing ecological disturbance.

3.3.2.1. Sediment demand downdrift coast: Best Case Scenario

In the best case scenario, all the sediment that is bypasses by the system reaches the eroding coast. In this scenario the nourishment volume is reduces by 1.1 Mm^3 per five years. Namely, the annual bypassed sand in granular state multiplied by the assumed nourishment recurrence time ($\frac{\rho_s}{\rho_{\text{granular}}} \times 140,000\, m^3/\text{year} x 5 years = 1.1\, Mm^3/5$ years). Therefore, the nourishment volume will be 1.9 Mm^3 instead of 3.0 Mm^3, a reduction of 38%. See Table **??** for the estimated best case scenario benefit of a sediment bypass system for the dredging activity of the channel and port. The table presents values, averaged over the five year. During the calculation it is assumed that the sediment bypass system can operate without a net-zero emission.

Table 3.2: Calculated effect on nourishment activity at downdrift coast of an artificial bypass system at IJmuiden following the best case scenario.

Activity (Per year)	**Do Nothing**	**Fixed bypass**
Required nourishment volume (Mm^3)	0.60 (3.0 per five years)	0.38 (1.9 per five years)
Added volume (Mm3)	0	0.23
Emission Nourishment activity (3.0 kg CO2/m3)	1.8 million kg CO_2	1.1 million kg CO_2

In the best-case scenario, it's not taken into account that beach nourishment may contribute more effectively to coastal stability than foreshore nourishments. Therefore, if bypassing occurs at the beach instead of the foreshore, reductions greater than 38% could potentially be achieved.

3.3.2.2. Outlet system design

The design process includes various variables that are adjusted and their impact assessed in order to construct the final design:

- Number of outlets
- Outlet distance from northern breakwater
- Location in the shore

Number of Outlets
The number of outlets in the design influences the volume of sediments distributed through each outlet. Distributing the sediment volume over multiple outlets can potentially reduce the added layer thickness, which could prove beneficial to benthic life. Furthermore, multiple outlets are frequently incorporated in designs to prevent an accumulation of sand at a single location and to avoid disruptions to the natural system.

Outlet Distance from Breakwater
The number of outlets in the design influences the volume of sediments distributed through each outlet.

Table 3.3: Overview of design considerations and their anticipated effects.

Design	Morphology	Ecology	Cost	Other
Inlet				
Increased sediment trap length or depth	Large trap lengths or depths can trap more sediment, therefore increasing efficiency of bypass system. However increasing depth can cause instability problems.	Larger disruption of shore therefore higher impact on ecology	Increasing trap length significantly increases cost since it requires more jet pumps and a longer jetty	-
Outlet				
Increase number of outlets	Better dispersal	Lower burial layers, which can be favourable for benthic life	Significantly increases cost of project	-
Increase distance from breakwater	Less shadow effect of breakwater, therefore higher longshore currents. Better dispersal is expected	-	Increasing the scale of the project significantly increases the cost.	-
Dispose at deeper shoreface	Less dispersal is expected due to lower longshore currents.	Larger impact on benthos expected since less mobile species living in deeper areas	Significantly higher costs since pipelines have to be extended into sea	Less hinder to people at the beach. This could favour operational constrainst

Distributing the sediment volume over multiple outlets can potentially reduce the added layer thickness, which could prove beneficial to benthic life. Multiple outlets are frequently incorporated in designs to prevent an accumulation of sand at a single location and to avoid disruptions to the natural system.

Location in Cross Shore

Discharging sediments in the dynamic foreshore, close to the beach, has been demonstrated to be effective in terms of sand dispersal (Boswood and Murray, 2001). This turbulent area, characterized by strong longshore currents, can transport sediment to the eroding coast. Moreover, the energetic breaker zone hosts benthic animals that have adapted to varying conditions and can, therefore, withstand larger burial depths. Nevertheless, depositing close to shore could pose issues for recreational activities.

Discussion

Increasing the scale, that is, with a greater number of outlets and increased discharge length seems beneficial in terms of sand dispersal and benthic impact. However, the cost of the project escalates with increasing scale. For instance, the Nerang River Entrance and Tweed River projects, despite having comparable inlet systems (jetty; 10 jet pumps) and bypass rates (approximately 500,000 m^3/yr), demonstrate notable differences in costs. The Nerang River project involves 1.4 km of pipeline without the use of booster pumps, while the Tweed River project includes 7 km of pipeline and 3 booster pumps. This distinction is reflected in the significant initiation costs of €4.3 million versus €25 million, and an average of €0.84/m^3 versus €6.17/m^3.

4
Model Framework

The Delft3D Flexible Mesh model is utilized in this study to simulate the morphological changes that potential sediment bypass system layouts at IJmuiden may induce. Through these simulations, the aim is to gain insight into the potential for Dutch coastal management. This chapter presents the setup of the model used for this purpose. A morphological and hydrodynamic validation is carried out to enlighten the model's predictive skill in simulating the rather complex coastal system of IJmuiden.

In addition, this chapter presents the methodology used to overcome the long simulation times posed by the used model. Furthermore, the approach and assumptions involved in incorporating the constructed potential sediment bypass systems (inlet and outlet) are described in this chapter.

4.1. General Model Set Up

The Delft3D flexible mesh used is an adapted version of a model constructed by the DCC. The DCC Delft3D-FM model is developed to analyse the morphodynamic development after implementing different nourishment concepts along the Dutch coast. Deltares (2022) provides a detailed description of the model as well as a validation.

This section provides a brief presentation of the model and presents the adaptions made compared to the version constructed by DCC.

The Dutch Coastline Challenge Flexible Mesh model (DCC-FM) is a comprehensive system, integrating three distinct modeling units. The Dutch Coastal Shelf model (DCSM-FM) initially calculates the North Sea's water levels and currents, setting the boundary conditions for the subsequent model. The core of the setup is the Hydrodynamic and morphodynamic model (DCC-FM-Flow), which is responsible for computing water levels, currents, sediment transport, and bed level updates. Lastly, the Wave model (DCC-FM-Waves), employing the spectral model SWAN, determines wave propagation with an interaction interval of 900 with the flow model via DIMR.

The model setup is to facilitate simulations of morphological development over a 15-year period under bruteforce conditions [1]. The boundary conditions are designed for 18 years (2016 to 2034) by replicating a 6-year period (March 1st 2016 – 2022) three times. A schematized workflow of the modelling approach is presented in Appendix D.1.

4.1.1. Grids Refinement

The original grid and its refinements have been modified to be suited for the area of interest. The refinement of the grid posed indications for the stability of the model. This resulted in a time-consuming

[1] Brute-force modeling refers to simulations conducted using complete, real-time data, without any simplification or extrapolation, which provides detailed scenario representation but can be computationally demanding

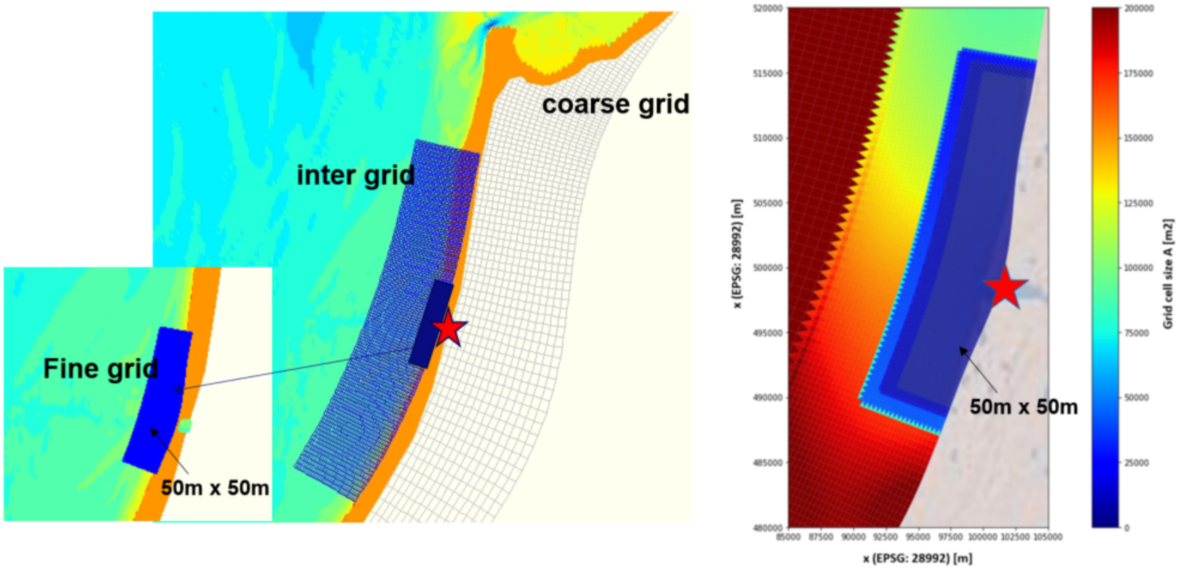


Figure 4.1: The domain of the Delft3D wave (left) and flow (right) grid with refinements surrounding IJmuiden, indicated by the star

trail-and-error process, exposing one of the challenges of this model. The finest grid that ensured stable calculation is the grid presented in figure 4.1 (a)flow module and (b) wave module with the finest grid sizes in the order of 50x50m.

This relative coarse grid resolution is likely to cause an underestimation of the alongshore sediment transports (Deltares, 2022). Resolutions in the order of 20 is desired to correctly capture wave-breaking processes.

4.1.2. Bathymetry

A high-resolution bathymetry data set containing bed-level data points in and near the IJmuiden port is added to the model. This data set is obtained from Lely (2023) and was compiled by a topography survey in 2023 (See figure 4.2

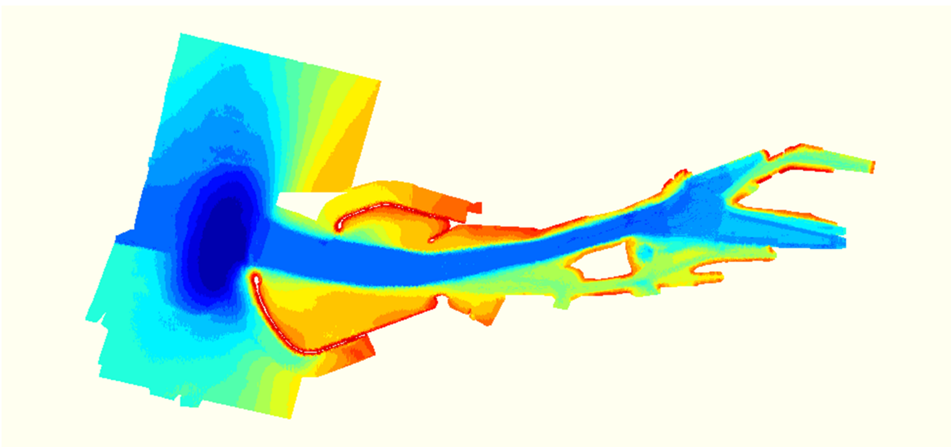


Figure 4.2: Added bathymetry dataset, obtained from Lely (2023)

Regarding the remaining bathymetry, measurement data taken in 2017, sourced from Vaklodingen and the Royal Netherlands Navy, is used. Further description can be found in the report of Deltares (2022).

4.1.3. Boundary Conditions

As outlined earlier, real-time wave, wind and water level data are incorporated at the boundary of the flow and wave module grids (see APPENDIX D). To expedite simulation time, multiple simulations have been performed where a single wave and wind condition is imposed. This method aims to assess the system response under particular conditions.

Derived from the reduced wave climate identified by Tonnon, Werf, and Mulder (2009), ten representative conditions have been selected (See Table 4.1). These conditions are incorporated into the model at the flow and wave grid boundaries, ensuring one condition is constantly present throughout a simulation. The conditions are imposed in the model at the flow and wave grid boundaries. However, the tidal signal remains consistent with the original model.

Table 4.1: Reduced wave climate of 'Europlatform' and 'Meetpost Noordwijk' obtained from Tonnon et al. (Tonnon, Werf, and Mulder, 2009)

Wave condition	$H_{1/3}$	$T_{1/3}$	θ_{wave}	V_{wind}	θ_{wind}	Weight factor
	m	s	°N	m/s	°N	-
1	1.48	5.34	232	9.97	231	0.1224
2	2.46	6.34	232	13.37	227	0.0685
3	1.97	5.99	246	11.09	210	0.0118
4	1.48	5.45	261	8.24	197	0.0006
5	2.47	6.53	277	11.44	175	0.0460
6	2.97	7.00	277	13.30	171	0.0109
7	1.97	6.59	322	8.65	126	0.1206
8	2.96	7.71	322	11.93	127	0.0036
9	1.47	6.07	337	5.69	107	0.0652
10	0.96	5.63	352	3.62	73	0.0823

4.1.4. Computational time

Given the considerable computational time required by this model, a morphological acceleration factor of four (MORFAC = 4) is implemented to reduce this duration. Nonetheless, it still takes roughly 15 days to compute one morphological year.

4.2. Model validation

To assess the ability of the Delft3D-FM model to accurately represent the complex processes at IJmuiden, a validation is carried out. This validation is specific to the processes near the port of IJmuiden (See Section 2.4), providing additional detail to the thorough validation performed by Deltares (2022). They concluded that the model demonstrates reasonable morphological predictive skill for simulating large-scale human interventions that mainly rely on longshore processes.

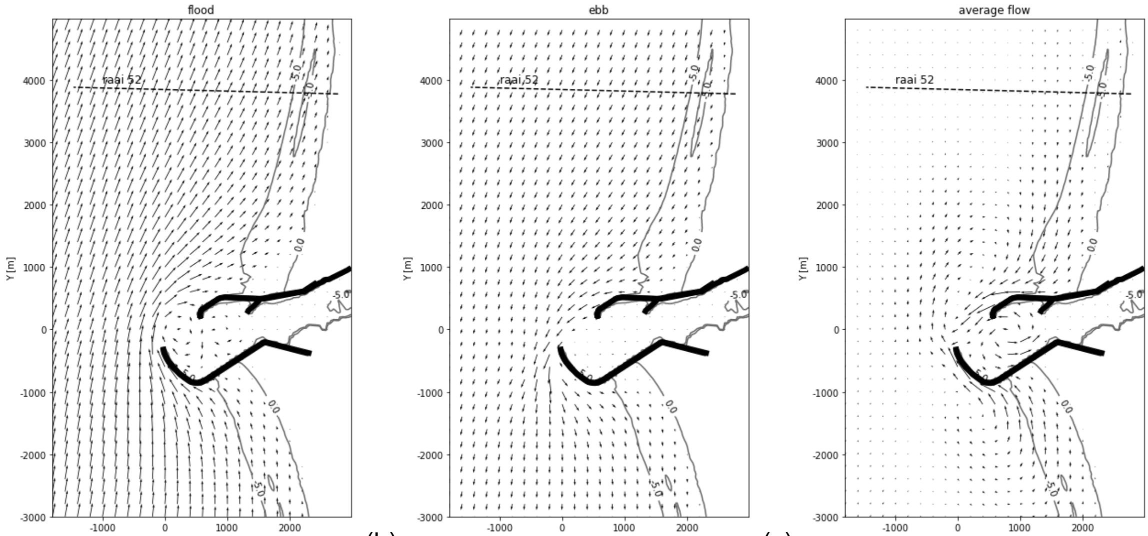
To address the long simulation times, for the validation performed, it is chosen to perform multiple short-term simulation under a single boundary condition. Using this method we aim to assess the response of the system under different conditions.

This section initially explores the model's capacity in simulating the complex tidal flow situation, calculated without the influence of waves and wind. This is followed by an validation of the simulated sediment transport patterns, and thirdly the morphological developments are validated.

4.2.1. Tidal flow patterns

Modelled flow and sediment pattern align with the processes described in literature (See section 2). Figure 4.3 and Figure 4.4 presents the modelled flow and sediment transport patterns, simulated over one tidal cycle. In this scenario, no wave and boundary are assumed, indicating that the patterns observed are purely a consequence of the tide.

The figures presents similar visual flow patterns as presented in figure 2.7. The complex pattern with the eddy generated during flood is considered to contribute to the sedimentation of channel and port.



(a) (b) (c)

Figure 4.3: Flow streamlines of a simulation conducted without the influence of waves and wind over one tidal cycle: (a) Flow during flood; (b) Flow during ebb; (c) Average flow.

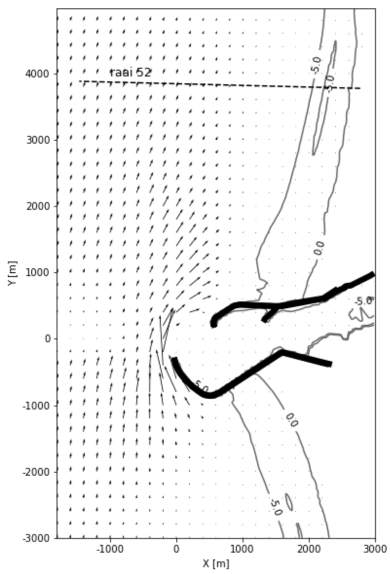


Figure 4.4: Simulated mean sediment transport patterns during one tidal cycle without the influence of waves or wind

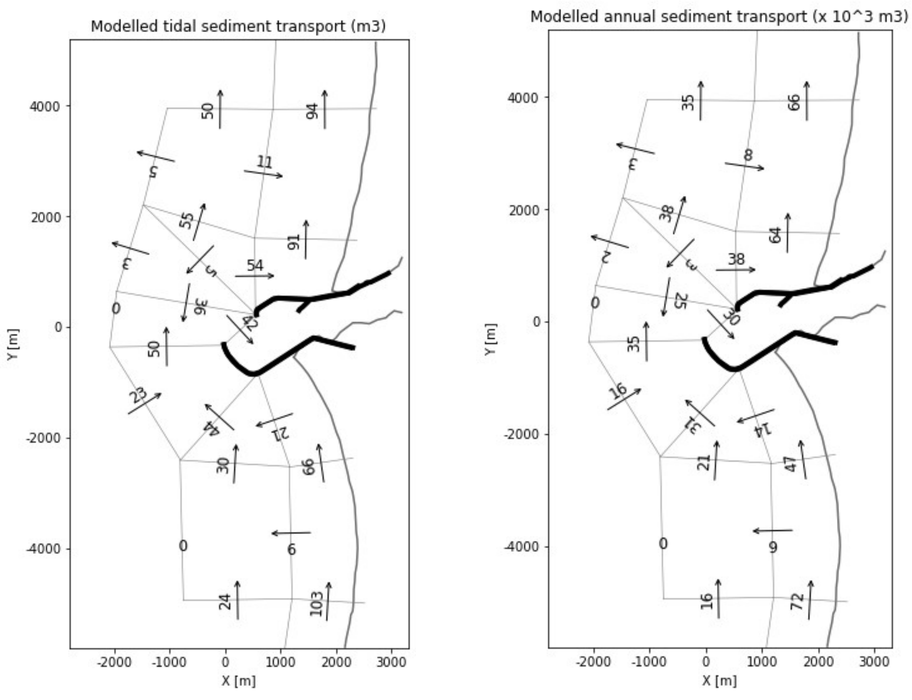
Moreover, stronger currents during flood compared to ebb is observable in the figure 2.7. This difference in velocity, originated by tidal asymmetry, results in a net south-to-north sediment transport, which is reproduces in Figure 4.4.

Given Deltares (2022)'s conclusion on the model's capability to accurately reproduce tidal signals and water levels. Together with the qualitative validation performed, it is assumed expected that the model is capable of reproducing the tide induced flow and sediment transport near IJmuiden.

4.2.2. Sediment transport patterns

A parallel online methodology, introduced by Tonnon, Werf, and Mulder (2009) is used to estimate the annual sediment transport patterns.
executes short-term simulations for each of ten conditions over a single tidal cycle. The resulting sediment transports across various cross-sections are then weighted and averaged to provide estimates for annual sediment transport volumes.

Implementing this methodology in this study yields slightly differing sediment quantification (Figure 4.5), compared to those calculated by Luijendijk et al. (2011) (Figure 2.3). Also the patterns just north of the IJmuiden port present different patterns than expected. This could indicate an underestimation of the southward directed sediment transport just north of the breakwaters. The figure 4.5 presents that around 72 000 m^3 per year is transported into the system in the surf zone. This is around half of the assumed alongshore transport of 140 000 m^3/yr.



(a) Tidal cycle (b) Annual

Figure 4.5: Modelled weighted cumulative sediment fluxes of 10 simulated wave conditions during one tidal cycle (a) and multiplied by 705 to estimate annual transports (b). The figures have been rotated by 13 degrees counter-clockwise.

Sediment inflow during NW storm conditions

From sediment transport calculations through the port entrance it is visible that condition 8 (NW Storm) yields the largest sediment inflow into the port
While these observations do not provide a quantitative validation of the model's performance, they are consistent with expected system responses. As such, these results are viewed as a qualitative indication of the model's predictive skill in representing sediment transport.

4.2.3. Morphological validation

Deltares (2022) performed a morphological validation study to examine the predictive skills of the DCC-FM model. In the validation, the morphological development of the Sand Engine[2]. However the predictive skill of the cross-shore behaviour is less accurate (Deltares, 2022). Diffusive processes smoothened breaker bars with consequently coastline retreat. Overall, it was concluded that the for

[2]Sand Engine or 'Zandmotor' is a Dutch coastal management pilot where large volumes of sand (Mega nourishment; 22 Mm3) is deposited near Den Haag.

Table 4.2: Modelled cumulative sediment transport (m^3) over 1 tidal cycle, inflow into the port, for the ten conditions of the reduced wave climate proposed by Tonnon, Werf, and Mulder (2009).

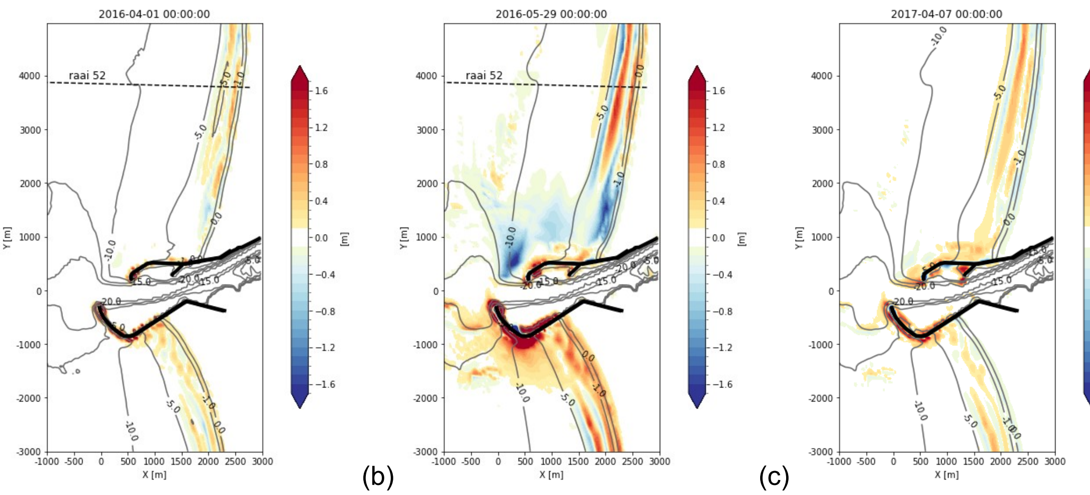
Condition	Sediment inflow into Port (m^3)
1	668
2	914
3	804
4	896
5	839
6	851
7	973
8	1745
9	860
10	581

the purposes of the DCC project, a comparison in between different nourishments, the model skill is within the acceptable limits.

Multiple simulations are performed to predict the morphological development under varying wave conditions. Figure 4.6 presents the resulting bed level changes compared to initial state, for a simulation under normal SW conditions, under SW storm conditions and under full wave climate (Brute Force).

These figures present clear sediment accumulation at the southern side of the breakwater, especially during SW storm conditions (See Figure 4.6b). Indicating that sediment transport obstruction by the breakwater is indeed captured by the model. Also accumulation directly adjacent to the northern breakwater can be observed. This could be explained either by the shadowing effect of the breakwater or by the divergence of the flow bypassing the harbor, thereby, reducing in velocity and causing sedimentation.

The smoothening effect, introduced by the Delft3D model shortcomings, is observed in the simulations, as the infilling of alongshore troughs and erosion of the beach and bars.



(a) (b) (c)

Figure 4.6: Simulated Bed Level Changes: The figures illustrate bed level alterations compared to the initial state at 2016, 1st march, under various conditions. (a) Depicts changes after 1 month under normal SW conditions (Hs=1.46; Dir=232°N), while (b) represents changes after 3 months under SW storm conditions (Hs=2.46; Dir=232°N). (c) Presents the variations under the full wave climate or Brute-Force after 13 months, with the simulation commencement dated March 3, 2016

4.2.4. Model Performance Conclusion

The processes critical to channel and port infilling, outlined in chapter 2, include eddy generation and streamline expansion during flood flow, direct inflow of sediment during ebb flow, sediment swept into the harbor during northwest storms, and sedimentation caused by progressing sand waves.

Both the eddy and streamline expansion are observed during the performed simulations (See figure 4.3. Further, longer-term simulations could present the effect of streamline expansion on sedimentation at the northern breakwater. The model also successfully reproduces direct sediment inflow during ebb flow and significant sediment inflow under northwest storm conditions.

However, the progressing sand waves into IJgeul is not observed during simulations. Longer timescales are required, even though the model might struggle to simulate this progression (Luijendijk, personal communication, 2023).

Although the sediment transport pattern are generally in line with the patterns observed in literature. There seems to be a underestimation of the alongshore sediment transport. Where calculations estimate 72 000 m^3 per year into the system where literature indicates alongshore transport of 140 000 m^3/yr. This underestimation could be the result of the grid cells being too coarse (50m x 50m), for which wave breaking is not fully captured. This underestimation with a factor of two is used during further calculations in this thesis.

The morphological validation indicates that the model replicates global morphological changes such as sediment accumulation on the south side during SW conditions, and sedimentation adjacent to the northern breakwater, potentially indicating the shadow effect. However, the prominent smoothening effect in the model complicates the discernment of actual morphological changes from model shortfalls.

In general, despite the model's proficient representation of hydrodynamic processes, the quantification of sediment transport is not adequately depicted. Nevertheless, the general direction of these sediment patterns is well captured. The morphological validation highlights that errors are introduced by the model regarding erosion and sediment accumulation due to the smoothening effect. Consequently, it is concluded that the model is better suited for exploring broad trends and patterns rather than generating precise quantitative values. The model's limitations, along with its long computation time and instability, should be taken into account when interpreting results and defining the scope of the study.

4.3. Simulation Methodology

The methodology in this study involves utilizing hydrodynamic and morphological simulations using the adapted DCC-FM model, to investigate the effect of alternative inlet and outlet concepts on sediment transport patterns. This section outlines the simulations performed and the incorporation of the bypass concepts into the model.

The method first employs a short-term (one tidal cycle) hydrodynamic simulation, using anticipated bed formations. This simulation aims to represent an estimated future state. The short simulation time offers the the possibility to assess the system behaviour under varying wave and wind conditions.

Secondly, short-term morphological simulations (1 - 3 months) are carried out, with different conceptual designs tested under south-west wave and wind conditions. This simulation offers the system to adapt to the bypass concepts. Here, sediment disposal is incorporated as a continuously added discharge of a slurry mixture at specific locations. The concentration of the added slurry discharge is kept relatively low to enhance dispersal during these short-term simulations.

Finally, a brute force simulation is carried out in which real time wave, wind and waterlevel data is assumed, as described in the model set-up section. In this simulation only the outlet concept is incorporated. Due to the long simulation time of (15 days for one year), just one alternative is simulated.
This methodolgy treads the inlet and outlet of the fixed bypass system as distinct components, each serving its purpose. The inlet is aimed at reducing channel and harbor infilling by preventing bypassing,

while the outlets aim to enhance coastal stability (minimize or avoid erosion) by depositing sediment at the downdrift coast.A schematic representation with the progression of these methods are presented in figure 4.7.

Furthermore, the ecological assessment is based on the outcome of the morphological simulations using the Benthimeter. The development and description of this tool is treated in APPENDIX A.

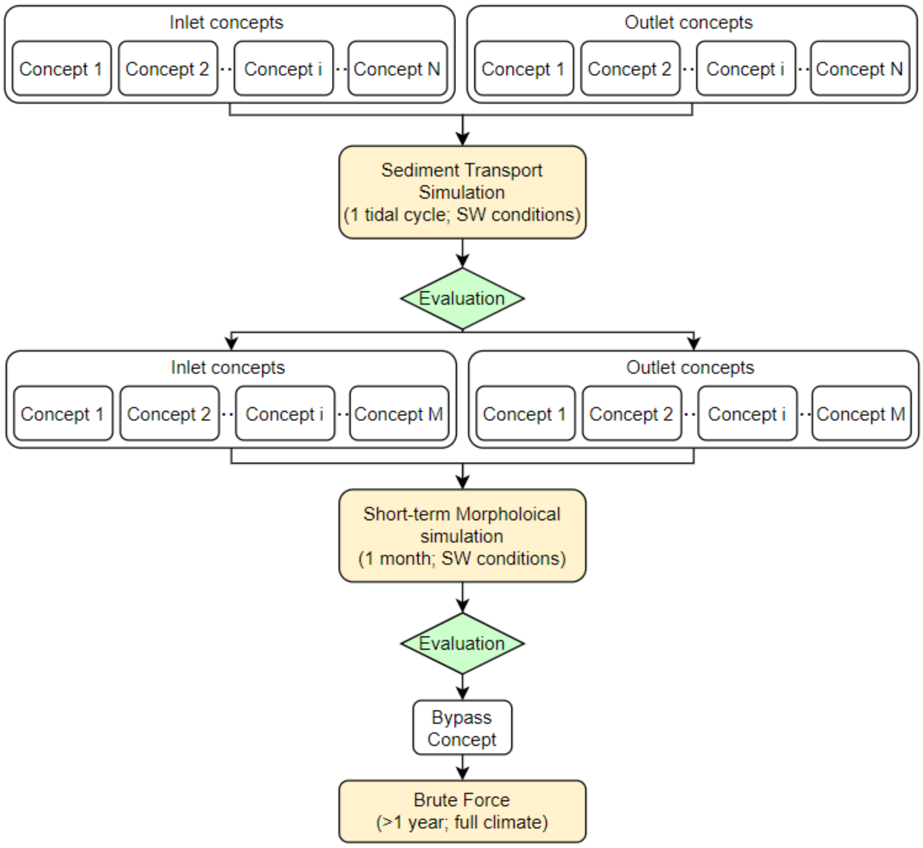


Figure 4.7: Methodology flowchart

4.3.1. Short-term Hydrodynamic Simulation (1 tidal cycle): Anticipated Future Bathymetry.

This simulation evaluates the impact of a future-anticipated bathymetry on sediment transport dynamics across a single tidal cycle. The estimated future state, informed by bathymetries of comparable projects employing fixed bypass systems or continuous point nourishments, is integrated into the model by modifying the bathymetry file. The simulation then runs for one tidal cycle under a specific wave and wind condition to identify any changes in sediment transport patterns.

With the morphological update deliberately disabled (*MorUpdate = false*), it is attemped to reproduce a situation in wich the system has reached a form of equilibrium, having adapted to the fixed bypass system.

The aim of these simulation is to get a quick insight in the potential effects of bypass concepts on the sediment transport. Due to the short simulaiton time of approximately 3-4 hours each, numburous testing of various design components (inlet and outlet alternatives) under differing conditions, is possible.

4.3.1.1. Incorporating inlet alternatives into the model

Inlets are incorporated into the model by adjusting the bathymetry file. To expedite the process, a simplified method of defining cones is used, wherein bed level points within the polygons (shown in Figure 4.9) are lowered to a level relative to NAP (see Figure 4.8). The depth is varied during maximum depth used is 7.5 m, as per Richardson and McNair (1981).

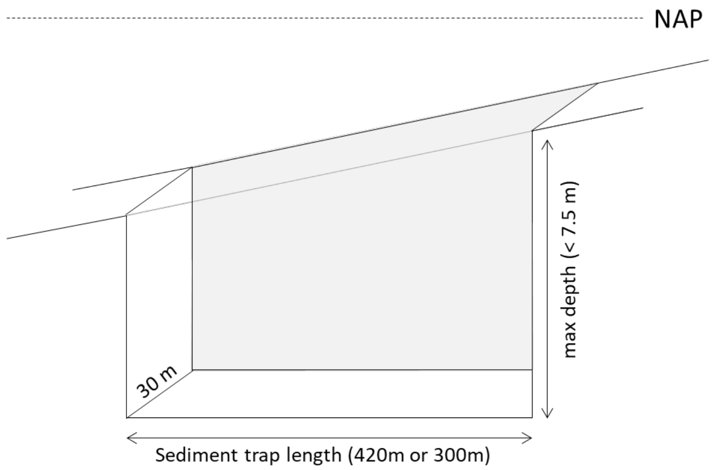
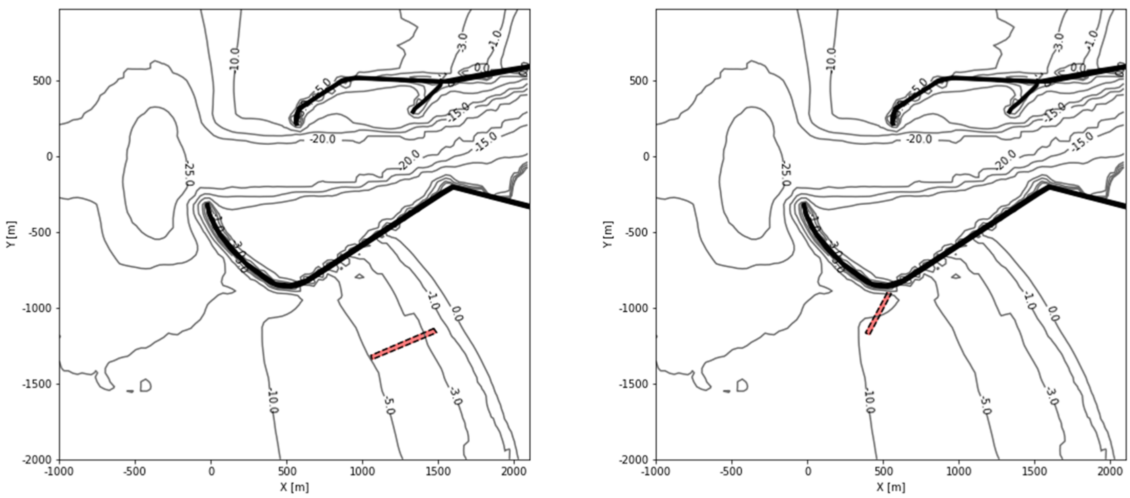


Figure 4.8: Schematized visualization on how sediment trap is incorporated into the model



(a) Jetty from beach

(b) Breakwater mounted Jetty

Figure 4.9: Figure indicating the proposed sediment trap dimensions and location of the two alternatives. (a) Represents the Jetty from beach concept with an sediment trap area of 30m x 420m (15 jetpumps; 30 meters apart); (b) Breakwater mounted jetty concept with a sediment trap area of 30m x 300 m (11 jetpumps; 30 meters apart)

4.3.1.2. Incorporating outlet alternatives into the model

The short-term hydrodynamic simulation (spanning one tidal cycle) utilizes an anticipated topography derived from a previously performed morphological simulations with the DCC FM model.

Figure C.9 illustrates the bed level change after three years of continuous addition of sediment (0.19 Mm^3/year) at two outlet locations at an initial depth of 5 meters. This leads to a total of 1.1 Mm3 over three years.

Due to the difference in specific density between suspended sediment particles ($\rho_s = 2650kg/m^3$) and particles in a granular body ($\rho = (1-n)\rho_s$ with n representing porosity ≈ 0.4), the volume change over three years is 1.87 Mm3 rather than 1.1 Mm3.

The design bypass volume of 140,000 m3/year equates to a bed volume change of 232,000 m^3. This magnitude is comparable to that of the described DCC simulation 33_12a, and it's hypothesized that after several years of simulation, the outlets would display similar shape and height when discharging at a depth of 5 meters.

To evaluate the impact of varying the number of outlets (1; 3; 6) on sediment transport patterns, three different simulations are performed. Figure 4.10 provides an overview of the modified bathymetry for these simulations.

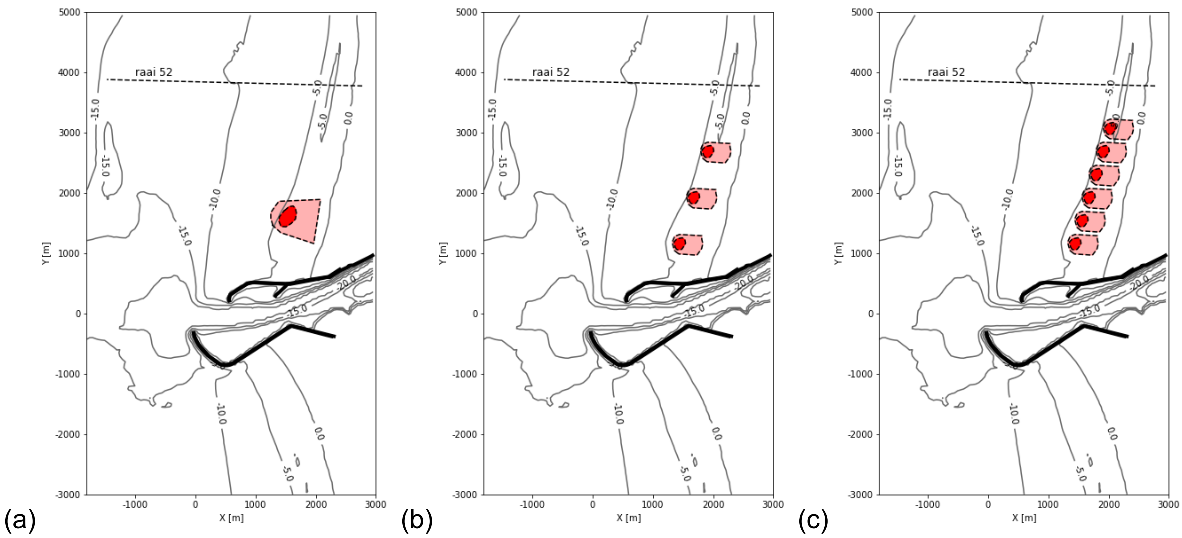


Figure 4.10: Overview of initial outlet test cases for a sediment transport simulation over one tidal cycle: (a) Single outlet, with dark area elevated by 4 m and light area by 1 m; (b) three outlets with dark areas elevated by 3 m and light areas by 1 m; and (c) Six outlets, with dark areas elevated by 1.5 m and light areas by 0.5 m.

The short-term simulations cover a single tidal cycle (12.42 hours). Due to the brief duration, the benthic impact indicator (calculated using the Benthimeter) is not applicable here.

4.3.2. Short-term Morphological Simulation (1 - 3 Months)

This simulation enables morphological updates, allowing the system to adapt to changes in bathymetry. The primary objective is to observe the morphological effects within a relatively short timeframe (simulation time is 1 to 3 days), enabling the testing of multiple design concepts.

To expedite morphological development, only South-West wave and wind conditions are specified, emulating the predominant conditions on the Dutch coast which drive south-to-north net sediment transport. By focusing on these conditions over a shorter period, the aim is to generate transport volumes comparable to annual sediment transport volumes reported in literature. Figure 4.11 presents the sedimen inflow and outflow as simulated for these simualtions under normal SW and SW strom conditions. From these figure we can very roughly estimate that simulations under normal SW conditions for one month respresent roughly 1/10th year. Where the simulation under SW storm for three months is comparable to the general annual alongshore sediment fluxes found in literature.

While translating short simulation outcomes under South-West conditions to represent long-term effects under the full wave and wind climate poses challenges, this approach still offers valuable insights into the system's response to the implementation of fixed sediment bypass components.

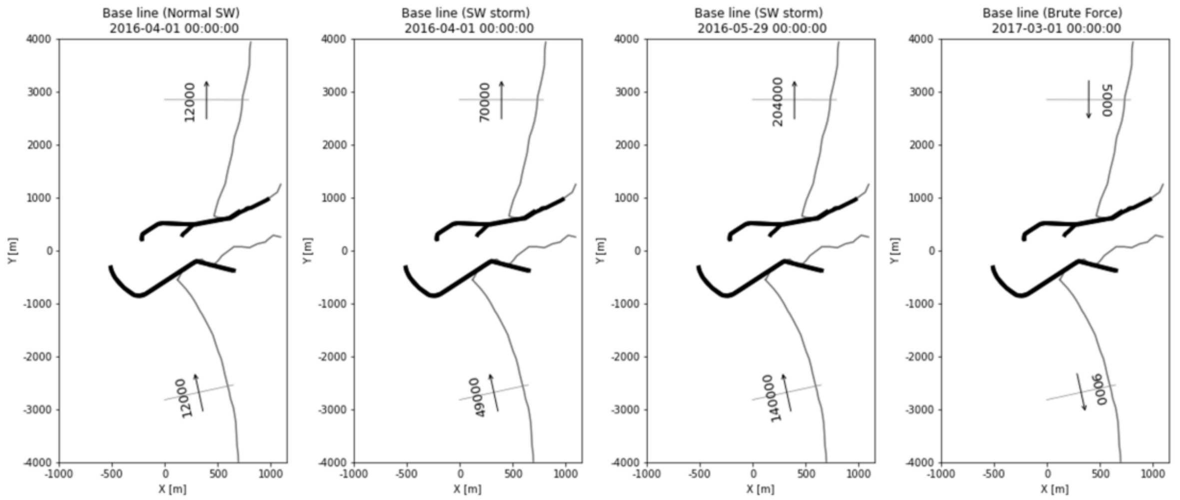


Figure 4.11: Figure presenting the the sediment inflow and outfow at IJmuiden coastal system in m^3, simulated under normal SW conditions (a) for 1 month; under SW strom conditions for 1 month (b) and nearly 3 months (c); Full climate using Brute force after one year (d)

4.3.2.1. Incorporating inlet alternatives into the model

During these simulations, the inlet concepts are incorporated into the Delft3D model, following the same methodology applied in short-term hydrodynamic simulations. Namely, an initial deepening of the bathymetry file within defined polygons, as depicted in Figure 4.9.

Several attempts were made to integrate continuous dredging at jet pump locations and maintaining a minimal depth within the polygons throughout the simulation. Despite the theoretical possibility of these strategies, their practical implementation using the Delft3D software proved to be challenging and could not be achieved within the scope of this study.

The method used, allows the sediment trap area to undergo sedimentation without continuous dredging to maintain its depth. While this method results in a decreasing sediment trap capacity over time and thus may not accurately represent the long-term inlet processes, it provides valuable insights into the duration it takes for the deepened areas to fill. Consequently, this method serves as a useful indicator of the sediment trap capacity.

4.3.2.2. Incorporating outlet alternatives into the model

This simulation method assesses a wide range of concepts with varying outlet number (1 versus 6), distance to breakwater (near IJmuiden versus near Heemskerk), location in shoreface (ranging from -1 m to -5 m depth), and bypass volume (140,000/12 in one month versus ≈140,000 in one month).

In these simulations, the sediment disposal is incorporated as a continuous discharge (m^3/s) of slurry mixture (kg/m^3) at a specific location (x,y). A concentration of 10% by volume is assumed for the added slurry discharge (260 kg/m^3). By maintaining this value relatively low compared to typical slurry transport concentrations (20 - 30% (Venture, 1997)) , it is hoped to enhance dispersal during this short-term simulation.

Table 4.3 provides different input values for three bypass volume concepts. They include: 1) One outlet bypassing 1/12th of the yearly total design bypassing volume in one month; 2) Six outlets collectively bypassing 1/12th of the yearly total design bypassing volume in one month; 3) Six outlets collectively bypassing the yearly total design volume in one month.

Table 4.3: Inputs for Three Different Bypass Concepts Utilized in Short-term Morphological Simulation: An Exploration of Varying Volumes.

Type	Morph. duration (morfac=4)	Sediment bypass volume	Discharge per outlet (m3/s)	Slurry conc. (kg/m3)	Hydrod. duration (s)	Expected dV (m3)
1 outlet	1 month	11,700	0.045	260	669,600	20,000
6 outlets	1 month	11,700	0.0075	260	669,600	20,000
6 outlets	1 month	140,000	0.087	260	669,600	230,000

4.3.3. Brute Force simulation: Full Climate

In this simulation, we maintain the original model boundary setup, which incorporates historical wave, wind, and water-level data from March 1st, 2016 to March 1st, 2022. Due to the exceptionally long simulation times, however, it was not feasible to simulate long term effects. For instance, with a Morphological Factor (MorFac) of 4, simulating a single morphological year took 15 days. Consequently, the simulation is limited to just 14 months, incorporating one bypass concept (Six Outlets, From Beach) and a baseline scenario without a bypass.

Unfortunately, it was not succeed to include the inlet processes into the model. As a result, only an outlet concept was simulated using this method.

The inflow and outflow sediment fluxes computed a year after simulation start (expressed in m^3 and presented in Figure 4.11)(d) suggest a net southward sediment transport for the simulated period from March 1st, 2016 to March 1st, 2017. As revealed in the appendix B.5, 2017 experienced a net southward transport along the Dutch coast. Since our simulation started in March 2016, and proceed in the beginning of 2017, this could be the cause of the simulated southward transport. Alternatively, an overestimation of the southward sediment transports observed during the sediment transport validation, could explain these findings.

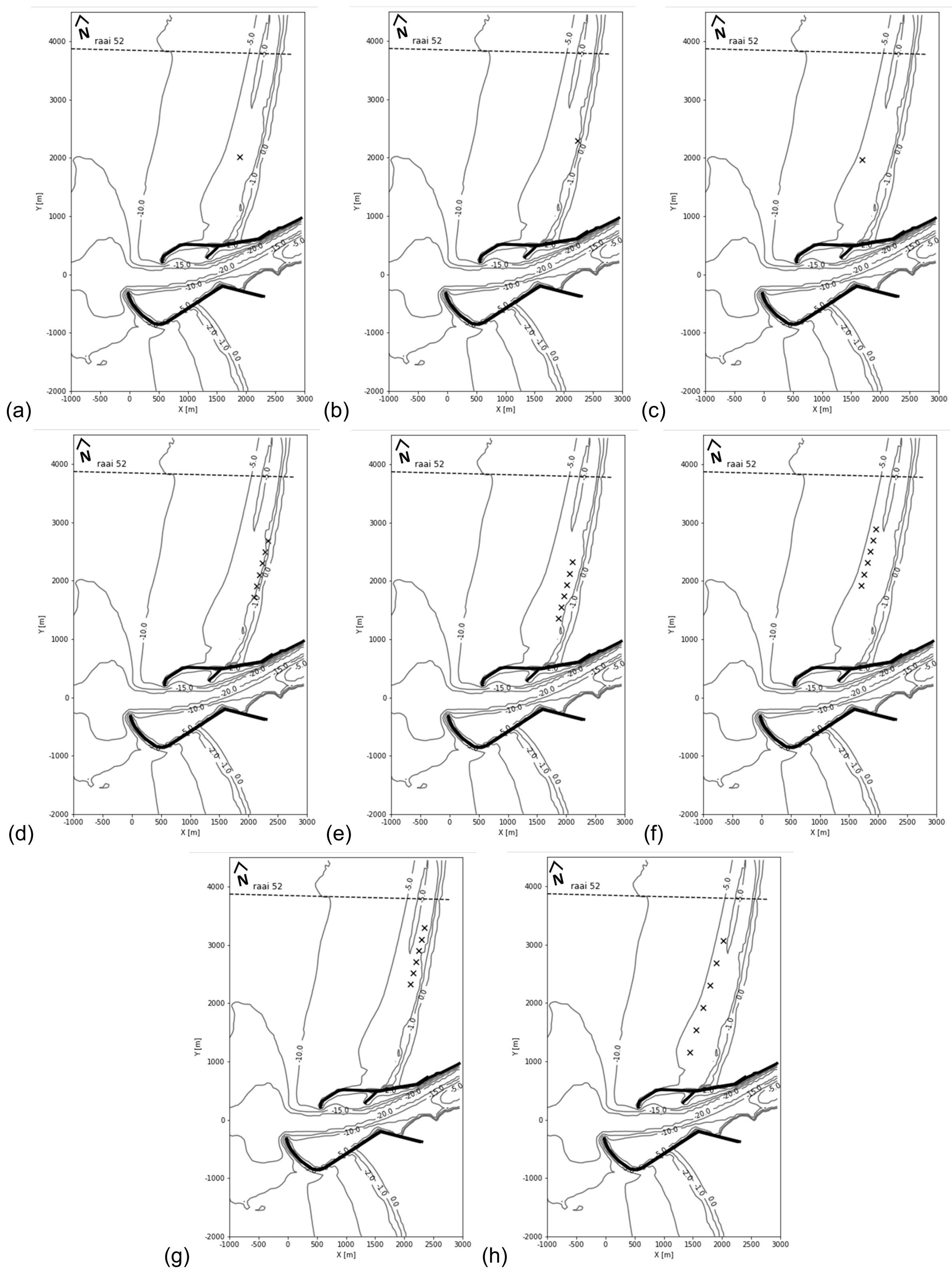


Figure 4.12: Overview of the proposed outlet location concepts at which continuous discharge of sediment slurry mixture is disposed in the model. (a;b;c) are single outlet concepts in which the yearly design bypass volume is equally deposited throughout the year. (d;e;f;g) concepts with equally spaced (200 m) six outlets varying in location and the yearly design bypass volume is equally deposited throughout the year. (h) concept with six outlets location spaced 500 m apart, and the total design bypass volume (140,000 m3/year) is added during one month.

5 Benthimeter Development

This chapter presents the development of the benthic impact evaluation tool, named the Benthimeter. First, a background into the benthic life will be provided, followed by the development of the tool itself. It should be noted that this method marks an innovative attempt to include ecology in coastal practices. The results and calculations performed using the Benthimeter should not be interpreted as true since no validation is performed, and the tool is based on a simplistic representation of the complex ecological interactions.

5.1. Literature Benthic

Depositing large amounts of sediment directly buries the benthic animals within the deposition area. It is generally believed that sediment layers thicker than 50 cm are lethal for most animals (Herman et al., 2021). Second, altered morpho- and hydrodynamics can cause indirect effects, such as increased sedimentation in nearby areas, leading to the indirect burial of benthic communities. Another indirect effect of heightening an area can be long-term habitat modification, altering the ecotope[1] and therefore animal occurrence and distribution.

Benthic diversity is often used to describe benthos as indicator for the system functioning. The diversity or specie richness is a quantification that relates to the number of species in an area. Generally it is observed that for increasing disturbance, the number of species reduces. Figure 5.1 provides an example of this pattern based on the work of Pearson and Rosenberg (1978). The peak of the abundance (nr of animals) can be explained that particular species can withstand certain levels of disturbance and can therefore thrive without the presence of other species.

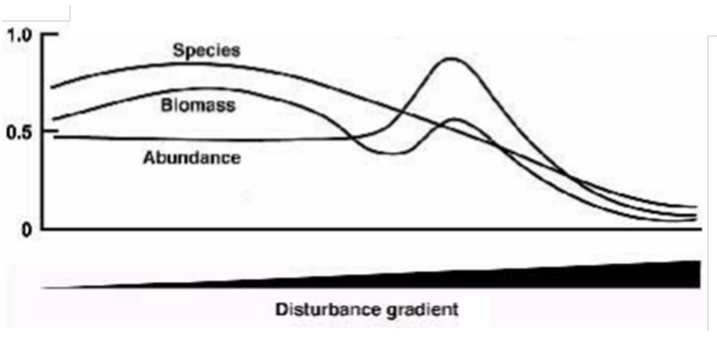
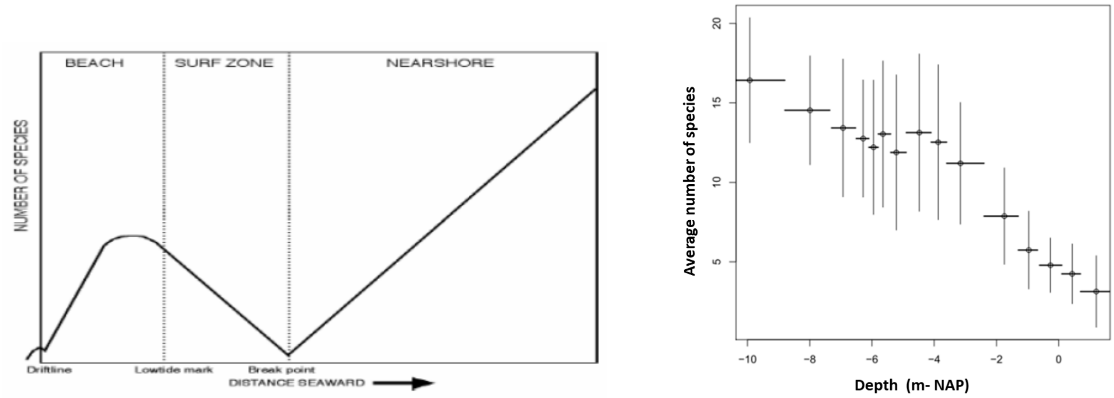


Figure 5.1: Generalised diagram for the gradient in species richness (species), numbers (abundance) and biomass (biomass) along the disturbance gradient (Moorsel, 2005)

[1]An "ecotope" is A physically limited ecological unit, whose composition and development are determined by abiotic, biotic and anthropogenic aspects together (Tansley, 1935)



(a) (b)

Figure 5.2: Relationship between number of species and (a) distance to shore (Brown and McLachlan, 1990), and (b) depth group A (Weibull + Normal) and (b) group B (Logistic function) describing carrying capacity related to depth (Herman et al., 2016)

5.1.1. Benthic diversity patterns at coastal areas

Benthic community presents a highly variable pattern in occurrence, annually but also locationally, due to the many influencing factors such as flow rate, turbulence, presence of predators, food availability, and sediment characteristics Bouma et al., 2005. Consequently, constructing relations to describe or predict a specific area's diversity becomes challenging.

Despite this, the relation constructed by Brown and McLachlan (1990) is one that is frequently used. This relations indicate the trend of increase in in diversity for an increasing distance from coast (Janssen and Mulder, 2004; Brown and McLachlan, 1990). It also indicates an increase in diversity from break point towards the beach.

A number of studies have been conducted to refine this conceptual model (Vergouwen and Holzhauer, 2016; Herman et al., 2016; Baptist et al., 2012; Janssen and Mulder, 2004; Ysebaert and Herman, 2002; Armonies, Buschbaum, and Hellwig-Armonies, 2014; Kröncke et al., 2018). These studies generally agree on an increase in diversity in deeper waters. However, the existence of a minimum at break point followed by an increase in diversity towards the beach, is disputed in literature (Holzhauer et al., 2019; Herman et al., 2016). Some, reason the high-energy nature of the surfzone complicates sampling and interpretation of results.

Coastal habitats have also been described based on depth, which is easy to measure and the depth is a relevant indirect factor for the present of ecotopes (Herman et al., 2016). See Figure 5.2(b) for an example of such description of the diversity related to the depth.

Ecosystem effects of nourishment is separated into direct impact as a result of burial by the dumping of sand. And indirect effect as a result of a change in hydro - and morphodynamic conditions and therefore in habitat.

5.1.2. Benthic response to burial

The effect of burial on species depends on known factors, as described in a number of studies (Kjeilen-Eilertsen et al., 2004). (Baptist et al., 2009))(Bijkerk, 1988)(Essink, 1999)). Overall, the effect of burial predominantly relies on organisms' mobility and the sedimentation rate (Baptist et al., 2009). Sedentary species, often found in deeper, more stable substrates, exhibit limited mobility, making them highly sensitive. Fatal burial depths in the order of centimeters is described (Essink, 1999; Bijkerk, 1988; Herman et al., 2021; Smit et al., 2006; Kjeilen-Eilertsen et al., 2004). Conversely, species with greater mobility, typically residing in the energetic breaker zone, display better resilience, surviving burial depths up to 1 meter due to their adaptation to dynamic conditions (Essink, 1999; Bijkerk, 1988; Herman et al., 2021; Smit et al., 2006).

Besides the burial depth, fatigue can play a role. Baptist et al. (2009) describes that continues depositon of material can reduce tha ability of animals to dig out of the layer over time. This is especcially significant when the depositon is fine material (silt) (Baptist et al., 2009). Since bypass systems have a continous nourishment character this can be a potential implication for benthic life.

5.1.3. Recovery

Recovery of a disturbed area may take place by immigration from its surroundings and by settlement of larvea from the water column. At nourished area some of the benthos may survive the burial and can contribute to the recovery of the local community. Also import of Benthos that survived the extraction site may contribute to the recolonization (Dalfsen and Essink, 2001).

In general, recovery of species can be divided in r-strategists and k-strategist. R-stategists are recognized as fast-reproducing, fast growing opportunistic species. While k-strategist are the larger, long-living, slow reproducing species (Shepherd and Stojkov, 2007).

In dynamic coastal ares of the Netherlands recovery of benthic community is relatively fast. No long lasting effects on the benthos are expected of a single disturbance event. Complete recovery of community is estimated to take 2-4 years (Dalfsen and Essink, 2001).

5.2. Benthimeter

By the development of the *Benthimeter*, an attempt is made to visualize and quantify the impact on the benthic community. The quantification is calculated as the *total ecological impact*. This is the difference between the total ecological value of the base line simulation and the calculated total ecological value over the entire grid area (See equation A.10), and is expressed in *ha*. The translation of this 'ha' metric into tangible ecological damage presents challenges and is beyond the scope of this research. Therefore, the quantification serves solely as a tool for comparing different strategies.

One key measure introduced by this approach is the *normalised benthic diversity N* (-), a metric that quantifies the diversity of a specific grid cell within a designated area. The N values can range between 0 and 1, with a higher value indicating increased diversity. The *normalised benthic diversity* N (-) of cells in the area of interest, are multiplied by their area A (ha). The summed value represents the *Ecological value* (ha) at a certain time.

$$Ecological\ value\ [ha] = \sum N_i \cdot A_i \tag{5.1}$$

$$Ecological\ damage\ [ha] = Ecological\ value_{ref} - Ecological\ value \tag{5.2}$$

Figure A.1 present the method utilized in the Benthimeter to calculate the *normalised ecological value* of a cell each time step. In this approach, the normalised diversity of a cell depends on three factors, namely the amount of burial damage, the level of recovery and carrying capacity of a cell. The carrying capacity for benthic diversity is defined as the maximum diversity a habitat (grid cell) can sustain. The carrying capacity is reached when the diversity of a habitat is fully recovered after being damaged by burial. In this method, it is assumed that at time zero (before nourishment), the diversity of cells in the grid are undisturbed (i.e. calculated according to the carrying capacity relation of Figure A.2). The diversity changes exclusively due to nourishment initiated bottom change, i.e. a bed level correction is made to correct for the bottom change in the reference situation as seen in formula A.11. In addition, carrying capacity determines the degree of recovery following the seasonal dependent logistic recovery model (see function 5.4). In summary, the ecological indicator to evaluate the state of the benthic population, expressed as *normalised benthic diversity*, is acquired by performing three calculations for each timestep for each gridcell:

- Computing the carrying capacity
- Computing burial damage
- Computing the recovery of the benthic diversity

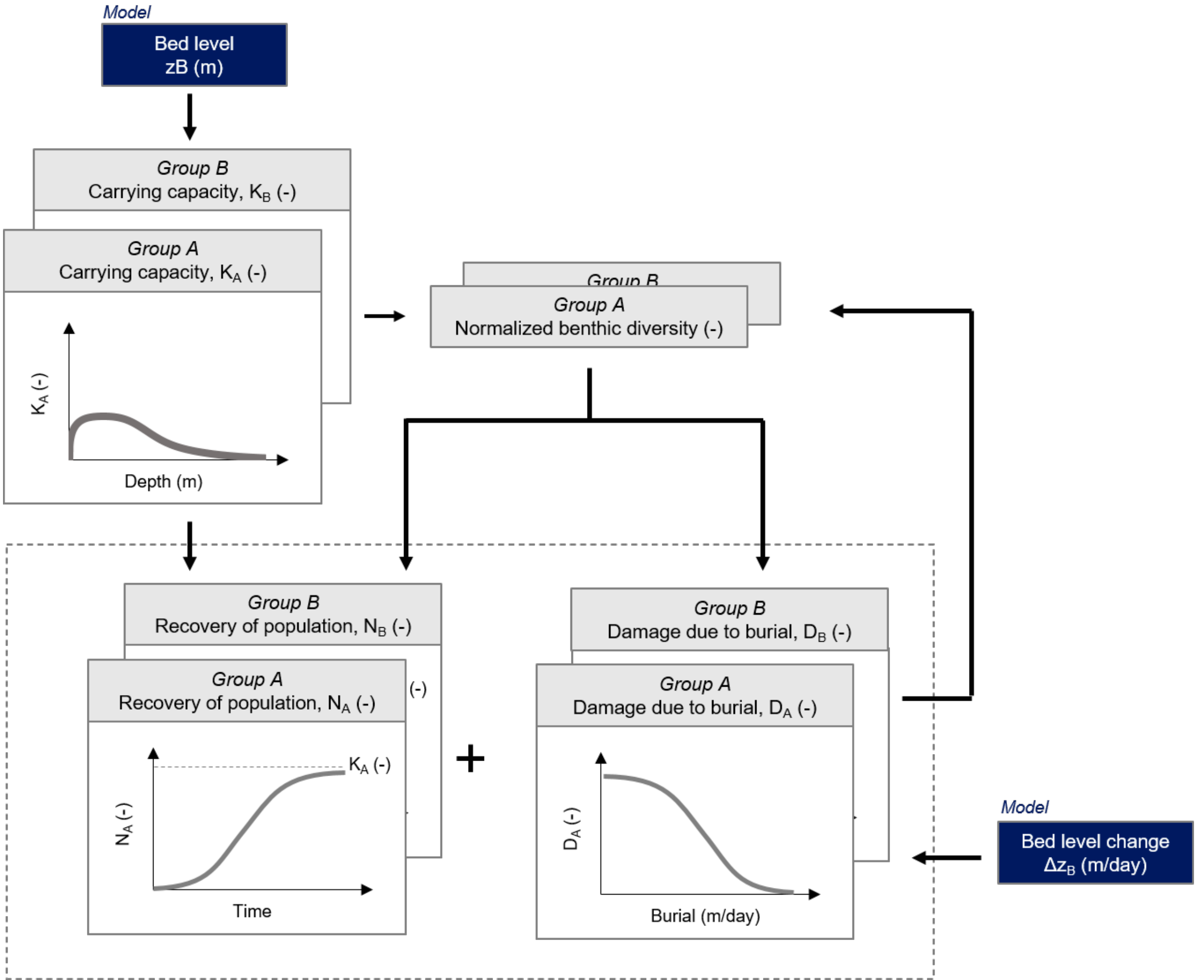


Figure 5.3: Benthimeter flowchart of the calculation performed every timestep to estimate the benthic response to bed level change.

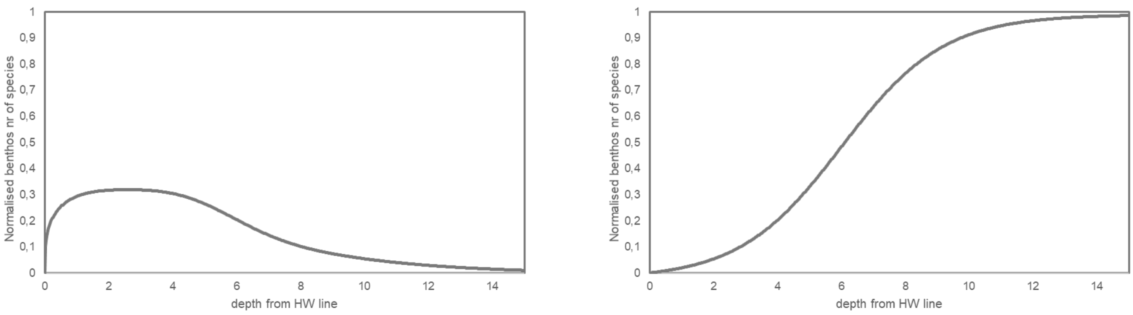
5.2.1. Grouping of species

The normalised benthic diversity is calculated separately for two distinct groups of benthic species, and then combined to determine the total diversity of a cell at a given timestep. This division is made based on species mobility, with Group A representing mobile species and Group B denoting less mobile species. This division is based on statements and burial data acquired from earlier research (Baptist et al., 2009; Bijkerk, 1988; Herman et al., 2021; Smit et al., 2006). In Appendix A.16 the groups can be found.

5.2.2. Carrying capacity

Carrying capacity, defined as the maximum diversity that a particular environment can support, is utilized in the Benthimeter to:

- Establish the initial *normalized benthic diversity* of a cell at (t=0)
- Define the maximum *normalized benthic diversity* a cell can reach
- Establish the degree of recovery
- Establish the extent of damage due to habitat modification



(a) (b)

Figure 5.4: Functions for (a) group A (Weibull + Normal) and (b) group B (Logistic function) describing carrying capacity related to depth.

The carrying capacity for each group (A & B), is constructed based on described Dutch coastal benthic diversity pattern found in literature (see Figure A.2) ((Holzhauer et al., 2019); (J. A. van Dalfsen, 2009); (Janssen et al., 2008); Armonies, Buschbaum, and Hellwig-Armonies, 2014). In particular the study Holzhauer et al. (2019) and Herman et al. (2016) was used since they studied not only the occurrence of species along the cross-shore but also described the morphological features of the cross-shore with the accompanying depth ranges. Therefore, besides the depth of a morphological feature, also the dynamics are provided, and can used as indications for the occurrence of type of species (Group A or/and B) (See Appendix A.20)

The resulting carrying capacity relations, present the main patterns found in literature, namely generally lower diversity in energetic region while the species richness increases in deeper, calmer regions. Besides, typical mobile species (group A) are better adapted to deal with high hydrodynamic stresses and thus the distributions of species over space varies for different groups (Janssen and Mulder, 2005,Armonies, Buschbaum, and Hellwig-Armonies, 2014,Baptist et al., 2009).

5.2.3. Benthic response to burial

To calculate the impact of burial on benthic diversity, the tool uses bed level changes simulated with a Delft3D model. A distinction has been made between direct and indirect burial. Direct burial is defined as the immediate increase in bed level resulting from events such as sediment deposition. In contrast, indirect burial is described as the progressive morphological change over time due altered natural processes.

There is a clear difference in burial tolerance between more mobile species (group A) and less mobile species (group B). Typically, the mobile species exhibit greater resistance to burial, with fatal burial depths ranging from 10-110 cm. Conversely, less mobile species display fatal burial depths between 1 cm and 10 cm (Baptist et al., 2009; Bijkerk, 1988; Herman et al., 2021; Smit et al., 2006).

The method proposed by Smit et al. (2006) is employed to estimate the damage to benthic diversity due to burial. This method involves fitting fatal burial depth data for various species to a cumulative log-normal distribution, as shown in APPENDIX Figure A.16. The Species Sensitivity Distribution (SSD) curve is then transformed into a survival distribution (= 1-SSD), depicted in Figure 5.5.

The proportion of surviving benthic diversity at each timestep is computed using Equation 5.3. The parameters introduced in this equation are described in more detailed in APPENDIX A.

$$N_{t+1} = N_t \cdot (1 - SSD) \tag{5.3}$$

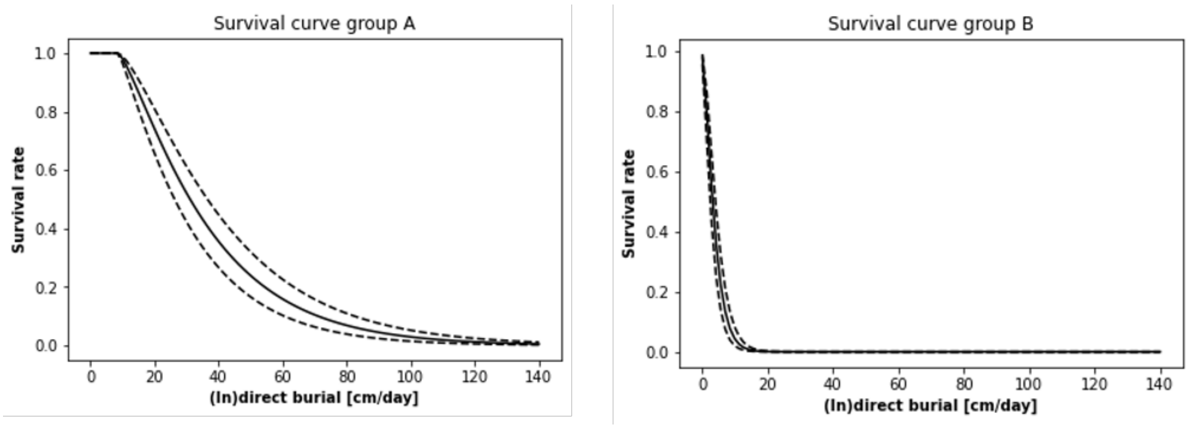


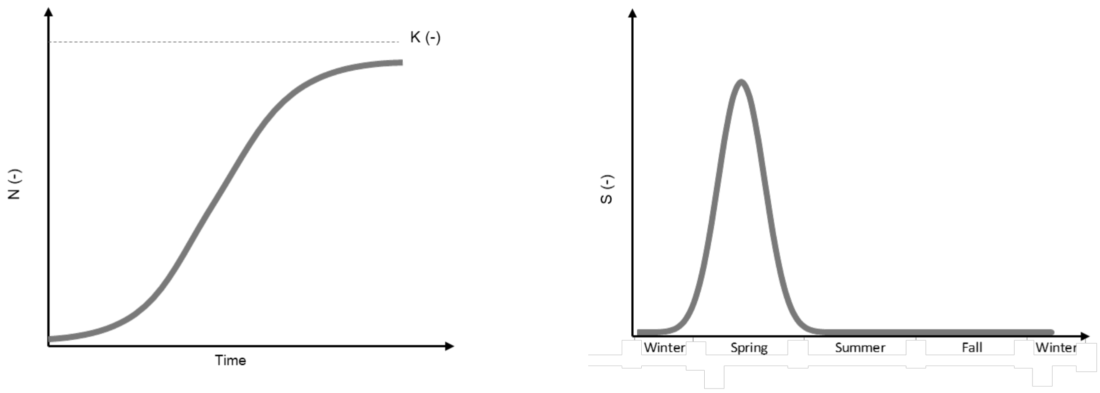
Figure 5.5: Relations used to calculate the fraction of *normalised benthic diversity* surviving a coverage of sediment layer with a certain thickness. Left figure presents the survival curve of the mobile species group (Group A) and right figure, the less mobile species (Group B).

5.2.4. Recovery

The recovery of *normalised benthic recovery* is included in the *Benthimeter* through the reproduction mechanism. Adult immigration is excluded due to it's debatable significance and due the limited data on this mechanism. The complexity of measuring the immigration distance of a benthic animal, speaks for itself.

The restoration of the benthic diversity through reproduction is described by a logistic growth function. This growth model is based on the population growth model described by Shepherd and Stojkov (2007). Logistic growth curves generally provide an effective abstraction of the complex recovery dynamics of benthic communities. As Function 5.4 depicts, the amount of recovery is dependent on the current normalised benthic diversity of a cell N (-), the depth-dependent carrying capacity K (-), a value for the reproduction rate r (-/year), and a seasonal (time) dependent multiplication function S(t).

$$\frac{dN}{dt} = S(t) \cdot r \cdot \left(\frac{K-N}{K}\right) N \tag{5.4}$$



(a) (b)

Figure 5.6: Conceptualized graph presenting the (a) the logistic growth curve, and (b) the course of the seasonality factor during the year (Equation 5.4).

When the reproduction rate increases, carrying capacity will be reached more quickly. Fast-reproducing opportunistic species frequently recover completely after total damage within a year, whereas for slow-reproducing species can take up to four years (Dalfsen and Essink, 2001). Varying values for the reproduction rate are imposed for the mobile and less mobile groups (Gittenberger and Loon, 2011). Based on typical reproduction rates, provided by Baptist et al. (2012). The used values obtained during calibration are provided in A.10.

In the current version of the Benthimeter, migration processes are not yet considered. For small-scale disturbing events, this mode of recovery may have a significant contribution to the total recovery of the benthic population (Moorsel, 2005).

5.2.5. Uncertainty analysis

The 'Benthimeter' offers an unique function that enables the user to define site specific variables as stochastic parameters with a certain uncertainty. By means of Monte Carlo[2] method parameter value are randomly sampled from a defined normal distribution, and used to calculate response of benthos to nourishments. The user can define the number of runs to create confidence intervals, however in this study 1000 runs is used. In this version of the *Benthimer* only a limited number of variables are defined as stochastic variables with a normal distribution. See Figure A.10 for the site specific variable under which the stochastic ones. However, it must be noted that part of the uncertainties of the variables are based on educated guesses. Therefore, the term simulation intervals is rather used than confidence intervals, to present the uncertainties. See figure for an example of a calculation performed on earlier simulated by the Dutch Coastline Challenge.

Figure 5.7 presents an example of the application of the 'Benthimeter' on a 10 year simulation in which the Sand Engine have been replicated and incorporated in a Delft3D model for the coast of Egmond. The Delft3D simulation results are obtained from the Dutch Coastline Challenge (DCC, 2022). The figure presents the median simulated ecological damage, as well as simulation intervals. Different site specific parameters can be assigned in the tool as stochastic parameters. Allowing for the assessment of the uncertainty by means of a Monte Carlo method. In this particular example case, the calculation is 1000 times performed, sampling values from the parameter distributions. For this particular example case the value for the performance indicator, 'Impact on Benthic Community', would be 99.5 ha/year.

5.2.6. Discussion Benthimeter

One of the main strengths of the Benthimeter is that it is designed to post-process Delft3D simulations. Delft3D is a widely used and relatively reliable forecasting tool, making the Benthimeter well-suited for use in a range of hydrodynamic and ecological modeling applications. The compatibility of the Benthimeter with Delft3D simulations allows users to easily incorporate the tool into their existing modeling workflows, providing a convenient and efficient way to evaluate the impacts of nourishment projects on benthic species.

As mentioned previously, the complexity of benthic ecosystems and the many factors that can affect them make it challenging to develop a tool that can accurately predict the response of benthic species to nourishments. The Benthimeter represents a conceptual model of the benthic response, based on a relatively simple set of assumptions and input parameters. While this simplicity allows for quick and easy interpretation of the results, it also means that the Benthimeter may not accurately capture the full range of factors that can influence benthic diversity.

One of the key challenges in evaluating the ecological impacts of nourishment projects is determining what level of damage is acceptable or unacceptable. The Benthimeter provides a measure of the affected benthic diversity (ha), but it is difficult to translate this metric into tangible ecological damage. A threshold value beyond which a nourishment strategy would be considered "good" or "bad" remains challenging and subjective. Therefore, further research into translating the quantification metric into

[2] A Monte Carlo simulation is a mathematical method that uses random sampling to perform calculations and generate results. This technique can be used to model complex systems and evaluate the likelihood of different outcomes. By using a large number of samples, Monte Carlo simulations can provide reliable estimates of the likelihood of different outcomes and help inform decision-making.

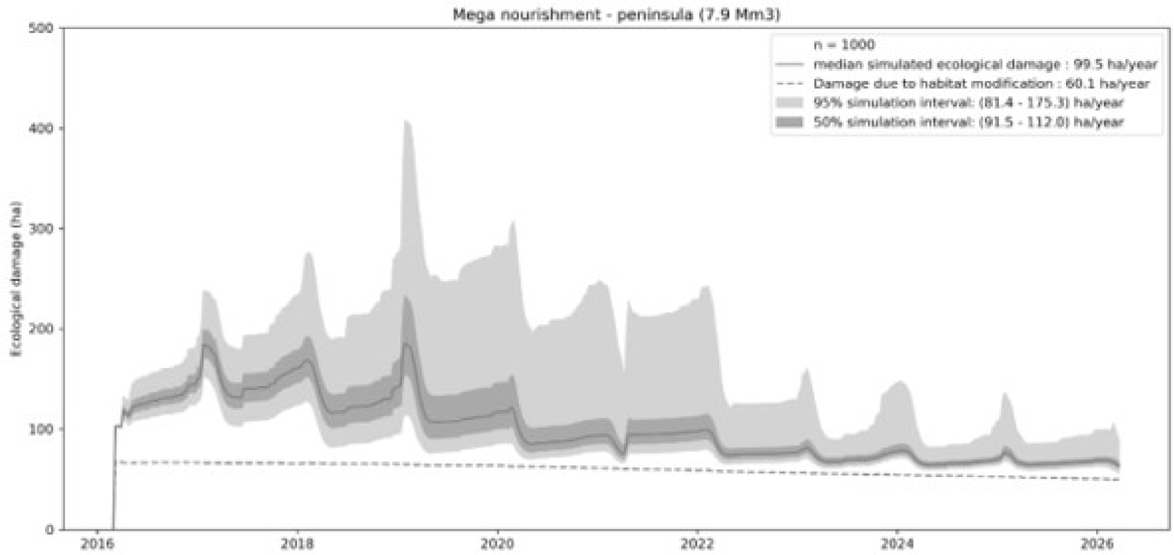


Figure 5.7: Figure illustrating an example of the result of an Benthic impact calculation performed using the developed 'Benthimeter'. This particular case represents a simulated hypothetical meganourishment Penisula (7.9 Mm3) in the shape of the Sand Engine, for the coast of Egmond. The results of the Delft3D simulation are obtained from the Dutch Coastline Challenge (DCC, 2022).

ecological impact benefit the tools applicability.

Besides the actual calculated differences are currently not reliable enough to be used and discussed independently. The real benefit of this method is the conception, creation, and use of a simple prediction tool.

Overall, with the development of the Benthimeter a first step is made into the construction a tool for quantifying and visualizing the response of benthic species to nourishment strategies. However, the tool requires further calibration and validation before it can directly be used in the planning and decision-making phase of coastal management.

6

Performance Indicators

This chapter outlines the indicators that have been chosen to evaluate the effects of the artificial sediment bypass system concepts simulated in this thesis. Each indicator is intended to provide insight into how the bypass system impacts the primary goals of this study:

6.1 *Infilling of channel and port* - This to indicate the dredging activity required in the channel and port.

6.2 *Sediment demand downdrift coast* - To indicate the impact of the bypass system on the sediment demand of the downdrift coast and therefore the nourishment activity.

6.3 *Impact on the benthic community* - To indicate the ecological consequences of the bypass system.

6.4 *Financial feasibility* - To provides a rough estimate of the cost-effectiveness of a bypass design, including both the initiation cost and operational costs (€/m^3).

Note that these indicators are intended for comparative use among various bypass concepts in relation to the Reference Situation. Their primary purpose is to rank the performance of different bypass designs, rather than to quantify their absolute performance values.

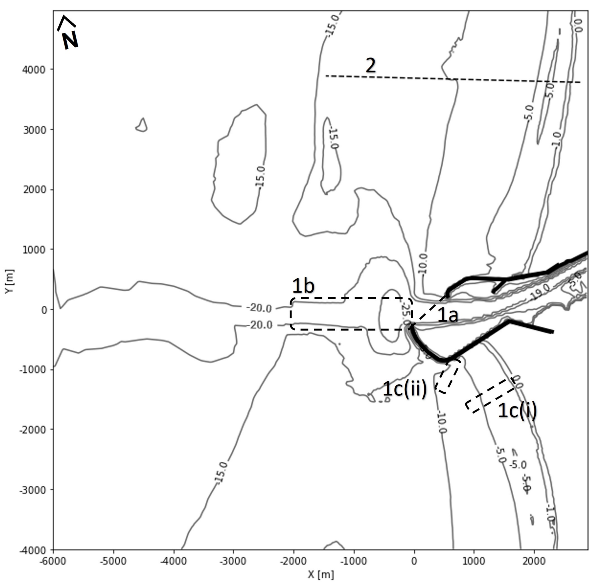


Figure 6.1: Overview of locations where sediment fluxes are measured to evaluating the effect on dredge (1) and noursishment activity (2). Sediment flux through section at location (1a) is used to indicate port infilling, at (1b) to indicate channel infilling, and at (1c) to evaluate the sediment trap's efficiency. The sediment flux through the section at location (2) is used to indicate the effect on sediment supply to downdrift eroding coast.

6.1. Channel and Port Dredging Activity

Accumulation of sediment in the access channel and harbor necessitates dredging, contributing to emissions and increased maintenance costs. To assess whether a bypass system concept could reduce this infilling on the channel and port, and therefore dredging activity three quantitative measures and one qualitative measure is used:

a Sediment flux into port (m^3)
b Net sediment flux into first 2 km of channel (m^3)
c Net sediment flux into sediment trap area (m^3)
d Visual analysis of bed level changes compared to base-line simualtion

These, measures are obtained from the outcomes of the Delft3D simulations in which bypass alternatives are incorporated. To assess the sediment transport, observation cross sections are included in the model, and the cumulative sediment flux through these sections is calculated. Figure 6.2 illustrates the quantification of this performance indicator. In this particular case the respective values for this performance indicator calculated for the base line (Do Nothing) simulation under normal SW conditions over 1 tidal cycle are added to the figure.

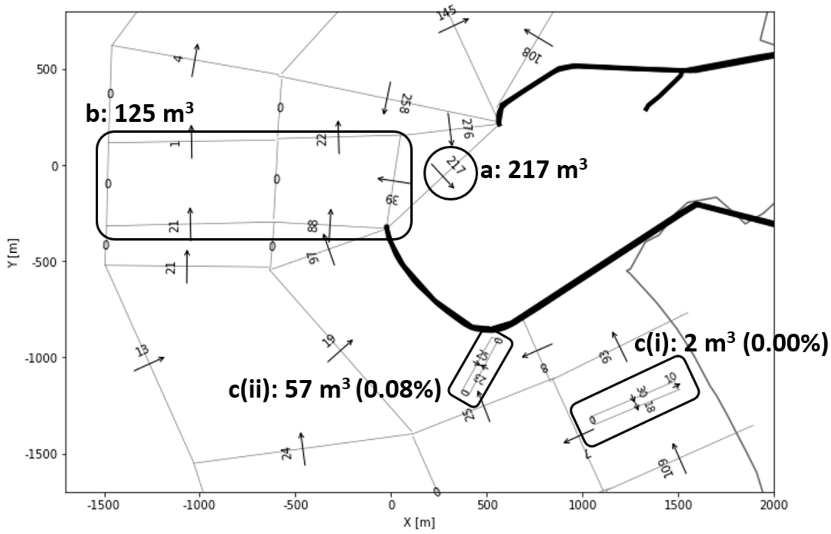


Figure 6.2: This figure illustrates the methodology for quantifying the performance indicator: 'Channel and Port Dredging Activity.' The simulation depicts the Base Line under normal southwest conditions, observed over a single tidal cycle. The resulting sediment values are represented in cubic meters (m^3).

Based on the "Conservation of mass" principle, it is justified to examine the net sediment flux rather than bed level changes, as a gradient in sediment flux drives erosion or sedimentation. When more sediment enters than leaves the channel or port, sedimentation occurs. Therefore, allowing for a more consistent and quantifiable measure since it was found that directly measuring bed level changes could yield significantly varied outcomes with minor adjustments to the measurement polygon, highlighting the preference for sediment flux as a more reliable and stable indicator.

By evaluating the net sediment flux into the sediment trap area, it is attempted to assess the sediment trap capacity of alternatives. The sediment trap is a crucial component of a sediment bypass system as this process determines whether the system is capable of withdrawing sufficient amounts of sediment from the system. This removed sediment is no longer available for natural bypassing, likely leading to reduced infilling of the channel and port. The amount of sediment trapped by the sediment trap is presented as the partition (%) of the total annual sediment transported into the system (72 000 m^3), as calculated during the model validation of chapter 4.2.

It is important to note that the absolute values derived should not be interpreted as definitive truths, but rather as comparative measures among different bypass concepts. These values are not completely aligned with dredging quantities, as observed during model validation. Nonetheless, the directions and general patterns are consistent, which validates their use for comparison.

Besides the sediment fluxes, also a visual evaluation based on the simulated bed level changes compared to the base-line simulation, is carried out. This approach provides a more tangible understanding of the effect of bed deepening in the sediment trap area.

6.2. Performance Indicator: Sediment Demand Downdrift Coast

The structural erosion of the downdrift beach from Heemskerk to Castricum necessitates regular foreshore nourishment, resulting in emissions, benthic life disruption, and increased maintenance costs. To evaluate the influence on nourishment activity, one quantitative measure and one qualitative measure are employed:

a Sediment flux through Raai 52 at Heemskerk (m^3)
b Sediment dispersal determined by visual analysis of bed level changes compared to base-line simulation

Raai 52 is selected as the reference point as it is the location at the starting location of the most recent nourishment (See section 2). It is hypothesized that an increased sediment supply to that location would reduce the gradient in the alongshore sediment transport, therefore reduce the erosion rate. This in turn decreases the 'sediment demand' and reduces the necessity for nourishment.

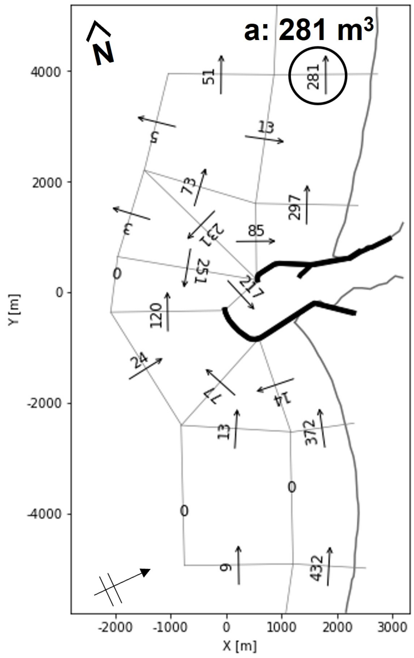


Figure 6.3: Illustration of the methodology to quantify the 'Sediment Demand Downdrift Coast.' The simulation depicts the Base Line under normal southwest conditions, observed over a single tidal cycle. The resulting sediment values are represented in cubic meters (m^3).

The analysis is limited to the depth range from 0 m to -10 m MSL, given that the sediment bypass systems aims to bypass sediment to the downdrif near-shore. As a result, the deeper regions' tranport processes are assumed not to be affected.

Figure 6.3) presents the an example of the quantification of this sediment flux through Raai 52 at Heemskerk for a base-case simulation under normal SW conditions over one tidal cycle. For this particular case the respective values for this performance indicator would be 281 m^3.

We should keep in mind that the gradients in the alongshore transport are not the only drivers for coastal erosion. Other potential drivers include cross-shore processes, sea-level rise, and land subsidence (Herman et al., 2021). Therefore, the determined values should not be interpreted as providing an exact quantification of the reduction in sediment demand on the downdrift coast. Rather, these values should serve as indicators of the relative effectiveness of different alternatives compared to a basel-line situation.

In addition to sediment flux measurements, a visual analysis of bed level changes between various sediment bypass system alternatives and the base-line scenario is conducted to assess the 'Sediment Demand on the Downdrift Coast.' The focus of this assessment lies on the dispersal of sediment discharged on the downdrift side of the IJmuiden Port. Greater dispersal towards the northern coast (downdrift direction) is assumed favorable.

6.3. Performance Indicator: Impact on Benthic Community

Impact on benthic community served as the performance indicator to assess the ecological impact of a sediment bypass system at IJmuiden. This is due to their limited mechanisms to avoid disturbance such as deposition of sediment, in combination with their important role in the ecosystem (Ysebaert and Herman, 2003)(Bijkerk, 1988). Making that macrobenthos is often described as a reliable indicator for the overall functioning of a sandy coastal ecosystem (Ysebaert and Herman, 2003).

In contrast to traditional foreshore or beach nourishments, a fixed sediment system introduces relatively small volumes of sediment throughout the year. This more 'continuous' approach might allow benthic organisms to dig out from the added layer, thereby potentially reducing the total ecological impact of the fixed sediment bypass systems compared to traditional foreshore or beach nourishment.

To asses whether is hypothesis is indeed observed for the IJmuiden case the newly developed Benthimeter will be applied. The Benthimeter calculates a metric for the ecological damage, expressed in *ha*. The translation of this metric toward tangible ecological damage is excluded from this thesis. Also, the tool requires a validation before is can directly be used to estimate the actual ecological damage. Therefore, the calculated ecological damage using the Benthimeter is used to compare different strategies, rather than evaluate the actual ecological impact. Figure 6.4 provides an example of the results of the benthimeter calculation performed on an bypass concept with six outlet locations and a large bypass volume.

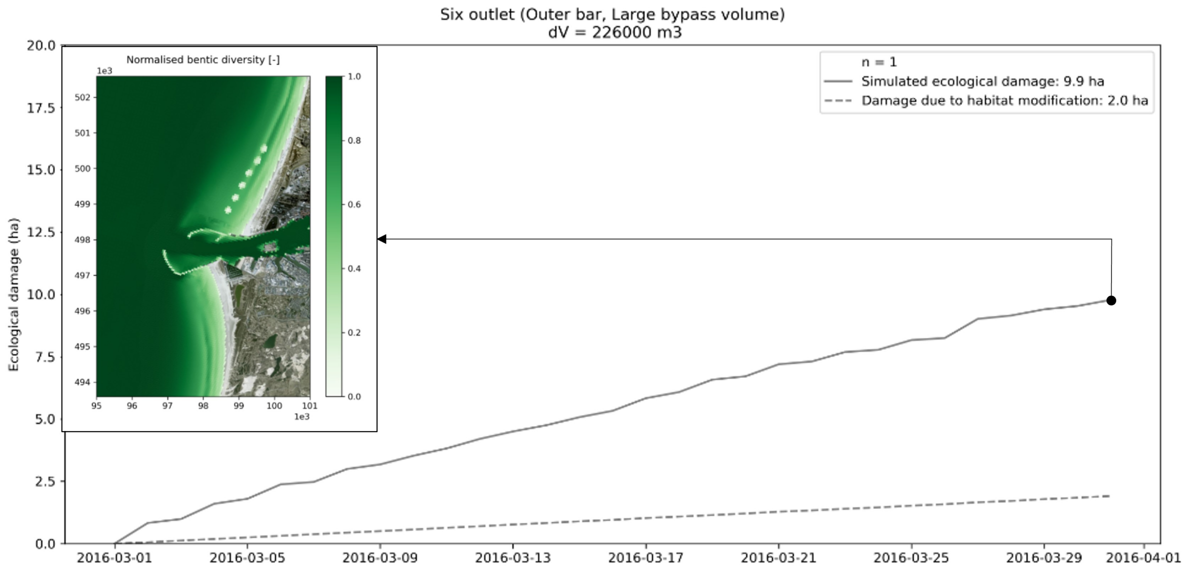


Figure 6.4: Example of results Benthimeter calculation for concept with 6 outlets, disposal at outer bar, bypass quantity of 140,000 m^3/mnt.

6.4. Performance Indicator: Feasibility

In project execution, financial feasibility plays a crucial role as it often dictates whether a project is executed or not. While this study doesn't focus on comprehensive financial analysis, a basic cost estimation is still conducted. This estimate comprises both the initiation costs and the cost per bypassed cubic meter of sediment, which collectively provide a rough assessment of the potential economic feasibility of the proposed design alternatives.

Financial feasibility is an important factor for projects since it determines whether a project can be executed or not. Although determining the financial feasibility is not the objective of this study, a rough calculation will be executed in order to have an estimate of the initiation costs and the cost per bypassed cubic meter of sediment.

From the case studies presented in chapter 3.2 it became clear that the scale of the project significantly affects the costs. We saw that Tweed River Entrance Project (TREP), exhibiting significantly larger scale, initiation costs (€25 million vs €4.3 million) and cost per bypassed sediment volume (€6.17/m^3 vs €0.84/m^3) are approximately 6 times higher compared to Nerang river Project. Based on these two 'data points', through a linear interpolation, a relation is defined to calculate the initiation costs and the cost per bypassed cubic meter of sediment. The total pipeline length is used as the parameter to define the scale. Where the pipeline length of TREP is 7 km and at Nerang River only 1.4 km.

Following this simplified method the following relations are obtained, where pipeline length is defined in km:

Initiation Cost (* million €) = -0.88 + 3.7 * pipeline length

Bypass cost per cubic meter (€/m^3) = -0.45 + 0.95 * pipeline length

A quick estimate to find the break-even point is done by calculating the NPV over time assuming the cash flow as the annual savings. The general rate of return used by the Dutch government in 2022 is 2.69% (Waterstaat, 2022).

$$NPV = Ini + \sum \frac{Cash\,Flow_t}{(1+r)^t} \tag{6.1}$$

7

Evaluation

Simulations are performed to calculate the morphological response of the system to different sediment bypass concepts. This chapter presents the results and their effects on the performance indicators established in chapter 6. Therefore this chapter will have a similar structure:

7.1 *Channel and Port Dredging Activity*
7.2 *Sediment Supply to Downdrift Eroding Coast*
7.3 *Impact on the Benthic Community*
7.4 *Financial Feasibility*

Each section not only presents the relevant results but also aims to deliver a clear and straightforward interpretation and discussion of these findings.

7.1. Channel and Port Dredging Activity

This section evaluates the performance of two different sediment bypass concepts – Alternative 1 ("Jetty from Beach") and Alternative 2 ("Breakwater Jetty") – based on two types of simulations: short-term hydrodynamic (encompassing 1 tidal cycle under standard SW conditions) and short-term morphodynamic (spanning 1 month under SW storm conditions).

In the case of Alternative 1, a specific area measuring 420m x 30m has been deepened (refer to Figure 4.9 for the exact location). The depth of this deepening varies across the simulations, going to -9 m NAP in one morphodynamic simulation and -5 m NAP in another.

For Alternative 2, an area of 300m x 30m is deepened to -17 m NAP in the model.

The impacts of these bypass concepts on channel and port dredging activity are assessed based on specific indicators:

1a Sediment flux through the port entrance
1b Net sediment flux into channel
1c Net sediment trap (% of 72 000 m^3)
  i Location Alternative 1
  ii Location Alternatvie 2

The calculated values for these indicators are presented in Table 7.1. For the full set of results, refer to the APPENDIX E.

Table 7.1: Performance indicators for dredging in channel and port, given in m^3. Sub-figures 1a, 1b, and 1c depict flux into port, net flux into channel, and net flux into sediment traps at Alternative 1 ('Jetty from Beach', location 'i') and Alternative 2 ('Jetty from Southern Breakwater', location 'ii') respectively. Conditions: SW1 (H_s = 1.48 m, T_s = 5.34 s, direction = 232°), SW storm SW2 (H_s = 2.48 m, T_s = 5.34 s, direction = 232°).

Simulation	**Indicators**			
	1a	**1b**	**1c(i)**	**1c(ii)**
Short term hydrodynamic (12.42 hr)				
SW (condition 1)				
Base-line (Do Nothing)	218	125	2 (0.00%)	57 (0.08%)
Alternative 1 (Jetty from beach)	218	125	254 (0.36%)	-
Alternative 2 (Breakwater jetty)	218	125	-	67 (0.10%)
Short-term morphodynamic (1 month)				
SW storm (condition 2)				
Base-line (Do Nothing)	1,638	5,334	309 (0.4%)	2,923 (4.2%)
Alternative 1 (To -9 m- NAP)	1,639	5,395	6,112 (8.7%)	-
Alternative 1 (To -5 m- NAP)	1,639	5,327	1,581 (2.3%)	-
Alternative 2 (To -15 m -NAP)	1,641	5,337	-	6,294 (9.0%)

In addition to the quantification of the effect on the performance indicators, visual analysis of the bed levels compared to base-line simulation is used for evaluation. The results of this method is presented in Figure 7.1.

(a) (b)

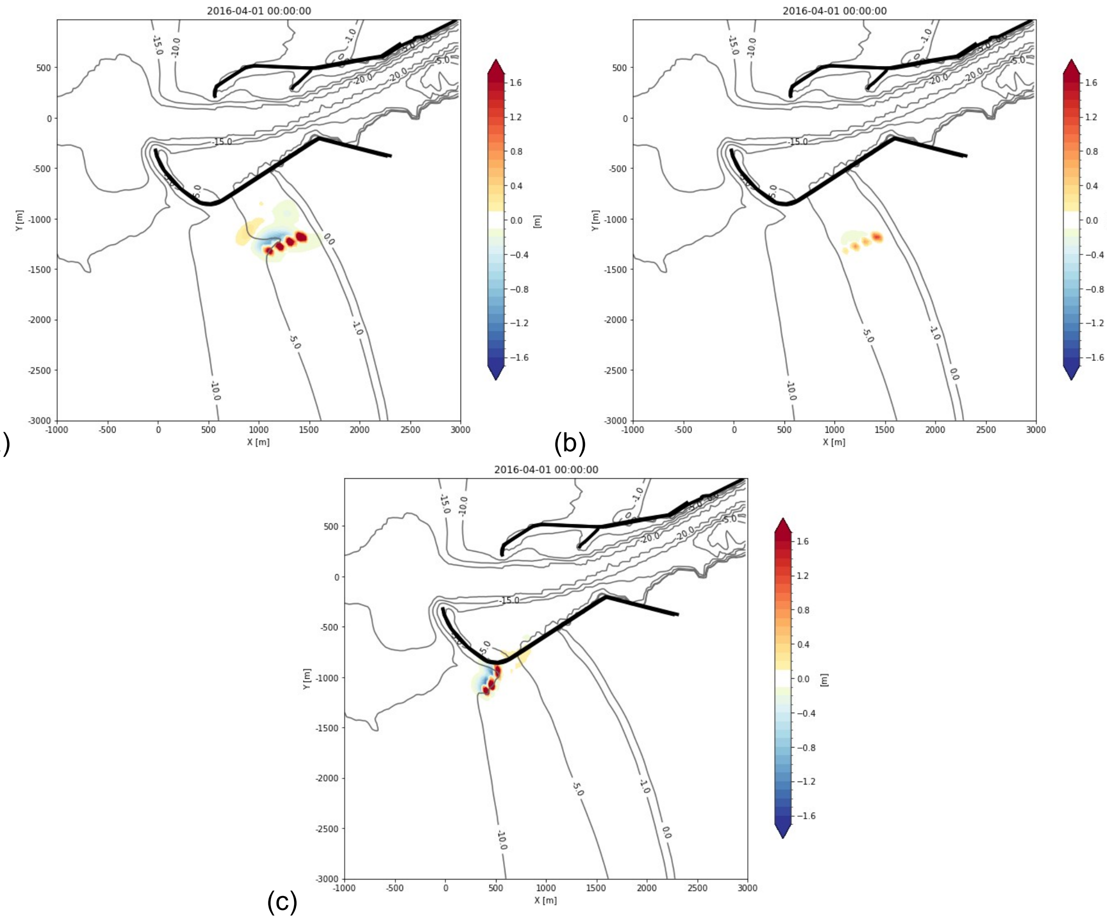


Figure 7.1: Modelled bed level changes compared to reference simulation for Alternative 1: 'Jetty from beach'. Here, an initial deepening to -9m MSL (a) and to -5m MSL (b) is performed over an area of 420m x 30m. Alternative 2: 'Jetty from Breakwater' is initially deepened to -15 m- MSL. Results are obtained one month after start of simulation on March 1, 2016.

7.1.1. Discussion and interpretation of results: Dredge Activity

Although the simulation results did not display a direct reduction in net sediment flux into the channel and port, they highlighted the effectiveness of the created traps for sediment capture under SW conditions. The results present a sediment capture of 9% of the total sediment simulated sediment flux (72,000 m^3) during one month. This efficient trap capacity is also confirmed by the bed level changes compared to Reference simulation, visualized in Figure 7.1, which demonstrates the rapid infilling within the time scale of months of the sediment traps established in the 'Jetty from beach' alternative.

The findings imply that the designed traps can efficiently capture sediment, thereby enabling the jet pumps to relocate sediment from the southern site to the northern site. As a result, less sediment remains available for bypassing. This is illustrated by the erosion patterns observed immediately north of the sediment trap cones in Figure 7.1. Given the predominant south-to-north sediment transport pattern at IJmuiden and across the Dutch coast in general, as established in literature, it's reasonable to anticipate that reduced sediment availability at the southern site would lower the bypassing of sediment along the breakwaters and consequently reduce channel and port infilling .

It is thus expected, with a degree of confidence, that this infilling reduction would become apparent in extended-period simulations (spanning multiple years) incorporating continuous dredging of the sediment trap into the model. Literature presented that noticeable effects typically emerge about one or two years after implementing a fixed sediment bypass system (Keshtpoor et al., 2013). Therefore, the absence of immediate changes in channel or port infilling should not be interpreted as an unexpected outcome.

One might argue whether the best case scenario is a realistic scenario. Based on the physical logic, the relocated sediment is no longer available for bypassing, hence on the long term it will not contribute to channel or port infilling. This principle is proven to be effective in similar projects around the world such as the Nerang River Project. However, this principle becomes less obvious when NW conditions are present. Since at the Dutch coast does not present SW conditions year round, some of the bypassed sand will become available to be transported towards port and can still contribute to]channel and port infilling. Therefore, the benefit for dredge activity is likely to be smaller than is calculated during the best-case scenario.

An important point to note is the significant difference between the annual dredge volumes (6.5 Mm3/yr) and the South to North alongshore sediment transport (140,000 m3/yr), for which the bypass system is designed. The best case scenario calculations pointed out that a maximal dredge reduction of 0.23 Mm3/year (-3.5%).

This finding could imply that there are other key processes causing the significant required dredging activity. Other potential causes, such as mud infilling or migrating sand waves, could play significant roles. Literature suggests that 80 - 90% of the dredged sediment from the port consists of mud, indicating the potential complexity of sedimentation drivers not examined in this study. Additionally, Lely (2023) indeed highlights the role of sand wave migration into the channel, which is also not addressed by a fixed bypass system.

Given the results and the estimated best-case scenario, the benefits of implementing an artificial bypass system on dredging activity and its emissions appear minimal.

7.2. Sediment demand downdrift coast

Three different simulation methods are used, namely the short-term hydrodynamic simulation (1 tidal cycle under normal SW conditions); short-term morphodynamic simulation (1-3 months) under normal SW and SW storm conditions; and the brute-force simulation (13 months) assuming real-time wave, wind, and water level data.

The effect of varying design attributes are assessed, including (1) the number of outlets, (2) the distance from the northern breakwater, and (3) the location in the shoreface.

The sediment flux across Raai 52 (Heemskerk) is established as a quantifiable indicator for sediment supply to the eroding coast and therefore for the nourishment activity. Additionally, qualitative analysis is performed by visually evaluating changes in bed levels compared to baseline or 'Do Nothing' simulation. This visual assessment helps to evaluate the sediment dispersal of the bypassed sand.

Varying number of outlet locations: Short-term hydrodynamic simulation
Three simulations are performed with varying number of outlets (1; 3; 6). The bathymetry is initially increased at the locations depicted in Figure E.4. The results are presented in Table 7.2.

Table 7.2: Simulated effect of varying number of outlet location on indicator Sediment flux through Raai 52 in m^3. Short-term simulation (one tidal cycle) under normal SW conditions ((H_s = 1.48 m, T_s = 5.34 s, direction = 232°))

	Baseline	**1 Outlet**	**2 Outlets**	**3 Outlets**
Sediment flux through Raai 52 ($\mathbf{m^3}$)	281	285 (+1.4%)	279 (-0.7%)	270 (-3.9%)

Varying number of outlets, distance from norhtern breakwater and location in the shoreface: Short-term Morphological simulations
This section covers the short-term morphological simulations, wherein the morphological updates allow the system to respond and adapt to the changes induced by the fixed bypass system. Table 7.3 presents the results of the short term morphological simulation in which concepts configurations differ in terms of the number of outlets, their locations, and bypass quantities (as detailed in Chapter 3.3, Bypass Design). The simulations different southwest conditions, condition 1 is an average SW condition (Hs=1.48m, Ts=5.34s, Dir=232°N) and condition 2 represents SW storm (Hs=2.46m, Ts=6.34s, Dir=232°N). To assess the effect of longer simulation times, some simulations were performed over a 3 month time span.

Table 7.3: Simulated sediment supply to downdrift coast (represented by 'Sediment flux through Raai 52' in m^3) for different outlet concepts. The simulations, incorporate outlet concepts as continuous discharge of slurry at specified locations. Three different conditions are used: SW Condition 1 (Hs=1.48m, Ts=5.34s, Dir=232°N), SW Storm Condition 2 (Hs=2.46m, Ts=6.34s, Dir=232°N) and simulation under the full real-time wave, wind, and waterlevel data (Brute-Force).

Concept	**Disposal location in shoreface ($\mathbf{m^3}$)**	**Bypased sediment volume (dV) ($\mathbf{m^3}$)**	**Sediment flux through Raai 52 ($\mathbf{m^3}$)**
SW normal (Cond. 1)			
a: Baseline	-	-	10,952
b: 1 Outlet	Outer bar	20,000	10,961 (+0.1%)
c: 1 Outlet	Inner bar	20,000	10,965 (+0.1%)
d: 1 Outlet	From beach	20,000	10,962 (+0.1%)
e: 6 Outlets	From beach	20,000	10,959 (+0.1%)
f: 6 Outlets	Inner bar	20,000	10,961 (+0.1%)
g: 6 Outlets	Outer bar	20,000	10,953 (+0.0%)
h: 6 Outlets (Near Heemskerk)	Inner bar	20,000	10,929 (-0.2%)
i: 6 Outlets (Large volume)	Outer bar	230,000	10,844 (-1.0%)
SW storm (Cond. 2)			
j: Baseline	-	-	66,522
k: 6 Outlets	From beach	20,000	66,541 (+0.0%)
l: 6 Outlets (Large volume)	Outer bar	230,000	65,607 (-1.4%)
m: Baseline (3 months)	-	-	196,147
n: 6 outlets (3 months)	Outer bar	660,000	187,255 (-4.5%)
Full wave climate (Brute-Force)			
o: Baseline (12 months)	-	-	-11,565
p: 6 outlets (12 months)	From beach	247,000	-11,270

7.2.1. Discussion and interpretation of results: Sediment demand downdrift coast

The effect of a continuously adding a volume of 230,000 m3 per year was assessed by simulating the transport pattern of different bypass concepts under varying conditions. However, the assessment revealed minimal impact on the indicator, sediment flux through Raai 52. Notably, no increase in sediment flux towards the eroding coast was observed after three months, even for concepts proposing large bypassing volumes (dV = 230,000 per month) under SW storm conditions. In fact, slight reductions in flux volumes were observed for concepts with larger bypassing volumes (See Table 7.3). A plausible explanation for this could be an increased disturbance of natural wave and current conditions.

However, visual assessments of the bed level changes compared to the reference simulation under SW conditions highlight an expected northward dispersal of the added sediment (See Figure 7.2 and 7.3). This is particularly noticeable for outlet locations near the beach where wave breaking induces turbulence and alongshore currents, thereby enhancing dispersal. Similar observations were made for locations further away from the northern breakwater, attributable to a reduced shadowing effect of the breakwaters. These findings are consistent with the expected system behavior.

Simulations run over an extended duration (three months under SW conditions) already showed further northward dispersal, nearly reaching Raai 52. A similar logic to that applied to the infilling of the channel and port can be applied here: that the addition of sediment to the eroding coast (from Raai 52) will become more evident when simulated for longer durations. Thus, given the predominant south to north sediment transport at the Dutch coast,it is expected, with some amount of confidence, that the bypass system by disposing to the downdrift side of IJmuiden, will likely contribute to erosion mitigation.

This hypothesis, grounded in conceptual reasoning and supported by a visual examination of bed level changes from morphological simulations, requires nuanciation. It is namely observed that outlets relatively close, within roughly 1.5 km to the breakwater (in the recirculation zone) showed sediment dispersal towards IJmuiden, even though SW conditions were assumed (See most southern outlet on Figure 7.3c). This highlights the necessity for sufficient space between outlets and the breakwater due to the large breakwaters extending 2800m (southern) and 1850m (northern) into the sea, which is significantly larger than the training walls of the Australian projects. Indicating that the recirculation area is larger.

Another point of discussion is that although the Dutch coast exhibits predominant SW conditions, NW conditions are also frequently prevailing. The dominant sediment transport direction is also less obvious compared to the cases in at the Gold Coast in Australia where an average net transport of 500,000 m^3 to the North is observed. APPENDIX B.1 presents the sediment transport quantities and direction over the past decade along the Dutch coast. From this figure the also large southward transport is observed, and even years where the net transport was southward directed, for instance in 2017.

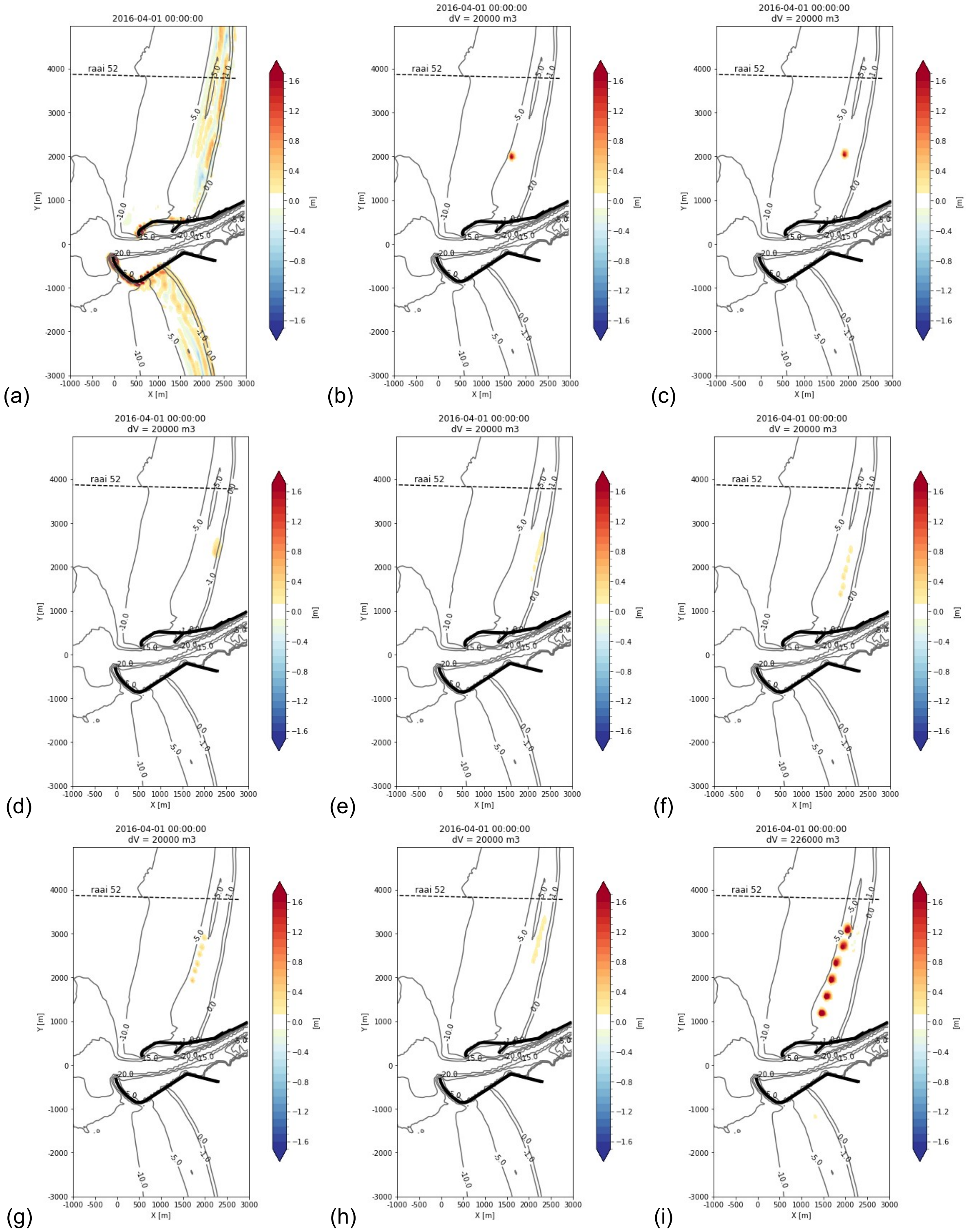


Figure 7.2: Bed level changes plots of simulation with different bypass concepts. Simulation assumes normal SW conditions (H_s = 1.48 m, θ_{wave}=232°, v_{wind} =9.97 m/s, θ_{wind}=231°). See table 7.3 for the the details of the different concepts.

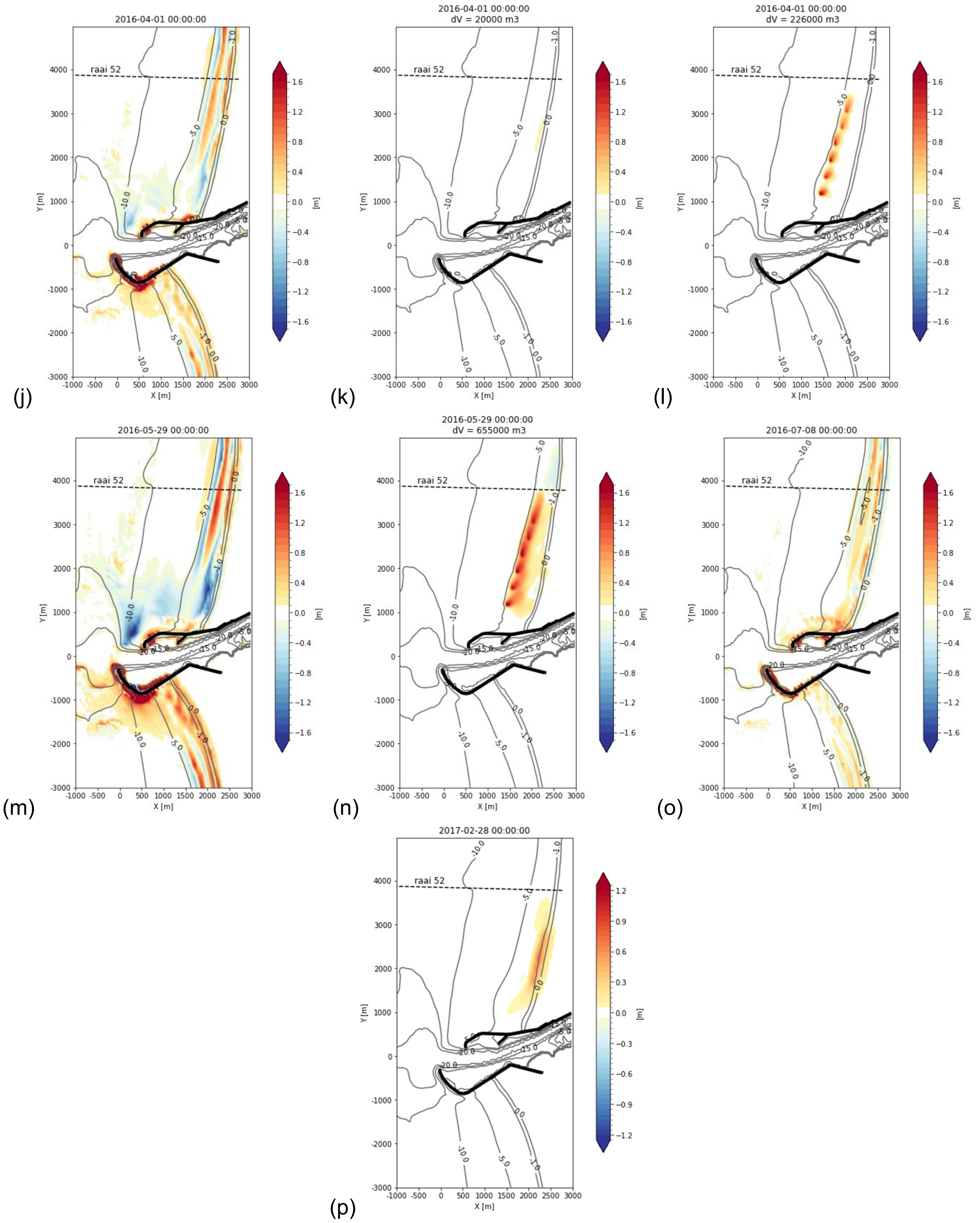


Figure 7.3: Bed level changes plots (H_s = 2.48 m, θ_{wave}=232°, v_{wind} =13.37 m/s, θ_{wind}=227°). See table 7.3 for the the details of the different concepts.

7.3. Impact on Benthic Community

This section covers the evaluation of the ecological performance indicator: *Impact on benthic community*. The impact on this indicator is quantified for various bypass outlet concepts. It is important to note that the impact during the dredging process is outside the scope of this study. Therefore, the inlet concepts are not considered during this ecological impact evaluation. The results of the benthic impact calculations, conducted using the 'Benthimeter' tool, are detailed in Table 7.4. For a comprehensive understanding of this tool's development, please refer to APPENDIX A.

7.3.1. Calculation Ecological Impact: Artificial bypass system concepts

Table 7.4: Results of 'Benthimeter' calculation for various sediment bypass concepts.

Concept	**Disposal location in shoreface** $(\mathbf{m^3})$	**Bypassed sediment volume (dV)** $(\mathbf{m^3})$	**Benthic damage** $(\mathbf{ha})$	**Damage due to habitat modification** $(\mathbf{ha})$
SW normal (Cond. 1)				
a: Baseline	-	-	-	-
b: 1 Outlet	Outer bar	20,000	1.3	0.2
c: 1 Outlet	Inner bar	20,000	1.3	0.2
d: 1 Outlet	From beach	20,000	0.9	0.2
e: 6 Outlets	From beach	20,000	0.8	0.1
f: 6 Outlets	Inner bar	20,000	0.9	0.2
g: 6 Outlets	Outer bar	20,000	1.2	0.2
h: 6 Outlets (Near Heemskerk)	Inner bar	20,000	1.2	0.2
i: 6 Outlets (Large volume)	Outer bar	230,000	9.9	2.0
SW storm (Cond. 2)				
j: Baseline	-	-	-	-
k: 6 Outlets	From beach	20,000	1.2	0.2
l: 6 Outlets (Large volume)	Outer bar	230,000	15.9	2.1
m: Baseline (3 months)	-	-	-	-
n: 6 outlets (3 months)	Outer bar	660,000	34.5	6.0
Full wave climate (Brute-Force)				
o: Baseline (13 months)	-	-	-	-
p: 6 outlets (13 months)	From beach	247,000	2.3 ha/year	1.0 ha/year

During calculations performed on short-term morphological simulation results, the recovery of benthic diversity was not considered. This is due to the short duration of the simulated periods, which do not allow sufficient time to experience a full recovery cycle. However, the 'Brute Force' simulation, which spans 13 months, was assumed long enough to incorporate recovery. The benthic impact calculation for the 'six-outlet, from beach' concept, simulated with Brute Force method, resulted in an average ecological damage of 2.3 ha/year. Of this 1.0 ha/year is accounted for by habitat modification. The simulation was performed for one year, as depicted in Figure 7.4.

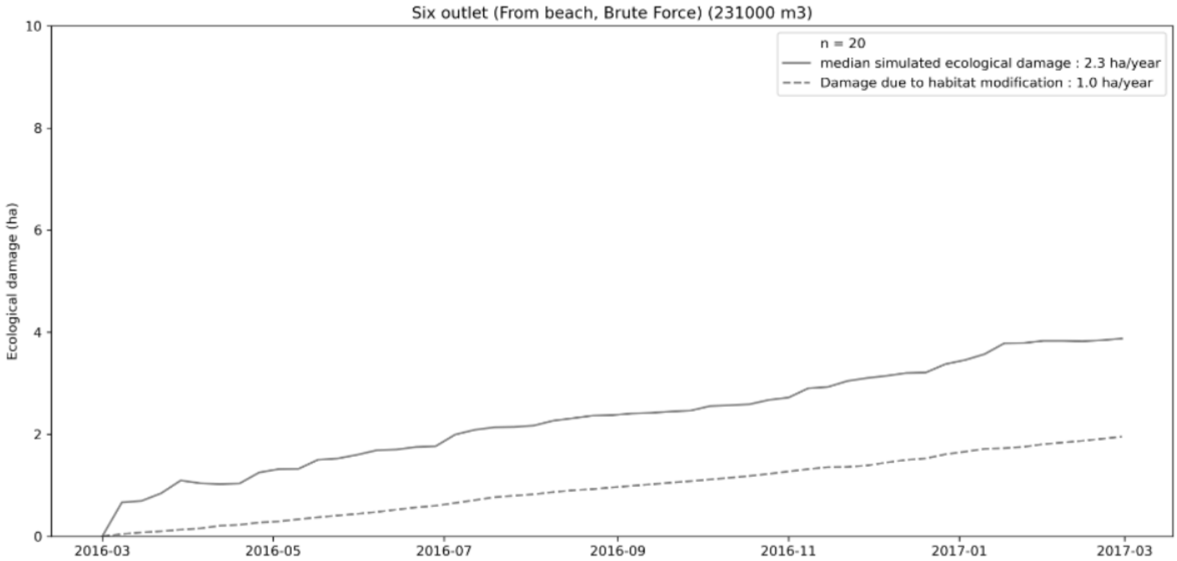


Figure 7.4: Results 'Benthimeter' calculations performed on bypass concept with six outlet locations simulated using Brute Force, for one year.

7.3.2. Calculation Ecological Impact: Foreshore nourishment Heemskerk

In the best case scenario, the required nourishment volume decreases from 3 Mm^3 to 1.9 Mm^3. To save computational time, a simplified benthos impact assesment is performed. In this approach no long-term (10 years) Delft3D simulation had to be performed, to calculate morphological development after introducing the nourishment.

Instead, a 'trick' is applied where the bed level of t=0 is assumed constant throughout 10 years. At t=1 (1 day) the bed within the estimated nourishment area is elevated with 0.8 meter. This is repeated at t = 5 years, to reconstruct the recurring fore shore nourishment. This created bed level data file is than used to calculate the benthic impact and recovery according to the mechanisms outlined by the Benthimeter.

While this method provides a preliminary estimate of potential damage, it does not account for the indirect burial of benthic life initiated by the nourishment. Therefore, it is presumed that this approach introduces an underestimation of the actual impact. See Figure 7.5 for the resulting ecological impact calculation. The figure presents full recovery after approximately 2-4 years and an average ecological damage of **126.5 ha per year** when nourishing twice over the coarse of 10 years.

Based on Brand, Ramaekers, and Lodder (2022) the dimensions and location of the foreshore nourisment are estimated. The crest of foreshore nourishment are typically placed at the seaward side of the outer bar at a depth of -5 m and have an average thickness of 0.8m (Brand, Ramaekers, and Lodder, 2022). The Heemskerk (2022-2024) nourishment is placed over a length of 8500m (Raai 4300 to Raai 5150). Would result in the following dimensions 8500m x 440m x 0.8m (=3Mm3). Figure 7.5 present a schematic overview of this estimated nourishment dimension and location.

Similartly the ecological dammage is calculated for a hypothetical 1.9 Mm^3 nourishment. Regarding the estimated layout, the depth of 0.8 m and the width of 440 m are assumed to remain consistent, resulting in a length of approximately 5.5 km (≈2.0 Mm3). his estimated layout is depicted in Figure 7.5b. Figure 7.5c presents the calculated ecological impact with an average of **82.2 ha/year**, a reduction of 44.3 ha/year (-35%) in comparison to the 3 Mm^3 nourishment.

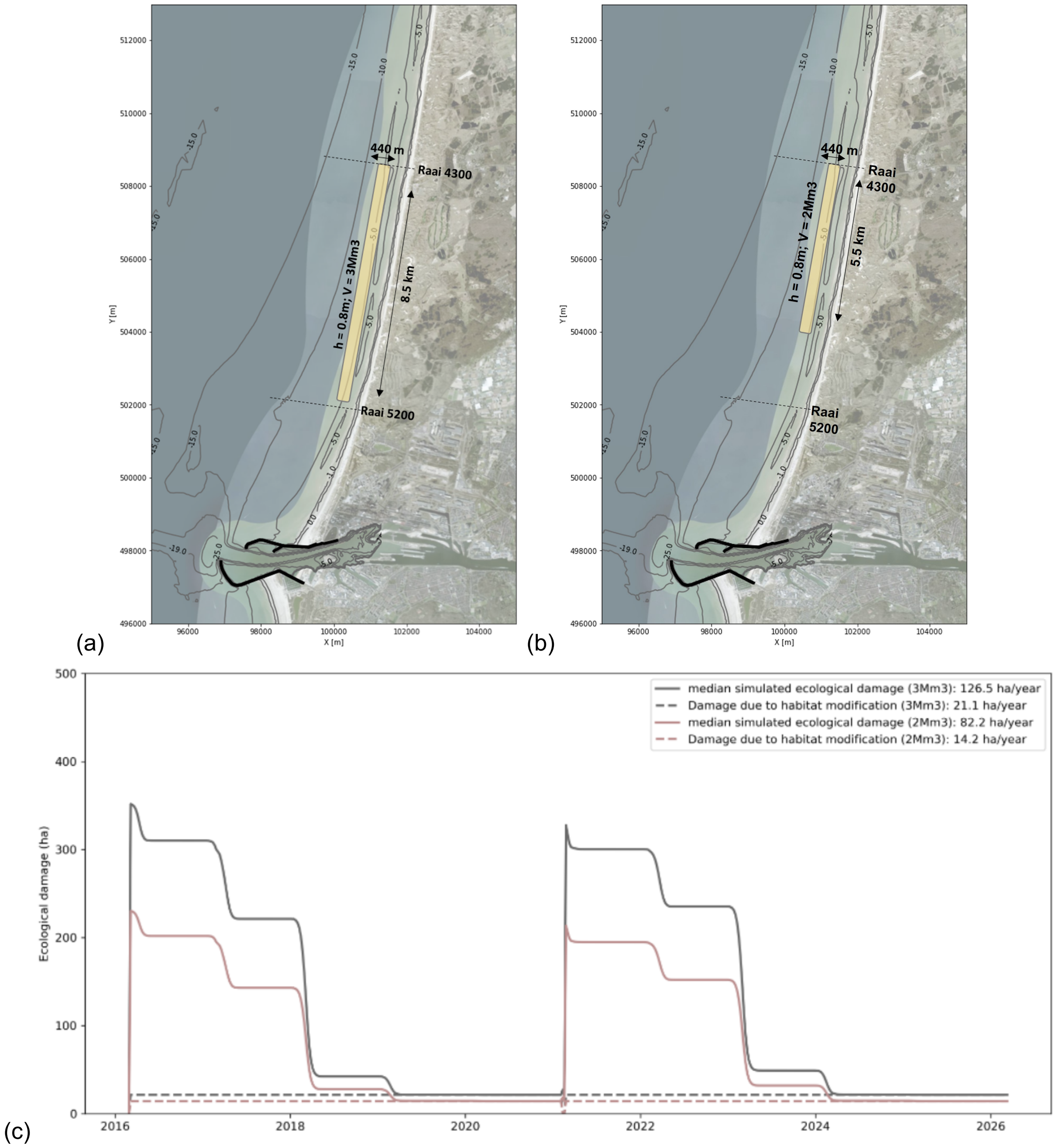


Figure 7.5: Assumed layout of the (a) 3Mm3 and (b) 2 Mm3 foreshore nourishment and their (c) calculated benthic impact using a simplified Benthimeter calculation.

7.3.3. Discussion and Interpretation of Results: Impact on Benthic Community

If we combine the calculated average benthic damage of concept simulated with brute-force and the impact induced by the renewed nourihsment. The total estimated ecological damage amount to **84.5 ha/year**, a reduction of 42 ha/year (-33%).

This discussion focuses on the ecological consequences of the sediment bypass concepts on the benthic community. The findings in this study support the hypothesis that smaller, gradual layers of sediment allow for better survival of benthic organisms compared to larger foreshore nourishments. We saw less average ecological impact in the simulation with the bypass concept using the brute force simulation compared to the the impact due to the nourishment. Also the concepts in which the number of outlets was larger (6 vs 1), present slightly lower calculated benthic impact.

Table 7.5: Impact on benthic community calculated with the 'Benthimeter', for sediment bypass concept simulated under real time wave, wind, and waterlevel data (Brute Force) over the period of 13 months.

Activity	**Base-Line (Do Nothing)**	**Six outlets (Discharge from beach)**
Required nourishment volume ($\mathbf{Mm^3}$)	3.0	1.9
Calculated benthic impact nourishment activity (ha/year)	127	82
Bypassed volume ($\mathbf{m^3}$/year)	-	230,000
Calculated average benthic impact bypass activity (ha/year)	-	2.3
Total calculated benthic impact (ha/year)	126.5	84.5

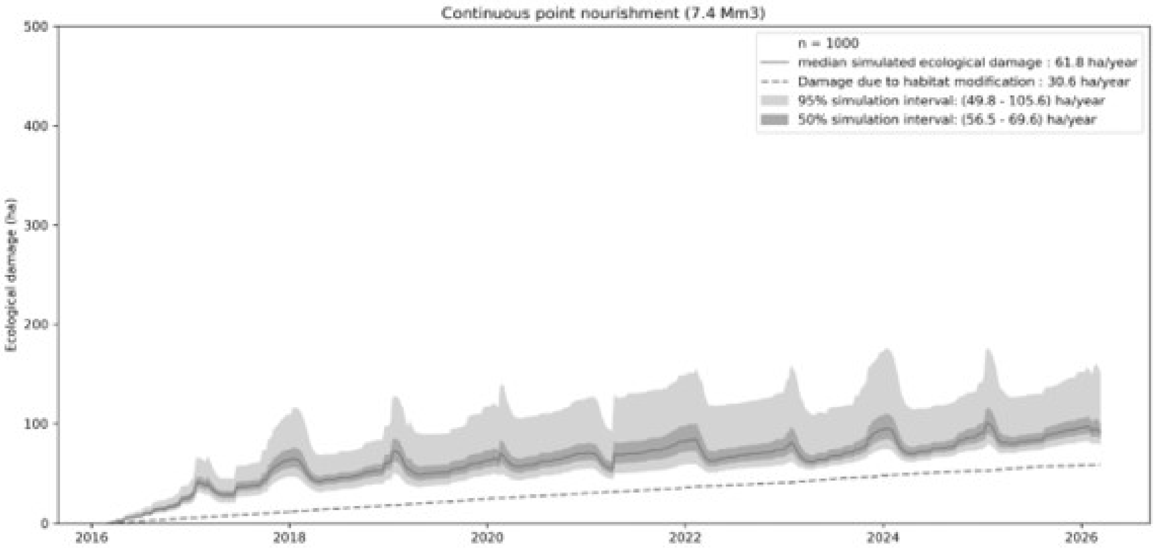


Figure 7.6: Figure illustrating an example of the result of an Benthic impact calculation performed using the 'Benthimeter'. This particular case represents a simulated hypothetical continuous point nourishment (7.4 Mm3 in ten years), for the coast of Egmond. The results of the Delft3D simulation are obtained from the Dutch Coastline Challenge (DCC, 2022).

Aligning with well-established theories in literature, the results display increased biodiversity with depth and better adaptability of benthic animals in more dynamic areas. This adaptability is linked to a stronger burial potential. Consequently, it is suggested that near shore nourishment could be beneficial for the benthic community, since fewer species naturally inhabit this region and those present are more resilient to burial. This suggestion is supported by the calculated results, which show less benthic damage for concepts discharging from the beach, compared to those discharging at the outer or inner bar under similar conditions.

These findings, consistent with literature, strengthen the credibility of the Benthimeter as a tool for assessing the ecological impact of coastal management strategies. The observed reduced benthic impact for the sediment bypass concept, compared to the nourishment strategy, confirms the initial hypothesis. Thus, it anticipated that a sediment bypass system present less disruption to the benthic community, over the considered period of 1 to 10 year.

However, caution must be payed as these calculations are extrapolations based on a one-year simulation, making the prediction of long-term impacts more complex. To mitigate this, the Benthimeter was applied to ten-year brute force simulations from the Dutch Coastline Challenge (DCC). Figure 7.6 illustrates the calculated benthic impact of a continuous nourishment approach and a mega nourishment (Sand Engine shape) incorporated near Egmond into the Delft3D model. An increasing trend for the continuous nourishment approach might indicate cumulative damage due to insufficient recovery time. In contrast, the mega nourishment shows a slowly decreasing trend. Perhaps on the long term this accumulative damage exceeds the damage of the nourishment. Or perhaps an equilibrium will be established in which the ecosystem will adapt to the continuous supply of sediment from the artificial bypass system. Research into the benthic development at similar earlier establish bypass projects around the world could provide insight into these long term ecological effects.

Furthermore, the results reveal a significantly higher benthic impact under SW storm conditions compared to normal SW conditions, indicating the importance of indirect burial due to energetic conditions. This pattern is evident in Figure 5.7, where peaks in indirect damage occur during winter conditions, just before spring recovery. This behaviour could be attributed to the increased dispersion of sediment due to larger waves and currents.

7.4. Feasibility

This section aims to evaluate the feasibility of three proposed sediment bypass concept for IJmuiden, informed by the insights garnered from this study. t is hypothesized that designs featuring multiple outlet locations, discharge from the beach, and a sufficient distance from the northern breakwater may offer the best performance in reducing sediment demand along the downdrift coast and in mitigating the impact on the benthic community.

Regarding dredging activity, we observed that the alternative incorporating a jetty from the beach demonstrated the highest sediment trap capacity. Thus, it is anticipate that this design will be more effective in reducing dredging activity within the channel and port.

Considering these assumptions, three artificial sediment bypass system layouts have been proposed for the calculations, as illustrated in Figure 7.7. The first proposal has a total pipeline length of 4200m, discharging sediment at six beach outlets roughly one km away from the northern breakwater. The second proposal situates the outlets further north, leading to increased costs but potentially improving dispersal due to the reduced shadowing effect of the breakwater. This design necessitates a total pipeline length of 5200m. The third proposal involves outlets disposing sediment further north, at locations identified as being characterized by structural erosion. This would require a total pipeline length of 6200m.

Calculations following the method described in section 6.4 yield the values presented in Table 7.6.

Table 7.6: Calculation results of performance indicator: financial feasibility. Results are assuming best case scenario.

Activity	**Base-Line (Do Nothing)**	**Design 1**	**Design 2**	**Design 3**
Required nourishment volume ($\mathbf{Mm^3}$)	3.0 (0.6 Mm3/year)	1.9 (0.38 Mm3/year)	1.9 (0.38 Mm3/year)	1.9 (0.38 Mm3/year)
Nourishment costs (€3.50/m3)	€ 10.5 million (€2.1 million/year)	€6.6 million (€1.33 million/year)	€6.6 million (€1.33 million/year)	€6.6 million (€1.33 million/year)
Required dredging volume channel and port (Mm3/yr)	6.5	6.3	6.3	6.3
Dredging costs (€3.50/$\mathbf{m^3}$)	€22.8 million/year	€22 million/year	€22 million/year	€22 million/year
Bypassed volume ($\mathbf{m^3}$/year)	-	140,000	140,000	140,000
Bypass costs (€/m3)	-	3.54	4.49	5.44
Total bypass costs (m3/year)	-	€0.50 million/year	€0.63 million/year	€0.76 million/year
Total operational costs	€ 24.9 million	€23.8 million	€24.0 million	€24.1 million
Initiation costs	-	€ 14.7 million	€ 18.4 million	€ 22 million
Break even point (r = 2.69%)	-	17 years	31 years	63 years

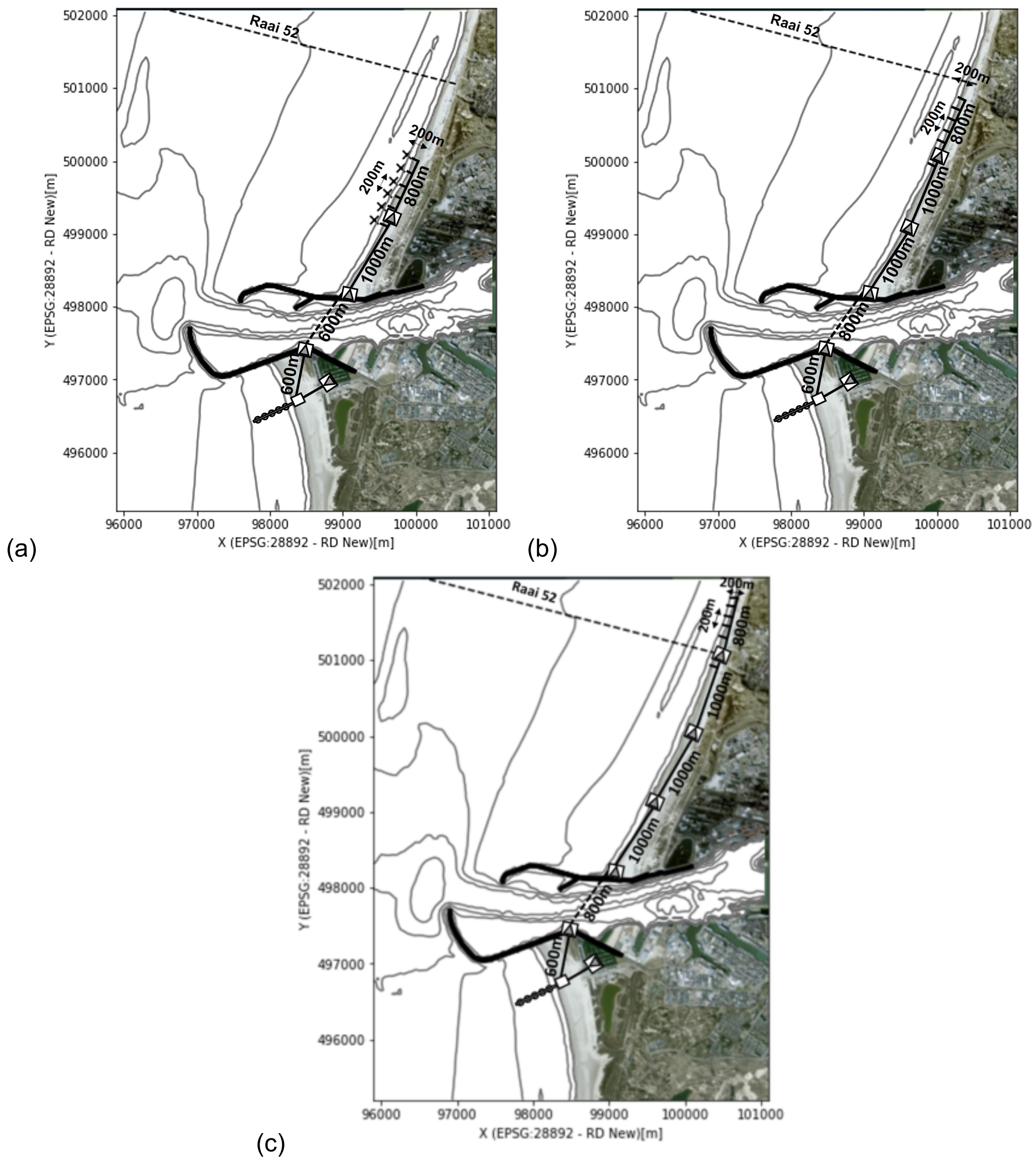


Figure 7.7: Design overview of three artificial bypass design for IJmuiden, that are subject to the financial feasibility calculations.

Best case scenario

The best case scenario assumes the maximum reduction in dredging and nourishment activity as is determined by bypassing 140,000 m^3 per year. The estimated operational costs for this situation with the proposed design as well as the initiation costs and break even points are presented in Table 7.6.

7.4.1. Discussion feasibility

Table 7.6 illustrates the financial feasibility under the best case scenario. In this scenario, all three concepts demonstrate lower operational costs compared to the current situation, thereby suggesting a potential break-even point. However, this is based on the assumption that bypassing 140,000 m3 per year will directly lead to proportional reductions in dredging and nourishment activities. This correlation most likely not always hold true, given the complexities of sediment dynamics and the various other environmental factors that could influence the effectiveness of a bypass system.

The financial feasibility is primarily driven by the reduction in dredging and nourishment activities. Therefore, the financial feasibility is inherently connected to the effectiveness of the bypass system. The results suggest that even with relatively high bypass costs per cubic meter (€5.44/m3), total operational costs remain lower compared to current management practices. This could indicate that in the trade-off between operational costs and effectiveness, the latter should be emphasized to enhance the project's financial feasibility. This underlines the need for further research into optimal design concerning dredge and nourishment activity reduction, as these activities contribute significantly to the total costs of current coastal practices.

The results also highlight the significant contribution of initiation costs for the recovery period for the initial investment. This underscores the relationship between scale and feasibility, revealing a notable decrease in feasibility as the scale increases. It highlights the timeless compromise between operational effectiveness and financial feasibility in project management.

Although rough estimate, some insights are obtained into the major cost drivers, namely, dredging activity and potentially, the initial costs of the sediment bypass. The operational costs of bypassing sediment are considered less impactful on overall feasibility. To make this presumed project highly feasible, focus should primarily be on reducing dredging activity. However, in the case of IJmuiden, a sediment bypass system is hypothesized to be less effective for this purpose. This simplified method for determining financial feasibility should not be seen as indicative of the actual expected costs of a bypass system or the current management practices. In reality, the IJmuiden port operates under an annual contract with the dredging contractor, making any reduction in dredging activity unrelated to the costs. Therefore, this method essentially serves as a preliminary framework for addressing feasibility.

Though this approach offers some initial insights into the financial implications, it's important to emphasize that our method didn't entail a detailed, site-specific financial analysis. As such, the results yielded from this method should be considered too uncertain to definitively determine the financial viability of a project. Therefore, before making any concrete decisions or conclusions, this approach should be supplemented by more in-depth, comprehensive feasibility studies.

8 Conclusion and Recommendations

This thesis explored the potential of a fixed artificial bypass system for a sustainable and eco-friendly approach to coastal management in IJmuiden. To conclude the degree of meeting this objective, the following research questions will be answered:

> ***Would the implementation of an artificial sediment bypass system be beneficial to the overall morphology and ecology?***

The research conducted in this study suggests that introducing a fixed artificial bypass system in IJ-muiden can reduce dredging activities and sediment demand of the downdrift coast. By correlating the outcomes of this research with established literature, it is evident that during its operational phase, a bypass system is likely to generate fewer emissions and demonstrate a less adverse impact on benthic communities compared to current management practices. As such, it is anticipated that an artificial bypass system would enhance sustainable and eco-friendly coastal management at IJmuiden.

The rationale behind this conclusion is provided in the answer to the following sub-questions:

> (i)*How might the impact of a fixed sediment bypass system effectively be evaluated?*

A framework is developed to assess the overall effectiveness of sediment bypass concepts based on four performance indicators:

(a) *Dreding Activity Channel and Port*

The evaluation of this performance indicator involves computing the net sediment flux and analyzing bed level changes relative to the baseline. This straightforward approach has shed light on the anticipated impacts of a bypass system, thereby contributing objective of this thesis. However, this method did not result in a quantitative estimation of the reduction in dredging activity. If applied to long-term simulations, clearer differences in sediment fluxes in the port and channel might be observed. Still, it remains questionable whether these numerical results could be used to estimate the effect on dredging due to the simplified description of the very complex coastal system of IJmuiden.

Further research into the processes and conditions could improve the predictive skill of the Delft3D model, which serves as a starting point for interpreting the results. Limitations of the current model, for instance, the exclusion of mud and progression of sand waves into the model, thereby inability to reproduce the significant sediment accumulation.

(b) *Sediment Demand Downdrift Coast*

Insights into the sand dispersal of the bypassed sand were gained from applying this method to various short-term simulations. These insights became particularly clear during the visual evaluation of bed level differences compared to the baseline case.

Despite this, the effects on sediment flux through Raai 52 were not yet observed within the simulated timeframe. A more extended simulation duration is expected to make these effects more visible. While the precise quantification of the reduction in sediment demand of the downdrift coast remains challenging due to the method's simplicity, it does provide the ability to compare different concepts, which is a valuable tool for making coastal management decisions.

However, should the predictive capability of the Delft3D model improve, we recommend using direct bed level changes as an indicator rather than sediment transport. This change would provide a more direct indication of the degree of erosion.

(c) *Impact on Benthic Community*

The 'Benthimeter' is a tool intended for comparing benthic impact for different coastal management strategies. Its compatibility with Delft3D simulations could allow users to integrate this tool into their existing modelling workflows, thereby offering an efficient way to evaluate the impacts of coastal management projects on the benthic community.

Incorporating a Monte Carlo method into the Benthimeter could amplify the tool's value. This incorporation allows the user to obtain helful information about the uncertainty of model parameters and helps improve the reliability of the Benthimeter's predictions.

However, the Benthimeter represents a conceptual model of the benthic response based on a relatively simple set of assumptions and input parameters. Therefore, the tool does not accurately capture the full range of factors that can influence benthic diversity. Also, the tool is not yet validated, and therefore not yet applicable to be directly used in ecological damage calculations.

In conclusion, the development of the Benthimeter can be seen a good first step towards modelling benthic impact. Further calibration and validation is, however, essential for wider application of the tool.

(d) *Feasibility*

The proposed method for evaluating the feasibility solely depends on the pipeline's total length. This relationship is derived from the initial and operational costs of the Tweed River Entrance Project and the Nerang River Project. While it is clear that the pipeline's length is not the sole determinant of a project's costs, the scale is generally considered a critical factor in the feasibility of fixed bypass projects. Hence, although this approach does not precisely predict costs, it could offer a useful first indication of potential cost ranges.

Therefore, the proposed method to determine the feasibility is effective in its simplicity and quick evaluation. However, this method is assumed too uncertain for a comprehensive evaluation of the financial feasibility.

(ii)*What is the expected impact of implementing a fixed sediment bypass system at IJmuiden port?*

The developed framework is applied to various fixed sediment system concepts to test their performance on the four performance indicators:

(a) *Dredging Activity Channel and Port*

Subtracting 230,000 m^3 per year from the southern side could lead to a proportional reduction in channel and port infilling. This best-case scenario calculation demonstrated that dredging activity could be reduced by 0.23 Mm3/year (3.5%). The numerical results showed that efficient infilling of the created sediment traps is occurring. Namely, 10% of this 230,000 m^3 was captured in the sediment trap within one month. Therefore, it is anticipated that a bypass system can subtract this 230,000 m3 per year from the updrift coast, thereby reducing dredging activities. However, within the simulation duration, the exact level of this reduction in dredging activity is not obtained throughout this study.

An important point to note is the significant difference between the annual dredge volumes (6.5 Mm3/yr) and the average net South to North alongshore sediment transport (140,000 m3/yr). Indicating that further research should include identifying the processes primarily leading to the required dredging activity. Literature mentions mud infilling and the migration of sand waves as potentially significant contributors.

(b) *Sediment Demand Downdrift Coast*

Adding 230,000 m^3 per year could potentially reduce the recurring 5-year nourishment volume by 1.1 Mm3 (-37%). The results in this study confirmed northward dispersal of the bypasses material under South-West wave conditions. Given the predominant south-west wave conditions, it is anticipated that the bypassed sediment is anticipated to reach the eroding coast and reduce its sediment demand to some degree. However, due to the simulations' duration constraints (one year), it's challenging to predict the long-term outcomes and the exact extent to which this optimal scenario could be realized.

Findings of this research indicate three important factors that can enhance the efficiency of an artificial bypass system at IJmuiden. First, maintaining sufficient distance between the northern breakwater and the outlet locations is essential to mitigate the shadowing effect. Secondly, the system's performance can be improved through the implementation of multiple outlets. Lastly, the study found that discharging sediment directly from the beach into the energetic zone optimizes dispersal. Consequently, careful consideration of these aspects is recommended when designing a sediment bypass system.

(c) *Impact on Benthic Community*

The results of the benthic impact evaluation support the hypothesis that a continuous nourishment approach could reduce the impact on benthic communities. However, given that the volume of nourishment activities determines the ecological damage in current practices, the ecological advantage of an artificial bypass system is dependent on the reduction in nourishment volume. This makes it challenging to ascertain the actual reduction in benthic impact in the IJmuiden case.

Assuming that the total bypassed volume contributes to a reduction in nourishment, our calculations suggest that the damage to the benthic community could be reduced by an average of 44 ha/year, representing a 33% decrease.

Although this is not an easily interpretable metric, and the calculations are based on simplified descriptions, we anticipate that an artificial bypass system will result in less ecological impact than current practices.

(d) *Feasibility*

The feasibility estimates reveal that reducing dredging and nourishment activities primarily drives the project feasibility. Making it evident that the economic feasibility largely depends on the effectiveness of the sediment bypass system. Our analysis also indicated that the operational costs of bypassing are less consequential to the overall feasibility than the initial implementation costs.

The performed feasibility analysis is assumed too uncertain; therefore, no conclusions are drawn concerning the feasibility of a fixed sediment bypass system for IJmuiden. However, the global application of these systems implies their potential viability.

8.1. recommendations for further research

Based on the research conducted during this thesis, the following suggestion for further research have emerged:

- *Simulate equilibrium state*: Due the simulations covering just limited period (1 year), the equilibrium state is not yet reached. Simulating this state would provide information on the long term effects of implementing an artificial bypass system.
- *Improve simulation efficiency*: Current simulations are time-intensive. Future research into method for improving the model's efficiency and reducing simulation times, would provide a quicker and more effective tool for testing different concepts under actual wind and wave conditions over several years.
- *Improve predictive skill of model*: The current system response prediction is used as an input for the evaluation method introduced in this research. Improving its predictive skill could enhance the overall results. For instance, the observed smoothing effect could be addressed to improve the model's predictive ability.
- *Calibrate and validate the ecological model*: The 'Benthimeter', used for assessing ecological impact, could be improved through more extensive research into the complex ecological relationships. Calibration and validation of the 'Benthimeter' could lead to more accurate results. For instance, including factors such as the migration of benthic species or the increased diversity observed in the troughs could enhance the tool.
- *Identify the primary processes leading to dredging activity*: Understanding the main drivers of dredging activity could provide valuable insights. Factors such as mud infilling and the migration of sand waves could be potential contributors.
- *Conduct a comprehensive feasibility analysis*: A feasibility analysis should consider more than just the length of the pipeline. Other significant factors influencing the project's cost should be included to provide a comprehensive evaluation of the project's viability.
- *Design optimization for sediment discharge*: The design of the bypass system, including spacing between the northern breakwater and multiple outlet points, significantly impacts its efficiency. Research focused on optimizing these design elements could further improve the sediment bypass system's effectiveness. Also operation bypassing schedule could improve the effectiveness.

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A

Benthic Impact Assessment Tool Development

A.1. Introduction

In this chapter, which can be seen as a stand-alone study, the method of developing the tool is presented. Site and situation-specific variables, that can be adjusted by the user, are treated. And finally, the tool will be reviewed based on the twelve test cases.
Nourishment is gaining popularity in terms of coastal protection strategies. At first this was achieved by supplying sand directly on the beach. Foreshore nourishment became more popular since the nineties. Nowadays, experimental mega nourishments are performed, which have a great potential in terms of coastal protection, costs and nourishment frequency. However, all types of sand nourishment affect the coastal ecosystem in various ways (Baptist et al., 2009). We separate direct impact as a result of burial by the dumping of sand and indirect impact as a result of bed level changes due to secondary sediment transport arising because of altered morphological behavior.

A group in particular mostly affected by nourishment are the benthic species. Combined with their central role in the ecosystem, and their quick adaptation ability to changes in the environment makes that the status of benthic community is often used as an indicator for assessing the impact of human induces disturbance to the functioning of an coastal ecosystem.

For this purpose a tool was designed that can be used to estimate the benthic response to nourishments and therefore be used to optimise nourishment configuration, location and timing. The so-called *Benthimeter*, is constructed to quantify and visualize the damage and recovery to benthic life over time. Relations are included to estimate damage due to burial, seasonal recovery over time, and a maximum carrying capacity depending on depth (See figure A.1). The indicator used to describe the effect of nourishments is *normalised benthic diversity* relative to the diversity in the autonomous situation (simulation without nourishment).

A.2. Tool description

The tool is a post-processing module that intends to quantify and visualise benthic response to nourishment strategies, based on bed-level outcome of morphological forecasting simulations. During development of the tool, Delft3D morphological outcome in the form of bed-level changes during time intervals of 1 week over a period of 4 to 10 years are used. These initial test cases that were used to tune the parameters are described in section A.4 The benthimeter creates maps visualising the benthic diversity of an area and the induces damage from nourishments at a given timestep (e.g. see E.3). Also the time and space integrated benthic damage is calculated in the benthimeter (e.g. see E.3) . Both calculation are performed within 10 seconds, however depending on the user's preferences on the quantity of image output and the number of Monte Carlo runs the simulation time can become hours.

In this approach, the normalised diversity of a cell depends on three factors, namely the amount of burial damage, the level of recovery and carrying capacity of a cell. The carrying capacity for benthic diversity is defined as the maximum diversity a habitat (grid cel) can sustain. The carrying capacity is reached when the diversity of a habitat is fully recovered after being damaged by burial. In this method, it is assumed that at time zero (before nourishment), the diversity of cells in the grid are undisturbed (i.e. calculated according to the carrying capacity relation of Figure A.2). The diversity changes exclusively due to nourishment initiated bottom change, i.e. a bed level correction is made to correct for the bottom change in the reference situation as seen in formula A.11. In addition, carrying capacity determines the degree of recovery following the seasonal dependent logistic recovery model (see function A.6). In summary, the ecological indicator to evaluate the state of the benthic population, expressed as *normalised benthic diversity*, is acquired by performing three calculations for each timestep for each gridcell:

- Computing the carrying capacity
- Computing burial damage
- Computing the recovery of the benthic diversity

Despite the fact that several processes are considered in this approach, it remains a conceptual representation of reality. Therefore, the objective of the tool is not to obtain an accurate quantitative description of benthos response to nourishments, but to provide a feeling for the benthic response towards different types of interventions (i.e. instantaneous vs. continuous). During the development of this tool, assumptions and simplifications were based on this notion.

A.3. Methods

A.3.1. Grouping of species

All benthic species have a different response to burial, type of recovery and preference for abiotic conditions. Describing the entire benthic community with a single set of characteristics would oversimplify reality and thus introduce errors. On the other hand, the inclusion of different characteristics for all species would make the development and interpretation overly complicated. Therefore the decision is made to group various species into groups based on a number of traits. Within the *Benthimeter* the *normalised benthic diversity* of a cell is calculated separately for each group and then added up to obtain the total diversity of a cell at a given timestep.

Two groups have been specified: group A representing mobile species and group B representing the less mobile species. This division is based on statements and burial data acquired from earlier research (Baptist et al., 2009; Bijkerk, 1988; Herman et al., 2021; Smit et al., 2006). In Appendix.. the groups can be found. Due to the flexible approach of the Benthimeter, users can change these group characteristics and can add groups if wished.

A.3.2. Carrying capacity

In general, the biodiversity in the subtidal zone is related to a large number of factors, however literature often describes the hydrodynamic variables to be important determinants of macrobenthic community structure (Ysebaert and Herman, 2002; Ysebaert et al., 2003; Holzhauer et al., 2019; Cozzoli et al., 2017. Literature typically support the idea that the quantity of species varies with hydrodynamic activity, where number of species generally is lower in energetic region while the species richness increases in deeper, calmer regions. Besides, typical mobile species (group A) are better adapted to deal with high hydrodynamic stresses and thus the distributions of species over space varies for different groups (Janssen and Mulder, 2005,Armonies, Buschbaum, and Hellwig-Armonies, 2014,Baptist et al., 2009).

The carrying capacity, a term used to denote the maximum diversity of species that a particular environment can support is included in the *Benthimeter* to:

- Determine the initial (t=0) *normalized benthic diversity* of a cell
- Define the maximum *normalized benthic diversity* a cell can have

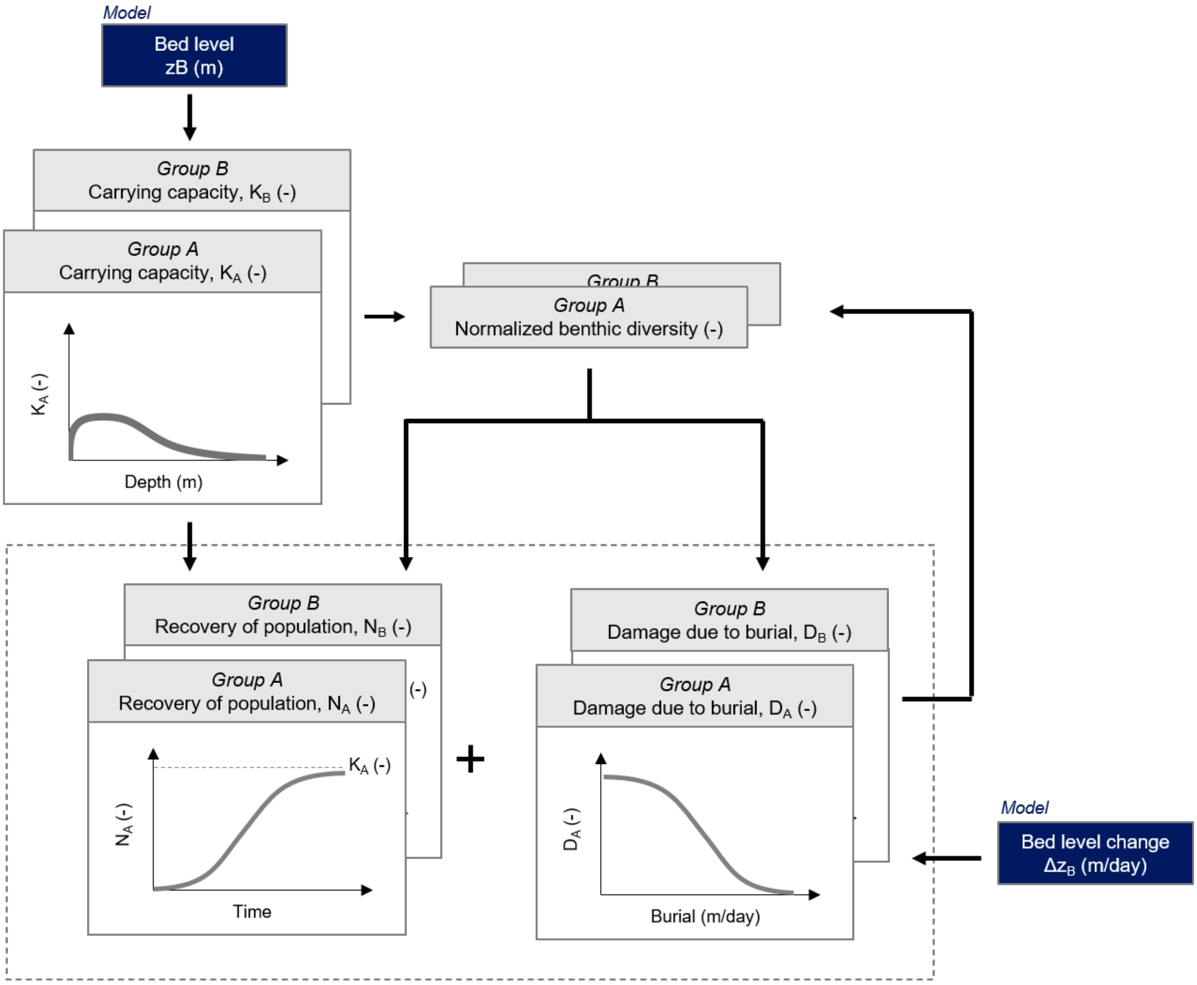


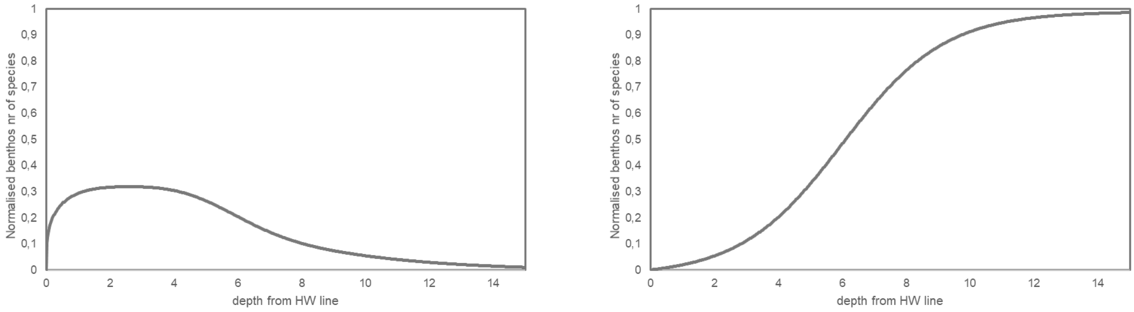
Figure A.1: Benthimeter flowchart of the calculation performed every timestep to estimate the benthic response to bed level change.

- Determine the degree of recovery

The complex carrying capacity is simplified into a depth related function for the mobile species (Group A) and the less mobile species (Group B) (see Figure A.2). The relation used for the mobile species shows a quick increase followed by slow decline in diversity. This is presented by an Weibull function with a normal distribution function (Funtion A.1). For group B holds that the diversity increases when depth increases (less energetic), this is presented by an logistic function.

Several studies were used to gain understanding and feeling for the diversity distribution of typical Dutch cross-shores, in order to construct the relations (see Figure A.2) (Holzhauer et al., 2019; J. A. van Dalfsen, 2009; Janssen et al., 2008; Armonies, Buschbaum, and Hellwig-Armonies, 2014). In particular the study Holzhauer et al. (2019) was used since they studied not only the occurrence of species along the cross-shore but also described the morphological features of the cross-shore with the accompanying depth ranges. Therefore, besides the depth of a morphological feature, also the dynamics are provided, and can used as indications for the occurrence of type of species (Group A or/and B) (See Appendix) A.20.

$$N_A(h) = \frac{k}{\lambda} \cdot \left(\frac{h}{\lambda}\right)^{k-1} \cdot e^{-(h/\lambda)^k} + \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{1}{2}\left(\frac{h-\mu}{\sigma}\right)^2} \tag{A.1}$$



(a) (b)

Figure A.2: Functions for (a) group A (Weibull + Normal) and (b) group B (Logistic function) describing carrying capacity related to depth.

$$N_B(h) = \frac{1}{1 + e^{-(h-\mu)/s}} \qquad (A.2)$$

where:

N_A(h)	:	Normalized value for benthic diversity of group A	(-)
N_B(h)	:	Normalized value for benthic diversity of group B	(-)
h	:	Depth relative to the Mean High Water level (= MHW - z_b)	(m)
κ	:	Parameter defining the shape of weibull distribution	(-)
λ	:	Parameter defining the scale of weibull distribution	(-)
σ	:	Parameter defining the scale of normal distribution	(-)
μ	:	Parameter defining the mean of normal distribution of logistic function	(-)
s	:	Parameter defining the steepness of logistic function	(-)

In figure A.3 an example is presented in which the *Benthimeter* is applied on output of a Delft3D simulation of the foreshore at Egmond aan Zee. In this example, the initial situation (t=0), without nourishment is presented, i.e. the *normalised benthic diversity* is calculated using the carrying capacity relations. The carrying capacity of a cell is obtained by adding the the values for group A and B.

It could contribute to the overall damage of a nourishment strategy by habitat modification. This happens in a situation where the carrying capacity, however the carrying capacity of the cell is less compared to the carrying capacity of the cell in the reference situation. To an extreme extent, this is the case, for a sand motor nourishment where a large part emerges above the water level and is not habitable for benthic animals (i.e. carrying capacity is zero). The recovery of this damage due to habitat modification happens t

A.3.3. Benthic response to burial

Bed level changes from a Delft3D model serve as the input for the *Benthimeter* to estimate the damage by burial for the benthic diversity. In this approach, a distinction has been made between direct and indirect burial. Where direct burial of nourishments are represented by an instantaneous increase in bed level (direct burial), while the morphological change over time is used to describe the indirect burial. The more mobile species (group A) have a larger resistance against burial with typical fatal burial depths between 10-110 cm, whereas the less mobile species (group B) show fatal burial depths between 1 cm and 10 cm (Baptist et al.2009; Bijkerk, 1988; Herman et al., 2021; smit-2006).

The method described by Smit et al. 2006 is used to calculate the benthic diversity damage due to burial. In this approach, data on fatal burial depths for various species are fitted to a distribution function (e.g. see figure A.16). The type of distribution is arbitrary, but often a cumulative log-normal or gamma distribution is used to find a representative function for damage for a group. Finally, the SSD-

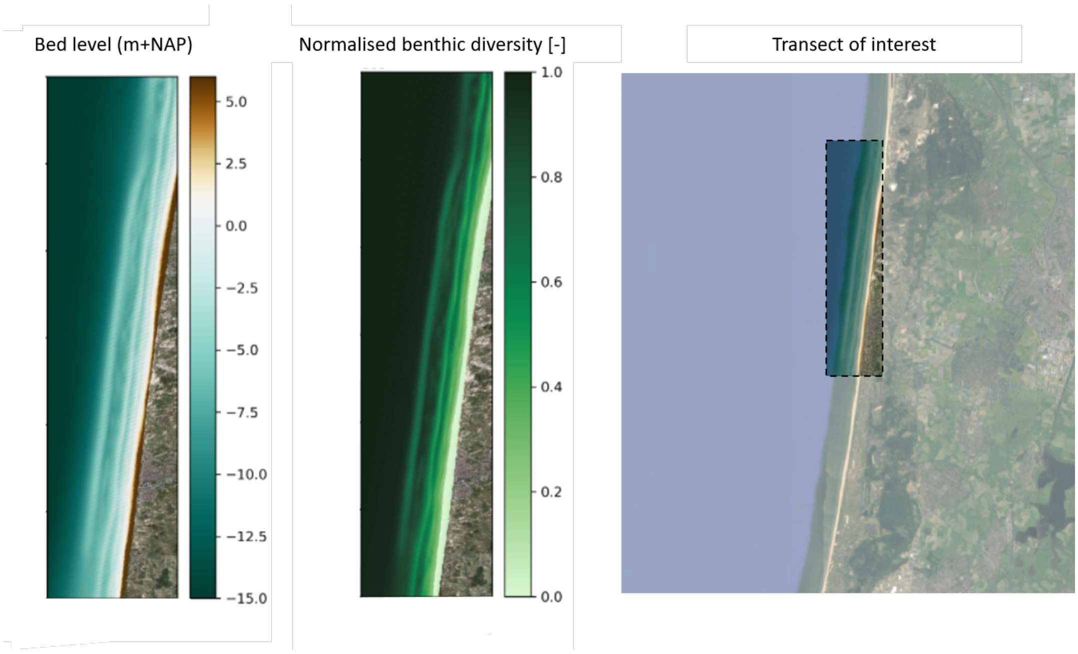


Figure A.3: Example of the application of the*Benthimeter* where bed-level (left) of a grid is translated to *normalised benthic diveristy* (middle). In this example the intitial situation before nourishment is presented, i.e. the *normalised benthic diversity* is calculated using the carrying capacity relations.

curve is transformed to a survival distribution (=1-SSD) (see Figure A.4).

The data used in this method is provided in Appendix... . As the table shows there is limited data available in literature, where both mobility is known and the fatal burial depth. However findings described in different studies are combined to construct the data set.

During development of this tool, a model is used that generates output at at time-interval of 1 week. Therefore, bed-level changes during a week are used as input. However, fatal burial data (Appendix ..) is provide in m/day, i.e. a translation from m/week to m/day is required. When, daily average is used to calculate the survival fraction, peak burial is not taken accounted for. Since, the survival curves are non-linear relations (See Figure A.4). A constant (c_d) is introduces to deal with this problem. It stands for the number of days over which the burial can be averaged, i.e. c_d of 1 means that the weekly bed level change results from events of a single day. In the model a different value is used to compute

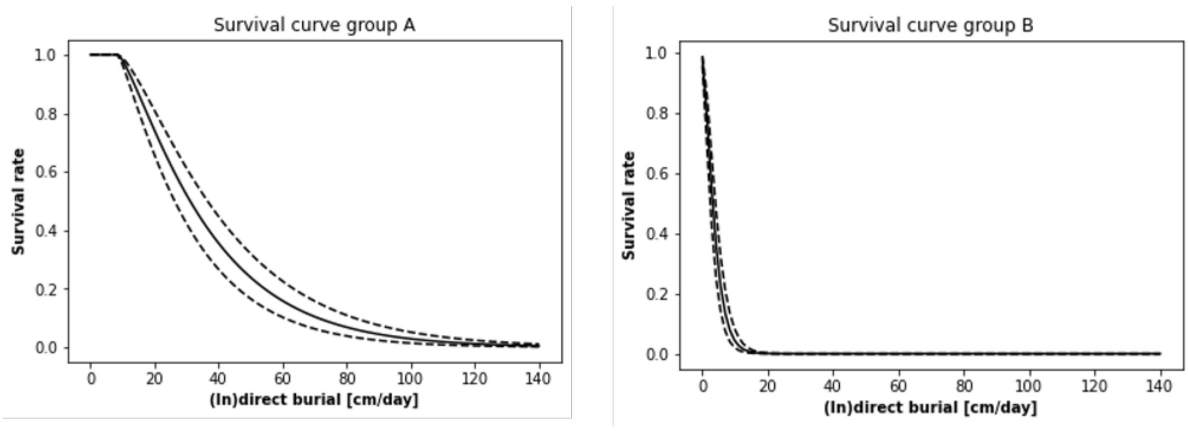


Figure A.4: Relations used to calculate the fraction of *normalised benthic diversity* surviving a coverage of sediment layer with a certain thickness. Left figure presents the survival curve of the mobile species group (Group A) and right figure, the less mobile species (Group B).

direct burial compared to indirect burial damage.

$$N_{t+1} = N_t \cdot (1 - SSD)^{\Delta t \cdot c_d} \quad (A.3)$$

$$SSD \sim \Gamma\,(\Delta z, c_d, \alpha, c_s, loc, scale) \quad (A.4)$$

where:

N_t	:	Normalised benthic diversity at the current timestep	(-)
c_d	:	Constant to account translate non-daily data to representative daily values	(-)
c_s	:	Constant to adjust sensitivity towards burial	(-)
N_{t+1}	:	Normalised benthic diversity at the next timestep	(-)
Δt	:	Timestep between time instance t and t+1	(days)
Δz_B	:	Bed level change over timestep Δt	(m/days)
Δt	:	Timestep between time instance t and t+1	(days)
	:	Bed level change threshold after which damage occurs	(m)

A.3.4. Recovery

In nature recovery of a disturbed area mainly take by reproduction or by immigration from its surroundings. Optionally, import of Benthos that survived the extraction site may contribute to the recolonization (Dalfsen and Essink, 2001). The recovery of *normalised benthic recovery* is included in the *Benthimeter* through the reproduction mechanism. Adult immigration is excluded due to it's debatable significance and due the limited data on this mechanism. The complexity of measuring the immigration distance of a benthic animal, speaks for itself.

The restoration of the benthic diversity through reproduction is described by a logistic growth function. This growth model is based on the population growth model described by Shepherd and Stojkov (2007). Logistic growth curves generally provide an effective abstraction of the complex recovery dynamics of benthic communities. As the function depicts, the amount of recovery is dependent on the current normalised benthic diversity of a cell N (-), the depth-dependent carrying capacity K (-) and a value for the reproduction rate r (-/year) (see Function A.5.

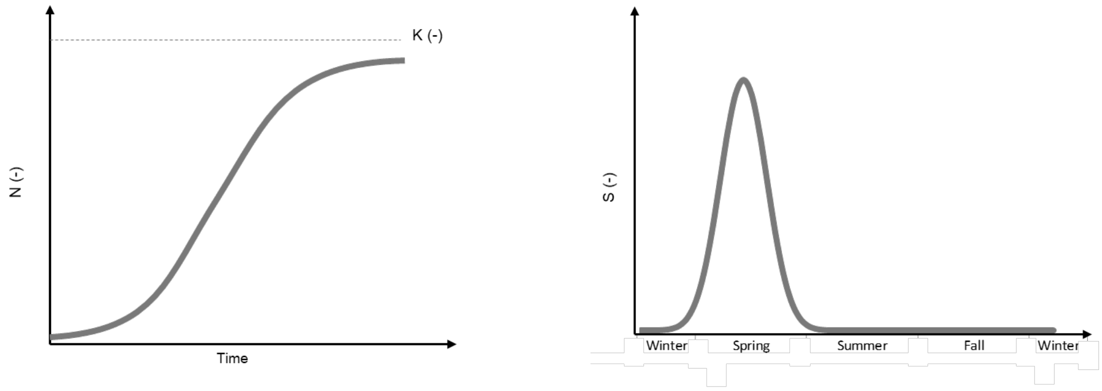
$$\frac{dN}{dt} = r \cdot \left(\frac{K - N}{K}\right) N \quad (A.5)$$

A seasonal (time) dependent multiplication function is incorporated into the reproduction rate as a skewed harmonic wave with a peak at spring to capture the seasonal reproduction cycle (Baptist et al., 2009). The time varying seasonality factor (Function A.7) is calculated by sin power function. The larger the power value (s), the narrower the reproduction timeframe will be. The function is divided by its integral, so that the yearly cumulative seasonality factor equals one (see Function A.8.

$$\frac{dN}{dt} = S(t) \cdot r \cdot \left(\frac{K - N}{K}\right) N \quad (A.6)$$

$$S(t) = \frac{sin(\omega t + \phi)^s}{\int_0^{2\pi} sin(\omega t + \phi)^s dt} \quad (A.7)$$

$$\int_{yearn}^{yearn+1} S(t)dt = 1 \quad (A.8)$$



(a) label 1 (b) label 2

Figure A.5: 2 Figures side by side

where:

$S(t)$	:	Multiplication factor accounting for time dependency in the reproduction of benthos	(-)
ω	:	Angular frequency: $\frac{\pi}{nrtimesteps/year}$	(rad/Δt)
Δt	:	Timestep between time instance t and t+1	(days)
ϕ	:	Phase shift to align seasonality pattern to simulation	(rad)
Δt	:	Timestep between time instance t and t+1	(days)
s	:	Parameter defining reproduction timeframe (even integer)	(-)

When the reproduction rate increases, carrying capacity will be reached more quickly. Fast-reproducing opportunistic species frequently recover completely after total damage within a year, whereas for slow-reproducing species can take up to four years (Dalfsen and Essink, 2001). Varying values for the reproduction rate are imposed for the mobile and less mobile groups (Gittenberger and Loon, 2011). Baptist et al. 2012 presented typical reproduction rates between 0.5 and 15 for benthic species at the Dutch coast. Reproduction values of a typical r-strategist (Capitella capitata; r=15.3), a typical intermediate-strategist (Macoma balthica; r =1.0) and a typical k-strategist (Echinocardium cordatum; r=0.5), as provided by Baptist et al. (2012) might be used as an indication for divining r-values in the Benthimeter.

In the current version of the Benthimeter, migration processes are not yet considered. For small-scale disturbing events, this mode of recovery may have a significant contribution to the total recovery of the benthic population (Moorsel, 2005).

A.3.5. Ecological response evaluation

In order to evaluate the benthic response of different nourishment strategy simulations, the normalised benthic diversity of cell of grid is integrated in space, as indicated in the functions below. The *normalised benthic diversity* N (-) of cells in the area of interest, are multiplied by their area A (ha). The summed value represents the *Ecological value* (ha) at a certain time. In Figure A.6 the *Ecological value* throughout time for the reference test case ’35_30_c4_v202101’, calculated using the *benthimeter*, is presented. It can be noted that this reference case already shows a variability in the ecological value, due to burial damage and recovery of the diversity.

$$Ecological\ value = \sum N_i \cdot A_i \tag{A.9}$$

As mentioned, the intend of this ecological evaluation method is to get an indication of the nourishment induces damage to benthic diversity. Therefore, the ecological damage is defined as the difference between the ecological value of the reference simulation and the ecological value of the simulation of

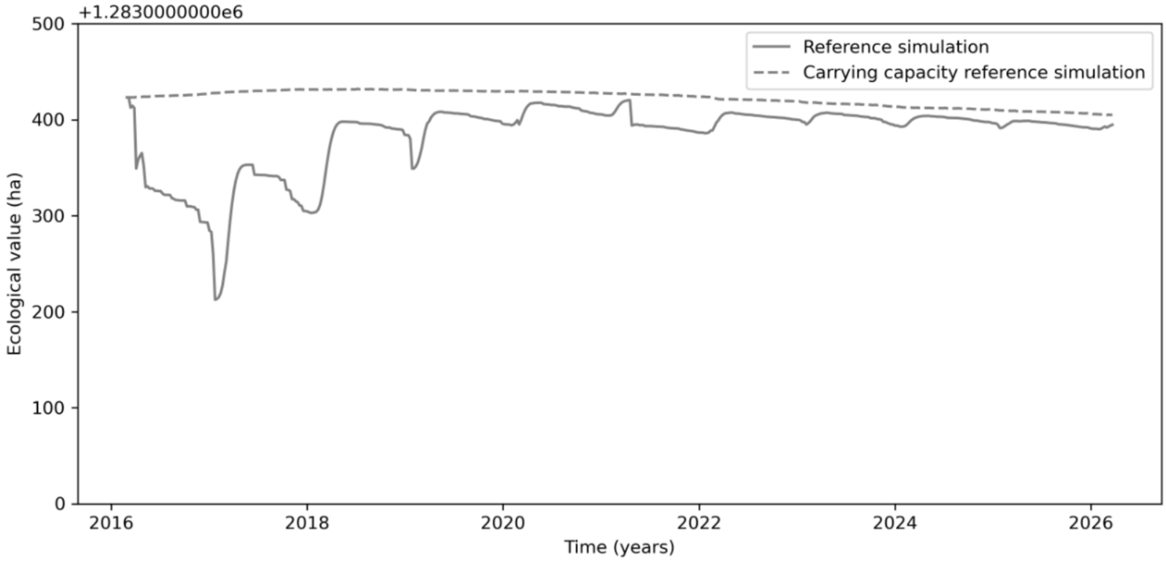


Figure A.6: Ecological value over time of reference simulation '35_30_c4_v202101' calculated using *Benthimeter*. The evaluated transect can be seen in figure A.3

interest (see Function A.10.

$$Ecological\ damage = Ecological\ value_{ref} - Ecological\ value \tag{A.10}$$

It is attempted to isolate only the nourishment induces dames using two different approaches. 1) Is in line with the methodology applied up to this point, where the ecological value of the reference simulation changes over time. The ecological damage is the difference between the ecological value of the reference simulation and the simulation being evaluated (see Figure A.7). 2) A bed level correction is made to correct for bed level changes in the reference simulation (Equation A.11. By doing this the ecological value of the reference simulation remains constant and bed level changes relative to the bed level changes in the reference simulation, serve as input in the *benthimeter*(See Figure A.8.

$$\begin{aligned} \Delta z_{ref} &= z_{ref,t_0} - z_{ref,t_n} \\ \Delta z &= z_{t_0} - z_{t_n} \\ z_{corrected} &= z_{t_0} + \Delta z - \Delta z_{ref} \end{aligned} \tag{A.11}$$

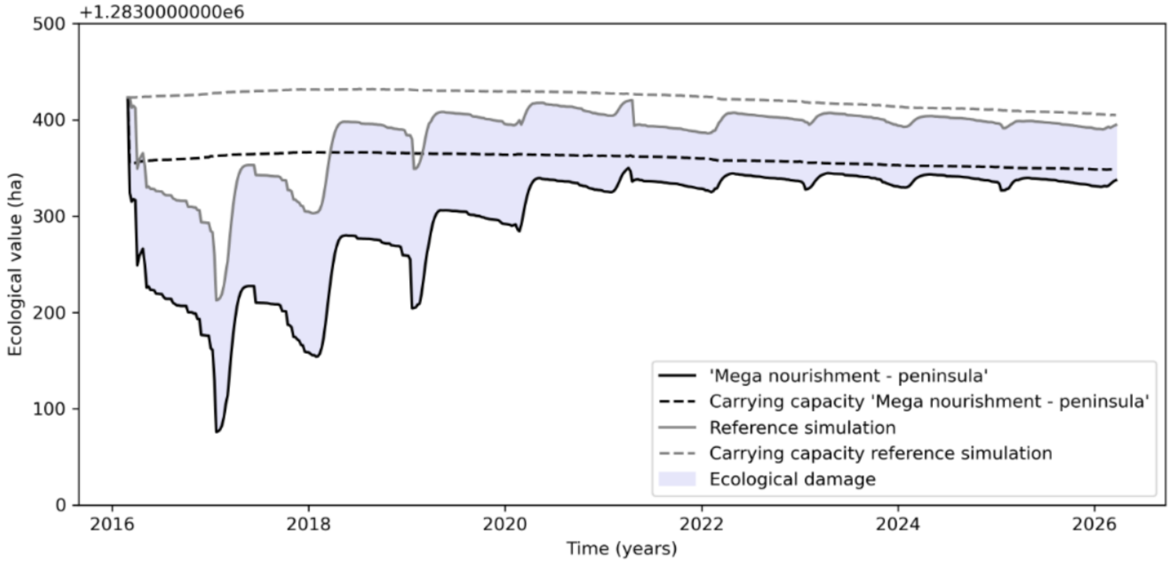


Figure A.7: Approach 1 for defining ecological damage: difference between ecological value reference simulation and the simulation to evaluate.

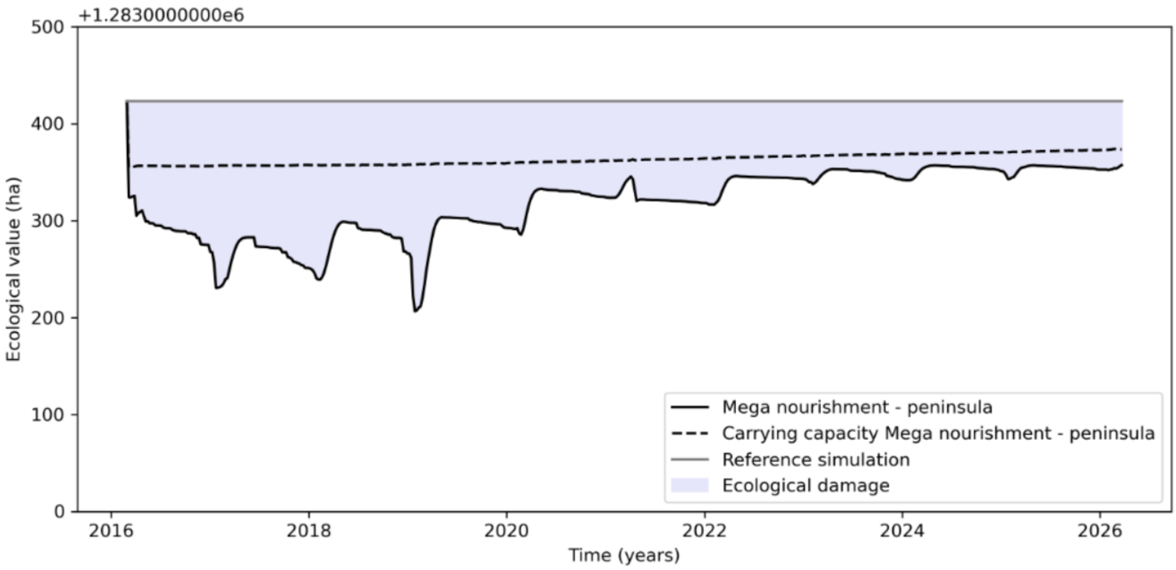


Figure A.8: Approach 2 for defining ecological damage: Difference between ecological value reference simulation and the simulation to evaluate, with bed level correction (see Equation A.11

A.3.6. Uncertainty analysis

The 'Benthimeter' uses simple functions to describe very complex processes of benthic life in the nearshore. Due to these simplifications and assumptions, uncertainties in the parameters for the carrying capacity, burial damage and recovery are introduces. The tool offers the possibility to define values for the parameters with a certain uncertainty. The uncertainty is includes as a normal distribution around the mean value. By means of Monthe Carlo[1] method parameter value are randomly sampled from a defined normal distribution, and used to calculate response of benthos to nourishments. The user can define the number of runs to create confidence intervals, however in this study 1000 runs is used. In this version of the *Benthimer* only a limited number of variables are defined as stochastic variables

[1]A Monte Carlo simulation is a mathematical method that uses random sampling to perform calculations and generate results. This technique can be used to model complex systems and evaluate the likelihood of different outcomes. By using a large number of samples, Monte Carlo simulations can provide reliable estimates of the likelihood of different outcomes and help inform decision-making.

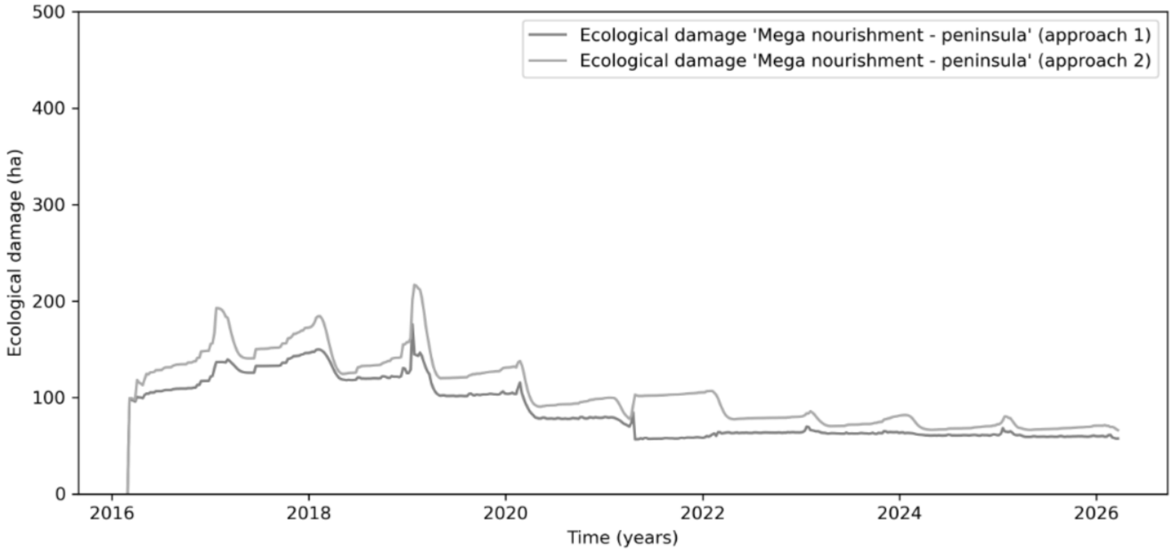
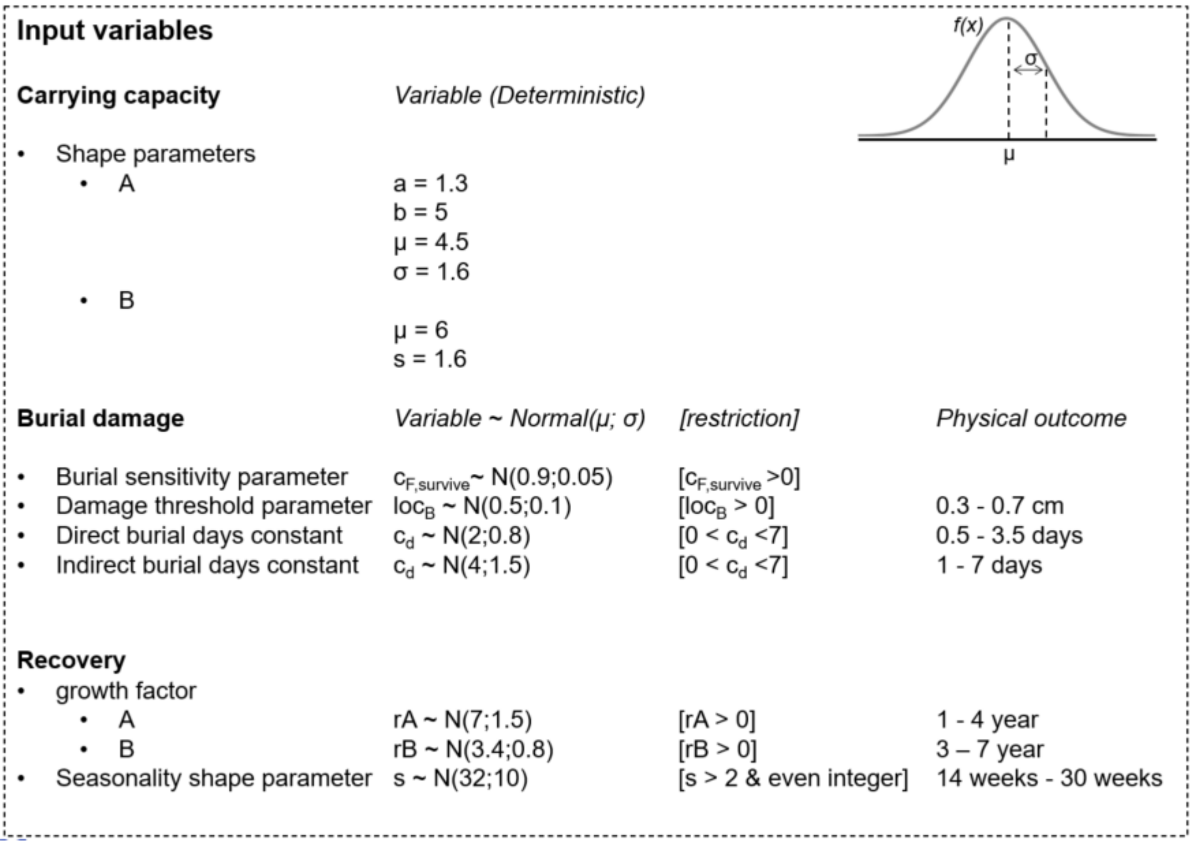


Figure A.9: Example illustrating the two approaches for determining ecological damage. 1) No bed level correction, and 2) with bed level correction (see Equation A.11). Test case 'Mega nourishment - penisula' was used for this example.

with a normal distribution. See Figure A.10 for the site specific variable under which the stochastic ones. However, it must be noted that part of the uncertainties of the variables are based on educated guesses. Therefore, the term simulation intervals is rather used than confidence intervals, to present the uncertainties.



Input variables

Carrying capacity	*Variable (Deterministic)*		
• Shape parameters			
• A	$a = 1.3$ $b = 5$ $\mu = 4.5$ $\sigma = 1.6$		
• B	$\mu = 6$ $s = 1.6$		
Burial damage	*Variable ~ Normal(μ; σ)*	*[restriction]*	*Physical outcome*
• Burial sensitivity parameter	$c_{F,survive} \sim N(0.9;0.05)$	$[c_{F,survive} > 0]$	
• Damage threshold parameter	$loc_B \sim N(0.5;0.1)$	$[loc_B > 0]$	0.3 - 0.7 cm
• Direct burial days constant	$c_d \sim N(2;0.8)$	$[0 < c_d < 7]$	0.5 - 3.5 days
• Indirect burial days constant	$c_d \sim N(4;1.5)$	$[0 < c_d < 7]$	1 - 7 days
Recovery			
• growth factor			
• A	$rA \sim N(7;1.5)$	$[rA > 0]$	1 - 4 year
• B	$rB \sim N(3.4;0.8)$	$[rB > 0]$	3 – 7 year
• Seasonality shape parameter	$s \sim N(32;10)$	[s > 2 & even integer]	14 weeks - 30 weeks

Figure A.10: Caption

A.4. Test cases and results

Several cases were used to tune the parameters and construct the tool. All test cases address morphological forecasts of the coast of Egmond. The model includes nourishments as an instantaneous rise in bed level at time step t=1. Whereas for continuous nourishment strategies, the bed level change is distributed over a number of time steps. The first set of cases consists of four Delft3D simulations of mega nourishment strategies that were run with identical settings. Different settings were used for the second set of cases. For both sets of simulations holds that a MorFac[2] of 4 is used, resulting in a morphological time step of 1 week.

Test case set 1: Mega nourishment concepts

This set contains morphological output from simulations in which roughly 8 Mm3 of sand was added to the grid over a period of 10 years (see Figure A.11):

- Reference simulation (0.0 Mm3): *35_30_c4*
- Peninsula (7.9 Mm3): *35_33a_c4*
- Island (8 Mm3): *35_33b_c4*
- Submerged (7.6 Mm3): *35_33c_c4*
- Continuous point nourishment (7.4 Mm3): *35_31a_c4*

Testcase set 2

The second test case consists of eighth simulations, ran with the same settings:

- Reference simulation (0.0 Mm3): *33_00a*
- Foreshore nourishment (2.5 Mm3): *33_11a*
- Continuous 2 point beach nourishment (2.0 Mm3): *33_12a*
- Continuous 2 point foreshore nourishment outer bar (2.5 Mm3): *33_12b*
- Mega nourishment - Peninsula (9.9 Mm3): *33_13a*
- Beach nourishment (0.5 Mm3): *33_21a*
- Beach nourishment - 'Zandbrommers'[3] (0.6 Mm3): *33_21b*
- Foreshore nourishment (0.5 mm3): *33_21c*
- Continuous point beach nourishment (0.5 Mm3): *33_22a*

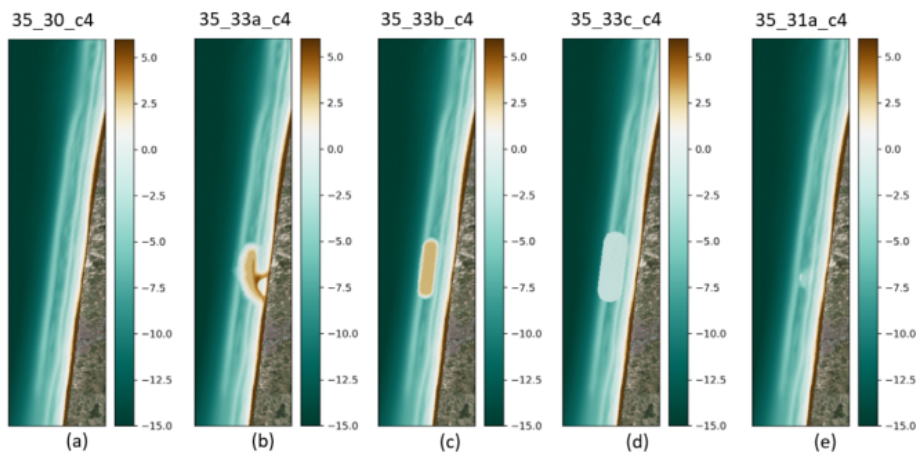


Figure A.11: Overview of the first set of test cases in which different types of hypothetical mega nourishment strategies are simulation. (a) represents the bed level of the reference case, (b) represents peninsula case at time step t=1, (c) represents Island nourishment at time step t=1, (d) represents the submerged strategy at time step t=1 and (e) the continuous point nourishment at t=50.

[2] Morphological acceleration factor for to increase simulation speed

[3] Several small scale peninsula nourishments located next to each other at the beach.

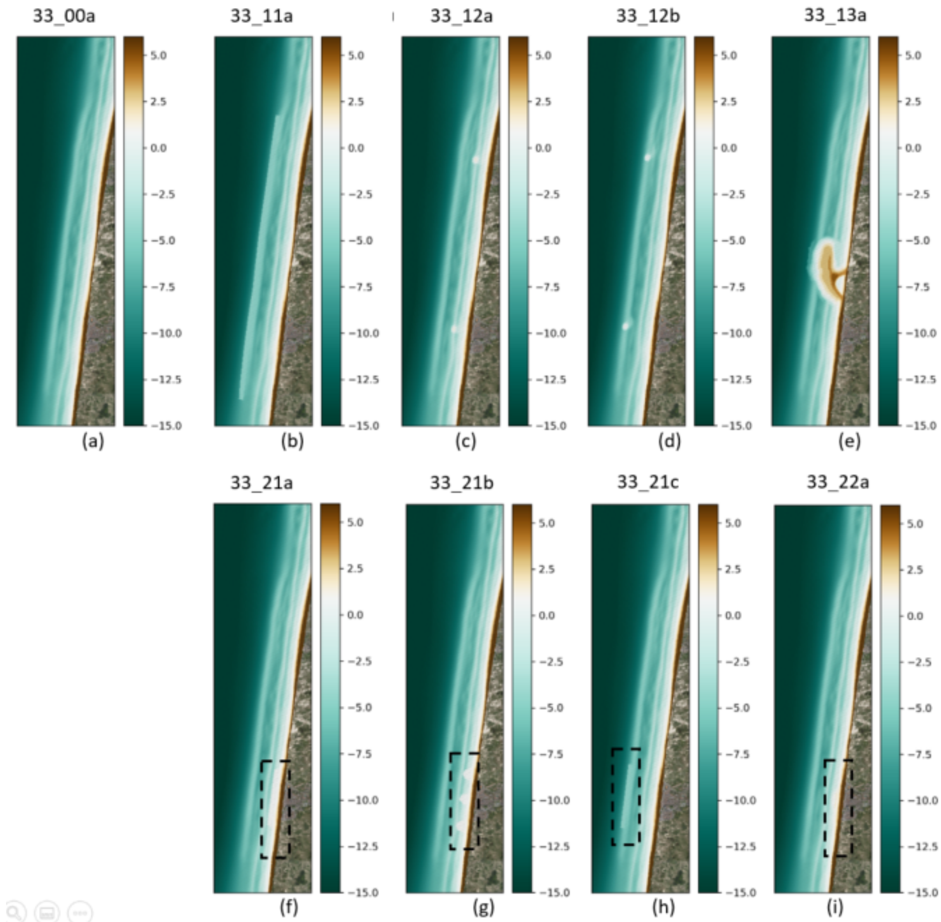


Figure A.12: Overview of the bed levels (m+NAP) of the second set of test cases in which different types of hypothetical nourishment strategies are simulated. (a) represents the bed level of the reference case, (b) is a foreshore nourishment at t=1, (c) and (d) are continuous point nourishments at t=50, (e) is the peninsula nourishment at t=1, (f) represents the beach nourishment at t=0, (g) the beach nourishment strategy 'zandbrommers', (h) a foreshore nourishment and (i) a continuous point beach nourishment.

Test case set 1: Mega nourishment concepts

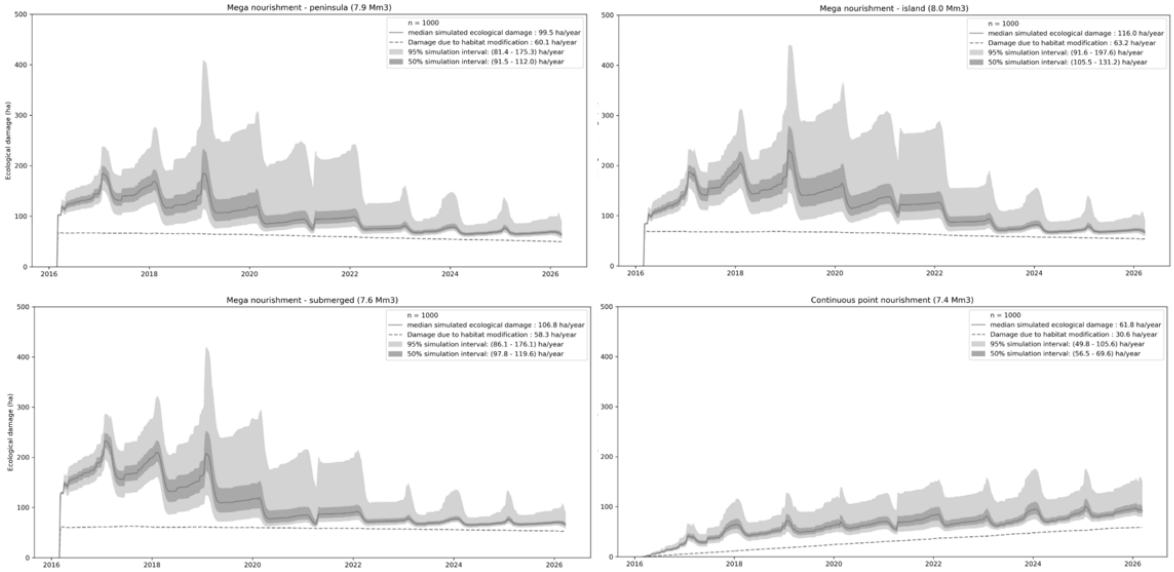


Figure A.13: Overview of the estimated ecological damage of the test cases in set 1 over time, calculated using the *Benthimeter*.

Test case set 2: Nourishment concepts

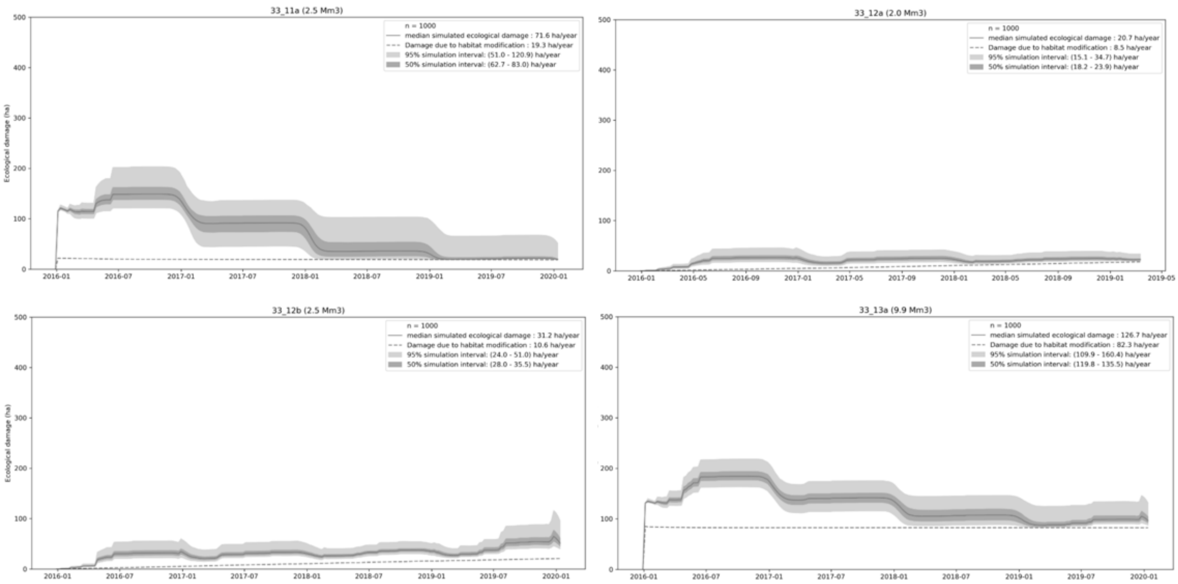


Figure A.14: Overview of the estimated ecological damage of the test cases in set 2 over time, calculated using the *Benthimeter*.

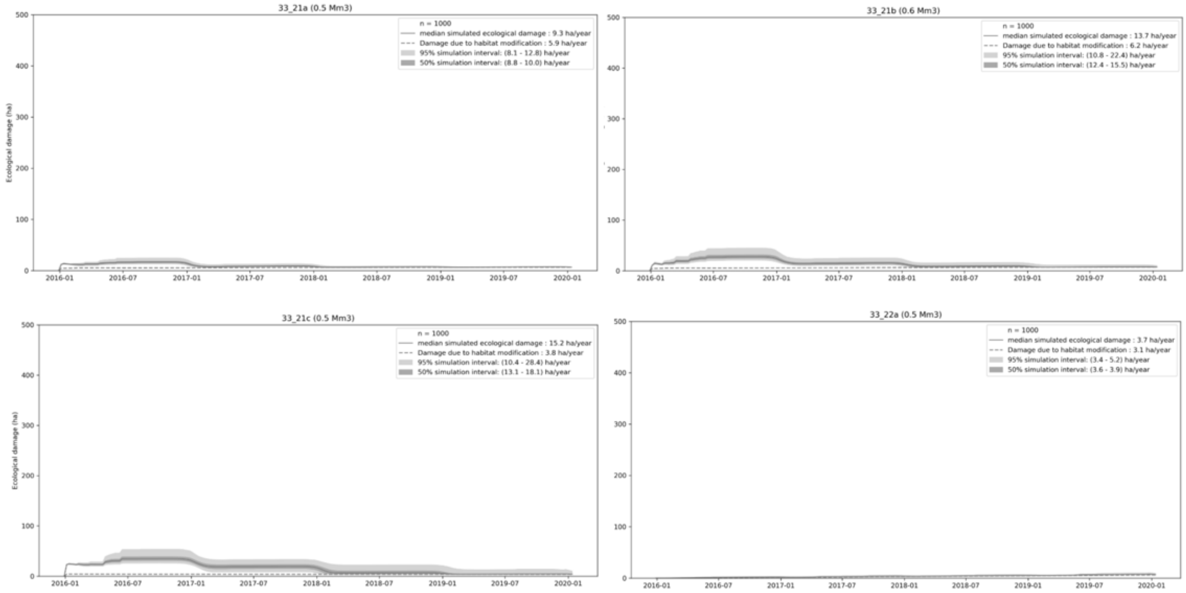


Figure A.15: Overview of the estimated ecological damage of the test cases in set 2 over time, calculated using the *Benthimeter*.

A.5. Discussion

As mentioned previously, the complexity of benthic ecosystems and the many factors that can affect them make it challenging to develop a tool that can accurately predict the response of benthic species to nourishments. The Benthimeter represents a conceptual model of the benthic response, based on a relatively simple set of assumptions and input parameters. While this simplicity allows for quick and easy interpretation of the results, it also means that the Benthimeter may not accurately capture the full range of factors that can influence benthic diversity.

One of the key challenges in evaluating the ecological impacts of nourishment projects is determining what level of damage is acceptable or unacceptable. The Benthimeter provides a measure of the affected benthic diversity (ha), but it is difficult to determine a threshold value beyond which a nourishment strategy would be considered ”good” or ”bad”. Besides the actual calculated differences are currently not reliable enough to be used and discussed independently. The real benefit of this study is the conception, creation, and use of a simple prediction tool.

The parameters values used to describe the recovery of the diversity (r-values, seasonality) are highly variable among species. During development only two groups were selected as prepresentatives out of a very large number of species, not spanning the total range of values possible. Also processes such as migration, nourishment survival, changes in suitability due to other reasons than nourishments, food-web interaction etc. are not taken into account when describing the population dynamics. Especially, migration is something that could be interesting to add in further versions. One could also argue the significance of adding the seasonality to the recovery since we are interested in the average damage and years to fully recover.

The method suggests that long-term ecological impacts of nourishment are dictated by damage resulting from habitat modification. However, it’s important to note that the term ”damage” might not be appropriate in all cases. One could argue that an altered habitat isn’t necessarily worse or better than the original state since it could provide life to new ecology. The interpretation of habitat modification as damage is clearer in some scenarios. For instance, in the case of the Sand Motor, aquatic benthos can no longer inhabit the area emerged above water, therefore this habitat modification can be clearly interpreted as damage compared to former situation.

Despite that the tool has shortcomings and cannot yet be used to accurately estimate the ecological damage of a nourishment strategy. there are also a number of strengths to be identified, conserning the applicability, the uncertainty analysis and the method itself.

One of the strengths of the Benthimeter is that it is designed to post-process Delft3D simulations. Delft3D is a widely used and relatively reliable forecasting tool, making the Benthimeter well-suited for use in a range of hydrodynamic and ecological modeling applications. The compatibility of the Benthimeter with Delft3D simulations allows users to easily incorporate the tool into their existing modeling workflows, providing a convenient and efficient way to evaluate the impacts of nourishment projects on benthic species.

The inclusion of a Monte Carlo method in the Benthimeter represents another valuable strength of the tool, providing useful information about the uncertainty of model parameters and helping to improve the reliability of the Benthimeter's predictions of benthic response to nourishments.

An attempt has been made to identify the parameters that cause large uncertainties in the Benthimeter using the Monte Carlo method. One such parameter is the constant that accounts for the mismatch between weekly bed level change and the in literature provided fatal burial depths (m/day). This constant is a key factor in the Benthimeter's predictions of benthic response to nourishments, and its uncertainty can have a significant impact on the reliability of the model's predictions. As a recommendation for future work, one solution to this problem could be to run models that produce daily output vs weekly output, in order to obtain the translation constant (c_d) empirically. This would allow for a more accurate determination of the damage due to burial and could improve the reliability of the *Benthimeter*.

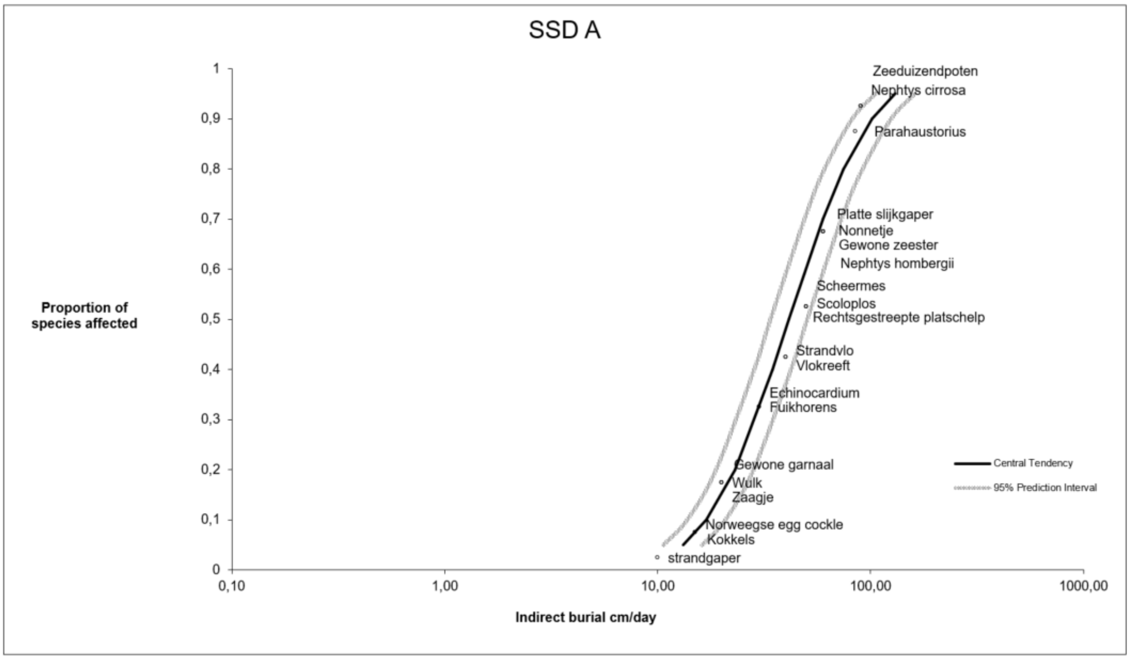
The two approach for defining the ecological damage that are described in the method. Approach 1 avoids using ”tricks” to correct for the smoothening effect of the Delft3D model, which may be seen as an advantage by some. By not trying to correct for the model's shortcomings, approach 1 avoids introducing potential biases or errors into the results.

On the other hand, approach 2 in which a bed level correction is made to isolate the effect of the nourishment induces bed level changes, on the ecosystem. This allows for a more focused evaluation of the impact of this specific activity on the ecosystem. However, using a bed level correction can introduce biases or other errors into the results, so it is important to consider these potential drawbacks as well.

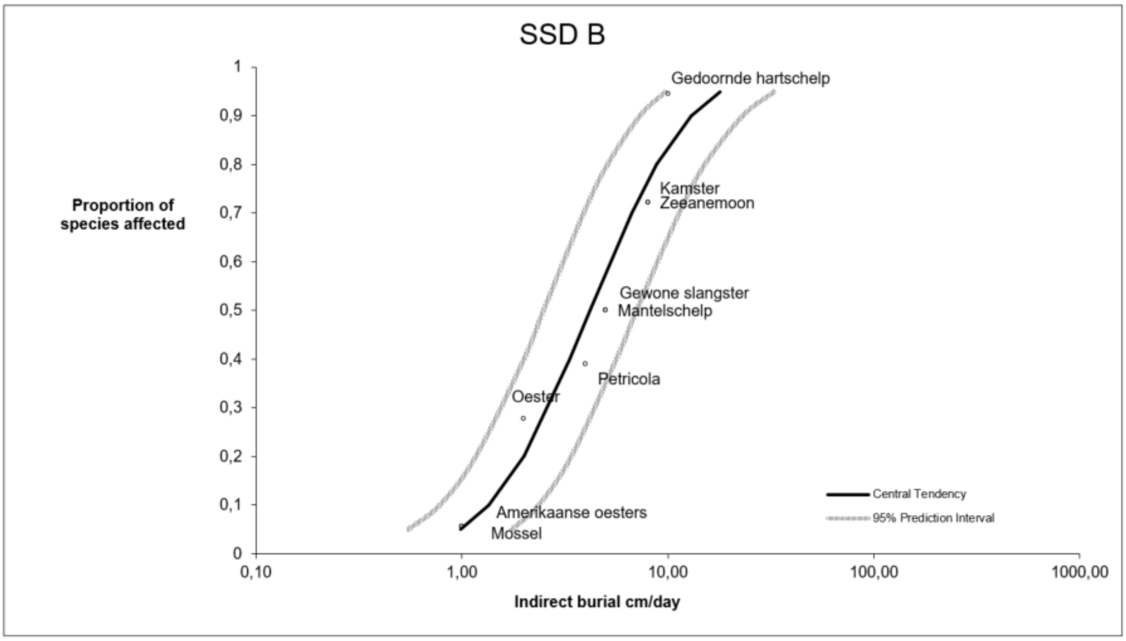
Overall, the Benthimeter can be a potentially valuable tool for quantifying the response of benthic species to nourishments, but its limitations should be kept in mind when interpreting and applying the results. Further research into the underlying ecological processes and the uncertainty of model parameters may improve the reliability of the tool, but the inherent complexity of benthic ecosystems will likely continue to pose challenges for predicting their response to nourishments. Overall, the development of the *Benthimeter* represents a valuable step towards optimizing nature-friendly coastal management.

A.6. Benthimeter: Additional Data

A.6.1. Specie Survival Distribution of gathered benthic data



(a)



(b)

Figure A.16: Constructed species sencitivity curves for benthic species group A (a) and benthic species group B (b).

A.6.2. Morphological features

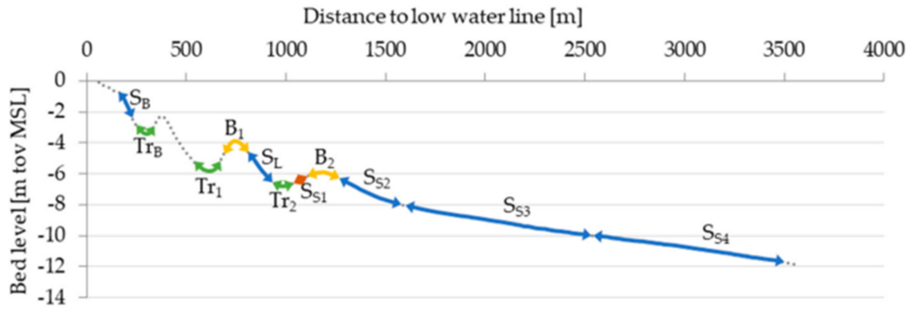


Figure A.17: Schematic cross-shore profile of the nearshore of Ameland with morphological features. In seaward direction: (S_B) beach slope, (Tr_B) beach trough, (Tr_1) first trough, (B_1) first bar crest, (S_{S1}) seaward slope first bar crest, (Tr_2) landward slope second trough, (B_2) second bar crest, (S_{S2}) seaward slope second bar crest, (S_{S3}) seaward slope, (S_{S4}) gentle slope (Holzhauer et al., 2019).

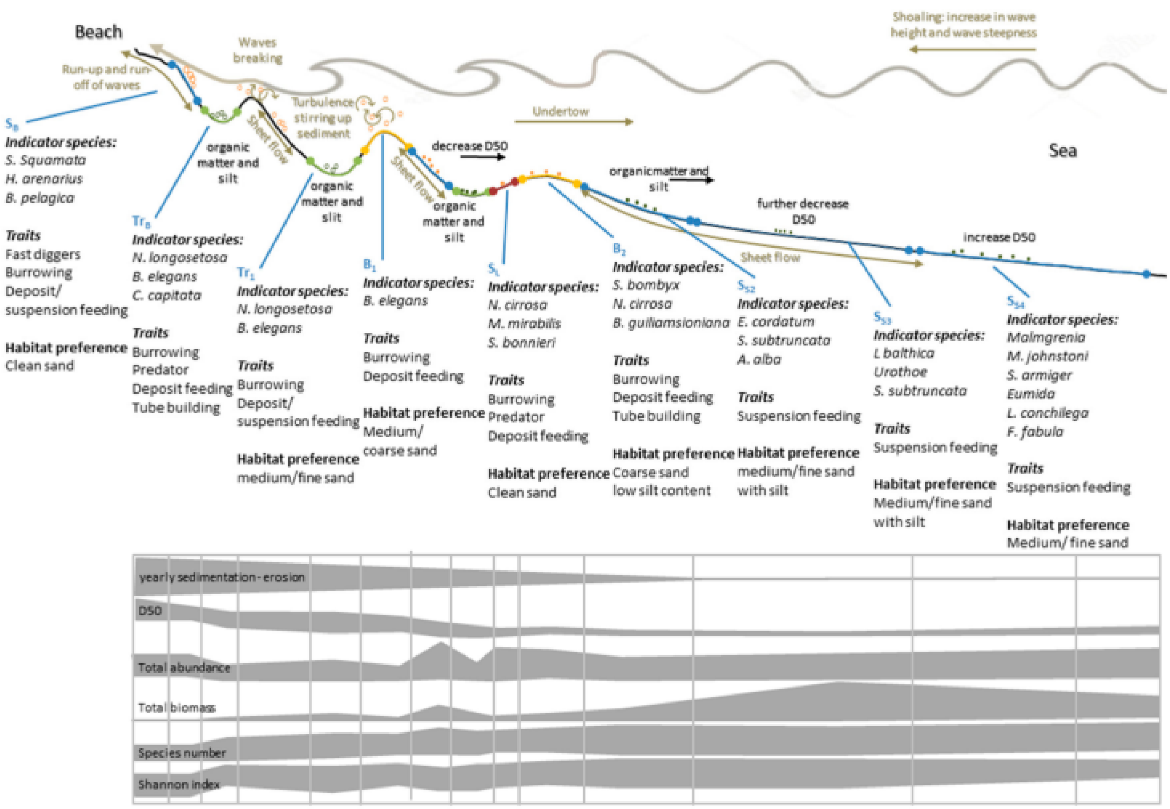


Figure A.18: Conceptual drawing of the cross-shore wave related process, environmental parameters measured and the macrobenthic species identified as indicator species for the morphological features (Holzhauer et al., 2019).

A.6.3. Specie diversity distribution

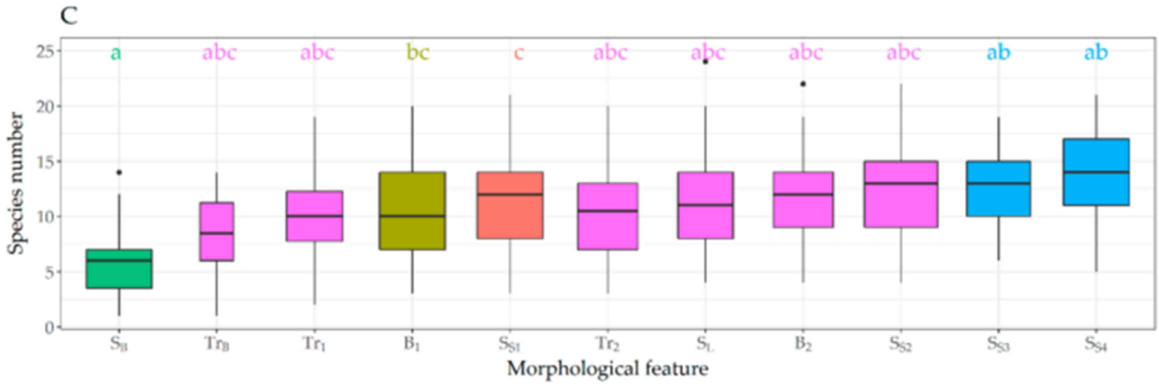


Figure A.19: Number of species for each morphological feature. Obtained from survey study of Holzhauer et al. 2019

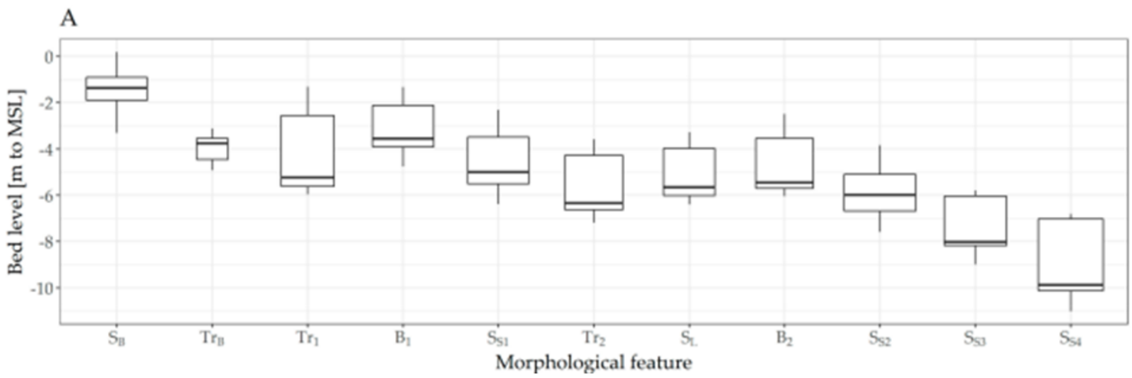


Figure A.20: Boxplots of the bed level in meter to MSL for each morphological feature. Obtained from survey study of Holzhauer et al. 2019.

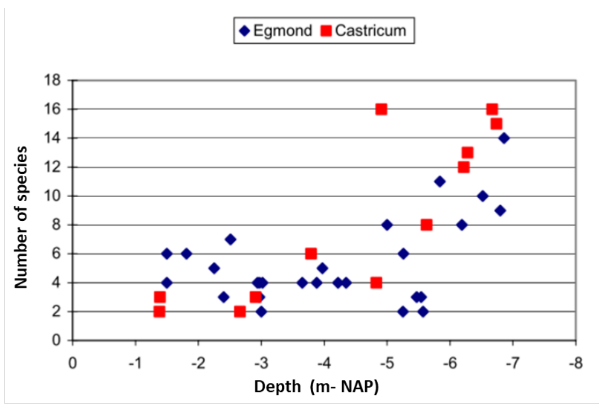


Figure A.22: Distribution of the number of species as a funtion of the depth, monitored along different transects at the Dutch coast (Janssen and Mulder, 2004)

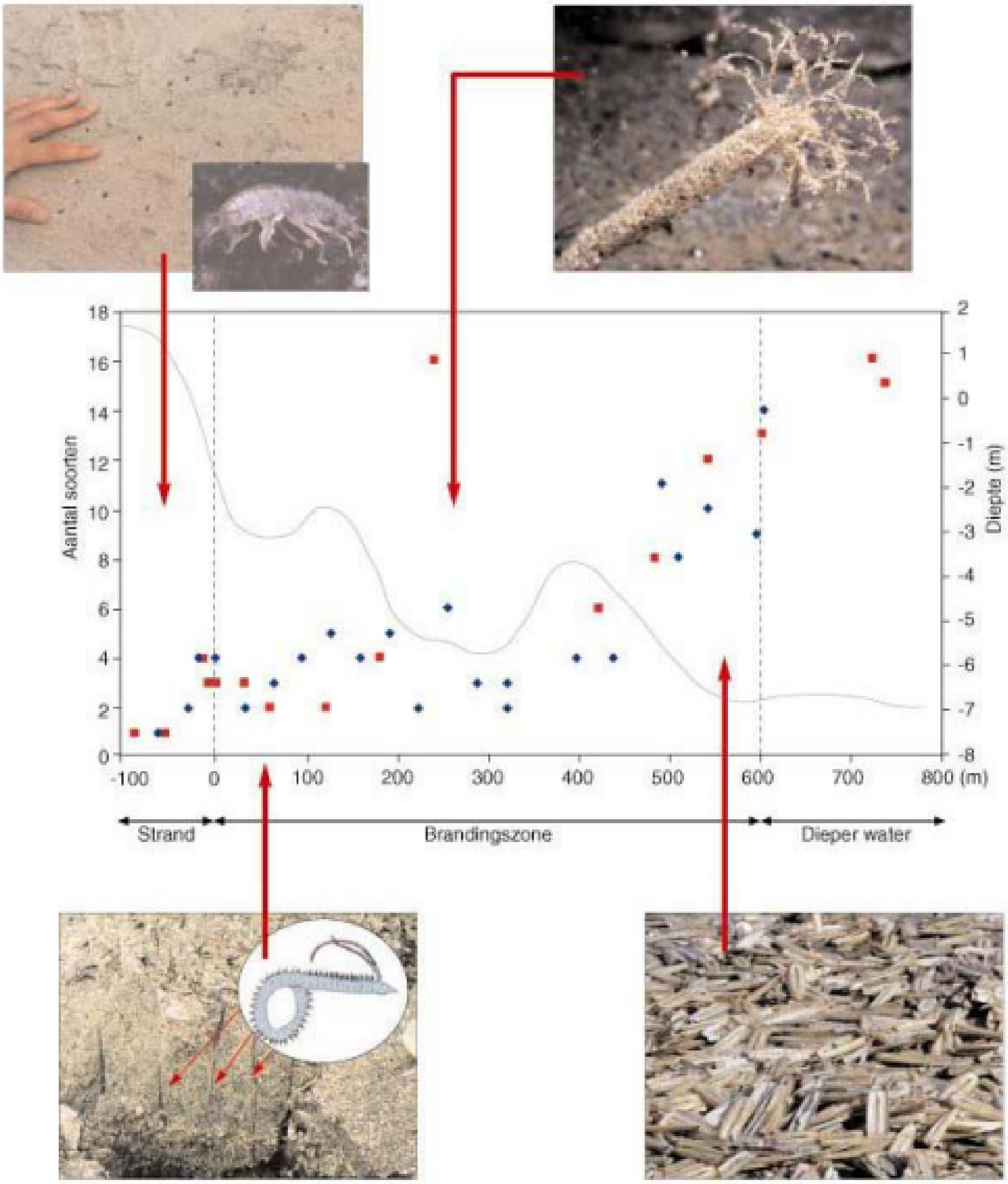


Figure A.21: Number of species in the beach and surf zones in realtion to depth and distance from the low-water line. Characteristic species are shown: Talitrus saltator sand hopper (beach); Scolelepis squamata (beach and surf zone); Lanice conchilega sand mason (trough between the two bars); Ensis americanus razor clam (deeper water) (Janssen and Mulder, 2005)

B

System description

B.1. Environmental conditions

B.1.1. Wave conditions

golfhoogte (m)	golfrichting (graden)												
	345.00 - 15.00	15.00 - 45.00	45.00 - 75.00	75.00 - 105.00	105.00 - 135.00	135.00 - 165.00	165.00 - 195.00	195.00 - 225.00	225.00 - 255.00	255.00 - 285.00	285.00 - 315.00	315.00 - 345.00	totaal
0 - 0.5	2.242	1.418	0.506	0.259	0.208	0.240	0.320	0.568	1.116	1.149	1.524	1.963	11.512
0.5 - 1.0	4.876	3.413	1.765	0.778	0.551	0.601	0.869	2.732	3.617	2.525	2.864	4.337	28.928
1.0 - 1.5	4.016	1.861	1.226	0.580	0.357	0.278	0.591	2.830	3.221	2.354	2.656	4.175	24.146
1.5 - 2.0	2.125	0.882	0.591	0.180	0.083	0.088	0.241	1.955	2.580	1.751	1.894	2.973	15.343
2.0 - 2.5	0.945	0.370	0.292	0.062	0.006	0.025	0.076	1.228	1.781	1.330	1.189	1.818	9.122
2.5 - 3.0	0.408	0.134	0.077	0.009	0.004	0.010	0.037	0.665	1.097	0.744	0.757	1.104	5.047
3.0 - 3.5	0.168	0.065	0.009	0.001	0.004	0.003	0.022	0.263	0.696	0.509	0.493	0.616	2.851
3.5 - 4.0	0.077	0.013	0.001	0.000	0.001	0.000	0.003	0.121	0.299	0.281	0.301	0.387	1.485
4.0 - 4.5	0.030	0.001	0.000	0.000	0.000	0.000	0.000	0.025	0.131	0.204	0.201	0.208	0.800
4.5 - 5.0	0.018	0.000	0.000	0.000	0.001	0.000	0.001	0.003	0.051	0.109	0.095	0.115	0.393
5.0 - 5.5	0.015	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.015	0.068	0.046	0.055	0.202
5.5 - 6.0	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.007	0.037	0.021	0.028	0.097
6.0 - 6.5	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.006	0.019	0.016	0.012	0.055
6.5 - 7.0	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.007	0.012
7.0 - 7.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.003
>7.5	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.003
totaal	14.924	8.160	4.467	1.870	1.217	1.247	2.160	10.392	14.617	11.081	12.063	17.803	100.000

Figure B.1: Occurrence probability distribution of wave height (Hm0) measured at IJmuiden Rest, 2004

B.1.2. Wind conditions

golfhoogte (m)	golfrichting (graden)												
	345.00 - 375.00	15.00 - 45.00	45.00 - 75.00	75.00 - 105.00	105.00 - 135.00	135.00 - 165.00	165.00 - 195.00	195.00 - 225.00	225.00 - 255.00	255.00 - 285.00	285.00 - 315.00	315.00 - 345.00	totaal
0 - 0.5	3.903	3.534	3.474	3.435	3.435	3.374	3.453	3.51	3.609	3.751	3.911	4.19	3.777
0.5 - 1.0	4.486	3.983	3.836	3.776	3.598	3.62	3.726	3.833	3.957	4.101	4.336	4.764	4.182
1.0 - 1.5	4.902	4.387	4.265	4.141	4.024	4.055	4.187	4.293	4.397	4.498	4.699	5.079	4.588
1.5 - 2.0	5.191	4.801	4.666	4.562	4.455	4.588	4.647	4.752	4.838	4.896	5.058	5.361	4.964
2.0 - 2.5	5.613	5.277	5.083	4.958	5.014	4.933	5.027	5.14	5.269	5.315	5.438	5.696	5.363
2.5 - 3.0	5.986	5.8	5.481	5.2	5.825	5.557	5.51	5.534	5.615	5.731	5.804	6.074	5.74
3.0 - 3.5	6.551	6.2	6.1	6.5	0	6.25	5.688	5.913	6.025	6.053	6.172	6.514	6.161
3.5 - 4.0	6.818	6.25	6.2	0	0	6	6.18	6.223	6.364	6.387	6.525	6.854	6.529
4.0 - 4.5	7.268	6.3	0	0	0	6.85	0	6.647	6.68	6.784	6.915	7.171	6.905
4.5 - 5.0	7.65	0	0	0	0	0	0	7.025	7.084	7.071	7.336	7.629	7.336
5.0 - 5.5	7.963	0	0	0	0	0	0	0	7.29	7.372	7.5	8.007	7.646
5.5 - 6.0	8.4	0	0	0	0	0	0	0	7.65	7.68	7.937	8.125	7.995
6.0 - 6.5	9.2	0	0	0	0	0	0	0	8.2	7.94	8.033	8.571	8.306
6.5 - 7.0	0	0	0	0	0	0	0	0	8.25	0	0	9.25	8.75
7.0 - 7.5	0	0	0	0	0	0	0	0	0	0	0	8.967	8.967
>7.5	0	0	0	0	0	0	0	0	0	0	0	0	0
totaal	4.695	4.154	4.053	3.903	3.746	3.744	3.998	4.448	4.657	4.665	4.792	5.106	4.61

Figure B.2: Occurrence probability distribution of wave period (Tm02) measured at IJmuiden Rest, 2004

B.1.3. Tidal patterns

B.1.3.1. Tidal signal at IJmuiden

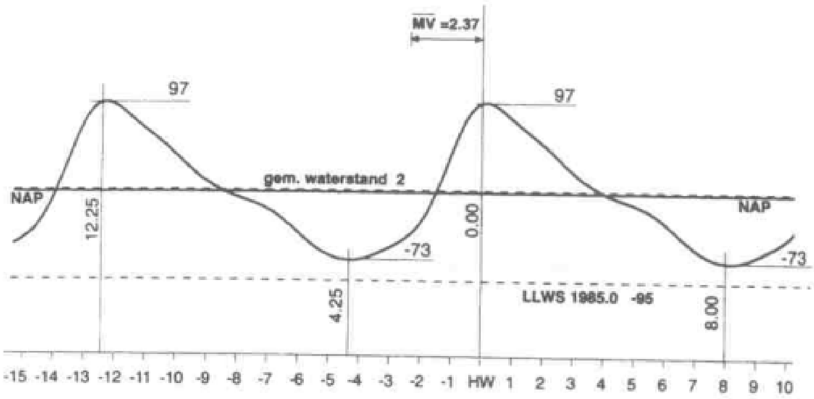


Figure B.3: Tidal curve of the average tide at IJmuiden (Rest, 2004)

B.1.3.2. Tide induces velocities around breakwaters

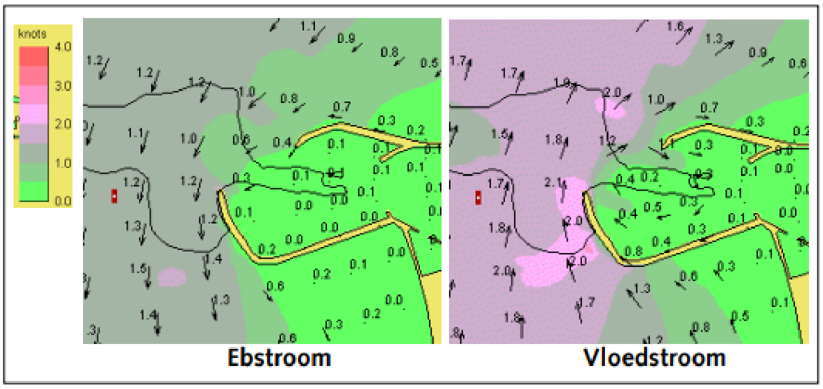


Figure B.4: Tidal flow pattern velocities (in knots) around the breakwaters of IJmuiden port during ebb flow (ebstroom) and flood flow (vloedstroom), during spring tide and average discharge from the IJ (Kruif and Keijer, 2003)

B.1.4. Sediment transport patterns Dutch Coast

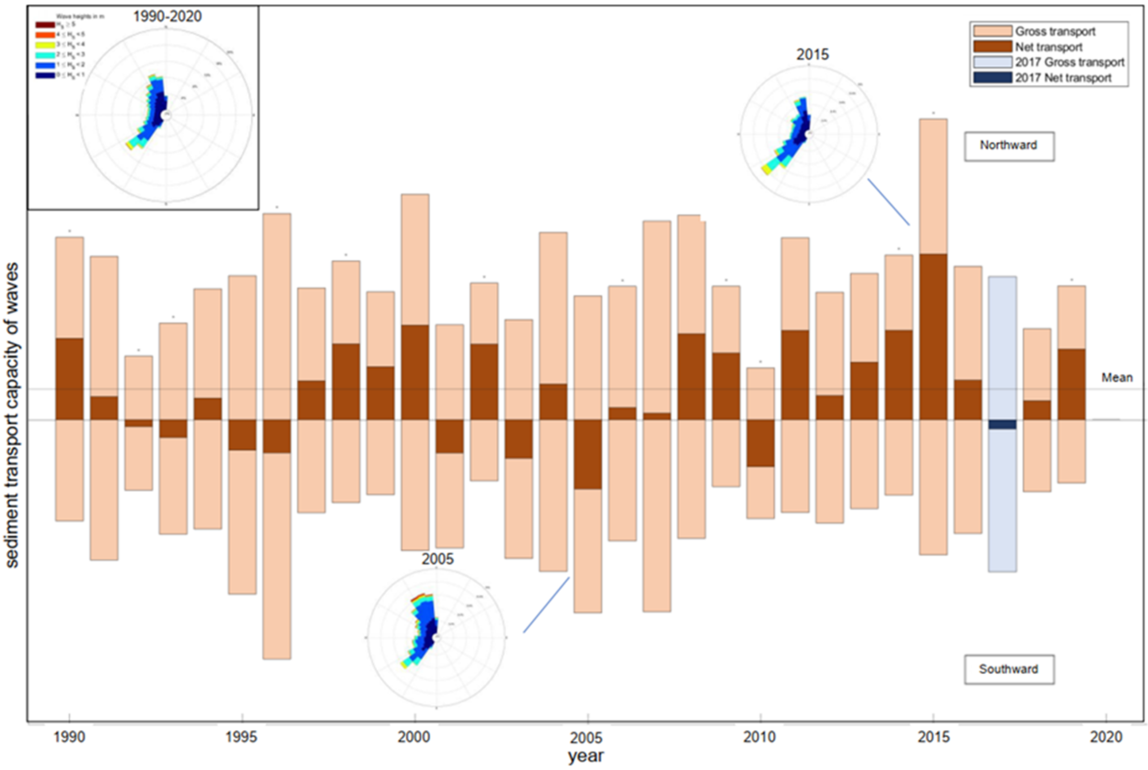


Figure B.5: Sediment transport capacity of waves estimated for the year 1990 - 2017 along the Dutch Coast (SOURCE ONBEKEND)

B.2. Historic dredge activity data channel and port

Table B.1: Annual dredging quantities IJgeul and IJmuiden port, obtained from Rijkswaterstaat and (**empty citation**)

	IJgeul	**Port**	
Year	Volume Sand (Reusink et al, 2002) (Mm^3)	Volume (Reusink et al, 2002) (Mm^3)	Volume (Rijkswaterstaat) (Mm^3)
1968	0,57	2,97	
1969	0,03	2,51	
1970	0,18	1,99	
1971		2,19	
1972		1,97	
1973		2,13	
1974		2,19	
1975		2,21	2,33
1976		2,6	2,75
1977	0,30	2,18	2,28
1978	1,82	2,94	3,05
1979	1,20	2,93	3,39
1980	1,88	4,29	4,43
1981	1,92	4,42	5,18
1982	1,38	3,55	3,94
1983	1,97	3,11	3,54
1984	2,55	2,81	3,37
1985	2,13	2,89	3,51
1986	1,92	2,95	3,31
1987	4,10	3,47	3,65
1988	5,14	2,54	2,60
1989	5,15	3,89	4,04
1990	4,09	3,83	4,48
1991	3,61	4,38	5,03
1992	2,84	2,97	3,12
1993	2,84	3,17	3,37
1994	3,43	3,49	3,71
1995	3,27	0,29	3,23
1996	4,51	1,86	2,07
1997	3,18	2,23	2,41
1998	5,27	3,16	3,81
1999	4,71	1,84	2,60
2000	4,75	1,98	2,32
2001	2,29		2,87
2002			3,26
2003			1,98
2004			4,11
2005			2,16
2006			4,13
2007			3,05
2008			3,86
2009			2,18
2014			1,70
2015			3,56
2016			2,12
2017			2,12
2018			2,97
2019			3,28
2020			3,42
2021			1,44

C

Sediment Bypass Design

C.1. Background: Inlet Components of Bypass System

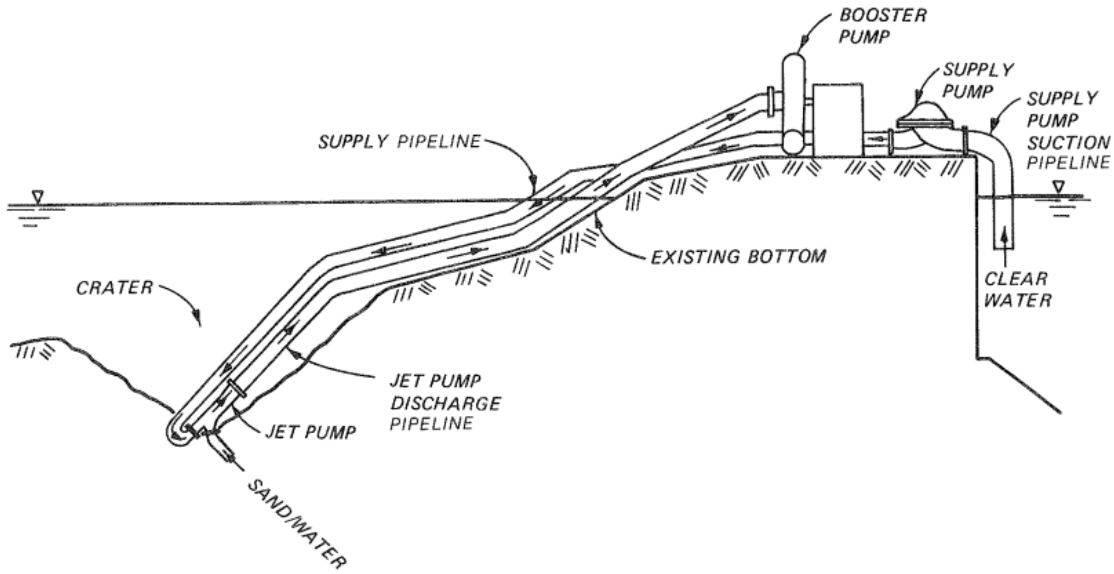


Figure C.1: Conceptual elevation view of the components of a simple land based jet pump system (Richardson and McNair, 1981)

The components of the simple jet pumps shown in Figure C.1 and C.2 and their purposes are as follows:

- **Supply pump.** Water from the clear water intake (usually underground reservoir) is pumped via the supply pipeline to the jet pump.
- **Jet pump.** The pump inject clear water with high velocity into the bed. The high-velocity water stirs up the sediment, forming a mixture of sand and water known as slurry. The jet pump then pumps this slurry through the jet pump discharge pipeline.
- **Crater.** Also commonly referred to as cones, these formations occur at the seafloor as a result of the excavation process. For rigid structures, jet pumps are buried in the bed, causing an excavation above. In the case of flexible pipelines, the jet pump trails down the bottom of the crater, extracting the sand. Maintenance of the crater involves regular dredging by the jet pump. This crater functions as a sediment trap, catching littoral drift that would otherwise bypass the area.

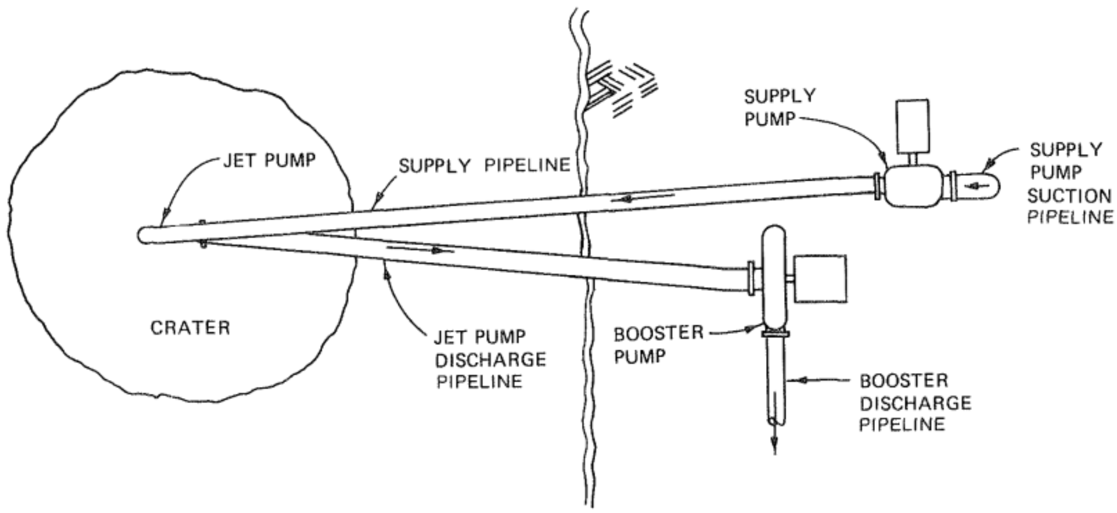


Figure C.2: Conceptual elevation top view of the components of a simple land based jet pump system(Richardson and McNair, 1981)

- **Booster pump.** This component's function is to furnish the necessary energy to transport the slurry to the predetermined discharge location. Depending on how far the slurry needs to be moved, one or more booster pumps may be utilized. Regular dredge pumps are often employed as booster pumps.

C.2. Fixed Bypass Systems: International Case Studies

C.2.0.1. Historic timeline fixed bypass system projects around the world

Table C.1: Overview of fixed bypass systems around the world, modifed from Soares (2017)

Location	Lifetime	Technical Solution	Tidal range (m)	Bypassed volume (m3/year)
South Lake Worth Inlet, FL (USA)	1937 - now	Fixed structure with jet pump updrift (pump station with a crane) and nourishment of downdrift beaches via pipeline	0.9	45,000
Lake Worth Inlet FL (USA)	1958 - now	Fixed structure with jet pump updrift (pump station with a crane) and nourishment of downdrift beaches via pipeline	0.8	150,000
Nerang River (AUS)	1986 - now	Fixed structure with jet pumps updrift (jetty and nourishment of downdrift beaches via pipeline	1.3	500,000
Indian River Inlet DE (USA)	1990 - now	Fixed structure with jet pump updrift (crane) and nourishment of downdrift beaches via pipeline	1.5	70,000
Port of Portland (AUS)	1996 - now	Sandshifter recovers sand from a trap 60 m offshore of the updrift breakwater and pumps it 3 km downdrift	1.0	50,000
Tweed River (AUS)	2001 - now	Fixed structure with jet pumps updrift (jetty) and nourishment of downdrift beaches via pipeline	1.3	500,000
Port of Ngqura (RSA)	2007 - now	Fixed structure with jet pumps updrift (jetty) and nourishment of downdrift beaches via pipeline	2.5	200,000
Fukude (JPN)	2014 - now	Fixed structure with jet pumps updrift (jetty) and nourishment of downdrift beaches via pipeline	2.0	80,000

C.2.1. Case Study: Tweed River Entrance Project

The Tweed River Entrance Sand Bypassing Project in the southern Gold Coast, initiated in 1995, serves as an example of a successful fixed system implementation. This project aimed to offset coastal erosion and maintain the Tweed River Entrance's navigability (Castelle et al., 2009). After the extention of the the Tweed river training walls in 1960 sediment was trapped at the southern side of the river. Although improving the navigability, the loss of sand supply to the downdrift beaches resulted in in the disrupted sediment flux leading to serious erosion. After 20 years bypassing started to occur and sand banks were blocking the channel once more.

The initiated project aimed to restore the navigability and develop a permanent system to maintain the restored beach amenity and navigable entrance. The permanent bypass system consists of:

- 10 Jet pumps mounted to jetty located at updrift beach
- Clear water intake pump
- Control station with pump
- 7 km of pipelines
- 2 booster pumps

The collection jetty is 450 m in length and is located just 250 m south of the southern breakwater. The ten mounted jet pumps operate with up to five pump at the same time to discharge slurry into the slurry pit located on shore (See figure C.4. Clean water pumped with a low pressure pump (KSB-Ajax submersible pump, 146 kW, 665l/s) from Tweed river through a 600 mm medium density polyethylene pipeline to supply the jet pumps (Soares, 2017).

From the slurry pit at shore, the slurry is pumped trough a 400 mm polyurethane lined stell slurry pipeline under underground to the outlets. The slurry pump is a KSB LCC GIW 10x12 - 125wr, oupled to a 630 kw motor to mainatain a slurry flow rate of 400 l/s. This pump can deliver slurry over a distance of 1.4 km. A second pump/motor combination is installed to in serie to supply further distances .

The system is designed to discharge to only one of the four outlet at the time - the operating outlet is selected by operating and locking valves, which are located at branches along the slurry pipelines. See figure C.3 for an overview of the bypass system. The pumps are designed to operate at slurry densities up to 50% by volume.

Bypassing is normally operated at night using a computerised control system, which arranges cycling between jet pumps (and backwashes) using slurry density data measured at each pump.

Figure C.3: Tweed river sediment bypass system overview Soares, 2017

Acworth and Lawson (2011) present significant accretion coastline trend after 1 year of the construction. Ware (2016) concludes that the system helped improving navigation at the Tweed River entrance. Government (2022) mentions on there website that dredging of the channel is still required. During this literature study the exact improvement concerning infilling of the channel is not found.

Yearly between 350,000 and 830,000 m^3 is bypassed by the system at an average cost per cubic meter of 6.17/m^3. The construction costs of the project were 25 million euro (Soares, 2017).

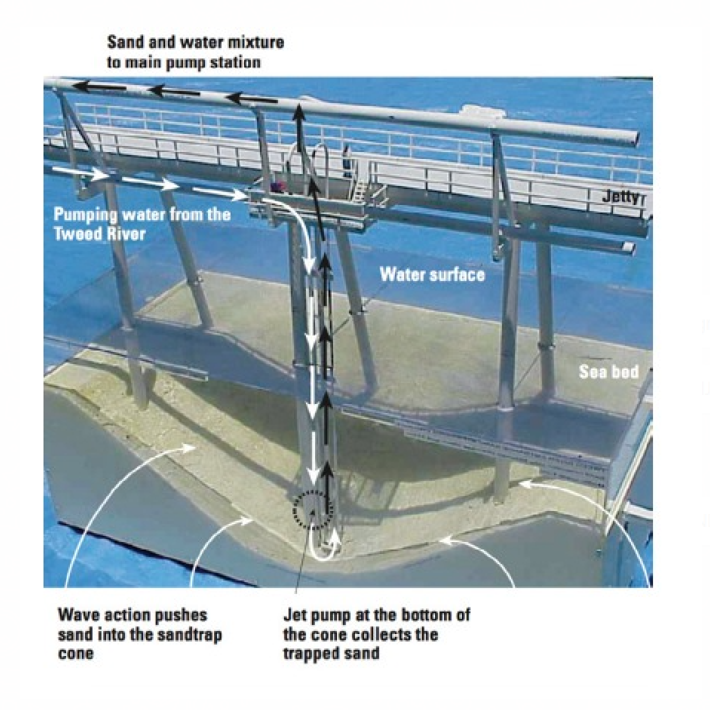


Figure C.4: Tweed River Entrance Sand Bypass Project, sediment collecting system overview (Ware, 2016)

Figure C.5: Overview of the sand bypass sytem in Nerang River (Soares, 2017)

C.2.2. Nerang River Entrance Project

The progressive movement of the entrance to the north at a rate of 20 - 40 m per year has involved accretion of the Southern The Spit and erosion at South Stradbroke Island (See figure C.7. Hazardous navigation through the changing entrance shoals, and the possible threat of breakthrouhgh at the Sourth stradbroke island in the future, lead the contruction of the construction of the training walls and the fixed bypass system (Boswood and Murray, 2001).
The predominant south-easterly winds, significant northern drift of sand and severe wave climate has lead to net northward alongshore transport of 500,000 m^3 per year (Soares, 2017).

The sand bypass system at Nerang river concists of:

- 10 Jet pumps mounted to jetty located at updrift beach
- Clear water intake pump
- Control station with pump
- 1.4 km of pipeline

At the Nerang River Entrance, the jetty reaches 490 meters offshore up to the 6.0-meter below MSL (mean sea level) contour (Venture, 1997). Equipped with ten jet pumps spaced 30 meters apart, the structure creates a 270-meter trap length between the -2.0-meter and -6.0-meter MSL (Boswood and Murray, 2001). Positioned at a level of -11.0 meters MSL for effective removal, the jet pumps result in cones that form at the natural angle of repose of sand. With only 30 meters between jet pumps, sufficient overlap is achieved for an effective sand trap (Venture, 1997). The system was designed to bypass average rate of 500,000 m^3/yr. The inlet has a maximum sand trap capacity of 40,000 m^3 (Boswood and Murray, 2001)

An top view of the described system used at the Nerang River entrance can be found in Figure C.7 presents the described jetty mounted system that was used in at the Nerang River entrance (Venture, 1997)

After construction of the system they observed significant accretion of the downdrift beach. Also, no maintenance dredging of the channel between the walls has been required after initiation in 1986 until putblication of Boswood and Murray (2001) in 2001. This gives an indication of the efficient sediment

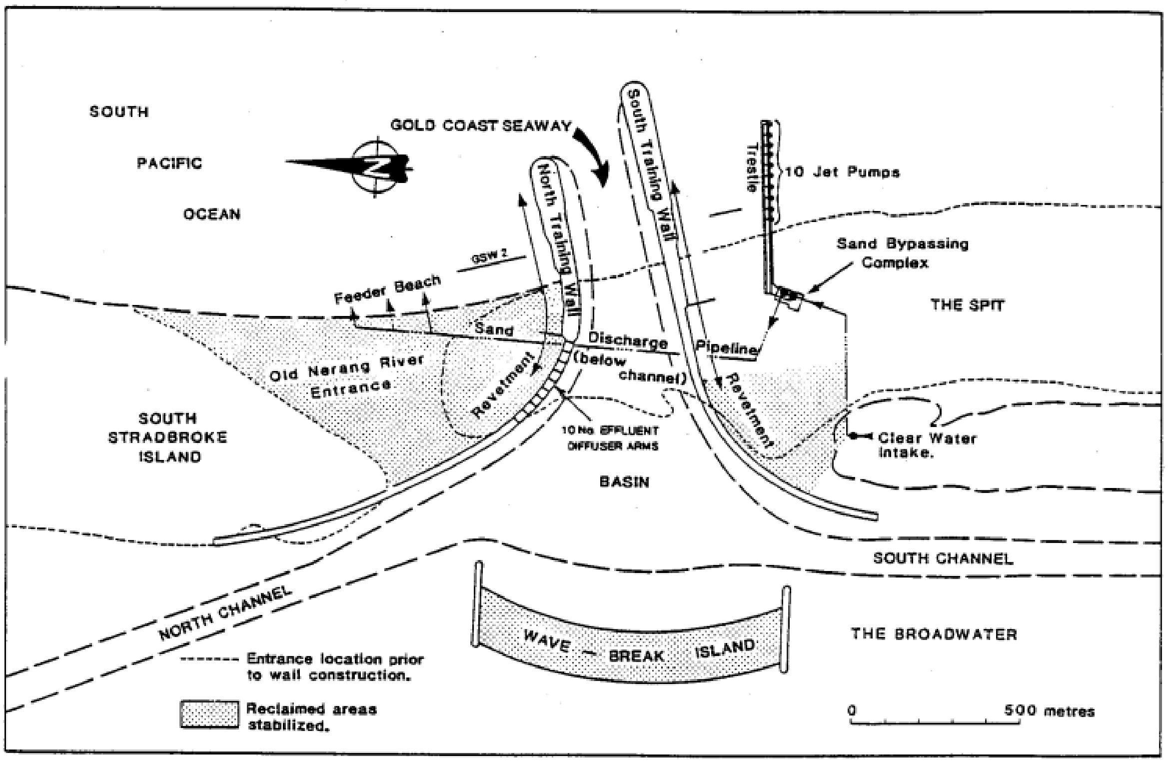


Figure C.6: Overview of artificial sediment bypass system used at Nerang River entrance (Boswood and Murray, 2001)

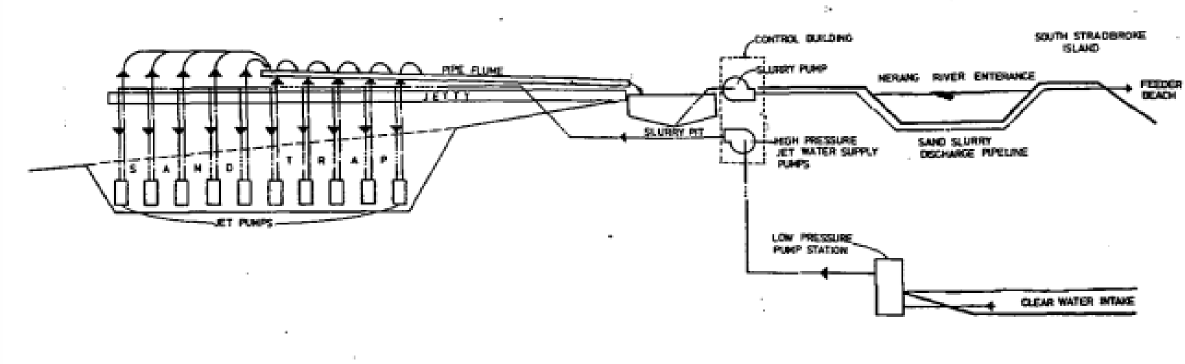


Figure C.7: Nerang river entrance jetty mounted system (Venture, 1997)

trap in this design.

On average the system bypasses 500,000 m^3/year, the peak annual rate is 750,000 m^3/year and the nomial transport capacity is 300 m^3/hr. The system was designed for the operation of 4 to 7 jet pumps that run automatically overnight, and sometimes weekends, to take advantage of cheaper electricity rates.

The construction costs of the bypass system and ancillary works were 4.3 million euros (Boswood and Murray, 2001). Yearly between 300,000 and 750,000 m^3 is bypassed by the system at an average cost per cubic meter of 0.84/m^3 (Soares, 2017). This cost include the following total cost:

- Electricity (average of 150,000 /yr)
- Salaries of the 3 continues staff (average of 136,000 /yr)
- Maintenance and repairs (average of 200,000 /yr)

C.2.3. Case Study: Ngqura port bypass

Figure C.8: Schematic view of Port of Ngqura Sand Bypass system (Soares, 2017)

Ngqura port bypass system is unique since it is the only fixed bypass system that is applied to a port. The system includes:

- A jetty located at updrift beach
- A clear water intake
- A main pump station
- Three booster pumps
- 3.8 km pipeline system

The jetty reaches 225 m offshore, located 150 from the western breakwater, houses jet pumps positioned 36 m apart and situated at a depth of -7.5 m CD (Schmidt, 2016). The pumps create a slurry containing 12-15% sand that can be pumped through the pipelines (D=400mm) (Schmidt, 2016). The pipeline is burried along its entire length.

The system experienced operational challenges such as an inability to handle particles larger than 150 mm. This necessitated periodic dredging around the jet pumps to remove larger materials through airlifting. One week of maintenance every three months is required (Schmidt, 2016).

The bypass system transports between 40 - 200 m^3 of sand per year, despite its original design capacity of 320,000 m^3/yr. The reason why these rates were not achieved were described by Transnet (2023) as the following:

- Lack of replenishment of the sand in the sandtrap
- Sandtrap is filled with coarse material
- Only three of the six jet pump are operational
- The jet pumps were elevated from -7.5 to -4.1 m to CD
- The system experience frequent downtime

The construction of this bypass system cost approximately 6.2 million euros (Soares, 2017). The average cost per cubic meter of sand transported was not determined in this literature study.

C.3. Sediment bypass design

C.3.1. Simulated morphological response to continous point nourishment, DCC Simulation.

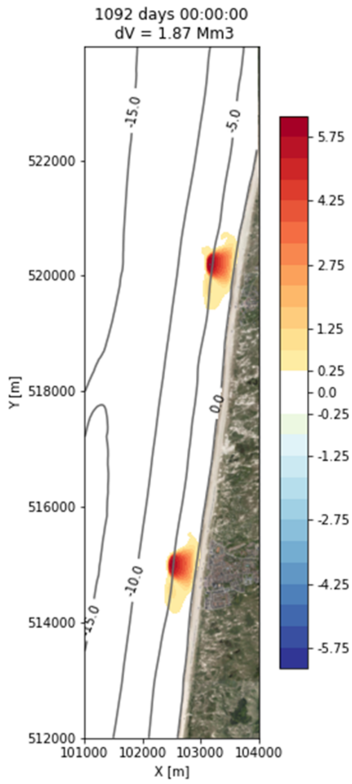


Figure C.9: Modelled bed level change after three years of continously nourishing 180,000 m^3/year per outlet location at Egmond. Simulation concept $33_1 2a$ of DCC

C.3.2. Identifying potential inlet and outlet locations

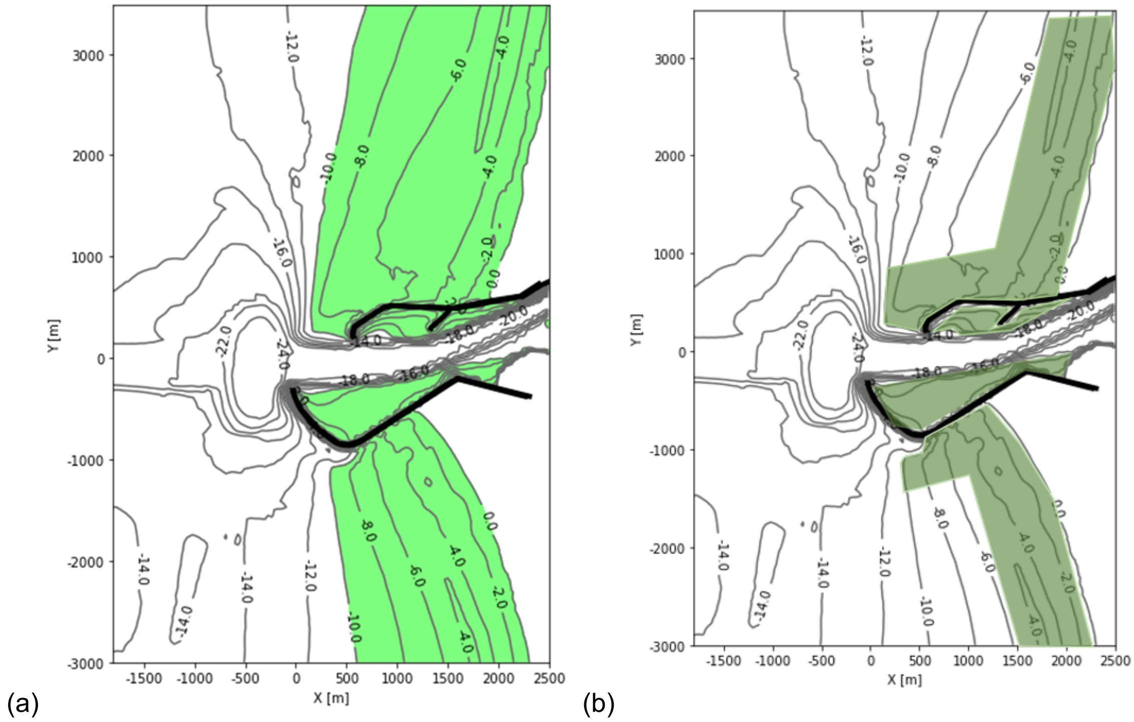


Figure C.10: Figures indicating practical locations to install jet pumps: (a) Indicates locations with depths less than 10 meters; and (b) indicates locations that are within roughly 500 m from land or breakwater.

D

Model description

D.1. Workflow generation of compressed boundary conditions

In order to include seasonality in the model, the imposed boundary conditions are compressed by a factor equal to the morfac. Therefore, the astronomical tide and residual tide are independently determined and post-processed, see Figure D.1.

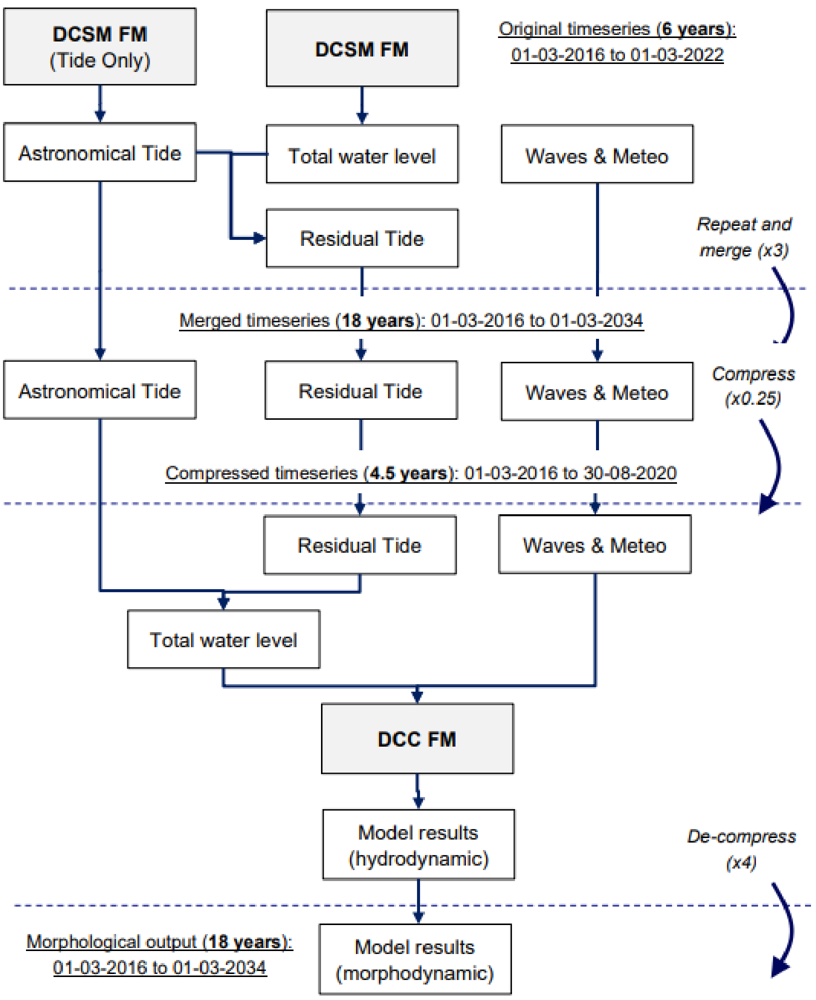


Figure D.1: Workflow of the post-processing of timeseries for boundary conditions and forcing (Deltares, 2022)

D.2. Imposed Boundary condition

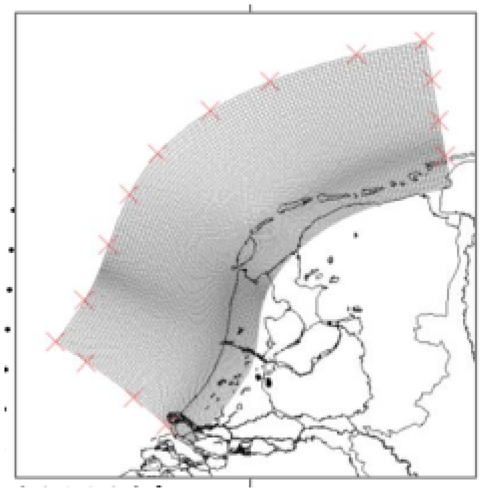


Figure D.2: Locations used for the generation of wave conditions surrounding the coarse wave grid (Deltares, 2022)

E

Simulation Results

E.1. Short-term hydrodynamic simulation results

E.1.1. SW condition 1

E.1.1.1. Base-line (Do Nothing)

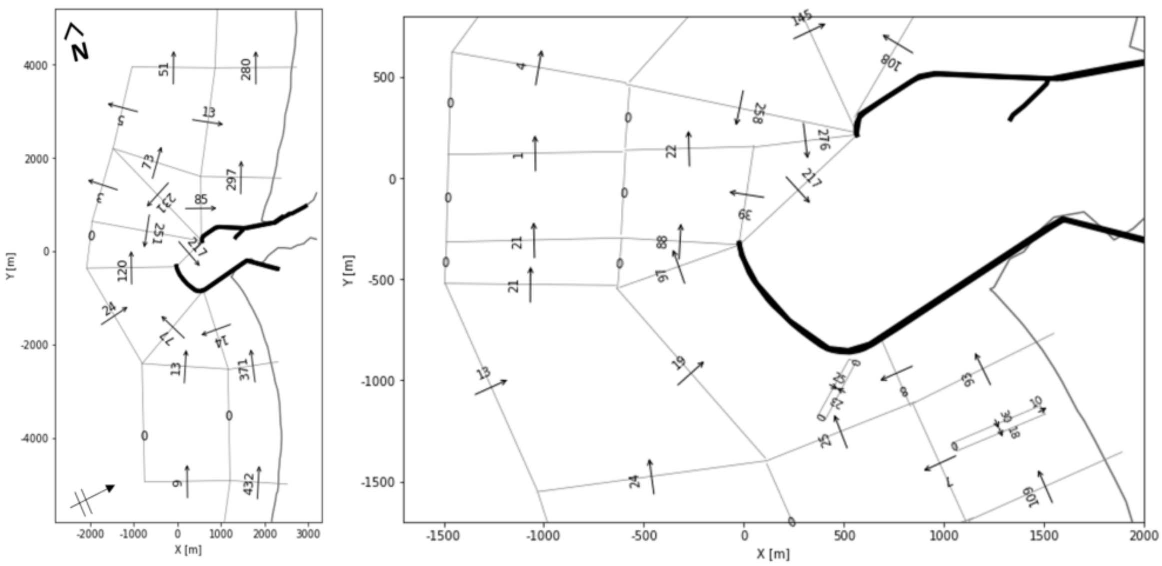


Figure E.1: Result base-line simulation of short-term hydrodynamic simulation (1 tidal cycle) under normal SW condition.

E.1.1.2. Inlet Alternative 1

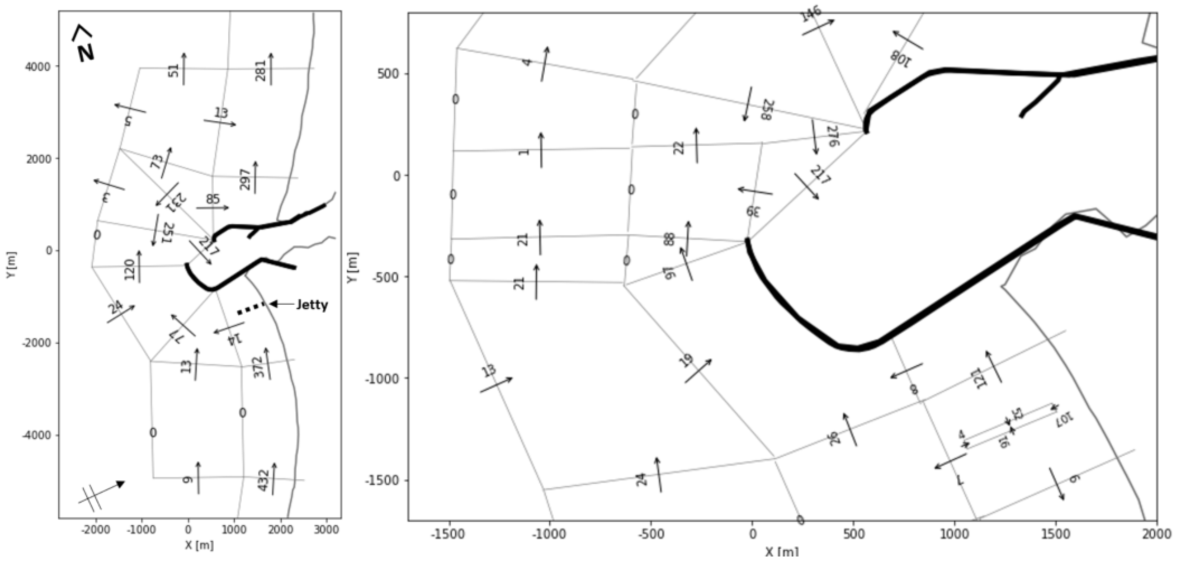


Figure E.2: Result hydrodynamic (1 tidal cycle) simulation under normal SW condition for inlet Alternative 1.

E.1.1.3. Inlet Alternative 2

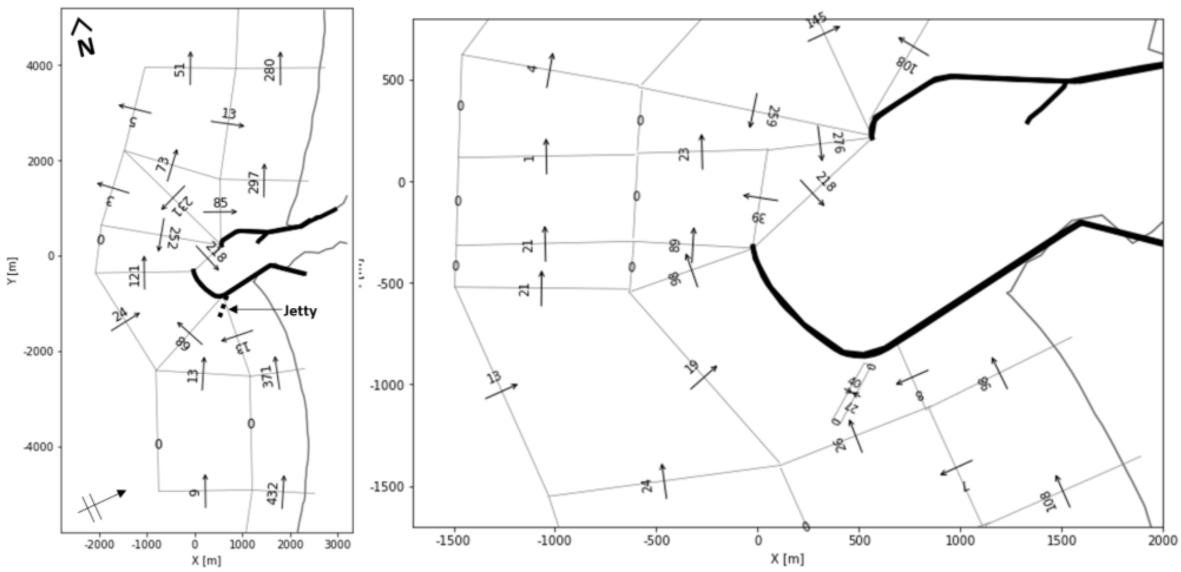


Figure E.3: Result hydrodynamic (1 tidal cycle) simulation under normal SW condition for inlet Alternative 2.

E.1.1.4. Baseline and three different outlet concepts with varying number of outlet locations

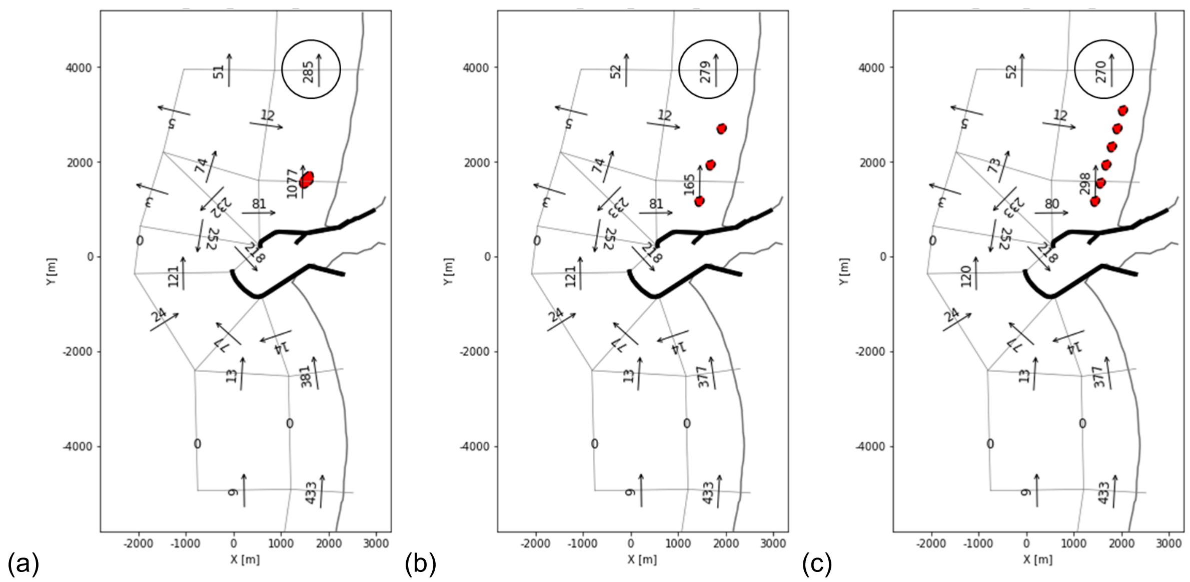


Figure E.4: Simulated sediment transports (in m^3) over one tidal cycle under SW wave conditions (H_S = 1.48 m, T_S = 5.34 s and direction = 232 °): (a) single outlet; (b) three outlets; and (c) six outlets.

E.2. Short-term morphological simulation results

E.2.1. Normal SW conditions (Condition 1)

E.2.1.1. Base-line (Do Nothing): 1 month

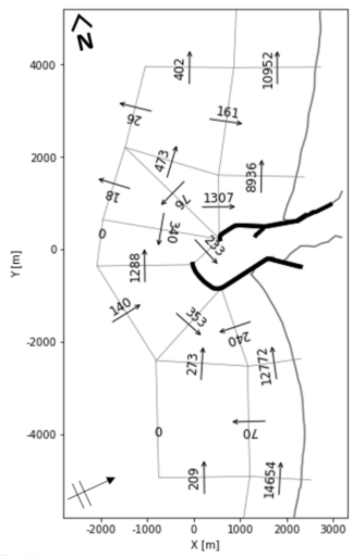


Figure E.5: Result base-line simulation of short-term morphodynamic simulation (1 month) under SW condition 1 (H_S = 1.48 m, T_S = 5.34 s and direction = 232 °).

E.2.1.2. Single Outlet 11,700m3/mnt bypass concept: 1 month

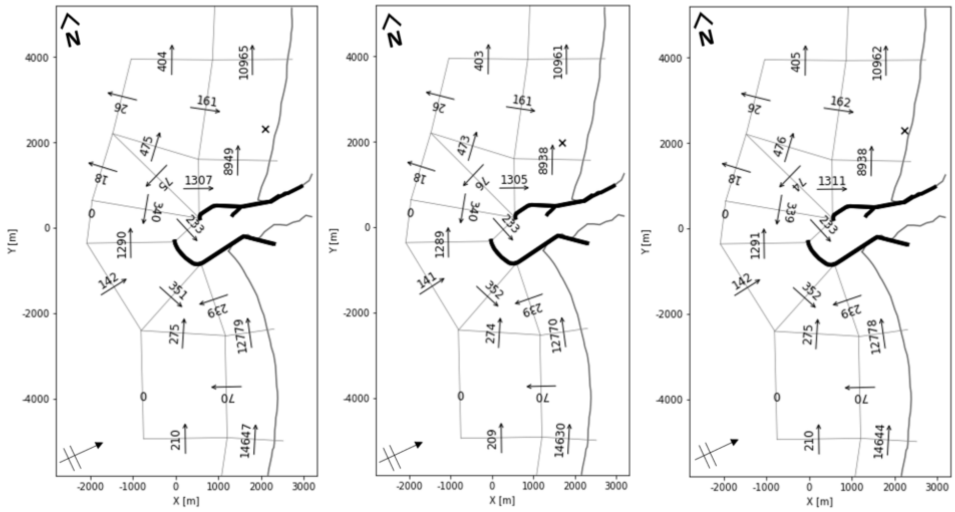


Figure E.6: Simulated sediment transports (in m^3) for single outlet concepts with varying outlet location in shoreface (discharge depth), over one month under SW wave conditions (H_s = 1.48 m, T_s = 5.34 s and direction = 232 °): (a) discharge at 3 meter depth; (b) discharge at 4 meter depth; and (c) discharge from beach at 1.5 meter depth.

E.2.1.3. Six Outlets 11,700m3/mnt bypass concept: 1 month

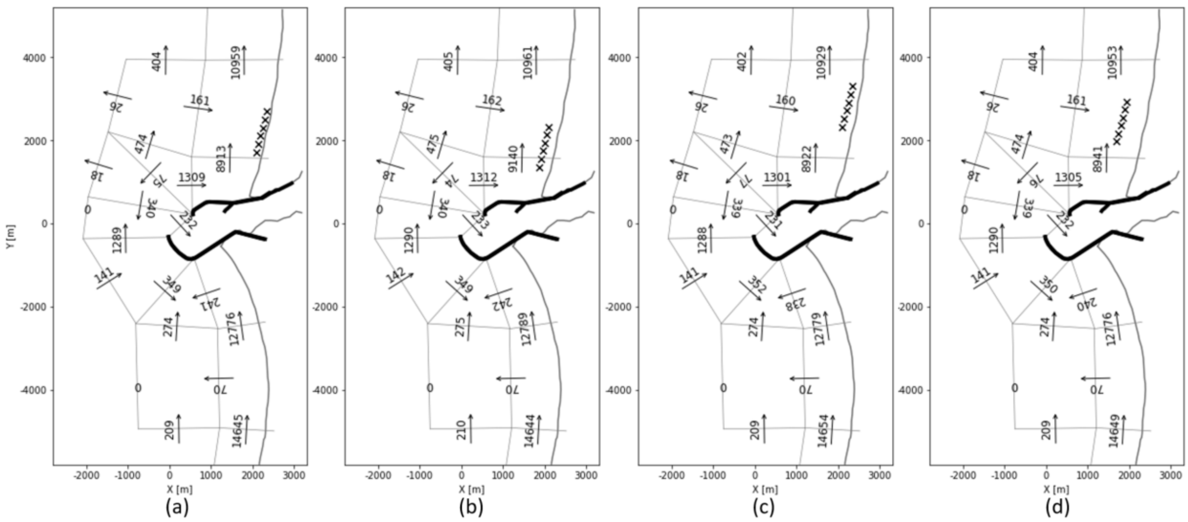


Figure E.7: Simulated sediment transports (in m^3) for outlet concepts with six outlet location with varying outlet location, over one month under SW wave conditions (H_s = 1.48 m, T_s = 5.34 s and direction = 232 °): (a) discharge from beach; (b) discharge at inner bar; (c) discharge at outer bar; and (d) discharge near Heemskerk. The concepts assume continuous discharge of 11,700m3 per month.

E.2.2. SW storm conditions (Condition 2)

E.2.2.1. Base-line (Do Nothing): One month

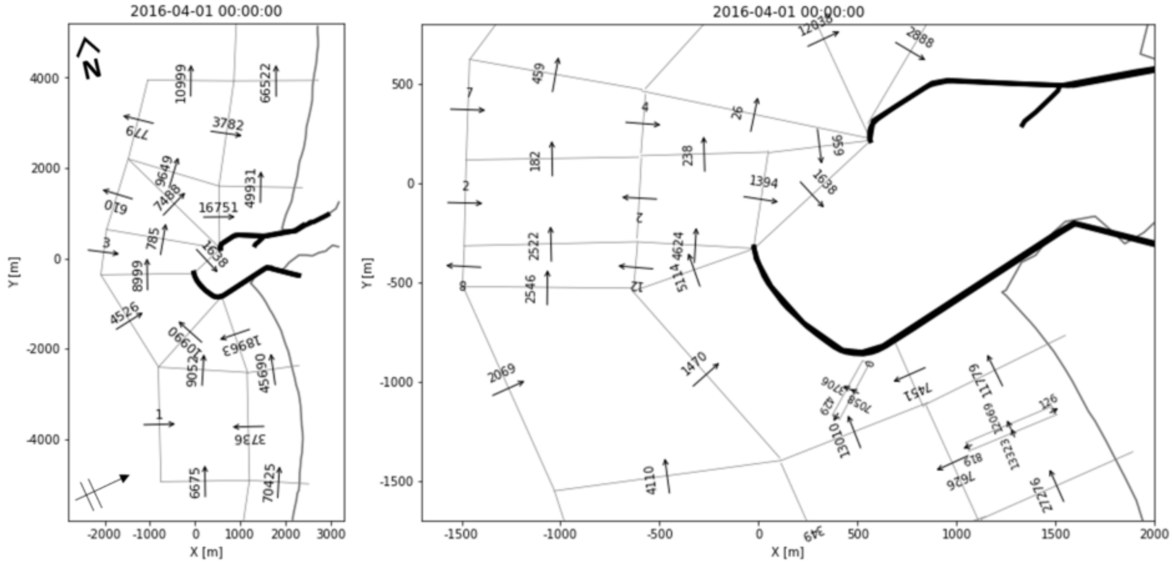


Figure E.8: Result base-line simulation of short-term morphodynamic simulation (1 month) under SW storm condition (H_s = 2.48 m, θ_{wave}=232°, v_{wind} =13.37 m/s, θ_{wind}=227°).

E.2.2.2. Inlet alternative 1 (deepened to -9 m-NAP): One month

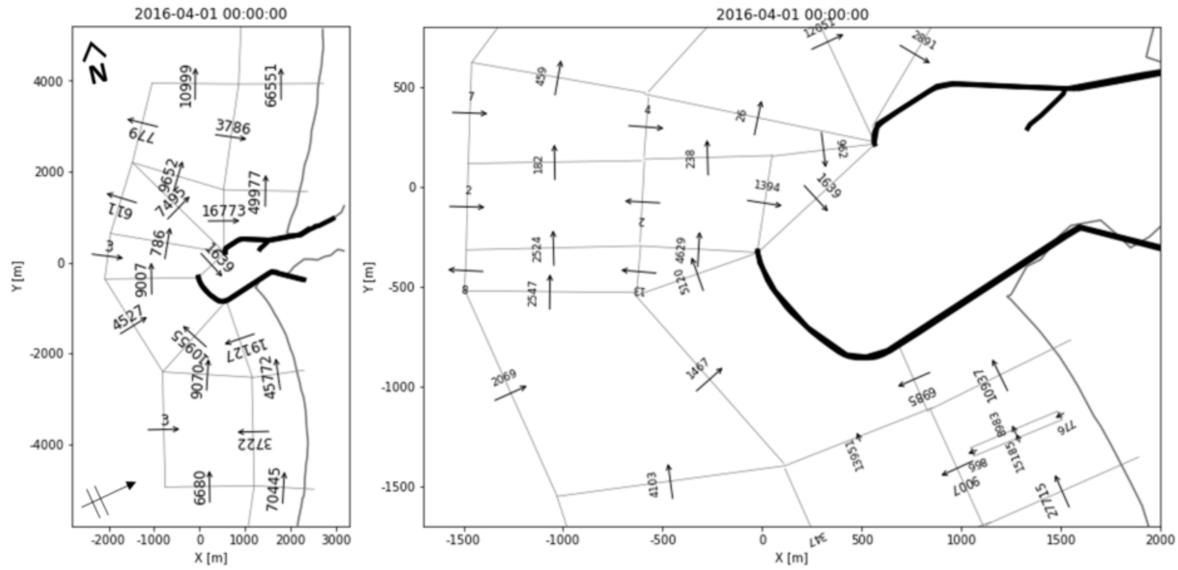


Figure E.9: Result simulation of short-term morphodynamic simulation (1 month) under SW storm condition (H_s = 2.48 m, θ_{wave}=232°, v_{wind} =13.37 m/s, θ_{wind}=227°). Inlet alternative 1 is incorporated into the simulation by deepening the an area to -9 m -NAP.

E.2.2.3. Inlet alternative 1 (deepened to -5 m-NAP): One month

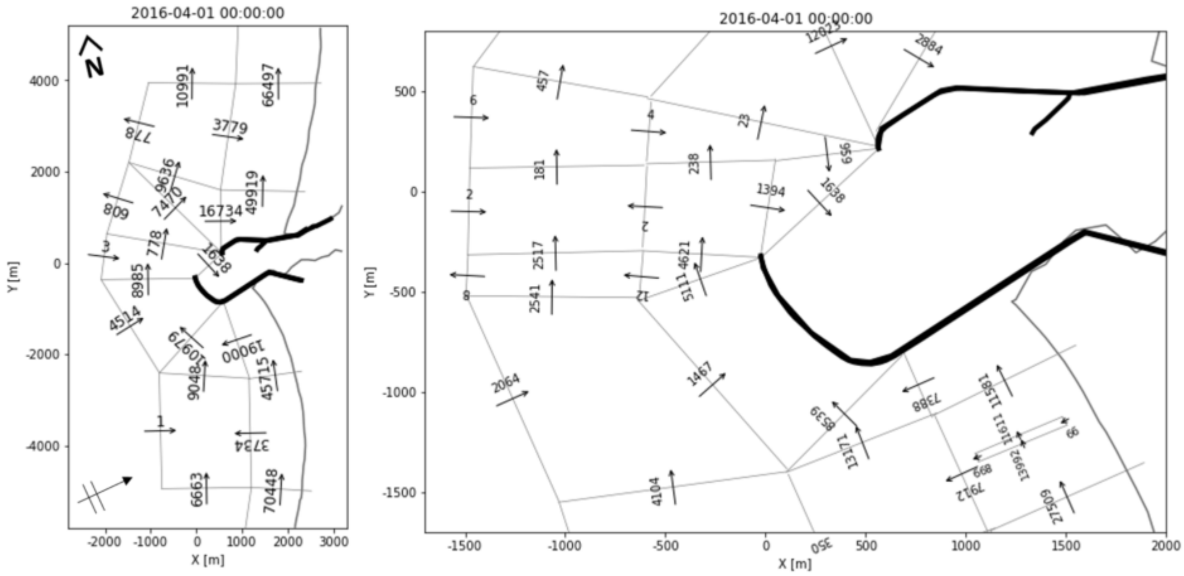


Figure E.10: Result simulation of short-term morphodynamic simulation (1 month) under SW storm conditions (H_s = 2.48 m, θ_{wave}=232°, v_{wind} =13.37 m/s, θ_{wind}=227°). Inlet alternative 1 is incorporated into the simulation by deepening the an area to -5 m -NAP.

E.2.2.4. Inlet alternative 2 (deepened to -15 m-NAP): One month

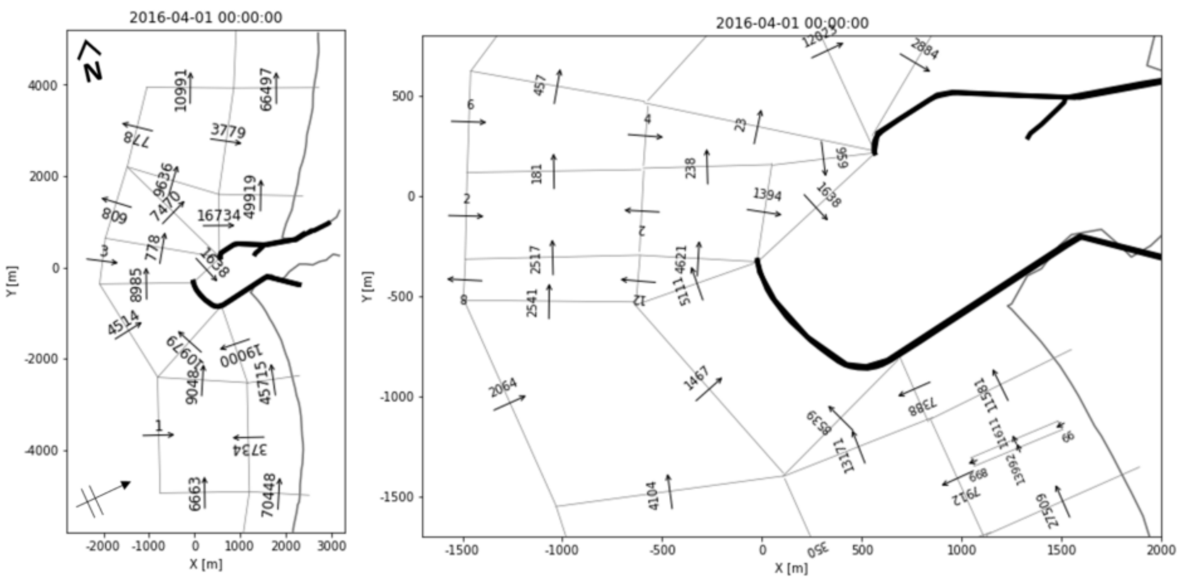


Figure E.11: Result simulation of short-term morphodynamic simulation (1 month) under SW storm condition (H_s = 2.48 m, θ_{wave}=232°, v_{wind} =13.37 m/s, θ_{wind}=227°). Inlet alternative 2 is incorporated into the simulation by deepening the an area to -15 m -NAP.

E.2.2.5. Base-line (Do Nothing) and 6 outlet concept (Large bypass volume): One and three months

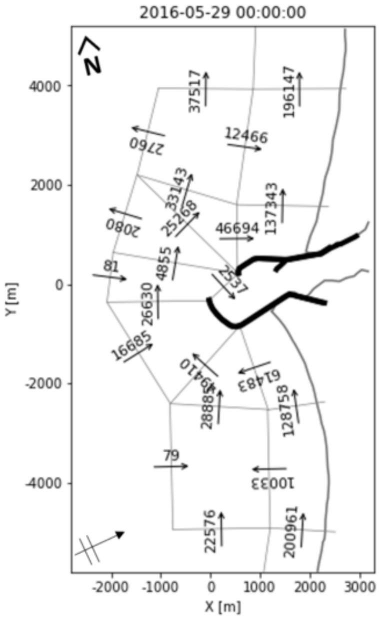


Figure E.12: Results base-line simulation. Simulation assumed SW storm condition (H_s = 2.48 m, θ_{wave}=232°, v_{wind} =13.37 m/s, θ_{wind}=227°) during three months.

E.2.2.6. 6 outlet concept (Large bypass volume): One and three months

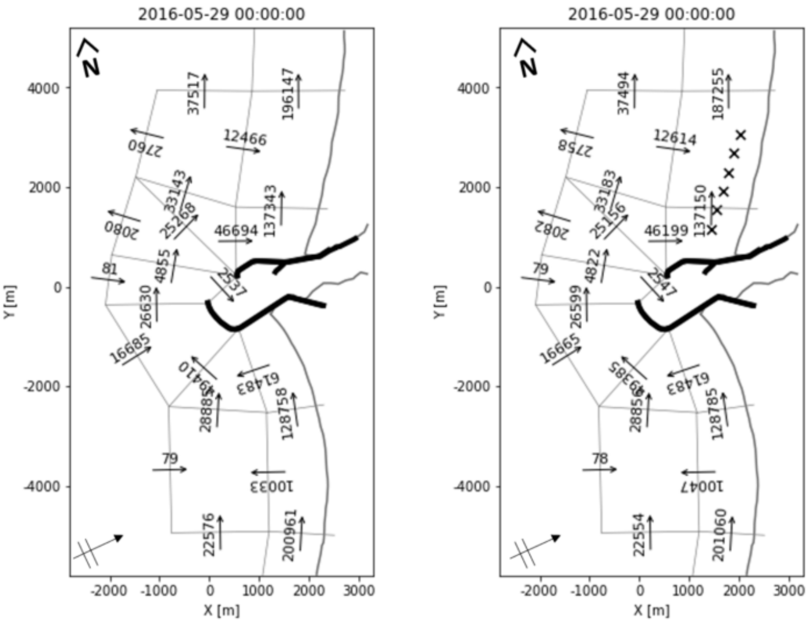


Figure E.13: Results of six outlet concept in which large bypass volume is assumed. Simulation assumed SW storm condition (H_s = 2.48 m, θ_{wave}=232°, v_{wind} =13.37 m/s, θ_{wind}=227°) during one month (a) and three months (b).

E.2.2.7. Bed level changes throughout time inlet Alternative 1

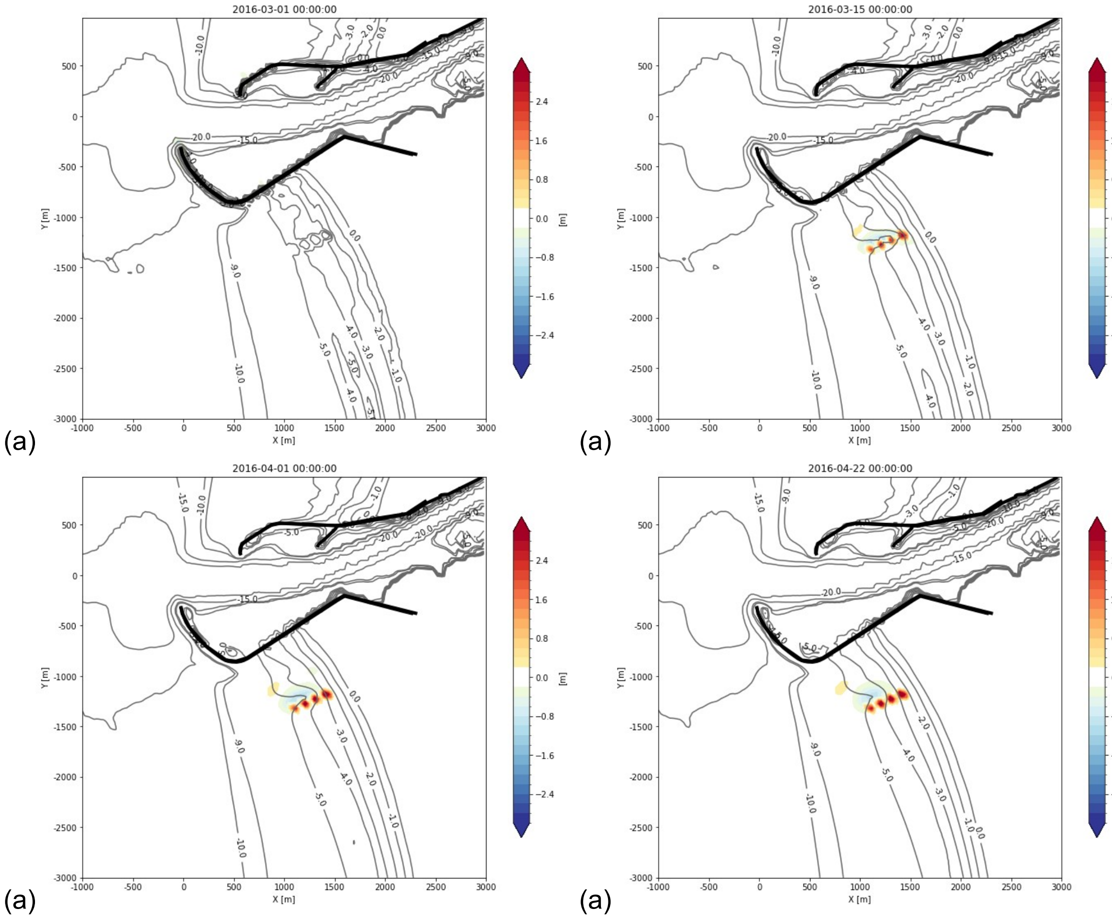


Figure E.14: Modelled bed level changes compared to reference simulation for Alternative 1: 'Jetty from beach'. Here, an initial deepening to -9m MSL is performed over an area of 420m x 30m. Simulation starts (t=0) on March 1, 2016 (a), and the figure captures the progression 15 days post-start (b); 1 month post-start (c) and 53 days post-start (d).

E.3. Ecological impact results

E.3.1. Result benthimeter calculations

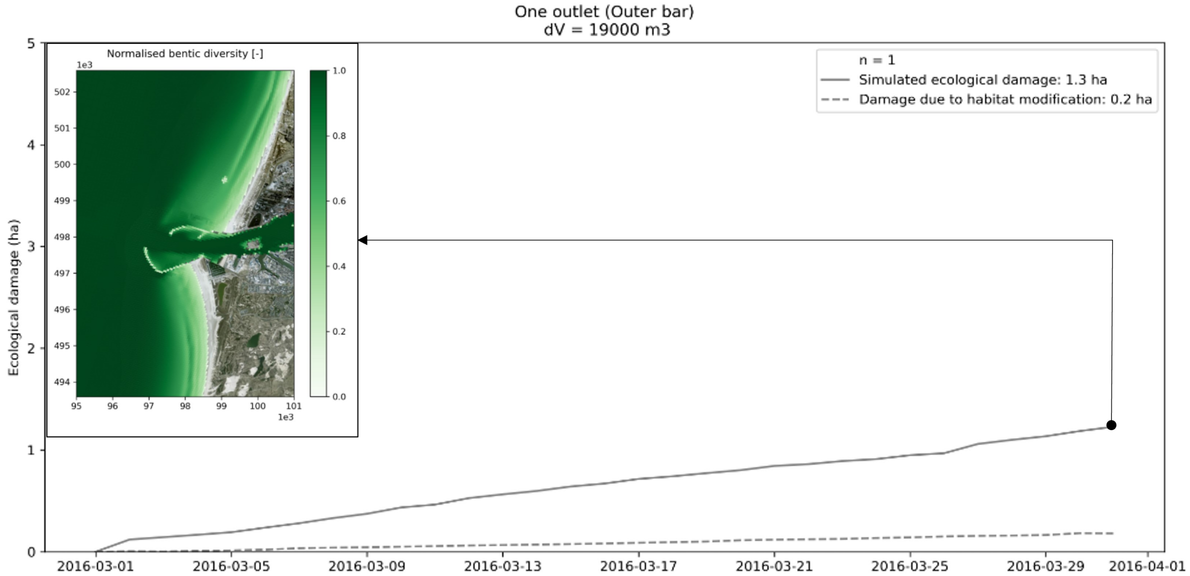


Figure E.15: Results Benthimeter calculation for concept 1 outlet disposal at outer bar, bypass quantity of 11,700 m^3/mnt.

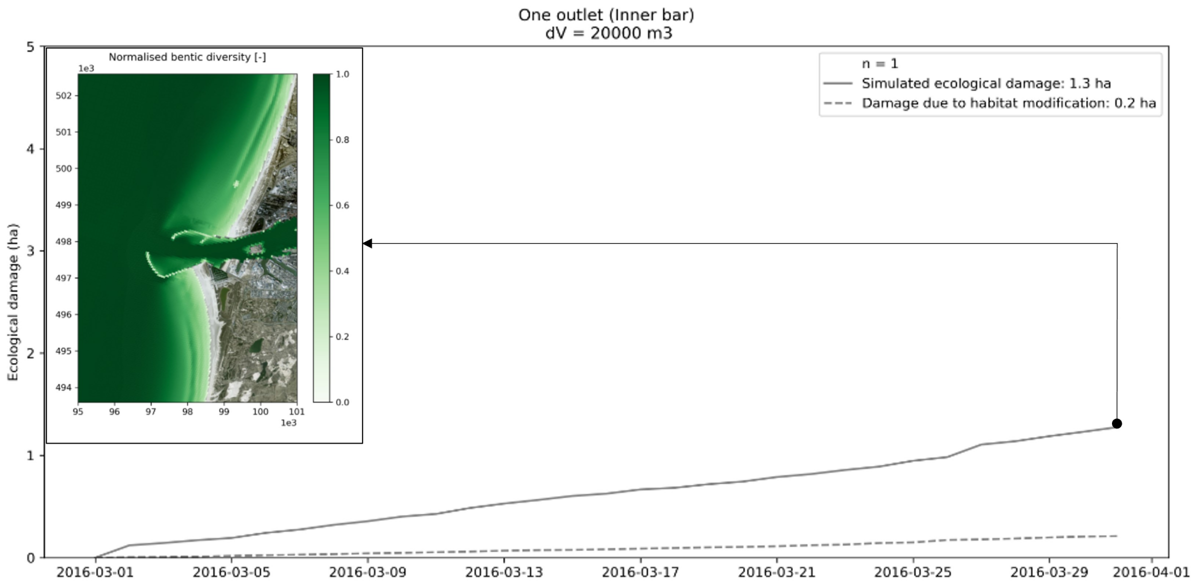


Figure E.16: Results Benthimeter calculation for concept 1 outlet disposal at inner bar, bypass quantity of 11,700 m^3/mnt.

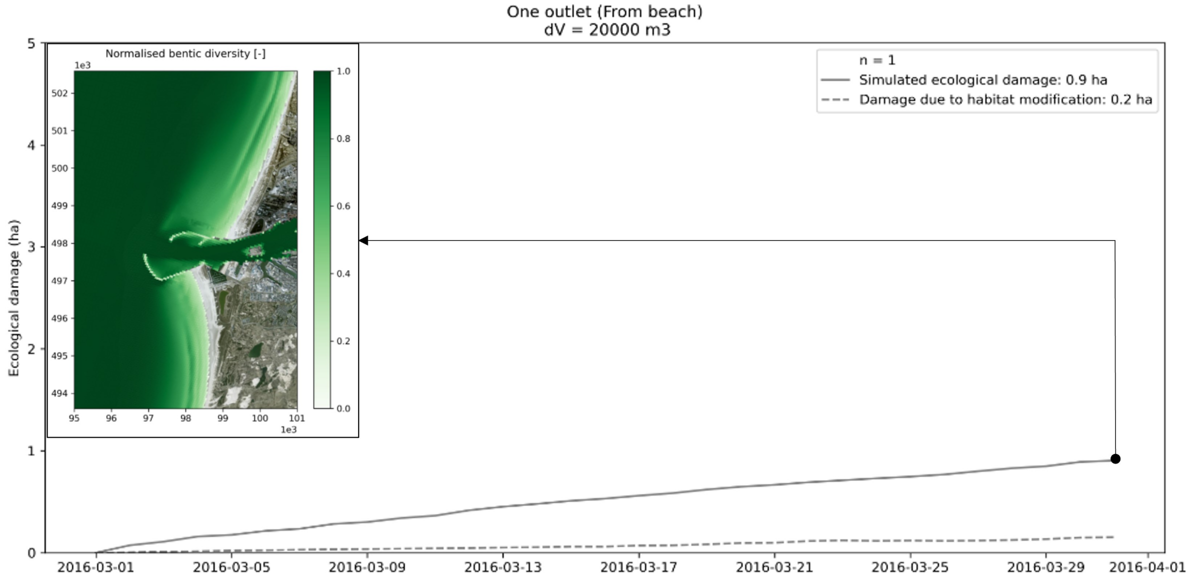


Figure E.17: Results Benthimeter calculation for concept 1 outlet disposal from beach, bypass quantity of 11,700 m^3/mnt.

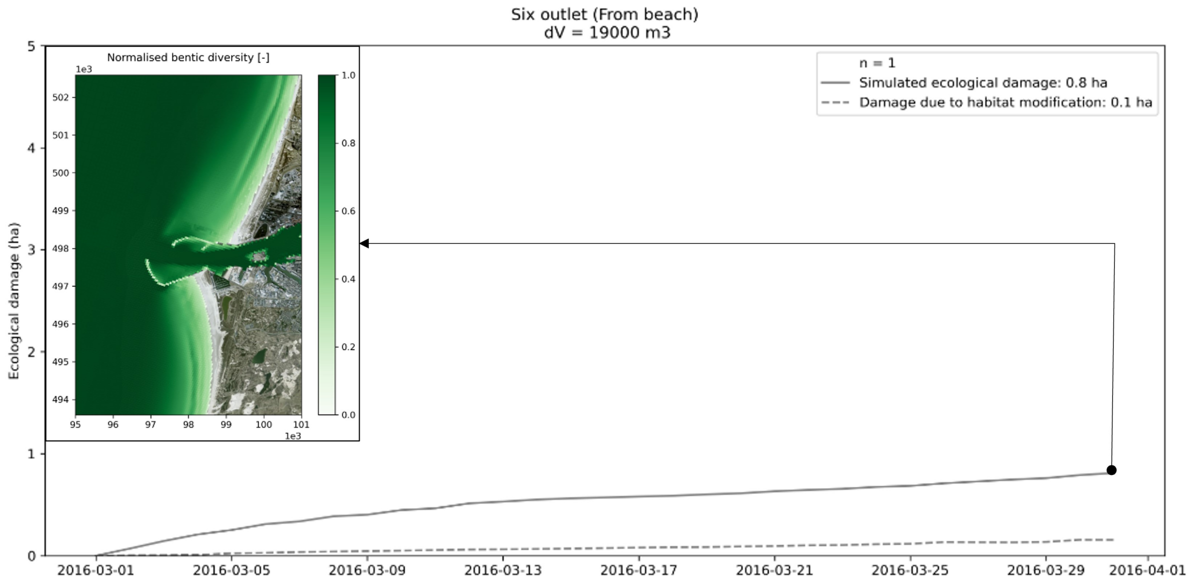


Figure E.18: Results Benthimeter calculation for concept with 6 outlets, disposal from beach, bypass quantity of 11,700 m^3/mnt.

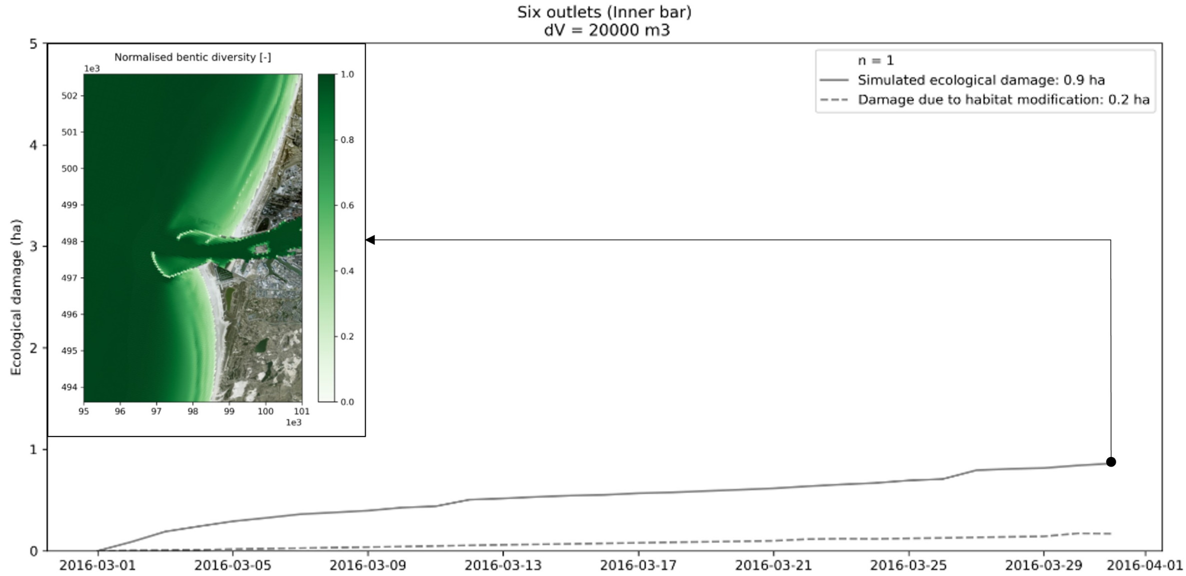


Figure E.19: Results Benthimeter calculation for concept with 6 outlets, disposal from beach, bypass quantity of 11,700 m^3/mnt.

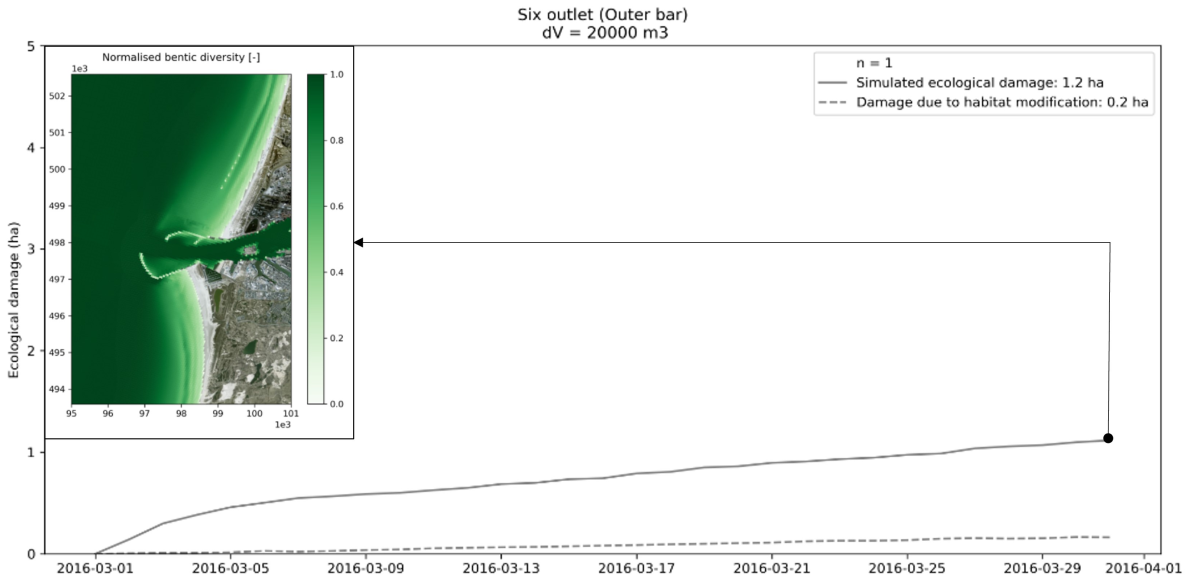


Figure E.20: Results Benthimeter calculation for concept with 6 outlets, disposal from beach, bypass quantity of 11,700 m^3/mnt.

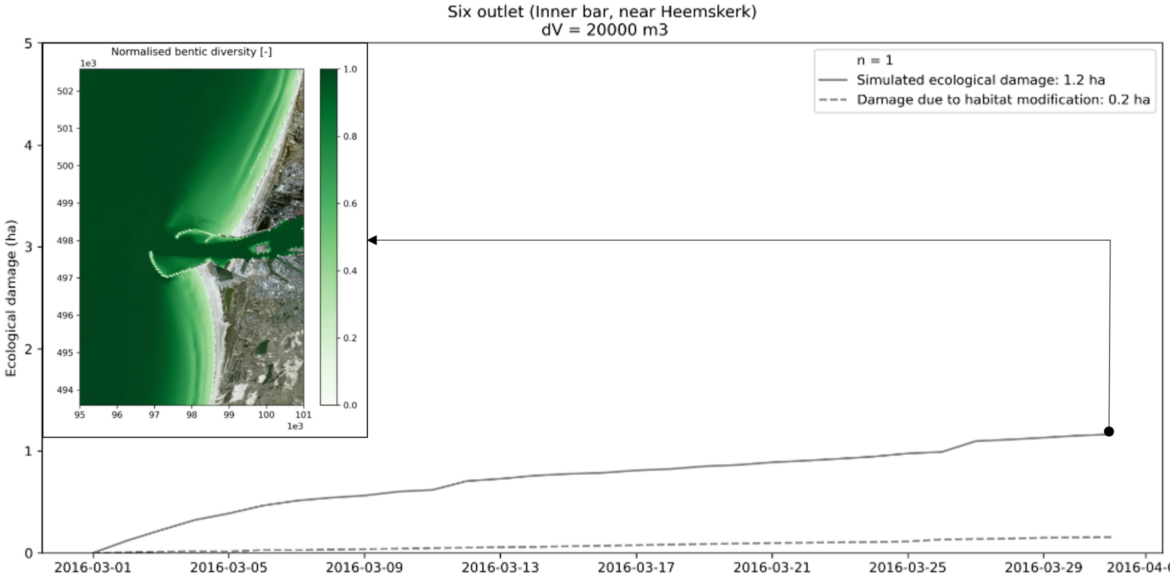


Figure E.21: Results Benthimeter calculation for concept with 6 outlets, disposal from beach, bypass quantity of 11,700 m^3/mnt.

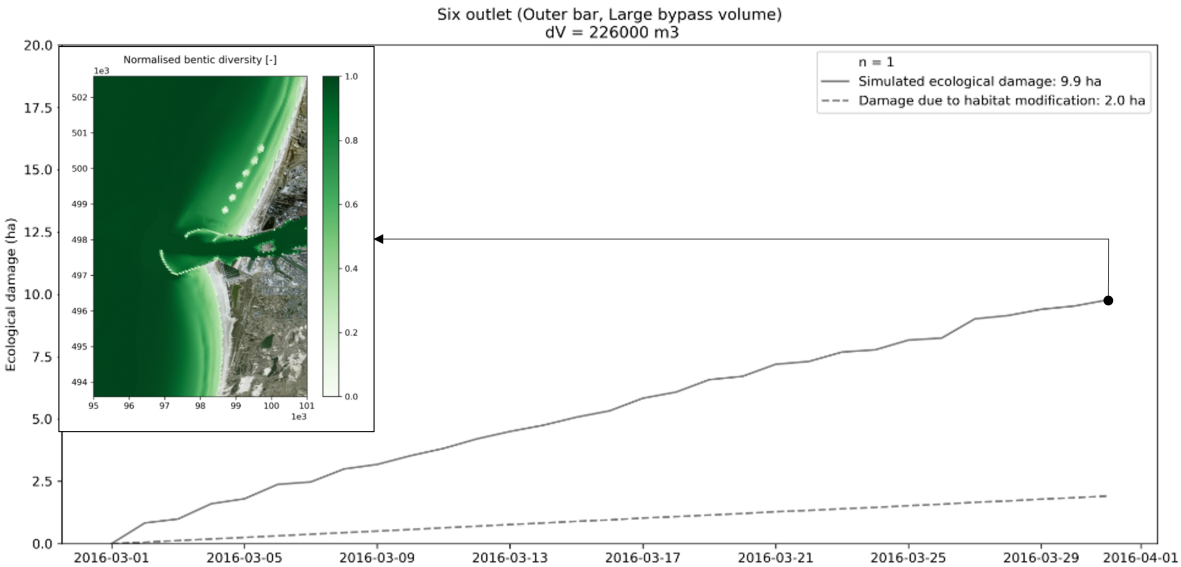


Figure E.22: Results Benthimeter calculation for concept with 6 outlets, disposal from beach, bypass quantity of 140,000 m^3/mnt.

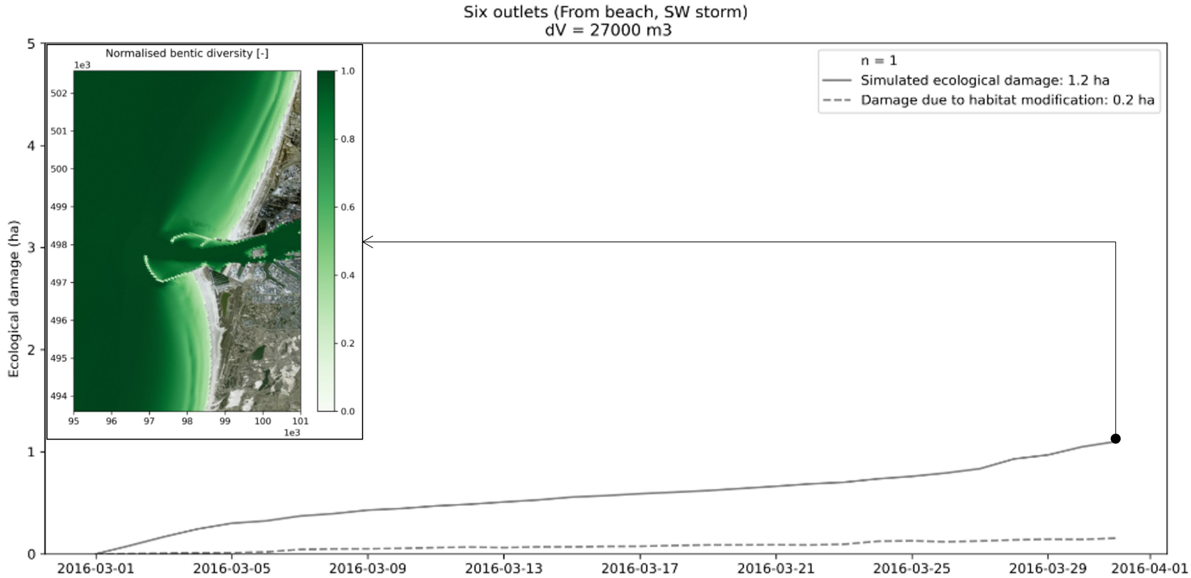


Figure E.23: Results Benthimeter calculation for concept with 6 outlets under SW storm, disposal from beach, bypass quantity of 11,700 m^3/mnt.

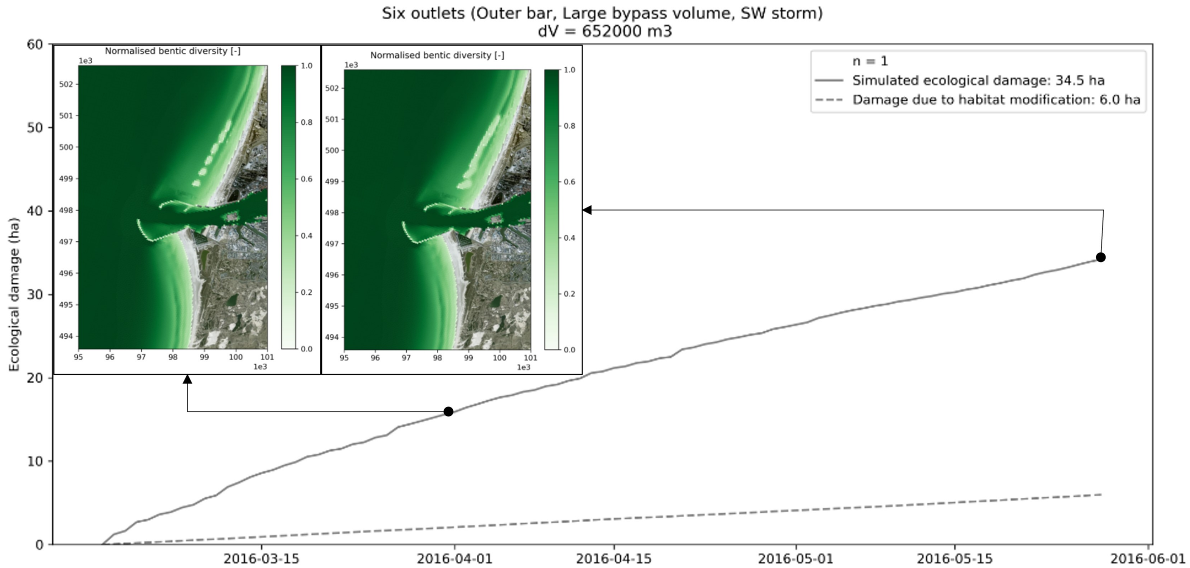


Figure E.24: Results Benthimeter calculation for concept with 6 outlets under SW storm, disposal at outer bar, bypass quantity of 140,000 m^3/mnt.